CONTEXT SENSITIVE ROADWAY SURFACING SELECTION GUIDE

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U.S. Department of Transportation
Federal Highway Administration

CTIP

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
12300 West Dakota Avenue
Lakewood, CO 80228

FOREWORD

The Federal Lands Highway (FLH) Division of the Federal Highway Administration (FHWA) is the primary road-builder for the National Park Service, Forest Service, Fish and Wildlife Service, and several other government agencies. The roads constructed or rehabilitated by FLH are generally low to medium volume roads. FLH's customers, as well as communities, environmental organizations, and individual landowners, are increasingly concerned about the selection of roadway surfacing types – in particular the riding surface on proposed projects. Often the project stakeholders have difficulty agreeing on a preferred surfacing type because of biases of performance, aesthetics, or other issues.

A Guide has been prepared that documents the available options for roadway surfacings, and provides a decision-making process to allow consideration of functionality, performance, durability, safety, life-cycle costs, as well as aesthetics and environmental impacts. This Guide presents a review of FLH's Project Delivery Process (PDP) and a proposed roadway surfacing selection process that includes consideration of context sensitivity, to be used in conjunction with the PDP. A CD-ROM titled *Roadway Surfacing Options Photo Album* accompanies this Guide.

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Notice

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16. Abstract

This Context Sensitive Roadway Surfacing Guide documents the available options for roadway surfacing, and provides a decision-making process to allow consideration of all conventional engineering design factors, such as, structural capacity, performance, durability, safety, life-cycle costs, but will also allow consideration of aesthetics, context compatibility, and environmental impacts. The Guide presents a review of FLH's Project Delivery Process (PDP) and a roadway surfacing selection process that includes consideration of context sensitivity, to be used in conjunction with the PDP. A CD-ROM titled *Roadway Surfacing Options Photo Album* accompanies the Guide.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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ACRONYMS

Acronym	Definition
3R	Rehabilitation, Restoration, and Resurfacing
4R	Rehabilitation, Restoration, Resurfacing, and Reconstruction
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
BOD	Biological Oxygen Demand
CATX	Categorical Exclusion
CBR	California Bearing Ratio
CFLHD	Central Federal Lands Highway Division
CIR	Cold In-Place Recycling
CMAC	Cold Mix Asphalt Concrete
COTR	Contract Officer's Technical Representative
CSD	Context Sensitive Design
CSS	Context Sensitive Solutions
DEIS	Draft Environmental Impact Statement
DOT	Department of Transportation
EA	Environmental Assessment
EIS	Environmental Impact Statement
EFLHD	Eastern Federal Lands Highway Division
ESAL	Equivalent Single Axle Load
FDR	Full Depth Reclamation
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
FONSI	Finding of No Significant Impact
HACP	Hot Asphalt Concrete Pavement
HIR	Hot In-Place Recycling
LCC	Life-Cycle Cost
NCHRP	National Cooperative Highway Research Program
NEPA	National Environmental Policy Act
NPS	National Park Service
OGFC	Open-Graded Friction Course
PCC	Portland Cement Concrete
PCCP	Portland Cement Concrete Pavement
PDP	Project Delivery Process
PG	Performance Grade
PS&E	Plans, Specifications, and Estimate
RAP	Reclaimed Asphalt Pavement
RCA	Reclaimed Concrete Aggregate
RCC	Roller Compacted Concrete
RMP	Resin Modified Pavement
ROD	Record of Decision
ROW	Right of Way
SCR	Special Contract Requirements

Acronym	Definition
SHPO	State Historic Preservation Officer
SLC	Structural Layer Coefficient
SMA	Stone Matrix/Mastic Asphalt
SN	Skid Number
SOW	Statement of Work
T&E	Threatened and Endangered
TRB	Transportation Research Board
USFS	United States Forest Service
WFLHD	Western Federal Lands Highway Division

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA), its customers, communities, environmental organizations, and individual landowners are increasingly interested in the road surfacing types used for new road projects. Arising from this increased interest in the appearance of roadway surfacings, the Federal Lands Highway (FLH) Division of the FHWA has developed a Context Sensitive Roadway Surfacing Selection Guide (Guide). The purpose of this Guide is to provide consistent, objective, and comprehensive information regarding all roadway surfacing types and to present a rational, transparent, systematic process for selecting surfacing types for a particular project or site application. The selection process itself is intended to facilitate discussion and understanding of critical project issues and their relative importance to the overall project. A review of the existing literature indicates that this Guide is the first to explicitly include aesthetics and context sensitivity in the roadway surfacing selection process.

This Guide is intended to be used by all stakeholders with an interest in the roadway surfacing selection process for a FLH project. Therefore, an effort has been made to present this information in a manner that is understandable to those without a technical background in road or pavement design. The Guide contains a brief explanation of technical terms that relate to road construction materials and performance, an introduction to pavement design concepts, and a description of the FLH project delivery process. Within the context of the roadway project delivery process, the Guide presents a rational selection process to facilitate the identification of the optimum roadway surfacing for a particular project. The selection process allows consideration of the required engineering design factors, such as structural capacity, ride comfort, performance, durability, and safety, but also allows consideration of other important factors, such as aesthetics, context compatibility, and environmental impacts, in an integrated manner. While the step by step approach to surfacing selection is intended to be rigorous, it is also flexible and still allows for engineering judgment in the final decision-making process. The Guide may be used for any roadway project, but it is particularly useful for roads in culturally, environmentally, or historically sensitive areas where aesthetics and context compatibility have elevated considerations.

A unique feature of this Guide is the inclusion of a comprehensive, yet concise, catalog of over 50 roadway surfacing products. This catalog is provided as background to the selection process and is an easy-to-use source of independent product technical data. The product descriptions contain information on where the surfacings can be used, design parameters, contractor availability, serviceability expectations, safety, potential environmental impacts, appearance, and cost. A bibliography and reference sources are also provided when additional, more detailed, product information is needed. The catalog also includes some products that are often used as part of the roadway pavement structure, but are not suitable for use as a permanent roadway surfacing, such as some recycling products. These have been included in the Guide since they are frequently used as temporary surfacings and their behavior is integral to the performance of the permanent surfacing placed immediately above them, especially on road rehabilitation projects. The Guide is intended for use on both new road construction or reconstruction projects (i.e. 4R projects) as well as on road resurfacing and rehabilitation projects (i.e. 3R projects).

One of the main focuses of the Guide is to present the widest possible range of surfacing alternatives, including those which are not commonly used, to maximize the effectiveness of the selection process as a tool for identifying the optimum surfacing for a particular project, based on the specific project's conditions and needs. Since stakeholders may be unfamiliar with many of the surfacings included in the Guide and since appearance and aesthetics can be key discriminators in the selection process, the Guide also includes a CD-ROM photo album that shows examples of the various products in service. While many of the applications depicted are from FLH projects, the photo album includes some applications from around the world.

Ultimately, the Guide is intended to facilitate the public consultation process and to assist in the selection of an appropriate roadway surfacing for a particular project or application, especially in culturally, environmentally, or historically sensitive areas. The selection process permits a balance between functionality, strength, and cost while ensuring that the completed roadway enhances or is at least compatible with the surrounding landscape. In addition, one of the hoped for benefits of this Guide is to bring a greater awareness to the diversity of road surfacing products currently available, to encourage their appropriate use, and to achieve greater recognition for the importance of context compatibility in the selection of roadway surfacings.

CHAPTER 1 — INTRODUCTION

BACKGROUND

The Federal Lands Highway (FLH) Division of the Federal Highway Administration (FHWA) works in cooperation with Federal land management agencies, state highway agencies, and local highway agencies to plan, design, construct, and rehabilitate highways and bridges on federally owned lands or roads that access federally owned lands. The program includes forest highways, public lands highways, park roads, parkways, refuge roads, and Indian reservation roads. These roads serve recreational travel and tourism, provide sustained economic development in rural areas, and provide needed transportation access. Overall, the FLH program provides funding for more than 145,000 kilometers (90,000 miles) of federally owned and public authority owned roads that serve Federal lands. The roads constructed or rehabilitated by FLH are generally low to medium volume roads.

The FLH has found that customers, communities, environmental organizations, and individual landowners are increasingly concerned about the road surface types used for proposed road projects. The FLH is finding it more difficult to reach consensus on surface type selection due to the lack of consistent and comprehensive information regarding alternative surface types and a defined process for selecting surface types. As a result, FLH has funded development of a Context Sensitive Roadway Surfacing Selection Guide (Guide). This Guide documents the available options for roadway surfacing and provides a decision-making process to allow consideration of engineering design factors, such as structural capacity, performance, durability, and safety, as well as other factors, including aesthetics, context compatibility, and environmental impacts. A CD-ROM photo album of roadway surfacings accompanies this Guide.

One recent project, the Guanella Pass Road Improvement Project located in the state of Colorado, illustrates the challenges the FLH currently faces when attempting to reconstruct a road. The maintaining agency desired a surface that was easy and inexpensive to maintain. The U.S. Forest Service (USFS) requested a surface that resulted in little to no sediment transport into nearby creeks. Many of the public and environmental groups wanted a surface that appeared rustic and discouraged excessive speed. As a result, three surface types were selected for use on different segments of the road in an attempt to address, at least partially, all of the concerns expressed by these parties. The surface types were 1) asphalt concrete with a chip seal, 2) multiple surface treatments, and 3) gravel with a dust suppressant. Reaching agreement on the use of these three surface types was a long and protracted process, creating substantial project delays. Given this experience, the engineering and environmental staff from the FLH agreed that there was a need for some additional “tools” that would expedite road surface selection for future road projects. These tools include:

- A comprehensive catalog of available roadway surfacing types that would facilitate the identification of viable roadway surfacings and allow them to be understood and evaluated by both technical and non-technical persons;
- A rational and transparent evaluation and selection process that allowed competing needs and objectives, such as performance, aesthetics, and cost, to be considered in a roadway surfacing selection process; and
- Presentation and brochure material that would explain the process to users and attendees at public information meetings.

This Guide was developed by an independent consultant to provide the above "tools" to FLH to assist in selecting a context sensitive roadway surfacing for FLH projects. Oversight of the preparation of the Guide came from the Central Federal Lands Highway Division (CFLHD)-based Contracting Officer's Technical Representative (COTR), and an Advisory Committee comprised of cross-functional representatives from the CFLHD, the Eastern Federal Lands Highway Division (EFLHD), the Western Federal Lands Highway Division (WFLHD), and the FHWA Resource Center.

The traditional approach to transportation infrastructure design has been to provide the highest level of functionality and safety at the least possible cost. Environmental impacts, cultural sensitivity, and aesthetics have not always been included in these design considerations. However, in 1997, FHWA published its groundbreaking document, *Flexibility in Highway Design*,(1) and more recently in May 2004, AASHTO published *A Guide for Achieving Flexibility in Highway Design*.(2) These documents provide ideas, processes, and options for designing more environmentally friendly highways, without compromising safety and mobility. Such an approach is referred to as Context Sensitive Solutions or CSS. A vital component of the CSS approach is to seek public input early in the design process so that community interests can be identified and creative thinking fostered in arriving at solutions. Such solutions will not be universally applicable but will be influenced by the specific characteristics of the site and the context of its use.

Though the CSS approach has been mainly applied to geometric design, it also sets the framework for the development of this FLH Guide. In its role as the primary road-builder for Federal Lands, the FLH interacts with numerous stakeholder groups. These include land owners, permitting agencies, community groups, and environmental organizations. When considering preliminary design alternatives, it is critical that roadway surfacing treatment options, especially those that may be innovative, be effectively communicated to the stakeholder groups. Effective communication of these alternatives should include:

- Photographs of the treatments in service.
- Costs of the treatments.
- Information on the functionality, durability, life expectancy, maintenance requirements, constructability, etc.
- Assessment of any environmental impacts.
- Any other relevant information, such as limitations on use, availability, etc.

This Guide provides the necessary information and resources needed to educate stakeholders about the different roadway surfacing options available and the process used to select the preferred surfacing type for a particular project.

STRUCTURAL PAVEMENT DESIGN CONCEPTS

It is important that a project team understands the fundamental principles of roadway pavement structural design prior to beginning the surfacing selection process. A basic introduction to some structural pavement design concepts is presented here. For the purposes of this introduction, the term "pavement" includes the roadway surfacing and any native or imported materials under the surfacing that are counted on to work in combination to provide a structure capable of supporting vehicular traffic and protecting the subgrade.

Roadway pavements are generally classified as either flexible or rigid. Flexible pavements are allowed to deflect somewhat under load, and the applied traffic loading is distributed down through the pavement structure. Examples of flexible pavements include Hot Asphalt Concrete Pavement (HACP) or granular surfacing. Rigid pavements are designed as rigid slabs that transfer very low pressures to the underlying support layer. Therefore, rigid pavement structures tend to have a lower overall pavement thickness than flexible pavements designed for the same traffic. The most common type of rigid pavement is Portland Cement Concrete Pavement (PCCP). Unit surfaces (e.g. brick, concrete pavers) function based on a combination of flexible and rigid pavement principles, but may be generally classified as flexible unless they are supported on a rigid base.

Roadway surfacings are also often classified as unbound or bound surfacings. Unbound surfacings are composed of particulate material that is not held together by a binding agent. Untreated aggregate, sand, or dirt roads are examples of unbound surfacings. Bound surfacings are composed of particulate material that is held together by a binding agent, such as asphalt or portland cement. Generally speaking, unbound surfaces have higher maintenance requirements than bound surfaces due to surface material loss and defects, leading to a more rapid decrease in ride quality and structural support.

Flexible Roadway Pavements

Flexible roadway pavements have four basic components, subgrade, base, surfacing, and a drainage system. The convention in flexible structural pavement design is to use successively stiffer layers from the subgrade up to the surfacing.

The subgrade is the roadway foundation and consists of the natural soil, or a placed and compacted earth or rock fill where the grade of the road needs to be raised. A properly designed pavement must ensure that sufficient layers of higher quality material are placed above the subgrade to protect it from excessive stress (caused by vehicle wheel loads) that would lead to deformation and, ultimately, failure. The strength of either natural or constructed subgrades can be improved by the addition of stabilizing products, such as cement, lime, fly ash, or a range of proprietary products. By increasing the subgrade strength, the use of stabilizers may allow for a reduction in the overlying base layer thickness.

The base layer is typically a high quality processed aggregate material. Frequently, the base layer is made up of two components, a lower subbase layer typically comprised of a sandy material with some gravel and placed directly on the subgrade, and a higher quality aggregate base layer comprised of a high quality crushed and graded material above it. Treated bases, using binding agents such as cement or asphalt, are sometimes used to increase structural capacity of the base layer.

The surfacing layer can range in thickness from relatively thin (e.g. chip seal) to relatively thick (e.g. HACP). Thin surfacing layers typically do not provide any strength to the pavement structure, but they can enhance ride quality and safety while preventing water infiltration into the pavement structure that can weaken the underlying layers. Thicker surface layers, such as HACP, provide some strength to the overall pavement structure, with the amount of structural support increasing with surfacing layer thickness. For thick surfacing designs, HACP is placed in lifts. Where more than one lift is needed, the top lift is referred to as the wearing course and the underlying lifts are referred to as binder courses. The wearing course is designed to provide a durable surface that can withstand the abrasion from tire impact, retain frictional characteristics, and contribute to the structural capacity of the pavement. The binder courses are designed to be sufficiently stiff to effectively distribute load and avoid permanent deformation.

On low volume aggregate surfaced roads, the aggregate is often used for the surfacing layer as well as the base course. In some cases, a different gradation of aggregate is used for the surfacing layer to improve ride quality and durability. In addition, the surfacing layer is sometimes treated to stabilize the material or to suppress dust generation.

Natural soils and aggregates lose strength when saturated, so providing adequate subsurface drainage of the aggregate layers is essential to the performance of a flexible pavement. In regions with prolonged sub-freezing temperatures, drainage is even more critical, since in the presence of a ready supply of water, fine grained soils may heave as they freeze and then become extremely weak as they thaw. Water infiltration is minimized by designing and constructing roadway surfacings with adequate cross slope to shed water off the surface. The subgrade should also be crowned to avoid ponding of water in the aggregate subbase. Some degree of water infiltration will occur in all pavements through cracks, unsealed shoulders, and the surfacing itself. The aggregate base and subbase layers in a pavement should be free draining to minimize the time and degree to which the pavement is saturated.

For rural roads, road drainage is best achieved by the use of open ditches with inverts extending below the top of the subgrade. The drainage system should have positive fall and regular outlets to avoid ponding of water in the ditches. Aggregate base and subbase layers should extend the full width of the road platform to allow drainage into the ditch. For urban roads where a concrete curb is used, road runoff is collected and removed through a system of catch basins and storm sewers.

Rigid Roadway Pavements

Rigid pavements also have four basic components, subgrade, subbase, concrete slab, and a drainage system. The subgrade and drainage components are essentially similar to those for flexible pavements.

The subbase layer (also referred to as a base layer) is a relatively thin aggregate layer placed directly on the subgrade. While it does contribute a little to the pavement strength, its main function is to provide a uniform working surface for constructing the slab and to enhance uniformity of subgrade support. For high traffic applications, the slab is sometimes supported on an open graded drainage layer that provides sub-slab drainage and prevents the subgrade from pumping under repeated load applications.

The most commonly used rigid pavement is portland cement concrete pavement (PCCP). A pattern of control joints is required to avoid random shrinkage cracking. Good load transfer between adjacent slabs is required for good concrete pavement performance. For low traffic applications, aggregate interlock across the joint is usually adequate. For higher volume roads, dowel bars may be required across the transverse joints.

STRUCTURAL PAVEMENT DESIGN

The structural design of a road pavement involves the selection of a combination of road construction materials and their thicknesses to provide a serviceable road pavement for a predetermined length of time, typically 15 to 30 years, and anticipated traffic loading. This design period is called the design life and is defined as the period over which the road provides an acceptable level of performance with only preventative maintenance activities required. A wide range of considerations affect the choice of materials and layer thicknesses. The typical information that a pavement designer needs to establish a design is as follows:

- Subgrade: Since this is the foundation of the pavement structure it must be characterized from the perspective of soil type, strength, drainage characteristics, seasonal variability, etc.
- Traffic: To complete a pavement design, at least three traffic parameters are needed, namely, the Average Annual Daily Traffic (AADT), which is the average number of vehicles per day using the road section; the percentage of the AADT that consists of heavy vehicles such as trucks and buses; and the projected traffic growth rate over the life of the roadway.
- Climate: The climate has a large influence on the representative strength to be selected for the subgrade. It is necessary to know whether the road will be subject to prolonged sub-freezing temperatures, the extent of precipitation, range of in service temperatures for asphalt mix selection, etc.

A wide range of other considerations, such as desired level of service, drainage, life-cycle costing, construction materials, degree of reliability, environmental considerations, and context sensitivity are also relevant. Successful structural pavement design always requires an integration of adequate structural design and appropriate materials selection, taking into account local experience, cost effectiveness, and level of service required for the specific roadway project.

Pavement Distress and Maintenance

Over time, roadway surfacings begin to exhibit signs of distress due to traffic loading and wear, water infiltration, material loss, and environmental conditions. Common types of distress include cracking, rutting, raveling, washboarding, potholing, spalling, and faulting. If not treated, surface distresses can lead to accelerated pavement degradation and, ultimately, total pavement failure. However, if the surfacing is treated with timely pavement maintenance, pavement serviceability can be maintained and the effective pavement life can be extended. In most cases, the design life given for a particular surfacing is based on the assumption that the road will receive regularly scheduled maintenance; if the regularly scheduled maintenance is not performed, the actual life of a pavement can be significantly reduced. Common pavement maintenance techniques include crack and/or joint sealing, patching, additional surface treatments, overlays, grading, and ditch and culvert cleaning. The types and frequency of maintenance required varies for different surfacing types. Generally speaking, surfacings that have lower initial costs require more frequent maintenance and, thus, have higher maintenance costs. Surfacings with high maintenance requirements may be acceptable for a low volume road if the funds available for road construction are limited and maintenance crews are readily available to perform periodic maintenance. On the other hand, frequent maintenance requirements may be unacceptable for a high volume road where user delays would be significant.

Pavement Life-Cycle Costs

Most roadway surfacings require some maintenance intervention during their design life. Thus, when comparing the costs of alternative roadway surfacings, one must consider the anticipated future maintenance costs in addition to the initial construction cost.

In addition to future maintenance costs, differences in the expected service lives of different surfacings must also be considered. By taking into consideration initial construction costs, expected maintenance costs, expected service life, and the time value of money, a life-cycle cost can be calculated for a specified analysis period. The overall objective of a life-cycle cost approach to surfacing selection strategy is to provide the best long-term value to the owner or agency for their investment in road infrastructure.

The selection process used in this Guide assumes that appropriate life-cycle cost analysis data will be available when comparing alternative surfacing strategies. The extent of life-cycle cost analysis required for a particular project will depend on its size and complexity. The FHWA recommended practice, *Life-Cycle Cost Analysis in Pavement Design*,[3] should be consulted for more details on how to undertake an appropriate life-cycle cost analysis.

ROADWAY SURFACING TYPES

To help facilitate the roadway surfacing selection process, a list of available roadway surfacing products was assembled and pertinent information was compiled for each roadway surfacing product. A list of the available roadway surfacing options identified for this Guide is provided in Table 1. Given the wide range of road surfacing types available, a rational system for classification is helpful. For the purposes of this Guide, the roadway surfacing options were classified into four major categories: Paved and Sealed Surfaces, Aggregate and Soil Surfaces, Unit Surfaces, and Recycling and Reclamation Alternatives. Paved and Sealed Surfaces include flexible and rigid bound surfacings, non-structural asphalt surface treatments, structural asphalt surfacings, and Portland cement concrete surfacings. Aggregate and Soil Surfaces include untreated aggregate/soil surfacings and aggregate/soil surfacings that have been treated or stabilized with dust palliatives, soil stabilizers, or geosynthetic products. Unit Surfaces include different unit paver types and natural stone cobbles. Recycling and Reclamation Alternatives include products that are produced in situ on the road and/or contain some recycled road materials and include recycled HACP, hot and cold In-Place Recycling, and Full Depth Reclamation. A few of the roadway products included are rarely, if ever used as roadway surfacings, but were included in the list because they are commonly used as subgrade or base course layers and are sometimes used as temporary surfacing during construction or as direct support for the surfacings.

Information pertinent to the selection process was collected for each roadway surfacing product; this information is presented in a series of road surfacing product summary tables, located in Appendix A. The information in the product summary tables is organized based on the various criteria that will be used in the roadway surfacing selection process. Product information is presented related to the following criteria: application, design, construction, serviceability, safety, environmental concerns, aesthetics, and cost. In addition, sections have been included for general information, example projects, and select print and internet references. The intent of the summary tables is to provide unbiased product information, in quantitative measures when possible, that can be used by planners and designers at various stages of the roadway project.

The summary tables include information on certain impacts, mainly related to the environment and safety, that are associated with a particular road surfacing product. The impacts presented are limited mainly to direct impacts; indirect impacts are not discussed in detail. Direct impacts differ from indirect impacts in that direct impacts are those that result from the interaction of a component of the surfacing material with the local environment while indirect impacts occur as a potential consequence of the use or misuse of the road with the surfacing in place. Two possible indirect impacts not discussed for the surfacing types include vegetative and water quality impacts due to the use of deicing agents and roadkill due to increased speeds. While surface type is a factor for both of these indirect environmental impacts, a number of other factors contribute to such impacts (e.g. climate and maintenance practices for use of deicing agents and geometrics for increased speeds). As a result, it was determined to be too speculative to indicate potential indirect impacts as a consequence of the use of a specific roadway surface. Nevertheless, these indirect impacts may need to be considered, especially when evaluating bound versus unbound surfaces.

Although every effort has been made to be objective in the assessment of the various roadway surfacing products, a limited amount of information is available for many of the "non-traditional" products, especially proprietary products. Since most of this information is provided by the manufacturer/supplier, there is potential for the product information to be biased. Also, many proprietary products are "reformulated" regularly such that past performance is not necessarily an indication of future performance. As much as possible, the information provided in the tables is based on recent independent performance evaluations, case studies, field investigations, and owner/user testimony. The product summary tables should be continuously updated as new information becomes available in the future.

Roadway surfacing product use, performance, and cost can vary significantly, depending on the project location. Project-specific factors that vary by location include climate, environmental setting and conditions, availability of materials, equipment, and experienced contractors, local construction practices, maintenance practices, labor and material costs, and traffic characteristics. The information presented in the product summary tables represents, to the extent possible, general conditions and ranges found across the United States; however, local practices, experiences, and costs should be used to supplement the product summary sheets, whenever possible.

This Guide deals primarily with roadway surfacings, but also addresses related aspects of pavement design and the type of support needed for the exposed surface layer. It concentrates mainly on surface options for road reconstruction (i.e. 4R projects), but also includes resurfacing and rehabilitation treatments (i.e. 3R projects). The majority of road construction projects are for all-weather surfaced roads; however, there are also applications where seasonal roads are used and will continue to be used.

Table 1. Roadway Surfacing Product Listing.

CLASSIFICATION	SUB-CATEGORIES	ROAD SURFACING PRODUCTS
PAVED AND SEALED SURFACES	Asphalt Surfacing - Surface Treatments or Layers (non-structural)	Cape Seal Chip Seal Chip Seal over Geotextile Fog Seal Microsurfacing Multiple Surface Treatments (Seals) Open Graded Friction Course Otta Seal Sand Seal Scrub Seal Slurry Seal Ultrathin Friction Course

	Asphalt Surfacing - Surface Layers (structural)	Cold Mix Asphalt Concrete Pavement
		Hot Mix Asphalt Concrete Pavement (HACP)
		  Exposed Aggregate HACP
		  Imprinted/Embossed HACP
		  Pigmented HACP
		  Porous HACP
		Resin Modified Pavement
		Synthetic Binder Concrete Pavement

	Portland Cement Concrete (PCC) Surfacings	Cellular PCC
		Portland Cement Concrete Pavement (PCCP)
		  Exposed Aggregate PCCP
		  Pigmented PCCP
		  Porous PCCP
		  Stamped PCCP
		Roller Compacted Concrete
		Whitetopping

AGGREGATE AND SOIL SURFACES	Unbound and Mechanically Stabilized Surfacings	Cellular Confinement Fiber Reinforcement Geotextile/Geogrid Reinforcement Gravel (crushed or uncrushed) Sand
	Other Stabilized Surfacings (including dust palliative applications)	Chlorides Clay Additives Electrolyte Emulsions Enzymatic Emulsions Lignosulfonates Organic Petroleum Emulsions Synthetic Polymer Emulsions Tree Resin Emulsions

Table 1. Roadway Surfacing Product Listing (continued).

CLASSIFICATION	SUB-CATEGORIES	ROAD SURFACING PRODUCTS
	Stabilized Aggregate and Soil (other than surfacing)	Fly Ash (temporary surface) Lime (temporary surface) Portland Cement (temporary surface)
UNIT SURFACES		Brick Pavers Natural Stone Cobbles Unit Pavers Porous Unit Pavers
RECYCLING AND RECLAMATION ALTERNATIVES	Recycling Alternatives	Cold In-Place Recycling (temporary surface) Hot In-Place Recycling PCCP Recycling and Rehabilitation (temporary surface) Recycled HACP
	Full Depth Reclamation (FDR)	FDR-Cementitious (temporary surface) FDR-Emulsified Asphalt (temporary surface) Foamed Asphalt (temporary surface) Pulverization (temporary surface)

CHAPTER 2 — PROJECT DELIVERY PROCESS

INTRODUCTION

In order for the surfacing selection methodology presented in this document to be useful and effective for FLH projects, the process should fit within FLH's existing Project Delivery Process (PDP), which guides all aspects, including design and environmental review, of an FLH roadway project from its conception through to its construction. The purpose of this section is to provide a brief description of those steps in the PDP that can best accommodate the suggested surfacing selection methodology described in Chapter 3 of this Guide.

THE PROJECT DELIVERY PROCESS

The PDP has five principal steps: planning and programming, project development, advertise and award, construction, and evaluation. Because this Guide's suggested surfacing selection methodology takes into consideration environmental and aesthetic concerns, in addition to functionality, safety, and cost, the environmental review process appears to best accommodate the roadway surfacing selection process. As a result, the following discussion addresses only the Planning and Programming and Project Development steps that describe the environmental processes and design processes, and how these processes may accommodate the surface selection methodology. The relevant activities that occur during these steps are shown in Figure 1.

Planning and Programming

During the planning and programming step, it is helpful to consider the potential social, economic, and environment impacts a proposed roadway improvement may have while the project is still in the conceptual phase. In FHWA's *Flexibility in Highway Design*, the following questions are suggested for consideration when planning and programming decisions are being made:

1. How will the proposed project affect the physical character of the surrounding area?
2. Does the area have important or unique historic, natural, or visual characteristics?
3. What are the safety, capacity, and cost concerns associated with the project?

Preliminary answers to these questions can be developed through initial scoping activities, and addressed in the reconnaissance and scoping report (also known as the project planning report). The environmental information contained in that report typically includes the following:

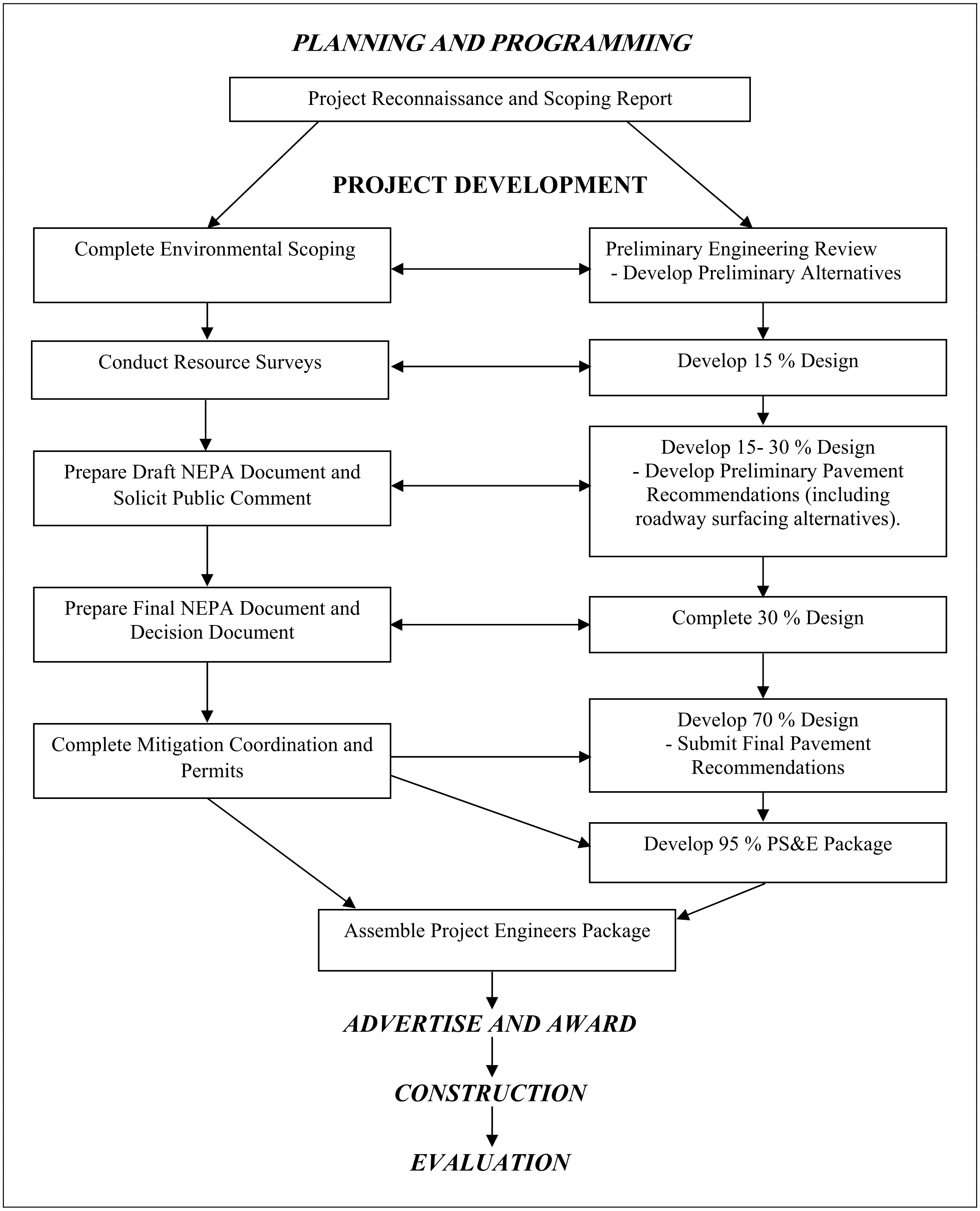

Figure 1. Flowchart. Project Delivery Process.

- Initial National Environmental Policy Act (NEPA) classification - Class 1 – Environmental Impact Statement (EIS), Class II – Categorical Exclusion (CATX), and Class III – Environmental Assessment (EA).
- Draft purpose and need statement.
- Preliminary list of alternatives.
- Potential environmental concerns or benefits associated with the project.
- Typical and atypical issues needed to be taken into consideration in the development of the project design.
- Existing survey data (traffic, environment, or mapping).
- Determination of whether the proposed project is consistent with local, state, or federal land management plans.
- Identifying the type of expertise needed on the cross-functional design team.

The principles of context sensitivity are implemented in this step and continue to be implemented during the subsequent Project Development step. Context sensitive design (CSD), also known as context sensitive solutions (CSS) — *is an approach to transportation design that considers the total context within which the transportation improvement project will exist. It is an interdisciplinary approach that involves all stakeholders to develop a transportation facility that fits its physical setting and preserves scenic, aesthetic, historic, and environmental resources, while maintaining safety and mobility.*[(4)] When practicing context sensitive design, the landscape, the community, and valued resources are understood before the engineering design is started.

During the Planning and Programming step, the project's context begins to be defined in the project planning report. As noted in *A Guide for Achieving Flexibility in Highway Design*,[(2)] the identification and engagement of all appropriate project stakeholders is critical to ensuring that the cross-functional design team accurately captures the context of the project. At the Planning and Programming step, typically the FLH partner agencies and sometimes the regulatory and resources agencies are contacted for information to assist in developing a preliminary characterization of the project's context and factors that need to be considered throughout the remainder of the PDP. Figure 2 depicts the many factors that could yield information regarding the project's context and that may need to be considered during planning as well as the remainder of the PDP.

Project Development

All of the project design and the majority of the project environmental compliance activities occur during the Project Development step of the PDP. During this step, engineering and environmental data are gathered through meetings with the various stakeholders, resource surveys, and engineering analysis to permit FLH to complete the design of the project and develop a NEPA decision document. As depicted in Figure 1, the project design and environmental compliance activities occur concurrently because each readily affects the other. As a result, it is critical that, as the arrows in Figure 1 indicate, the design and environmental data collected is shared amongst the cross-functional design team given that each affects the

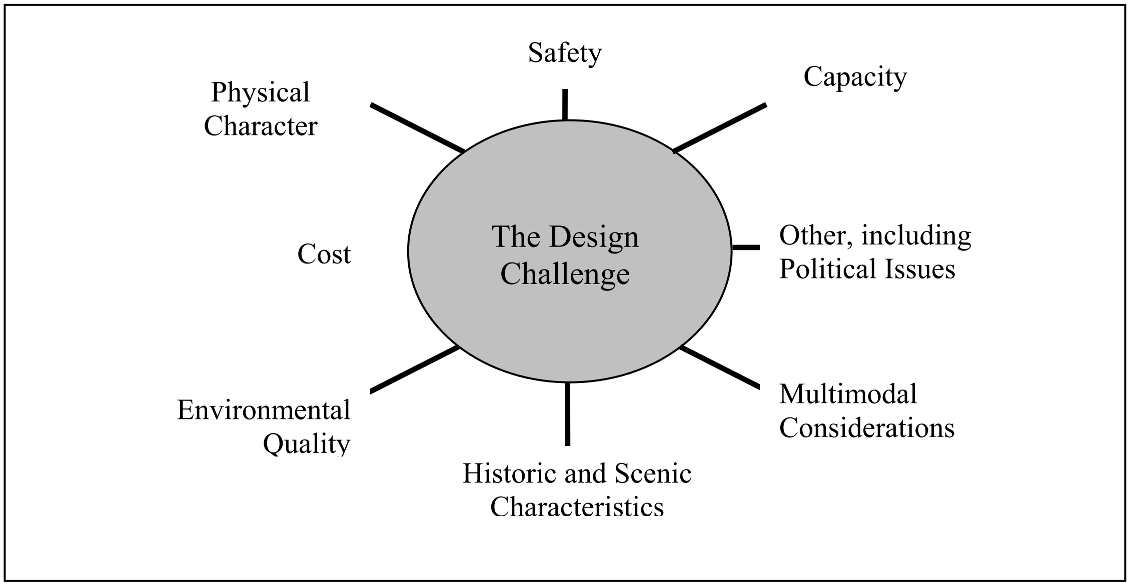

Figure 2. Schematic. Factors Considered in the Planning Phase of a Project.[(1)]

other. Below is a brief description of the environmental and design activities that occur concurrently with each other.

Preliminary Engineering Review and Environmental Scoping

Once the project NEPA classification is confirmed, scoping activities are formally undertaken, building on the information and input obtained during the planning and programming step. These scoping activities include conducting interagency and public meetings, the identification of preliminary alternatives, and the refinement of the purpose and need. At this point mailing lists are developed and project stakeholders are identified and contacted to solicit their input regarding the context of the project and possible impacts. Stakeholders may include, but are not limited to, various resource and regulatory agencies, individuals directly affected by the project, community-based organizations and interest groups, and local government officials. A series of questions presented below may be used by the cross-functional design team and stakeholders to help further define the context of a proposed project. This list is not meant to be a complete list and the users of this Guide may have other needs to be addressed to better define the context.

a) What are the physical characteristics of the corridor?
b) Is it an urban, suburban, or rural setting?
c) How is the corridor being used (other than for vehicular traffic)?
d) Are there destination spots along the corridor that require safe access for pedestrians to cross?
e) Do bicycles and other non-motorized vehicles or pedestrians travel along the corridor?

f) Are there important viewsheds from the road?

g) Are there important viewsheds that include the road?

h) What is the size of the existing roadway and how does it fit into its surroundings?

i) Are there historic or especially sensitive environmental features along the roadway?

j) How does the road compare to other roads in the area?

k) Are there particular features or characteristics of the area that the community wants to preserve or change?

l) Is there more than one community or social group in the area? Are different groups interested in different features/characteristics? Are different groups affected differently by possible solutions?

m) Are there concentrations of children, elderly, or disabled individuals with special design or access needs (e.g., pedestrian crosswalks, curb cuts, audible traffic signals, median refuge areas) in the project area?

n) What is the local community's perception of the road project?

o) Are there protected species or concentrations of wildlife in the area that may require special crossings to ensure the safety of both wildlife and motorists?

Develop 15% Design and Resource Surveys

Based on the information gathered during the environmental scoping activities, environmental data gaps are identified and resources surveys are conducted as needed. During this time the 15% design is developed. As resource data are collected and the design is developed, this information is shared among the cross-functional design team to assist the designers in implementing early avoidance of environmental resources and to ensure that the resources surveys adequately cover the areas affected by the design.

Development of 30% Design and Prepare NEPA Documents (Draft, Final, and Decisional)

The results from resource surveys are reviewed in relation to the design elements and preliminary impacts are identified. This information is reviewed by the cross-functional design team, the stakeholders, and the public during the development of the Draft NEPA documents and during the comment period. During the development of the NEPA documents the roadway design progresses to 30% and numerous context sensitive project design decisions, including roadway surface type can be effectively considered at this time, such as:

a) Project location/alignment

b) Surfacing material/color

c) Noise mitigation measures

d) Guide rail style and/or position

e) Median/shoulder design – surfacing, curbs, widths
f) Lighting/sign selection and design
g) Placement and design of drainageways and stormwater basins
h) Placement of foot, cycle, or horse paths
i) Roadway cross section (travelway, shoulder, and construction limit width)
j) Right-of-way width
k) Retaining wall location/height/appearance
l) Bridge and culvert location and appearance

To make decisions about each design element, the team must consider other factors, such as the following:

Engineering and Cost

a) Design traffic load (capacity)
b) Safety considerations
c) Design speed
d) Initial costs
e) Life-cycle costs
f) Maintenance costs

Environmental

a) Protected species and/or habitat
b) Wetlands and streams
c) Water quality
d) Historic structures
e) Archaeological sites
f) 4(f) properties
g) Social and economic aspects
h) Visual quality
i) Land use
j) Secondary impacts

These factors will be different for each project and balancing decisions related to these factors may require some trade-offs.

For projects requiring an Environmental Assessment (EA) or an Environmental Impact

Statement (EIS), some of the preliminary alternatives may be eliminated because they carry too many negative effects that impact the environment, engineering design, or construction cost. This screening produces a "short list" of alternatives that are addressed in detail in the draft and final NEPA documents.

With regards to categorical exclusion (CATX) documents, there may be unusual circumstances in which a CATX considers context sensitive issues. The resurfacing of a roadway, for example, would typically qualify as a CATX. However, if the surfacing material proposed is different from what exists on the roadway, an analysis should be conducted to determine if the new surfacing material would impact the character of the roadway in a manner that may be incompatible with the surrounding area (the project's context). This is not to say that an EA would be needed, just that the choice made for a surfacing material should be compatible with the project context.

As the NEPA decision documents (Record of Decision, EA/Finding of No Significant Impact) are developed and signed, the 30% design is completed. Completion of the 30% design typically includes selection of roadway surface type to be used on the project.

Development of 70 and 95% Design Packages and Mitigation Coordination and Permits

This group of activities is often referred to as the "detailed design phase." At this point the environmental review process is complete and the identification of context sensitive solutions for the design is finished although some "tweaking" of the design and alignment decisions may occur during this phase. The pavement design is finalized during the development of the 70% design package. The FLH environmental staff members of the cross-functional team review the 70 and 95% design packages to ensure that all commitments made in the NEPA decision documents are implemented.

CHAPTER 3 — SURFACING SELECTION METHODOLOGY

INTRODUCTION

A selection methodology has been developed to facilitate the process of selecting an appropriate roadway surfacing for a project or a particular segment of a project. The selection process is meant to be transparent, methodical, defensible, and allow aesthetics and context sensitivity to be considered in the selection of roadway surfacing. The selection process is a two stage process consisting of a screening stage and a selection stage. Figure 3 shows the relationship between the PDP and the surfacing selection process.

SCREENING STAGE

The purpose of the screening stage is to identify a manageable number of surfacing types that are best suited for a particular project, based on a set of selected screening criteria. These shortlisted surfacing types are then carried forward for detailed evaluation in the selection stage. Surfacing type suitability is described by one of four designations: highly suitable, acceptable, not ideal, and not applicable. Common screening criteria include traffic volume level, project setting (i.e. urban, rural, historic, decorative), cost, bound or unbound surfacing, and whether the project is for rehabilitation or new construction. The screening stage eliminates from further consideration all those surface types that are clearly not applicable for a particular application. After nonviable surfacings are removed from consideration, the remaining surface types are sorted in preferential order based on suitability for the selected screening criteria.

Choosing Screening Criteria

In the screening stage of the surfacing selection process, selected screening criteria are used to discard from consideration surfacing types that are not applicable and to rank the remaining surfacing options that are applicable. The number of screening criteria selected by the project team for use in the screening stage will depend on the type of roadway application, amount of project information available, and judgement. When available, information collected in the PDP Planning and Programming step and the initial project development activities should be used to help select screening criteria. For projectss in significant historical, cultural, or environmental settings, there may be very specific criteria that are pre-set based on project objectives and needs. In these cases, it is useful to apply all such pre-set criteria to the screening process so the selection stage is streamlined as much as possible. On the other hand, for standard road sections, there may be very few pre-set selection criteria, especially early on in the PDP. In these cases, there may be many surfacings that have the same score. Therefore, a larger number of surfacings will need to be evaluated in the Stage 2 evaluation process or additional criteria (e.g. past experience or local preferred practice) will have to be used to narrow the group of surfacings for Stage 2 evaluation. In general, using several screening criteria (as opposed to fewer) will usually help to differentiate between the surfacings in the screening stage.

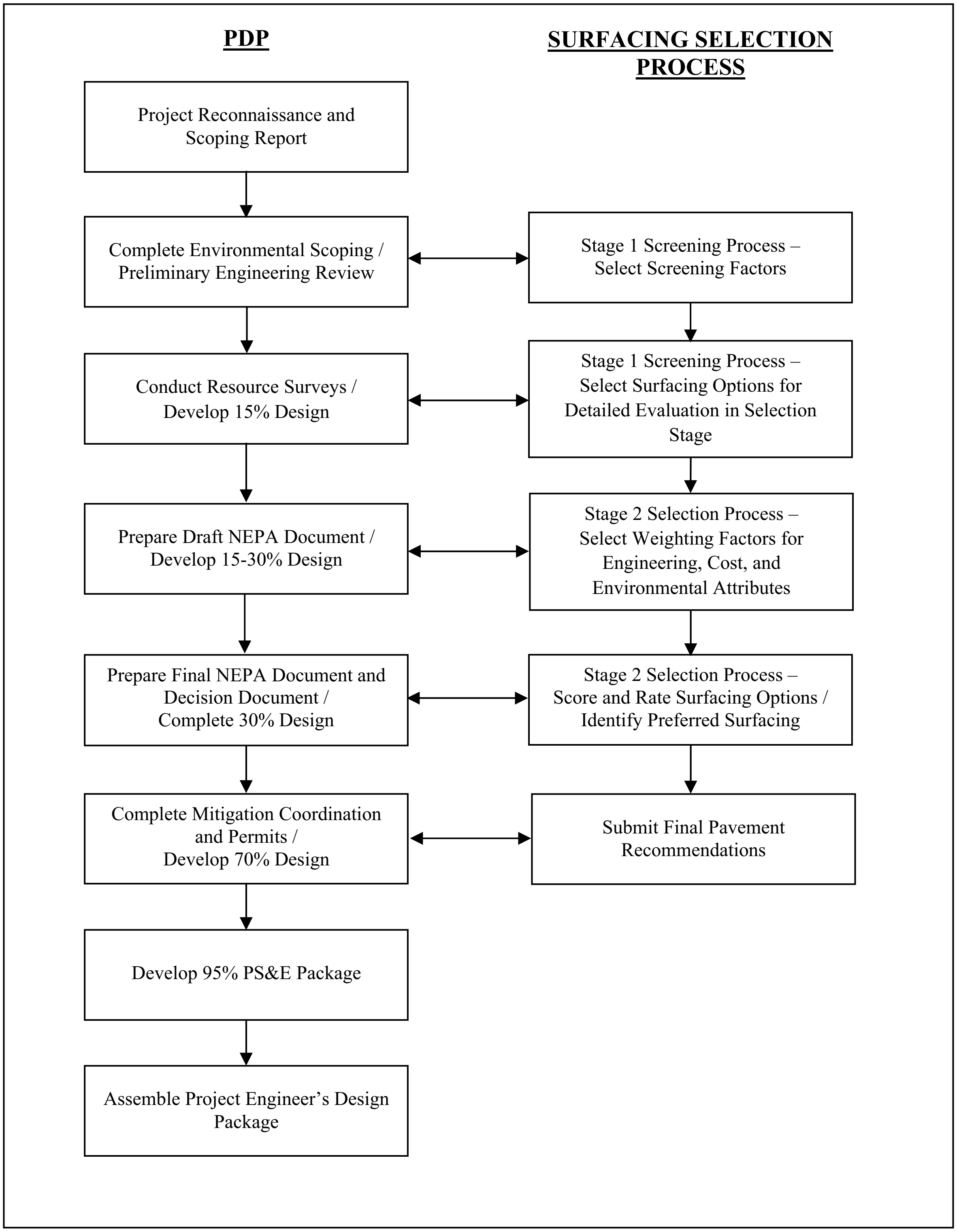

Figure 3. Flowchart. Relationship of the PDP and the Surfacing Selection Process.

Screening Criteria Descriptions

Traffic: From an objective performance perspective, most roadway surface types have maximum traffic ranges for which they are appropriate. Thus, design traffic in terms of AADT should be a basic required input to the screening process. Screening on the basis of traffic is effective for higher traffic volumes but does not reduce the list of options for low traffic volume roads.

A publication entitled, *Park Road Standards* [(5)] provides some guidance on traffic classifications. For the Principal Park Road and Rural Parkway functional classification it suggests six traffic categories, with corresponding design speeds (assuming flat terrain). These are shown in Table 2.

In the context of this project, six traffic categories are excessive for the purpose of differentiating roadway surface types. Many surfacing types that are suitable for traffic volumes of 1,000 vehicles per day are also suitable for traffic levels greater than 8,000 vehicles per day. Therefore the six traffic categories have been consolidated into four categories which can be described as very low, low, medium and high traffic, as shown in Table 2. In Table 3, 2,500 vehicles per day is used as a representative value for the high traffic screening criteria to determine the suitability of different surfacing types.

Table 2. Traffic Volume Classifications.

Design Volume (Vehicles/day)	Suggested Descriptive Term	Design Speed (mph)	
		Preferred	Minimum
< 200	Very Low	40	30
200 – 400	Low	50	40
400 – 1000	Medium	50	40
1000 – 4000	High	55	45
4000 – 8000		60	50
>8000		60	50

Decorative Setting: Some projects may require a decorative surfacing. For example, a decorative surfacing may be desirable for a high-profile entrance driveway because it is aesthetically pleasing. In another case, a colored surfacing may be desired to delineate a walkway or bicycle path for safety purposes. In many applications decorative surfacings are preferred over conventional PCCP or HACP surfacings, but they generally also have a higher associated cost. Therefore, in general, decorative surfacing should only be used as a screening criterion when aesthetics is a primary factor in initial project scoping, or where only a short section of roadway is involved.

Historic Setting: For roadways within a historically significant setting, aesthetics may be a significant concern, requiring the use of a surfacing with an appearance that is compatible with the surroundings. In these cases, all conventional asphalt and concrete surfaces would typically be eliminated. Instead, surfacings with an aesthetically compatible appearance, such as stamped and/or pigmented asphalt or concrete, unpaved, or cobblestone surfacings may be more appropriate, depending on the particular historical setting and cost constraints.

<u>Urban or Rural Setting</u>: The user can use the setting, either rural or urban, as a screening criterion. For example, an urban setting would normally rule out the use of unpaved surfacings. If a rural application were indicated, then more rustic surfacing options may be favored.

<u>Cost</u>: Cost is an important criterion for most projects. Roadway surfacings have a wide range of unit costs, ranging from unpaved, unbound surfacings at the low end to hand placed cobblestones at the high end. In an application involving a small area of specialty pavement, cost may not be a concern. However, for larger projects, such as 30 km (19 miles) of forest access road, low cost may be an important criterion. Cost may also be a primary concern when road construction funding is limited. A detailed cost analysis is not required in the screening stage; surfacings are generally classified by typical unit costs.

<u>Unbound or Paved Surface</u>: *Park Road Standards* [5] suggests that above an AADT of 400 only paved surfaces should be used. At the commencement of a project, it is usually possible to establish whether a particular road needs to have an all-weather paved surface. In addition to functional considerations, unpaved surfaces are often preferred in scenic rural landscapes, based on aesthetics.

<u>3R or 4R Projects</u>: 3R projects involve rehabilitation of the pavement structure and may involve upgrades of safety features. 4R projects involve complete reconstruction of a roadway, which may include widening, new alignment, and/or grade changes. Some surfacing types, such as in-place recycling, are only practical for 3R projects because the in-place material is required. Thus, for 4R projects, some surfacing options can be eliminated in the screening stage.

<u>Climate and Percent Fines (in unbound material)</u>: When unbound or stabilized soil/aggregate surfacings are acceptable for a project, climate or percent fines (in unbound material) can be used as screening criteria. These criteria are especially useful when considering stabilized surfaces because the effectiveness of many stabilizing agents is significantly affected by climate (i.e. wet or dry) and percentage of fines in the material to be stabilized.

The roadway surfacings can be sorted by their suitability for the application based on the appropriate selected screening criteria. Each surfacing can be assessed for each of the selected screening criteria listed above. The assessment should assign one of four designations, as follows:

A: Highly suitable,
B: Acceptable for use,
C: Not ideal, but can be used, or
X: Not suitable.

See Table 3 for suggested designations for each surfacing for common screening criteria. Table 3 only includes products that are suitable for use as a permanent surfacing. Although most of the road construction products presented in Table 1 are suitable for use as a roadway surfacing, a few materials, listed in Table 4, are common road base materials. Although these base materials can be used as a temporary roadway surfacing, they are not recommended for use as a permanent surfacing. They have been included in Appendix A since they are commonly used products and their use may allow a wider range of surfacing options to be considered, especially for rehabilitation applications. In addition, non-structural surfacings rely entirely on the underlying strata for structural support; therefore, information on common base materials can be useful when assessing the pavement structure as a whole.

Once all of the surfacings are assessed for each of the selected screening criteria, any surfacing that is designated as not applicable (X) for any of the selected screening criteria is removed from further consideration. The remaining surfacings can be sorted in several ways, including: by most number of highly suitable (A) designations, least number of not ideal (C) designations, or highest total suitability score. When a large number of surfacings are applicable and must be sorted, it is often easiest to sort the surfacings using the highest total suitability score. For each surfacing, the total suitability score is calculated by assigning numerical values to the designations for each screening criterion (A=3, B=2, C=1) and summing up the numerical values to obtain a total score for the surfacing. The surfacings can then be sorted according to their total score. This process lends itself very well to being performed with a spreadsheet, but it can also be performed manually.

Once all the surfacings are sorted, it is up to the project team to determine the number of surfacings to carry forward to the selection stage. In many cases where surfacings are sorted by highest total suitability score, the distribution of scores allows the team to clearly select the top four to eight ranked surfacings for detailed evaluation in the selection stage. However, it is possible, based on the number and which screening criteria are used, for a case to occur where a large number of surfacings have the same score. When this happens, the team must decide if all the surfacings proceed to the selection stage or if the list should be trimmed based on additional considerations (e.g. past experience, agency familiarity with particular surfacings, surfacing on adjacent roadways, etc.). Also, if there is a particular interest in specific surfacings that are not among the top group, they may be evaluated in the selection stage as well, regardless of score.

The intent of the screening stage is to identify the most suitable roadway surfacings for a particular project, based on selected criteria, and reduce the number of roadway surfacings to a manageable number for detailed evaluation. This stage allows the project team to avoid performing a detailed evaluation for each individual surfacing listed in the surfacing catalog and allows the team to focus on the most suitable surfacings.

Table 3. Suggested Suitability Designations for Screening Stage

Road Surfacing Type	Traffic			
	Very Low	Low	Medium	High
Asphalt Surfacing (non-structural)				
Cape Seal	A	A	A	B
Chip Seal	A	A	A	B
Chip Seal over Geotextile	A	A	A	B
Fog Seal	A	A	B	C
Microsurfacing	A	A	A	A
Multiple Surface Treatments (Seals)	A	A	A	B
Open Graded Friction Course	A	A	A	A
Otta Seal	A	A	B	C
Sand Seal	A	A	B	C
Scrub Seal	A	A	A	C
Slurry Seal	A	A	A	B
Ultrathin Friction Course	A	A	A	A
Asphalt Surfacing (structural)				
Cold Mix Asphalt Concrete Pavement	A	A	A	B
Hot Asphalt Concrete Pavement (HACP)	A	A	A	A
Exposed Aggregate HACP	A	A	B	C
Imprinted / Embossed HACP	A	A	B	C
Pigmented HACP	A	A	A	A
Porous HACP	A	A	C	X
Resin Modified Pavement	A	A	A	A
Synthetic Binder Concrete Pavement	A	A	A	A
Portland Cement Concrete (PCC) Surfacings				
Cellular PCC	A	A	B	X
Portland Cement Concrete Pavement (PCCP)	A	A	A	A
Exposed Aggregate PCCP	A	A	A	B
Pigmented PCCP	A	A	A	B
Porous PCCP	A	A	A	C
Stamped PCCP	A	A	B	C
Roller Compacted Concrete	A	A	A	B
Whitetopping	A	A	A	A
Unbound & Mechanically Stabilized Surfacings				
Cellular Confinement	B	B	C	X
Fiber Reinforcement	B	C	X	X
Geotextile/Geogrid Reinforcement	B	C	C	X
Gravel (crushed or uncrushed)	B	C	X	X
Sand	C	X	X	X
Other Stabilized Surfacings				
Chlorides	B	C	X	X
Clay Additives	B	C	X	X
Electrolyte Emulsions	B	C	X	X
Enzymatic Emulsions	B	C	X	X
Lignosulfonates	B	C	X	X
Organic Petroleum Based Emulsions	B	C	C	X
Synthetic Polymer Emulsions	A	B	C	X
Tree Resin Emulsions	A	B	C	X
Unit Surfaces				
Brick Pavers	A	A	B	C
Natural Stone Cobbles	B	B	C	X
Unit Pavers	A	A	A	A
Porous Unit Pavers	B	B	B	C
Recycling Alternatives				
Hot In-Place Recycling	A	A	A	A
Recycled HACP	A	A	A	A

A:	**Highly suitable**
B:	**Acceptable for use**
C:	**Not ideal, but can be used**
X:	**Not suitable**
	Not applicable

Table 3. Suggested Suitability Designations for Screening Stage (cont.)

Road Surfacing Type	Setting				Surfacing Requirement		
	Decorative	Historic	Urban	Rural	Low Cost	Unbound	Paved
Asphalt Surfacing (non-structural)							
Cape Seal	X	X	A	B	A	X	B
Chip Seal	B	C	B	A	A	X	C
Chip Seal over Geotextile	B	C	B	A	B	X	B
Fog Seal	X	X	A	B	A	X	C
Microsurfacing	C	C	A	B	B	X	B
Multiple Surface Treatments (Seals)	B	C	B	A	A	X	B
Open Graded Friction Course	X	X	A	B	B	X	A
Otta Seal	X	X	B	B	A	X	B
Sand Seal	X	X	A	B	A	X	B
Scrub Seal	X	X	A	B	A	X	B
Slurry Seal	C	C	A	B	A	X	B
Ultrathin Friction Course	X	X	A	B	B	X	A
Asphalt Surfacing (structural)							
Cold Mix Asphalt Concrete Pavement	X	X	A	B	B	X	B
Hot Asphalt Concrete Pavement (HACP)	X	X	A	B	B	X	A
Exposed Aggregate HACP	B	C	A	B	C	X	A
Imprinted / Embossed HACP	A	B	A	C	X	X	B
Pigmented HACP	B	C	A	B	B	X	A
Porous HACP	X	X	A	B	B	X	A
Resin Modified Pavement	X	X	A	B	B	X	A
Synthetic Binder Concrete Pavement	A	A	A	B	X	X	A
Portland Cement Concrete (PCC) Surfacings							
Cellular PCC	X	A	B	C	C	X	B
Portland Cement Concrete Pavement (PCCP)	X	X	A	B	C	X	A
Exposed Aggregate PCCP	A	B	A	B	C	X	A
Pigmented PCCP	A	B	A	B	C	X	A
Porous PCCP	X	X	A	C	C	X	A
Stamped PCCP	A	A	A	B	C	X	B
Roller Compacted Concrete	X	X	A	B	C	X	B
Whitetopping	X	X	A	B	B	X	A
Unbound & Mechanically Stabilized Surfacings							
Cellular Confinement	X	B	X	A	B	A	X
Fiber Reinforcement	X	A	X	A	A	A	X
Geotextile/Geogrid Reinforcement	X	A	X	A	B	A	X
Gravel (crushed or uncrushed)	X	A	X	A	A	A	X
Sand	X	A	X	A	A	A	X
Other Stabilized Surfacings							
Chlorides	X	A	X	A	A	A	X
Clay Additives	X	A	X	A	A	A	X
Electrolyte Emulsions	X	A	X	A	A	A	X
Enzymatic Emulsions	X	A	X	A	A	A	X
Lignosulfonates	X	A	X	A	A	A	X
Organic Petroleum Based Emulsions	X	A	X	A	A	A	X
Synthetic Polymer Emulsions	C	A	C	A	B	A	X
Tree Resin Emulsions	C	A	C	A	B	A	X
Unit Surfaces							
Brick Pavers	A	A	A	X	X	X	B
Natural Stone Cobbles	B	A	A	X	X	X	C
Unit Pavers	A	B	A	X	X	X	A
Porous Unit Pavers	A	A	A	C	X	X	B
Recycling Alternatives							
Hot In-Place Recycling	X	X	A	B	B	X	A
Recycled HACP	X	X	A	B	B	X	A

A:	**Highly suitable**
B:	**Acceptable for use**
C:	**Not ideal, but can be used**
X:	**Not suitable**
	Not applicable

Table 3. Suggested Suitability Designations for Screening Stage (cont.)

Road Surfacing Type	Project Type		Climate			% Fines (in unbound material)		
	3R	4R	Wet	Damp to Dry	Dry	< 5	5 - 30	> 30
Asphalt Surfacing (non-structural)								
Cape Seal	A	A						
Chip Seal	A	A						
Chip Seal over Geotextile	A	C						
Fog Seal	A	B						
Microsurfacing	A	C						
Multiple Surface Treatments (Seals)	A	A						
Open Graded Friction Course	A	A						
Otta Seal	A	A						
Sand Seal	A	B						
Scrub Seal	A	X						
Slurry Seal	A	B						
Ultrathin Friction Course	A	B						
Asphalt Surfacing (structural)								
Cold Mix Asphalt Concrete Pavement	A	A						
Hot Asphalt Concrete Pavement (HACP)	A	A						
Exposed Aggregate HACP	A	A						
Imprinted / Embossed HACP	B	A						
Pigmented HACP	A	A						
Porous HACP	C	A						
Resin Modified Pavement	A	A						
Synthetic Binder Concrete Pavement	A	A						
Portland Cement Concrete (PCC) Surfacings								
Cellular PCC	B	A						
Portland Cement Concrete Pavement (PCCP)	B	A						
Exposed Aggregate PCCP	B	A						
Pigmented PCCP	B	A						
Porous PCCP	C	A						
Stamped PCCP	B	A						
Roller Compacted Concrete	X	A						
Whitetopping	A	X						
Unbound & Mechanically Stabilized Surfacings								
Cellular Confinement	A	A	A	A	A	A	B	X
Fiber Reinforcement	A	A	A	A	A	A	A	B
Geotextile/Geogrid Reinforcement	A	A	A	A	A	A	A	C
Gravel (crushed or uncrushed)	A	A	A	A	A	A	A	C
Sand	A	A	C	A	B	A	B	C
Other Stabilized Surfacings								
Chlorides	A	A	C	A	B	X	A	X
Clay Additives	A	A	X	B	A	A	B	X
Electrolyte Emulsions	A	A	A	A	A	X	A	B
Enzymatic Emulsions	A	A	B	A	A	X	A	B
Lignosulfonates	A	A	X	A	A	X	A	C
Organic Petroleum Based Emulsions	A	A	A	A	A	A	A	C
Synthetic Polymer Emulsions	A	A	A	A	A	C	A	X
Tree Resin Emulsions	A	A	A	A	A	C	A	C
Unit Surfaces								
Brick Pavers	X	A						
Natural Stone Cobbles	X	A						
Unit Pavers	X	A						
Porous Unit Pavers	X	A						
Recycling Alternatives								
Hot In-Place Recycling	A	X						
Recycled HACP	A	A						

A:	**Highly suitable**
B:	**Acceptable for use**
C:	**Not ideal, but can be used**
X:	**Not suitable**
(shaded)	**Not applicable**

Table 4. Products not Suitable for Use as a Permanent Roadway Surfacing.

CLASSIFICATION	SUB-CATEGORIES	ROAD PRODUCT
AGGREGATE AND SOIL SURFACES	Stabilized Aggregate and Soil	Fly Ash Lime Portland Cement
RECYCLING AND RECLAMATION ALTERNATIVES	Recycling Alternatives	Cold In-Place Recycling PCCP Recycling and Rehabilitation
	Full Depth Reclamation (FDR)	FDR-Cementitious FDR-Emulsified Asphalt Foamed Asphalt Pulverization

SELECTION STAGE

The purpose of the selection stage is to subject a shortlist of suitable surfacing options to a detailed evaluation that considers a wide range of criteria and desirable attributes, including durability, aesthetics, safety, performance, functionality, and life-cycle costs. In the selection stage, it is assumed that the options evaluated are functionally acceptable, but that it is necessary to identify the option that best meets a series of sometimes competing criteria. In the selection stage, a more detailed selection process is applied. The selection methodology is similar to and based on a procedure presented by Hicks, Seeds, and Peshkin. [(6)] However, the attributes and factors included in the process have been customized to meet the intended objectives of this Guide.

The surfacing evaluation involves selection attributes, scoring factors, and weighting factors. The selection attributes are properties or characteristics of roadway surfacings that are important and should be considered in the selection process. Scoring factors represent how well a particular surfacing ranks for each selection attribute. Weighting factors represent the relative importance of each attribute to the selection process. These three components are used to calculate a total score that can be used to compare different surfacings and to facilitate the selection of a surfacing for a particular road section.

Selection Attributes and Scoring Factors

A total of eleven selection attributes have been identified. Provisions can be made to include a twelfth specific user-defined attribute. For example, an attribute related to compatibility with an adjoining road section or compatibility to the existing road surface on the alignment may be desirable in some cases. The selection attributes are subdivided under three categories as follows:

Performance and Durability Attributes

Durability: Durability refers to a surfacing's probability to last over the expected life of the surfacing without premature defects. All surfacings show signs of distress and defects over time; preventative maintenance techniques are utilized at scheduled intervals to prevent, minimize, or control these defects. However, a surfacing with low durability will require numerous unscheduled repairs to correct defects, such as potholes and washboarding.

Life Expectancy: Life expectancy is the period of time over which the road surface provides an acceptable level of performance with only preventative maintenance activities required.

Maintenance Requirements: Maintenance requirements refers to the frequency that scheduled maintenance interventions are required. Significant maintenance requirements may be acceptable for agencies that have their own maintenance crews, but not for agencies that must contract out maintenance work or for agencies that have limited annual budgets for road maintenance. In addition, surfacings with high maintenance requirements may be undesirable on roads with high traffic volumes because they cause frequent traffic disruptions and user delays.

Safety/Surface Characteristics: Surface characteristics affect the safety of a surfacing with respect to skid resistance, hydroplaning potential, visibility, windshield hazards, and ability to be striped with lane demarcations. Different surfacings provide different levels of safety; however, all surfacings considered for a particular project should meet or exceed all minimum safety design standards for the class of road. Any surfacing that does not meet minimum safety requirements for a particular project should be removed from consideration in the selection process. Surface characteristics can also impact ride quality and road noise levels. Surface characteristics can be a significant consideration in recreational areas where the road must support pedestrians, bicycles, and/or in-line skaters in addition to vehicular traffic.

Constructability and Cost Attributes

Life-Cycle Cost: Life-cycle cost is the net present value of a surfacing for a specified analysis period, taking into consideration initial construction costs, user costs, expected maintenance costs, any required rehabilitation, and the time value of money. The value of life-cycle costs is that they provide a relative comparison of long-term costs for different surfacing types. Often, a rough estimate of life-cycle cost can be determined quickly based on available information and may be adequate for the purposes of comparing a range of surfacing options.

Availability: Availability refers to the availability of materials, equipment, and qualified contractors in the project area. In remote areas, batch plants may not be located within an adequate distance of the project site to provide portland cement concrete or hot mix asphalt concrete. Therefore, a mobile plant would have to be assembled near the site to provide these materials. Similarly, specialty equipment or qualified contractors may not be locally available, requiring mobilization from distant areas. Conversely, some areas may have an abundance of certain materials or qualified contractors, making their use advantageous.

Construction Impacts: Construction impacts refer to impacts on the surrounding community during initial road construction. Impacts include: road closures that lead to user delays, limited access, and reduced revenue for nearby businesses; required construction staging areas, equipment laydown areas, and material storage areas; increased construction traffic; and construction noise.

Weather Limitations: Weather limitations address the temperature and precipitation limitations on when a surfacing can be constructed. Depending on the surfacing type and local climate, construction may be limited to a short construction season due to minimum temperature requirements for product placement. Also, some stabilized soil/aggregate surfacings require a certain period of time without precipitation after construction.

Context Sensitivity and Environmental Attributes

Environmental Impacts: Environmental impacts include a wide range of impacts, such as short term environmental impacts during construction and long term environmental impacts during service. Impacts to be considered include water quality, aquatic species, plant quality, and air quality. Other issues include leachate generation, surface runoff, erosion, heat generation, source of raw materials, energy requirements, manufacturing/placement process, hauling requirements, and road noise. Some indirect environmental impacts may also need to be considered, such as increased traffic volumes as a consequence of improving a roadway surfacing standard.

Visual Quality: Visual quality refers to the surfacing's appearance and whether or not it is aesthetically pleasing. Visual quality should be considered from a range of perspectives, including that of a driver using the road and tourists who will mainly see the road as part of an overall scenic vista.

Context Compatibility: Context compatibility refers to how well a surfacing fits into the environmental, cultural, historical, and/or visual context of the surrounding environment.

Assigning Scores

Each surfacing option is given a score for each of the above attributes. Scoring factors are determined from information presented in the catalog of surfacing types, past experience, and engineering judgment. The assigned score is between 1 and 5, with 1 indicating the worst or least desirable qualities and 5 indicating the best or most desirable qualities with regard to that particular attribute (see Table 5). Surfacings are scored relative to the other surfacings under consideration because it allows for greater differentiation between surfacings. Some scoring factors will be heavily influenced by specific site conditions. Therefore, designers are discouraged from using "default" scoring factors and should give considerable attention to specific site conditions when assigning scoring factors to surfacings.

Weighting Factors

Weighting factors are assigned in terms of percentages with the total adding to 100 percent; the higher the assigned weighting factor, the more important that attribute is considered to be in the overall selection process for that application. Weighting factors can be assigned in different ways. On smaller non-controversial projects, the project engineer or designer can select them. On larger, more controversial projects, they should be determined by the entire project team so as to obtain consensus on the relative importance of the various attributes and to document the rationale used in assigning the weightings. Stakeholders' comments and concerns should be collected prior to the selection process and used to help determine the relative importance of the attributes. Weighting factors can (1) initially be assigned to each of the three attribute categories (i.e. Performance and Durability, Constructability and Cost, and Context Sensitivity and Environmental) and then subdivided among the attributes within the category, or (2) be directly assigned to each of the attributes. Either way, the weighting factors should be appropriately distributed in the end. As a check, the cumulative weighting factor for each category should be compared to the other categories; comparing the cumulative weighting factors for the different categories shows which category is of primary importance. In addition, the weighting factor for each attribute should be compared to all other attributes to ensure that the relative importance of each attribute is appropriate. It is expected that a few iterations and some debate will be required for the project team to achieve consensus on the weighting factors to use. However, it is these revisions and this debate that makes the surface selection process transparent.

For most situations, no category should have a weighting factor less than 20% or greater than 50% and no individual attribute should have a weighting factor greater than 20%. Although some attributes may be assigned a low weighting factor, the designer should always ensure that all surfacings meet minimum functional and safety requirements for the project. **It is difficult to assign default weighting factors for each of the attributes because each project has unique requirements that should be fully considered when assigning weighting factors.** The most effective approach to assigning weighting factors is to initially assign all weighting factors based on project objectives and goals and then begin adjusting the factors, through discussion among the project team and by continuous comparison of weights between different attributes and categories, until consensus is achieved. By involving a group of people with individual perspectives on the project, such as engineering design, environmental impacts, and operations/maintenance, and facilitating discussion to reach consensus among the group, there is a high probability that the weighting factors selected will adequately balance, to the extent possible, the various objectives of the project. As project team members become familiar with the selection process over time, it may be possible to develop additional guidelines and rules of thumb for assigning weighting factors.

Table 5. Scoring Factors for Surfacing Attributes

ITEM	ATTRIBUTE	SCORE OF 1 INDICATES	SCORE OF 5 INDICATES
	PERFORMANCE AND DURABILITY		
1	Durability	Low or questionable durability	Similar to high quality HMAC or PCC
2	Life Expectancy	Short	Long
3	Maintenance Requirements	Frequent intervention	Minimal requirements
4	Safety, Ride / Surface Quality	Driver safety concerns or very poor frictional characteristics and/or rough ride	High frictional characteristics and/or smooth ride
	CONSTRUCTABILITY AND COST		
5	LCC	Highest LCC	Lowest LCC
6	Availability of Materials and Qualified Contractors	Materials need to be transported long distance and/or no contractors in State	Materials and contractors readily available locally
7	Impacts during construction	Construction process is very slow and / or disruptive	Fast and efficient construction process with minimal disruption
8	Weather limitations during construction	Significant restrictions	Minimal restrictions
	CONTEXT SENSITIVITY		
9	Environmental Impacts	Significant	Minimal
10	Visual Quality	Very conventional	Highly pleasing appearance
11	Context Compatibility	Inappropriate for surroundings	Very appropriate
12	Other		

Rating the Surfacing Options

Once all scoring and weighting factors have been assigned, the surfacings can be rated to identify one or more preferred surfacings. The total rating for each surfacing option is calculated by summing the totals of the product of the scoring factor and the weighting factor for each attribute. This can be done conveniently using a spreadsheet. An example rating worksheet is included in Appendix B. The option receiving the highest rating should represent the surfacing option that best meets the overall project objectives. In some cases, the top two or three options may have a relatively close rating. It should be kept in mind that the selection process is just a tool for comparing different surfacings in a rational manner and providing the project team with additional information to help in the decision-making process. If the project team is not comfortable with the surfacing selected by the selection process, it may be an indication that the weighting factors assigned do not truly reflect the objectives and goals of the project and may require additional scrutiny.

In some instances, it may be appropriate to re-run the selection stage after adjusting the weighting factors. The use of this approach to evaluate how sensitive the final selection is to the weighting of a particular factor may be useful in arriving at the best option and does not necessarily invalidate the process. However, any adjustments to weighting factors at this stage must be defensible, transparent, and not arbitrarily applied to force a desired solution.

EXAMPLE PROJECTS

The surfacing selection process has been used to determine the most suitable surfacings for three example projects. A summary of project information and the selection process for each example is included in Appendix C. To illustrate the capabilities of the selection process for different project conditions, the examples include a historic parkway, a scenic byway, and a local rural road. The examples go through the selection process step-by-step and provide some commentary on the reasoning that the project team used to make certain choices or decisions. The example cases show that the surfacing selection process is robust and can be used for a wide range of projects.

CHAPTER 4 — CONCLUSIONS

The goal of roadway surfacing selection is to choose a roadway surfacing that lasts, is cost-effective, and fits the project setting. This Guide is intended to aid in accomplishing this goal by 1) providing a surfacing selection process that is straightforward, logical, transparent, defensible, and understandable by the general public; 2) fully integrating the surface selection process within the existing PDP process; 3) ensuring ample opportunities for discussion and debate among stakeholders regarding project objectives and how to balance these often conflicting objectives; and 4) providing the broadest possible list of surfacing product alternatives to consider in the surface selection process. A further hoped for benefit of this Guide is to bring a greater awareness to the diversity of road surfacing products currently available, to encourage their appropriate use, and to achieve greater recognition for the importance of context compatibility in the selection of roadway surfacings.

The Guide offers a step-by-step approach while keeping the design process flexible and still allowing for engineering judgment in the final selection process. To properly achieve the intended goals and spirit of context-sensitive design, a certain minimum level of effort and consideration must be put into the selection process. Before beginning the selection process, the project team should review all available project-specific information related to the project setting and objectives. The surfacing selection should be fully integrated into the PDP process as described in Chapter 2 of the Guide. Stakeholder input should be considered to ensure that project objectives and the selection process adequately address, to the extent possible, stakeholders' needs and concerns. The CD-ROM Photo Album, included as Appendix D, should be used to convey how the various surfacing options will appear in service.

The selection process itself is intended to facilitate discussion and understanding of critical project issues and their relative importance to the overall project. Discussion and debate among team members are beneficial to obtaining weighting factors that adequately balance competing project needs and that are not improperly skewed toward one particular outcome. Completing this process is necessary to maximize the effectiveness of the selection process as a tool for identifying the most suitable roadway surfacings for a particular project.

APPENDIX A ─ ROADWAY SURFACING OPTIONS CATALOG

TABLE OF CONTENTS

PRODUCT SUMMARY TABLE DESCRIPTION

GENERAL INFORMATION

Generic Name(s): Common name(s), not a proprietary or trademark name, used to describe a particular roadway surfacing type.

Trade Name(s): Proprietary or trademark name(s) used to describe a particular roadway surfacing type.

Product Description: A brief description of the product and its composition.

Product Suppliers: A few product manufacturers, suppliers, or contractors. Company names are provided for informational purposes only. Where appropriate, relevant trade associations where the names of suppliers or contractors can be obtained are provided. The listing of names should not be interpreted as an endorsement for any particular company. In most cases, additional companies are available that can provide the same or similar product.

APPLICATION

Typical Use: How the product is typically used as part of the roadway system (i.e. surfacing, binder course, base, subbase, subgrade, stabilizer, dust suppressant, preventative maintenance treatment, etc.).

Traffic Range: Traffic volume that is acceptable or cost-effective for a particular product. For traffic volumes outside of the specified range, life expectancy may be significantly decreased or maintenance costs may be unacceptably high. For this Guide, traffic volumes are categorized into the following classifications, based on information shown in Table 2:

Classification	Traffic Volume (AADT)
Very Low	< 200
Low	200 – 400
Medium	400 – 1000
High	> 1000

Restrictions: Conditions where a product should not be used or used with special care.

***Traffic*:** Issues of concern may include loading conditions (e.g. % trucks, vehicle weights), intersections or turning lanes (frequent turning, braking), etc.

***Climate*:** Issues of concern may include precipitation, temperature extremes, humidity, etc.

Weather: As it relates to in service conditions. Issues of concern may include seasonal restrictions, freeze/thaw, excessive slipperiness when wet, snow, etc.

Terrain: Issues of concern may include roadway alignment, including maximum gradients and turning radii, etc.

Soil Type: Issues of concern may include soil classification, strength, plasticity, % fines, gradation, expansive properties, etc. It will be assumed that the pavement has been adequately designed structurally to take into account the subgrade soil characteristics.

Other: Any additional issues of concern regarding application.

Other Comments: Any additional information that is pertinent in describing a product's applicability.

DESIGN

Unless stated otherwise, it is assumed that best design practices will be followed and that certain design elements will be part of the design. These design elements include: providing adequate cross slope to facilitate runoff and prevent water from ponding on the roadway; providing drainage ditches adjacent to the roadway in rural applications, and a curb and subsurface drainage system in urban applications, to carry away surface runoff and allow drainage of the base; designing cut slopes and embankments to be stable; providing adequate clear zones to remove roadway obstructions or hazards; providing erosion control and shoulder treatment; providing adequate drainage structures to accommodate natural drainage across the roadway, and providing wildlife/fish passage structures, when appropriate.

SLC: Structural Layer Coefficient for use in the *AASHTO Guide for Design of Pavement Structures*.

Other Design Values: Other design parameters commonly used to describe a particular product.

Base/Subbase Requirements: Requirements for the structural layer(s) underlying and supporting the road surfacing.

Other Comments: Any additional information that is pertinent in the roadway design for a product.

CONSTRUCTION

Availability of Experienced Personnel: Information regarding availability of experienced personnel and type of personnel typically used (e.g. maintenance crew, general contractor, specialty contractor).

Materials: Raw construction materials that are used in construction of the roadway surfacing layer.

Equipment: Primary equipment needed to construct the roadway surfacing layer.

Manufacturing/Mixing Process: Brief description of the product manufacturing process and/or any off-site processing prior to placement on the roadway.

Placement Process: Brief description of the placement process.

Weather Restrictions: Weather restrictions (rain, snow, temperature, etc.) on when the roadway surfacing layer can be constructed or placed.

Construction Rate: Typical rate at which the roadway surfacing layer can be constructed or placed by an experienced crew.

Lane Closure Requirements: A description of lane closure requirements and required set time before traffic is allowed on the constructed layer.

Other Comments: Any additional information that is pertinent to the construction of a surfacing layer with a particular product.

SERVICEABILITY

Reliability and Performance History: Information describing how long a product has been used as a road surfacing and how much product information and documented project experience is readily available.

Life Expectancy: An estimate of how long the roadway surfacing will last under normal conditions. The life expectancy will vary depending on the traffic volumes, climatic conditions, and level of preventative maintenance that is used. Life expectancies should not be compared from product to product because performance lives are not necessarily based on equal site conditions. For example, a single and double chip seal may have similar performance durations, but a double chip seal is typically used when increased durability is needed due to site conditions.

Ride Quality: A description of the surface quality as perceived by someone driving on the roadway. Ride quality is related to the surface smoothness and the nature, severity, and extent of surface distresses present. In general, ride quality deteriorates with time over the life of a surfacing.

Table 6. Ride Quality Ratings

Ride Quality Rating	Description
Excellent	New or almost new high quality surfacing, such as HACP, minimal roughness/distress level, even at high speeds.
Good	Good surface condition, low roughness/distress level, some unevenness, especially at higher speeds.
Fair	Moderate roughness/distress level, moderate speeds acceptable for low volume roads.
Poor	High roughness/distress level, suitable only for low speeds.
Very Poor	Very rough ride, can only be driven at very low speeds, may require four-wheel drive.

Main Distress / Failure Modes: Common ways in which the roadway surfacing can be expected to deteriorate or fail.

Preservation Needs: Preventative maintenance needs, including type and frequency of treatment.

SAFETY

Hazards: Any relevant driving hazards, including dust, excessive spray from water on the roadway surface, loose aggregate particles that can be a windshield hazard, etc.

Skid Resistance: The frictional resistance of a surfacing. Used as a measure of how well vehicles can stop on a road surface, especially in wet or icy conditions. For example, a slippery surface has a low skid resistance.

Road Striping Possible?: Whether or not a road surfacing can be striped for lane and roadway edge demarcation.

Other Comments: Any additional pertinent safety-related information.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Where the raw materials come from. Are the materials natural or manufactured, renewable or nonrenewable, a waste byproduct of another process, etc.

Delivery and Haul Requirements: Issues related to local availability of materials and transportation/shipping requirements. The local availability of materials will vary depending on the project location. A project-specific assessment of material availability and delivery and haul requirements should be made.

Potential Short-Term Construction Impacts: Potential short-term environmental impacts due to the construction of a roadway layer, such as noise, dust, aquatic habitat impact, etc.

Potential Long-Term Environmental Impacts: Potential environmental impacts or concerns of a roadway surfacing layer over the life of the road.

Leachate**:** Do component materials leach out of the constructed layer over time?

Surface Runoff**:** Is the water quality of surface runoff from the road affected by the surfacing type? If the road surfacing is impermeable and is replacing a permeable surfacing, consideration must be given to whether the existing drainage ditches and culverts are adequate for the possible increase in road surface drainage and velocity. Inadequate drainage structures can lead to an increase in soil erosion.

Erosion: Is the surfacing layer easily erodable by surface runoff from precipitation? Unless otherwise noted, this information does not address the use of a product or surfacing as a low water crossing.

Water Quality**:** Issues related to potential water quality impacts.

Aquatic Quality**:** Issues related to potential impacts on aquatic life.

Plant Quality**:** Issues related to potential impacts on plants and trees.

Air Quality**:** Issues related to potential impacts on air quality.

Other**:** Other long-term potential environmental impact issues.

Ability to Recycle/Reuse: Opportunities to recycle or reuse a product when its serviceable life is over.

Other Environmental Considerations: Any additional environmental issues.

AESTHETICS

Appearance: Appearance of the surfacing layer, including color and texture.

Appearance Degradation Over Time: Comments on how the appearance of the surface can change over its serviceable life. This will also include comments on the visual impacts of necessary routine maintenance.

COST

Supply Price: Price for the product. This price range is a "ballpark" number provided for preliminary cost comparisons between different products. Prices can vary significantly with location, product availability, and size of the project. Local price estimates should be obtained during roadway planning and design. Prices included are based on Year 2004 price estimates.

Supply + Install Price: Estimated price range for the product installed based on typical conditions and design. This price range is a "ballpark" number provided for preliminary cost comparisons between different products. Prices can vary significantly with location, product availability, and size of the project. Local price estimates should be obtained during roadway planning and design. Prices included are based on Year 2004 price estimates.

EXAMPLE PROJECTS

Representative projects where a product has been used.

SELECT REFERENCES

A few references where additional/more detailed information can be obtained.

PAVED AND SEALED SURFACES

ASPHALT SURFACING–SURFACE TREATMENTS OR LAYERS (NON-STRUCTURAL)

CAPE SEAL

GENERAL INFORMATION

Generic Name(s): Cape Seal

Trade Names: N/A

Product Description: A Cape seal is a thin surface treatment constructed by applying a slurry seal or microsurfacing to a newly constructed chip seal. A Cape seal is more than the placement of one type of surface treatment over another; it is designed to be an integrated system where the primary purpose of the slurry is to fill voids in the chip seal. The slurry helps prevent chip loss and the chips prevent undue traffic abrasion and erosion of the slurry. Cape seals provide a durable, sealed roadway surfacing that has excellent skid resistance and is smoother than chip seals.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org.

APPLICATION

Typical Use: Road surfacing, corrective or preventative maintenance treatment for minor surface irregularities, small cracks, raveling, and loss of surface friction and to improve ride quality.

Traffic Range: Low to High (AADT < 2,000) for road surfacing; Low to High for corrective or preventative maintenance treatment.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: Cape seals are generally not used for roadway gradients steeper than 12%.

Soil Type: N/A

Other: Cape seals are less susceptible to damage from snow plows than single chip seals or slurry seals in snow plowing areas.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Cape seals are effective in areas where HACP is not available and high resistance to shearing forces is required.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: For new road construction/reconstruction, Cape seals are usually constructed over an aggregate base course. Since the Cape seal does not add structural capacity to the roadway, the base/subbase must be designed to support the anticipated traffic loading. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to Cape seal placement. A prime coat is sometimes used above the aggregate base prior to Cape seal application.

Other Comments: Cape seal performance is highly dependent on the quality of workmanship and the component materials used.

CONSTRUCTION

Availability of Experienced Personnel: The two components of Cape seals, chip seals and slurry seals or microsurfacing, are commonly used surfacings and experienced contractors are, in general, widely available. However, fewer contractors have experience in constructing Cape seals as an integrated system and availability may be limited in some areas.

Materials: Cape seals are comprised of chips seals overlain by slurry seals or microsurfacing. Chip seals are constructed of a bituminous binding agent (emulsified asphalt or paving grade asphalt cement) and clean, uniform-sized crushed aggregate chips, typically 6 to 19 mm (1/4 to 3/4 in.). Modified asphalt cements can be used to enhance certain performance characteristics. Advantages of emulsified asphalt include a cooler application temperature (20 to 85 °C [70 to 185 °F]) than paving grade asphalts, and the water that evaporates is environmentally safe. Cutback asphalts are not recommended for use in Cape seals.

Slurry seals are constructed of a mixture of emulsified asphalt, dense-graded crushed fine aggregate, mineral filler or other additives, and water. The emulsified asphalt is usually cationic and quick-setting. Modified asphalt emulsions can be used to enhance certain performance characteristics.

Microsurfacing is constructed of a mixture of polymer-modified emulsified asphalt, dense-graded crushed fine aggregate, mineral filler or other additives, and water. Polymers are added to the emulsified asphalt to increase mixture stiffness and flexibility, which leads to better rut and crack resistance. Special quick-setting emulsifiers are used for the emulsified asphalt.

Equipment: Equipment required for Cape seal construction includes: asphalt distributor, aggregate spreader, pneumatic-tired roller, mechanical broom, and slurry seal or microsurfacing mixing machine. Equipment is locally available in most large urban areas and regionally available in more remote areas.

Manufacturing/Mixing Process: For the chip seal, the binding agent (either an emulsified asphalt or asphalt cement) is produced by an asphalt supplier and shipped to the site. Aggregate is usually crushed and separated by size to obtain uniform-sized chips for use. If the chips are to be pre-coated with bituminous materials, this action is performed at the plant before the chips are shipped to the site. For the slurry seal or microsurfacing, the mixing machine carries all the unmixed materials and, when construction commences, combines the materials in exact mix proportions in a continuous flow pugmill. For continuous operation, haul vehicles must replenish materials to the mixing machine.

Placement Process: The bituminous binding agent is sprayed onto the prepared working surface at the specified application rate (typically 10-15% less than for a chip seal) by the distributor; then, the aggregate chips are spread onto the surface at the specified application rate (typically 10% less than for chip seal) using an aggregate spreader. After the aggregate chips are placed, the surface is rolled with a pneumatic-tired roller to embed and realign the aggregate chips in the binder. Once the binding agent has hardened, the road surface should be swept with a mechanical broom to remove all loose chips from the surface. The chip seal component is allowed to cure for four to ten days before the slurry seal or microsurfacing is applied. The chip seal surface should be broomed before the slurry seal or microsurfacing is applied. Once the slurry seal or microsurfacing has cured, the Cape seal can be reopened to traffic.

Weather Restrictions: Do not construct any component of the Cape seal if it is raining or there is an imminent risk of rain. The specified minimum air temperature for Cape seal placement varies between different agencies, but is normally 10 °C (50 °F) or above. When using asphalt emulsion, do not apply when freezing temperatures are expected within 24 hours.

Construction Rate: Cape seal construction consists of two separate processes, chip seal construction and slurry seal or microsurfacing construction. Cape seal construction rates are commonly 8,400 m^2/day (10,000 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The chip seal surface can be opened to traffic at lower speeds as soon as it is constructed. Normal traffic speeds can be allowed once the loose chips have been swept from the roadway surface. The roadway lane(s) must be closed again for slurry seal or microsurfacing placement, but can be reopened after curing (typically one hour for microsurfacing or one to twelve hours for slurry seals). Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Cape seals have been used with success in South Africa, where they were developed, and Australia for more than 40 years. The technology was introduced to the United States in 1977. Cape seal use in the United States has been limited, but is commonly used in some areas (e.g. California). The amount of design and construction information available is fairly limited; project experience will vary by region.

Life Expectancy: Life expectancy varies depending on mix types, traffic volumes and degree of routine maintenance. Typical serviceable lives range from 7 to 15 years (average 9 years). Chip seals placed over aggregate or stabilized bases are generally more susceptible to premature structural failures as opposed to chip seals placed over an existing paved roadway.

Ride Quality: Cape seals, similar to other non-structural asphalt surfacings, do not improve ride quality; ride quality is mainly determined by the roughness of the underlying layer. On a properly prepared application surface, a good to very good ride quality can be achieved after construction.

Main Distress / Failure Modes: Delamination of slurry seal, bleeding, shoving, cracking, raveling, loss of surface friction.

Preservation Needs: Cape seals require little, if any, preventative maintenance treatments.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided high quality aggregates are used, Cape seals provide excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because Cape seals provide a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Bituminous binding agent, aggregates, and any additives must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: If paving grade asphalt cement is used, significant heat is generated during the placement process. Construction processes may impact vegetation adjacent to the roadway. If clean aggregates are not used for chip seal construction, dust can be a problem during construction.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Cape seals are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by Cape seal surfacings.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Cape seals can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: The amount of heat generation associated with Cape seal construction is significantly less when emulsified asphalt is used, compared to hot laid paving grade asphalt cement. For Cape seals, tire/road noise is typically low to moderate with the same or slightly higher noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)], but with a lower noise level than chip seals.

AESTHETICS

Appearance: Immediately after placement, the Cape seal's appearance is generally black with a relatively smooth texture. A Cape seal's appearance can be modified with the careful selection of colored aggregates and by the use of pigments in the binding agent.

Appearance Degradation over Time: Over time, the Cape seal surface will wear, exposing more of the aggregate and modifying the appearance.

COST

Supply Price: N/A

Supply+Install Price: \$2.70 to \$3.60/m^2 (\$2.25 to \$3.00/yd^2).

EXAMPLE PROJECTS

Salinas and Sacramento, CA.

SELECT RESOURCES

Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org.

Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.

USDA Forest Service (1999), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

CHIP SEAL

GENERAL INFORMATION

Generic Name(s): Chip Seal, Single Surface Treatment, Bituminous Surface Treatment

Trade Names: N/A

Product Description: A chip seal is a single thin surface treatment constructed by spraying a bituminous binding agent and immediately spreading and rolling a thin aggregate cover. The bituminous binding agent can be an emulsified asphalt, cutback asphalt, or asphalt cement. The aggregate used is a single-sized crushed aggregate chip; the maximum chip size is most commonly 6 to 9.5 mm (1/4 to 3/8 in.), although larger chips have been used successfully on roads with heavy truck traffic. The thickness of the constructed chip seal layer is equal to the maximum size of the aggregate chips used.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org; and

California Chip Seal Association, 14929 Slover Avenue, Fontana, CA 92335, www.chipseal.org.

APPLICATION

Typical Use: Road surfacing; preventative maintenance treatment for small cracks, bleeding, raveling, and loss of surface friction. Chip seals are a widely used alternative for surfacing low volume roads. They protect underlying materials from water and erosion and provide a relatively smooth riding surface. In general, chip seals provide an economical and relatively durable surface that is safe under normal weather and driving conditions. Chip seals can also be placed over new or existing HACP to modify, maintain, or improve the surface texture and friction properties and/or seal small cracks.

Traffic Range: Very Low to Medium when chip seal is placed over aggregate base, Very Low to High (typically AADT < 2,000) when chip seal is placed over existing HACP.

Restrictions:

Traffic: Chip seals should generally be limited to traffic mixes with less than 15% trucks. The use of chip seals should be avoided in areas with frequent truck turning or braking.

Climate: None.

Weather: None.

Terrain: Chip seals are generally not used for roadway gradients steeper than 8%.

Soil Type: N/A

Other: Chip seals can be damaged by plowing in snow plowing areas. Chip seals should not be applied to pavements with majority of ruts greater than 12 mm (0.5 in.) deep.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Chip seals can also be used over old chip seals to provide a continuous build-up of surfacing over time.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: Chip seals are often constructed over an aggregate base course. Since chip seals do not add structural capacity to the roadway, the base/subbase must be designed to support the anticipated traffic loading. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to chip seal placement. A prime coat is sometimes used above the aggregate base prior to chip seal application.

Other Comments: Chip seal performance is highly dependent on the quality of workmanship and the component materials used.

CONSTRUCTION

Availability of Experienced Personnel: Chip seals are a commonly used surfacing and experienced contractors are, in general, widely available. Maintenance crews are used by some agencies for chip seal construction.

Materials: Chip seals are constructed of a bituminous binding agent (emulsified asphalt, cutback asphalt, or asphalt cement) and clean, uniform-sized crushed aggregate chips, typically 6 to 9.5 mm (1/4 to 3/8 in.). Modified asphalt cements can be used to enhance certain performance characteristics. Some agencies require that chips be pre-coated with a bituminous material to improve adhesion and reduce the amount of loose chips. Pre-coated aggregates are not recommended for use with emulsified asphalt.

Paving Grade Asphalt Cement: Advantages of using paving grade asphalt cement is that it cures quickly, does not require any additives in the asphalt cement, and the material achieves full strength as soon as it cools. Disadvantages of asphalt cement include a high application temperature (121 to 177 °C [250 to 350 °F]) and the need to place the aggregate quickly before that asphalt cement cools.

Cutback Asphalt: Advantages of using cutback asphalts include cooler application temperatures (30 to 115 °C [85 to 240 °F]) than paving grade asphalts and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include higher cost than emulsified asphalts, hydrocarbon emissions into the atmosphere during the evaporation process, and potential fire hazards during construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas.

Emulsified Asphalt: Advantages of emulsified asphalt include a cooler application temperature (20 to 85 °C [70 to 185 °F]) than paving grade or cutback asphalts, and the water that evaporates is environmentally safe.

Equipment: Equipment required for chip seal construction includes: asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The binding agent (either an emulsified or cutback asphalt or asphalt cement) is produced by an asphalt supplier and shipped to the site. Aggregate is usually crushed and separated by size to obtain uniform-sized chips for use. If the chips are to be pre-coated with bituminous materials, this action is performed at the plant before the chips are shipped to the site.

Placement Process: The bituminous binding agent is sprayed onto the prepared working surface by the distributor; then, the aggregate chips are spread onto the surface using an aggregate spreader. After the aggregate chips are placed, the surface is rolled with a pneumatic-tired roller to embed and realign the aggregate chips in the binder. The surface should be rolled before the binding agent begins to set. The constructed surface should consist of a single layer of aggregate chips with about two-thirds of the voids being filled with the binding agent. The time available for rolling before the binder hardens will depend on the type of binding agent, binder temperature when it is placed, air temperature, and wind, but can range from several minutes to several hours or more. Once the binding agent has hardened, the road surface should be swept with a mechanical broom to remove all loose chips from the surface. A fog seal can be applied to the chip seal after construction to improve the bonding of the chips to the road surface.

Weather Restrictions: Do not construct chip seals if it is raining or there is an imminent risk of rain, or, if using emulsified asphalt, when freezing temperatures are expected within 48 hours. The specified minimum air temperature for chip seal placement varies between different agencies, but is normally 10 °C (50 °F) or above.

Construction Rate: Chip seal construction rates are in the range of 25,000 m^2/day (30,000 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The chip seal surface can be opened to traffic at lower speeds as soon as it is constructed. Normal traffic speeds can be allowed once the loose chips have been swept from the roadway surface. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Chip seals are a very common roadway surfacing and have been used on projects for more than 50 years; an extensive amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 3 to 7 years (average 5 years). Chip seals placed over aggregate or stabilized bases are generally more susceptible to premature structural failures as opposed to chip seals placed over an existing paved roadway.

Ride Quality: Chip seals, similar to other non-structural asphalt surfacings, do not improve ride quality; ride quality is mainly determined by the roughness of the underlying layer. On a properly prepared application surface, a good to very good ride quality can be achieved after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, raveling, bleeding, loss of surface friction.

Preservation Needs: Preventative maintenance includes periodic crack sealing. Fog seals can be applied to extend the serviceable life of chip seals.

SAFETY

Hazards: Rutting can lead to water accumulation on the pavement surface, causing a driving hazard. Road splash/spray can reduce visibility during periods of higher traffic volume. Loose aggregate chips can create a windshield hazard. When cutback asphalts are used, the solvents can create a health hazard (fumes) and a fire/explosion hazard during construction; proper engineering controls and construction practices should be utilized to minimize safety risks.

Skid Resistance: Provided high quality aggregates are used, chip seals provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because chip seals can provide a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) or solvents (for cutback asphalts) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Bituminous binding agent and aggregate must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: If paving grade asphalt cement is used, significant heat is generated during the placement process. Construction processes may impact vegetation adjacent to the roadway. Asphalt binder spills should be promptly contained from spreading off-site and removed. If clean aggregate is not used, dust can be a problem during construction and sweeping. Excess loose chips can be thrown/ brushed/ washed from the surface into the surrounding environment. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used.

Cutback asphalts can potentially impact water quality and aquatic species due to runoff if heavy rains occur before the cutback asphalt cures. Surface runoff should be properly contained or managed during the curing stage when the project is adjacent to bodies of water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Chip seals are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by chip seal surfacings. In parking areas, oil and other vehicle fluids can be collected by surface runoff, affecting the water quality.

Erosion: Chip seals are a bound surface and are not particularly susceptible to surface erosion. Some aggregate loss can be expected due to a combination of traffic and erosional processes.

Water quality: Chip seals have a minimal impact on water quality. Water quality could be affected by sediment loading from dust or crushed chips from the chip seal surface.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Chip seals can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: The amount of heat generation associated with chip seal construction varies significantly with the type of bituminous binding agent used. Paving grade asphalt cement results in the highest level of heat generation, with cutback asphalt seals generating less heat and emulsified asphalt seals generating even less heat. For chip seals, tire/road noise is typically low to moderate with a slightly higher [2 dB(A)] noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)].

AESTHETICS

Appearance: Immediately after placement, the chip seal's appearance is influenced by the black bituminous binder and the aggregate chip color. If the chips are pre-coated, the chip seal will be black and will not be characterized by the natural aggregate color. A chip seal's appearance can be modified with the careful selection of colored aggregates and by the use of pigments in the binding agent.

Appearance Degradation Over Time: Over time, the chip seal surface will wear, exposing more of the aggregate. The use of preventative maintenance treatments, such as fog seals, will add a black appearance to the surface.

COST

Supply Price: N/A

Supply+Install Price: \$1.00 to \$1.50/m^2 (\$0.80 to \$1.25/yd^2).

EXAMPLE PROJECTS

Chip seals are used extensively throughout the United States.
Utah State Route 9, near Springdale, UT (Access road to Zion National Park).

SELECT RESOURCES

Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org

Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.

Janisch, D.W., and Gaillard, F.S. (1998). *Minnesota Seal Coat Handbook*, Draft Report, Minnesota Local Road Research Board, Maplewood, MN, 116 pp.

USDA Forest Service (1999a), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

CHIP SEAL OVER GEOTEXTILE

GENERAL INFORMATION

Generic Name(s): Geotextile-Reinforced Chip Seal, Chip Seal over Paving Fabric

Trade Names: Numerous products available.

Product Description: A chip seal is a single thin surface treatment constructed by spraying a bituminous binding agent and immediately spreading and rolling a thin aggregate cover. The bituminous binding agent can be an emulsified asphalt, cutback asphalt, or asphalt cement. The aggregate used is a single-sized crushed aggregate chip; the maximum chip size is most commonly 6 to 9.5 mm (1/4 to 3/8 in.), although larger chips have been used successfully on roads with heavy truck traffic. A chip seal over geotextile is constructed by applying a tack coat to a prepared bound surfacing, immediately embedding a geotextile layer onto the prepared surface, and then constructing a traditional chip seal on top.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org; and

Asphalt Interlayer Association, www.aia-us.org.

APPLICATION

Typical Use: Road surfacing; preventative maintenance treatment for small cracks, raveling, and loss of surface friction. The geotextile reinforcement acts as a moisture barrier and reduces reflection cracking of the chip seal. Even after the chip seal begins to crack, the geotextile reinforcement continues to prevent or greatly reduce moisture infiltration from the surface into the underlying layers.

Traffic Range: Very Low to Medium when chip seal is placed over an existing surface treatment, Very Low to High (typically AADT < 2,000) when chip seal is placed over existing HACP.

Restrictions:

Traffic: Chip seals over geotextile should generally be limited to traffic mixes with less than 15% trucks. Chip seal over geotextile use should be limited in areas with trucks turning or braking. Slippage has occurred when used in applications with large shearing forces at the surface (e.g. tight radius curves, breaking at intersections, etc.)

Climate: None.

Weather: None.

Terrain: Chip seals over geotextile are generally not used for roadway gradients steeper than 8%.

Soil Type: N/A

Other: Chip seals over geotextile can be damaged by plowing in snow plowing areas. In areas where snow plowing is common, a double chip or Cape seal over geotextile is recommended instead of a single chip seal over geotextile.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. The inclusion of a geotextile does not protect the chip seal from normal wear and loss of aggregate, so it does not necessarily extend the serviceable life of the treatment. The main benefit of adding a geotextile is to create a waterproofing membrane that keeps water from entering the base aggregate. A dry base has about 40% higher load bearing capacity than the same base section when saturated. The geotextile also protects the chip seal from distresses migrating upwards through the pavement. Therefore, it is usually justified where a chip seal has been chosen to be placed over an asphalt concrete pavement which is badly fatigue cracked but is not pumping or deflecting under load. Geotextile fabrics should never be placed over pavements exuding water from an underground source; the water will strip the geotextile and chip seal off of the pavement.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: Chip seals over geotextile can be constructed over an aggregate base course. Since chip seals do not add significant structural capacity to the roadway, the base/subbase must be designed to support the anticipated traffic loading. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to geotextile and chip seal placement.

Other Comments: Chip seal over geotextile performance is highly dependent on the quality of workmanship and the component materials used. The most important elements of chip seal over geotextile construction is to ensure that the fabric is fully bonded to the existing surface, and saturated from the tack coat binder prior to chip seal construction.

CONSTRUCTION

Availability of Experienced Personnel: Chip seals over geotextile are not a commonly used surfacing and the availability of experienced contractors is limited in many areas.

Materials: Chip seals are constructed of a bituminous binding agent (emulsified asphalt, cutback asphalt, or asphalt cement) and clean, uniform-sized crushed aggregate chips, typically 6 to 9.5 mm (1/4 to 3/8 in.). Modified asphalt cements can be used to enhance certain performance characteristics. Some agencies require that chips be pre-coated with a bituminous material to improve adhesion and reduce the amount of loose chips. Nonwoven geotextiles are manufactured from polypropylene textile. The geotextile used should meet the requirements of AASHTO 1996 M-288 guidelines for paving fabric. A commonly recommended geotextile is 4.1 oz. polypropylene needle punched 101 pound grab tensile strength fabric.

Paving Grade Asphalt Cement: Advantages of using paving grade asphalt cement is that it cures quickly, does not require any additives in the asphalt cement, and the material achieves full strength as soon as it cools. Disadvantages of asphalt cement include a high application temperature (121 to 177 °C [250 to 350 °F]) and the need to place the aggregate quickly before that asphalt cement cools. Paving grade asphalt cement should be used for placement of the geotextile.

Cutback Asphalt: Advantages of using cutback asphalts include cooler application temperatures (30 to 115 °C [85 to 240 °F]) than paving grade asphalts and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include higher cost than emulsified asphalts, hydrocarbon emissions into the atmosphere during the evaporation process, and potential fire hazards during construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas. Cutback asphalts should not be used for placement of the geotextile.

Emulsified Asphalt: Advantages of emulsified asphalt include a cooler application temperature (20 to 85 °C [70 to 185 °F]) than paving grade or cutback asphalts, and the water that evaporates is environmentally safe. Emulsified asphalt should not be used for placement of the geotextile.

Equipment: Equipment required for chip seal over geotextile construction includes: asphalt distributor, aggregate spreader, pneumatic-tired roller, mechanical broom, and mechanical laydown equipment. Mechanical laydown equipment can consist of: a dedicated piece of equipment, a bolt-on attachment to an existing piece of equipment, or a laydown device attached to the spreader truck. Manual laydown equipment is not recommended because the extra time (compared to mechanical laydown equipment) needed allows the tack coat to cool and precludes good embedment of the geotextile, preventing full initial fabric saturation. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The binding agent (either an emulsified or cutback asphalt or asphalt cement) is produced by an asphalt supplier and shipped to the site. Aggregate is usually crushed and separated by size to obtain uniform-sized chips for use. If the chips are to be pre-coated with bituminous materials, it is performed at the plant before the chips are shipped to the site.

Placement Process: Before construction begins, the existing surface should be cleaned of water and debris and cracks greater than 3 mm (0.125 in.) wide should be cleaned and sealed. A tack coat is applied to the prepared surface and the geotextile is rolled out onto the tack coat using mechanical laydown equipment to minimize the amount of wrinkling or folding. The tack coat should be such that it saturates the geotextile without having excess material that can cause bleeding at the surface. Sand is sprinkled on the geotextile surface (optional) and pneumatic rollers are used to roll the geotextile to ensure full saturation and intimate contact between the geotextile and underlying pavement. After rolling, any excess sand is swept from the surface with mechanical brooms. At this point, the chip seal can be constructed. The bituminous binding agent is sprayed onto the prepared working surface by the distributor; then, the aggregate chips are spread onto the surface using an aggregate spreader. After the aggregate chips are placed, the surface is rolled with a pneumatic-tired roller to embed and realign the aggregate chips in the binder. The surface should be rolled before the binding agent begins to set. The constructed surface should consist of a single layer of aggregate chips with about two-thirds of the voids being filled with the binding agent. The time available for rolling before the binder hardens will depend on the type of binding agent, binder temperature when it is placed, air temperature, and wind, but can range from several minutes to several hours. Once the binding agent has hardened, the road surface should be swept with a mechanical broom to remove all loose chips from the surface. A slurry seal can be applied to the chip seal after construction to improve the bonding of the chips to the road surface.

Weather Restrictions: Do not construct chip seals over geotextile if it is raining or there is an imminent risk of rain. The specified minimum air temperature for chip seal placement varies between different agencies, but is normally 10 °C (50 °F) or above.

Construction Rate: Chip seal over geotextile construction rates are in the range of 8,400 m^2/day (10,000 yd^2/day). The chip seal can be constructed the same day that the geotextile is placed.

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The chip seal surface can be opened to traffic at lower speeds as soon as it is constructed. Normal traffic speeds can be allowed once the loose chips have been swept from the roadway surface. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Chip seals over geotextile are not a very common roadway surfacing. Some research, design and construction information, and project experience is available. Performance histories give mixed results regarding the performance of chip seals over geotextile. Many failures can be attributed to poor construction or improper use of the surfacing. On the other hand, agencies familiar with this type of surfacing and who use experienced contractors have reported good results.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 3 to 7 years (average 5 years). Longer serviceable lives, typically 10 to 20 years, are possible if a double chip seal or Cape seal is constructed over the geotextile.

Ride Quality: Chip seals over geotextile, similar to other non-structural asphalt surfacings, do not improve ride quality; ride quality is mainly determined by the roughness of the underlying layer. On a proper prepared application surface, a good to very good ride quality can be achieved after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Raveling, bleeding, loss of chips and surface friction, slippage of the surfacing.

Preservation Needs: Preventative maintenance may include periodic crack sealing.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume. Loose aggregate chips can create a windshield hazard. When cutback asphalts are used, the solvents used can create a health hazard (fumes) and a fire/explosion hazard during construction; proper engineering controls and construction practices should be utilized to minimize safety risks.

Skid Resistance: Provided high quality aggregates are used, chip seals provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because chip seals over geotextile can provide a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) or solvents (for cutback asphalts) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Nonwoven geotextiles are manufactured from polypropylene textile specifically for use as a construction material.

Delivery and Haul Requirements: Bituminous binding agent, aggregate, and geotextile must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: If paving grade asphalt cement is used, significant heat is released during the placement process. Construction processes may impact vegetation adjacent to the roadway. If clean aggregate is not used, dust can be a problem during construction and sweeping. Excess loose chips can be thrown/brushed/washed from the surface into the surrounding environment. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used.

Cutback asphalts can potentially impact water quality and aquatic species due to runoff if heavy rains occur before the cutback asphalt cures. Surface runoff should be properly contained or managed during the curing stage when the project is adjacent to bodies of water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Chip seals over geotextile are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by chip seal over geotextile surfacings

Erosion: Chip seals over geotextile are a bound surface and are not particularly susceptible to surface erosion. Some aggregate loss can be expected due to a combination of traffic and erosional processes.

Water quality: Chip seals over geotextile have a minimal impact on water quality. Water quality could be affected by sediment loading from dust or crushed chips from the chip seal surface.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Chip seals over geotextile can be pulverized and reused as an unbound or stabilized material. The presence of the geotextile may eliminate hot or cold in-place recycling options.

Other Environmental Considerations: The amount of heat generation associated with chip seal construction varies significantly with the type of bituminous binding agent used. Paving grade asphalt cement results in the highest level of heat generation, with cutback asphalt seals generating less heat and emulsified asphalt seals generating even less heat. For chip seals over geotextile, tire/road noise is typically low to moderate with the same or slightly higher [2 dB(A)] noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)].

AESTHETICS

Appearance: Immediately after placement, the chip seal's appearance is influenced by the black bituminous binder and the aggregate chip color. A chip seal's appearance can be modified with the careful selection of colored aggregates and by the use of pigments in the binding agent.

Appearance Degradation Over Time: Over time, the chip seal surface will wear, exposing more of the geotextile fabric. The use of preventative maintenance treatments, such as fog seal or slurry seal, will add a black appearance to the surface.

COST

Supply Price: N/A

Supply+Install Price: \$3.40 to \$4.80/m^2 (\$2.80 to \$4.00/yd^2).

EXAMPLE PROJECTS

Yaqui Pass Road, San Diego County, CA.
City of Sunnyvale, CA.

SELECT RESOURCES

Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org.
Asphalt Interlayer Association, www.aia-us.org.

FOG SEAL

GENERAL INFORMATION

Generic Name(s): Fog Seal

Trade Names: N/A

Product Description: A fog seal is a light application of emulsified asphalt diluted with water. Fog seals were used extensively in the past to seal new pavements immediately after construction. They often performed poorly due to excessive slipperiness when wet and bleeding during hot weather; these problems where mainly due to excessive application rates or inappropriate choice of seal materials. Currently, fog seals are predominately used to enrich oxidized asphalt surfaces or to seal very small cracks and surface voids.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org.

APPLICATION

Typical Use: Preventative maintenance treatment for small cracks, oxidation, and raveling.

Traffic Range: Very Low to High.

Restrictions:

Traffic: Fog seal use is sometimes restricted on high volume roadways due to concerns over reduced skid resistance and short life expectancy; for high volume applications, a high degree of construction experience and quality control is required.

Climate: None.

Weather: None.

Terrain: Fog seal may not be appropriate for winding roads due to slipperiness.

Soil Type: N/A

Other: None.

Other Comments: Fog seals should not be used on roadway surfaces with low skid resistance. Fog seals work best on coarse or porous surfaces where the emulsified asphalt can penetrate the surfacing. When applied to smooth, dense surfacings, fog seals can lie on top of the existing surface and create a slippery surface. Fog seals can extend the life of roadway surfacings and can be used as a "holding" strategy (i.e. delay the need for major maintenance or rehabilitation). Fog seals are often used on newly constructed chip seals to provide a uniform black color and to minimize aggregate loss.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: N/A

Other Comments: None.

CONSTRUCTION

Availability of Experienced Personnel: Fog seals are a commonly used maintenance treatment and experienced contractors are, in general, widely available. Maintenance crews are used by some agencies for fog seal application.

Materials: Fog seals consist of slow-setting emulsified asphalt diluted with water. The emulsified asphalt can be diluted with up to five parts (typically one part) water to one part emulsified asphalt. Modified asphalt cements, including rejuvenators, can be used to enhance the fog seal's effectiveness. Quick setting asphalt emulsions such as CQS-1h may be used to decrease cure time.

Equipment: Fog seal application only requires an asphalt distributor truck.

Manufacturing/Mixing Process: The emulsified asphalt must be diluted with water prior to fog seal application. The dilution ratio should be such that the entire surfacing is covered without excessive ponding that can create a slippery surface. Extended storage of a diluted asphalt emulsion is not recommended.

Placement Process: The diluted emulsified asphalt is applied cold with application temperatures ranging from 20° to 85°C (70° to 185°F). The diluted emulsified asphalt is sprayed onto the prepared working surface by the distributor. Typical application rates for the diluted emulsified asphalt are 0.45 to 0.70 liter/m^2 (0.10 to 0.15 gal/yd^2). A uniform coverage of the fog seal should be achieved for best performance.

Weather Restrictions: Do not construct fog seals if it is raining or there is an imminent risk of rain. The specified minimum air temperature for fog seal application varies between different agencies, but is normally 4 °C (40 °F) or above.

Construction Rate: Fog seal application rates are commonly 25,200 m^2/day (30,000 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being treated is closed during construction, so adequate traffic control is needed. The fog seal surface can be opened to traffic after the emulsified asphalt has set, typically 1 to 3 hours, depending on the weather. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Fog seals are a very common roadway surfacing treatment; an extensive amount of construction information and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 1 to 3 years (average 2 years).

Ride Quality: Fog seals do not affect the ride quality of a roadway.

Main Distress / Failure Modes: Surface wear, bleeding.

Preservation Needs: None.

SAFETY

Hazards: None.

Skid Resistance: Fog seals can lower the skid resistance of a surfacing and create a slippery surface if it is applied too thick.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents are manufactured products. Water is a natural resource.

Delivery and Haul Requirements: Emulsified asphalt must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Spraying processes may impact vegetation adjacent to the roadway, especially in windy conditions.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Fog seals help seal the surfacing, which promotes surface runoff. However, surface runoff water quality is not generally impacted by fog seals.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Fog seal treatments are too thin to recycle. However, fog seal-treated asphalt materials can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: The amount of heat generation associated with fog seal application is significantly less than hot laid surfacings.

AESTHETICS

Appearance: Immediately after placement, fog seals are black. A fog seal's appearance can be modified with the use of pigments in the emulsified asphalt.

Appearance Degradation Over Time: Over time, the fog seal surface will wear, typically in strips or patches, exposing the underlying roadway material.

COST

Supply Price: N/A

Supply+Install Price: \$0.25 to \$0.60/m^2 (\$0.20 to \$0.50/yd^2).

EXAMPLE PROJECTS

Fog seals are used extensively throughout the United States, mainly as a maintenance treatment.

SELECT RESOURCES

Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org

Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.

USDA Forest Service (1999), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

MICROSURFACING

GENERAL INFORMATION

Generic Name(s): Microsurfacing

Trade Names: Microsurfacing, Ralumac, Macroseal

Product Description: Microsurfacing, an enhanced slurry seal, is composed of a mixture of polymer-modified emulsified asphalt, dense-graded crushed fine aggregate, mineral filler or other additives, and water. The main difference between microsurfacing and slurry seals is that microsurfacing can be placed with a thickness up to about three times the size of the largest aggregate in the mix; slurry seals are applied at the thickness of the largest aggregate in the mix. High quality materials and careful mix design are used to create a high-stability mix that is quick-setting and can be placed at thicknesses up to 38 mm (1.5 in.) for rut filling. In addition to rut-filling, microsurfacing is used as a preventative maintenance treatment for roadways with bituminous surfacing.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: International Slurry Surfacing Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.slurry.org

APPLICATION

Typical Use: Preventative maintenance or corrective treatment for minor surface irregularities, small cracks (less than 6 mm [0.25 in.] wide), rutting (fill ruts up to 38 mm [1.5 in.] deep in one pass), raveling, bleeding, and loss of surface friction and to improve ride quality.

Traffic Range: Very Low to High. Typically used for AADT>400.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Microsurfacing is less susceptible to damage from snow plows than single chip seals or slurry seals in snow plowing areas.

Other Comments: Microsurfacing is smoother than chip seals and may be preferred by non-vehicular users (i.e. bicyclists, in-line skaters, etc.) in recreational areas. When microsurfacing is used to address pavement rutting, the cause of rutting should be established in advance. Microsurfacing can rehabilitate rutting due to densification but is not a solution for correcting rutting due to inadequate structural capacity or high instability (i.e. shoving).

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: N/A

Other Comments: None.

CONSTRUCTION

Availability of Experienced Personnel: Microsurfacing construction generally requires experienced specialty contractors. In remote areas, specialty contractors may not be locally available, but they are generally available on a statewide or regional level.

Materials: Microsurfacing is constructed of a mixture of polymer-modified emulsified asphalt, dense-graded crushed fine aggregate, mineral filler or other additives, and water. Polymers are added to the emulsified asphalt to increase mixture stiffness and flexibility, which leads to better rut resistance, durability, and crack resistance. Special quick-setting emulsifiers are used for the emulsified asphalt. Aggregates should consist of 100% crushed high quality aggregate. The maximum aggregate size varies with gradation type: 6 mm (1/4 in.) for Type II slurry, and 9 mm (3/8 in.) for Type III slurry. Type II gradation is typically used for medium volume roadways and Type III gradation is typically used for rut filling and high volume roadways.

Equipment: Microsurfacing requires a special microsurfacing machine with an attached spreader box with a double strike-off blade design. The microsurfacing unit can be truck-mounted or self-propelled. When filling ruts over 12 mm (0.5 in.), a special rut box should be used to address the ruts individually. Equipment is locally available in many large urban areas and regionally available in more remote areas. The microsurfacing unit should be calibrated using site-specific materials and mix proportions prior to each construction job.

Manufacturing/Mixing Process: The microsurfacing unit carries all the unmixed materials and, when construction commences, combines the materials in exact mix proportions in a continuous flow pugmill. For continuous operation, haul vehicles must replenish materials to the mixing machine.

Placement Process: It is important that any areas of base failure be repaired before microsurfacing is applied. A tack coat is usually not required unless the surface is extremely dry and raveled or consists of concrete or brick. The microsurfacing mix is automatically fed into a spreader box attached to the rear of the equipment and applied to the roadway. Microsurfacing is commonly applied at a rate of 11 to 16 kg/m^2 (20 to 30 lb/yd^2) with a corresponding thickness of 9 to 16 mm (0.375 to 0.625 in.). Rolling or compaction is seldom required but may be beneficial in areas of minimal traffic such as parking lots or airports. For high volume applications, two lifts of microsurfacing can be placed, consisting of a leveling layer and a surface layer.

Weather Restrictions: Do not place microsurfacing if it is raining or there is an imminent risk of rain, or there is a danger of freezing within 24 hours. The specified minimum air temperature for microsurfacing placement is normally 10 °C (50 °F) or above.

Construction Rate: Microsurfacing construction rates can typically be about 450 Mg/day (500 tons/day) or about 10.5 lane-km per day (6.6 lane-miles per day) with a continuous run operation.

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. Depending on the type of emulsified asphalt used and weather conditions, roads can usually be opened to straight rolling traffic about one hour after placement. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Microsurfacing was pioneered in Germany in the 1960s and 1970s and introduced to the United States in 1980. Most agencies have some experience with microsurfacing while some have extensive experience. Microsurfacing research reports, design and construction guidelines, and performance data are available.

Life Expectancy: Life expectancy varies depending on mix types, traffic volumes and environmental conditions. Typical serviceable lives range from 5 to 8 years (average 7 years).

Ride Quality: Microsurfacing can improve the ride quality of a previously paved roadway by filling in ruts and other defects. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Bleeding, removal, and wear of the microsurfacing due to tire abrasion.

Preservation Needs: Fog seals can be applied to extend the serviceable life of microsurfacing.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volumes.

Skid Resistance: Microsurfacing provides excellent skid resistance and is frequently used to restore skid resistance to worn HACP.

Road Striping Possible?: Yes.

Other Comments: Because microsurfacing provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Emulsified asphalt, aggregates, and additives must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: None.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Microsurfacing is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Microsurfacing can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: Microsurfacing is cold-mixed and cold-laid and has much lower energy requirements and heat generation compared to hot mixed and hot-placed road surfacings. For microsurfacing, tire/road noise is typically low to moderate with a slightly higher noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)]., but with a lower noise level than chip seals.

AESTHETICS

Appearance: Microsurfacing is typically black in appearance, similar to HACP. Microsurfacing's color can be modified by the use of pigments in the microsurfacing mix.

Appearance Degradation Over Time: Over time, the microsurfacing may wear, exposing more of the aggregate and modifying the appearance. As microsurfacing approaches the limit of its service life it becomes streaky and the underlying asphalt pavement becomes exposed. The use of preventative maintenance treatments, such as fog seals, will maintain the black surface color.

COST
Supply Price: N/A **Supply+Install Price**: \$105 to \$132/Mg (\$95 to \$120/ton) or \$3.10 to \$3.90/m^2 (\$2.60 to \$3.30/yd^2).
EXAMPLE PROJECTS
Campground access roads and parking lots; Keystone Lake, Skiatook Lake, and Oologah Lake, OK; Army Corps of Engineers project. Interstate 75, Wayne County, MI, from I-94 Interchange to 8-Mile Road.
SELECT RESOURCES
International Slurry Surfacing Association, (410) 267-0023, www.slurry.org. Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp. International Slurry Seal Association (2003). *Recommended Performance Guidelines for Micro-Surfacing*, A143, International Slurry Seal Association, 16 pp. USDA Forest Service (1999), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

MULTIPLE SURFACE TREATMENTS (SEALS)

GENERAL INFORMATION

Generic Name(s): Multiple Surface Treatments, Double Chip Seal, Triple Chip Seal, Sandwich Seal

Trade Names: N/A

Product Description: A chip seal is a single thin surface treatment constructed by spraying a bituminous binding agent and immediately spreading and rolling a thin aggregate cover. The bituminous binding agent can be an emulsified asphalt, cutback asphalt, or asphalt cement. To increase the service life or durability of the surfacing, double or triple chip seals are often applied. Double and triple chip seals consist of 2 and 3 layers of chip seal, respectively. The first chip seal has the largest aggregate size (generally up to 19 mm [3/4 in.]) and determines the thickness of the completed surface layer. For each successive layer, the aggregate size is approximately one-half the size of the aggregate in the previous layer. Each additional layer partially fills in the voids in the previous layer. This technique greatly reduces particle loss and extends the service life of the surfacing. Multiple surface treatments are less susceptible to the effects of minor construction defects than a single chip seal.

A sandwich seal is similar to a double chip seal, except the first layer of asphalt binder is omitted. A large aggregate, typically 15 to 19 mm (5/8 to 3/4 in.), is placed, followed by asphalt emulsion and another layer of smaller aggregate, typically 6 to 13 mm (1/4 to 1/2 in.). The emulsion application rate is more than the amount typical for a single chip seal, but less than the rate for a double chip seal. Sandwich seals are useful as a corrective measure for bleeding on existing roadway surfaces.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org; or

California Chip Seal Association, 14929 Slover Avenue, Fontana, CA 92335, www.chipseal.org.

APPLICATION

Typical Use: Road surfacing; preventative maintenance treatment for small cracks, bleeding, raveling, and loss of surface friction. Multiple surface treatments are a widely used alternative for surfacing low volume roads. They protect underlying materials from water and erosion and provide a relatively smooth riding surface. In general, multiple surface treatments provide an economical and relatively durable surface that is safe under normal weather and driving conditions. Multiple surface treatments can also be placed over new or existing HACP to modify, maintain, or improve the surface texture and friction properties and/or seal small cracks. However, it should be noted that a multiple surface treatment is not as durable as well constructed HACP. Multiple surface treatments may also be used as a crack relief layer or membrane prior to the application of new HACP.

Traffic Range: Very Low to Medium when multiple surface treatments are placed over aggregate base, Very Low to High (typically AADT < 2000) when multiple surface treatments are placed over existing HACP.

Restrictions:

Traffic: Multiple surface treatments should generally be limited to traffic mixes with less than 15% trucks. The use of multiple surface treatments should be avoided in areas with frequent truck turning or braking.

Climate: None.

Weather: None.

Terrain: Multiple surface treatments are not recommended for roadway gradients steeper than 8%.

Soil Type: N/A

Other: Multiple surface treatments can be damaged by snowplow operations, but are more durable that single chip seals.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Local practice or supplier recommendations should be followed. Multiple surface treatments are more appropriate than single chip seals for new road construction over a base material while single chip seals are used more often as a preventative maintenance treatment over an existing sealed or paved surface. Multiple surface treatments are less sensitive to minor construction defects than single chip seals.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: Multiple surface treatments are often constructed over an aggregate base course. Since multiple surface treatments do not add significantly to the structural capacity of the roadway, the base/subbase is designed to support the anticipated traffic loading. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to surface treatment placement. A prime coat is sometimes used above the aggregate base prior to surface treatment application.

Other Comments: Multiple surface treatment performance is highly dependent on the quality of workmanship and the component materials used.

CONSTRUCTION

Availability of Experienced Personnel: Multiple surface treatments are a commonly used surfacing and experienced contractors are, in general, widely available. Maintenance crews are used by some agencies for multiple surface treatment construction.

Materials: Multiple surface treatments are constructed of a bituminous binding agent (emulsified asphalt, cutback asphalt, or asphalt cement) and clean, crushed aggregate chips. The first layer has the largest aggregate size (generally up to 19 mm [3/4 in.]) and determines the thickness of the surface layer thickness. For each successive layer, the aggregate size is approximately one-half the size of the aggregate in the previous layer. Modified asphalt cements can be used to enhance certain performance characteristics. Some agencies require that chips be pre-coated with a bituminous material to improve adhesion and reduce the amount of loose chips. Pre-coated chips are not generally recommended when using emulsified asphalt.

Paving Grade Asphalt Cement: Advantages of using paving grade asphalt cement is that it cures quickly, does not require any additives in the asphalt cement, and the material achieves full strength as soon as it cools. Disadvantages of asphalt cement include a high application temperature (121 to 177 °C [250 to 350 °F]) and the need to place the aggregate quickly before that asphalt cement cools.

Cutback Asphalt: Advantages of using cutback asphalts include cooler application temperatures (30 to 115 °C [85 to 240 °F]) than paving grade asphalts and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include higher cost than emulsified asphalts, hydrocarbon emissions into the atmosphere during the evaporation process, and potential fire hazards during construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas.

Emulsified Asphalt: Advantages of emulsified asphalt include a cooler application temperature (20 to 85 °C [70 to 185 °F]) than paving grade or cutback asphalts, and water that evaporates is environmentally safe.

Equipment: Equipment required for multiple surface treatment construction includes: asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The binding agent (either an emulsified or cutback asphalt or asphalt cement) is produced by an asphalt supplier and shipped to the site. Aggregate is usually crushed and separated by size to obtain uniform-sized chips for use. If the chips are to be pre-coated with bituminous materials, it is performed at the plant before the chips are shipped to the site.

Placement Process: The bituminous binding agent is sprayed onto the prepared working surface by the distributor; then, the aggregate chips are spread onto the surface using an aggregate spreader. After the aggregate chips are placed, the surface is rolled with a pneumatic-tired roller to embed and realign the aggregate chips in the binder. The surface should be rolled before the binding agent begins to set. The time available for rolling before the binder hardens will depend on the type of binding agent, binder temperature when it is placed, air temperature, and wind, but can range from several minutes to several hours or more. Once the binding agent has hardened, the road surface should be swept with a mechanical broom to remove all loose chips from the surface. This process is repeated for each additional treatment layer. The initial application of bituminous binding agent is omitted when constructing a sandwich seal. A fog seal can be applied to the multiple surface treatment after construction to improve the bonding of the chips to the road surface.

Weather Restrictions: Do not construct multiple surface treatments if it is raining or there is an imminent risk of rain. When using emulsified asphalt, do not apply when freezing temperatures are expected within 24 hours. The specified minimum air temperature for multiple surface treatment placement varies between different agencies, but is normally 10 °C (50 °F) or above.

Construction Rate: Chip seal construction rates are in the range of 12,500 m^2/day (15,000 yd^2/day) for each treatment layer. Depending on the number of treatment layers and curing times, multiple surface treatments can be constructed in one to several days.

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The surfacing can be opened to traffic at lower speeds as soon as it is constructed. Normal traffic speeds can be allowed once the loose chips have been swept from the roadway surface. Road surface striping may be performed after the final treatment layer is constructed and lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Multiple surface treatments are a very common roadway surfacing and have been used on projects for more than 50 years; an extensive amount of research, design and construction information, and project experience is available. Performance reliability and life expectancy varies with materials used, construction practices, and application. Local project experience can be a useful resource.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 4 to 8 years (average 6 years). Multiple surface treatments placed over aggregate or stabilized bases are generally more susceptible to premature structural failures as opposed to multiple surface treatments placed over an existing paved roadway.

Ride Quality: Multiple surface treatments, similar to other non-structural asphalt surfacings, do not improve ride quality; ride quality is mainly determined by the roughness of the underlying layer. On a properly prepared application surface, a good to very good ride quality can be achieved after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Loss of Chips and Surface Friction, Bleeding, Potholing.

Preservation Needs: Preventative maintenance includes periodic crack sealing. Fog seals can be applied to extend the serviceable life of multiple surface treatments.

SAFETY

Hazards: Rutting can lead to water accumulation on the pavement surface, causing a driving hazard. Road splash/spray can reduce visibility during periods of higher traffic volume. Loose aggregate chips can create a windshield hazard. When cutback asphalts are used, the solvents used can create a health hazard (fumes) and a fire/explosion hazard during storage and construction; proper engineering controls and construction practices should be utilized to minimize safety risks.
Skid Resistance: Provided high quality aggregates are used and they are well bonded to the surface, multiple surface treatments provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because multiple surface treatments can provide a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) or solvents (for cutback asphalts) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Bituminous binding agent and aggregate must be hauled to the site. Haul distances may be significant for remote sites, unless local aggregate sources can be identified.

Potential Short-Term Construction Impacts: If paving grade asphalt cement is used, significant heat is generated during the placement process. Construction processes may impact vegetation adjacent to the roadway. If clean aggregate is not used, dust can be a problem during construction and sweeping. Excess loose chips can be thrown/brushed/washed from the surface into the surrounding environment. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used. Cutback asphalts can potentially impact water quality and aquatic species due to runoff if heavy rains occur before the cutback asphalt cures. Surface runoff should be properly contained or managed during the curing stage when the project is adjacent to bodies of water.

Potential Long-Term Environmental Impacts:
Leachate: None.

Surface Runoff: Multiple surface treatments are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by multiple surface treatment surfacings

Erosion: Multiple surface treatments are a bound surface and are not susceptible to surface erosion. Some aggregate loss may be possible due to a combination of traffic and erosional processes.

Water quality: Multiple surface treatments have a minimal impact on water quality. Water quality could be affected by sediment loading from dust or crushed chips from the multiple surface treatment surface.

Aquatic species: None.
Plant quality: None.
Air Quality: None.
Other: None.
Ability to Recycle/Reuse: Multiple surface treatments can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: The amount of heat generation associated with multiple surface treatments construction varies significantly with the type of bituminous binding agent used. Paving grade asphalt cement results in the highest level of heat generation, with cutback asphalt seals generating less heat and emulsified asphalt seals generating even less heat. For multiple surface treatments, tire/road noise is typically low to moderate with the same or slightly higher [2 dB(A)] noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)].

AESTHETICS

Appearance: Immediately after placement, the multiple surface treatment's appearance is influenced by the black bituminous binder and the aggregate chip color. If the chips are pre-coated, the multiple surface treatments will be black and will not be characterized by the natural aggregate color. A multiple surface treatment's appearance can be modified with the careful selection of colored aggregates and by the use of pigments in the binding agent.

Appearance Degradation Over Time: Over time, the multiple surface treatment will wear, exposing more of the aggregate. The use of preventative maintenance treatments, such as fog seals, will add a black appearance to the surface.

COST

Supply Price: N/A

Supply+Install Price: \$1.50 to \$3.00/m^2 (\$1.25 to \$2.50/yd^2).

EXAMPLE PROJECTS

Multiple surface treatments are used extensively throughout the United States.
Antelope House and Mummy Cave Overlook Roads, Canyon de Chelly National Monument, AZ.

SELECT RESOURCES

Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org.
Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.
Janisch, D.W., and Gaillard, F.S. (1998). *Minnesota Seal Coat Handbook*, Draft Report, Minnesota Local Road Research Board, Maplewood, MN, 116 pp.
USDA Forest Service (1999), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

OPEN GRADED FRICTION COURSE

GENERAL INFORMATION

Generic Name(s): Open Graded Friction Course (OGFC)

Trade Names: N/A

Product Description: Open graded friction course (OGFC) is a porous hot mix asphalt concrete wearing course, containing little sand or dust and with high air voids content (typically from 15 to 25%). The open graded friction course is designed to allow water to drain through to an impermeable barrier and, following the cross slope of the roadway, drain into a side ditch. The drainage capacity of an OGFC is a direct function of the air voids. OGFC has very good frictional properties, provides quick drainage, and reduces hydroplaning, splash/spray from vehicles, headlight glare, and road noise. OGFC is also less susceptible to deformation than HACP.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706, (888) HOT-MIXX, www.hotmix.org.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High. OGFC is used mainly on medium and high volume roads; on very low to low volume roads, the low volume of traffic allows dust and other materials that can clog the OGFC pores to accumulate on the road surface.

Restrictions:

Traffic: OGFC is not recommended for areas subjected to significant heavy vehicle braking or turning.

Climate: OGFC use in cold climates, where snow and ice are common, is limited and requires special winter maintenance procedures. Because OGFC has an open structure, it can freeze sooner than conventional asphalt concrete mixes. Snow and ice control should be limited to snow plowing and chemical deicers. Road crew must apply road salt at lower application rates, but more frequently. Winter maintenance sand cannot be used because it can clog the pores of the OGFC mix.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: N/A; structural capacity of OGFC is not considered in the structural design of the pavement system. OGFC is normally used to increase frictional properties of the road surface and improve driving conditions. It is placed directly above conventional HACP layers.

Other Design Values: N/A

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Traditionally, asphalt cement grades have been designated as pen grade (60/70, 85/100, etc.) or by viscocity grades (AC-20, AC-30, etc.). Currently, asphalt cements are specified by Performance Grades (PG), such as PG 64-22, indicating the high and low temperature range in °C. The use of polymers to expand the temperature range of an asphalt will improve rutting resistance at high temperatures and reduce thermal cracking at low temperatures.

OGFC is typically only used as a surface wearing course with a maximum layer thickness of 19 mm (0.75 in.). In a typical OGFC pavement structure, the underlying binder course is impermeable and the water entering through the surface course is drained to ditches. The water must be allowed to drain freely out of the pavement at the pavement's edge.

The primary mix performance problems are raveling and stripping of underlying layers. Gap-graded mixes with low fines content (high air voids) may have asphalt binder draindown problems, i.e. loss of asphalt binder. Polymers and other additives are used to control draindown, improve adhesion, and improve resistance to aging.

CONSTRUCTION

Availability of Experienced Personnel: OGFC is a commonly used surfacing in many states and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.

Materials: Open graded friction course (OGFC) consists of porous HACP, containing little sand or dust and with high air voids content (typically from 15 to 25%). HACP is composed of a blend of coarse and fine aggregate with asphalt cement as a binder. Polymer modified asphalt cements and fibers are frequently used to control draindown, improve adhesion, and improve resistance to raveling and oxidation.

Equipment: Equipment required for OGFC construction includes: haul vehicles, asphalt distributor (if tack coat is applied), asphalt paver machine, and compaction equipment (i.e. static steel wheel roller). Equipment is widely available in urban areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: OGFC is hot mixed at an asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. Asphalt concrete mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in trucks to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to approximately 1.5 hours.

Placement Process: A tack coat is usually applied to the binder course before OGFC is placed. Upon arrival at the site, the OGFC mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The OGFC is then rolled with compaction equipment to seat the material before the asphalt binder solidifies, which occurs at about 85 °C (185 °F) for neat asphalt and 115 °C (240 °F) for polymer modified asphalt. The time available for compaction before the mix has cooled will depend on the mix temperature when it is placed, layer thickness, air temperature, and wind, but can range from several minutes to more than 30 minutes.

Weather Restrictions Do not place OGFC if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for asphalt concrete placement varies between different agencies, but is normally about 16 °C (60 °F).

Construction Rate: OGFC placement rates will depend on the speed that the asphalt concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or higher. Typical production rates are 900 to 1,360 Mg/day (1,000 to 1,500 tons/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The paving is relatively fast so can be done during a night lane closure, assuming temperature requirements can be met, to minimize traffic disruption. The OGFC surface can be opened to traffic as soon as the OGFC has cooled and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: OGFC is a common roadway surfacing and has been used on roadway projects for about 50 years; an extensive amount of research, design and construction information, and project experience is available. Many states experienced problems with OGFC in the 1970s, leading them to stop using OGFC. Mix design improvements, including use of polymers and additives, have since led to improvements in OGFC performance and increased usage.

Life Expectancy: Life expectancy for OGFC typically ranges from 8 to 12 years.

Ride Quality: OGFC ride quality is very good. OGFC has good frictional characteristics, eliminates hydroplaning on the pavement surface, and significantly reduces the level of road/tire noise. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Raveling, shoving, stripping (in underlying layer), cracking.

Preservation Needs: Preventative maintenance includes crack sealing every 2 to 5 years. Asphalt seals can be used to extend the life of OGFC, but they will reduce the water-removing function of an OGFC.

SAFETY

Hazards: None.

Skid Resistance: OGFC provides very good to excellent skid resistance, thereby reducing the potential for wet skidding and hydroplaning accidents.

Road Striping Possible?: Yes.

Other Comments: Because OGFC provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. Because OGFC has an open structure, it can freeze sooner than conventional asphalt concrete mixes. OGFC can reduce water spray by 90% compared to a dense-graded surface.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: OGFC must be hauled from an asphalt plant unless a mobile asphalt plant is assembled. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the OGFC mixing and placement process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: OGFC is designed to allow infiltration of surface water into the surfacing layer. The water collected in the pavement is drained to the pavement edges. Surface runoff water quality is not generally impacted by OGFC roadways.

Erosion: OGFC is a bound material and is not susceptible to surface erosion. Shoulders and base material should be protected from fast moving water.

Water quality: OGFC does not impact water quality.

Aquatic species: OGFC does not impact aquatic species.

Plant quality: OGFC does not impact plant quality.

Air Quality: OGFC does not impact air quality.

Other: None.

Ability to Recycle/Reuse: OGFC can be fully recycled as a pavement construction material.

Other Environmental Considerations: OGFC's characteristic black surface will absorb heat from sunlight; select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. OGFC typically reduce tire/road noise by 3 decibels compared to conventional HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)] and 5 decibels compared to PCCP.

AESTHETICS

Appearance: Immediately after placement, OGFC is generally black with a coarse surface texture.

Appearance Degradation Over Time: Over time, OGFC can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing, the surface appearance deteriorates further.

COST

Supply Price: N/A

Supply+Install Price: \$250 to \$300/Mg (\$225 to \$275/ton), or \$11.00 to \$13.40/m^2 (\$9.20 to \$11.20/yd^2) for 19 mm (0.75 in.) thick layer.

EXAMPLE PROJECTS

State transportation agencies in Georgia, Oregon, and Texas have used OGFC on numerous highway and Interstate projects.

SELECT RESOURCES

Asphalt Institute, (859) 288-4960, www.asphaltinstitute.org.
National Asphalt Pavement Association (NAPA), (888) HOT-MIXX, www.hotmix.org.

OTTA SEAL

GENERAL INFORMATION

Generic Name(s): Otta Seal, Graded Gravel Seal

Trade Names: N/A

Product Description: An Otta seal is an asphalt surface treatment constructed by placing a graded aggregate on top of a thick application of relatively soft bituminous binding agent. The bituminous binding agent can be an emulsified asphalt, cutback asphalt, or asphalt cement. The binder works its way into the aggregate with rolling and traffic. In comparison to other surface treatments, material and construction specifications are not as strict. Local aggregates that would not meet the requirements for high quality paving aggregate are often used in Otta seals. The requirements on aggregate gradation, particle shape and strength are also relaxed.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to Low for a single Otta seal; Very Low to High (AADT < 2000) for a double Otta seal.

Restrictions:

Traffic: Double Otta seals are not recommended for roadways with frequent truck traffic or areas subject to trucks turning or braking.

Climate: None.

Weather: None.

Terrain: Single Otta seals are generally not used for roadway gradients greater than 8%. Double Otta seals are generally not used for roadway gradients greater than 12%.

Soil Type: N/A

Other: Single Otta seals can be damaged by snow plow operations.

Other Comments: Otta seals have been used as an impermeable surfacing for moisture-susceptible gravel roads with low bearing capacity (i.e. roads during spring thaw period). The Otta seal shields the base material from moisture infiltration and is flexible enough to withstand the relatively large deflections associated with low bearing capacity roads without exhibiting significant distress. If there is permanent deformation of the base, the Otta seal will not knead back together.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: Otta seals are usually constructed over an aggregate base course. Since Otta seals do not add structural capacity to the roadway, the base/subbase must be designed to support the anticipated traffic loading. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to Otta seal placement. A prime coat is usually not used above the aggregate base prior to Otta seal application.

CONSTRUCTION

Availability of Experienced Personnel: Otta seal use in the United States has been very limited, so experienced contractors are generally not available. However, Otta seals are less sensitive to quality of workmanship and materials than other roadway surfacings. Otta seals can be constructed by qualified contractors or agency maintenance crews. Crews familiar with seal coating will be able to apply their equipment and experience.

Materials: An Otta seal is constructed of a graded aggregate on top of a thick application of relatively soft bituminous binding agent. The bituminous binding agent can be an emulsified asphalt (e.g. HFMS-2s), cutback asphalt (e.g. MC3000 to MC800), or asphalt cement (e.g. 150/200 penetration grade). Bituminous binder application rates vary from about 1.6 to 2.0 liter/m^2 (0.35 to 0.44 gal/yd^2) for asphalt cement to about 1.9 to 2.4 liter/m^2 (0.45 to 0.56 gal/yd^2) for emulsified asphalt, depending on binder type and aggregate gradation. In comparison to other surface treatments, material and construction specifications are not as strict. Local aggregates that would not meet the requirements for high quality paving aggregate are often used in Otta seals. Natural gravels are acceptable. The maximum aggregate size in the graded aggregate is generally 13 to 19 mm (1/2 to 3/4 in.). The graded aggregate can be crushed or uncrushed and contain up to 10% fines. Quantities of aggregate range from 27.1 to 33.6 kg/m^2 (50 to 62 lb/yd^2). The requirements on aggregate gradation, particle shape and strength are relaxed.

Paving Grade Asphalt Cement: Advantages of using paving grade asphalt cement is that it cures quickly, does not require any additives in the asphalt cement, and the material achieves full strength as soon as it cools. Disadvantages of asphalt cement include a high application temperature (121 to 177 °C [250 to 350 °F]) and the need to place the aggregate quickly before that asphalt cement cools.

Cutback Asphalt: Advantages of using cutback asphalts include cooler application temperatures (30 to 115 °C [85 to 240 °F]) than paving grade asphalts (130°C [265 °F] or higher) and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include higher cost than emulsified asphalts, hydrocarbon emissions into the atmosphere during the evaporation process, and potential fire hazards during construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas.

Emulsified Asphalt: Advantages of emulsified asphalt include a cooler application temperature (20 to 85 °C [70 to 185 °F]) than paving grade or cutback asphalts. In addition, water that evaporates from emulsified asphalt is environmentally safe.

Equipment: Equipment required for Otta seal construction includes: asphalt distributor, aggregate spreader, pneumatic-tired roller, and mechanical broom. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The binding agent (either an emulsified or cutback asphalt or asphalt cement) is produced by an asphalt supplier and shipped to the site. Aggregate is processed to remove oversized aggregate and excess fines.

Placement Process: The bituminous binding agent is sprayed onto the prepared working surface by the distributor; then, the graded aggregate is spread onto the surface using an aggregate spreader. After the aggregate is placed, the surface is rolled with a pneumatic-tired roller to embed, realign the aggregate chips in the binder, and begin drawing the binder through the aggregate to the surface. Due to the fines in the aggregate, two or three days of compaction, either by rollers or traffic, is required for the binder to coat all the aggregate particles. During the first few weeks, aggregates dislodged from the surfacing by traffic should be swept back into the wheelpaths. After about three weeks, the surface should be swept by a mechanical broom to remove all loose aggregate from the surfacing. Single Otta seals are often overlaid with a sand seal. If a double seal is constructed, the second layer is constructed in a similar manner two to three months after the first layer is constructed. With attention to detail, a second application can be applied 1 day after the first application; however, two to three months is recommended.

Weather Restrictions: Do not construct Otta seals if it is raining or there is an imminent risk of rain. The specified minimum air temperature for Otta seal placement varies between different agencies, but is normally 10 °C (50 °F) or above.

Construction Rate: Otta seal construction rates are commonly 33,500 m^2/day (40,000 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The Otta seal surface can be opened to traffic at lower speeds, commonly 30 km/hr (20 mph), as soon as it is constructed. Normal traffic speeds can be allowed after about three weeks, when the loose aggregate has been swept from the roadway surface. Road surface striping may be performed after the loose aggregate is swept from the surfacing.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Otta seals were developed in Norway in the 1960s. They have been used frequently in Norway, Sweden, Iceland, and Botswana, and to a less extent in several other countries. Otta seal performance has been good in countries that are familiar with this type of surfacing. Otta seal design is empirical in nature and trial sections are often construction to determine the proper material application rates. Experience with Otta seals in the United States is very limited.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Reported serviceable lives for single and double Otta seals range 4 to 8 years and 8 to 15 years, respectively.

Ride Quality: Otta seals, similar to other non-structural asphalt surfacings, do not improve ride quality; ride quality is mainly determined by the roughness of the underlying layer. On a proper prepared application surface, a good ride quality can be achieved after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, raveling, bleeding, potholes, loss of surface friction.

Preservation Needs: Only minor preventative maintenance, consisting of localized patching and sealing, is required between reapplications.

SAFETY

Hazards: Loose aggregate chips can create a windshield hazard. When cutback asphalts are used, the solvents used can create a health hazard (fumes) and a fire/explosion hazard during construction; proper engineering controls and construction practices should be utilized to minimize safety risks.

Skid Resistance: Skid resistance will vary depending on the quality of materials used during construction.

Road Striping Possible?: Yes.

Other Comments: Because Otta seals can provide a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) or solvents (for cutback asphalts) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Bituminous binding agent must be hauled to the site. Haul distances may be significant for remote sites. Relaxed aggregate specifications often allow for the use of locally available aggregate and reduce or eliminate aggregate hauling costs.

Potential Short-Term Construction Impacts: If paving grade asphalt cement or cutback asphalts are used, significant heat is generated during the placement process. Construction processes may impact vegetation adjacent to the roadway. Dust can be a problem during construction and sweeping. Excess loose aggregate can be thrown/brushed/washed from the surface into the surrounding environment. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used. Cutback asphalts can potentially impact water quality and aquatic species due to runoff if heavy rains occur before the cutback asphalt cures. Surface runoff should be properly contained or managed during the curing stage when the project is adjacent to bodies of water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Otta seals are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by Otta seal surfacings.

Erosion: Otta seals are a bound surface and are not particularly susceptible to surface erosion. Some aggregate loss can be expected due to a combination of traffic and erosional processes.

Water quality: Otta seals have a minimal impact on water quality. Water quality could be affected by sediment loading from dust or crushed aggregate particles from the Otta seal surface.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Otta seals can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: The amount of heat generation associated with Otta seal construction varies significantly with the type of bituminous binding agent used. Paving grade asphalt cement results in the highest level of heat generation, with cutback asphalt seals generating less heat and emulsified asphalt seals generating even less heat. For Otta seals, tire/road noise is typically low to moderate with the same or slightly higher noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)].

AESTHETICS

Appearance: Immediately after placement, the Otta seal's appearance is similar to a gravel road and is influenced by the aggregate color. With time and traffic, the black bituminous binding agent works its way up through the aggregate, creating a surface appearance similar to cold mix asphalt concrete.

Appearance Degradation Over Time: Over time, the Otta seal will generally maintain its appearance.

COST

Supply Price: N/A

Supply+Install Price: \$2.00 to \$2.70/m^2 (\$1.70 to \$2.30/yd^2).

EXAMPLE PROJECTS

Cass County Roads 25 & 171, Cass County, MN; MN Highway 74, north of Whitewater State Park, Elba, MN.

SELECT RESOURCES

Johnson, Greg (2003). "Minnesota's Experience with Thin Bituminous Treatments for Low-Volume Roads," Transportation Research Record 1819, TRB, National Research Council, Washington, D.C., pp. 333-337.

Norwegian Public Roads Administration (1999). "A Guide to the Use of Otta Seals," PIARC XXIst World Road Congress, Kuala Lumpur, Malaysia.

Thurmann-Moe, T., and Ruistuen, H. (1983). "Graded Gravel Seal (Otta Surfacing)," Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 333-335.

SAND SEAL

GENERAL INFORMATION

Generic Name(s): Sand Seal

Trade Names: N/A

Product Description: A sand seal is a thin asphalt surface treatment constructed by spraying a bituminous binding agent and immediately spreading and rolling a thin fine aggregate (i.e. sand or screenings) cover. A sand seal is basically the same as a chip seal except that finer aggregate is used in the cover. The bituminous binding agent can be an emulsified asphalt, cutback asphalt, or asphalt cement. The maximum aggregate size is usually smaller than 2 mm (#10 sieve). Sand seals are often used in areas where good sources of aggregate for chip seals are not available.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org.

APPLICATION

Typical Use: Road surfacing; preventative maintenance treatment for small cracks, oxidation, bleeding, raveling, and loss of surface friction.

Traffic Range: Very Low to Low when sand seal is placed over aggregate base, Very Low to High (typically AADT < 2,000) when sand seal is placed over existing HACP.

Restrictions:

Traffic: Sand seals should generally be limited to traffic mixes with a low percentage of trucks.

Climate: None.

Weather: None.

Terrain: Sand seals are generally not used for roadway gradients steeper than 8%.

Soil Type: N/A

Other: Sand seals can be damaged by snow plow operations. Sand seals should not be applied to pavements with a majority of ruts greater than 12 mm (0.5 in.) deep.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Sand seals are commonly applied to existing asphalt pavements to enrich dry, weathered, or oxidized surfaces, seal small cracks, and improve skid resistance.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: Sand seals can be constructed over an aggregate base course. Since sand seals do not add structural capacity to the roadway, the base/subbase must be designed to support the anticipated traffic loading. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to sand seal placement. A prime coat is sometimes used above the aggregate base prior to sand seal application.

Other Comments: Sand seal performance is highly dependent on the quality of workmanship and the component materials used.

CONSTRUCTION

Availability of Experienced Personnel: Sand seals are a commonly used surfacing in some regions, but not others. Experienced contractors are, in general, available in most areas. Maintenance crews are used by some agencies for sand seal construction.

Materials: Sand seals are constructed of a bituminous binding agent (emulsified asphalt, cutback asphalt, or asphalt cement) and fine aggregate; the maximum aggregate size is typically less than 2 mm (#10 sieve). Modified asphalt cements, including rejuvenators, can be used to enhance certain performance characteristics, such as bonding to the road surface.

Paving Grade Asphalt Cement: Advantages of using paving grade asphalt cement is that it cures quickly, does not require any additives in the asphalt cement, and the material achieves full strength as soon as it cools. Disadvantages of asphalt cement include a high application temperature (121 to 177 °C [250 to 350 °F]) and the need to place the aggregate quickly before that asphalt cement cools.

Cutback Asphalt: Advantages of using cutback asphalts include cooler application temperatures (30 to 115 °C [85 to 240 °F]) than paving grade asphalts and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include higher cost than emulsified asphalts, hydrocarbon emissions into the atmosphere during the evaporation process, and potential fire hazards during storage and construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas.

Emulsified Asphalt: Advantages of emulsified asphalt include a cooler application temperature (20 to 85 °C [70 to 185 °F]) than paving grade or cutback asphalts, and the water that evaporates is environmentally safe.

Equipment: Equipment required for sand seal construction includes: asphalt distributor, sand spreader, pneumatic-tired roller, and mechanical broom. The use of a vacuum type sweeper should be considered in areas sensitive to dust. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The binding agent (either an emulsified or cutback asphalt or asphalt cement) is produced by an asphalt supplier and shipped to the site.

Placement Process: The bituminous binding agent is sprayed onto the prepared working surface by the distributor; then, the fine aggregate is spread onto the surface using a sand spreader. Typical application rates are 0.70 to 1.25 liter/m^2 (0.15 to 0.28 gal/yd^2) for emulsified asphalt and 5.5 to 12 kg/m^2 (10 to 22 lb/yd^2) for fine aggregate. After the fine aggregate is placed, the surface is rolled with a pneumatic-tired roller. The set time for the binder will depend on the type of binding agent, binder temperature when it is placed, air temperature, and wind, but can range from several minutes to several hours or more. Once the binding agent has hardened, the road surface should be swept with a mechanical broom to remove all loose sand from the surface.

Weather Restrictions: Do not construct sand seals if it is raining or there is an imminent risk of rain. The specified minimum air temperature for sand seal placement varies between different agencies, but is normally 10 °C (50 °F) or above. When using emulsified asphalt, do not apply when freezing weather is predicted within 24 hours of intended application.

Construction Rate: Sand seal construction rates are commonly 25,200 m^2/day (30,000 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The sand seal surface can be opened to traffic at lower speeds, typically 30 km/hr (20 mph) maximum speed, as soon as it is constructed. Normal traffic speeds can be allowed once the binder has set and excess sand is swept from the roadway surface. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Sand seals are not as commonly used as many other thin asphalt surfacings, but are used frequently by some agencies. The amount of design and construction information available is fairly limited; project experience will vary by region.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 2 to 6 years (average 3 years). Sand seals placed over aggregate or stabilized bases are generally more susceptible to premature structural failures as opposed to multiple surface treatments placed over an existing paved roadway.

Ride Quality: Sand seals, similar to other non-structural asphalt surfacings, do not improve ride quality; ride quality is mainly determined by the roughness of the underlying layer. On a properly prepared application surface, a good to very good ride quality can be achieved after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, raveling, bleeding, streaking and surface wear due to traffic abrasion, loss of surface friction.

Preservation Needs: Other than occasional patching, maintenance is not normally performed on the surfacing between sand seal applications.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume. When cutback asphalts are used, the solvents used can create a health hazard (fumes) and a fire/explosion hazard during storage and construction; proper engineering controls and construction practices should be utilized to minimize safety risks.

Skid Resistance: Provided high quality aggregates are used, sand seals provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: N/A

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) or solvents (for cutback asphalts) are manufactured products. Aggregates are naturally occurring.

Delivery and Haul Requirements: Bituminous binding agent and sand, if not available locally, must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: If paving grade asphalt cement is used, significant heat is generated during the placement process. Construction processes may impact vegetation adjacent to the roadway. If clean sand is not used, dust can be a problem during construction and sweeping. Excess sand can be thrown/brushed/washed from the surface into the surrounding environment. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used.

Cutback asphalts can potentially impact water quality and aquatic species due to runoff if heavy rains occur before the cutback asphalt cures. Surface runoff should be properly contained or managed during the curing stage when the project is adjacent to bodies of water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Sand seals are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by sand seal surfacings

Erosion: Sand seals are a bound surface and are not particularly susceptible to surface erosion. Some sand loss can be expected due to a combination of traffic and erosional processes.

Water quality: Sand seals have a minimal impact on water quality. Water quality could be affected by sediment loading from dust or loose fine aggregate from the sand seal surface.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Sand seals can be pulverized and reused as an unbound or stabilized material.

Other Environmental Considerations: The amount of heat generation associated with sand seal construction varies significantly with the type of bituminous binding agent used. Paving grade asphalt cement results in the highest level of heat generation, with cutback asphalt seals generating less heat and emulsified asphalt seals generating even less heat. For sand seals, tire/road noise is typically low to moderate with about the same noise level as HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)].

AESTHETICS

Appearance: Immediately after placement, the sand seal's appearance is influenced by the black bituminous binder and, to a lesser extent, by the sand color. A sand seal's appearance can be modified by the use of pigments in the asphalt cement, but would not normally be done because of the short service life of the surfacing.

Appearance Degradation Over Time: Over time, the sand seal surface will wear, exposing more of the underlying surface. The use of preventative maintenance treatments, such as fog seals, will add a black appearance to the surface.

COST

Supply Price: N/A

Supply+Install Price: \$0.60 to \$1.50/m^2 (\$0.50 to \$1.25/yd^2).

EXAMPLE PROJECTS

None.

SELECT RESOURCES

Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org

Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.

USDA Forest Service (1999a), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

SCRUB SEAL

GENERAL INFORMATION

Generic Name(s): Scrub Seal

Trade Names: N/A

Product Description: A scrub seal is a thin asphalt surface treatment constructed by spraying emulsified asphalt onto an existing pavement, dragging a broom across the surface to scrub the emulsified asphalt into the surface cracks, immediately spreading a thin fine aggregate (i.e. sand or screenings) over the emulsified asphalt, dragging another broom over the surface to scrub the fine aggregate into the surface cracks, and rolling the surface with a pneumatic tire roller. Polymer-modified emulsified asphalt is normally used. Scrub seals can rejuvenate dry, oxidized pavements and fill small cracks up to 6 mm (0.25 in.) wide.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org.

APPLICATION

Typical Use: Preventative maintenance treatment for small cracks, oxidation, bleeding, raveling, and loss of surface friction.

Traffic Range: Very Low to High (typically AADT < 1,500).

Restrictions:

Traffic: Scrub seals should generally be limited to traffic mixes with a low percentage of trucks.

Climate: None.

Weather: None.

Terrain: Scrub seals are generally not used for roadway gradients steeper than 8%.

Soil Type: N/A

Other: Scrub seals can be damaged by snow plow operations. Scrub seals should not be applied to pavements with majority of ruts greater than 12 mm (0.5 in.) deep.

Other Comments: None.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: N/A

Other Comments: Scrub seal performance is highly dependent on the quality of workmanship and the component materials used.

CONSTRUCTION

Availability of Experienced Personnel: Scrub seals are a commonly used surfacing in some regions, but not in others. Availability of experienced contractors may be limited in some areas.

Materials: Scrub seals are constructed of emulsified asphalt and fine aggregate; the maximum aggregate size is typically less than 2 mm (#10 sieve). Modified emulsified asphalts, including rejuvenators, can be used to enhance certain performance characteristics.

Equipment: Equipment required for scrub seal construction includes: asphalt distributor, sand spreader, pneumatic-tired roller, scrub seal drag brooms, and mechanical broom. The use of a vacuum type sweeper should be considered in areas sensitive to dust. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The binding agent (i.e. emulsified asphalt) is produced by an asphalt supplier and shipped to the site.

Placement Process: The emulsified asphalt is sprayed onto the prepared working surface by the asphalt distributor and worked into the existing surface with a drag broom pulled behind the distributor; then, the fine aggregate is spread onto the surface using a sand spreader and worked into the existing surface using a drag broom. Typical application rates are 0.70 to 1.80 liter/m^2 (0.15 to 0.40 gal/yd^2) for emulsified asphalt and 5.4 to 10.8 kg/m^2 (10 to 20 lb/yd^2) for fine aggregate. After the fine aggregate is placed, the surface is rolled with a pneumatic-tired roller. The set time for the binder is typically a few hours, but will depend on the type of binding agent, binder temperature when it is placed, air temperature, and wind conditions. Once the binding agent has hardened, the road surface should be swept with a mechanical broom to remove all loose fine aggregate from the surface.

Weather Restrictions: Do not construct scrub seals if it is raining or there is an imminent risk of rain or if freezing temperatures are expected within 24 hours. The specified minimum air temperature for scrub seal placement varies between different agencies, but is normally 10 °C (50 °F) or above.

Construction Rate: Scrub seal construction rates are commonly 20,000 m^2/day (23,800 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being treated is closed during scrub seal application, so adequate traffic control is needed. The scrub seal surface can be opened to traffic at lower speeds, typically 30 km/hr (20 mph) maximum speed, as soon as it is constructed. Normal traffic speeds can be allowed once the binder has set and excess fine aggregate is swept from the roadway surface. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Scrub seals are not as commonly used as many other maintenance treatment surfacings, but are used frequently by some agencies. The amount of design and construction information available is fairly limited. Project experience will vary by region.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 2 to 6 years (average 3 years).

Ride Quality: Scrub seals have little to no effect on ride quality.

Main Distress / Failure Modes: Raveling, bleeding, wear by tire abrasion, loss of surface friction.

Preservation Needs: None.

SAFETY

Hazards: None.

Skid Resistance: Provided high quality aggregates are used, scrub seals initially provide good skid resistance.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) are manufactured products. Aggregates are naturally occurring.

Delivery and Haul Requirements: Emulsified asphalt and fine aggregate, if not available locally, must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Dust can be a problem during construction and sweeping. Excess fine aggregate can be thrown/brushed/washed from the surface into the surrounding environment.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Scrub seals are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by scrub seal surfacings. In parking areas, oil and other vehicle fluids can be collected by surface runoff, affecting the water quality.

Erosion: Scrub seals are a bound surface and are not particularly susceptible to surface erosion. Some aggregate loss can be expected due to a combination of traffic and erosional processes.

Water quality: Scrub seals have a minimal impact on water quality. Water quality could be affected by sediment loading from dust or loose fine aggregate from the scrub seal surface.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Scrub seals can be pulverized with underlying pavement layers and reused as an unbound or stabilized material.

Other Environmental Considerations: For scrub seals, tire/road noise is typically low to moderate with about the same noise level as HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)].

AESTHETICS

Appearance: Immediately after placement, the scrub seal's appearance is influenced by the black bituminous binder and the fine aggregate color. A scrub seal's appearance can be modified with the careful selection of colored aggregates and by the use of pigments in the asphalt cement; however, this is not normally done because of the additional cost relative to the life expectancy.

Appearance Degradation Over Time: Over time, the scrub seal surface will wear, exposing more of the underlying surface.

COST

Supply Price: N/A

Supply+Install Price: \$0.60 to \$1.60/m^2 (\$0.50 to \$1.30/yd^2).

EXAMPLE PROJECTS
Merced County, CA. U.S. Highway 169, from I-29 to Union Star, MO.
SELECT RESOURCES
Asphalt Emulsion Manufacturers Association, (410) 267-0023, www.aema.org USDA Forest Service (1999), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

SLURRY SEAL

GENERAL INFORMATION

Generic Name(s): Slurry Seal

Trade Names: N/A

Product Description: Slurry seals are a cold-mixed thin surface treatment constructed of a mixture of emulsified asphalt, dense-graded crushed fine aggregate, mineral filler or other additives, and water. Slurry seals are applied at the thickness of the largest aggregate in the mix; 3 mm (1/8 in.) for Type I slurry, 6 mm (1/4 in.) for Type II slurry, and 9 mm (3/8 in.) for Type III slurry. Type II is the most commonly used slurry seal gradation. Slurry seals are used as a protective or preventive maintenance technique for paved surfaces or thin asphalt surface treatments; slurry seals are applied to existing surfaces to seal small cracks, correct minor surface irregularities, stop raveling, improve ride quality, and improve friction properties.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: International Slurry Surfacing Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.slurry.org

APPLICATION

Typical Use: Preventative maintenance treatment for small cracks or raveling.

Traffic Range: Very Low for Type I, Very Low to Medium for Type II, and Very Low to High (typically AADT < 5,000) for Type III

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: Slurry seals are generally not used for roadway gradients steeper than 8%.

Soil Type: N/A

Other: Slurry seals can be damaged by snow plow operations. Slurry seals should not be applied to pavements with majority of ruts greater than 12 mm (0.5 in.) deep.

Other Comments: Slurry seals have a smoother texture than chip seals and may be preferred by non-vehicular users (i.e. bicyclists, in-line skaters, etc.) in recreational areas.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: N/A

Other Comments: None.

CONSTRUCTION

Availability of Experienced Personnel: Slurry seal construction generally requires experienced specialty contractors. In remote areas, specialty contractors may not be locally available, but they are generally available on a statewide or regional level.

Materials: Slurry seals are constructed of a mixture of emulsified asphalt, dense-graded crushed fine aggregate, mineral filler or other additives, and water. The emulsified asphalt is usually cationic and quick-setting. Modified emulsified asphalts can be used to enhance certain performance characteristics.

Equipment: Slurry seal construction requires a special slurry seal mixing machine with a spreader box attached. The slurry seal mixing machine can be truck-mounted or self-propelled. Equipment is locally available in large urban areas and regionally available in more remote areas. The slurry seal mixing machine should be calibrated using site-specific materials and mix proportions prior to each construction job.

Manufacturing/Mixing Process: The slurry seal mixing machine carries all the unmixed materials and, when construction commences, combines the materials in exact mix proportions in a continuous flow pugmill. For continuous operation, haul vehicles must replenish materials to the mixing machine.

Placement Process: Once the slurry is mixed by the slurry seal mixing machine, the mix is automatically fed into a spreader box attached to the rear of the equipment and applied to the roadway. Rolling or compaction is seldom required but may be desirable in low traffic areas such as parking lots and airports.

Weather Restrictions: Do not construct slurry seals if it is raining or there is an imminent risk of rain, or there is a danger of freezing within 24 hours. The specified minimum air temperature for slurry seal placement is normally 10 °C (50 °F) or above.

Construction Rate: Slurry seal construction rates typically range from 135 to 270 Mg/day (150 to 300 tons/day). This would be equivalent to about 10,000 to 20,000 m^3 /day (12,000 to 24,000 yd^3/day)

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. Depending on the type of emulsified asphalt used and weather conditions, roads can be opened to traffic one to twelve hours after placement. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Slurry seals are a common roadway maintenance treatment and have been used on roadway projects for more than 50 years; design and construction guidelines and performance data is available.

Life Expectancy: Life expectancy varies depending on mix types, traffic volumes, and environmental conditions. Typical serviceable lives range from 3 to 8 years (average 5 years).

Ride Quality: Slurry seals may slightly improve the ride quality of a previously paved roadway. However, slurry seals will not mitigate significant defects (rutting, depressions, severe cracking, etc.) in the existing surface. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Flushing, rutting, cracking (from the underlying pavement).

Preservation Needs: None.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volumes.

Skid Resistance: Slurry seals provide excellent initial skid resistance.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Emulsified asphalt, aggregates, and additives must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: None.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Slurry seals help to seal old pavement surfaces, which promotes surface runoff. However, surface runoff water quality is not generally impacted by slurry seals.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Slurry seals can be pulverized and reused with the underlying HACP as an unbound or stabilized material.

Other Environmental Considerations: Slurry seals are cold-mixed and have much lower energy requirements and heat generation compared to hot mixed and hot-placed road surfacings For slurry seals, tire/road noise is typically low to moderate with the same or slightly higher noise level than HACP [72 to 79.5 dB(A) at a distance of 7.5 m (25 ft)], but with a lower noise level than chip seals.

AESTHETICS

Appearance: Slurry seals have a black appearance similar to HACP. A slurry seal's color can be modified by the use of pigments in the slurry mix, but this is not normally done because of cost.

Appearance Degradation Over Time: Over time, the slurry seal surface will wear, exposing more of the underlying surface and modifying the appearance. Reapplication of the slurry seal will maintain the black surface color.

COST

Supply Price: N/A

Supply+Install Price: \$0.90 to \$1.80/m^2 (\$0.75 to \$1.50/yd^2).

EXAMPLE PROJECTS

City of Las Vegas, NV.

SELECT RESOURCES

International Slurry Surfacing Association, (410) 267-0023, www.slurry.org

Asphalt Institute. *A Basic Asphalt Emulsion Manual*, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.

International Slurry Seal Association (2003). *Recommended Performance Guidelines for Emulsified Asphalt Slurry Seal*, A105, International Slurry Seal Association, 16 pp.

USDA Forest Service (1999), *Asphalt Seal Coat Treatments*, San Dimas Technology and Development Center.

ULTRATHIN FRICTION COURSE

GENERAL INFORMATION

Generic Name(s): Ultrathin Friction Course, Ultrathin Bonded Wearing Course

Trade Names: NovaChip

Product Description: An ultra-thin friction course is constructed of a thin layer of gap graded, coarse aggregate hot mix asphalt concrete that provides a smooth, durable, and skid-resistant surface. The thin layer, typically 9 to 19 mm (0.375 to 0.75 in.) thick, combines attributes of stone matrix asphalt and open graded friction course asphalt mixes. The hot mix asphalt layer is bound to the existing surface with a polymer modified emulsion that is specifically designed to seal the existing surface and bond the new mix to the existing surface. Ultrathin friction course can be used on asphalt or concrete pavements as a preventative maintenance or surface rehabilitation treatment. Ultrathin friction course provides excellent skid resistance, reduced tire/road noise, and reduced vehicle splash/spray.

Product Suppliers: Sunland Asphalt Company, www.sunlandasphalt.com; or

E.J. Breneman, LP, www.ejbreneman.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers are available.

APPLICATION

Typical Use: Road surfacing, preventative maintenance or surface rehabilitation treatment.

Traffic Range: Very Low to High. Typically used for AADT>1,000.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: Ultrathin friction course should be placed over a structurally sound pavement with rut depths less than 13 mm (0.5 in.), minor to moderate cracking, and/or minor bleeding.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: N/A

Other Comments: None.

CONSTRUCTION

Availability of Experienced Personnel: Ultrathin friction course is a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.

Materials: Ultrathin friction course is composed of a gap graded aggregate with asphalt cement as a binder and polymer modified emulsified asphalt to bind the overlay with the existing surface.

Equipment: Equipment required for ultrathin friction course construction includes: haul vehicles, a special asphalt paver machine, and compaction equipment (static steel wheel roller). Because a specialty paver is required, availability is limited to large or specialty paving contractors.

Manufacturing/Mixing Process: Ultrathin friction course is normally hot mixed at an asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. Ultrathin friction course mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in haul vehicles to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to approximately 1.5 hours. Since the quantities of ultrathin friction course are relatively small and the quality requirements are very high, production from a mobile asphalt plant would likely not be economical.

Placement Process: Cracks in the surfacing to be covered should be sealed or repaired before ultrathin friction course is placed. The polymer modified emulsified asphalt membrane and thin asphalt layer are placed in one pass using a special asphalt paver (e.g. NovaPaver), specially designed for ultrathin friction course placement. The emulsified asphalt is sprayed onto the prepared surface by the machine and the asphalt concrete layer is placed immediately after the emulsified asphalt. The paving machine has a special combination tamping bar-vibratory screed that compacts and levels the surfacing layer after it has been applied. Once the ultrathin friction course has been placed, a steel drum roller is used to seat the asphalt concrete overlay into the emulsified asphalt membrane layer.

Weather Restrictions: Do not place ultrathin friction course if it is raining or there is ponded water on the prepared paving surface. The specified minimum air temperature for ultrathin friction course placement varies between different agencies, but is normally about 15 °C (60 °F).

Construction Rate: Ultrathin friction course placement rates are in the range of 7.2 to 14.4 lane-km perday (4.4 to 8.9 lane-miles/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The ultrathin friction course surface can be opened to traffic within minutes of being placed. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Ultrathin friction course is a relatively new but very common roadway surfacing. Ultrathin friction course was first developed in France in 1986 and was introduced to the United States in 1992. Since that time, ultrathin friction course has been used by nearly all state transportation agencies. Research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, and traffic volumes. Typical serviceable lives range from 10 to 12 years.

Ride Quality: Very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, shoving.

Preservation Needs: Preventative maintenance includes periodic crack sealing.

SAFETY

Hazards: None.

Skid Resistance: Ultrathin friction course provides excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because ultrathin friction course provides a high-quality road surfacing, there is a tendency for road usage to be higher and for drivers to exceed posted speed limits.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Ultrathin friction course must be hauled from an asphalt plant. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the mixing and placement process. The paving operation proceeds quickly with little impact on vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Ultrathin friction course is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by ultrathin friction course overlays.

Erosion: Ultrathin friction course is a bound material and is not susceptible to surface erosion. Shoulders and base material should be protected from fast moving water.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Ultrathin friction course can be fully recycled as a pavement construction material.

Other Environmental Considerations: Ultrathin friction course's characteristic black surface will absorb heat from sunlight; select aggregates can be used to lighten the color and increase heat reflectivity of the surface. For ultrathin friction course, tire/road noise is typically 1.4 to 2.1 decibels lower than conventional HACP and 3.2 to 4.1 decibels lower than conventional PCCP.

AESTHETICS

Appearance: Immediately after placement, ultrathin friction course is generally black with a very smooth surface.

Appearance Degradation Over Time: Over time, ultrathin friction course can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing, the surface appearance deteriorates further.

COST

Supply Price: \$4.20 to \$4.80/m^2 (\$3.50 to \$4.00/yd^2).

Supply+Install Price: \$7.25 to \$8.00/m^2 (\$6.00 to \$6.70/yd^2).

EXAMPLE PROJECTS

Garden State Parkway, NJ.
Interstate I-65, Cullman, AL.
U.S. Highway 50, Lake Tahoe, CA.

SELECT RESOURCES

Koch Pavement Solutions, http://www.kochpavementsolutions.com/Solutions/novachip.htm.
Kandhal, P.S., and Lockett, L. (1997). *Construction and Performance of Ultrathin Asphalt Friction Course*, NCAT Report No. 97-5, National Center for Asphalt Technology, Auburn, AL, 23 pp.

ASPHALT SURFACING – SURFACE LAYERS (STRUCTURAL)

COLD MIX ASPHALT CONCRETE PAVEMENT

GENERAL INFORMATION

Generic Name(s): Cold Mix Asphalt Concrete (CMAC)

Trade Names: N/A

Product Description: Cold Mix Asphalt Concrete (CMAC) is a blend of coarse and fine aggregate with emulsified or cutback asphalt as a binder. CMAC differs from HACP in that no heating is required during the production process; this reduces energy requirements as well as emissions. Cold mixes can be placed immediately after mixing or stockpiled for later use. CMAC can be an economical alternative when there is a long haul distance to the nearest hot mix plant.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org.

APPLICATION

Typical Use: Road surfacing, binder course.

Traffic Range: Very Low to High.

Restrictions:

Traffic: CMAC is prone to damage from heavy wheel loadings and excessive turning movements. Therefore, CMAC is not recommended for heavy industrial loading conditions (i.e. slow moving trucks, frequent braking, etc.).

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Cold mixes typically utilize slow or medium setting emulsified or cutback asphalts and are more pliable than typical HACP. This pliability aids in compaction and reduces cracking potential and is useful in applications where distortion due to frost or poor subgrade conditions may be a problem. CMAC is considered to be “self-healing” under solar heat and traffic. CMAC is also commonly used as roadway patching material.

DESIGN

SLC: 0.28 to 0.39.

Other Design Values: None.

Base/Subbase Requirements: CMAC is usually constructed over an aggregate base course, but may be placed directly over a prepared subgrade of native materials. The required CMAC thickness depends on the level of base/subgrade support provided. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to CMAC placement. A prime coat is sometimes used above the aggregate base prior to paving. CMAC pavements have the ability to handle subgrade weaknesses better than most surfacing alternatives.

Other Comments: CMAC performance is highly dependent on the quality of workmanship and the component materials used.

CONSTRUCTION

Availability of Experienced Personnel: CMAC is a commonly used surfacing in some regions of the United States, particularly in the western states. In these areas, experienced contractors are, in general, widely available. For other regions, availability of experienced contractors may be limited.

Materials: Cold Mix Asphalt Concrete (CMAC) is a blend of coarse and fine aggregate with emulsified or cutback asphalt as a binder. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics. Emulsified asphalt grades used for CMAC are: MS-1, MS-2, MS-2h, HFMS-1, HFMS-2, HFMS-2h, HFMS-2s, SS-1, SS-1h, CMS-2, CMS-2s, CMS-2h, CSS-1, and CSS-1h. The medium setting emulsified asphalts are designed for mixing with coarse aggregates. High-float medium setting emulsified asphalt gives better aggregate coating under extreme temperature conditions. Slow setting emulsified asphalts are designed for maximum mixing stability and are used for dense graded aggregates with high fines content. Cutback asphalts used for CMAC include: MC-70, MC-250, MC-800, MC-3000, SC-250, SC-800, and SC-3000.

Cutback Asphalt: Cutback asphalts have application temperatures of 30 to 115 °C (85 to 240 °F) and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include hydrocarbon emissions into the atmosphere during the evaporation process and potential fire hazards during construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas.

Emulsified Asphalt: Advantages of emulsified asphalt include a cooler application temperature (10 to 70 °C [50 to 160 °F]) than cutback asphalts, and the water that evaporates is environmentally safe.

Equipment: Equipment required for CMAC construction include: haul vehicles, asphalt distributor, stationary or rotary mixer or motor grader, and compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller). Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: CMAC can be plant mixed or road mixed. Plant mixed CMAC can be stockpiled for later use. For road mixing, emulsified or cutback asphalts are produced by an asphalt supplier and shipped to the site.

Placement Process: For road mixing with a rotary mixer, the aggregate is spread to a uniform thickness over the entire roadway. The aggregate is then sprayed with the asphalt and mixed using multiple passes of the rotary mixer. Asphalt should be added in increments of about 2.25 L/m^2 (0.50 gal/yd^2) with each pass of the rotary mixer. Additional passes of the rotary mixer are made between asphalt applications, as necessary, to achieve uniform mixing. Once the total amount of asphalt has been added and mixed, the material must be allowed to aerate (i.e. allow the emulsion diluents to evaporate) if adequate aeration did not occur during the mixing process. Once aeration is completed, the CMAC is graded and compacted. CMAC should be placed and compacted with a maximum lift thickness of 75 mm (3 in.).

For road blade mixing with a motor grader, the aggregate is piled in windrows and asphalt is applied using an asphalt distributor at a rate of 3.5 L/m^2 (0.75 gal/yd^2) per pass. Between asphalt applications, the asphalt and aggregate are mixed together using multiple passes of the motor grader. The motor grader makes as many passes as necessary to obtain a uniform mix. Once the total amount of asphalt has been added and mixed, the material must be allowed to aerate (i.e. allow the emulsion diluents to evaporate off) if adequate aeration did not occur during the mixing process. Once aeration is completed, the CMAC is compacted and graded.

For plant mix CMAC, the cold mix is transported to the site and placed in windrows if aeration is still required. Once aeration is complete, the cold mix is spread, graded, and compacted. Better product quality control can be achieved with the plant mixed CMAC.

Weather Restrictions: Do not place CMAC if it is raining or there is ponded water on the prepared paving surface. The specified minimum air temperature for CMAC placement varies between different agencies, but is normally about 10 °C (50 °F).

Construction Rate: Typical production rates are 900 to 1,360 Mg/day (1,000 to 1,500 tons/day).

Lane Closure Requirements: The roadway lane being constructed is closed during construction, so adequate traffic control is needed. The CMAC surface can be opened to traffic as soon as construction is completed. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: CMAC is a common roadway surfacing in some areas of the United States; research, design and construction information, and project experience is available. Agencies have had mixed results with regard to CMAC performance, some agencies have experienced very good performance while other have not. Poor mix design or construction can lead to rutting, raveling, and premature failure. CMAC is more reliable as a binder course than as a wearing course.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives range from 15 to 20 years.

Ride Quality: CMAC provides good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Rutting, raveling, cracking.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching. Thin surface treatments can be applied to extend the serviceable life of CMAC.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume. When cutback asphalts are used, the solvents used can create a health hazard (fumes) and a fire/explosion hazard during construction; proper engineering controls and construction practices should be utilized to minimize safety risks.

Skid Resistance: Provided high quality aggregates are used in the cold mix, CMAC provides good skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because CMAC provides a good-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) or solvents (for cutback asphalts) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: For plant mix CMAC, the cold mix must be hauled from an asphalt plant unless a mobile asphalt plant is assembled. For road mix CMAC, emulsified or cutback asphalts must be hauled to the site. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway, especially where road mixing is used. If clean aggregate is not used, dust can be a problem during mixing. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used. Cutback asphalts can potentially impact water quality and aquatic species due to runoff if heavy rains occur before the cutback asphalt cures. Surface runoff should be properly contained or managed during the curing stage when the project is adjacent to bodies of water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: CMAC is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by CMAC roadways.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: CMAC can be fully recycled as a pavement construction material.

Other Environmental Considerations: CMAC's characteristic black surface will absorb heat from sunlight; select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. For CMAC, tire/road noise is similar to HACP and typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle.

AESTHETICS

Appearance: Immediately after placement, CMAC is generally black with a smooth surface. CMAC's appearance can be modified with the careful selection of colored aggregates, by the use of pigments in the asphalt cement, and by inclusion of a coarser aggregate in the CMAC.

Appearance Degradation Over Time: Over time, the cold mix may wear, exposing more of the aggregate in the wheel paths. Short or medium term improvements in appearance can be achieved by the use of thin surface treatments, such as fog seals and slurry seals.

COST

Supply Price: N/A

Supply+Install Price: $33 to $44/Mg ($30 to $40/ton).

EXAMPLE PROJECTS

SR 230, Elko County, NV.

SELECT RESOURCES

Asphalt Institute, (859) 288-4960, www.asphaltinstitute.org

Asphalt Institute (1989). *Asphalt Cold Mix Manual*, Manual Series No. 14 (MS-14), Third Edition, Asphalt Institute, Lexington, KY, 185 pp.

HOT ASPHALT CONCRETE PAVEMENT (HACP)

GENERAL INFORMATION

Generic Name(s): Hot Asphalt Concrete Pavement (HACP), Hot Asphalt Concrete Pavement, Hot Mix Asphalt Concrete (HMAC), Bituminous Concrete

Trade Names: N/A

Product Description: HACP is a high quality pavement material that is hot mixed at a plant and then hot laid. It is the most common surfacing for paved roads in the U.S., accounting for more than 90% of paved roads.

HACP is composed of a carefully designed blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. The asphalt mix proportions need to be designed to suit the particular application. The asphalt cement grade needs to be selected based on service temperature ranges and traffic volumes. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706, (888) HOT-MIXX, www.hotmix.org.

APPLICATION

Typical Use: Road surfacing, binder course, base course.

Traffic Range: Very Low to High.

Restrictions:

Traffic: A high stability mix should be used for heavy industrial loading conditions (i.e. slow moving trucks, frequent braking, etc.). Mixture criteria should be tailored for the conditions of use.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Traditionally, asphalt cement grades have been designated as penetration grade (60/70, 85/100, etc.) or by viscosity grades (AC-20, AC-30, AR-4000, AR-8000, etc.). Currently, asphalt cements are specified by Performance Grades (PG), such as PG 64-22, indicating the high and low temperature range in °C. The use of modifiers to expand the serviceable temperature range of an asphalt will improve rutting resistance at high temperatures and reduce thermal cracking at low temperatures.

For very low to low traffic applications, HACP mixes should be designed so that additional compaction from traffic is not relied upon to help achieve the target HACP air void content as is commonly done for high volume applications. Inadequately compacted HACP will have a higher air void content, making it more permeable and susceptible to oxidation. When HACP oxidizes, it becomes brittle, which leads to cracking. Polymers can be used in the asphalt cement to improve ductility and reduce the effects of oxidation.

DESIGN

SLC: 0.30 to 0.46. Typical default values: 0.44 for Superpave, Marshall, and Hveem, 0.40 for minor asphalt mixes, 0.35 for HACP binder course.

Other Design Values: None.

Base/Subbase Requirements: HACP is usually constructed over an aggregate base course, but may be placed directly over a prepared subgrade of native materials. The required HACP thickness depends on the level of base/subgrade support provided. Subgrade and base materials should be graded and compacted to provide a stable working surface prior to HACP placement. A prime coat is normally used above the aggregate base prior to paving. Tack coats can be used to improve the bond between hot mix layers.

Other Comments: As a general guideline, the minimum HACP lift thickness should be three times the nominal maximum aggregate size. For coarse-graded mixtures, the minimum lift thickness should be four times the nominal maximum aggregate size.

CONSTRUCTION

Availability of Experienced Personnel: HCAP is a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.

Materials: HACP is composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics.

Equipment: Equipment required for HACP construction includes: haul vehicles, asphalt distributor (if prime or tack coats are applied), asphalt paver machine, and compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller). Equipment is widely available in urban areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: HACP is hot mixed at an asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. HACP mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in haul vehicles to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to 2 or 3 hours. When the project site is far from an asphalt plant, a portable asphalt plant can be assembled near the project site. When selecting a site for a portable asphalt plant, impacts to the environment and local residents and businesses must be considered.

Placement Process: Upon arrival at the site, the asphalt concrete mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The HACP is then rolled with compaction equipment to achieve the required density. The compaction process should be completed before the asphalt binder stiffens to the point where additional compactive effort will damage the pavement mat, which generally occurs between a temperature of about 85 °C (185 °F) and 150 °C (300 °F), depending on the asphalt binder. The time available for compaction before the mix has cooled will depend on the mix temperature when it is placed, layer thickness, air temperature, and wind, but can range from several minutes to more than 30 minutes.

Weather Restrictions: Do not place HACP if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for HACP placement varies between different agencies, but is normally about 7 °C (45 °F).

Construction Rate: HACP placement rates will depend on the speed that the asphalt concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or higher. Compactor speeds are normally limited to 4.8 km/hr (3 mph), so overall construction rates are often dictated by the number of compactors on site. Typical production rates are 900 to 4,500 Mg/day (1,000 to 5,000 tons/day). Coordination of asphalt concrete delivery, paving speed, and compaction is necessary due to the limited time asphalt concrete is workable.

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The HACP surface can be opened to traffic as soon as the HACP has cooled and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: HACP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available. The Superpave mix design method is relatively new, with most research and project experience occurring since 1990.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives range from 15 to 20 years.

Ride Quality: Very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, loss of surface friction.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching every 7 to 9 years. Thin surface treatments can be applied to extend the serviceable life of HACP.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided high quality aggregates are used in the asphalt concrete mix, HACP provides good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because HACP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Hot mix asphalt concrete must be hauled from a stationary asphalt plant unless a mobile asphalt plant is assembled, in which case the materials for the concrete mix must be hauled to the mobile plant. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the mixing and placement process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None

Surface Runoff: HACP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by HACP roadways. In parking areas, oil and other vehicle fluids can be collected by surface runoff, affecting the water quality.

Erosion: HACP is a bound material and is not susceptible to surface erosion. Shoulders and base material should be protected from fast moving water.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: HACP can be fully recycled as a pavement construction material.

Other Environmental Considerations: HACP's characteristic black surface will absorb heat from sunlight; select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. For HACP, tire/road noise is typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle. Mixtures such as Stone Matrix Asphalt and Porous Friction Courses result in reduced tire/road noise levels compared to conventional dense-graded mixtures. The reduction in sound level is typically about 3 dB(A) for Porous Friction Courses and 2 dB(A) for Stone Matrix Asphalt.

AESTHETICS

Appearance: Immediately after placement, HACP is generally black with a very smooth surface. Conventional HACP's appearance can be modified with the careful selection of colored aggregates, by the use of pigments in the asphalt cement, and by inclusion of a coarser aggregate in the HACP.

Appearance Degradation Over Time: Over time, HACP can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing and patching, the surface appearance is further altered. Where special mixes are used, the future availability of similar mixes should be assured for maintenance purposes to ensure a uniform surface appearance. Surface appearance may be altered by the use of surface treatments, such as fog seals and slurry seals.

COST

Supply Price: N/A

Supply+Install Price: $33 to $44/Mg ($30 to $40/ton).

EXAMPLE PROJECTS

HACP is used extensively throughout the United States.

SELECT RESOURCES

Asphalt Institute, (859) 288-4960, www.asphaltinstitute.org.
National Asphalt Pavement Association (NAPA), (888) HOT-MIXX, www.hotmix.org.

EXPOSED AGGREGATE HACP

GENERAL INFORMATION

Generic Name(s): Exposed Aggregate Hot Asphalt Concrete Pavement, Exposed Aggregate Asphalt Concrete

Trade Names: N/A

Product Description: Hot asphalt concrete pavement (HACP) is a high quality pavement material that is hot mixed at a plant and then hot laid. It is the most common surfacing for paved roads in the U.S., accounting for more than 90% of paved roads.

HACP is composed of a carefully designed blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. The asphalt mix proportions need to be designed to suit the particular application. The asphalt cement grade needs to be selected based on service temperature ranges and traffic volumes. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics.

In the exposed aggregate asphalt concrete, the coating of the aggregate at the surface is removed by sandblasting, shotblasting or other methods. This results in improved texture and an attractive appearance, particularly if a colorful aggregate is used. The techniques and equipment used for the removal of rubber build-up on airport runways can also be used to produce exposed aggregate asphalt concrete.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706, (888) HOT-MIXX, www.hotmix.org. The most common equipment for surface removal of asphalt are the 'Skidabrader' (Ruston, LA, Tel: 318-251-1935, www.skidabrader.com) and the 'Blastrac' (International Surface Preparation, Bellaire, TX, Tel: 800-374-4043, www.surfacepreparation.com).

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Low to Medium.

Restrictions:

Traffic: Exposed aggregate HACP is not recommended for applications with significant heavy truck traffic.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Because of the increased cost to expose the aggregate, this surfacing is mainly used for low to medium volume and low traffic speed applications, such as short access roads and driveways.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Traditionally, asphalt cement grades have been designated as penetration grade (60/70, 85/100, etc.) or by viscosity grades (AC-20, AC-30, AR-4000, AR-8000, etc.). Currently, asphalt cements are specified by Performance Grades (PG), such as PG 64-22, indicating the high and low temperature range in °C. The use of modifiers to expand the serviceable temperature range of asphalt will improve rutting resistance at high temperatures and reduce thermal cracking at low temperatures.

DESIGN

SLC: 0.30 to 0.46, Typical default values: 0.44 for Superpave, Marshall, and Hveem, 0.40 for minor asphalt mixes.

Other Design Values: None.

Base/Subbase Requirements: HACP is usually constructed over an aggregate base course, but may be placed directly over a prepared subgrade of native materials. The required HACP thickness depends on the level of base/subgrade support provided. Subgrade and base materials should be graded and compacted to provide a stable working surface prior to HACP placement. A prime coat is normally used above the aggregate base prior to paving. Tack coats can be used to improve the bond between hot mix layers.

Other Comments: None.

CONSTRUCTION

Availability of Experienced Personnel: HACP is a commonly used surfacing and experienced contractors are, in general, widely available. However, exposed aggregate HACP is not a common surfacing and the availability of experienced contractors is limited. Specialty contractors who supply and operate the 'Skidabrader' and the 'Blastrac', especially for runway maintenance and road skid resistance restoration are available in major cities. A specialty contractor with experience with exposed aggregate HACP construction is recommended.

Materials: HACP is composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics. Care should be exercised in aggregate selection, especially where specific color effects are desired. In all cases only high quality and durable aggregates should be used.

Equipment: Equipment required for HACP construction includes: haul vehicles, asphalt distributor (if prime or tack coats are applied), asphalt paver machine, and compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller). Equipment is widely available in urban areas, but availability may be limited in remote areas. In addition to regular equipment required for HACP construction, sand and shot blasting equipment (e.g. Skidabrader, Blastrac) are required to remove the asphalt coating from the coarse aggregate at the pavement surface.

Manufacturing/Mixing Process: HACP is hot mixed at an asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. HACP mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in haul vehicles to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to 2 or 3 hours. When the project site is far from an asphalt plant, a portable asphalt plant can be assembled near the project site. When selecting a site for a portable asphalt plant, impacts to the environment and local residents and businesses must be considered.

Placement Process: Upon arrival at the site, the asphalt concrete mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The HACP is then rolled with compaction equipment to achieve the required density.

The aggregate can be exposed by one of two methods: (1) sand or shot blasting or (2) terrazzo buffers. Once the asphalt concrete is constructed, the asphalt coating covering the aggregate at the pavement surface can be removed by sand or shot blasting. This is a fairly quick and easy process carried out using self-propelled specialty equipment. Where steel shot is used the steel shot is separated from the asphalt and aggregate debris using magnets. This allows the shot to be recovered and reused. Alternatively, the surface asphalt coating can be removed by grinding/buffing with terrazzo grinders/buffers typically used in finishing terrazzo floors. This technique is suitable for small areas (less than 93 m^2 [1,000 ft^2]). Care must be taken not to remove too much of the asphalt cement; removing too much could result in coarse aggregate pop outs, especially in colder climates where snow plowing is required. The asphalt cement coating should be removed just enough to expose the coarse aggregate, typically about 3 mm (0.13 in.). A trial section should be completed before extensive surface removal is undertaken.

Weather Restrictions: Do not place HACP if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for HACP placement varies between different agencies, but is normally about 7 °C (45 °F).

Construction Rate: HACP placement rates will depend on the speed that the asphalt concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or higher. Compactor speeds are normally limited to 4.8 km/hr (3 mph), so overall construction rates are often dictated by the number of compactors on site. Typical production rates are 900 to 4,500 Mg/day (1,000 to 5,000 tons/day). Coordination of asphalt concrete delivery, paving speed, and compaction is necessary due to the limited time asphalt concrete is workable. The production rate for removing the surface asphalt coating to expose the aggregate ranges from about 4,500 to 18,000 m^2 /day (5,400 to 21,500 yd^2 /day) using dedicated shot blasting equipment.

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The HACP surface can be opened to traffic as soon as the HACP aggregate is exposed and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: HACP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available. However, exposed aggregate HACP is not a common surface and available information is limited. Exposed aggregate HACP should perform very similar to conventional HACP, providing only the thin surface asphalt cement is removed.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives range from 15 to 20 years.

Ride Quality: Good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, popouts.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching every 7 to 9 years. Thin surface treatments can be applied to extend the serviceable life of HACP, but will cover the exposed aggregate. To maintain the exposed aggregate surfacing, a conventional HACP overlay would be needed followed by the shot blasting treatment to again expose the aggregate.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided high quality aggregates are used in the asphalt concrete mix, exposed aggregate HACP provides good to excellent skid resistance. Exposed aggregate asphalt concrete has better frictional characteristics than conventional HACP, however, the improvement in skid resistance will only be maintained if the HACP contains a high quality aggregate.

Road Striping Possible?: Yes.

Other Comments: Because exposed aggregate HACP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: HACP must be hauled from an asphalt plant unless a mobile asphalt plant is assembled. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the mixing and placement process. Construction processes may impact vegetation adjacent to the roadway. Dust can be generated during grinding/sandblasting. A system needs to be implemented during construction to contain and collect the sand following sand blasting. Modern dedicated shot blasting equipment is designed to contain and control all the abraded product inside an enclosure so essentially there are no fugitive particles.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: The surface is relatively impermeable, so surface runoff from the road should be managed properly to minimize erosion adjacent to road.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Exposed aggregate HACP can be fully recycled as a pavement construction material.

Other Environmental Considerations: HACP's characteristic black surface will absorb heat from sunlight; select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. The exposed aggregate further lightens the overall color of the surfacing. For exposed aggregate asphalt concrete, tire/road noise can range from slightly lower to slightly higher than the level for HACP, which is typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle.

AESTHETICS

Appearance: The surface appearance will not be as black as conventional asphalt pavements because it will be influenced by the color of the coarse aggregate in the HACP mix. The overall color can be controlled by careful selection of the source aggregate.

Appearance Degradation Over Time: Some surface wearing is possible with time, as well as some aggregate loss. However, with the use of high quality aggregates, the loss in serviceability with time should be similar to a high quality wearing course HACP.

COST

Supply Price: N/A

Supply+Install Price: \$80 to \$140/Mg (\$70 to \$130/ton); or \$7.00 to \$12.50/m^2 (\$5.90 to \$10.50/yd^2), based on a 40 mm (1.5 inch) thick lift. The cost of the asphalt cement coating removal by shot blasting on its own ranges from \$3.00 to \$5.50/m^2 (\$2.50 to \$4.60/ yd^2).

EXAMPLE PROJECTS

Rideau Hall access driveway (residence of the Governor General of Canada), Ottawa, Canada.

SELECT RESOURCES

Asphalt Institute, (859) 288-4960, www.asphaltinstitute.org.
National Asphalt Pavement Association (NAPA), (888) HOT-MIXX, www.hotmix.org.

IMPRINTED/EMBOSSED HACP

GENERAL INFORMATION

Generic Name(s): Imprinted Hot Asphalt Concrete Pavement, Stamped Asphalt Concrete, Embossed Colored Asphalt Concrete

Trade Names: StreetPrint

Product Description: Imprinted HACP is a decorative paving system that is created by stamping a design into HACP when it is hot, using a special woven wire cable pattern template. The imprinted depressions are less than 10 mm (0.375 in.) deep. The imprinted asphalt concrete surface is covered with a coating product consisting of cement-modified acrylic resins, epoxy-based polymers, and a blend of aggregates. The coating system can be designed to provide a wide range of colors and textures.

Hot mix asphalt concrete is a high quality pavement material that is hot mixed at a plant and then hot laid. It is the most common surfacing for paved roads in the U.S., accounting for more than 90% of paved roads.

Hot mix asphalt concrete is composed of a carefully designed blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. The asphalt mix proportions need to be designed to suit the particular application. The asphalt cement grade needs to be selected based on service temperature ranges and traffic volumes. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics.

Product Suppliers: Integrated Paving Concepts, PMB 48, 936 Peace Portal Drive, Blaine, WA 98230-4040, (800) 688-5652, www.streetprint.com.

APPLICATION

Typical Use: Road surfacing, typically on short road sections, crosswalks, pathways, plazas, or parking areas, where decorative treatment is desired.

Traffic Range: Very Low to High (typically less than 1,300 AADT), depending on climate. At higher traffic volumes, the coating system will wear away faster.

Restrictions:

Traffic: Imprinted asphalt concrete is not recommended for heavy industrial loading applications (i.e. high volume of heavy commercial vehicles, frequent braking and turning, etc.).

Climate: Where winter conditions require regularly applied aggregate/salt on the roads, the resulting abrasion accelerates the wearing away of the coating system.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: Imprinted asphalt concrete is mainly used for decorative purposes, since it simulates a wide range of other, more expensive, pavement types, such as cobblestone, brick pavers, etc. Imprinted asphalt concrete has been used most frequently in areas with high pedestrian traffic. The cement modified acrylic coloring is frequently used to delineate crosswalks and bus stops.

DESIGN

SLC: 0.30 to 0.46. Typical default values: 0.44 for Superpave and Hveem, 0.40 for minor asphalt mixes.

Other Design Values: None.

Base/Subbase Requirements: Imprinted asphalt concrete is usually constructed over an aggregate base course. The required asphalt concrete thickness depends on the level of base/subgrade support provided. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to HACP placement. A prime coat is normally used above the aggregate base prior to paving. Tack coats can be used to improve the bond between hot mix layers.

Other Comments: As a general guideline, the minimum asphalt concrete lift thickness should be three times the nominal maximum aggregate size. The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Traditionally, asphalt cement grades have been designated as pen grade (60/70, 85/100, etc.) or by viscocity grades (AC-20, AC-30, etc.). Currently, asphalt cements are specified by Performance Grades (PG), such as PG 64-22, indicating the high and low temperature range in °C. With the use of polymers, the serviceable temperature range is extended so rutting can be avoided at high temperatures and transverse cracking can be avoided at low temperatures.

CONSTRUCTION

Availability of Experienced Personnel: HACP is a commonly used surfacing and experienced contractors are, in general, widely available. Certified imprinted asphalt concrete installers are available locally in most large urban areas and regionally in more remote areas. Therefore, availability may be limited for projects in remote areas.

Materials: Hot mix asphalt concrete is composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics. The surface coating applied to the imprinted asphalt surface is composed of cement-modified acrylic resins, epoxy-based polymers, and a blend of aggregates.

Equipment: Equipment required for imprinted HACP construction include: haul vehicles, asphalt distributor (if prime or tack coats are applied), asphalt paver machine, compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller), imprinting templates, and infrared or hot air heaters (if the HACP is existing instead of freshly placed). Equipment is widely available in urban areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Hot mix asphalt concrete is normally hot mixed at an asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. Asphalt concrete mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in trucks to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to 2 or 3 hours.

Placement Process: Upon arrival at the site, the asphalt concrete mixture is transferred from the trucks into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The asphalt concrete is then rolled with compaction equipment to achieve the required density.

For freshly placed HACP, imprinting is performed while the asphalt concrete is still warm to hot. For existing HACP, the surface must be heated to a depth of at least 12.5 mm (0.5 in.) using infrared or hot air heaters, until the asphalt concrete is pliable enough to accept the imprinting template. When the surface is hot, the imprinting templates, constructed of specially woven wire cable welded to a desired pattern, are placed on the asphalt concrete surface and pressed into the asphalt concrete using standard compaction equipment. The imprint depth is typically 10 mm (0.375 in.). The template is then removed from the asphalt concrete surface and the process is repeated for the next area. Once the asphalt concrete is imprinted and allowed to cool, a surface coating, consisting of cement-modified acrylic resins, epoxy-based polymers, and a blend of fine aggregates, is applied to the surface to seal the surface, add coloring, and improve surface performance characteristics.

Weather Restrictions: Do not place HACP if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for asphalt concrete placement varies between different agencies, but is normally about 7 °C (45 °F). The surface coating should not be applied if it is raining or if rain is expected within 2 hours of coat application. Air temperatures should be above 10 ºC (50 ºF) at the time the surface coating is applied and for at least 8 hours after the coating is applied.

Construction Rate: HACP placement rates will depend on the speed that the asphalt concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or 4.4 lane-km per day (2.7 lane-miles per day). Imprinting of the asphalt concrete surface will dictate the placement rate; imprinting can be performed at a rate of 480 to 720 m^2/day (400 to 600 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The imprinted HACP surface can be opened to traffic as soon as the asphalt concrete has cooled and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Imprinted asphalt concrete is a relatively new surfacing; emerging as a surfacing alternative within the past 10 years. Design and construction information and extensive project experience over the past 10 years, is available.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives for asphalt pavements range from 15 to 20 years. Depending on traffic volumes, reapplication of the polymer or resin color coating and restamping will be needed during that period, as discussed below.

Ride Quality: Ride quality can vary from poor to good after construction, depending on the type of texture and embossing utilized. Ride quality will decrease with increased surface texture. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, and wearing of the color coating.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching every 7 to 9 years. Color coating needs to be reapplied every 3 to 5 years and restamping may be needed every 6 to 10 years.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: The imprinted HACP surface coating is designed to provide good skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because HACP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. The color coating is a manufactured product composed of cement modified acrylic coloring.

Delivery and Haul Requirements: HACP must be hauled from an asphalt plant unless a mobile asphalt plant is assembled, in which case the required hot mix asphalt concrete mix components must be hauled to the mobile plant. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the asphalt concrete mixing and placement process. If the asphalt concrete is already in-place, significant heat is required to heat the asphalt concrete surfacing for stamping. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Imprinted HACP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by imprinted asphalt concrete.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Imprinted HACP can be reused as recycled aggregate base. The color coating may restrict the use of imprinted HACP as RAP for recycled HACP.

Other Environmental Considerations: Light surface colors can be selected to increase heat reflectivity of the surface. For HACP, tire/road noise is typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle. For imprinted HACP, tire/road noise is typically the same or slightly higher than conventional HACP.

AESTHETICS

Appearance: Imprinted asphalt concrete can be a highly decorative surfacing. More than 15 different textures (e.g. brick, cobble, herringbone, etc.) and nearly 50 colors are available to choose from. Imprinted HACP can be used to blend in with the surrounding environment (e.g. slate or rock pattern, colored in earth tones, in a wilderness area) or to contrast the surrounding environment (e.g. pedestrian crosswalk, fire lane, or handicap parking area colored in bright, contrasting colors), depending on the application and designer's intent.

Appearance Degradation Over Time: Over time, some color and imprint wear is possible. Additional applications of color coating and restamping can be used to maintain the appearance of the surface. Surfaces can also become discolored by tire marks and oil leakage. If not maintained, the imprinted asphalt concrete will eventually begin to look like conventional asphalt concrete.

COST

Supply Price: N/A

Supply+Install Price: \$60 to \$95/m^2 (\$50 to \$80/yd^2) based on a 40 mm (1.5 inch) HACP wearing course. For the application of the pattern and color excluding the cost of the HACP, the cost would be in the range of \$55 to \$85/m^2 (\$45 to \$70/yd^2).

EXAMPLE PROJECTS

Downtown Historic District, City of Portsmouth, VA.
Birkdale Village, Huntersville, NC.

SELECT RESOURCES

Integrated Paving Concepts, (800) 688-5652, www.streetprint.com.

PIGMENTED HACP

GENERAL INFORMATION

Generic Name(s): Pigmented Asphalt Concrete Pavement, Colored Asphalt Concrete, Colored Asphalt

Trade Names: N/A

Product Description: Hot asphalt concrete pavement (HACP) is a high quality pavement material that is hot mixed at a plant and then hot laid. Pigmented, or colored, HACP can be used to blend in with the surrounding environment (pavement colored in earth tones in a wilderness area, for example) or to contrast the surrounding environment (e.g. pedestrian crosswalk, fire lane, or handicap parking area colored in bright, contrasting colors), depending on the application and designer's intent.

HACP is composed of a carefully designed blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. The asphalt mix proportions need to be designed to suit the particular application. The asphalt cement grade needs to be selected based on service temperature ranges and traffic volumes. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics.

There are two basic methods for obtaining a colored finish with an asphalt surfacing: (1) the color is incorporated into the surface course mix at the time of manufacture or (2) an overall decorative surface treatment can be applied to the surface after HACP construction. The majority of colored asphalt concrete mixes are produced using the first method.

Decorative surface treatments include emulsified asphalt surfacings and various chemical coatings. For emulsified asphalt treatments (e.g. chip seals, slurry seals, microsurfacing), color can be obtained by mixing pigments with the emulsified asphalt. Surface color can also be achieved by applying a cement-modified acrylic, thermoplastic, or epoxy based coating. Information regarding emulsified asphalt surfacings can be found on the corresponding product summary sheets and will not be covered in this product summary.

Product Suppliers: Asphacolor Corporation, (800) 258-7679, www.asphacolor.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers are available.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges and traffic volumes. Traditionally, asphalt cement grades have been designated as pen grade (60/70, 85/100, etc.) or by viscosity grades (AC-20, AC-30, etc.). Currently, asphalt cements are specified by Performance Grades (PG), such as PG 64-22, indicating the high and low temperature range in °C. With the use of polymers, the serviceable temperature range is extended so rutting can be avoided at high temperatures and transverse cracking can be avoided at low temperatures.

Any light-colored surface finish can be disfigured by stains, such as from oil spills, that are not evident on traditional black asphalt concrete surfacings. Also, the asphalt concrete color can rarely be matched when future patching is required over utility cuts, etc.

DESIGN

SLC: 0.30 to 0.46. Typical default values: 0.44 for Superpave, Marshall, and Hveem, 0.40 for minor asphalt mixes.

Other Design Values: None.

Base/Subbase Requirements: HACP is usually constructed over an aggregate base course, but may be placed directly over a prepared subgrade of native materials. The required HACP thickness depends on the level of base/subgrade support provided. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to HACP placement. A prime coat is normally used above the aggregate base prior to paving. Tack coats can be used to improve the bond between hot mix layers.

Other Comments: The effect of color pigments on HACP performance is generally none to minimal. Color pigments are typically only added to the surface course layer, since it is the only visible layer.

CONSTRUCTION

Availability of Experienced Personnel: Pigmented HACP construction is identical to conventional HACP construction. HCAP is a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas. For colored surface coatings, experienced specialty contractors are required; they are widely available near large urban areas and regionally available in other areas.

Materials: HACP is composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics. Pigments are generally nontoxic, nonhazardous, dry materials manufactured specifically for use as color additives. Iron oxide is the most common pigment and is widely available; some other pigments can be very expensive and have limited availability.

Equipment: Equipment required for HACP construction includes: haul vehicles, asphalt distributor (if prime or tack coats are applied), asphalt paver machine, and compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller). Equipment is widely available in urban areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: HACP is normally hot mixed at a stationary asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. When the color is added during HACP mixing, pigments are added to the heated aggregates and mixed prior to adding the asphalt cement binder. HACP mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in haul vehicles to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to 2 or 3 hours. When the project site is far from an asphalt plant, a portable asphalt plant can be assembled near the project site. When selecting a site for a portable asphalt plant, impacts to the environment and local residents and businesses must be considered.

Placement Process: Upon arrival at the site, the asphalt concrete mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The HACP is then rolled with compaction equipment to achieve the required density. When a pigmented surfacing is applied as opposed to adding the pigment during the mixing process, colored chemical surface coatings are typically sprayed onto the finished HACP surface.

Weather Restrictions: Do not place HACP if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for HACP placement varies between different agencies, but is normally about 7 °C (45 °F).

Construction Rate: HACP placement rates will depend on the speed that the asphalt concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or higher. Compactor speeds are normally limited to 4.8 km/hr (3 mph), so overall construction rates are often dictated by the number of compactors on site. Typical production rates are 900 to 4,500 Mg/day (1,000 to 5,000 tons/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The HACP surface can be opened to traffic as soon as the HACP has cooled and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened. Chemical surface coatings have varying cure times, but typically range from a few minutes to an hour.

Other Comments: Asphalt concrete producers must dedicate their plant to pigmented asphalt concrete production for the entire production duration, creating logistical problems and increasing cost. Also, asphalt concrete suppliers will not want to dedicate their plant to pigmented asphalt concrete for small asphalt concrete order quantities.

SERVICEABILITY

Reliability and Performance History: Pigmented HACP performs identically to conventional HACP. HACP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available. The Superpave mix design method is relatively new, with most research and project experience occurring since 1990.

For chemical surface coatings, product specific information should be collected regarding performance and durability.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives range from 15 to 20 years. Surface applied color coatings will commonly last 1 to 2 years for light spray applications and 3 to 6 years or more for thicker and more durable surface coatings.

Ride Quality: Very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, loss of surface friction, color fading or wearing (for surface applied coatings).

Preservation Needs: Preventative maintenance includes crack sealing every 2 to 5 years and localized patching every 7 to 9 years. Pigmented crack sealer or asphalt concrete is preferred for preventative and corrective maintenance. However, the asphalt concrete color can rarely be matched exactly since the original surface color fades with time. Thin surface treatments can be applied to extend the serviceable life of pigmented HACP, but they will hide the original pigmented surface.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided high quality aggregates are used in the asphalt concrete mix, pigmented HACP provides good to excellent skid resistance. Colored surface coatings can obscure the natural aggregate texture and can create slippery surface conditions; however, some coatings include skid resistant materials that provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because HACP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Pigments and surface coatings are products manufactured specifically for road coloring applications.

Delivery and Haul Requirements: Hot mix asphalt concrete must be hauled from a stationary asphalt plant unless a mobile asphalt plant is assembled, in which case the required hot mix asphalt concrete mix components must be hauled to the mobile plant. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the HACP mixing and placement process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Pigmented HACP and colored surface coatings are impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by pigmented HACP roadways.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Pigmented HACP can be fully recycled as a pavement construction material. The color coating may restrict the use of pigmented asphalt concrete as RAP for recycled HACP.

Other Environmental Considerations: Select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. For HACP, tire/road noise is typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle.

Colored surface coatings are generally safe and environmentally friendly products. Nonetheless, product specific information should be reviewed before using a colored surface coating.

AESTHETICS

Appearance: Pigmented asphalt concrete can be a highly decorative surfacing. Numerous colors are available; earth tones such as red, brown, green, and tan (and numerous variations) are most common. Pigmented asphalt concrete can be used to blend in with the surrounding environment (earth tone colors in a wilderness area, for example) or to contrast the surrounding environment (e.g. pedestrian crosswalk, fire lane, or handicap parking area colored in bright, contrasting colors), depending on the application and designer's intent.

Appearance Degradation Over Time: Over time, some color wear and fading is possible. For surface coatings, non-uniform wear is possible and will expose the underlying asphalt concrete color. Additional applications of colored surface coating can be used to maintain the appearance of the surface. When the entire asphalt concrete surfacing layer is colored, surface wear will not affect the color. Surfaces can also become discolored by tire marks and oil leakage. Pigmented crack sealants and asphalt concrete must be used for preventative and corrective maintenance to maintain the uniform appearance of the surfacing.

COST

Supply Price: \$2.10 to 4.30/m^2 (\$1.80 to \$3.60/yd^2) for spray coating; \$16.10 to 21.40/m^2 (\$13.50 to \$18.00/yd^2) for pigment for 25 mm (1 in.) thick asphalt concrete surface layer.

Supply+Install Price: \$4.00 to 6.70/m^2 (\$3.30 to \$5.60/yd^2) for spray coating; \$18.00 to 24.00/m^2 (\$15.00 to \$20.00/yd^2) for pigment for 25 mm (1 in.) thick asphalt concrete surface layer.

EXAMPLE PROJECTS

San Francisco Mission Bay Park, San Francisco, CA.
Crosswalks, City of Burlington, VT.

SELECT RESOURCES

Asphalt Institute, (859) 288-4960, www.asphaltinstitute.org.
National Asphalt Pavement Association (NAPA), (888) HOT-MIXX, www.hotmix.org.

POROUS HACP

GENERAL INFORMATION

Generic Name(s): Porous Asphalt Pavement, Porous Asphalt Concrete, Pervious Asphalt Pavement, Permeable Asphalt Pavement

Trade Names: N/A

Product Description: Porous asphalt pavement is a paved surface and subbase comprised of asphalt concrete and gravel or crushed aggregate, formed in a manner that results in a permeable surface. The various layers have the potential for stormwater detention. Stormwater that passes through the pavement may completely or partially infiltrate the underlying soil, the excess being collected and routed to an overflow facility through perforated underdrain pipes.

A typical porous asphalt pavement consists of a top porous asphalt concrete course, a filter course, a reservoir course (designed to temporarily retain infiltrated water and for frost protection), and existing soil or subbase material. The top porous asphalt concrete layer is an open graded asphalt concrete surface course (having about 16% air voids), approximately 50 to 100 mm (2 to 4 in.) thick. The filter course is a 25 to 50 mm (1 to 2 in.) thick layer of 12.5 mm (0.5 in.) crushed stone aggregate designed to provide filtration and stability for the reservoir course during paving of the asphalt concrete layer. The reservoir course is a base of 37.5 to 75 mm (1.5 to 3 in.) stone with a depth determined by the storage volume needed. In addition to transmitting mechanical loads, the reservoir course stores infiltrated stormwater until it can infiltrate into the soil.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706, (888) HOT-MIXX, www.hotmix.org.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to Low. Porous asphalt, because of its high voids content, is not sufficiently durable to sustain medium or high traffic volumes. Further, to achieve adequate permeability the asphalt layer thickness is generally restricted to 100 mm (4 in.) thick.

Restrictions:

Traffic: Porous asphalt is not recommended for applications with significant heavy truck traffic.

Climate: The use of porous asphalt in areas requiring intensive winter maintenance is limited, because of a risk of the pores clogging with winter road sanding material. Porous asphalt is not recommended for windy climates where wind erosion would provide windblown sediment that can clog the asphalt pores.

Weather: None.

Terrain: Porous asphalt is not recommended for roadway gradients steeper than 5%; roadway gradients as flat as possible are desired.

Soil Type: Porous asphalt is mainly used in areas with permeable soils with an infiltration rate greater than 1.3 cm/hr (0.5 in./hr). Where soils have low permeability, the reservoir thickness should be increased to provide additional storage. With soils composed of clay or silt, additional drainage may be required.

Other: Depth to seasonal high groundwater levels and bedrock should be greater than 1.2 m (4 ft.).

Other Comments: Porous asphalt use is usually limited to applications with drainage areas less than 6.1 hectares (15 acres). Porous asphalt has mainly been used for low volume parking lots and roads and recreational areas.

DESIGN

SLC: 0.35 to 0.40.

Other Design Values: None.

Base/Subbase Requirements: The reservoir course (base) should be deep enough to provide sufficient water storage volume and provide frost protection if the soils are frost susceptible and in a climatic zone subject to freezing temperatures. Additional granular thicknesses over and above that needed for structural design may be required.

Other Comments: The depth of the stone reservoir should be such that it drains completely within 72 hours. This allows the underlying soils to dry out between storms and also provides capacity for the next storm. If frost penetrates deeper than the thickness of the pavement and reservoir course, and the subgrade has potential for frost heaving, additional material should be added to the reservoir course to below the frost zone. The reservoir (base) course should be deep enough to provide sufficient water storage volume. A minimum residence time of 12 hours should be a target for the design storm to provide exfiltration for pollutants removal.

When fine-grained natural soils are present, a geosynthetic separation/filtration layer is typically placed at the bottom of the reservoir layer.

CONSTRUCTION

Availability of Experienced Personnel: Porous asphalt pavement construction requires experienced contractors, particularly for placing the porous asphalt layers. Porous asphalt is not a commonly used surfacing and experienced contractors are, in general, not widely available.

Materials: The top porous asphalt concrete course consists of porous hot mix asphalt concrete, containing little sand or dust and with high air voids content (typically 16%). Hot mix asphalt concrete is composed of a blend of coarse and fine aggregate with asphalt cement as a binder. Modified asphalt cements and fibers are frequently used to control draindown, improve adhesion, and improve resistance to raveling and oxidation. The filter course is constructed of 13 mm (0.5 in) crushed stone aggregate. The reservoir course is constructed of 40 to 75 mm (1.5 to 3 in.) crushed stone aggregate.

Equipment: Equipment required for porous asphalt construction includes: haul vehicles, asphalt paver machine, grading equipment, and compaction equipment (i.e. static steel wheel roller). This equipment is widely available.

Manufacturing/Mixing Process: Porous asphalt concrete is hot mixed at a stationary asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. Porous asphalt concrete mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). After mixing, the product is placed in haul vehicles to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to approximately 1.5 hours. When the project site is far from an asphalt plant, a portable asphalt plant can be assembled near the project site. When selecting a site for a portable asphalt plant, impacts to the environment and local residents and businesses must be considered.

Placement Process: If needed, the site is excavated to design subgrade depth and graded using light equipment to minimize compaction of the subgrade surface. If the subgrade soils are fine-grained, a geosynthetic separation/filtration layer is placed on the subgrade prior to construction of the reservoir layer. Then, the base reservoir and filtration layers are placed and compacted. After the base is constructed, the porous asphalt concrete surface layer can be placed. Upon arrival at the site, the asphalt concrete mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The asphalt concrete is then rolled with compaction equipment to seat the material before the asphalt binder solidifies, which generally occurs between a temperature of about 85 °C (185 °F) and 150 °C (300 °F), depending on the asphalt binder. The time available for compaction before the mix has cooled will depend on the mix temperature when it is placed, layer thickness, air temperature, and wind, but can range from several minutes to more than 30 minutes.

Weather Restrictions: Do not place porous asphalt concrete if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for porous asphalt concrete placement varies between different agencies, but is normally about 10 °C (50 °F). The aggregate base materials should not be constructed on wet or frozen soils.

Construction Rate: Typical porous asphalt concrete pavement construction rates are on the order of 500 to 1,000 Mg/day (550 to 1,100 tons/day). The relatively low production rates reflect the specialty nature of porous asphalt concrete pavement and the typically small project size.

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The porous asphalt concrete surface can be opened to traffic 2 days after construction is completed. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: In the past, performance reliability of porous asphalt concrete pavements has been very low, with failure rates on the order of 75%. Failure has been caused by poor design, poor construction, heavy vehicle traffic, low permeability soils, and resurfacing with impermeable materials. There is now a better understanding of the construction and design features and reliability is improving.

Life Expectancy: Porous asphalt concrete pavement life expectancy will be less than for conventional HACP. Depending on traffic and environmental conditions, life expectancy will be 10 to 15 years or longer for low traffic volumes. However, premature failure has been common due to poor design, construction, or inappropriate application.

Ride Quality: Ride quality is very good. Ride quality deteriorates over the service life.

Main Distress / Failure Modes: Raveling, cracking, rutting, pore clogging.

Preservation Needs: Vacuum sweeping, followed by high pressure jet hosing to clean pores, should be performed periodically. Periodic filling of potholes, sealing cracks, and filling ruts is required. Porous asphalt should be used for repairs. Rehabilitation requires removal and replacement of the porous surface layer.

SAFETY

Hazards: None.

Skid Resistance: Due to their good frictional characteristics and rapid surface water removal, porous pavements reduce the potential for wet skidding and hydroplaning accidents.

Road Striping Possible?: Yes.

Other Comments: Because HACP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. Because porous asphalt has an open structure, it can freeze sooner than conventional HACP. Porous asphalt can reduce water spray by 90% compared to a dense-graded surface.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Porous asphalt concrete must be hauled from a stationary asphalt plant unless a mobile asphalt plant is assembled, in which case the required hot mix asphalt concrete mix components must be hauled to the mobile plant. Haul distances may be significant for remote sites. Significant haul distances may also be required for the aggregates, if not locally available.

Potential Short-Term Construction Impacts: Significant heat is generated during the porous asphalt mixing and placement process. Construction processes may impact vegetation adjacent to the roadway. Significant excavation and disposal of existing soils may be required to install the reservoir and filter layers.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: The pavement surface is permeable, allowing infiltration of stormwater, which is temporarily stored in the reservoir course until it can infiltrate into the ground. Contaminants in the surface runoff that are not easily trapped or reduced can flow through the pavement structure and become a potential source of groundwater contamination. Therefore, porous asphalt pavements are not recommended for areas near groundwater drinking supplies or other sensitive bodies of water. However, local infiltration of storm water is generally preferable to large stormwater collection and disposal systems.

Erosion: None.

Water quality: The filter layer below porous asphalt removes particulate matter and so improves stormwater quality. However, if the surface water infiltrating the pavement surface contains contaminants that are not easily trapped or reduced, the contaminants will flow through the pavement structure and be introduced into the surrounding soil.

Aquatic species: None. However, porous asphalt can be a vehicle for contaminates to be introduced into nearby bodies of water. Therefore, porous asphalt pavements are not recommended for areas near groundwater drinking supplies or other sensitive bodies of water.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Porous asphalt concrete can be fully recycled as a pavement construction material.

Other Environmental Considerations: Pre-treatment of stormwater is recommended where oil and grease or other potential groundwater contaminants are expected. The possible environmental benefits of porous asphalt pavement include: removal of fine particulates and soluble pollutants through soil infiltration, attenuation of peak flows, reduction in the volume of runoff leaving the site and entering storm sewers, reduction in soil erosion, and groundwater recharge.

Porous asphalt concrete pavement's characteristic black surface will absorb heat from sunlight; select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. Porous asphalt concrete pavements typically reduce tire/road noise by 3 decibels compared to conventional HACP and 5 decibels compared to PCCP.

AESTHETICS

Appearance: Immediately after placement, porous asphalt is generally black with a coarse surface texture.

Appearance Degradation Over Time: Over time, Porous asphalt concrete can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing and patching, the surface appearance is further altered.

COST

Supply Price: N/A

Supply+Install Price: \$5.00 to \$11.00/m^2 (\$4.20 to \$9.20/yd^2) for a 50 mm (2 in.) thick lift.

EXAMPLE PROJECTS

Fort Necessity National Battlefield, Farmington, PA.

SELECT RESOURCES

U.S. Environmental Protection Agency (1999). *Stormwater Technology Fact Sheet: Porous Pavement*, EPA 832-F-99-023, U.S. EPA, Office of Water, Washington, D.C., 6 pp.

RESIN MODIFIED PAVEMENT

GENERAL INFORMATION

Generic Name(s): Resin Modified Pavement (RMP)

Trade Names: Resin Modified Pavement, SALVIACIM

Product Description: Resin Modified Pavement (RMP) is a surfacing alternative that provides many of the performance characteristics of PCCP with the economy and ease of construction of HACP. RMP is a low cost alternative to PCC when resistance to heavy loads, tracked vehicle equipment, or fuel spillage is required, with a cost savings of 30% to 50% compared to PCCP. RMP is an open graded asphalt concrete mixture with 25% to 35% voids that are filled with a latex-rubber modified cement grout. The composite surface is generally 40 to 65 mm (1.5 to 2.5 in.) thick.

Product Suppliers: Alyan Corporation, P.O. Box 788, Vienna, VA 22183, (703) 255-1381, www.alyancorp.com.

APPLICATION

Typical Use: Road surfacing, parking areas.

Traffic Range: Very Low to High.

Restrictions:

Traffic: RMP is limited to low speed traffic applications (less than 65 km/hr [40 mph]) due to possibility of low skid resistance during early stages of performance life and in icy conditions.

Climate: None.

Weather: None.

Terrain: RMP is not recommended for roadway gradients greater than 5%. Gradients are generally limited to less than 2%; for gradients of 2% to 5%, excessive hand work is required during construction.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: 0.44 (assumed same as HACP).

Other Design Values: None.

Base/Subbase Requirements: RMP must be placed over a minimum of 50 mm (2 in.) of HACP.

Other Comments: None.

CONSTRUCTION

Availability of Experienced Personnel: RMP use in the United States has been limited, so experienced contractors are generally not locally available. However, local contractors with asphalt concrete construction experience teamed with experienced grout installers should be able to successfully construct a RMP pavement.

Materials: RMP is composed of an open graded asphalt concrete and a resin modified grout. The open graded asphalt concrete, composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder, should have 25% to 35% voids when compacted and a maximum particle size of 19 mm (0.75 in.). The resin modified grout is composed of portland cement, sand, fly ash, water, and a resin additive. The resin additive is a proprietary product, named Prosalvia 7, and is composed of water, a cross polymer resin of styrene and butadiene, and a water reducing agent.

Equipment: Equipment required for RMP construction includes: Trucks for hauling asphalt concrete and grout, asphalt concrete paving machine, small (5-ton maximum) steel wheel vibratory roller, lumber or other product to contain grout within a particular application area, and hand squeegees. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: The asphalt concrete component of RMP is mixed at a plant and hauled to the site. The asphalt concrete is usually mixed at temperatures of 121 to 135 °C (250 to 275 °F). The resin modified grout is typically mixed at a plant and hauled to the site, although a portable mixer can be used for small jobs to mix the grout at the site. The resin is added to the grout mix at the plant if the site is located within 20 minutes of the batch plant. If the haul distance from the plant to the site requires more than 20 minutes, the resin is added to the grout at the site.

Placement Process: The open graded asphalt concrete is placed using an asphalt concrete paving machine utilizing standard asphalt concrete construction procedures. Compaction of the asphalt concrete is not required; a small steel wheel roller is used just to smooth the asphalt concrete surface after placement. Typically, one roller pass when the asphalt concrete temperature is about 71 °C (160 °F) and another when the temperature is around 55 °C (130 °F) is adequate. The resin modified grout is then applied to the asphalt concrete surface from the rear of the mix truck. Pieces of lumber are often placed on the asphalt concrete surface to isolate the application area and prevent the grout from spreading outside of the application area or into areas where the grout has already been placed. Workers use hand squeegees to adequately distribute the grout within the application area. The steel wheel roller is used to roll and vibrate the application area to ensure that the grout penetrates all the voids in the asphalt concrete. Once the voids in the asphalt concrete are filled, workers use hand squeegees to remove the remaining excess grout. Curing compounds can then be applied to the RMP surface.

Weather Restrictions: Do not place RMP open graded asphalt concrete if it is raining or the air temperature is below 10 °C (50 °F). Grout should not be applied when the surface temperature is above 38 °C (100 °F).

Construction Rate: Typical RMP construction rates can be on the order of 1,700 to 2,500 m^3/day (2,000 to 3,000 yd^3/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. RMP can be opened to pedestrian traffic 24 hours after construction and light vehicle traffic after 3 days. Normal traffic loads can be allowed on the RMP surface once an adequate RMP strength is reached, typically 7 to 14 days. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: RMP was developed in France in the 1960s, under the trade name Salviacim, as a fuel and abrasion resistant surfacing material. Today, RMP is an accepted standard surfacing in France and has been used on projects in at least 25 other countries. RMP has been used on at least 30 projects in the United States since the late 1980s; projects have mainly been for airfields or military bases. RMP for road surfacing applications is still relatively new in the United States and research, design and construction information, and project experience is limited.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 15 to 25 years (typical design life is 20 years).

Ride Quality: RMP ride quality is inferior to most paved surfaces. RMP generally has a rough surface finish, leading to a fair ride quality. This smoothness level is usually adequate for low-speed applications. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, raveling.

Preservation Needs: In general, RMP requires relatively little preventative maintenance. Cracking has little impact on RMP performance. For cracks greater than 6 mm (0.25 in.) wide, periodic crack sealing may be required. Patching of localized failure areas may be required after 5 to 10 years. Patching will require the use of the same modified cement grout used in the original construction.

SAFETY

Hazards: None.

Skid Resistance: RMP has an irregular surface after construction, leading to poor to marginal skid resistance and limiting RMP use to low-speed applications. Skid resistance can improve with time as surface grout is worn away.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: The open graded asphalt concrete is composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement. Asphalt cement is produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. The resin modified grout is composed of portland cement, sand, fly ash, water, and a resin additive. Portland cement is manufactured from limestone. The resin additive is a manufactured chemical. Fly ash is an industrial by-product of coal combustion.

Delivery and Haul Requirements: Asphalt concrete and grout must be hauled from mixing plants to the site. Haul distances can be significant for remote sites; in these cases, a portable mixing plant can be set up on site assembled, in which case the required mix components must be hauled to the site.

Potential Short-Term Construction Impacts: Significant heat is generated during the asphalt concrete mixing and placement process. Construction processes may impact vegetation adjacent to the roadway. The application area should be contained to prevent excessive grout runoff into the surrounding environment.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: RMP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by RMP roadways.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: RMP can be milled or crushed for use as an unbound or stabilized material.

Other Environmental Considerations: Light-colored RMP can be used to reduce surface heat reflectivity. For RMP, tire/road noise is typically moderate to high with a higher noise level than HACP.

AESTHETICS

Appearance: RMP typically has a light to dark gray color and a relatively rough texture, similar to rough textured PCCP. The surface color can be modified using pigments or stains to color the grout.

Appearance Degradation Over Time: RMP will maintain its general appearance throughout its serviceable life. Surface grout will wear to some extent with time, exposing more of the asphalt concrete.

COST

Supply Price: N/A

Supply+Install Price: \$12/m^2 (\$10/yd^2) (typical average price for 50 mm [2 in.] thick RMP).

EXAMPLE PROJECTS

Travis Air Force Base, Fairfield, CA.
Hill Air Force Base, UT.
Miami International Airport, Miami, FL.

SELECT RESOURCES

Alyan Corporation, (703) 255-1381, www.alyancorp.com.
Anderton, G.L. (1996). *User's Guide: Resin Modified Pavement*, FEAP-UG-96/01, U.S. Army Center for Public Works, Alexandria, VA, 58 pp.

SYNTHETIC BINDER CONCRETE PAVEMENT

GENERAL INFORMATION

Generic Name(s): Synthetic Binder Concrete Pavement

Trade Names: PAVEBRITE

Product Description: Synthetic binder concrete pavement is a high quality pavement material that is hot mixed at a plant and then hot laid. Synthetic binder concrete pavement is composed of a carefully designed blend of coarse and fine aggregate and mineral filler with polymer modified synthetic binder. The synthetic binder is composed of a petroleum hydrocarbon resin that completely replaces asphalt cement in traditional HACP. Synthetic binder concrete pavement meets or exceeds specifications for HACP.

Product Suppliers: Neville Chemical Company, 2800 Neville Road, Pittsburgh, PA 15225-1496, (877) 704-4200, www.nevchem.com.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: A high stability mix should be used for heavy industrial loading conditions (i.e. slow moving trucks, frequent braking, etc.).

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: The synthetic binder is typically classified as PG 64-22, but can be modified to meet different performance grade specifications.

DESIGN

SLC: 0.44.

Other Design Values: None.

Base/Subbase Requirements: Synthetic binder concrete pavement is usually constructed over an aggregate base course, but may be placed directly over a prepared subgrade of native materials. The required synthetic binder concrete pavement thickness depends on the level of base/subgrade support provided. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to synthetic binder concrete placement.

Other Comments: As a general guideline, the minimum synthetic binder concrete lift thickness should be three times the nominal maximum aggregate size.

CONSTRUCTION

Availability of Experienced Personnel: Synthetic binder concrete pavement is a new surfacing and experienced contractors are, in general, not available. However, the construction process is nearly identical to HACP construction, for which experienced contractors are widely available. Experienced HACP contractors can be advised by the manufacturer to ensure that the synthetic concrete pavement is constructed properly.

Materials: Synthetic binder concrete pavement is composed of a carefully designed blend of coarse and fine aggregate and mineral filler with polymer modified synthetic binder. The synthetic binder is composed of a petroleum hydrocarbon resin that can replace asphalt cement in traditional HACP.

Equipment: Equipment required for synthetic concrete construction include: haul vehicles, asphalt paver machine, and compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller). Equipment is widely available in urban areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Synthetic binder concrete is normally hot mixed at an asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. If colored pavements are desired, the coloring pigments must be mixed with the synthetic binder prior to adding the aggregate to the mix. Synthetic binder concrete mixes are normally mixed at temperatures between 127 to 141 °C (260 to 285 °F). After mixing, the product is placed in haul vehicles to be transported to the project site. The synthetic concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the synthetic concrete mixture can remain at an adequate temperature for up to 2 or 3 hours. When the project site is far from an asphalt plant, a portable mixing plant can be assembled near the project site. When selecting a site for a portable mixing plant, impacts to the environment and local residents and businesses must be considered.

Placement Process: Upon arrival at the site, the synthetic concrete mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The synthetic concrete is then rolled with compaction equipment to achieve the required density. The synthetic concrete should be adequately compacted before it reaches a minimum specified temperature, typically 85 °C (185 °F). The time available for compaction before the mix has cooled will depend on the mix temperature when it is placed, layer thickness, air temperature, and wind, but can range from several minutes to more than 30 minutes.

Weather Restrictions: Do not place synthetic binder concrete if it is raining or there is ponded water on the prepared paving surface. The specified minimum air temperature for synthetic binder concrete placement can vary, but is normally about 7 °C (45 °F).

Construction Rate: Synthetic binder concrete pavement placement rates will depend on the speed that the synthetic concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or higher. Compactor speeds are normally limited to 4.8 km/hr (3 mph), so overall construction rates are often dictated by the number of compactors on site. Typical production rates are 900 to 4,500 Mg/day (1,000 to 5,000 tons/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The synthetic binder concrete surface can be opened to traffic as soon as the synthetic concrete has cooled and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened.

Other Comments: During synthetic binder concrete production, the plant needs to be dedicated exclusively to that mix. Prior cleaning of all plant equipment is needed to prevent contamination from previous asphalt binder. Similar prior cleaning would also be needed for the paver. These requirements impose logistical constraints on the scheduling of the work as well as limit the number of paving contractors who would be prepared to perform the work.

SERVICEABILITY

Reliability and Performance History: Synthetic binder concrete pavement is a new roadway surfacing and available research, design and construction, and performance history information is extremely limited at this time. Preliminary testing has shown that synthetic binder concrete meets or exceeds the specifications for hot mix asphalt concrete. It is expected that the performance of synthetic binder concrete pavements will meet or exceed that of conventional hot mix asphalt concrete, however this can only be determined over time.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes and degree of routine maintenance. No long-term performance information is available. Typical serviceable lives are expected to range from 15 to 20 years.

Ride Quality: Very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, loss of surface friction.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching every 7 to 9 years. In most circumstances, preventative maintenance measures will not match the original color of the pavement. Thin surface treatments can be applied to extend the serviceable life of synthetic binder concrete pavements.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided high quality aggregates are used in the synthetic binder concrete mix, synthetic binder concrete should provides good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because synthetic binder concrete provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: The synthetic binder used is composed of a specially formulated proprietary petroleum hydrocarbon resin. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Synthetic binder concrete must be hauled from a mixing plant unless a mobile mixing plant is assembled, in which case the required concrete mix components must be hauled to the mobile plant. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the mixing and placement process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Synthetic binder concrete is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by synthetic concrete roadways.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Synthetic binder concrete can be crushed or pulverized and reused as an unbound construction material.

Other Environmental Considerations: Light-colored aggregates and pigments can be used to lighten the pavement color and increase heat reflectivity of the surface. For HACP, tire/road noise is typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle. For synthetic binder concrete pavements, tire/road noise is expected to be similar to HACP.

AESTHETICS

Appearance: The synthetic binder is amber-colored. Therefore, the appearance of synthetic binder concrete pavement will be dominated by the color of the coarse aggregate used. If colored pavements are required, coloring pigments can be mixed with synthetic binder. Smaller quantities of pigment are required, compared to HACP, because the pigment does not have to mask the black color of the asphalt cement.

Appearance Degradation Over Time: Over time, synthetic binder concrete pavement is expected to maintain its general appearance. With maintenance activities, such as crack sealing and patching, the surface appearance can be further altered. Where special mixes or colors are used, the future availability of similar materials should be assured for maintenance purposes to lessen the aesthetic degradation.

COST

Supply Price: N/A

Supply+Install Price: N/A. Synthetic binder concrete pavement is a new product in the United States, so pricing has not been well established. The price is estimated to be on the order of four times greater than the price of HACP.

EXAMPLE PROJECTS

Richmond National Battlefield Park, Richmond, VA.
Pennsylvania Avenue, Washington, D.C.

SELECT RESOURCES

None.

PORTLAND CEMENT CONCRETE (PCC) SURFACINGS

CELLULAR PCC

GENERAL INFORMATION

Generic Name(s): Cellular Portland Cement Concrete, Flexible Portland Cement Concrete, Concrete Infilled Geocells

Trade Names: Geoweb, Hyson Cells

Product Description: Cellular portland cement concrete (PCC) consists of a geosynthetic, honeycomb-like, cellular confinement system (geocells) that is filled with PCC. Once constructed, the cellular mat is composed of numerous individual concrete blocks. The confinement system is designed such that there is a high degree of interlock between adjacent concrete blocks. The geosynthetic acts as reinforcement for the system so there is no need for steel reinforcement. The resulting product is a flexible surfacing that can support heavy loads. The surfacing can be constructed with a thickness of 100 to 200 mm (4 to 8 in.). Individual cell sizes range from 150 mm x 150 mm (6 in. x 6 in.) to 500 mm x 500 mm (20 in. x 20 in.). Cellular PCC has been used for heavy duty roads as well as boat ramps and low water crossings. Because the constructed mat is flexible, it can be constructed off-site and installed at a later time using heavy-lifting equipment.

High slump ready mix concrete must be used. Plasticizers and retarders are often used to facilitate construction. The cellular confinement system includes polymer tendons that are used to support the geosynthetic until the PCC can be placed. Anchors are also used to hold the geosynthetic down before and during concrete placement; if not anchored properly, the geosynthetic can "float" on the PCC as it is placed.

Product Suppliers: GeoProducts, LLC, 8615 Golden Spike Lane, Houston, TX 77086, (281) 820-5493, www.geoproducts.org; and
Presto Products Company, P.O. Box 2399, Appleton, WI 54912-2399, (800) 548-3424, www.prestogeo.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and geocell products are available.

APPLICATION

Typical Use: Road surfacing, channel erosion protection.

Traffic Range: Very Low to Medium.

Restrictions:

Traffic: Cellular PCC is suitable for heavy duty road applications.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: 0.25 to 0.30.

Other Design Values: Stiffness of cellular PCC mats can range from 100 to 1500 MPa (14,500 to 218,000 psi), depending on the slab thickness and level of subgrade support.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support. For low volume applications, cellular PCC can be constructed directly on the subgrade unless heavy loads dictate the need for greater base support. Subgrade and base materials should be compacted and graded to provide a uniform working platform prior to geocell placement.

Other Comments: Cellular PCC can be constructed with a thickness of 100 to 200 mm (4 to 8 in.). PCC should generally have a compressive strength greater than 30 MPa (4300 psi).

CONSTRUCTION

Availability of Experienced Personnel: Cellular PCC is not a commonly used surfacing, so availability of experienced contractors may be limited.

Materials: The pre-fabricated cellular confinement system and PCC are required for cellular PCC construction.

Equipment: Equipment required for cellular PCC construction includes: concrete mixing trucks for hauling PCC and concrete finishing equipment. Equipment requirements are minimal and equipment is widely available.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site.

Placement Process: The geocell sections are placed on the prepared subgrade/base, stretched out to their design length, and staked to hold the sections in place. Adjacent geocell sections are laid out and connected with adjoining sections. Once the geocell sections are in place, the geocells are infilled with ready mix PCC. The PCC should have a high plasticity to prevent the concrete from collapsing the cellular confinement system and to improve workability. Plasticizers and retarders are recommended. As an alternative, the geocells can be infilled with a uniformly graded aggregate and injected with cement grout. The geocell sections should be overfilled by 25 to 50 mm (1 to 2 in.). The surface is then finished by hand or machine, similar to conventional PCC.

Cellular PCC mats can be constructed off-site and hauled to the site for placement. In this case, heavy lifting equipment is required to place the cellular PCC mats.

Weather Restrictions: Do not place PCC if it is raining or if temperatures are near or below freezing. The Cellular PCC needs to be protected from freezing during the initial curing period (4 to 7 days). Do not place PCC on frozen base/subgrade soils. Special precautions are necessary if PCC is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation).

Construction Rate: Cellular PCC construction rates are in the range of 200 to 400 m^2/day (240 to 480 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction. Normal traffic loads can be allowed on the cellular PCC surface after initial curing and once an adequate PCC strength is reached, typically after 7 days. High strength PCC can be used to achieve design concrete strengths faster, so the road surfacing can be opened to traffic sooner. Cellular PCC can often be opened to light traffic after one day.

Other Comments: Construction defects are difficult to repair. For example, if the cellular confinement system collapses during concrete placement, it cannot be fixed; the area must be cleared and completely rebuilt.

SERVICEABILITY

Reliability and Performance History: Geocells were developed by the U.S. Army Corps of Engineers in the late 1970s. Cellular PCC has been used on projects where it will be used by occasional traffic, but it is not a commonly used road surfacing material. Research, design and construction information, and project experience are limited.

Life Expectancy: Life expectancy varies depending on traffic, subgrade support, and weather conditions. Typical design life for cellular PCC is 20 years.

Ride Quality: Cellular PCC with good base support can provide good ride quality. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Faulting, depressions, spalling.

Preservation Needs: Cellular PCC generally requires little maintenance. Periodic crack sealing and patching may be required.

SAFETY

Hazards: None.

Skid Resistance: When high quality aggregates are used, cellular PCC provides good initial skid resistance. When lower quality aggregates are used, polishing of the PCC aggregates at the surface can reduce the skid resistance over time. Surface grinding or texturing can be used to increase the skid resistance of the cellular PCC.

Road Striping Possible?: Yes.

Other Comments: Surface texturing can be used to increase the skid resistance of cellular PCC. The type, spacing, width, and depth of the texturing affects skid resistance and tire/road noise. Numerous surface texturing options are available, including drag textures (broom, artificial turf, burlap), tine textures (transverse, longitudinal), exposed aggregate textures, and hardened concrete textures (diamond ground, diamond groove, abraded). For local roads where hydroplaning is not a primary concern, burlap or broom textures are commonly used.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Geocells are manufactured from polyethylene. PCC is constructed of coarse and fine aggregates, portland cement, water, and chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: Geocells must be transported to the site from the distributor. Geocell sections collapse into a compact configuration to minimize the haul space required. Haul distances may be significant for remote sites. PCC must be hauled from the ready mix plant unless it is mixed on site, in which case the PCC mix components must be hauled to the site.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Cellular PCC is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by cellular PCC.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Cellular PCC cannot be economically recycled or reused.

Other Environmental Considerations: None.

AESTHETICS

Appearance: Cellular PCC has the general appearance of conventional PCC. The surface is normally light gray with a relatively smooth texture. The surface can be textured and/or colored to modify the surface appearance. The geosynthetic cellular support system is not visible in the completed surface.

Appearance Degradation Over Time: Cellular PCC will maintain its general appearance throughout its service life.

COST

Supply Price: N/A

Supply+Install Price: \$16.00 to \$20.00/m^2 (\$13.40 to \$16.70/yd^2).

EXAMPLE PROJECTS

Tesson Creek, Concord Village, MO.

SELECT RESOURCES

Visser, A.T., and Hall, S. (1999). “Flexible Portland Cement Concrete Pavement for Low-Volume Roads,” *Transportation Research Record 1652*, TRB, National Research Council, Washington, D.C., pp. 121-127.

PORTLAND CEMENT CONCRETE PAVEMENT (PCCP)

GENERAL INFORMATION

Generic Name(s): Portland Cement Concrete Pavement (PCCP), Portland Cement Concrete (PCC), Concrete

Trade Names: N/A

Product Description: Portland cement concrete pavement (PCCP) is a mixture of aggregate, cementitious material, and water that forms a rigid, paved surfacing. Additives are used to help with production and paving and to improve durability. Typical additives include air entraining admixture, water reducing agents, and supplementary cementitious materials (e.g. fly ash, ground blast furnace slag, silica fume, and calcinated clay). Concrete pavements are designed and constructed as plain concrete, plain concrete with dowelled joints, or as continuously reinforced. PCCP have very good performance characteristics with respect to strength, durability, and ride quality.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Concrete Pavement Association, 5420 Old Orchard Road, Suite A-100, Skokie, IL, 60077-1059, (847) 966-2272, www.pavement.com.

APPLICATION

Typical Use: Road structure and surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: N/A; Rigid pavements, such as PCCP, are not designed using AASHTO SLC. Instead, pavement thickness is determined based on the following factors: modulus of subgrade reaction (k), modulus of rupture for the concrete, load transfer between joints, traffic loading, and other factors, such as drainage and reliability. Concrete pavement designs can be performed using the 1998 Supplement to the 1993 AASHTO Guide for Design of Pavement Structures or using the thickness design guides available through the American Concrete Pavement Association.

Other Design Values: Typical PCC compressive strength is 20 to 50 MPa (2,900 to 7,250 psi). High strength concrete, with compressive strengths above 50 MPa (7,250 psi) is also available for special applications. Minimum specified PCC flexural strength is typically 4.1 MPa (600 psi); typical flexural strengths are 4.5 to 5.5 MPa (650 to 800 psi).

Base/Subbase Requirements: Subgrade and base materials should be compacted and graded to provide a stable working surface prior to PCCP placement. Base/subbase should consist of unbound or stabilized granular material with sufficient drainage characteristics. The base thickness should be a minimum of 100 mm (4 in.) Open graded base is frequently used as a drainage medium to prevent pumping at the joints.

Other Comments: A properly designed joint pattern is necessary to prevent random slab cracking, except for continously reinforced PCCP (CRCP). To provide better load transfer across slab joints, dowel bars should be specified, especially on high speed roads with heavy traffic loading.

CONSTRUCTION

Availability of Experienced Personnel: PCCP is a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.

Materials: Portland cement concrete (PCC) is a mixture of aggregate, cementitious material, water, and additives used to help with production and paving and to improve durability. Steel reinforcing bars are used for crack control of CRCP and dowels for transferring wheel loads between slabs.

Equipment: Equipment required for PCCP construction includes: concrete mixing trucks for hauling PCC, construction forms for roadway edges and construction joints, concrete paver, water truck, vibratory equipment, finishing equipment, and concrete saws (single or multiple gang). Continuous slip form concrete pavers are used on high productivity or larger projects. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site.

Placement Process: The concrete mix is discharged from mixing trucks and placed using automatic screeds or hand troweled. On large projects, continuous slip form concrete pavers can be used; if automatic dowel inserters are used, they should be checked to ensure proper placement and functioning of the equipment. The concrete is consolidated with vibrators to increase density and reduce voids. Thermal expansion joints are constructed at predetermined intervals. The concrete should be cured in place for 4 to 7 days or until a minimum strength is achieved, depending on exposure conditions. To facilitate curing, curing compounds can be applied, wet burlap can be used, or insulated sheets in low ambient temperatures can be used. Control joints must be saw-cut/formed before the stress in the concrete exceeds the strength to minimize random cracking. The time available to saw/form joints varies depending on concrete mix properties and ambient weather conditions.

Weather Restrictions: Do not place PCC if it is raining or if temperatures are near or below freezing. The PCCP needs to be protected from freezing during the initial curing period (4 to 7 days or until adequate strength is achieved). Do not place PCC on frozen base/subgrade soils. Special precautions are necessary if PCC is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation).

Construction Rate: Typical PCCP construction rates can be up to 2,300 m^3/day (3,000 yd^3/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction and curing, so adequate traffic control is needed. Normal traffic loads can be allowed on the PCCP surface after initial curing and once an adequate PCC strength is reached, typically after 7 or 14 days. High strength PCC can be used to achieve design concrete strengths faster, so the road surfacing can be opened to traffic sooner, as soon as eight hours after placement. Road surface striping may be performed after the lane is opened.

Other Comments: Water/cement ratios are critical components in successful PCCP construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction.

SERVICEABILITY

Reliability and Performance History: PCCP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical PCCP design life is 30 to 40 years.

Ride Quality: PCCP provides very good ride quality after construction. Ride quality deteriorates over the serviceable life, partially due to cracking and faulting at the PCCP joints.

Main Distress / Failure Modes: Cracking, faulting, spalling.

Preservation Needs: In general, PCCP require relatively little preventative maintenance. Jointed PCCP require periodic joint resealing. Depending on the type of sealant used, resealing may be required every 5 to 10 years. Surface grinding may be required to maintain good frictional characteristics and for improving ride quality.

SAFETY

Hazards: Adequate surface grading and surface texture are required to prevent ponding of water on the surface that can cause reduced traction due to hydroplaning and icing. Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: When high quality aggregates are used, PCCP provide very good initial skid resistance. The use of lower quality aggregates leads to aggregate polishing at the surface that can reduce the skid resistance over time. Surface grinding or texturing can be used to increase the skid resistance of the PCCP.

Road Striping Possible?: Yes.

Other Comments: Because PCCP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. PCCP surface texturing is often used to increase the skid resistance of PCCP and decrease the level of vehicle skidding and hydroplaning. The type, spacing, width, and depth of the texturing affects skid resistance and tire/road noise. Numerous surface texturing options are available, including drag textures (broom, artificial turf, burlap), tine textures (transverse, longitudinal), exposed aggregate textures, and hardened concrete textures (diamond ground, diamond groove, abraded). For local roads where hydroplaning is not a primary concern, burlap or broom textures are commonly used. For high speed applications, such as highways, transverse tine texturing is the most commonly used texturing. Transverse tining provides a good, durable, skid resistant surface, reduces road splash/spray, reduces headlight glare from wet surfaces, reduces hydroplaning potential, and facilitates surface drainage.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: PCCP is constructed of PCC, which contains coarse and fine aggregates, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Continuously reinforced PCCP contains reinforcing bars that are manufactured from steel. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: PCC must be hauled from the mixing plant. The mixing plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and consolidate the PCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water. Wet sludge from sawcutting operations also needs to be contained and disposed of properly.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: PCCP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by PCCP.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: PCCP can be crushed for use as an unbound or stabilized material. PCCP can also be rubblized in-place and covered with an overlay.

Other Environmental Considerations: Light-colored PCCP can be used to reduce surface heat reflectivity and roadway lighting needs. For PCCP, tire/road noise is typically moderate to high with a higher noise level than HACP. The potential for tire/road noise is increased for high speed roadways. The type of surface texturing can affect tire/road noise levels.

AESTHETICS

Appearance: PCCP typically has a smooth surface texture and light gray color. The appearance can be influenced by aggregate type and source, so visual aesthetics can be improved by using select aggregates, when available. Surface appearance can also be modified by using pigments or stains to color the concrete or finishing techniques to change the surface texture. Special treatments are available to remove some of the cement paste and expose the PCC aggregate.

Appearance Degradation Over Time: The PCCP surface will maintain its general appearance throughout its service life. Over time it is not uncommon for cracks to develop that will require crack sealing.

COST

Supply Price: \$120 to \$140/m^3 (\$90 to \$110/yd^3).

Supply+Install Price: \$130 to \$180/m^3 (\$100 to \$135/yd^3).

EXAMPLE PROJECTS

PCCP is used extensively throughout the United States.

SELECT RESOURCES

American Concrete Institute, (248) 848-3700, www.aci-int.org.
American Concrete Pavement Association, (847) 966-2272, www.pavement.com.
Portland Cement Association, (847) 966-6200, www.cement.org.

EXPOSED AGGREGATE PCCP

GENERAL INFORMATION

Generic Name(s): Exposed Aggregate Portland Cement Concrete Pavement (PCCP)

Trade Names: N/A

Product Description: Portland cement concrete (PCC) is a mixture of aggregate, cementitious material, and water that forms a rigid, paved surfacing. In the construction of exposed aggregate PCC, a thin layer of cement paste is removed from around the aggregate at the pavement surface, exposing a portion of the aggregate. Additives are used to help with production and paving and to improve durability. Typical additives include air entraining admixture, water reducing agents, and supplementary cementitious materials (e.g. fly ash, ground blast furnace slag, silica fume, and calcinated clay). Concrete pavements are designed and constructed as plain concrete, plain concrete with dowelled joints or as continuously reinforced. PCCP have very good performance characteristics with respect to strength, durability, and ride quality.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Concrete Pavement Association, 5420 Old Orchard Road, Suite A-100, Skokie, IL, 60077-1059, (847) 966-2272, www.pavement.com.

APPLICATION

Typical Use: Road structure and surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: N/A; Rigid pavements, such as PCCP, are not designed using AASHTO SLC. Instead, pavement thickness is determined based on the following factors: modulus of subgrade reaction (k), modulus of rupture for the concrete, load transfer between joints, traffic loading, and other factors, such as drainage and reliability. Concrete pavement designs can be performed using the 1998 Supplement to the 1993 AASHTO Guide for Design of Pavement Structures or using the thickness design guides available through the American Concrete Pavement Association..

Other Design Values: Typical PCC compressive strength is 20 to 50 MPa (2,900 to 7,250 psi). High strength concrete, with compressive strengths above 50 MPa (7,250 psi) is also available for special applications. Minimum specified PCC flexural strength is typically 4.1 MPa (600 psi); typical flexural strengths are 4.5 to 5.5 MPa (650 to 800 psi).

Base/Subbase Requirements: Subgrade and base materials should be compacted and graded to provide a stable working surface prior to PCCP placement. Base/subbase should consist of unbound or stabilized granular material with sufficient drainage characteristics. The base thickness should be a minimum of 100 mm (4 in.) Open graded base is frequently used as a drainage medium to prevent pumping at the joints.

Other Comments: A properly designed joint pattern is necessary to prevent random slab cracking, except for continously reinforced PCCP (CRCP). To provide better load transfer across slab joints, dowel bars should be specified, especially on high speed roads with heavy traffic loading.

CONSTRUCTION

Availability of Experienced Personnel: PCCP is a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.

Materials: PCC is a mixture of aggregate, cementitious material, water, and additives used to help with production and paving and to improve durability. Retarders are used to prepare the exposed aggregate surface. Steel reinforcing bars are used for crack control of CRCP and dowels for transferring wheel loads between slabs.

Equipment: Equipment required for PCCP construction includes: concrete mixing trucks for hauling PCC, construction forms for roadway edges and construction joints, concrete paver, water truck, vibratory equipment, finishing equipment, and concrete saws (single or multiple gang). Continuous slip form concrete pavers are used on high productivity or very large projects. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site.

Placement Process: The concrete mix is discharged from mixing trucks and placed using automatic screeds or hand troweled. On large projects, continuous slip form concrete pavers can be used; if automatic dowel inserters are used, they should be checked to ensure proper placement and functioning of the equipment. The concrete is consolidated with vibrators to increase density and reduce voids. Thermal expansion joints are constructed at predetermined intervals. For exposed aggregate concrete pavements, a retarder is spread over the pavement surface while the PCC is still wet; once the underlying PCC hardens, the still wet cement paste at the pavement surface is brushed or washed away, exposing the aggregate at the pavement surface. Control joints must be saw-cut/formed before the stress in the concrete exceeds the strength to minimize random cracking. The time available to saw/form joints varies depending on concrete mix properties and ambient weather conditions.

Weather Restrictions: Do not place PCC if it is raining or if temperatures are near or below freezing. The PCCP needs to be protected from freezing during the initial curing period (4 to 7 days or until adequate strength is achieved). Do not place PCC on frozen base/subgrade soils. Special precautions are necessary if PCC is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation).

Construction Rate: Typical PCCP construction rates can be up to 2,300 m^3/day (3,000 yd^3/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction and curing, so adequate traffic control is needed. Normal traffic loads can be allowed on the PCCP surface after initial curing and once an adequate PCC strength is reached, typically after 7 or 14 days. High strength PCC can be used to achieve design concrete strengths faster, so the road surfacing can be opened to traffic sooner, as soon as eight hours after placement. Road surface striping may be performed after the lane is opened.

Other Comments: Water/cement ratios are critical components in successful PCCP construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction.

SERVICEABILITY

Reliability and Performance History: PCCP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available. Exposed aggregate PCCP is less common, but information is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical PCCP design life is 30 to 40 years.

Ride Quality: PCCP provides very good ride quality after construction. Ride quality deteriorates over the serviceable life, partially due to cracking and faulting at the PCCP joints.

Main Distress / Failure Modes: Cracking, faulting, popouts, spalling

Preservation Needs: In general, PCCP require relatively little preventative maintenance. Jointed PCCP require periodic joint resealing. Depending on the type of sealant used, resealing may be required every 5 to 10 years. Surface grinding may be required to maintain good frictional characteristics and for improving ride quality.

SAFETY

Hazards: Adequate surface grading and surface texture are required to prevent ponding of water on the surface that can cause reduced traction due to hydroplaning and icing. Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: When high quality aggregates are used, PCCP provide very good initial skid resistance. The use of lower quality aggregates leads to aggregate polishing at the surface that can reduce the skid resistance over time.

Road Striping Possible?: Yes.

Other Comments: Because PCCP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. PCCP surface texturing is often used to increase the skid resistance of PCCP and decrease the level of vehicle skidding and hydroplaning. The type, spacing, width, and depth of the texturing affects skid resistance and tire/road noise.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: PCCP is constructed of PCC, which contains coarse and fine aggregates, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Reinforced PCCP contains reinforcing bars that are manufactured from steel. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: PCC must be hauled from the mixing plant. The mixing plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and consolidate the PCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water. Wet sludge from sawcutting operations and brushing the pavement surface also needs to be contained and disposed of properly.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: PCCP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by PCCP.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: PCCP can be crushed for use as an unbound or stabilized material. PCCP can also be rubblized in-place and covered with an overlay.

Other Environmental Considerations: Light-colored PCCP can be used to reduce surface heat reflectivity and roadway lighting needs. For exposed aggregate PCCP, tire/road noise is typically moderate with a lower noise level than conventional PCCP or HACP, but a higher noise level than porous PCCP. The potential for tire/road noise is increased for high speed roadways. The size and shape of aggregates at the pavement surface and depth of aggregate exposure affects tire/road noise levels.

AESTHETICS

Appearance: The appearance will be influenced by the gray cement paste and the aggregate type and source, so visual aesthetics can be improved by using select aggregates, when available.

Appearance Degradation Over Time: The exposed aggregate PCCP surface will maintain its general appearance throughout its service life. Over time it is not uncommon for cracks to develop that will require crack sealing.

COST

Supply Price: \$120 to \$140/m^3 (\$90 to \$110/yd^3)

Supply+Install Price: \$145 to \$200/m^3 (\$110 to \$150/yd^3)

EXAMPLE PROJECTS

Colonial Parkway, Williamsburg, VA.
Exposed aggregate PCCP is used extensively for driveways throughout the United States.

SELECT RESOURCES

American Concrete Institute, (248) 848-3700, www.aci-int.org.
American Concrete Pavement Association, (847) 966-2272, www.pavement.com.
Portland Cement Association, (847) 966-6200, www.cement.org.
Artcrete Concrete Products Intl., www.exposedaggregate.com.

PIGMENTED PCCP

GENERAL INFORMATION

Generic Name(s): Pigmented Portland Cement Concrete Pavement (PCCP), Pigmented Concrete, Colored Concrete

Trade Names: N/A

Product Description: Portland cement concrete (PCC) is a mixture of aggregate, cementitious material, and water that forms a rigid, paved surfacing. Additives are used to help with production and paving and to improve durability. Typical additives include air entraining admixture, water reducing agents, and supplementary cementitious materials (e.g. fly ash, ground blast furnace slag, silica fume, and calcinated clay). Concrete pavements are designed and constructed as plain concrete, plain concrete with dowelled joints or as continuously reinforced. PCCP have very good performance characteristics with respect to strength, durability, and ride quality.

There are three methods available for coloring a PCCP surface: (1) The color (pigment) is incorporated into the concrete mix during mixing; (2) Pigment is sprinkled onto a freshly poured PCC surface and mixed into the surface as part of the concrete finishing process; or (3) pigmented sealers or stains are applied to a hardened concrete surface.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Society of Concrete Contractors, 2025 S. Brentwood Blvd., Saint Louis, MO 63114, (314) 962-0210, www.ascconline.org.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: Any light-colored surface finish can be disfigured by stains, such as from oil spills.

DESIGN

SLC: N/A; Rigid pavements, such as PCCP, are not designed using AASHTO SLC. Instead, pavement thickness is determined based on the following factors: modulus of subgrade reaction (k), modulus of rupture for the concrete, load transfer between joints, traffic loading, and other factors, such as drainage and reliability. Concrete pavement designs can be performed using the 1993 AASHTO Guide for Design of Pavement Structures or using the thickness design guides available through the American Concrete Pavement Association..

Other Design Values: Compressive strength: 20 to 50 MPa (2,900 to 7,250 psi). High strength concrete, with compressive strengths above 50 MPa (7,250 psi) is also available for special applications.

Base/Subbase Requirements: Subgrade and base materials should be compacted and graded to provide a stable working surface prior to PCCP placement. Base/subbase should consist of unbound or stabilized granular material with sufficient drainage characteristics. The base thickness should be a minimum of 100 mm (4 in.) Open graded base is frequently used as a drainage medium to prevent pumping at the joints.

Other Comments: A properly designed joint pattern is necessary to prevent random slab cracking, except for continously reinforced PCCP (CRCP). To provide better load transfer across slab joints, dowel bars should be specified, especially on high speed roads with heavy traffic loading.

The effect of color pigments on PCCP performance is generally none to minimal.

CONSTRUCTION

Availability of Experienced Personnel: When the pigment is added during mixing, pigmented PCCP construction is identical to conventional PCCP construction. PCCP is a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas. For pigments added during finishing, an experienced concrete finishing contractor is required; they are widely available near large urban areas and regionally available in other areas. For colored surface coatings, experienced specialty contractors are required; they are widely available near large urban areas and regionally available in other areas.

Materials: PCC is a mixture of aggregate, cementitious material, water, and additives used to help with production and paving and to improve durability. Steel reinforcing bars are used for crack control of CRCP and dowels for transferring wheel loads between slabs.Many of the dry pigments obtain their color from the use of mineral oxides, such as iron or chromium. A variety of pigmented sealers are available, including acrylic, epoxy, and polyurethane products.

Equipment: Equipment required for PCCP construction includes: concrete mixing trucks for hauling PCC, construction forms for roadway edges and construction joints, concrete paver, water truck, vibratory equipment, finishing equipment, and concrete saws (single or multiple gang). Continuous slip form concrete pavers are used on high productivity or very large projects. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site. The pigment can be added to the PCC mix at the plant.

Placement Process: The concrete mix is discharged from mixing trucks and placed using automatic screeds or hand troweled. On large projects, continuous slip form concrete pavers can be used; if automatic dowel inserters are used, they should be checked to ensure proper placement and functioning of the equipment. The concrete is consolidated with vibrators to increase density and reduce voids. Thermal expansion joints are constructed at predetermined intervals. The concrete should be cured in place for 4 to 7 days or until a minimum strength is achieved, depending on exposure conditions. To facilitate curing, topical curing compounds are recommended. Control joints must be saw-cut/formed before the stress in the concrete exceeds the strength to minimize random cracking. The time available to saw/form joints varies depending on concrete mix properties and ambient weather conditions.

If a dry-shake color hardener is used, the pigment is sprinkled onto a freshly poured PCC surface and mixed into the surface as part of the concrete finishing process. If pigmented sealers or stains are used, they are applied to the concrete surface after it has hardened and fully cured.

Weather Restrictions: Do not place PCC if it is raining or if temperatures are near or below freezing. The PCCP needs to be protected from freezing during the initial curing period (4 to 7 days or until adequate strength is achieved). Do not place PCC on frozen base/subgrade soils. Special precautions are necessary if PCC is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation). Different pigmented sealers and stains may have different weather restrictions regarding application; restrictions for a particular product should be reviewed before it is applied.

Construction Rate: Typical pigmented PCCP construction rates can be up to 2,300 m^3/day (3,000 yd^3/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction and curing, so adequate traffic control is needed. Normal traffic loads can be allowed on the PCCP surface after initial curing and once an adequate PCC strength is reached, typically after 7 or 14 days. High strength PCC can be used to achieve design concrete strengths faster, so the road surfacing can be opened to traffic sooner, as soon as eight hours after placement. Road surface striping may be performed after the lane is opened. Colored surface coatings have varying cure times, but typically range from a few minutes to a few hours.

Other Comments: Water/cement ratios are critical components in successful PCCP construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction.

SERVICEABILITY

Reliability and Performance History: Pigmented PCCP performs identically to conventional PCCP. PCCP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available. For pigmented sealers and stains, product specific information should be collected regarding performance and durability.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical PCCP design life is 30 to 40 years. Surface applied pigments and coatings will commonly last 3 to 6 years or more.

Ride Quality: PCCP provides very good ride quality after construction. Ride quality deteriorates over the serviceable life, partially due to cracking and faulting at the PCCP joints.

Main Distress / Failure Modes: Cracking, faulting, spalling, color fading or wearing (for surface applied coatings).

Preservation Needs: In general, PCCP require relatively little preventative maintenance. Jointed PCCP require periodic joint resealing. Depending on the type of sealant used, resealing may be required every 5 to 10 years. Surface grinding may be required to maintain good frictional characteristics and for improving ride quality.

SAFETY

Hazards: Adequate surface grading and surface texture are required to prevent ponding of water on the surface that can cause reduced traction due to hydroplaning and icing. Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: When high quality aggregates are used, PCCP provide very good initial skid resistance. The use of lower quality aggregates leads to aggregate polishing at the surface that can reduce the skid resistance over time. Surface grinding or texturing can be used to increase the skid resistance of the PCCP.

Pigmented sealers can obscure the natural aggregate texture and can create slippery surface conditions; however, some coatings include skid resistant materials that provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because PCCP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. PCCP surface texturing is often used to increase the skid resistance of PCCP and decrease the level of vehicle skidding and hydroplaning. The type, spacing, width, and depth of the texturing affects skid resistance and tire/road noise. Numerous surface texturing options are available, including drag textures (broom, artificial turf, burlap), tine textures (transverse, longitudinal), exposed aggregate textures, and hardened concrete textures (diamond ground, diamond groove, abraded). For local roads where hydroplaning is not a primary concern, burlap or broom textures are commonly used. For high speed applications, such as highways, transverse tine texturing is the most commonly used texturing. Transverse tining provides a good, durable, skid resistant surface, reduces road splash/spray, reduces headlight glare from wet surfaces, reduces hydroplaning potential, and facilitates surface drainage.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: PCCP is constructed of PCC, which contains coarse and fine aggregates, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture. Reinforced PCCP contains reinforcing bars that are manufactured from steel. Pigments, sealers, and stains are manufactured products; many of the products obtain their coloring from mineral oxides. A variety of pigmented sealers are available, including acrylic, epoxy, and polyurethane products.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: PCC must be hauled from the mixing plant. The mixing plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and consolidate the PCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water. Wet sludge from sawcutting operations also needs to be contained and disposed of properly.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Pigmented PCCP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by pigmented PCCP

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Pigmented PCCP can be crushed for use as an unbound or stabilized material. Pigmented PCCP can also be rubblized in-place and covered with an overlay.

Other Environmental Considerations: Light-colored PCCP can be used to reduce surface heat reflectivity and roadway lighting needs. For PCCP, tire/road noise is typically moderate to high with a higher noise level than HACP. The potential for tire/road noise is increased for high speed roadways. The type of surface texturing can affect tire/road noise levels.

AESTHETICS

Appearance: Pigmented PCCP can be a highly decorative surfacing. Numerous colors are available; earth tones such as red, brown, green, and tan (and numerous variations) are most common. Pigmented PCCP can be used to blend in with the surrounding environment (earth tone colors in a wilderness area) or to contrast the surrounding environment (e.g. pedestrian crosswalk, fire lane, or handicap parking area colored in bright, contrasting colors), depending on the application and designer's intent.

Appearance Degradation Over Time: Over time, some color wear and fading is possible. For surface coatings, non-uniform wear is possible and will expose the underlying PCC color. Additional applications of colored surface coating can be used to maintain the appearance of the surface. When the entire PCCP surfacing layer is colored by pigment, surface wear will not affect the color. Surfaces can also become discolored by tire marks and oil leakage. Pigmented crack sealants and patching products must be used for preventative and corrective maintenance to maintain the uniform appearance of the surfacing.
COST
Supply Price: \$2.20 to \$4.40/kg (\$1.00 to \$2.00/lb) for pigment only. **Supply+Install Price**: \$6.50 to \$105/m^2 (\$5.00 to \$80/yd^2) for pigment only.
EXAMPLE PROJECTS
Desert View Entrance Station, Grand Canyon National Park, AZ.
SELECT RESOURCES
American Concrete Institute, (248) 848-3700, www.aci-int.org. American Society of Concrete Contractors, (314) 962-0210, www.ascconline.org. Portland Cement Association, (847) 966-6200, www.cement.org.

POROUS PCCP

GENERAL INFORMATION

Generic Name(s): Porous Portland Cement Concrete Pavement (PCCP), Pervious Concrete Pavement, Porous Concrete

Trade Names: N/A

Product Description: Porous PCCP is a paved surface and subbase comprised of PCC and gravel or crushed aggregate, formed in a manner that results in a permeable surface. The various layers have the potential for stormwater detention. Stormwater that passes through the pavement may completely or partially infiltrate the underlying soil, the excess being collected and routed to an overflow facility through perforated underdrain pipes.

A typical porous concrete pavement consists of a porous concrete surface, a filter course, a reservoir course (designed to temporarily retain infiltrated water and for frost protection), and existing soil or subbase material. The top porous concrete layer is an open graded PCC, typically 100 to 150 mm (4 to 6 in.) thick, consisting of 12.5 to 19 mm (0.5 to 0.75 in.) diameter gravel or crushed aggregate and very little to no sand. Water and portland cement are added as in conventional PCC. Using little to no sand in the mixture creates an open cell structure (with about 15 to 25% air voids) that allows stormwater to flow through the concrete and into the base layers. The filter course is a 25 to 50 mm (1 to 2 in.) thick layer of 12.5 mm (0.5 in) crushed stone aggregate designed to provide filtration and stability for the reservoir course during placement of the porous concrete layer.

Porous concrete pavement helps to reduce the amount of untreated runoff discharging into storm sewers, rivers, and streams.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Concrete Pavement Association, 5420 Old Orchard Road, Suite A-100, Skokie, IL, 60077-1059, (847) 966-2272, www.pavement.com.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to Medium.

Restrictions:

Traffic: Porous concrete is not recommended for applications with significant heavy truck traffic.

Climate: The use of porous concrete in areas requiring intensive winter maintenance is limited, because of a risk of the pores clogging with winter road sanding material. Porous concrete is not recommended for windy climates where wind erosion would provide windblown sediment that can clog the porous concrete pores.

Weather: None.

Terrain: Porous concrete is not recommended for roadway gradients steeper than 5%; roadway gradients as flat as possible are desired so as to increase water residence time.

Soil Type: Porous concrete is mainly used in areas with permeable soils with an infiltration rate greater than 1.3 cm/hr (0.5 in./hr). Where soils have low permeability, the reservoir thickness should be increased to provide additional storage. With soils composed of clay or silt, additional drainage may be required.

Other: Depth to seasonal high groundwater levels and bedrock should be greater than 1.2 m (4 ft.).

Other Comments: Porous concrete use is usually limited to applications with drainage areas less than 6.1 hectares (15 acres). Porous concrete has mainly been used for low volume parking lots and roads and recreational areas.

DESIGN

SLC: N/A; Rigid pavements, such as porous concrete, are not designed using AASHTO SLC. Instead, pavement thickness is determined based on the following factors: modulus of subgrade reaction (k), modulus of rupture for the concrete, load transfer between joints, traffic loading, and other factors, such as drainage and reliability. Concrete pavement designs can be performed using the 1993 AASHTO Guide for Design of Pavement Structures or using the thickness design guides available through the American Concrete Pavement Association.

Other Design Values: Compressive strength: 20 to 30 MPa (2,900 to 4,350 psi).

Base/Subbase Requirements: The reservoir course (base) should be deep enough to provide sufficient water storage volume and provide frost protection if the soils are frost susceptible and in a climatic zone subject to freezing temperatures. Additional granular thickness, over and above that normally used in the design of rigid pavements, will be required.

Other Comments: The depth of the stone reservoir should be such that it drains completely within 72 hours. This allows the underlying soils to dry out between storms and also provides capacity for the next storm. If frost penetrates deeper than the thickness of the pavement and reservoir course, and the subgrade has potential for frost heaving, additional material should be added to the reservoir course to below the frost zone. The reservoir (base) course should be deep enough to provide sufficient water storage volume. A minimum residence time of 12 hours should be a target for the design storm to provide exfiltration for pollutants removal. Concerns about clogging of porous concrete pavements should be addressed at the design stage by reducing erosion and sediment runoff through strategic design and water retaining ground cover.

When fine-grained natural soils are present, a geosynthetic separation/filtration layer is typically placed at the bottom of the reservoir layer.

CONSTRUCTION

Availability of Experienced Personnel: Porous concrete pavement construction requires experienced contractors. Porous concrete is not a commonly used surfacing and experienced contractors are, in general, not widely available. Specialized concrete mix design will also be needed.

Materials: PCC is a mixture of aggregate, cementitious material, water, and additives used to help with production and paving and to improve durability. The filter course is constructed of 12.5 mm (0.5 in) diameter open graded crushed stone aggregate. The reservoir course is constructed of 37.5 to 75 mm (1.5 to 3 in.) diameter open graded crushed stone aggregate.

Equipment: Equipment required for PCCP construction includes: concrete mixing trucks for hauling PCC, construction forms for roadway edges and construction joints, water truck, grading equipment, compaction equipment, vibratory equipment, finishing equipment, and concrete saws (single or multiple gang). Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site.

Placement Process: If needed, the site is excavated to design subgrade depth and graded using light equipment to minimize compaction of the subgrade surface. If the subgrade soils are fine-grained, a geosynthetic separation/filtration layer is placed on the subgrade prior to construction of the reservoir layer. Then, the base reservoir and filtration layers are placed and compacted. After the base is constructed, the porous concrete surface layer can be placed. The concrete mix is discharged from mixing trucks and placed using automatic screeds or hand troweled. The concrete is lightly consolidated with vibrators and finished. The concrete should be cured in place for 4 to 7 days or until a minimum strength is achieved, depending on exposure conditions. To facilitate curing, curing compounds can be applied, wet burlap can be used, or insulated sheets can be used in low ambient temperatures. Control joints must be saw-cut/formed before the stress in the concrete exceeds the strength to minimize random cracking. The time available to saw/form joints varies depending on concrete mix properties and ambient weather conditions.

Weather Restrictions: Do not place porous concrete if it is raining or if temperatures are near or below freezing. The porous concrete needs to be protected from freezing during the initial curing period (4 to 7 days or until adequate strength is achieved). Do not place porous concrete on frozen base soils. Special precautions are necessary if porous concrete is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation). The aggregate base materials should not be constructed on wet or frozen soils.

Construction Rate: Typical porous concrete pavement construction rates can be up to 750 m^3/day (980 yd^3/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction and curing, so adequate traffic control is needed. Normal traffic loads can be allowed on the porous concrete surface after initial curing and once an adequate PCC strength is reached, typically after 7 or 14 days. Road surface striping may be performed after the lane is opened.

Other Comments: Water/cement ratios are critical components in successful porous concrete construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction by experienced personnel.

SERVICEABILITY

Reliability and Performance History: In the past, performance reliability of porous concrete pavements has been very low, with failure rates on the order of 75%. Failure has been caused by poor design, poor construction, heavy vehicle traffic, low permeability soils, and resurfacing with impermeable materials. There is now a better understanding of the construction and design features and reliability is improving.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical porous concrete design life is 20 years.

Ride Quality: Porous concrete pavement provides very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, faulting, spalling, clogging of pores.

Preservation Needs: Vacuum sweeping, followed by high pressure jet hosing to clean pores, should be performed periodically to clean out the concrete pores. Periodic crack and joint sealing is required.

SAFETY

Hazards: None.

Skid Resistance: When high quality aggregates are used, PCCP provide very good initial skid resistance. The use of lower quality aggregates leads to aggregate polishing at the surface that can reduce the skid resistance over time.

Road Striping Possible?: Yes.

Other Comments: Because porous concrete provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. Because porous concrete has an open structure, it can freeze sooner than conventional PCCP and so may be more of a hazard for winter driving. Porous concrete can significantly reduce water spray compared to conventional PCCP.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Porous concrete is constructed of PCC, which contains aggregate, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: PCC must be hauled from the concrete batch plant. The batch plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and consolidate the PCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water. Wet sludge from sawcutting operations also needs to be contained and disposed of properly. Significant excavation and disposal of existing soils may be required to install the reservoir and filter layers.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: The pavement surface is permeable, allowing infiltration of stormwater, which is temporarily stored in the reservoir course until it can infiltrate into the ground. Contaminants in the surface runoff that are not easily trapped or reduced can flow through the pavement structure and become a potential source of groundwater contamination. Therefore, porous concrete pavements are not recommended for areas near groundwater drinking supplies or other sensitive bodies of water. However, local infiltration of storm water is generally preferable to large stormwater collection and disposal systems.

Erosion: Porous concrete is a bound material and is not susceptible to surface erosion.

Water quality: The filter layer below porous concrete removes particulate matter and so improves stormwater quality. However, if the surface water infiltrating the pavement surface contains contaminants that are not easily trapped or reduced, the contaminants will flow through the pavement structure and be introduced into the surrounding soil.

Aquatic species: Porous concrete does not impact aquatic species. However, porous concrete can be a pathway for contaminants to be introduced into nearby bodies of water. Therefore, porous concrete pavements are not recommended for areas near sensitive bodies of water.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Porous concrete can be crushed for use as an unbound or stabilized material. Porous concrete can also be rubblized in-place and covered with an overlay.

Other Environmental Considerations: Pre-treatment of stormwater is recommended where oil and grease or other potential groundwater contaminants are expected. The possible environmental benefits of porous concrete pavement include: removal of fine particulates and soluble pollutants through soil infiltration, attenuation of peak flows, reduction in the volume of runoff leaving the site and entering storm sewers, reduction in soil erosion, and groundwater recharge.

Light-colored porous concrete can be used to reduce surface heat reflectivity. Porous concrete pavements are less able to absorb and store heat than conventional PCCP (high air voids content reduces heat storage capacity). The open void structure in the porous concrete pavements allows cooler earth temperatures to cool the pavement. Porous concrete pavements typically reduce tire/road noise compared to conventional PCCP surfaces.

AESTHETICS

Appearance: Porous concrete typically has a coarse surface texture and light gray color. The appearance can be influenced by aggregate type and source, so visual aesthetics can be improved by using select aggregates, when available. Surface appearance can also be modified by using pigments or stains to color the concrete.

Appearance Degradation Over Time: The porous concrete surface will maintain its general appearance throughout its service life.
COST
Supply Price: N/A **Supply+Install Price**: \$44 to \$70/m^2 (\$37 to \$59/yd^2).
EXAMPLE PROJECTS
Local Streets, Indian Rocks Beach, FL.
SELECT RESOURCES
U.S. Environmental Protection Agency (1999). *Stormwater Technology Fact Sheet: Porous Pavement*, EPA 832-F-99-023, U.S. EPA, Office of Water, Washington, D.C., 6 pp.

STAMPED PCCP

GENERAL INFORMATION

Generic Name(s): Stamped Portland Cement Concrete Pavement (PCCP), Stamped Concrete, Pattern Imprinted Concrete

Trade Names: N/A

Product Description: Portland cement concrete (PCC) is a mixture of aggregate, cementitious material, and water that forms a rigid, paved surfacing. Additives are used to help with production and paving and to improve durability. Typical additives include air entraining admixture, water reducing agents, and supplementary cementitious materials (e.g. fly ash, ground blast furnace slag, silica fume, and calcinated clay). Concrete pavements are designed and constructed as plain concrete, plain concrete with dowelled joints or as continuously reinforced. Stamped PCCP are typically used in low traffic volume applications and so would typically be plain concrete construction. PCCP have very good performance characteristics with respect to strength, durability, and ride quality.

In stamped concrete, the surface of freshly placed PCC is patterned to resemble brick, slate, flagstone, tile, stone, or other traditional materials. The stamped concrete surface is covered with a coating product consisting of cement-modified acrylic resins and/or epoxy-based polymers and a blend of aggregates. The coating system can be designed to provide a wide range of colors and textures.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Society of Concrete Contractors, 2025 S. Brentwood Blvd., Saint Louis, MO 63114, (314) 962-0210, www.ascconline.org.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High (less than 1200 AADT).

Restrictions:

Traffic: Stamped concrete is not recommended for heavy industrial loading applications (i.e. slow moving trucks, frequent braking, etc.). Stamped concrete is not recommended for high speed traffic applications because the imprinted pattern can create a rough surface.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: Stamped concrete is mainly used for decorative purposes, since it simulates a wide range of other, more expensive, pavement types, such as flagstones, brick pavers, etc. Stamped concrete has been used most frequently in areas with high pedestrian traffic.

DESIGN

SLC: N/A; Rigid pavements, such as stamped PCCP, are not designed using AASHTO SLC. Instead, pavement thickness is determined based on the following factors: modulus of subgrade reaction (k), modulus of rupture for the concrete, load transfer between joints, traffic loading, and other factors, such as drainage and reliability. Concrete pavement designs can be performed using the 1993 AASHTO Guide for Design of Pavement Structures or using the thickness design guides available through the American Concrete Pavement Association.

Other Design Values: Compressive strength: 20 to 50 MPa (2,900 to 7,250 psi)

Base/Subbase Requirements: Subgrade and base materials should be compacted and graded to provide a stable working surface prior to PCCP placement. Base/subbase should consist of unbound or stabilized granular material with sufficient drainage characteristics. The base thickness should be a minimum of 100 mm (4 in.) In high traffic volume applications, open graded base is frequently used as a drainage medium to prevent pumping at the joints.

Other Comments: A properly designed joint pattern is necessary to prevent random slab cracking, except for continously reinforced PCCP (CRCP).

CONSTRUCTION

Availability of Experienced Personnel: PCCP is a commonly used surfacing and experienced contractors are, in general, widely available. Certified stamped concrete installers are available locally in most large urban areas and regionally in more remote areas. Availability may be limited for projects in remote areas.

Materials: PCC is a mixture of aggregate, cementitious material, water, and additives used to help with production and paving and to improve durability. Steel reinforcing bars are used for crack control of CRCP and dowels for transferring wheel loads between slabs. The surface coating applied to the stamped surface is composed of cement-modified acrylic resins and/or epoxy-based polymers, and a blend of aggregates.

Equipment: Equipment required for PCCP construction includes: concrete mixing trucks for hauling PCC, construction forms for roadway edges and construction joints, concrete paver, water truck, vibratory equipment, imprinting templates, finishing equipment, and concrete saws (single or multiple gang). Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site.

Placement Process: The concrete mix is discharged from mixing trucks and placed using automatic screeds or hand troweled. The concrete is consolidated with vibrators to increase density and reduce voids. Thermal expansion joints are constructed at predetermined intervals. Before the PCC sets, the imprinting templates, constructed of specially woven wire cable welded to a desired pattern, are placed on the PCC surface and pressed into the concrete using standard compaction equipment. The imprint depth is typically 9 mm (0.375 in.). The template is then removed from the PCCP surface and the process is repeated for the next area. Once the stamped concrete is imprinted and allowed to set, a surface coating, consisting of a release agent and clear seal, or cement-modified acrylic resins, or epoxy-based polymers and a blend of fine aggregates, is applied to the surface to seal the surface, add color, and improve surface performance characteristics. The concrete should be cured in place for 4 to 7 days or until a minimum strength is achieved, depending on exposure conditions. Control joints must be saw-cut/formed before the stress in the concrete exceeds the strength to minimize random cracking. The time available to saw/form joints varies depending on concrete mix properties and ambient weather conditions.

Weather Restrictions: Do not place PCC if it is raining or if temperatures are near or below freezing. The PCCP needs to be protected from freezing during the initial curing period (4 to 7 days or until adequate strength is achieved). Do not place PCC on frozen base/subgrade soils. Special precautions are necessary if PCC is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation). The surface coating should not be applied if it is raining or if rain is expected within 2 hours of coat application. Air temperatures should be above 10 ºC (50 ºF) at the time the surface coating is applied and for at least 8 hours after the coating is applied.

Construction Rate: Typical stamped concrete construction rates can be 335 to 500 m^2/day (400 to 600 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction and curing, so adequate traffic control is needed. Normal traffic loads can be allowed on the PCCP surface after initial curing and once an adequate PCC strength is reached, typically after 7 or 14 days. Road surface striping may be performed after the lane is opened.

Other Comments: Water/cement ratios are critical components in successful PCCP construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction.

SERVICEABILITY

Reliability and Performance History: PCCP is a very common roadway surfacing and has been used on roadway projects for more than 100 years; an extensive amount of research, design and construction information, and project experience is available. Stamped concrete is a relatively new surfacing, emerging as a surfacing alternative within the past 15 years. Design and construction information and extensive project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical stamped concrete design life is 30 to 40 years, depending on traffic.

Ride Quality: Stamped concrete provides fair to good ride quality after construction, depending on the imprint pattern. Ride quality deteriorates over the serviceable life, partially due to cracking and faulting at the PCCP joints.

Main Distress / Failure Modes: Cracking, faulting, spalling, color fading.

Preservation Needs: In general, PCCP require relatively little preventative maintenance. Jointed PCCP require periodic joint resealing. Depending on the type of sealant used, resealing may be required every 5 to 10 years. Color coating needs to be reapplied every 3 to 5 years.

SAFETY

Hazards: Adequate surface grading and surface texture are required to prevent ponding of water on the surface that can cause reduced traction due to hydroplaning and icing. Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: When high quality aggregates are used, PCCP provide very good initial skid resistance. The use of lower quality aggregates leads to aggregate polishing at the surface that can reduce the skid resistance over time. Surface coatings can obscure the natural aggregate texture and can create slippery surface conditions; however, some coatings include skid resistant materials that provide good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Stamped concrete is constructed of PCC, which contains coarse and fine aggregates, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture. Reinforced PCCP contains reinforcing bars that are manufactured from steel. The color coating is a manufactured product composed of cement modified acrylic and/or epoxy-based coloring.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: PCC must be hauled from the concrete batch plant. The batch plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and compact the PCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water. Wet sludge from sawcutting operations also needs to be contained and disposed of properly.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Stamped concrete is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by stamped concrete.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Stamped PCC can be crushed for use as an unbound or stabilized material. Stamped concrete can also be rubblized in-place and covered with an overlay.

Other Environmental Considerations: Light-colored stamped concrete can be used to reduce surface heat reflectivity. For stamped concrete, tire/road noise is typically moderate to high with a higher noise level than conventional PCCP and HACP.

AESTHETICS

Appearance: Stamped concrete can be a highly decorative surfacing. Numerous different patterns (e.g. brick, slate, flagstone, tile, stone, etc.) and colors are available to choose from. Stamped concrete can be used to blend in with the surrounding environment (e.g. slate or rock pattern, colored in earth tones, in a wilderness area) or to contrast the surrounding environment (e.g. pedestrian crosswalk, fire lane, or handicap parking area colored in bright, contrasting colors), depending on the application and designer's intent.

Appearance Degradation Over Time: Over time, some color and pattern wear is possible. Additional applications of color coating can be used to maintain the appearance of the surface. Surfaces can also become discolored by tire marks and oil leakage. Over time it is not uncommon for cracks to develop that will require crack sealing.

COST

Supply Price: N/A

Supply+Install Price: \$70 to \$86/m^2 (\$59 to \$72/yd^2).

EXAMPLE PROJECTS

Bear Lake Parking Lot, Rocky Mountain National Park, CO.

SELECT RESOURCES

American Concrete Institute, (248) 848-3700, www.aci-int.org.
American Society of Concrete Contractors, (314) 962-0210, www.ascconline.org.
Portland Cement Association, (847) 966-6200, www.cement.org.

ROLLER COMPACTED CONCRETE

GENERAL INFORMATION

Generic Name(s): Roller Compacted Concrete (RCC)

Trade Names: N/A

Product Description: Roller compacted concrete (RCC) is constructed of zero-slump (i.e. very stiff) concrete using traditional asphalt paving equipment. RCC does not require steel reinforcing, joints, dowel bars, or forms. RCC possesses most of the benefits of conventional portland cement concrete pavement (PCCP), but has a lower cost and shorter construction time. RCC has mainly been used in low-speed, heavy-duty pavement applications.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Concrete Pavement Association, 5420 Old Orchard Road, Suite A-100, Skokie, IL, 60077-1059, (847) 966-2272, www.pavement.com.

APPLICATION

Typical Use: Road surfacing. RCC is also used for industrial storage areas and loading yards.

Traffic Range: Very Low to High.

Restrictions:

Traffic: Roller compacted concrete can be designed to support a wide range of traffic loading conditions; it is frequently used for heavy duty industrial pavements. RCC is normally limited to low speed traffic applications with speeds less than about 60 km/hr (37 mph). RCC can be used for medium to high speed applications if high density paving machines are used or a surface treatment is applied to improve smoothness and skid resistance.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: N/A; Rigid pavements, such as RCC, are not designed using AASHTO SLC. Instead, pavement thickness is determined based on the following factors: modulus of subgrade reaction (k), modulus of rupture for the concrete, load transfer between joints, traffic loading, and other factors, such as drainage and reliability. The Portland Cement Association has guides available for RCC pavement design.

Other Design Values: Compressive strength: 28 to 69 MPa (4,000 to 10,000 psi).

Base/Subbase Requirements: Subgrade and base materials should be compacted and graded to provide a stable working surface prior to RCC placement.

Other Comments: Typical design RCC thicknesses on projects have ranged from 150 to 500 mm (6 to 20 in.)

CONSTRUCTION

Availability of Experienced Personnel: Contractors experienced in RCC construction are generally available on a regional level. In many areas, contractor availability may be limited and require mobilization of a work crew and equipment from a distant location.

Materials: RCC construction requires zero-slump (i.e. very stiff) PCC.

Equipment: Equipment required for RCC road construction includes: rear dump trucks for hauling RCC, asphalt concrete paver modified for RCC placement, water truck, smooth drum vibratory roller, and rubber tire roller. Equipment is widely available in most areas, but availability may be limited in remote areas. To reduce haul distances, batch plants have been set up on site.

Manufacturing/Mixing Process: RCC can be mixed at a central mix plant and hauled to the site or a batch plant can be set up on site. RCC requires vigorous mixing due to the low water content in the concrete mixture.

Placement Process: RCC is placed using an asphalt concrete paver. After placement, the RCC is compacted using a smooth drum vibratory roller. Vibratory compaction can be followed by several passes of a rubber tire roller to smooth out any surface voids or fissures. RCC placement and compaction generally must occur within 45 to 90 minutes after the point that water is initially added to the mixture at the plant. Moist curing is used on most projects after RCC placement, normally for a minimum of 7 days. A water truck or irrigation sprinkler system is used to keep the RCC surface moist with a fine mist. A thin asphalt surface treatment can be applied to the RCC surface to prevent moisture loss during curing.

Weather Restrictions: Do not place RCC if it is raining or if temperatures are near or below freezing. The RCC needs to be protected from freezing during the initial curing period (4 to 7 days). Do not place RCC on frozen base/subgrade soils. Special precautions and moist curing conditions are necessary if RCC is placed in high temperature conditions.

Construction Rate: Typical RCC construction rates can be on the order of 770 m^3/day (1,000 yd^3/day).

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control or temporary traffic diversion is needed. In some instances, the RCC surface has been opened to light traffic as soon as it is constructed. Normal traffic loads can be allowed on the RCC surface after initial curing and once an adequate RCC strength is reached, typically after 7 days. Road surface striping may be performed after the lane is opened.

Other Comments: Compaction and moisture content are critical components in successful RCC construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction.

SERVICEABILITY

Reliability and Performance History: RCC was first used for traffic applications for the forest industry in the late 1970s. RCC use expanded to industrial pavement and roadway applications in the 1980s. Although using RCC for road surfacing applications is still relatively new, a fair amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical RCC design life is 20 to 30 years.

Ride Quality: Traditionally, RCC ride quality has been fair and inferior to most paved surfaces. RCC generally has a rough surface finish since the low slump makes it difficult to compact uniformly, leading to irregularities and only a fair ride quality. This smoothness level is usually adequate for low-speed applications. Since the 1990s, RCC pavements with excellent ride quality have been constructed using high density asphalt paving machines (i.e. paving machines with modified screeds using dual tamping bars to achieve higher densities, commonly used in Europe). Another option for improving ride quality is to construct a thin asphalt concrete layer or asphalt surface treatment on the RCC surface. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, surface erosion.

Preservation Needs: In general, RCC requires relatively little preventative maintenance. Cracking has little impact on RCC performance. For large cracks, periodic crack sealing may be required.

SAFETY

Hazards: Adequate surface grading is required to prevent ponding of water on the surface that can cause reduced traction and hydroplaning.

Skid Resistance: RCC surfaces exhibit poor to marginal skid resistance, limiting their use to low-speed applications. The use of high density paving machines results in a smoother surface with better skid resistance, allowing RCC to be used for some moderate to high speed applications.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: RCC is constructed of PCC, which contains coarse and fine aggregates, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture. Portland cement is manufactured from limestone.

Delivery and Haul Requirements: If a batch plant is not set up on site, RCC must be hauled from the mixing plant. The mixing plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and compact the RCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: RCC is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by RCC roadways.

Erosion: During the first 2 to 3 years after RCC construction, erosion of fine surface materials occurs due to traffic and weathering. The surface erosion is limited to the top 2 mm (0.08 in.) of the RCC. The surrounding environment can be subjected to this eroded material, but the impact should be negligible.

Water quality: RCC has a minimal impact on water quality. Water quality could be affected by sediment loading from material eroded from the RCC surface.

Aquatic species: None.

Plant quality: None.

Air Quality: RCC does not have a long-term impact on air quality. Some dust generation can occur under heavy traffic, especially if a paste-rich surface is produced.

Other: None.

Ability to Recycle/Reuse: RCC can be crushed for use as an unbound or stabilized material.

Other Environmental Considerations: Light-colored RCC can be used to reduce surface heat reflectivity. For RCC, tire/road noise is typically moderate to high with a higher noise level than HACP. However, it does not have the noise problem created by joints in conventional PCCP.

AESTHETICS

Appearance: RCC has a relatively rough texture and appearance and light gray color. The surface color can be modified using pigments or stains to color the RCC.

Appearance Degradation Over Time: Some surface erosion and raveling can occur over time. However, RCC will maintain its general appearance throughout its serviceable life.

COST

Supply Price: N/A

Supply+Install Price: \$55 to \$70/m^3 (\$46 to \$59/yd^3).

EXAMPLE PROJECTS

Bighorn Avenue, Alliance, NE.
Los Tomates Border Station, Brownsville, TX.

SELECT RESOURCES

Portland Cement Association, (847) 966-6200, www.cement.org.

ACI Committee 325 (1995). *State-of-the-Art Report on Roller-Compacted Concrete Pavements*, ACI 325.10R-95, American Concrete Institute, 32 pp.

Portland Cement Association (1987). *Structural Design of Roller-Compacted Concrete for Industrial Pavements*, Portland Cement Association, 8 pp.

Piggott, R.W. (1999). *Roller Compacted Concrete Pavements: A Study of Long Term Performance*, Portland Cement Association, 62 pp.

WHITETOPPING

GENERAL INFORMATION

Generic Name(s): Portland Cement Concrete Whitetopping, Whitetopping, Ultrathin Whitetopping (UTW)

Trade Names: N/A

Product Description: Whitetopping is a pavement rehabilitation technique that involves construction of a portland cement concrete (PCC) overlay or inlay on top of hot asphalt concrete pavement (HACP). Three different types of whitetopping are commonly used in construction: conventional whitetopping, thin whitetopping, and ultrathin whitetopping (UTW). Conventional whitetopping is a PCC overlay or inlay, typically at least 200 mm (8 in.) thick, placed over an existing asphalt concrete surface. Conventional whitetopping does not rely on bonding with the HACP layer and no special treatment of the HACP layer is required. Thin and ultrathin whitetopping rely on bond development between the PCC overlay or inlay and the existing HACP; by creating a bond between the two layers, the existing HACP layer provides significant structural support and allows for the whitetopping overlay thickness to be reduced. Thin whitetopping typically has a thickness of 100 to 200 mm (4 to 8 in.). UTW typically has a thickness of 50 to 100 mm (2 to 4 in.). For thin and ultrathin whitetopping, joint spacing is reduced compared to conventional whitetopping.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: American Concrete Pavement Association (ACPA), 5420 Old Orchard Road, Suite A-100, Skokie, IL, 60077-1059, (847) 966-2272, www.pavement.com.

APPLICATION

Typical Use: Road surfacing, typically for road rehabilitation projects.

Traffic Range: Very Low to High.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Whitetopping is not recommended for applications where the existing asphalt concrete is badly deteriorated or when substantial portions of the asphalt concrete have to be removed during rehabilitation. Whitetopping should also be avoided when the asphalt concrete has material problems, such as asphalt stripping.

Other Comments: UTW is used primarily where rutting is a recurring problem in existing asphalt concrete surfaces or to add carrying capacity to existing asphalt sections.

DESIGN

SLC: N/A; Rigid pavements, such as conventional PCC whitetopping, are not designed using AASHTO SLC. Instead, the whitetopping thickness is determined based on the following factors: modulus of subgrade reaction (k_s) and the thickness of the granular and asphalt layers. Easy to use design charts and tables are available from the American Concrete Pavement Association ("Whitetopping – State of the Practice", Engineering Bulletin EB210.02)

Since UTW is a relatively new surfacing, design procedures are still being developed that adequately incorporate the bonding effect between the whitetopping overlay and the asphalt concrete.

Other Design Values: None.

Base/Subbase Requirements: It is recommended that whitetopping be placed over an asphalt concrete layer with a thickness of at least 75 mm (3 in.) after milling.

Other Comments: A properly designed joint pattern is necessary to prevent random slab cracking. Typical joint spacing for UTW is between 0.6 and 1.5 m (2 and 5 ft). As a rule of thumb, the recommended maximum joint spacing is 12 to 15 times the overlay thickness. By reducing the joint spacing, slab bending is reduced. As a result, stresses in the whitetopping overlay are mainly compressive instead of flexural in nature.

CONSTRUCTION

Availability of Experienced Personnel: Whitetopping is becoming a commonly used surfacing and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.

Materials: PCC is a mixture of aggregate, cementitious material, water, and additives used to help with production and paving and to improve durability. Concrete with a 28-day compressive strength of 30 MPa (4,000 psi) is normally used. Welded wire mesh or bar mats can be used for internal strengthening of the whitetopping and dowels can be included for transferring wheel loads between slabs. Several types of fiber reinforcement may be used, especially for UTW.

Equipment: Equipment required for PCC whitetopping construction includes: concrete mixing trucks for hauling PCC, construction forms for roadway edges and construction joints, concrete paver, water truck, vibratory equipment, and finishing equipment (e.g. burlap drag, tining comb). Continuous slip form concrete pavers are used on high productivity or very large projects. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: PCC can be mixed at a central mix plant and hauled to the site or a mobile concrete batching plant can be set up on site.

Placement Process: Prior to PCC placement, cold milling of the existing asphalt concrete surface is required for thin and ultrathin whitetopping. The milled surface should be thoroughly cleaned of loose material prior to PCC placement to ensure a good bond between the overlay and the milled surface. Whitetopping placement is similar to conventional PCCP. The concrete mix is discharged from mixing trucks and placed using vibrating screeds or hand troweled. On large projects, continuous slip form concrete pavers can be used. The concrete is consolidated with vibrators to increase density and reduce voids. Load transfer across joints is provided by aggregate interlock, or by the installation of dowel bars, for heavier traffic loading. In general, whitetopping is built using plain, unreinforced concrete. However, the use of fiber reinforcement can allow longer joint spacing to be utilized. The surface can be textured to improve skid resistance. The concrete should be cured in place for 4 to 7 days, depending on exposure conditions. To facilitate curing, curing compounds can be applied, or wet burlap can be used, or insulated sheets in low ambient temperatures. The joints can be formed by sawing, tooling, or by using inserts. Sawing within 4 to 12 hours of concrete placement is the most common method for joint construction.

Weather Restrictions: Do not place PCC if it is raining or if temperatures are near or below freezing. The whitetopping needs to be protected from freezing during the initial curing period (4 to 7 days). Special precautions are necessary if PCC is placed when temperatures are above about 35 ºC (94 ºF) or during high winds (rapid evaporation).

Construction Rate: Typical whitetopping construction rates can be up to 1,500 m^3/day (1,800 yd^3/day). Due to the large number of sawed joints, particularly for UTW, care should be taken not to place any more pavement than can reasonably be sawed in a day.

Lane Closure Requirements: The roadway lane being constructed is closed during construction and curing, so adequate traffic control is needed. Normal traffic loads can be allowed on the whitetopping surface after initial curing and once an adequate PCC strength is reached, typically after about 3 days. High strength PCC can be used to achieve design concrete strengths faster, so the road surfacing can be opened to traffic sooner, as soon as eight hours after placement. Road surface striping may be performed after the lane is opened.

Other Comments: Water/cement ratios are critical components in successful whitetopping construction projects and should be monitored closely. Construction defects are generally difficult to repair. Mix designs and trial mixes should be prepared in advance of construction.

SERVICEABILITY

Reliability and Performance History: Conventional whitetopping is a common roadway surfacing and was first used in 1918. Thin whitetopping and ultrathin whitetopping are relatively new surfacings; they were first used in the early 1990s. However, thin and ultrathin whitetopping have been used on numerous projects since their development. An extensive amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, original asphalt pavement support, environmental conditions, and traffic volumes. Typical conventional whitetopping serviceable lives are 20 to 30 years. Typical UTW serviceable lives are estimated at 5 to 15 years.

Ride Quality: Whitetopping provides very good ride quality after construction. Ride quality deteriorates over the serviceable life, partially due to cracking and faulting at the whitetopping joints.

Main Distress / Failure Modes: Cracking, faulting, popouts, spalling.

Preservation Needs: In general, whitetopping requires relatively little preventative maintenance. Joints may require periodic joint resealing. Depending on the type of sealant used, resealing may be required every 5 to 10 years. Many agencies do not seal whitetopping joints. Surface grinding may be required to maintain good frictional characteristics.

SAFETY

Hazards: Adequate surface grading and surface texture are required to prevent ponding of water on the surface that can cause reduced traction due to hydroplaning and icing. Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: When high quality aggregates are used, whitetopping provides very good initial skid resistance. The use of lower quality aggregates leads to aggregate polishing at the surface that can reduce the skid resistance over time. Surface grinding or texturing can be used to increase the skid resistance of the whitetopping surface.

Road Striping Possible?: Yes.

Other Comments: Because PCCP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding. Surface texturing is often used to increase the skid resistance of whitetopping and decrease the level of vehicle skidding and hydroplaning. The type, spacing, width, and depth of the texturing affects skid resistance and tire/road noise. Numerous surface texturing options are available, including drag textures (broom, artificial turf, burlap), tine textures (transverse, longitudinal), exposed aggregate textures, and hardened concrete textures (diamond ground, diamond groove, abrated). For local roads where hydroplaning is not a primary concern, burlap or broom textures are commonly used. For high speed applications, such as highways, transverse tine texturing is the most commonly used texturing. Transverse tining provides a good, durable, skid resistant surface, reduces road splash/spray, reduces headlight glare from wet surfaces, reduces hydroplaning potential, and facilitates surface drainage.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Whitetopping is constructed of PCC, which contains coarse and fine aggregates, portland cement, water, and, sometimes, chemical admixtures. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used. Fly ash, ground blast furnace slag, and silica fume, which are waste by-products, are sometimes included in the concrete mixture. Reinforced whitetopping may contain reinforcing bars that are manufactured from steel or synthetic fibers that are derived from various plastics.

Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: PCC must be hauled from the mixing plant. The mixing plant must be located near the site because a limited amount of time (i.e. 90 minutes or less) is available after mixing to deliver, place, and consolidate the PCC.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Wash water from concrete equipment can damage vegetation and water quality; settling basins or designated wash out pits should be utilized to collect and contain the wash water. Wet sludge from sawcutting operations also needs to be contained and disposed of properly.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Whitetopping is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by whitetopping.

Erosion: Whitetopping is a bound material and is not susceptible to surface erosion.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Whitetopping can be crushed for use as an unbound or stabilized material. Because thin and ultrathin whitetopping are relatively recent technologies, the full range of recycling options are not known.

Other Environmental Considerations: Light-colored whitetopping can reduce surface heat reflectivity. For whitetopping, tire/road noise is typically similar to conventional PCCP; noise is moderate to high with a higher noise level than HACP. Surface texturing can reduce tire/road noise.

AESTHETICS

Appearance: Whitetopping typically has a smooth surface texture and light gray color. The close spacing of sawn joints, as close as 0.6 m (2 ft.), in the ultrathin whitetopping,c produces a distinctly different surface appearance from conventional PCCP. The appearance can be influenced by aggregate type and source, so visual aesthetics can be improved by using select aggregates, when available. Surface appearance can also be modified by using pigments or stains to color the concrete or finishing techniques to change the surface texture.

Appearance Degradation Over Time: Whitetopping will maintain its general appearance throughout its service life.

COST
Supply Price: N/A **Supply+Install Price**: \$15.60 to \$19.10/m^2 (\$13.00 to \$16.00/yd^2) for UTW, 50 mm (2 in.) thick. \$24.00 to \$32.30/m^2 (\$20.00 to \$27.00/yd^2) for thin whitetopping, 127 to 178 mm (5 to 7 in.) thick. \$36.00/m^2 (\$30.00/yd^2) for conventional whitetopping, 200 mm (8 in.) thick.
EXAMPLE PROJECTS
Interstate I-20, near Bolton, MS. U.S. Highway 169 and Webster Street, North Mankato, MN.
SELECT RESOURCES
American Concrete Pavement Association, (847) 966-2272, www.pavement.com. Smith, K.D., Yu, H.T., and Peshkin, D.G. (2002). *Portland Cement Concrete Overlays: State of the Technology Synthesis*, FHWA-IF-02-045, Federal Highway Administration, Washington, D.C., 190 pp.

AGGREGATE AND SOIL SURFACES

UNBOUND AND MECHANICALLY STABILIZED SURFACINGS

CELLULAR CONFINEMENT

GENERAL INFORMATION

Generic Name(s): Cellular Confined Aggregate, Geocell, Cellular Confinement System

Trade Names: Geoweb, Hyson Cells

Product Description: Cellular confined aggregate, sometimes referred to as geocells, are constructed with a geosynthetic product that forms a honeycomb-like cellular structure that is infilled with aggregate to create a stabilized aggregate layer. Cellular confined aggregate improves the load distribution characteristics of the granular material due to the reinforcement provided by the geosynthetic, the passive resistance of material in adjoining cells, and the transfer of vertical stresses to adjoining cells. High friction values between the infill material and cell walls are developed by the use of geocells with textured or perforated walls. Perforated wall geocells have the added advantage of allowing lateral drainage through the granular layer, which is beneficial when the cellular confined aggregate is founded on low permeability, cohesive soil.

Product Suppliers: GeoProducts, LLC, 8615 Golden Spike Lane, Houston, TX 77086, (281) 820-5493, www.geoproducts.org; and

Presto Products Company, P.O. Box 2399, Appleton, WI 54912-2399, (800) 548-3424, www.prestogeo.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and geocell products are available.

APPLICATION

Typical Use: Soil reinforcement, road surfacing.

Traffic Range: As a reinforced base, cellular confined aggregate can be used for Very Low to High traffic volume applications. As a road surfacing, cellular confined aggregate can be used for Very Low to Medium traffic volume applications.

Restrictions:

Traffic: None.

Climate: None; however, use in wet and/or cold climates will lead to more frequent deterioration and more frequent maintenance.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: Cellular confined aggregate can be used to reduce the required granular layer thickness in a roadway design, allow the use of locally available marginal materials, or reduce the maintenance requirements of a gravel road over its design life. Depending on the infill material used, geocells can support grass growth where a more natural appearance is desired.

DESIGN

SLC: 0.35 (geocell with granular infill).

Other Design Values: None.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support. For low volume applications, geocells can be constructed directly on the subgrade unless heavy loads dictate the need for greater subbase/subgrade support. Subgrade and base materials should be compacted and graded to provide a uniform working platform prior to geocell placement. When built over fine-grained, cohesive soils, a nonwoven geotextile is placed on the subgrade surface as a separation layer to prevent the migration of fines into the cellular confined aggregate.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of the reinforced materials, although the infill materials are usually quite permeable. Cellular confined aggregate can be constructed with a thickness of 100 to 200 mm (4 to 8 in.). Lower quality granular materials can be used for applications where driving speeds are slow and ride quality is not critical. High quality granular materials should be used for roads that have higher driving speeds and ride quality is more important. Cellular confined aggregate is usually covered with a surface course. A minimum of 50 mm (2 in.) of dense graded crushed granular material that has good rut resistance is recommended as a surface course above the cellular confined aggregate. If a HACP layer is used for road surfacing, a minimum of 25 mm (1 in.) of cover aggregate over the geocells is recommended.

CONSTRUCTION

Availability of Experienced Personnel: Cellular confined aggregate is not a commonly used surfacing, but the installation is relatively simple. Qualified contractors are, in general, locally available in large urban areas and regionally available in remote areas.

Materials: The geocell geosynthetic product and aggregate are required for construction of cellular confined aggregate. Aggregate infill material should be granular with a maximum particle size of 50 mm (2 in.). The aggregate material should have less than 10% fines content and a plasticity index below 6.

Equipment: Equipment required for cellular confined aggregate construction includes: backhoe, excavator, or front-end loader, grading equipment, and compaction equipment. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: N/A

Placement Process: The geocell sections are placed on the prepared subgrade/base, stretched out to their design length, and staked to hold the sections in place. If the geocell sections are placed on a fine-grained material, a nonwoven geotextile should be placed prior to the geocell sections to act as a separation layer to prevent aggregate/subgrade mixing. Adjacent geocell sections are laid out and connected with adjoining sections. Once the geocell sections are in place, the geocells are infilled with aggregate. When infilling, the aggregate drop height should be less than 0.9 m (3 ft.). The geocell sections should be overfilled by 25 to 50 mm (1 to 2 in.) to allow for settling and compaction. The infill material is then compacted using tamping equipment. The cover aggregate can then be placed, compacted, and graded.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the soil is frozen.

Construction Rate: Cellular confined aggregate construction rates are in the range of 200 to 400 m^2/day (240 to 480 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction, but can be opened to traffic once construction is complete.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Cellular confined aggregate was developed by the U.S. Army Corps of Engineers in the late 1970s. Cellular confined aggregate has been used on a variety of projects, but it is not a commonly used surfacing material. Research, design and construction information, and project experience are available.

Life Expectancy: Life expectancy varies depending on traffic, subgrade support, and weather conditions. Cellular confined aggregate should not be used as a permanent surfacing material; some aggregate cover is required to protect the geocells from traffic abrasion. Typical life expectancy for cellular confined aggregate, assuming that an aggregate surface course is placed over the cellular confined aggregate, is expected to be 15 to 20 years. However, considerably longer lives are possible with regular maintenance.

Ride Quality: Cellular confined aggregate can provide fair to good ride quality if a thin aggregate surface course is placed over the geocells. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Surface erosion, aggregate/subgrade mixing (that effectively reduces the aggregate thickness providing structural support), edge failures.

Preservation Needs: When covered with a surface course, the cellular confined aggregate layer generally does not require maintenance. The aggregate surface course will require periodic grading (typically every 6 months) and the periodic placement of additional aggregate (typically every 1 to 2 years).

SAFETY

Hazards: Loose aggregate can create a windshield hazard. Large quantities of fugitive dust, which reduces driver visibility, can be produced by untreated surfacings during dry weather conditions.

Skid Resistance: Unbound gravel/aggregate road surfacings can provide poor to good skid resistance, depending on the type of aggregate and gradation. Hard, durable crushed aggregates can provide good skid resistance. The wearing course must also be well graded and compacted to reduce the amount of loose particles on the surface that can reduce skid resistance.

Road Striping Possible?: No.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Geocells are manufactured from polypropylene. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Geocells must be transported to the site from the distributor. Geocell sections collapse into a compact configuration to minimize the haul space required. Delivery distances may be significant for remote sites. If quality aggregates are not locally available, they must be transported to the site also.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: The amount of surface runoff will depend on the permeability of the surface material. Water infiltration into a dense, well-graded unbound wearing course that is adequately sloped will generally be small, with the majority of the water becoming surface runoff. However, if the surfacing is permeable, surface runoff will be reduced.

Erosion: Cellular confined aggregate helps to reduce erosion of poorly graded and compacted gravel/aggregate material. Dense, well-graded wearing course materials are generally less susceptible to erosion. Surface water control and management should be considered in the road design to minimize the potential for surface erosion.

Water quality: None. However, sediment loading from erosion of gravel/aggregate surfacings can possibly impact water quality. A buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles.

Aquatic species: None. However, sediment loading from erosion of gravel/aggregate surfacings can possibly impact aquatic species. A buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles.

Plant quality: None. However, dust generated from untreated gravel/aggregate surfacings can impact plant quality by covering the leaves and reducing the amount of sunlight received by the plant.

Air Quality: None. However, dust generated from untreated gravel/aggregate surfacings can have a long-term impact on air quality.

Other: None.

Ability to Recycle/Reuse: The aggregate infill can be reused as a construction material. Geocell geosynthetic material is not recyclable.

Other Environmental Considerations: Cellular confined aggregate is particularly useful on sections of gravel roads subject to periodic flooding or overtopping. The geocells help to retain the gravel infill from wash out.

AESTHETICS

Appearance: Cellular confined aggregate is typically covered with a wearing surface, so the geocell product does not alter the appearance of an aggregate material. The appearance will be of an aggregate surface with the overall color determined by the aggregate material type and source.

Appearance Degradation Over Time: Cellular confined aggregates do not experience appearance degradation over time. Without maintenance, unbound aggregate surfacings deteriorate over time in terms of surface uniformity.

COST

Supply Price: N/A

Supply+Install Price: \$36 to \$42/m^2 (\$30 to \$35/yd^2).

EXAMPLE PROJECTS

Overflow Parking Lot, Brazoria National Wildlife Refuge, Brazoria County, TX.
Stone Mountain Park, Stone Mountain, GA.

SELECT RESOURCES

Presto Products Company, www.prestogeo.com.

FIBER REINFORCEMENT

GENERAL INFORMATION

Generic Name(s): Fiber-Reinforced Soil, Fiber-Reinforced Sand

Trade Names: Geofibers

Product Description: Fiber reinforcement can be used to stabilize clays, sands, and sandy gravel soils. It can increase the shear strength, stiffness, and bearing capacity of the material being treated. Fibers can be natural or man made. Materials that have been used for fiber reinforcement include metallic, polypropylene, glass, wire, cellophane, straw, and hemp fibers. The fibers are mixed with the soil to create a uniformly reinforced soil mix with discrete, randomly oriented fibers. The soil is then placed and compacted. Typical fiber application rates are 0.1% to 0.5%, by weight. Fiber reinforcement improves the quality and suitability of soils as road making materials.

Product Suppliers: Fiber Reinforced Soil, LLC, P.O. Box 17455, Chattanooga, TN 37415, (423) 877-9550, www.fibersoils.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and fiber reinforcement products are available.

APPLICATION

Typical Use: Road surfacing, soil stabilizer.

Traffic Range: As a road surfacing, Very Low.

Restrictions:

Traffic: Fiber-reinforced soils should not be used as a surfacing for high speed traffic applications.

Climate: None; however, wet and/or cold climates will lead to more frequent deterioration and require more frequent maintenance.

Weather: Fiber-reinforced soils are very susceptible to adverse weather conditions. They will soften significantly in very wet weather and during periods of thaw.

Terrain: Fiber-reinforced soil surfaces should be limited to relatively flat terrains.

Soil Type: N/A

Other: Fiber-reinforced surfacings are highly susceptible to damage from snow plow operations.

Other Comments: None.

DESIGN

SLC: 0.05 to 0.20, Value will vary with soil type, fiber product, and application rate. Laboratory mixing should be performed to determine the strength of the stabilized material. Using laboratory strength testing results, an estimate of the SLC can be made using correlations or engineering judgment.

Other Design Values: Fiber reinforcement can increase the soil strength by 30% to 100% or more.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of unbound materials.

The strength and durability of fiber-reinforced soils is affected by the fiber type, length, diameter, and application rate and depth of treatment. Fiber reinforcement is also influenced by the soil type, percent fines, moisture content, and percent compaction. Typically, fines contents of up to 10% are preferred for granular surfacings. Polypropylene fibers are currently the most commonly used fiber type. Studies have shown that for sand soils, the optimum fiber length and application rate are 50 mm (2 in.) and 1% by weight, respectively. At application rates below 0.6%, the sand acts as a strain softening material; at application rates above 0.6%, fiber-reinforced sands behave as a strain hardening material.

A persistent performance problem with unbound surfaces is the generation of dust as the surface dries. Several dust suppression and stabilization products have been developed to reduce the amount of fugitive dust originating from the unbound surface. Many of these products also improve the strength and durability of the surfacing and reduce surface erosion. Use of dust suppressants in conjunction with fiber-reinforced soil is recommended.

CONSTRUCTION

Availability of Experienced Personnel: Fiber-reinforced soil is not a common road surfacing, so the availability of experienced contractors may be limited. However, the construction process is relatively straightforward and experienced soil stabilization contractors should be able to successfully construct fiber-reinforced soil surfacings, with guidance from the supplier's technical representative.

Materials: Fibers are the only material required. Materials that have been used for fiber reinforcement include metallic, polypropylene, glass, wire, cellophane, straw, and hemp fibers. Polypropylene is currently the most commonly used fiber type.

Equipment: Equipment required for fiber reinforcement construction includes: rotary mixer, grading equipment (i.e. bulldozer or motor grader), and compactor. Equipment is widely available in most areas.

Manufacturing/Mixing Process: If the unbound surfacing material is not already in place, fibers can be mixed with the material prior to shipment to the site.

Placement Process: The fibers are spread and mixed in situ with the unbound material using several passes of a rotary mixer to obtain a uniform mixture. Uniform mixing of the fibers into the unbound material becomes more difficult as the application rate is increased. Once mixing is complete, the surface is compacted and graded. The compactive effort required for fiber-reinforced soil may be slightly greater than for unreinforced soil.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the subgrade is saturated or frozen.

Construction Rate: Fiber reinforcement application rates are in the range of 2,000 to 4,000 m^2/day (2,400 to 4,800 yd^2/day).

Lane Closure Requirements: It is recommended that the roadway lane be closed during construction. The lane can be reopened once construction is completed.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Fiber reinforcement for road surfacings is a fairly new concept that has developed within the past 20 years. Only a limited amount of information is available on design and construction and project experience.

Life Expectancy: Life expectancy varies depending on traffic, surfacing material characteristics, fiber type and application rate, and weather conditions. Fiber reinforced surfacings will lose material annually due to erosion, mixing with subgrade, dust, and shoving. Regular maintenance and periodic applications of additional material must be performed to maintain the structural integrity of the fiber-reinforced layer. Even with regular maintenance, many fiber-reinforced surfacings must be reconstructed after 4 to 6 years; however, some roads will last much longer with regular maintenance.

Ride Quality: Fair to good ride quality can be achieved with fiber-reinforced surfacings. Ride quality deteriorates with time if timely maintenance is not conducted.

Main Distress / Failure Modes: Aggregate loss, rutting, erosion, washboarding, washouts.

Preservation Needs: Regrading of the road surfacing is periodically required, depending on traffic conditions; a regrading frequency of 6 months to 1 year is typical. In addition, surfacing material has to be added to repair distressed areas and replace the aggregate lost due to mixing with underlying soils, erosion, and dust. Depending on the thickness of the reinforced surface layer, new material may have to be added to the surface every 2 to 4 years.

SAFETY

Hazards: Loose aggregate can create a windshield hazard; if sand is the surfacing material, the sand particles are usually too small to cause vehicle damage. Large quantities of fugitive dust, which reduces driver visibility, can be produced by untreated surfacings during dry weather conditions.

Skid Resistance: Fiber reinforced soils usually provide poor to good skid resistance, depending on the type of material stabilized. Coarse granular soils provide better skid resistance.

Road Striping Possible?: No.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Fibers can be natural or man made. Materials that have been used for fiber reinforcement include metallic, polypropylene, glass, wire, cellophane, straw, and hemp fibers. Polypropylene fibers are the most commonly used and are manufactured materials.

Delivery and Haul Requirements: Fibers must be delivered to the site from the supplier. Delivery distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Dust generated during fiber application can damage vegetation adjacent to the road.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: None. Permeable surfacing materials, such as gravels and sands, will allow for increased infiltration into the road structure and less surface runoff.

Erosion: Poorly graded and compacted unbound surfacings can be highly susceptible to erosion. Dense, well-graded materials are generally less susceptible to erosion, but erosion is still a primary concern for these materials as well. Fiber reinforcement can help reduce erosion susceptibility to a certain extent. Surface water control and management should be considered in the road design to minimize the potential for surface erosion.

Water quality: Fiber reinforcement will reduce, but not eliminate erosion of untreated surface soils. Sediment loading from erosion of unbound surfacings can possibly impact water quality. If the surrounding environment is sensitive to sediment loading, then a buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles.

Aquatic species: Fiber reinforcement will reduce, but not eliminate erosion of untreated surface soils. Sediment loading from erosion of unbound surface materials can possibly impact aquatic species. If the surrounding environment is sensitive to sediment loading, a buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles.

Plant quality: None. However, dust generated from untreated fiber reinforced surfacings can impact plant quality by covering the leaves and reducing the amount of sunlight received by the plant.

Air Quality: Dust generated from untreated fiber-reinforced soils can have a long-term impact on air quality. Dust suppression products can be used to reduce fugitive dust generation.

Other: None.

Ability to Recycle/Reuse: Fiber-reinforced materials can be reused as a construction material. However, it is not practical to remove fibers from a fiber-stabilized material for reuse.

Other Environmental Considerations: For fiber-reinforced soils, tire/road noise will depend on the material gradation and surface smoothness, but will generally be high.

AESTHETICS

Appearance: The appearance and color will mainly be influenced by the soil type and gradation. However, the color of the fiber reinforcement, typically black for polypropylene, will also influence the appearance, depending on the amount of fibers added. The fibers will be visible in the surfacing material, with strands of fiber protruding from the soil mixture.

Appearance Degradation Over Time: Fiber-reinforced surfacings can deteriorate over time, in terms of surface uniformity. Fiber-reinforced surfaces can experience appearance degradation over time due to surface distresses, such as rutting, shoving, and material loss.

COST

Supply Price: $4.40/kg ($2.00/lb) of fiber.

Supply+Install Price: $10.00 to $16.00/m^2 ($7.70 to $12.30/yd^2) for a 200 mm (8 in.) thick reinforced layer.

EXAMPLE PROJECTS

None.

SELECT RESOURCES

Santoni, R.L., Tingle, J.S., and Webster, S.L. (2001). "Engineering Properties of Sand-Fiber Mixtures for Road Construction," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 127, No. 3, pp. 258-268.

Santoni, R.L., and Webster, S.L. (2001). "Airfields and Roads Construction Using Fiber Stabilization of Sands," *Journal of Transportation Engineering*, ASCE, Vol. 127, No. 2, pp. 96-104.

Schaefer, V.R., Ed. (1997). "2.11- Fiber Reinforced Soils," *Ground Improvement, Ground Reinforcement, Ground Treatment: Developments 1987-1997*, Geotechnical Special Publication No. 69, ASCE, Reston, VA.

GEOTEXTILE / GEOGRID REINFORCEMENT

GENERAL INFORMATION

Generic Name(s): Geotextile, Geogrid, Geotextile/geogrid-supported aggregate

Trade Names: Numerous products available.

Product Description: A geotextile is a flexible porous fabric constructed of synthetic fibers and designed specifically for use in applications related to soil, rock, or any other earthen materials. The geotextile can be manufactured with standard weaving machinery (referred to as a woven geotextile) or by matting fibers together in a random fashion (referred to as a nonwoven geotextile). A geogrid is manufactured from a polymer into a "fabric" with an open, grid-like structure and designed specifically for use in applications related to soil, rock, or any other earthen material. Geogrids are generally stronger, stiffer, and tougher products than geotextiles. Geotextiles and geogrids both belong to a group of synthetic products collectively referred to as geosynthetics. Geosynthetic products can be used in a wide range of applications to reinforce soils and to act as filter or separation layers in pavement construction. Geosynthetics are also used in the construction of paved roads but this product sheet only deals with their use on unpaved roads.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Geosynthetic Materials Association (GMA), (800) 225-4324, www.gmanow.com.

APPLICATION

Typical Use: Soil reinforcement, road surfacing (frequently on sites with poor strength subgrades or with shortage of quality aggregates).

Traffic Range: As a reinforced base, Very Low to High. As a road surfacing, Very Low to Low.

Restrictions:

Traffic: None.

Climate: None; however, wet and/or cold climates will lead to more frequent deterioration and more frequent maintenance.

Weather: Unbound road surfacings, including those reinforced with geotextiles/geogrids, are susceptible to adverse weather conditions. They will soften significantly in very wet weather and during periods of thaw.

Terrain: None.

Soil Type: Geotextile/geogrid-supported aggregates should have a maximum of 15% fines for use as a road surfacing and 10% for use as a base material.

Other: None.

Other Comments: Geosynthetics serve one of two primary functions when used with unbound aggregate layers in roadway applications: separation and/or reinforcement. Geotextiles are used primarily for separation and sometimes for reinforcement. Geogrids are used primarily for reinforcement and are more effective than geotextiles for that purpose. When used for separation, geotextiles are placed on top of a fine-grained subgrade prior to placing the aggregate layer. The purpose of the geotextile is to prevent (1) aggregate loss from the aggregate being pushed into the subgrade and (2) fines from the subgrade infiltrating into the aggregate layer and reducing the aggregate's structural and drainage properties.

For reinforcement purposes, the geotextile or geogrid is typically placed at or near the bottom of the aggregate base layer. The geosynthetic reinforces the base layer through shear interaction between the aggregate and geosynthetic, referred to as lateral base course restraint. Geogrids are considered to be better reinforcement materials than geotextiles because they are stiffer and more durable.

Geotextile separation layers have the potential to reduce aggregate requirements by 25%. Geotextiles and geogrids used together for reinforcement have the potential to reduce aggregate requirements by 50%. Therefore, geotextiles and/or geogrids can be used to reduce the thickness of aggregate layers required over soft soils or to reduce the amount of aggregate required in areas where aggregate is scarce. For the geotextile/geogrid to be beneficial as reinforcement, the geosynthetic must be stiffer than the underlying soil.

DESIGN

SLC: N/A; for low volume unpaved road design, geotextile and/or geogrid reinforcement is taken into consideration by increasing the equivalent bearing capacity of the underlying subgrade soil. For soft subgrade soils, the bearing capacity factor, N_C, for unreinforced, unpaved roads is 2.8, while N_C for geotextile-reinforced roads is 4.2 and N_C for geogrid and geotextile-reinforced soils is 6.7. Some agencies do not include separation as a structural design consideration; it is only used to prevent aggregate/subgrade intermixing.

Other Design Values: None.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support, taking into account the improved strength from the geosynthetic product.

Other Comments: The road surface should be sloped to promote surface drainage and prevent ponding on the road surface that can promote softening of the reinforced materials.

Geotextiles and geogrids are more effective when used with thin aggregate layers. As the base layer thickness increases, the stresses and strains near the bottom of the base layer decrease and the influence of the lateral base course restraint decreases as well. In addition, the mechanisms causing base/subgrade intermixing are reduced as the aggregate base thickness increases.

CONSTRUCTION

Availability of Experienced Personnel: Geotextile/geogrid-supported aggregate is a fairly common treatment and qualified contractors are, in general, widely available.

Materials: Geotextiles and/or geogrids and aggregate are required for construction of geotextile/geogrid-supported aggregate. Geotextiles/geogrids are shipped to the site in rolls. Nonwoven geotextiles perform better than woven geotextiles; nonwoven geotextiles offer better abrasion resistance, drainage capabilities, and interface friction with aggregates. Geogrids offerer higher strengths and better abrasion resistance than geotextiles.

Equipment: Equipment required for geotextile/geogrid-supported aggregate construction includes: rear or bottom dump trucks for hauling material, grading equipment (i.e. bulldozer or motor grader), water truck, and compactor. Equipment is widely available in most areas.

Manufacturing/Mixing Process: N/A

Placement Process: When using a geotextile, the geotextile is rolled out onto the prepared subgrade. The material should be placed so that there are no, or very few, wrinkles. Material from different rolls should be overlapped to ensure complete coverage. When using a geogrid, the geogrid is placed on the subgrade or geotextile separation layer, or after a thin lift of the aggregate material is placed. The geogrid should be placed taut and with no wrinkles. The unbound wearing course material is dumped by the haul trucks and spread using grading equipment, typically a motor grader, until the unbound layer has a uniform and adequate thickness and is graded to the proper slope. The use of a water truck and compaction equipment is highly recommended to adequately compact the surfacing layer.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the soil is frozen.

Construction Rate: Geotextile/geogrid-supported aggregate construction rates are in the range of 8,000 to 10,000 m^2/day (9,600 to 12,000 yd^2/day).

Lane Closure Requirements: The road is closed to traffic during construction but can be opened once construction is completed.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Geotextile/geogrid-supported aggregate is a common base and surfacing material. Research, design and construction information, and project experience are available.

Life Expectancy: Life expectancy varies depending on traffic, surfacing material characteristics, and weather conditions. Unbound gravel/aggregate surfaced roads can typically lose 25 mm (1 in.) of thickness per year; a geotextile separation layer will help reduce this loss rate by preventing aggregate loss due to aggregate/subgrade intermixing. Regular maintenance and periodic applications of additional material must be performed to maintain the structural integrity of the unbound layer. Even with regular maintenance, many unbound gravel/aggregate surfaced roads must be reconstructed after 6 to 10 years; however, some roads will last much longer with regular maintenance.

Ride Quality: Fair to good ride quality can be achieved with unbound gravel/aggregate road surfacings supported by geotextile/geogrid. Ride quality deteriorates with time if timely maintenance is not conducted.

Main Distress / Failure Modes: Aggregate loss, rutting, washboarding, potholes

Preservation Needs: The geotextile/geogrid material does not require maintenance. For unbound gravel/aggregate surfacings, regrading of the road surfacing is periodically required, depending on traffic conditions; a regrading frequency of 6 months is typical, but can easily range from 3 months to 2 years. In addition gravel has to be added to repair potholes and replace the aggregate lost due to erosion and dust. Depending on the thickness of the unbound layer, new material may have to be added to the surface every 1 to 3 years.

SAFETY

Hazards: Loose aggregate can create a windshield hazard. Large quantities of fugitive dust, which reduces driver visibility, can be produced by untreated surfacings during dry weather conditions.

Skid Resistance: Unbound gravel/aggregate road surfacings can provide poor to good skid resistance, depending on the type of aggregate and gradation. Hard, durable crushed aggregates can provide good skid resistance. The wearing course must also be well graded and compacted to reduce the amount of loose particles on the surface that can reduce skid resistance.

Road Striping Possible?: No.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Geotextiles and geogrids are manufactured products for the construction industry and are made of high density polyethylene (HDPE).

Delivery and Haul Requirements: Geotextiles and/or geogrids must be transported to the site from the distributor. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: None. The amount of surface runoff will depend on the permeability of the surface material. Water infiltration into a dense, well-graded unbound wearing course that is adequately sloped will generally be small, with the majority of the water becoming surface runoff.

Erosion: None. Poorly graded and compacted gravel/aggregate surfacing material can be highly susceptible to erosion. Dense, well-graded wearing course materials are generally less susceptible to erosion. Surface water control and management should be considered in the road design to minimize the potential for surface erosion.

Water quality: None. Sediment loading from erosion of gravel/aggregate surfacings can possibly impact water quality. A buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles.

Aquatic species: None. Sediment loading from erosion of gravel/aggregate surfacings can possibly impact aquatic species. A buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles.

Plant quality: None. Dust generated from untreated gravel/aggregate surfacings can impact plant quality by covering the leaves and reducing the amount of sunlight received by the plant. Particularly in agricultural areas, studies have shown that dust generation from roads adjacent to farmland can significantly reduce crop outputs. Dust suppression products can be used to reduce fugitive dust generation.

Air Quality: None. Dust generated from untreated gravel/aggregate surfacings can have a long-term impact on air quality. Dust suppression products can be used to reduce fugitive dust generation.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused as a construction material. The geotextile/geogrid material cannot be reused or recycled.

Other Environmental Considerations: For unbound gravel/aggregate surfacings, tire/road noise will depend on the material gradation and surface smoothness, but will generally be high.

AESTHETICS

Appearance: Geotextile/geogrid support does not alter the appearance of a soil/aggregate material. The color will be determined by the gravel/aggregate material type and source. The texture can vary depending on the aggregate gradation and maximum particle size, but will generally be rough (texture).

Appearance Degradation Over Time: Gravel/crushed aggregate surfaces can experience appearance degradation over time due to surface distresses, such as rutting, washboarding, and aggregate loss.

COST

Supply Price: N/A

Supply+Install Price: \$2.80 to \$5.00/m^2 (\$2.30 to \$4.20/yd^2), not including aggregate.

EXAMPLE PROJECTS

Marshall Municipal Airport, Marshall, MO.
IWV Road, Johnson County, IA.

SELECT RESOURCES

Geosynthetic Materials Association (GMA), (800) 225-4324, www.gmanow.com.

GRAVEL (CRUSHED OR UNCRUSHED)

GENERAL INFORMATION

Generic Name(s): Gravel, Crushed Aggregate, Pebbles, Crushed Rock

Trade Names: N/A

Product Description: Unbound gravel/crushed aggregate surfaced roads make up a significant portion of the rural low volume road system in the United States. Unbound surfaces typically have the lowest initial cost and can provide a durable riding surface when constructed with quality materials and adequately maintained. Unbound surfaces are generally restricted to low volume roads and slower speeds due to issues regarding safety, ride quality, dust, and vehicle damage from loose surface particles; however, well designed and maintained unbound surfaces can be used for high speed applications.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Stone, Sand, and Gravel Association (NSSGA), 1605 King Street, Alexandria, VA 22314, (800) 342-1415, www.nssga.org.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: As a road surfacing, unbound gravel/aggregate roads are best suited for Very Low to Low traffic volume applications (less than 250 AADT). However, they are frequently used for traffic volumes up to 400 AADT. Above this traffic range, the surface will require more frequent grading and maintenance, which increases cost.

Restrictions:

Traffic: For high speed applications (e.g. 100 km/hr [60 mph]), surface must be well maintained with good ride quality and smoothness to preserve safe driving conditions.

Climate: None; however, wet and/or cold climates will lead to more frequent deterioration and more frequent maintenance.

Weather: Unbound road surfacings, are very susceptible to adverse weather conditions. They will soften significantly in very wet weather and during periods of thaw.

Terrain: None.

Soil Type: N/A

Other: Unbound gravel/aggregate surfacings are susceptible to damage from snow plows in snow plowing areas.

Other Comments: Pebbles often have an aesthetically pleasing quality that can be desirable for a road surfacing. However, the often uniform gradation and smooth, rounded particle shape are not desirable qualities for a surface wearing course. Therefore, pebbles should be limited to particular applications where aesthetics are important and vehicle speeds are low (less than 30 km/hr [20 mph]). Stabilizers can be used to improve the performance and durability of materials.

DESIGN

SLC: 0.14 for good quality, crushed aggregate material, 0.08 to 0.11 for lower quality gravel.

Other Design Values: None.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of unbound materials. The base thickness and appropriate road surfacing should be selected based on anticipated traffic volumes. The minimum design thickness for the unbound gravel/aggregate layer is 100 mm (4 in.).

The strength and durability of unbound surfaces is significantly affected by the type and gradation of the surfacing material. In addition, the life expectancy and maintenance costs are strongly influenced by the quality of aggregate used. The use of poor quality material may initially be cheaper; however, the life cycle costs can be significantly greater than if a high quality aggregate was initially used. Well graded mixes of hard, durable, skid resistant, crushed aggregates with a small amount of fines are the best materials for use as an unbound surface. Various agencies have developed specific gradation requirements for unbound surface courses based on experience with local materials. Typically, fines contents of up to 15% are preferred for gravel surfacings. Most aggregate base materials restrict fines content to 10%.

A persistent performance problem with unbound road surfacings is the generation of dust as the surface dries. Several dust suppression and stabilization products have been developed to reduce the amount of fugitive dust originating from the unbound surface. Many of these products also improve the strength and durability of the surfacing and reduce surface erosion.

CONSTRUCTION

Availability of Experienced Personnel: Unbound gravel/aggregate surfaced roads are very common and qualified contractors are, in general, widely available. Maintenance crews are used by some agencies for gravel/aggregate road construction and maintenance.

Materials: Gravel/crushed aggregate/pebbles is the only material required. Well graded mixes of hard, durable, skid resistant, crushed aggregates with a small amount of fines are the best materials for use as an unbound surface. Depending on the application, marginal or poor quality aggregates may be acceptable if high quality materials are not locally available; however, some form of modification/stabilization may be required. Road aggregates can be obtained from natural gravel deposits or from quarried rock sources.

Equipment: Equipment required for unbound gravel/aggregate surfaces includes: rear or bottom dump trucks for hauling material, grading equipment (i.e. bulldozer or motor grader), water truck, and compaction equipment. Equipment is widely available in most areas.

Manufacturing/Mixing Process: Unbound materials, whether from pit or quarry sources, are processed at the aggregate plant to obtain certain particle characteristics (number of crushed faces, length-to-width ratio) and specified material gradation. The processing can involve crushing, screening and washing.

Placement Process: The unbound wearing course material is dumped on the prepared base/subbase/subgrade by the haul trucks and spread using grading equipment, typically a motor grader, until the unbound layer has a uniform and adequate thickness and is graded to the proper slope. The use of a water truck and compaction equipment is highly recommended to adequately compact the surfacing layer. The handling of the material needs to be minimal to reduce segregation, which reduces structural capacity and promotes potholing, raveling, and premature deterioration.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the soil is frozen.

Construction Rate: Unbound gravel/aggregate surfacing construction rates are in the range of 300 to 1,150 m^3/day (400 to 1,500 yd^3/day).

Lane Closure Requirements: It is recommended that the roadway lane be closed during construction. The lane can be reopened once construction is completed.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Unbound gravel/aggregate road surfacings have been used for centuries. Significant research, design and construction information, and project experience are available. Performance is highly dependent on the material source and properties. Local experience and construction practices for certain materials should be considered, when available.

Life Expectancy: Life expectancy varies depending on traffic, surfacing material characteristics, and weather conditions. Unbound gravel/aggregate surfaced roads can typically lose 25 mm (1 in.) of thickness per year. Regular maintenance and periodic applications of additional material must be performed to maintain the structural integrity of the unbound layer. Even with regular maintenance, many unbound gravel/aggregate surfaced roads must be reconstructed after 6 to 10 years; however, some roads will last much longer with regular maintenance.

Ride Quality: Fair to good ride quality can be achieved with unbound gravel/aggregate road surfacings. Ride quality deteriorates with time if timely maintenance is not conducted.

Main Distress / Failure Modes: Aggregate loss, rutting, washboarding, potholes, raveling.

Preservation Needs: Regrading of the road surfacing is periodically required, depending on traffic conditions; a regrading frequency of 6 months is typical, but can easily range from 3 months to 2 years. In addition gravel has to be added to repair potholes and replace the aggregate lost due to mixing with underlying soils, erosion, and dust. Unbound gravel/aggregate surfaced roads can commonly lose 25 mm (1 in.) of thickness per year. Depending on the thickness of the unbound layer, new material may have to be added to the surface every 1 to 3 years. Regrading operations can undo the benefits of dust suppressants so they may need to be reapplied after regrading.

SAFETY

Hazards: Loose aggregate can create a windshield hazard. Large quantities of fugitive dust, which reduces driver visibility, can be produced by untreated surfacings during dry weather conditions.

Skid Resistance: Unbound gravel/aggregate road surfacings can provide poor to good skid resistance, depending on the type, shape, and gradation of aggregate. Hard, durable crushed aggregates can provide good skid resistance. The wearing course must also be well graded and compacted to reduce the amount of loose particles on the surface that can reduce skid resistance. The difference in surface condition between the tightly packed traveled lanes and the loose shoulder material can create a driving hazard at higher speeds.

Road Striping Possible?: No.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Gravel/aggregates/pebbles are natural materials that are obtained by excavation, quarrying or dredging. The material must be mechanically processed to obtain the proper gradation and physical characteristics prior to shipment. On larger projects, blasted rock or gravel from road cuts may be suitable for processing as road aggregate.

Delivery and Haul Requirements: Gravel/aggregate must be transported to the site from the source location or distributor. Haul distances may be significant if quality materials are not available locally.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road. Special handling procedures, such as siting of stockpiles, etc., may be needed in environmentally sensitive areas.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: The amount of surface runoff will depend on the permeability of the surface material. Water infiltration into a dense, well-graded unbound wearing course that is adequately sloped will generally be small, with the majority of the water becoming surface runoff.

Erosion: Poorly graded and compacted gravel/aggregate material can be highly susceptible to erosion. Dense, well-graded wearing course materials are generally less susceptible to erosion. Surface water control and management should be considered in the road design to minimize the potential for surface erosion.

Water quality: Sediment loading from erosion of gravel/aggregate surfacings can possibly impact water quality. A buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles. Surface water should be managed in such a way that the eroded material is removed before the runoff enters the receiving waterbody.

Aquatic species: Sediment loading from erosion of gravel/aggregate surfacings can possibly impact aquatic species. A buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles. Surface water should be managed in such a way that the eroded material is removed before the runoff enters the receiving water body.

Plant quality: Dust generated from untreated gravel/aggregate surfacings can impact plant quality by covering the leaves and reducing the amount of sunlight received by the plant. Particularly in agricultural areas, studies have shown that dust generation from roads adjacent to farmland can significantly reduce crop outputs. Dust suppression products can be used to reduce fugitive dust generation.

Air Quality: Dust generated from untreated gravel/aggregate surfacings can have a long-term impact on air quality. Dust suppression products can be used to reduce fugitive dust generation.

Other: None.

Ability to Recycle/Reuse: The gravel/aggregate can be reused as a construction material.

Other Environmental Considerations: For unbound gravel/aggregate surfacings, tire/road noise will depend on the material gradation and surface smoothness, but will generally be high.

AESTHETICS

Appearance: The color will be determined by the material type and source. The texture can vary depending on the aggregate gradation and maximum particle size, but will generally be rough (texture).

Appearance Degradation Over Time: Gravel/crushed aggregate surfaces can experience appearance degradation over time due to surface distresses, such as rutting, washboarding, and aggregate loss.

COST

Supply Price: \$18.30 to \$20.90/m^3 (\$14.00 to \$16.00/yd^3).

Supply+Install Price: \$22.20 to \$32.70/m^3 (\$17.00 to \$25.00/yd^3).

EXAMPLE PROJECTS

Gravel/crushed aggregate surfaces are used extensively throughout the United States.

SELECT RESOURCES

National Stone, Sand, and Gravel Association (NSSGA), (800) 342-1415, www.nssga.org.

Bolander, P., Marocco, D., and Kennedy, R. (1995). *Earth and Aggregate Surfacing Design Guide for Low Volume Roads*, FHWA-FLP-96-001, Federal Highway Administration, Washington, D.C., 302 pp.

Skorseth, K., and Selim, A.A. (2000). *Gravel Roads Maintenance and Design Manual*, Report No. LTAP-02-002, South Dakota Local Transportation Assistance Program.

SAND

GENERAL INFORMATION

Generic Name(s): Sand

Trade Names: N/A

Product Description: Sand can be a naturally occurring material obtained directly from a pit, produced from a pit by screening, or manufactured by crushing and screening a bedrock source. Sand, like other granular materials, obtains its shear strength from interparticle locking and is greatly influenced by confining stress. Manufactured sands, because of their angular particle shape, are generally more stable than pit run products which are composed of more rounded particles. When used as a subgrade or subbase material, dense sand can provide good support for a pavement system, although not as good as a well graded gravel and sand mixture. When used as a road surfacing, clean, dry sands can present problems such as rutting, shoving, and erosion. Sands are only suitable for very low traffic volumes and for periodic access, preferably by four-wheel drive vehicles. Sand surfaces will likely become impassable in wet conditions. Sands with fines bind together better than clean sands, but typically will have a lower strength. Sand materials can be treated/stabilized using stabilizers, emulsions, or geosynthetics to create a more durable riding surface.

Product Suppliers: Representative list of suppliers can be obtained from: National Stone, Sand, and Gravel Association (NSSGA), 1605 King Street, Alexandria, VA 22314, (800) 342-1415, www.nssga.org.

APPLICATION

Typical Use: Can be used as a road surfacing, but more typically used as subgrade or subbase layer, or for roadway shoulders.

Traffic Range: As a road surfacing, Very Low.

Restrictions:

Traffic: Sand should not be used as a surfacing for traffic with a high percentage of heavy wheel loads. As a surfacing, sand should be limited to low speed applications (less than 30 km/hr [20 mph]).

Climate: Erosion can be a significant problem in windy, arid, or wet climates; sand surfaces in these climates should be stabilized or reinforced to reduce erosion.

Weather: Sand surfaces are very susceptible to adverse weather conditions; they can quickly become impassable in very wet weather and will soften significantly during thaw periods in areas subject to freezing temperatures.

Terrain: Sand surfaces should be limited to relatively flat terrains.

Soil Type: N/A

Other: Sand surfacings are generally not usable in winter in regions that receive heavy snowfall due to the damage from snow plow operations.

Other Comments: Sand is a poor surfacing material and should only be considered when other materials are not available or when sand is readily available and regular maintenance is allowable. In cases where sand is readily available, some method of stabilization or reinforcement is recommended to increase the performance of the sand surfacing.

DESIGN

SLC: 0.05 (sand with some fines) to 0.10 (clean, angular sand).

Other Design Values: None.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The minimum design thickness for the sand layer is 100 to 150 mm (4 to 6 in.).

The strength and durability of a sand surface is significantly affected by the type, particle shape, and gradation of the sand and the percent fines. Where possible, a well graded sand with some gravel sizes, if available should be selected. Typically, fines contents of up to 10% are preferred for sand surfacings.

A persistent performance problem with sands with fines is the generation of dust as the surface dries. Several dust suppression and stabilization products have been developed to reduce the amount of fugitive dust originating from an unbound surface. Many of these products also improve the strength and durability of the surfacing and reduce surface erosion.

CONSTRUCTION

Availability of Experienced Personnel: Sand surfaced roads are typically used in areas where sand is abundant, such as coastal areas. In these areas, qualified contractors experienced in construction with sands are, in general, widely available. Maintenance crews are used by some agencies for sand road construction and maintenance.

Materials: Sand is the only material required. Well graded sand mixes of hard, angular, durable fine aggregates with a small amount of fines are the best materials for use as a sand surface. Depending on the application, marginal or poor quality sands may be acceptable if high quality materials are not available; however, some form of modification/stabilization may be required. However, in practice, sand would only be used in the absence of gravel and only because it is the only available local material.

Equipment: Equipment required for sand surfacing construction includes: rear or bottom dump trucks for hauling material (if not available on site), grading equipment (i.e. bulldozer or motor grader), water truck, and compactor. Equipment is widely available in most areas.

Manufacturing/Mixing Process: Sands can be processed from a pit or quarry source to obtain a certain gradation or to remove organic material or excess fines. However, on-site material or material from a nearby source is usually used without modification.

Placement Process: The sand is dumped on the prepared base/subbase/subgrade by the haul trucks and spread using grading equipment, typically a motor grader, until the unbound layer has a uniform and adequate thickness and is graded to the proper slope. The use of a water truck and compaction equipment is highly recommended to adequately compact the surfacing layer.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the subgrade is saturated or frozen.

Construction Rate: Sand surfacing construction rates are in the range of 300 to 1,150 m^3/day (400 to 1,500 yd^3/day).

Lane Closure Requirements: It is recommended that the roadway be closed during construction. The road can be reopened once construction is completed.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Sand has been used as a road surfacing for centuries, but generally by default There is only a limited amount of information available on design and construction and project experience. Performance is highly dependent on the material source and properties. Local experience and construction practices for certain materials should be considered, when available.

Life Expectancy: Life expectancy varies depending on traffic, surfacing material characteristics, and weather conditions. Sand surfacings will lose material annually due to erosion, mixing with subgrade, dust, and shoving. However, a single heavy storm event can significantly damage the sand surfacing and make the road impassable. The sand surfacing can be repaired/reconstructed, but it will remain susceptible to damage during the next storm event unless the sand is stabilized. Regular maintenance and periodic applications of additional material must be performed to maintain the structural integrity of the unbound sand layer. Even with regular maintenance, many sand surfaced roads must be reconstructed after 4 to 6 years; however, some roads will last much longer with regular maintenance.

Ride Quality: Poor to fair ride quality can be achieved with sand surfacings. Ride quality deteriorates with time.

Main Distress / Failure Modes: Sand loss, rutting, erosion, washouts.

Preservation Needs: Regrading of the road surfacing is periodically required, depending on traffic conditions; a regrading frequency of 3 months is typical, but can easily range from monthly to yearly. In addition, sand has to be added to repair distressed areas and replace the aggregate lost due to mixing with underlying soils, erosion, and dust. Depending on the thickness of the unbound layer, new material may have to be added to the surface every 1 to 3 years and possibly after major storm events.

SAFETY

Hazards: Rutting can lead to water accumulation on the pavement surface, causing a driving hazard. Larger sand particles can create a windshield hazard, although the sand particles are usually too small to cause vehicle damage. Large quantities of fugitive dust, which reduces driver visibility, can be produced by untreated surfacings during dry weather conditions. If the sand surfacing is loose, vehicle handling and maneuverability can be reduced and conventional two wheel drive vehicles can easily become bogged down.

Skid Resistance: Sand surfacings usually provide poor to marginal skid resistance, depending on the type of aggregate and gradation. Hard, durable particles provide better skid resistance. The sand layer must also be well graded and compacted to reduce the amount of loose particles on the surface that can reduce skid resistance.

Road Striping Possible?: No.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Sands are natural materials that are obtained from pits or by dredging.

Delivery and Haul Requirements: Sands are usually obtained from on-site or nearby sources.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Sand surfacings are typically somewhat permeable, which allows for increased infiltration into the road structure and less surface runoff.

Erosion: Poorly graded and compacted sands can be highly susceptible to erosion. Dense, well-graded sands are generally less susceptible to erosion, but erosion is still a primary concern for these materials as well. Surface water control and management should be considered in the road design to minimize the potential for surface erosion. Side ditching is difficult to maintain and tends to fill in quickly. Adjacent cut slopes and ditch back slopes should be cut as flat as possible and vegetated.

Water quality: Sediment loading from erosion of sand surfacings can possibly impact water quality. If the surrounding environment is sensitive to sand sediment loading, then a buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles. Surface water should be managed in such a way that the eroded material is removed before the runoff enters the receiving waterbody.

Aquatic species: Sediment loading from erosion of sand can possibly impact aquatic species. If the surrounding environment is sensitive to sand sediment loading, a buffer zone should be provided between the roadway and nearby bodies of water and the road surface should be properly maintained to minimize erosion of surface particles. Surface water should be managed in such a way that the eroded material is removed before the runoff enters the receiving water body.

Plant quality: Sedimentation of large enough quantities of eroded sand can adversely affect plant species.

Air Quality: Dust generated from sand surfacings can have a long-term impact on air quality. Dust suppression products can be used to reduce fugitive dust generation.

Other: None.

Ability to Recycle/Reuse: The sand can be reused as a construction material.

Other Environmental Considerations: None.

AESTHETICS

Appearance: The appearance and color will be determined by the sand type and source. The texture can vary depending on the aggregate gradation and maximum particle size, but will generally be rough (texture). The surfacing will also show vehicle tracks and wheel rut paths.

Appearance Degradation Over Time: Sand surfaces deteriorate over time, in terms of surface uniformity. Sand surfaces can experience appearance degradation over time due to surface distresses, such as rutting, shoving, and sand loss. Without maintenance, the sand surface can develop, over time, an abandoned appearance and begin to support the growth of vegetation.

COST

Supply Price: N/A

Supply+Install Price: $7.30 to $10.90/Mg ($6.60 to $9.90/ton).

EXAMPLE PROJECTS

New Jersey Pinelands, NJ.
Oregon Dunes National Recreational Area, Siuslaw National Forest, Corvallis, OR.

SELECT RESOURCES

National Stone, Sand, and Gravel Association (NSSGA), (800) 342-1415, www.nssga.org.

OTHER STABILIZED SURFACINGS (INCLUDING DUST PALLIATIVE APPLICATIONS)

CHLORIDES

GENERAL INFORMATION

Generic Name(s): Chlorides, Salts, Calcium Chloride ($CaCl_2$), Magnesium Chloride ($MgCl_2$), Sodium Chloride ($NaCl_2$)

Trade Names: *$CaCl_2$*: Dowflake, LiquidDow, Roadmaster; *$MgCl_2$*: Dust-Off, Dus-Top, DustGuard, etc.

Product Description: Chlorides are the most commonly used products for dust suppression in unbound road surfacings. These compounds, which contain chloride salts, can be mixed with other ingredients and are applied either in a liquid or solid state flakes or pellets. Chlorides draw moisture from the air to keep the road surface moist (i.e. hydroscopic) and help resist evaporation of road surface moisture (i.e. deliquescent). By keeping the road surface moist, chlorides reduce the amount of dust generated. Chlorides also facilitate compaction and promote soil stabilization.

Product Suppliers: Cargill Salt, P.O. Box 5621, Minneapolis, MN, 55440-5621, (888) 385-7258, www.cargillsalt.com;
The Dow Chemical Company, P.O. Box 1206, Midland, MI, 48642, (800) 447-4369, www.dow.com; and
Tetra Chemicals, P.O. Box 73087, Houston, TX, 77273, (281) 367-1983, www.tetratec.com.

APPLICATION

Typical Use: Dust suppressant.

Traffic Range: Very Low. Chlorides can be used on unbound road surfacing with higher traffic volumes, but more frequent applications are required.

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed.

Climate: Chlorides are not effective in very arid or very wet climates. $MgCl_2$ requires a relative humidity greater than 32% at 25ºC (77°F) and $CaCl_2$ requires a relative humidity greater than 29% at 25ºC (77°F) to be effective. $CaCl_2$ performs better at higher humidity; $MgCl_2$ performs better during long dry spells. Chlorides can be leached from an unbound surfacing by rainfall, thus requiring frequent reapplication in very wet climates. $CaCl_2$ will not be leached by rainfall as easily as $MgCl_2$.

Weather: Unbound road surfacings, including those treated with chlorides, are very susceptible to adverse weather conditions. They will soften significantly in very wet weather and during periods of thaw. Chlorides can reduce the number of freeze-thaw cycles experienced by a surfacing by reducing the freezing temperature of the moisture contained within the unbound material.

Terrain: Unbound road surfacings treated with chlorides can become slippery when wet and should not be used on road sections with steep grades or tight curves.

Soil Type: Chlorides should be used in conjunction with competent unbound road surfacing materials (e.g. well-graded gravels). A moderate amount of fines is required to facilitate retention of the chlorides (10 to 25% range).

Other: None.

Other Comments: $CaCl_2$ is slightly more effective than $MgCl_2$ at absorbing water and decreasing evaporation. Chlorides can cause corrosion damage to vehicles. Sodium chloride is not as effective as $CaCl_2$ or $MgCl_2$ and is typically only used in cases when other chloride products are not available.

DESIGN

SLC: N/A

Other Design Values: N/A

Base/Subbase Requirements: Unbound road surfacings, including those treated with chloride, should be designed with adequate base and/or subbase support.

Other Comments: Chlorides work best on engineered aggregate surfaces rather than native or uncontrolled, variable materials.

CONSTRUCTION

Availability of Experienced Personnel: Chlorides are a commonly used dust suppressant and experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas. Maintenance crews are used by some agencies for chloride application.

Materials: Chloride additives, which contain chloride salts, can be mixed with other ingredients and are applied either in a liquid or solid state (flakes or pellets). $MgCl_2$ is more readily available in the western United States and $CaCl_2$ is more readily available in the central and eastern United States.

Equipment: Equipment required for chloride application includes: haul vehicles, spreader (for flakes or pellets) or tanker with spray bar (for liquid), grading equipment (i.e. bulldozer or motor grader), water truck (for flakes or pellets), and pneumatic tire roller. Equipment is widely available in urban areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Chlorides are obtained from natural brine deposits or as a byproduct of other manufacturing processes. Flakes or pellets are commonly provided in bulk or in 36 or 45 kg (80 or 100 lb) bags. Liquid chloride solutions are transported by rail car or tanker truck. Pellets have the highest chloride concentration, followed by flakes and liquid solution. As an alternative to sprayed-on or in-place mixing, the chloride additive can be mixed with the unbound surfacing material in a pug mill prior to placement.

Placement Process: Chlorides are typically sprayed on. The road surface should be graded to promote drainage and prevent ponding on the road surface that can soften the road surface and underlying subgrade. The top 50 to 100 mm (2 to 4 inches) of the road surface may be scarified and loosened, either with a disc or grading equipment, before chloride application. Scarifying the surface allows the chlorides to penetrate evenly and quickly into the road surface. The unbound surfacing material should be moist prior to chloride application if flakes or pellets are used. The chloride additive is applied uniformly using a spreader for pellets or flakes or a tanker with a spray bar for liquid chloride solutions. A water truck must be used to spray the surface and dissolve all flakes and pellets, when used. Chlorides can be blended with the surfacing material using a disc or grading equipment to improve performance, but is generally not as cost-effective as the sprayed-on application. If the surface is scarified, a pneumatic tire roller should be used to compact the surfacing material after the chloride additive is applied and mixed.

Weather Restrictions: Do not apply chlorides if rain is likely within 24 hours or during periods of prolonged sub-freezing temperatures.

Construction Rate: Chloride application rates can typically be about 3,300 to 5,000 m^2/hr (4,000 to 6,000 yd^2/hr).

Lane Closure Requirements: If the roadway surface is scarified prior to treatment, the roadway lane(s) being treated are closed during construction, so adequate traffic control is needed. The roadway can be opened to traffic as soon as the construction equipment is cleared from the roadway. If the chloride is applied to the surface without scarifying the surface, lane closures are not required.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Chlorides are commonly used dust suppressants and have been used on roadway projects for more than 50 years; an extensive amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on traffic and rainfall. The life expectancy decreases with increasing traffic, vehicle speed, and rainfall. Based on one published survey (Birst and Hough, 1999), $CaCl_2$ is effective for 3 to 6 months (71%) and 6 to 12 months (21%). $MgCl_2$ is effective for 3 to 6 months (33%) and 6 to 12 months (42%). In the majority of the cases, no benefit is seen after one year.

Ride Quality: Chloride additives do not affect initial ride quality of the unbound road surfacing; however, chlorides help to decrease the rate of serviceability loss due to potholes and washboarding by reducing the amount of surface particle loss.

Main Distress / Failure Modes: Rutting, washboarding, potholes, dust.

Preservation Needs: All unbound road surfacings should be inspected on a regular basis and maintenance undertaken as appropriate. Periodic grading can correct surface rutting. Regrading can be difficult due to flaking of the treated surfacing.

SAFETY

Hazards: During construction, exposure to chlorides can cause skin and eye irritation. Loose aggregate chips can create a windshield hazard.

Skid Resistance: Unbound road surfacings generally have poor to average skid resistance. Unbound road surfacings treated with chlorides can become slippery when wet

Road Striping Possible?: No.

Other Comments: Chlorides can increase visibility by reducing dust generation by 50% or more.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Chlorides are obtained from natural brine deposits or as a byproduct of other manufacturing processes.

Delivery and Haul Requirements: Chlorides must be hauled from the nearest manufacturer or supplier. Chlorides are generally widely available; however, haul distances may be significant for remote sites. $MgCl_2$ is more readily available in the western United States and $CaCl_2$ is more readily available in the central and eastern United States.

Potential Short-Term Construction Impacts: Chlorides act as a defoliant and may impact vegetation adjacent to the roadway during construction.

Potential Long-Term Environmental Impacts:

Leachate: There is a potential for leaching of chlorides from the road surface in moderate to heavy rains.

Surface Runoff: The amount of surface runoff will be determined by the unbound surfacing material and will not be significantly affected by the chlorides.

Erosion: Chlorides will reduce the amount of erosion compared to an untreated unbound surfacing.

Water quality: Water quality can be impacted by chlorides when leaching occurs unless an adequate buffer zone is provided. Public drinking water standards require chloride levels not to exceed 250 mg/L (PPM). Chlorides should not be used when shallow groundwater conditions exist because it may cause groundwater contamination.

Aquatic species: Chlorides can potentially impact aquatic species if a buffer zone is not provided. A buffer zone of at least 8 m (25 ft.) is recommended between chloride-treated roads and bodies of water. Criteria for protection of aquatic species require levels of less than 600 mg/L (PPM) for chronic exposure and 1200 mg/L (PPM) for short-term exposure. Trout can be affected by concentrations as low as 400 mg/L (PPM).

Plant quality: Chlorides can potentially impact certain plant species; susceptible species include alder, birch, pine, hemlock, larch, poplar, ash, spruce, ornamentals, maple, and numerous species of shrubs and grasses. Chloride use should be restricted within 8 to 9 m (25 to 30 ft.) of susceptible vegetation.

Air Quality: Chlorides reduce dust generation by 50% or more.

Other: Chlorides can initiate corrosive effects in steel and aluminum alloys.

Ability to Recycle/Reuse: Chloride-treated roadway materials can be fully recycled as a pavement construction material. Potential environmental impacts should be considered prior to reuse of chloride-treated materials.

Other Environmental Considerations: Heat is generated by mixing $CaCl_2$ flakes or pellets with water. For unbound road surfacings, tire/road noise depends on the gradation and surface roughness, but is generally high.

AESTHETICS

Appearance: Chlorides do not significantly alter the appearance of the road surfacing, which will be determined by the unbound surfacing aggregate type and source; however, chlorides may darken the appearance of the surfacing. The surfacing may also appear mottled or blotchy due to segregated fines absorbing more of the chlorides.

Appearance Degradation Over Time: All unbound road surfacing deteriorate over time. Chlorides do not affect the change in appearance over time.

COST

Supply Price: \$360 to \$450/Mg (\$400 to \$500/ton).

Supply+Install Price: \$0.30 to \$0.60/m^2 (\$0.25 to \$0.50/yd^2) for surface treatment.

EXAMPLE PROJECTS

Buenos Aires National Wildlife Refuge, AZ.
Deschutes National Forest, OR.
Winema National Forest, OR.

SELECT RESOURCES

Birst, S., and Hough, J. (1999). *Chemical Additive Usage on Unpaved Roads in Mountain Plains States*, UGPTI Department Publication No. 130, Upper Great Plains Transportation Institute, North Dakota State University, 119 pp.

USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

CLAY ADDITIVES

GENERAL INFORMATION

Generic Name(s): Clay Additives, Clay Filler, Bentonite, Montmorillonite

Trade Names: Central Oregon Bentonite, Pelbron, Stabilite, Volclay, and others.

Product Description: Clay additives are naturally occurring soils composed of the mineral montmorillonite. Montmorillonite is a highly plastic clay mineral with a high affinity for water. Clay additives are typically used to stabilize nonplastic crushed aggregates; the cohesive properties of the clay additive help to bind the aggregate particles and prevent raveling and washboarding. The clay additive will also attach to fines in the aggregate mix to reduce fugitive dust. Some dust is still to be expected with clay-stabilized aggregates, so additional dust suppressants are also used in conjunction with the clay additive when dust is an important concern.

Product Suppliers: American Colloid Company, 1500 West Shure Drive, Arlington Heights, IL 60004, (800) 426-5564, www.colloid.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and clay additive products are available.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low (AADT < 250). Above this traffic range, the surface will require more frequent product mixing and surface grading.

Restrictions:

Traffic: None.

Climate: None; however, wet and/or cold climates will lead to more rapid deterioration and more frequent maintenance requirements.

Weather: Clay-stabilized aggregate roads are very susceptible to adverse weather conditions. They can quickly become impassable in very wet weather and, in areas subject to freezing temperatures, will soften significantly during thaw periods.

Terrain: None.

Soil Type: The effectiveness of clay additives is affected by the aggregate mineralogy; negatively charged montmorillonite will adhere well to limestone, but will be repelled by a negatively charged igneous rock aggregate. Clay additives generally provide no benefit for high plasticity soils or soils with more than 20% to 30% fines.

Other: None.

Other Comments: None.

DESIGN

SLC: 0.10 to 0.14.

Other Design Values: None.

Base/Subbase Requirements: The road should be designed as a unbound gravel/aggregate road. The need for a subbase layer will depend on subgrade characteristics and traffic loading.

Other Comments: The road surface should be sloped to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials.

CONSTRUCTION

Availability of Experienced Personnel: Clay additive application is relatively straightforward and qualified contractors are, in general, widely available. Maintenance crews often can be used by agencies for clay additive applications.

Materials: Clay additives are naturally occurring soils composed of the mineral montmorillonite. Material is mined from sources in the northwestern United States and Mississippi. Clay additives can be applied in a dry form or as a slurry.

Equipment: Equipment required for clay additive application includes: tanker or water truck with spray bar, grading equipment (i.e. bulldozer or motor grader), and roller. A pugmill can be used to achieve more uniform mixing. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Thorough mixing is required to create a uniform mixture. The clay additive can be mixed with the aggregate in a pugmill (results in most uniform mixture) or in-place using a pulverizer, disc, or blade mixing.

Placement Process: For new construction projects where the aggregate must be hauled to the site, the clay additive (dry) should be thoroughly mixed with the aggregate in a pugmill before the aggregate is shipped to the site. This method provides the most uniform mixing. Alternatively, If the aggregate is in place, the aggregate should be loosened to the desired treatment depth. The clay additive is then applied uniformly to the loosened aggregate surface. If the additive is applied in dry form, a spreader is used; if the additive is applied in slurry form, a spray truck is used. Once applied, the clay additive is mixed with the aggregate using a pulverizer, disc, or by blade mixing. For the dry additive, a water truck is used to wet the mixture; water is provided to get the material to an optimum moisture content for compaction. Soda ash (dispersing agent) can be added to the water to reduce clumping when higher percentages (greater than 5%) of clay additive are applied. Once mixed, the treated material is graded and compacted.

Weather Restrictions: Avoid construction during rain or snow events and when the subgrade is saturated or frozen.

Construction Rate: Clay additive construction rates are in the range of 2,000 to 5,000 m^2/day (2,400 to 6,000 yd^2/day) for a mixing depth of 100 mm (4 in.).

Lane Closure Requirements: The roadway lane should be closed during construction, but can be opened to traffic once construction is complete.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired. Test sections are recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Clay additives are commonly used in some regions of the United States, but not in other areas; limited research, design and construction information, and documented project experience are available.

Life Expectancy: Life expectancy varies depending on traffic and weather conditions. Typical life expectancy is 2 to 4 years. Life expectancy could be longer if routine maintenance is performed.

Ride Quality: Ride quality depends on the aggregate used for surface material. Clay additives do not provide any improvement in ride quality; however, clay additives can reduce the rate of deterioration over the serviceable life. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved.

Main Distress / Failure Modes: Rutting, washboarding, potholes, raveling

Preservation Needs: Periodic grading/reshaping/compaction and localized repair may be required, typically every 3 to 6 months. Regrading does not negatively affect the clay additive's performance.

SAFETY

Hazards: Clay additives can contain a small amount of crystalline silica (typically 1% to 3%); crystalline silica dust can be an inhalation hazard for construction crews. Proper construction practices and engineering controls should be utilized to minimize exposure risks.

Skid Resistance: Excessive quantities of clay additives in a treated aggregate or a wet climate can cause roads stabilized with clay additives to become slippery. No noticeable change in skid resistance was noticed in a study where the clay additive application rate was varied between 3% and 12%.

Road Striping Possible?: No.

Other Comments: Clay additives can typically reduce road dust by 20% (1.5% clay additive treatment) to 70% (9% clay additive treatment). Studies have shown that clay additives can reduce road dust by 60% to 70% the first year, 40% to 50% the second year, and 20% to 30% the third year. In some cases, the driving public may not perceive any reduction in road dust generation because the improvement is not as dramatic as the dust reduction associated with some other dust control products. Clay additives can reduce the amount of flying aggregate particles by binding the surface particles.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Clay additives are naturally occurring materials that are mined for commercial use.

Delivery and Haul Requirements: Clay additives must be transported to the site from the distributor. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road, but off-site impacts can be mitigated by careful application.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Clay additives can reduce the permeability of the surface material and, thus promote more surface runoff. However, surface runoff water quality is not generally impacted by clay additives.

Erosion: Clay additives reduce the erodibility of the unbound roadway surface by binding surface particles together.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated aggregate can be reused as an aggregate for appropriate applications, considering the modified properties and gradation of the treated material.

Other Environmental Considerations: Clay additives are natural materials, and therefore are typically nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly.

AESTHETICS

Appearance: The addition of clay additives does not significantly alter the appearance of an aggregate road. The appearance will be of an aggregate surface with the overall color determined by the aggregate type and source.

Appearance Degradation Over Time: Without maintenance, clay-treated aggregate roads deteriorate over time in terms of surface uniformity.

COST
Supply Price: $145 to $181/Mg ($160 to $200/ton). **Supply+Install Price**: $10.60 to $14.10/$m^3$ ($8.10 to $10.80/$yd^3$) for an aggregate stabilized with clay.
EXAMPLE PROJECTS
Minutemen Missile Access Roads in Colorado, Montana, Nebraska, and Wyoming.
SELECT RESOURCES
Bergeson, K.L., and Brocka, S.G. (1996). "Bentonite Treatment for Fugitive Dust Control," Proceedings of the 1996 Semisesquicentennial Transportation Conference, Ames, IA.

ELECTROLYTE EMULSIONS

GENERAL INFORMATION

Generic Name(s): Electrolyte Stabilizers, Ionic Stabilizers, Sulfonated Oils, Electrochemical Stabilizers, Acids

Trade Names: CBR Plus, Condor SS, Road Bond EN-1, SA-44 System, Terrabond Clay Stabilizer, Terrastone, and others.

Product Description: Many of the emulsions for dust suppression and/or soil stabilization are proprietary in nature and the exact composition and stabilization mechanisms are not publicly available; therefore, it is often difficult to group or classify the various emulsions accurately.

Electrolyte emulsions contain chemicals that affect the electro-chemical bonding characteristics of soils and replace water molecules within the soil structure. The treated soil loses its affinity for water. When applied at low application rates to the surface of the unbound road surface, electrolyte emulsions perform well for dust suppression. They bond soil particles together and so reduce dust generation. At higher application rates, electrolyte emulsions can be used to stabilize soils. When applied and compacted properly, the treated soil can be stabilized to form a firm to hard bound layer that can be used as a road surfacing.

Most of the information available on electrolyte emulsions comes from brochures and literature provided by the manufacturer. Therefore, it may be difficult to find independent test information for a particular product. The performance and applicability of electrolyte emulsions can vary from one product to the next. In addition, products are frequently reformulated; so, historical case studies may no longer be representative of a current product. As a result, product specific testing and/or performance verification is recommended when selecting an electrolyte emulsion.

Product Suppliers: CBR Plus North America, 580 Hornby Street, Suite 640, Vancouver, BC Canada, V6C3B6, (604) 683-0430, www.cbrplus.com; and

C.S.S. Technology, Inc., P.O. Box 1618, Granbury, TX 76048, (817) 279-1136, www.csstech.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and electrolyte emulsion products are available.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low (AADT < 250).

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed. Additional traffic loading restrictions may be required depending on the material being treated (e.g. the load-carrying capacity of a clay soil is typically much less than that of a granular material).

Climate: None.

Weather: Minor grading/reshaping and localized repair may be required after heavy rainfalls.

Terrain: None.

Soil Type: Categorically speaking, electrolyte emulsions work on a variety of soils as long as a minimum amount of clay particles are present (greater than 10%) and the plasticity index is greater than 10. Electrolyte emulsions generally work best on soils with 10% to 20% clay, but are effective on soils with higher clay contents as well.

Other: None.

Other Comments: None.

DESIGN

SLC: N/A for dust suppression applications; typically 0.08 to 0.14 (increases with increased quality of treated material) for stabilization applications.

Other Design Values: Electrolyte emulsions can increase the soil strength by 30% to 50%, in terms of CBR, for example. Stabilized natural soil road surfacings are for very low traffic applications, and generally are designed empirically and are not subject to structural analysis.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support. In cases where natural soils are stabilized in situ, no subbase layer is provided.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials.

CONSTRUCTION

Availability of Experienced Personnel: Electrolyte emulsions are a commonly used dust suppressant and soil stabilizer and experienced contractors are, in general, widely available. Maintenance crews are used by some agencies for spray-on applications.

Materials: Electrolyte emulsion products are typically purchased in liquid concentrate form. Water is required to dilute the electrolyte concentrate once it is delivered to the site.

Equipment: Equipment required for electrolyte emulsion application includes: tanker or water truck with spray bar, grading equipment (i.e. bulldozer or motor grader), and roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Electrolyte concentrate must be mixed with water to achieve the desired concentration level prior to application. Dilution ratios of 1 part electrolyte concentrate mixed with 100 to 600 parts water or more are common.

Placement Process: Electrolyte emulsions can be applied by a sprayed-on method or mixed-in method, but mixed-in method is most common. Recommended mixing depth for dust suppression and stabilization ranges from 25 to 50 mm (1 to 2 in.) and 100 to 200 mm (4 to 8 in.), respectively. The moisture content of the soil prior to treatment should be below optimum for compaction so that the soil moisture content will be near optimum once the electrolyte emulsion is added, considering the water provided by the emulsion; if the material is very dry or saturated, processing to achieve moisture content adjustments is recommended prior to treatment. For dust suppression applications, scarifying the surface allows the electrolyte emulsion to penetrate evenly and quickly into the road surface. For soil stabilization applications, the soil is loosened to the desired treatment depth. The electrolyte emulsion is then applied uniformly using a tanker or water truck with a spray bar and mixed with the loose soil. The electrolyte emulsion is often applied in multiple passes to get better overall mixing. Once mixed, the treated material is graded and compacted.

Weather Restrictions: Do not apply electrolyte emulsions if is raining or if temperatures are below freezing.

Construction Rate: Electrolyte emulsion application rates are in the range of 2,000 to 5,000 m^2/day (2,400 to 6,000 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction, but can be opened to traffic once construction is complete.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired. Test sections are recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Electrolyte emulsions are a common dust suppressant and soil stabilizer and were initially developed more than 40 years ago. Research, design and construction information, and project experience are available. Performance can vary significantly between different products and is influenced by traffic, soil type, weather conditions, application method and rate, and contractor performance. As a result, product specific testing and/or performance verification is recommended when selecting an electrolyte emulsion.

Life Expectancy: Life expectancy varies depending on traffic and weather conditions. Typical life expectancy is 3 to 5 years for stabilization applications, with some treated surfaces still in service after 15 years or more. Electrolyte emulsions do not leach from the soil; therefore, the treatment is "permanent", in theory. When an effective electrolyte emulsion product is applied in the proper situation, constructed properly, and maintained, good performance and long life expectancies are realized.

Ride Quality: Ride quality depends on the treated aggregate. Ride quality deteriorates over the serviceable life. Electrolyte emulsions do not provide any improvement in ride quality; however, the rate of deterioration is less than the rate for untreated surfaces. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved. Electrolyte emulsions can reduce aggregate loss by 50% or more.

Main Distress / Failure Modes: Dust, rutting, washboarding, potholes.

Preservation Needs: Periodic grading may be required, typically every 6 months to 1 year. For dust suppression applications, grading should be performed in a manner such that the stabilized "surface crust" is not broken.

SAFETY

Hazards: Some electrolyte products are highly acidic in their concentrated form. Proper handling and mixing procedures should be followed when mixing the concentrated liquid with water to create an emulsion.

Skid Resistance: Electrolyte emulsion-treated materials form a firm to hard, skid resistant surface.

Road Striping Possible?: No.

Other Comments: Electrolyte emulsions can typically reduce road dust by 60% to 80%.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Electrolyte emulsions are typically byproducts or intermediate products of various manufacturing processes. Sulfonated D-limonene and sulfonated naphthalene are two of the chemicals that can be primary components of electrolyte emulsions.

Delivery and Haul Requirements: Electrolyte concentrate must be hauled to the site from the distributor. Haul distances may be significant for remote sites. Hauling requirements are reduced somewhat by the fact that the product is shipped in concentrated form and can be mixed with water at the site.

Potential Short-Term Construction Impacts: Spills or runoff during the emulsion mixing process could have a negative impact on nearby vegetation, water quality, or aquatic species.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Electrolyte emulsion-treated soil is relatively impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by electrolyte emulsion treatments.

Erosion: Electrolyte emulsions reduce the erodibility of the unbound roadway surface by binding surface particles together.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused in any manner similar to the untreated material.

Other Environmental Considerations: Environmental impacts of electrolyte emulsions may vary between different proprietary products; specific product information should be collected and reviewed prior to product use. Once diluted to normal application rates, electrolyte emulsions are typically nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly.

AESTHETICS

Appearance: The addition of electrolyte emulsion does not significantly alter the appearance of a soil or aggregate road. The appearance will be of a soil/aggregate surface with the overall color determined by the soil/aggregate type and source. The treated soil /aggregate will have a slightly darker appearance than the parent material.

Appearance Degradation Over Time: Without maintenance, electrolyte emulsion-treated roads deteriorate over time in terms of surface uniformity.

COST

Supply Price: N/A

Supply+Install Price: \$0.40 to \$0.80/m^2 (\$0.35 to \$0.70/yd^2).

EXAMPLE PROJECTS

City of Calgary, Canada.
Ozark National Forest, AR.

SELECT RESOURCES

Scholen, Douglas E. (1992). Non-Standard Stabilizers, FHWA-FLP-92-011, U.S. Department of Transportation, Washington, D.C., 113 pp.

USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

ENZYMATIC EMULSIONS

GENERAL INFORMATION

Generic Name(s): Enzymatic Emulsions, Enzymes

Trade Names: Bio Cat 300-1, EMC SQUARED, Perma-Zyme 11X, Terrazyme, UBIX No. 0010, and others.

Product Description: Many of the emulsions for dust suppression and/or soil stabilization are proprietary in nature and the exact composition and stabilization mechanisms are not publicly available; therefore, it is often difficult to group or classify the various emulsions accurately.

Enzymatic emulsions contain enzymes (protein molecules) that react with soil molecules to form a cementing bond that stabilizes the soil structure and reduces the soil's affinity for water. Categorically speaking, enzymatic emulsions work on a variety of soils as long as a minimum amount of clay particles are present. When applied at low application rates to the surface of the unbound road surface, enzymatic emulsions perform well for dust suppression. They bond soil particles together and so reduce dust generation. At higher application rates, enzymatic emulsions can be used to stabilize soils. When applied and compacted properly, the treated soil can be stabilized to form a dense, firm to hard, water-resistant bound layer that can be used as a road surfacing.

Most of the information available on enzymatic emulsions comes from brochures and literature provided by the manufacturer. Therefore, it may be difficult to find independent test information for a particular product. The performance and applicability of enzymatic emulsions can vary from one product to the next. In addition, products are frequently reformulated; so, historical case studies may no longer be representative of a current product. As a result, product specific testing and/or performance verification is recommended when selecting an enzymatic emulsion.

Product Suppliers: C.S.S. Technology, Inc., P.O. Box 1618, Granbury, TX 76048, (817) 279-1136, www.csstech.com; and

Enfra LLC, 13521 Tea House Street, Santa Ana, CA 92705, (714) 397-4076, www.permazymeusa.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and enzymatic emulsion products are available.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low (AADT < 250).

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed. Additional traffic loading restrictions may be required depending on the material being treated (e.g. the load-carrying capacity of a clay soil is typically much less than that of a granular material).

Climate: None.

Weather: Enzymatic emulsion-treated surfaces can become slippery when wet, particularly with soils with high clay content (greater than 20% or 30%). Minor grading/reshaping and localized repair may be required after heavy rainfalls.

Terrain: None.

Soil Type: Categorically speaking, enzymatic emulsions work on a variety of soils as long as a minimum amount of clay particles are present (greater than 10%) and the plasticity index is greater than 8. Enzymatic emulsions generally work best on soils with 12% to 24% clay, plasticity index between 8 and 35. Enzymatic emulsions work best when the moisture content is 2% to 3% below optimum moisture content for compaction.

Other: None.

Other Comments: None.

DESIGN

SLC: N/A for dust suppression applications; typically 0.08 to 0.14 (increases with increased quality of treated material) for stabilization applications.

Other Design Values: Enzymatic emulsions can increase the soil strength by 30% to 300%.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials.

CONSTRUCTION

Availability of Experienced Personnel: Enzymatic emulsions are not as commonly used as some other dust suppressant and soil stabilizer products, but experienced contractors are, in general, available.

Materials: Enzymatic emulsion products are typically purchased in liquid concentrate form. Water is required to dilute the enzymatic concentrate once it is delivered to the site.

Equipment: Equipment required for enzymatic emulsion application includes: tanker or water truck with spray bar, grading equipment (i.e. bulldozer or motor grader), and roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Enzymatic concentrate must be mixed with water to achieve the desired concentration level prior to application. Dilution ratios of 1 part enzymatic concentrate mixed with 100 to 500 parts water are common.

Placement Process: Enzymatic emulsions can be applied by a sprayed-on method or mixed-in (windrowing) method, but mixed-in method is most common. Recommended mixing depths for dust suppression and stabilization range from 25 to 50 mm (1 to 2 in.) and 100 to 200 mm (4 to 8 in.), respectively. The moisture content of the soil prior to treatment should be below optimum for compaction so that the soil moisture content will be below or near optimum once the enzymatic emulsion is added, considering the water provided by the emulsion; if the material is very dry or saturated, processing to achieve moisture content adjustments is recommended prior to treatment. For dust suppression applications, scarifying the surface allows the enzymatic emulsion to penetrate evenly and quickly into the road surface. For soil stabilization applications, the soil is loosened to the desired treatment depth. The enzymatic emulsion is then applied uniformly using a tanker or water truck with a spray bar and mixed with the loose soil. The enzymatic emulsion is often applied in multiple passes to get better overall mixing. Once mixed in place, the treated material is graded and compacted.

Weather Restrictions: Do not apply enzymatic emulsions if rain is likely within 24 hours or if temperatures are below 4 °C (40 °F) or 16 °C (60 °F), depending on the product used.

Construction Rate: Enzymatic emulsion construction rates are in the range of 2,000 to 5,000 m^2/day (2,400 to 6,000 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction, but can be opened to light traffic once construction is complete. The stabilized material should be allowed to cure for 2 to 3 days before normal traffic, including heavy loads, are allowed onto the surface.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired. Test sections are recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Enzymatic emulsions are still relatively new compared to some other commonly used dust suppressant and soil stabilizer products. Limited research, design and construction information, and project experience are available. Performance can vary significantly between different products and is influenced by traffic, soil type, weather conditions, application method and rate, and contractor performance. As a result, product specific testing and/or performance verification is recommended when selecting an enzymatic emulsion.

Life Expectancy: Life expectancy varies depending on traffic and weather conditions. Typical life expectancy is 5 to 7 years for stabilization applications, with some treated surfaces still in service after 12 years or more. When an effective enzymatic emulsion product is applied in the proper situation, constructed properly, and maintained, good performance and long life expectancies are realized.

Ride Quality: Ride quality depends on the treated aggregate. Ride quality deteriorates over the serviceable life. Enzymatic emulsions do not provide any improvement in ride quality; however, the rate of deterioration is less than the rate for untreated surfaces. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved. Enzymatic emulsions can reduce aggregate loss by 50% or more.

Main Distress / Failure Modes: Dust, rutting, washboarding, potholes.

Preservation Needs: Periodic grading may be required, typically every 1 year and possibly after heavy rainfalls. For dust suppression applications, grading should be performed in a manner such that the stabilized "surface crust" is not broken. For soil stabilization applications, additional sprayed-on applications may be required periodically to extend the serviceable life.

SAFETY

Hazards: Proper handling and mixing procedures should be followed when mixing the concentrated liquid with water to create an emulsion.

Skid Resistance: Enzymatic emulsion-treated materials form a firm to hard, skid resistant surface. However, the road can become slippery when wet when the surface contains high clay content (greater than 20% or 30% clay).

Road Striping Possible?: No.

Other Comments: Enzymatic emulsions can typically reduce road dust by a significant amount.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Enzymes are natural materials that are manufactured from natural materials or obtained as byproducts of the food processing and manufacturing industries.

Delivery and Haul Requirements: Enzymatic concentrate must be hauled to the site from the distributor. Haul distances may be significant for remote sites. Hauling requirements are reduced somewhat by the fact that the product is shipped in concentrated form and can be mixed with water at the site.

Potential Short-Term Construction Impacts: Spills or runoff during the emulsion mixing process could have a negative impact on nearby vegetation, water quality, or aquatic species.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Enzymatic emulsion-treated soil is relatively impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by enzymatic emulsion treatments

Erosion: Enzymatic emulsions reduce the erodibility of the unbound roadway surface by binding surface particles together.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused in any manner similar to the untreated material.

Other Environmental Considerations: Environmental impacts of enzymatic emulsions may vary between different proprietary products; specific product information should be collected and reviewed prior to product use. Once diluted to normal application rates, enzymatic emulsions are typically biodegradable, nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly.

AESTHETICS

Appearance: The addition of enzymatic emulsion does not significantly alter the appearance of a soil or aggregate road. The appearance will be of a soil/aggregate surface with the overall color determined by the soil/aggregate type and source. The treated soil /aggregate will have a slightly darker appearance than the parent material.

Appearance Degradation Over Time: Without maintenance, enzymatic emulsion-treated roads deteriorate over time in terms of surface uniformity.

COST

Supply Price: N/A

Supply+Install Price: \$2.40 to \$4.80/m^2 (\$2.00 to \$4.00/yd^2) for mixing to a depth of 150 mm (6 in.).

EXAMPLE PROJECTS

Laguna Atascosa National Wildlife Refuge, Rio Hondo, TX.
Auto Tour Roads, Buenos Aires National Wildlife Refuge, Pima County, AZ.

SELECT RESOURCES

Scholen, Douglas E. (1992). Non-Standard Stabilizers, FHWA-FLP-92-011, U.S. Department of Transportation, Washington, D.C., 113 pp.

USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

LIGNOSULFONATES

GENERAL INFORMATION

Generic Name(s): Lignosulfonates, Lignin, Lignin Sulfate, Lignin Sulfides

Trade Names: Dustac, RB Ultra Plus, Polybinder, DC-22, Calbinder, and others.

Product Description: Lignosulfonates are derived from the lignin that naturally binds cellulose fibers together to give trees firmness. They have cementitious properties that bind the road surface particles together. Lignosulfonates also draw moisture from the air to keep the road surface moist (i.e. hydroscopic). When applied at low application rates to the top 25 mm (1 in.) of an unbound road surfacing, lignosulfonates are well suited for dust suppression because they bond soil particles together and help to maintain a moist road surface, and so reduce dust generation. At higher application rates and deep mixing, typically 100 to 200 mm (4 to 8 in.), lignosulfonates can be used to stabilize subgrade or base materials containing fines. Lignosulfonates increase the compressive strength and load bearing capacity of the treated material, bind materials to reduce particle loss, and provide a firm to hard dust-free surface.

Product Suppliers: Representative list of manufacturers and suppliers can be obtained from: Lignin Institute, 5775 Peachtree-Dunwoody Road, Suite 500-G, Atlanta, GA 30342, (404) 252-3663, www.lignin.info.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low (AADT < 250).

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed. Additional traffic loading restrictions may be required depending on the material being treated (e.g. the load-carrying capacity of a clay soil is typically much less than that of a sand or gravel).

Climate: Lignosulfonates work best in arid to moderate precipitation areas; they perform poorly in extremely wet regions.

Weather: Lignosulfonate-treated surfaces can become slippery when wet, particularly with soils with high fines content or plasticity. Minor grading/reshaping and localized repair may be required after heavy rainfalls.

Terrain: Because lignosulfonate-treated surfaces can become slippery when wet, they are not recommended for areas with steep terrain and regular precipitation.

Soil Type: Lignosulfonates can be used for a variety of soil types, but are most cost effective for soils having 8% to 30% fines and a plasticity index greater than 8. They do not work as well for sandy soils; permeable soils allow rapid leaching of product. For soils with high clay contents, the treated soils tend to remain slightly plastic, permitting reshaping and additional compaction under vehicle loads. Some studies have shown little to no improvement for soils with a high plasticity index (i.e. greater than 20).

Other: None.

Other Comments: None.

DESIGN

SLC: N/A for dust suppression applications; typically 0.08 to 0.14 (increases with increased quality of treated material) for stabilization applications.

Other Design Values: Lignosulfonates can increase the dry strength of soils by a factor of 2 or 3.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote leaching and softening of the treated materials. For soil stabilization applications, a thin asphalt surface treatment (e.g. chip seal) can be placed on top of the stabilized layer to reduce surface water infiltration into the stabilized material and, thus, reducing leaching of the lignosulfonates.

CONSTRUCTION

Availability of Experienced Personnel: Lignosulfonates are a commonly used dust suppressant and soil stabilizer and experienced contractors are, in general, widely available. Maintenance crews are used by some agencies for spray-on applications.

Materials: Lignosulfonates are a waste by-product of the pulp and paper industry. The main component of lignosulfonates is lignin, which comes from trees. Lignosulfonates can be purchased in liquid concentrate or dry powder form. Water is required to dilute the lignosulfonate once it is delivered to the site.

Equipment: Equipment required for lignosulfonate application includes: tanker or water truck with spray bar, grading equipment (i.e. bulldozer or motor grader), and steel drum vibratory roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Lignosulfonates must be mixed with water to achieve the desired concentration level prior to application.

Placement Process: When used for dust suppression, lignosulfonates can be applied by a sprayed-on method or mixed-in method, with mixed-in being more effective, but more costly. When used for soil stabilization, the mixed-in method is used. Recommended mixing depth for dust suppression and stabilization ranges from 25 to 50 mm (1 to 2 in.) and 100 to 200 mm (4 to 8 in.), respectively. The moisture content of the soil prior to treatment should be close to optimum for compaction; if the material is very dry or saturated, processing to achieve moisture content adjustments is recommended prior to treatment. For dust suppression applications, scarifying the surface allows the lignosulfonates to penetrate evenly and quickly into the road surface. For soil stabilization applications, the soil is loosened to the desired treatment depth. The lignosulfonate is then applied uniformly using a tanker or water truck with a spray bar and mixed with the loose soil. The lignosulfonate is often applied in multiple passes to get better overall mixing. Once mixed, the treated material is graded and compacted.

Weather Restrictions: Do not apply lignosulfonates if rain is likely within 24 hours or if the soil/aggregate is frozen.

Construction Rate: Lignosulfonate application rates are in the range of 3,300 to 5,000 m^2/hr (4,000 to 6,000 yd^2/hr). for spray-on applications.

Lane Closure Requirements: For spray-on applications, the road may remain open during application, although it is preferable to allow some time for the lignosulfonate to infiltrate into the surface material. For mixed-in applications, the lane should be closed during construction, but can be opened to traffic once construction is complete.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired. Higher application rates are needed for higher clay contents. Multiple applications are often required to obtain the desired performance. Test sections are recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Lignosulfonate is a very common dust suppressant and soil stabilizer and has been used on projects for more than 50 years. Research, design and construction information, and project experience are available. Performance can vary significantly based on traffic, soil type, weather conditions, application method and rate, contractor performance, and manufacturer.

Life Expectancy: Life expectancy varies depending on traffic and rainfall. Typical life expectancy can range from several months to more than a year for dust suppressant applications and 3 to 5 years for stabilization applications.

Ride Quality: Ride quality depends on the material being stabilized. Lignosulfonates do not provide any improvement in ride quality; however, they can reduce the rate of deterioration over the serviceable life. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved. Lignosulfonates can reduce aggregate loss by 50% or more.

Main Distress / Failure Modes: Dust, rutting, washboarding, potholes.

Preservation Needs: For dust suppressant applications, little to no preventative maintenance is required due to the short life expectancy. For soil stabilization applications, additional sprayed-on lignosulfonate applications may be required periodically, yearly to several times per year. Periodic patching or road grading may also be required. For mixed-in applications, regrading should not reduce lignosulfonate effectiveness.

SAFETY

Hazards: Concentrated lignosulfonate is corrosive to aluminum due to its acidity.

Skid Resistance: When dry, lignosulfonate-treated materials form a firm to hard, skid resistant surface. However, the surface can become slippery when wet, particularly with soils with high fines content or plasticity.

Road Striping Possible?: No.

Other Comments: Lignosulfonates can typically reduce road dust by more than 50%.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Lignosulfonates are a waste byproduct of the paper pulp industry. The main component of lignosulfonates is lignin, which comes from trees.

Delivery and Haul Requirements: Lignosulfonate products must be hauled to the site from the distributor. Haul distances may be significant for remote sites. Delivery and haul requirements will vary depending on whether the lignosulfonate is purchased in liquid concentrate or dry powder form.

Potential Short-Term Construction Impacts: Spills or runoff into surface water or infiltration into groundwater during construction can lower dissolved oxygen levels, possibly resulting in fish kills or increases in groundwater concentrations of iron, sulfur compounds, and other pollutants.

Potential Long-Term Environmental Impacts:

Leachate: Lignosulfonates are water soluble, so products can be leached from the road surface, particularly during heavy or sustained periods of rainfall.

Surface Runoff: The percentage of surface runoff versus infiltration into the road surface will vary depending on the treated soil type and gradation.

Erosion: Lignosulfonates reduce the erodibility of the unbound roadway surface by binding surface particles together.

Water quality: Lignosulfonates applied as a dust palliative have a minimal impact on water quality. Lignosulfonates discharged at high-level concentrations into water bodies have been shown to increase the biological oxygen demand (BOD) of the water body. The BOD of small streams may be increased by leaching of lignosulfonates from the road surface.

Aquatic species: At normal application rates, lignosulfonates are not expected to impact aquatic species; however, leaching of lignosulfonates from the road surface during extended heavy rain events may increase the BOD of small streams, which may negatively impact aquatic species.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: With time, the lignosulfonates will degrade or leach from the soil. The treated soil/aggregate can be reused in any manner similar to the untreated material.

Other Environmental Considerations: Environmental impacts of lignosulfonates may vary between different proprietary products; specific product information should be collected and reviewed prior to product use. At normal application rates, lignosulfonates are typically biodegradable, nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly. Few studies are available that document the affects of leaching of surface applied lignosulfonates on the BOD of streams or the rate at which lignosulfates move through soil. Best Management Practices (BMPs) should be employed to prevent lignosulfates from reaching water bodies.

AESTHETICS

Appearance: The addition of lignosulfonate does not significantly alter the appearance of a soil or aggregate road. The appearance will be of a soil/aggregate surface with the overall color determined by the soil/aggregate type and source.

Appearance Degradation Over Time: Without maintenance, lignosulfonate-treated roads deteriorate over time in terms of surface uniformity.

COST

Supply Price: N/A

Supply+Install Price: \$0.30 to \$0.60/m^2 (\$0.25 to \$0.50/yd^2) for surface application (spray-on method).

EXAMPLE PROJECTS

Buenos Aires National Wildlife Refuge, Pima County, AZ.
CR-12/29, Larimer County, CO.

SELECT RESOURCES

Lignin Institute, (404) 252-3663, www.lignin.info
Lunsford, Lt. G.D. and Mahoney, J. (2001). *Dust Control on Low-Volume Roads: A Review of Techniques and Chemicals Used*, Report No. FHWA-LT-01-002, Federal Highway Administration, Washington, D.C., 58 pp.
USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

ORGANIC PETROLEUM EMULSIONS

GENERAL INFORMATION

Generic Name(s): Organic Petroleum Emulsions, Emulsified Asphalt, Cutback Asphalt, Dust Oil, Bituminous Binder, Prime Coats

Trade Names: CSS-1, MC-70, Fuel Oil, Duo Prime Oil, Asphotac, Coherex, PennSuppress-D, Road Pro, and others.

Product Description: Organic petroleum products include cutback asphalts, asphalt emulsions, modified asphalt emulsions, and emulsified oils. These products can be used for dust suppression or to stabilize soils. These products bind soil particles together due to the adhesive properties of the asphalt component of the products. Organic petroleum products work on a variety of soil types with up to 25 to 30% clay fines and a plasticity index (PI) of less than 10. The penetration depth decreases as the amount of fines increases; therefore, lower viscosity mixtures should be used for soils with fines. The surface can be scarified to increase penetration depth and decrease penetration time. Organic petroleum products can be sprayed on or mixed in, depending on the particular product (most are sprayed on). Several manufacturers recommend that their product be applied in two separate applications. A product specific analysis is needed to determine or verify the product's environmental impact.

Most of the information available on petroleum emulsions comes from brochures and literature provided by the manufacturer. Therefore, it may be difficult to find independent test information for a particular product. The performance and applicability of petroleum emulsions can vary from one product to the next. In addition, products are frequently reformulated; so, historical case studies may no longer be representative of a current product. As a result, product specific testing and/or performance verification is recommended when selecting a petroleum emulsion.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from:
Asphalt Emulsion Manufacturers Association, PMB 250, 3 Church Circle, Annapolis, MD 21401, (410) 267-0023, www.aema.org;
American Refining Group, Inc., 77 North Kendall Ave., Bradford, PA 16701, (814) 368-1200, www.amref.com; and
Midwest Industrial Supply, Inc., P.O. Box 8431, Canton, OH 44711, (800) 321-0699, www.midwestind.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and petroleum emulsion products are available.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low.

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: Categorically speaking, petroleum emulsions provide effective dust control and soil stabilization on a variety of soils, including sands, silts, and clays. Certain manufacturers may recommend which soil types their product is best suited for. Organic petroleum products work on a variety of soil types with up to 25 to 30% clay fines and a plasticity index (PI) of less than 10.

Other: Surfaces treated with petroleum emulsions are susceptible to damage by snow plowing operations. Well-maintained surfaces are less susceptible to damage than worn surfaces and mixed-in applications are less susceptible than sprayed-on applications.

Other Comments: None.

DESIGN

SLC: N/A for dust suppression applications; 0.10 to 0.25 for soil stabilization. Value will vary with soil type, petroleum emulsion product, and application rate. Laboratory mixing should be performed to determine the strength of the stabilized material. Using laboratory strength testing results, an estimate of the SLC can be made using correlations or engineering judgment.

Other Design Values: None.

Base/Subbase Requirements: Where local soils are stabilized to form a road surfacing, it is unlikely that an imported base or subbase layer will be included.

Other Comments: The road surface should be sloped to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials.

CONSTRUCTION

Availability of Experienced Personnel: Contractors experienced in the application of petroleum dust suppressants and soil stabilizers are, in general, widely available.

Materials: Most petroleum emulsions are typically purchased in liquid emulsion form, but are diluted prior to application. Of the emulsified asphalts, SS-1, SS-1h, CSS-1, and CSS-1h are commonly used. Other petroleum emulsion products are composed of oils or petroleum resins. Waste oils should not be used. Cutback asphalts can be used, although there are environmental concerns associated with cutback asphalts.

Cutback Asphalt: Advantages of cutback asphalts include a lower application temperature, 30 to 115 °C (85 to 240 °F), and higher asphalt percentages than emulsified asphalts (approximately 80% compared to approximately 60%). Disadvantages of cutback asphalts include hydrocarbon emissions into the atmosphere during the evaporation process and potential fire hazards during construction due to the use of solvents in the cutback asphalt. Due to environmental concerns, the use of cutback asphalts has been prohibited in some areas.

Emulsified Asphalt: Advantages of emulsified asphalt include cooler application temperature (20 to 85 °C [70 to 185 °F]) than cutback asphalts and the water that evaporates is environmentally safe.

Equipment: Equipment required for petroleum emulsion application includes: tanker or water truck with spray bar, disc or rotary mixer, grading equipment (i.e. bulldozer or motor grader), and roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Emulsified or cutback asphalts are mixed at a stationary asphalt plant and shipped to the site. Other petroleum emulsion products are shipped in emulsion form from the supplier. Some products will be diluted with water, at typical dilutions of about 4 parts water to 1 part emulsion.

Placement Process: Petroleum emulsions can be applied by a sprayed-on method or mixed-in method, although most petroleum products are used for dust suppression and are applied by the sprayed-on method. Recommended mixing depths for dust suppression and stabilization ranges from 25 to 50 mm (1 to 2 in.) and 100 to 150 mm (4 to 6 in.), respectively. For dust suppression applications, scarifying the surface allows the petroleum emulsion to penetrate evenly and quickly into the road surface. For soil stabilization applications, the soil is loosened to the desired treatment depth. The petroleum emulsion is then applied uniformly using a tanker or water truck with a spray bar and mixed with the loose soil using a disc, rotary mixer, or blading equipment. The petroleum emulsion is often applied in multiple passes to get better overall mixing. Once mixed, some products require time for the excess water and/or hydrocarbons to evaporate before the material is graded and compacted. Even when the mixed-in method is used, some of the emulsion (up to 40%) is saved for a spray-on application prior to compaction. This spray-on application is applied to ensure that a good crust is formed at the surface.

Weather Restrictions: Weather restrictions can very between products. In general, do not apply petroleum emulsions if rain is likely within 24 hours or if temperatures are below 10 °C (50 °F).

Construction Rate: Petroleum emulsion application rates are in the range of 2,000 to 5,000 m^2/day (2,400 to 6,000 yd^2/day).

Lane Closure Requirements: For sprayed-on applications, the roadway can remain open, although emulsion splash/spray on vehicles can be a problem. For mixed-in applications, the roadway lane should be closed during construction, but can be opened to traffic once construction is completed.

Other Comments: The required dilution and application rates will vary based on the petroleum emulsion product used, characteristics of the material to be treated, and the degree of stabilization desired.

SERVICEABILITY

Reliability and Performance History: Emulsified and cutback asphalts are commonly used products. Research, design and construction information, and project experience are available. For other petroleum emulsion products, the amount of available information varies from product to product. Performance can vary significantly between different products and is influenced by traffic, soil type, weather conditions, application method and rate, and contractor performance. As a result, product specific testing and/or performance verification is recommended when selecting a petroleum emulsion.

Life Expectancy: Life expectancy varies depending on application rate and depth, traffic, and weather conditions. Typical life expectancy is 6 to 9 months for dust suppression applications. Typical life expectancy is 5 to 9 years for stabilization applications.

Ride Quality: Ride quality depends on the material being stabilized. Petroleum emulsions do not provide any improvement in ride quality; however, they can reduce the rate of deterioration over the serviceable life. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved. Petroleum emulsions can reduce aggregate loss by 50% or more.

Main Distress / Failure Modes: Dust, cracking, raveling, washboarding, potholes.

Preservation Needs: For soil stabilization applications, additional light sprayed-on applications may be required periodically to extend the serviceable life. The first maintenance application is typically 1 to 1.5 years after initial construction; subsequent applications typically occur every 2 to 3 years. Localized patching and repair work may be required periodically.

SAFETY

Hazards: When cutback asphalts are used, the solvents used can create a health hazard (fumes) and a fire/explosion hazard during construction; proper engineering controls and construction practices should be utilized to minimize safety risks.

Skid Resistance: Petroleum emulsion-treated materials form a firm to hard, skid resistant surface. However, skid resistance is reduced significantly in wet weather.

Road Striping Possible?: No.

Other Comments: Petroleum emulsions can typically reduce road dust by a significant amount. Field tests have shown that particular petroleum emulsion products reduced fugitive dust by at least 50% to 90% after three months, 20% to 40% after six months, and 10% or less after 12 months.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Petroleum emulsions primarily consist of manufactured petroleum products, including asphalt, oils, or petroleum resins.

Delivery and Haul Requirements: Petroleum emulsion must be hauled to the site from the distributor. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Hydrocarbon emissions into the atmosphere can be a significant impact if cutback asphalts are used. Spills or runoff during the emulsion mixing process could have a negative impact on nearby vegetation, water quality, or aquatic species. A spill prevention and containment plan should be in place to minimize the potential for off site runoff of spills.

Potential Long-Term Environmental Impacts:

Leachate: None once the petroleum emulsion has cured.

Surface Runoff: Petroleum emulsion-treated soil is relatively impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by petroleum emulsion treatments.

Erosion: Petroleum emulsions reduce the erodibility of the unbound roadway surface by binding surface particles together. Sediment loading in surface runoff water can be reduced by more than 50%.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate may be reused as a construction material, depending on any environmental concerns related to the emulsion used.

Other Environmental Considerations: Environmental impacts of petroleum emulsions may vary between different proprietary products; specific product information should be collected and reviewed prior to product use. Most petroleum emulsions are typically nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly, although some may contain toxic materials. Some petroleum emulsion products may contain carcinogenic polycyclic aromatic hydrocarbons.

AESTHETICS

Appearance: The addition of petroleum emulsion generally alters the appearance of a soil or aggregate road by changing the color to dark brown or dark gray.

Appearance Degradation Over Time: Without maintenance, petroleum emulsion-treated roads deteriorate over time in terms of surface uniformity.

COST

Supply Price: N/A

Supply+Install Price: \$3.00 to \$4.00/m^2 (\$2.50 to \$3.30/yd^2).

EXAMPLE PROJECTS

Vermount Road, Franklin County , KS.

SELECT RESOURCES

USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

SYNTHETIC POLYMER EMULSIONS

GENERAL INFORMATION

Generic Name(s): Synthetic Polymer Emulsions, Polyvinyl Acetate, Vinyl Acrylic

Trade Names: Aerospray 70A, Earthbound, Liquid Dust Control, PolyPavement, PX-300, Soil Sement, TerraBond, and more.

Product Description: Many of the emulsions for dust suppression and/or soil stabilization are proprietary in nature and the exact composition and stabilization mechanisms are not publicly available; therefore, it is often difficult to group or classify the various emulsions accurately.

Synthetic polymer emulsions primarily consist of acrylic or acetate polymers that are specifically produced for dust control or soil stabilization, or are by-products from the adhesive or paint industries. The polymers cause a chemical bond to form between soil particles, creating a dense and water-resistant road surface. In general, polymer emulsions can be used on most soils; however, certain products are more effective on specific soil types. When applied at low application rates (sprayed-on or mixed-in) to the surface of the unbound road surface, synthetic polymer emulsions perform well for dust suppression. They bond soil particles together and so reduce dust generation. At higher application rates (mixed-in), synthetic polymer emulsions can be used to stabilize soils. Graded aggregates can be stabilized to form a very hard bound layer that can be used as a road surfacing.

Most of the information available on synthetic polymer emulsions comes from brochures and literature provided by the manufacturer. Therefore, it may be difficult to find independent test information for a particular product. The performance and applicability of synthetic polymer emulsions can vary from one product to the next. In addition, products are frequently reformulated; so, historical case studies may no longer be representative of a current product. As a result, product specific testing and/or performance verification is recommended when selecting a synthetic polymer emulsion.

Product Suppliers: Enviroseal Corporation, 1019 SE Holbrook Ct., Port Lucie, FL 34952, (800) 775-9474, www.enviroseal.com; and

Midwest Industrial Supply, Inc., P.O. Box 8431, Canton, OH 44711, (800) 321-0699, www.midwestind.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and synthetic polymer emulsion products are available.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low (AADT < 250).

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed. Additional traffic loading restrictions may be required depending on the material being treated (e.g. the load-carrying capacity of a clay soil is typically much less than that of an aggregate material).

Climate: Synthetic polymer emulsions require a period of dry weather after construction to dry out and begin curing. In extremely wet climates, a sufficient dry spell may not occur for the initial drying of the stabilized material.

Weather: For extended periods of wet weather (greater than 2 weeks), some materials treated with synthetic polymer emulsion will soften and have reduced abrasion resistance.

Terrain: None.

Soil Type: Categorically speaking, synthetic polymer emulsions provide effective dust control and soil stabilization on a variety of soils, including sands, silts, and clays. Certain manufacturers may recommend which soil types their product is best suited for. In general, synthetic polymer emulsions work best for silty sand materials with fines content between 5% and 20% and plasticity index below 8. For granular materials with little to no fines (less than 2%), an excessive amount of polymer may be required for stabilization.

Other: Surfaces treated with synthetic polymer emulsions are susceptible to damage by snowplowing operations. Well-maintained surfaces are less susceptible to damage than worn surfaces and mixed-in applications are less susceptible than sprayed-on applications.

Other Comments: None.

DESIGN

SLC: N/A for dust suppression applications; 0.05 to 0.20 for soil stabilization. Value will vary with soil type, synthetic polymer product, and application rate. Laboratory mixing should be performed to determine the strength of the stabilized material. Using laboratory strength testing results, an estimate of the SLC can be made using correlations or engineering judgment.

Other Design Values: The unconfined compressive strength of soils stabilized with synthetic polymers can range from 5.5 to 15.1 MPa (800 to 2,200 psi). Synthetic polymer emulsions can increase the soil strength by up to 200%.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support to prevent rutting, potholes, etc.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials.

CONSTRUCTION

Availability of Experienced Personnel: Contractors experienced in the application of dust suppressants and soil stabilizers are, in general, widely available. Contractors will experience using a particular product may be limited in a certain area. Contractors should work closely with the product supplier's technical representative to ensure that the product is applied properly.

Materials: Synthetic polymer emulsions are typically purchased in liquid concentrate form. Water is required to dilute the polymer concentrate once it is delivered to the site.

Equipment: Equipment required for synthetic polymer emulsion application includes: tanker or water truck with spray bar, disc or rotary mixer, grading equipment (i.e. bulldozer or motor grader), and roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Synthetic polymer concentrate must be mixed with water to achieve the desired concentration level prior to application.

Placement Process: Synthetic polymer emulsions can be applied by a sprayed-on method or mixed-in method. Recommended mixing depths for dust suppression and stabilization ranges from 25 to 50 mm (1 to 2 in.) and 100 to 200 mm (4 to 8 in.), respectively. For dust suppression applications, scarifying the surface allows the synthetic polymer emulsion to penetrate evenly and quickly into the road surface. For soil stabilization applications, the soil is loosened to the desired treatment depth. The synthetic polymer emulsion is then applied uniformly using a tanker or water truck with a spray bar and mixed with the loose soil using a disc, rotary mixer, or blading equipment. The synthetic polymer emulsion is often applied in multiple passes to get better overall mixing. Once mixed, the treated material is graded and compacted. Even when the mixed-in method is used, some of the emulsion (up to 40%) is saved for a spray-on application prior to compaction. This spray-on application is applied to ensure that a good crust is formed at the surface.

Weather Restrictions: Do not apply synthetic polymer emulsions if rain is likely within 48 hours or if temperatures are below 6 °C (42 °F).

Construction Rate: Synthetic polymer emulsion application rates are in the range of 2,000 to 5,000 m^2/day (2,400 to 6,000 yd^2/day).

Lane Closure Requirements: For sprayed-on applications, the roadway can remain open, although emulsion splash/spray on vehicles can be a problem. For mixed-in applications, the roadway lane should be closed during construction, but can be opened to traffic once the stabilized material has dried, typically after less than 1 or 2 hours (warm, sunny weather) to 1 day (cool, cloudy weather). Synthetic polymer emulsions will take approximately 30 days to cure completely and develop their full strength.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired. Laboratory tests and/or test sections are recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Synthetic polymer emulsions are commonly used dust suppressant and soil stabilizer products. Limited research, design and construction information, and project experience are available. Performance can vary significantly between different products and is influenced by traffic, soil type, weather conditions, application method and rate, and contractor performance. As a result, product specific testing and/or performance verification is recommended when selecting a synthetic polymer emulsion.

Life Expectancy: Life expectancy varies depending on application rate and depth, traffic, and weather conditions. Typical life expectancy is 6 months to 1 year for dust suppression applications. Typical life expectancy is 5 to 10 years for stabilization applications.

Ride Quality: Ride quality depends on the material being stabilized. Synthetic polymer emulsions do not provide any improvement in ride quality; however, they can reduce the rate of deterioration over the serviceable life. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved. Synthetic polymer emulsions can reduce aggregate loss by 50% or more.

Main Distress / Failure Modes: Dust, rutting, washboarding, potholes.

Preservation Needs: For soil stabilization applications, additional light sprayed-on applications may be required periodically to extend the serviceable life. The first maintenance application is typically 1 to 1.5 years after initial construction; subsequent applications typically occur every 2 to 3 years. Localized patching and repair work may be required periodically.

SAFETY

Hazards: Proper handling and mixing procedures should be followed when mixing the concentrated liquid with water to create an emulsion. Rutting can lead to water accumulation on the pavement surface, causing a driving hazard.

Skid Resistance: Synthetic polymer emulsion-treated materials form a firm to hard, skid resistant surface.

Road Striping Possible?: No.

Other Comments: Synthetic polymer emulsions can typically reduce road dust by a significant amount. Field tests have shown that a particular synthetic polymer product reduced fugitive dust by at least 95% after three months and at least 80% after 11 months.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Synthetic polymer emulsions primarily consist of acrylic or acetate polymers that are specifically produced for dust control or soil stabilization, or are by-products from the adhesive or paint industries.

Delivery and Haul Requirements: Synthetic polymer concentrate must be hauled to the site from the distributor. Haul distances may be significant for remote sites. Hauling requirements are reduced somewhat by the fact that the product is shipped in concentrated form and can be mixed with water at the site.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Tests have shown that synthetic polymer emulsions can reduce surface runoff by about 20% compared to the untreated soil.

Erosion: Synthetic polymer emulsions reduce the erodibility of the unbound roadway surface by binding surface particles together. Sediment loading in surface runoff water can be reduced by 50%.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused in any manner similar to the untreated material.

Other Environmental Considerations: Environmental impacts of synthetic polymer emulsions may vary between different proprietary products; specific product information should be collected and reviewed prior to product use. Categorically speaking, synthetic polymer emulsions are typically nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly.

AESTHETICS

Appearance: The addition of synthetic polymer emulsion does not significantly alter the appearance of a soil or aggregate road. The appearance will be of a soil/aggregate surface with the overall color determined by the soil/aggregate type and source.

Appearance Degradation Over Time: Without maintenance, synthetic polymer emulsion-treated roads deteriorate over time in terms of surface uniformity.

COST

Supply Price: \$0.80 to \$4.25/L (\$3.00 to \$16.00/gal)

Supply+Install Price: \$2.40 to \$14.30/m^2 (\$2.00 to \$12.00/yd^2) for mixing to a depth of 150 mm (6 in.).

EXAMPLE PROJECTS

Kelso Dunes Access Road, Mojave National Preserve, CA.
Auto Tour Roads, Buenos Aires National Wildlife Refuge, Pima County, AZ.

SELECT RESOURCES

USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

TREE RESIN EMULSIONS

GENERAL INFORMATION

Generic Name(s): Tree Resin Emulsions, Tall Oil Emulsions, Pitch Emulsions, Pine Tar Emulsions

Trade Names: Dustbinder, Dustrol EX, Enduraseal 200, RESIN PAVEMENT, RESINPAVE, ROAD OYL, TerraPave, and others.

Product Description: Tree resin emulsions are derived from tree resins (mainly pine, fir, and spruce) combined with other additives to produce an emulsion that can be used for dust suppression or soil stabilization. When applied at low application rates to the top 25 mm (1 in.) of an unbound road surfacing, tree resin emulsions are well suited for dust suppression because they bond soil particles together and so reduce dust generation. At higher application rates and deep mixing, typically 100 to 200 mm (4 to 8 in.), tree resin emulsions can be used to stabilize subgrade or base materials containing fines. Graded aggregates (typical maximum particle size less than 10 mm [3/8 in.]) can be stabilized to form a relatively hard surface layer that can be used as a road surfacing; the stabilized aggregate is purported to be up to three times stronger than asphalt concrete. The bound aggregate surfacing is usually 50 mm (2 in.) thick.

Most of the information available on tree resin emulsions comes from brochures and literature provided by the manufacturer. Therefore, it may be difficult to find independent test information for a particular product. The performance and applicability of tree resin emulsions can vary from one product to the next. In addition, products are frequently reformulated; so, historical case studies may no longer be representative of a current product. As a result, product specific testing and/or performance verification is recommended when selecting a tree resin emulsion.

Product Suppliers: ARR-MAZ Products, LP, 621 Winter Haven, FL 33880, (800) 541-8926, www.roadproductscorp.com.

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and tree resin emulsion products are available.

APPLICATION

Typical Use: Dust suppressant, soil stabilizer.

Traffic Range: Very Low to Low (AADT < 250); above this traffic range, the surface will require more frequent product applications and surface grading.

Restrictions:

Traffic: Required application frequency will increase with increased truck traffic or increased vehicle speed. Additional traffic loading restrictions may be required depending on the material being treated (e.g. the load-carrying capacity of a clay soil is typically much less than that of a sand or gravel material).

Climate: Tree resin emulsions can be used in all climates, but work best in areas with arid or moderate precipitation conditions.

Weather: For extended periods of wet weather (greater than 2 weeks), some materials treated with tree resin emulsion will soften and allow ruts to form.

Terrain: Surfaces treated with tree resin emulsions can become slippery when wet, particularly with soils with high fines content or high plasticity; therefore, tree resin emulsions are not recommended for steep terrain applications in wet climates.

Soil Type: Categorically speaking, tree resin emulsions provide effective dust control and soil stabilization on a variety of soils, including sands, silts, and clays. Certain manufacturers may recommend which soil types their product is best suited for. In general, tree resin emulsions work best for silty sand materials with fines content between 5% and 30% and plasticity index below 8. Tree resin emulsions provide little to no improvement for soils with high plasticity (plasticity index greater than 30). For granular materials with little to no fines (less than 2%), an excessive amount of tree resin emulsion may be required for stabilization.

Other: Surfaces treated with tree resin emulsions are susceptible to damage by snowplowing operations. Well-maintained surfaces are less susceptible to damage than worn surfaces and mixed-in applications are less susceptible than sprayed-on applications.

Other Comments: None.

DESIGN

SLC: N/A for dust suppression applications; 0.10 to 0.30 for soil stabilization (lower values for clay soils, higher values for granular materials). Value will vary with soil type, tree resin product, and application rate. Laboratory mixing should be performed to determine the strength of the stabilized material. Using laboratory strength testing results, an estimate of the SLC can be made using correlations or engineering judgment.

Other Design Values: Tree resin emulsions can increase the unconfined compressive strength of clay soils by 25% to 75% or more. The compressive strength of granular materials treated with tree resin emulsions can be 3 times greater than HACP.

Base/Subbase Requirements: Where local soils are treated with tree resin emulsion to form a stabilized surfacing, it is unlikely that an imported base/subbase layer would be provided. The stabilized zone and underlying soil should be designed to provide adequate structural support for traffic.

Other Comments: The road surface should be sloped to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials.

CONSTRUCTION

Availability of Experienced Personnel: Contractors experienced in the application of dust suppressants and soil stabilizers are, in general, widely available. Contractors will experience using a particular product may be limited in a certain area. Contractors should work closely with the product supplier's technical representative to ensure that the product is applied properly.

Materials: Tree resin emulsions are typically purchased in liquid concentrate form. Water is required to dilute the resin concentrate once it is delivered to the site.

Equipment: Equipment required for tree resin emulsion application includes: tanker or water truck with spray bar, disc or rotary mixer, grading equipment (i.e. bulldozer or motor grader), and roller. For treatment of aggregates, a pugmill for mixing is recommended. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Tree resin concentrate must be mixed with water to achieve the desired concentration level prior to application. For stabilization of aggregates, mixing the aggregate and emulsion in a pugmill is recommended.

Placement Process: Tree resin emulsions can be applied by a sprayed-on method or mixed-in method. Recommended mixing depths for dust suppression and stabilization ranges from 25 to 50 mm (1 to 2 in.) and 100 to 200 mm (4 to 8 in.), respectively. For dust suppression applications, scarifying the surface allows the tree resin emulsion to penetrate evenly and quickly into the road surface. For soil stabilization applications, the soil is loosened to the desired treatment depth. The tree resin emulsion is then applied uniformly using a tanker or water truck with a spray bar and mixed with the loose soil using a disc, rotary mixer, or blading equipment. The tree resin emulsion is often applied in multiple passes to get better overall mixing. Once mixed, the treated material is graded and compacted. Even when the mixed-in method is used, some of the emulsion (up to 40%) is saved for a spray-on application prior to compaction. This spray-on application is applied to ensure that a good crust is formed at the surface.

For mixing with aggregates to form a bound surfacing, the aggregate and emulsion are mixed in a pugmill, spread onto the prepared base, and compacted. The surface is then sprayed with a light spray-on application of tree resin emulsion.

Weather Restrictions: Do not apply tree resin emulsions if rain is likely within 48 hours or if temperatures are below 6 °C (42 °F).

Construction Rate: Tree resin emulsion application rates are in the range of 2,000 to 5,000 m^2/day (2,400 to 6,000 yd^2/day).

Lane Closure Requirements: For sprayed-on applications, the roadway can remain open, although emulsion splash/spray on vehicles can be a problem. For mixed-in applications, the roadway lane should be closed during construction, but can be opened to traffic once the stabilized material has dried, typically after 1 to 4 days. Tree resin emulsions will take approximately 30 days to cure completely and develop their full strength.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired. Laboratory tests and/or test sections are recommended to determine/verify the appropriate application rate. Some project managers have reported that tree resin emulsions are messy and difficult to work with.

SERVICEABILITY

Reliability and Performance History: Tree resin emulsions are commonly used dust suppressant and soil stabilizer products. Limited research, design and construction information, and project experience are available. Performance can vary significantly between different products and is influenced by traffic, soil type, weather conditions, application method and rate, and contractor performance. As a result, product specific testing and/or performance verification is recommended when selecting a tree resin emulsion.

Life Expectancy: Life expectancy varies depending on application rate and depth, traffic, and weather conditions. Typical life expectancy is 6 months for dust suppression applications. Typical life expectancy is 5 to 10 years or more for stabilization applications.

Ride Quality: Ride quality depends on the material being stabilized. Synthetic polymer emulsions do not provide any improvement in ride quality; however, they can reduce the rate of deterioration over the serviceable life. By reducing particle loss and washboarding, surface distress is reduced and ride quality is preserved. Tree resin emulsions can significantly reduce aggregate loss.

Main Distress / Failure Modes: Dust, rutting, washboarding, potholes.

Preservation Needs: For soil stabilization applications, additional light sprayed-on applications may be required periodically to extend the serviceable life. The first maintenance application is typically 1 to 1.5 years after initial construction; subsequent applications typically occur every 2 to 3 years. Localized patching and repair work may be required periodically.

SAFETY

Hazards: Proper handling and mixing procedures should be followed when mixing the concentrated liquid with water to create an emulsion. Rutting can lead to water accumulation on the pavement surface, causing a driving hazard.

Skid Resistance: Tree resin emulsion-treated materials form a firm to hard, skid resistant surface. However, surfaces treated with tree resin emulsions can become slippery when wet, particularly with soils with high fines content or high plasticity.

Road Striping Possible?: No.

Other Comments: Tree resin emulsions can typically reduce road dust by a significant amount. Field tests have shown that a particular tree resin emulsion product reduced fugitive dust by at least 70% after 3 months, 50% after 6 months, and 30% after 12 months.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Tree resin emulsions are derived from tree resins (mainly pine, fir, and spruce) combined with other additives. The tree resins are a byproduct of the pulp and paper industry.

Delivery and Haul Requirements: Tree resin concentrate must be hauled to the site from the distributor. Haul distances may be significant for remote sites. Hauling requirements are reduced somewhat by the fact that the product is shipped in concentrated form and can be mixed with water at the site.

Potential Short-Term Construction Impacts: Construction processes may impact vegetation adjacent to the roadway. Large tree resin emulsion spills during construction could potentially impact water quality and aquatic species in nearby streams. A spill prevention and containment plan should be in place to reduce the probability of spills and off-site runoff.

Potential Long-Term Environmental Impacts:

Leachate: None once the product has cured.

Surface Runoff: Tree resin emulsions can reduce the permeability of surface materials, resulting in an increase in surface runoff. However, surface runoff water quality is not generally impacted by tree resin emulsion-treated surfacings. In parking areas, oil and other vehicle fluids can be collected by surface runoff, affecting the water quality.

Erosion: Tree resin emulsions reduce the erodibility of the unbound roadway surface by binding surface particles together. Sediment loading in surface runoff water can be significantly reduced.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused in any manner similar to the untreated material.

Other Environmental Considerations: Environmental impacts of tree resin emulsions may vary between different proprietary products; specific product information should be collected and reviewed prior to product use. Categorically speaking, tree resin emulsions are typically nontoxic, nonhazardous, noncorrosive, and generally environmentally friendly.

AESTHETICS

Appearance: The addition of tree resin emulsion does not significantly alter the appearance of a soil or aggregate road. The appearance will be of a soil/aggregate surface with the overall color determined by the soil/aggregate type and source.

Appearance Degradation Over Time: Without maintenance, tree resin emulsion-treated roads deteriorate over time in terms of surface uniformity.

COST

Supply Price: N/A

Supply+Install Price: \$21.40 to \$53.60/m^2 (\$18.00 to \$45.00/yd^2) for 50 mm (2 in.) thick stabilized aggregate layer.

EXAMPLE PROJECTS

Chicago Center for Green Technology, Chicago, IL.

SELECT RESOURCES

USDA Forest Service (1999), *Dust Palliative Selection and Application Guide*, San Dimas Technology and Development Center, 23 pp.

STABILIZED AGGREGATE AND SOIL (OTHER THAN SURFACING)

FLY ASH

GENERAL INFORMATION

Generic Name(s): Fly Ash, Coal Ash, Bottom Ash

Trade Names: N/A

Product Description: Fly ash is a residue of coal combustion that occurs at power generation plants throughout the United States. Fly ash can be used to lower the water content of soils, reduce shrink-swell potential, increase workability, and increase soil strength and stiffness. Two types of fly ash can be used to stabilize soils: Class C and Class F. Both classes of fly ash contain pozzolans, but Class C fly ash is rich in calcium that allows it to be self-cementing. Class F fly ash requires an activation agent (e.g. lime or cement) for a pozzolanic reaction to occur and create cementitious bonds within the soil.

Product Suppliers: Representative list of producers can be obtained from: American Coal Ash Association, 15200 East Girard Avenue, Suite 3050, Aurora, CO 80014, (720) 870-7897, www.acaa-usa.org.

APPLICATION

Typical Use: Soil stabilizer.

Traffic Range: Fly ash-stabilized soils/aggregates are not used as a surfacing material. Fly ash-stabilized subgrade and subbase materials can be used for very low to high traffic volume applications.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: Fly ash can be used to modify/stabilize a variety of materials, including clays, silts, sands, and gravel.

Other: For fly ashes with greater than 10% sulfates, high initial strengths have been observed for fly ash stabilized materials, but the durability of the stabilized material may be reduced.

Other Comments: Fly ash stabilization is often used as a construction expedient when wet soil conditions are present and weather conditions or time constraints prevent the contractor from processing the soil to dry it out. The fly ash lowers the water content and plasticity of the soil and improves workability; this allows for construction of an adequate working platform for construction operations. Fly ash is also used to reduce the shrink/swell potential of clay soils.

DESIGN

SLC: 0.10 to 0.20. Value will vary with soil type and fly ash mixing percentage. Laboratory mixing should be performed to determine the strength of the stabilized material. Using laboratory strength testing results, an estimate of the SLC can be made using correlations, local practice, or engineering judgment.

Other Design Values: Fly ash stabilization of clay soils can increase CBR values from 2 to 3 (untreated) to 25 to 35 (treated). Unconfined compressive strengths for fly ash-stabilized clay soils can vary from 700 to 3,500 kPa (100 to 510 psi), depending on fly ash source and application rate and the material being stabilized.

Base/Subbase Requirements: The use of fly ash stabilized subgrade can reduce the design thickness for base and/or subbase layers.

Other Comments: The base thickness and appropriate road surfacing should be selected based on anticipated traffic volumes.

CONSTRUCTION

Availability of Experienced Personnel: Fly ash stabilization is relatively straightforward and qualified contractors are, in general, widely available.

Materials: Fly ash and water are required for fly ash stabilization. Fly ash is a residue of coal combustion that occurs at power generation plants throughout the United States. Two types of fly ash can be used to stabilize soils: Class C and Class F. Class C fly ash is produced from burning lignite and subbituminous coal mostly found in the western United States. Class F fly ash is produced from burning anthracite or bituminous coal mostly found in the eastern, southern, and midwestern United States.

Equipment: Equipment required for fly ash stabilization includes: mechanical spreader, tanker or water truck with spray bar, rotary mixer or disc, grading equipment (i.e. bulldozer or motor grader), and light sheepsfoot or pneumatic roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Subgrade and base materials are usually treated with fly ash using in-place mixing.

Placement Process: The fly ash is uniformly applied to the existing surface and water is sprayed on the surface. A rotary mixer or disc is then used to mix the fly ash, soil, and water together. If water can be added by the rotary mixer during processing, this approach is recommended. Maximum strengths are obtained when the moisture content is 0 to 7 percent below the optimum water content, depending on the material being treated. Subgrade soils are usually treated to a depth of 200 mm (8 in.). For deeper mixing and stabilization, the material should be mixed and compacted in 200 mm (8 in.) lifts. Once mixed, the loose surface is graded and compacted. Delays in compaction can result in lower maximum strengths for the stabilized material. Therefore, construction specifications often require that mixing, grading, and compaction must be finished within 2 hours of fly ash spreading.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the soil is frozen. Fly ash stabilization should only be performed when air temperatures are greater 10 ºC (50 ºF).

Construction Rate: Fly ash application rates are in the range of 2,950 to 4,200 m^2/day (3,500 to 5,000 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction. If possible, it is recommended that the lane remain closed until a wearing surface can be applied; however, the treated material can be opened to temporary traffic after one day.

Other Comments: The required application rate will vary based on the characteristics of the fly ash and the material to be treated and the degree of modification/stabilization desired. Application rates can be in the range of 10% to 20%. Laboratory testing is recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Fly ash stabilization has been used for soil stabilization for roads for more than 50 years. Research, design and construction information, and project experience are available.

Life Expectancy: Life expectancy varies depending on traffic, degree of stabilization, total road structure, and weather conditions. Fly ash-stabilized materials should not be used as a permanent surfacing material. Typical life expectancy for fly ash-stabilized subgrade or base materials, assuming that the roadway has a proper structural design, is more than 20 years and will generally last for the lifetime of the roadway.

Ride Quality: N/A; not a surfacing.

Main Distress / Failure Modes: The road surfacing distress mode should not be directly impacted by the use of fly ash stabilization. Where a stabilized subbase layer is used, any differential movement of the underlying subgrade, due to expansive soils or frost action, could in turn crack the stabilized subbase and lead to cracking of the road surfacing.

Preservation Needs: N/A; not a surfacing.

SAFETY

Hazards: None.

Skid Resistance: N/A; not a surfacing.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Fly ash is a residue of coal combustion that occurs at power generation plants throughout the United States.

Delivery and Haul Requirements: Fly ash must be transported to the site from the distributor. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road.

Potential Long-Term Environmental Impacts:

Leachate: Fly ash stabilization can lower the permeability of the treated soil, but the treated material is still susceptible to leaching. Fly ash composition varies depending on the source of coal and the type of power plant that generated the fly ash. Most fly ashes contain heavy metals, as well as other compounds, that could potentially impact the environment. A water leach test should be performed on the soil-fly ash mixture to determine if the leachate meets regulatory standards for use.

Surface Runoff: Since it is not used as a surfacing, fly ash does not impact surface runoff.

Erosion: Fly ash-stabilized materials are a bound material and not very susceptible to erosion, especially considering that the stabilized material is not used as a surfacing material.

Water quality: Fly ash-stabilized materials have the potential to leach out heavy metals and other compounds that may affect groundwater and nearby surface waters. Laboratory testing and transport modeling may be required to determine potential water quality impacts if water sources are located near the stabilized area.

Aquatic species: Fly ash-stabilized materials have the potential to leach out heavy metals and other compounds that may affect aquatic species. Laboratory testing and transport modeling may be required to determine potential aquatic species impacts if water sources are located near the stabilized area.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused as a construction material.

Other Environmental Considerations: N/A

AESTHETICS

Appearance: Fly ash stabilization does not significantly alter the appearance of a soil/aggregate material. The appearance will be of a soil/aggregate surface with the overall color determined by the material type and source. However, the fly ash-stabilized material is typically covered with a wearing surface.

Appearance Degradation Over Time: Fly ash-stabilized materials do not experience appearance degradation over time.

COST

Supply Price: N/A

Supply+Install Price: \$2.50 to \$4.50/m^2 (\$2.10 to \$3.80/yd^2)

EXAMPLE PROJECTS
Ozark National Forest, AR. Newark International Airport, Newark, NJ.
SELECT RESOURCES
Acosta, H.A., Edil, T.B., and Benson, C.H. (2003). "Soil Stabilization and Drying Using Fly Ash," Geo Engineering Report No. 03-03, University of Wisconsin-Madison, 137 pp. Ferguson, Glen (1993). "Use of Self-Cementing Fly Ashes as a Soil Stabilization Agent," *Fly Ash for Soil Improvement*, American Society of Civil Engineers, pp. 1-14.

LIME

GENERAL INFORMATION

Generic Name(s): Lime, Quicklime, Hydrated Lime

Trade Names: N/A

Product Description: Lime can be obtained in the form of quicklime or hydrated lime. Quicklime is manufactured by calcination of limestone at high temperatures, which chemically transforms calcium carbonate into calcium oxide. Hydrated lime is created when quicklime chemically reacts with water. Lime can be used to stabilize clay soils and submarginal base materials (i.e. clay-gravel, caliche, etc.). When added to clay soils, lime reacts with water in the soil and reduces the soil's water content. The lime also causes ion exchange within the clay, resulting in flocculation of the clay particles. This reaction changes the soil structure and reduces the plasticity of the soil. These changes will increase soil workability and can increase the soil strength and stiffness. In the long term, calcium hydroxide in the water reacts with the silicates and aluminates (pozzolans) in the clay to form cementitious bonds that further increase the soil strength.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Lime Association, 200 North Glebe Road, Suite 800, Arlington, VA 22203, (703) 243-5463, www.lime.org.

APPLICATION

Typical Use: Soil stabilizer.

Traffic Range: Lime-stabilized subgrade and subbase materials can be used for very low to high traffic volume applications.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: Lime works best for clayey soils, especially those with moderate to high plasticity (plasticity index greater than 15). Lime does not work well with silts and granular materials because the pozzolanic reaction does not occur due to a lack of sufficient aluminates and silicates in these materials. For lime to effectively stabilize silts or granular materials, pozzolanic admixtures (i.e. fly ash) should be used in addition to lime.

Other: For soils with high sulfate contents (greater than 0.3%), lime stabilization is generally not recommended.

Other Comments: Lime stabilization is often used as a construction expedient when wet soil conditions are present and weather conditions or time constraints prevent the contractor from processing the soil to dry it out. The lime lowers the water content and plasticity of the soil and improves workability; this allows for construction of an adequate working platform for construction operations. Lime is also used to reduce the shrink/swell potential of clay soils.

Lime-stabilized soils/aggregates are rarely used as a surfacing material, except for possible use as temporary construction or haul roads. Unprotected lime-stabilized materials have poor resistance to the abrasive action of continued traffic. Therefore, lime-stabilized materials should be covered with some type of wearing surface.

DESIGN

SLC: 0.08 to 0.14. Value will vary with soil type and lime mixing percentage. Laboratory mixing should be performed to determine the strength of the stabilized material. Using laboratory strength testing results, an estimate of the SLC can be made using correlations, local practice, or engineering judgment.

Other Design Values: For clayey soils treated with lime, unconfined compressive strengths of greater than 690 kPa (100 psi) are common and can be 2,750 kPa (400 psi) or greater, depending on the soil.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can promote softening of the treated materials. The base thickness and appropriate road surfacing should be selected based on anticipated traffic volumes.

CONSTRUCTION

Availability of Experienced Personnel: Lime stabilization is commonly used for soil modification and stabilization and experienced contractors are, in general, widely available.

Materials: Quicklime or hydrated lime and water are required for lime stabilization. Quicklime is highly reactive with water and releases large quantities of heat during the chemical reaction. A detailed safety program is needed when constructing with quicklime. Although quicklime is more effective (25% more reactive), hydrated lime is commonly used because it is safer to work with.

Equipment: Equipment required for lime stabilization includes: mechanical spreader, tanker or water truck with spray bar, rotary mixer, grading equipment (i.e. bulldozer or motor grader), and light sheepsfoot or pneumatic roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Lime can be mixed with base materials at the aggregate plant; however, subgrade and base materials are usually treated with lime using in-place mixing.

Placement Process: The lime is uniformly applied to the existing surface and water is sprayed on the surface. A rotary mixer is then used to mix the lime, soil, and water together. If water can be added by the rotary mixer during processing, this approach is recommended. Enough water should be added to raise the soil moisture content to 3% above optimum moisture content, to allow for hydration of the lime. Subgrade soils are usually treated to a depth of 200 mm (8 in.). For deeper mixing and stabilization, the material should be mixed and compacted in 200 mm (8 in.) lifts. Once mixed, the loose surface is graded and compacted. For lime stabilization, the lime treated soil must be given time for the chemical reactions to change the material, or for the soil to “mellow”; the mellowing period is typically 1 to 7 days. After the mellowing period is over, the soil should be remixed, graded, and compacted. For drying or soil modification, mellowing is not usually required.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the soil is frozen. Warm temperatures are required for the chemical reactions to occur between the lime and soil; therefore, the air temperature should be above 4 ºC (40 ºF) for soil stabilization applications.

Construction Rate: Lime application rates are in the range of 2,950 to 4,200 m^2/day (3,500 to 5,000 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction. If possible, it is recommended that the lane remain closed until a wearing surface can be applied; otherwise, the treated material can be opened to traffic after one day for temporary use.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of modification/stabilization desired. For soil modification purposes, lime application rates are normally 2% to 3% (by weight). Larger quantities of lime are required for pozzolanic reactions, and thus strength gain, to occur. For soil stabilization, lime application rates are normally 5% to 6% (by weight). Laboratory testing is recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Lime is a commonly used product for soil/aggregate modification and stabilization and has been used for well over 40 years. Significant research, design and construction information, and project experience are available.

Life Expectancy: Life expectancy varies depending on traffic, degree of stabilization, and weather conditions. Lime stabilized materials can be used as a temporary road surfacing, but should not be used as a permanent surfacing material. For soils treated with a low percentage of lime and not adequately protected from moisture, some studies claim that the lime can leach out of the treated soil and the soil will regain the properties of the untreated material. This leaching process has been observed in projects after 5 to 12 years or more. For higher application rates associated with soil stabilization, the lime is bound to the soil particles through the pozzolanic reactions that occur and is not susceptible to leaching. As a result, typical life expectancy for lime stabilized subgrade or base materials, assuming that the roadway has a proper structural design, is more than 20 years and can be greater than 45 years for some projects.

Ride Quality: Lime treated materials can provide fair to good ride quality, depending on the material characteristics, when used as a temporary road surfacing.

Main Distress / Failure Modes: Cracking of the stabilized layer due to differential movement of the underlying subgrade.

Preservation Needs: None.

SAFETY

Hazards: Quicklime is highly reactive with water and releases large quantities of heat during the chemical reaction. A detailed safety program is needed when constructing with quicklime.

Skid Resistance: Lime stabilized materials can provide marginal to adequate skid resistance when used as a temporary road surfacing.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Lime and water are required for lime stabilization. Lime is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, lime manufacturing produces large amounts of carbon dioxide (CO_2).

Delivery and Haul Requirements: Lime must be transported to the site from the distributor. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: The construction process and equipment can damage vegetation adjacent to the road. If the lime-stabilized material is not protected from surface runoff, some lime could be washed into the surrounding environment and have an environmental impact by raising the pH of the water (lime treated soils have a pH of around 10). However, lime has a relatively low solubility in water, so the amount of lime product carried by the surface runoff should be small. Best Management Practices (BMPs) should be employed during construction to prevent the surrounding environment and water bodies from being exposed to large quantities of lime.

Potential Long-Term Environmental Impacts:

Leachate: For soils treated with a low percentage of lime and not adequately protected from moisture, the lime can leach out of the treated soil. The amount of movement due to leaching for calcium oxide particles is on the order of 125 mm (5 in.). Therefore, leaching of lime from the stabilized material should not adversely affect the surrounding environment.

Surface Runoff: Lime-stabilized soils generally have relatively low permeability and, thus promote surface runoff. However, surface runoff water quality is not generally impacted by lime stabilization. In parking areas, oil and other vehicle fluids can be collected by surface runoff, affecting the water quality.

Erosion: Lime-stabilized materials are a bound material and not very susceptible to erosion. At lower application rates, lime-modified soil may still be subject to erosion when exposed to fast-moving waters; however, the lime-modified soil will usually be protected by a surfacing layer that will protect it from erosion.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be reused as a construction material.

Other Environmental Considerations: None.

AESTHETICS

Appearance: Lime stabilization does not significantly alter the appearance of a soil/aggregate material. The appearance will be of a soil/aggregate surface with the overall color determined by the material type and source. However, the lime-stabilized material is typically covered with a wearing surface.

Appearance Degradation Over Time: Lime stabilized materials do not experience appearance degradation over time.

COST

Supply Price: N/A

Supply+Install Price: \$1.60 to \$2.40/m^2 (\$1.30 to \$2.00/yd^2) for 200 mm (8 in.) mixing depth.

EXAMPLE PROJECTS

Natchez Trace Parkway, Madison, MS.
Bald Knob National Wildlife Refuge, White County, AR.

SELECT RESOURCES

Little, Dallas (1987). *Fundamentals of the Stabilization of Soils with Lime*, Bulletin No. No. 332, National Lime Association, Arlington, VA, 21 pp.

Little, Dallas (1999). *Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates, Volume 1: Summary of Findings*, National Lime Association, 97 pp.

National Lime Association (2004). *Lime-Treated Soil Construction Manual: Lime Stabilization & Lime Modification*, Bulletin 326, National Lime Association, Arlington, VA, 41 pp.

PORTLAND CEMENT

GENERAL INFORMATION

Generic Name(s): Portland Cement, Cement, Cement-Modified Soil (CMS), Cement-Treated Base (CTB), Soil-Cement

Trade Names: N/A

Product Description: Portland cement can be used to stabilize any soil except highly organic soils. Portland cement increases soil strength, decreases compressibility, reduces swell potential, and increases durability. Cement stabilization creates a hard, bound, impermeable layer. Cement stabilized materials are rarely used as a surfacing material because they can become brittle and crack under traffic loads; Cement-treated soils are most frequently used as a stabilized subgrade or road base.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Portland Cement Association, 5420 Old Orchard Road, Skokie, IL, 60077-1083, (847) 966-6200, www.cement.org.

APPLICATION

Typical Use: Soil stabilizer.

Traffic Range: Cement-stabilized materials are rarely used as a surfacing material. Cement-stabilized subgrade and base materials can be used in roads for very low to high traffic volume applications.

Restrictions:

Traffic: None.

Climate: Cement stabilized bases should not be used in areas subject to seasonal frost heave.

Weather: None.

Terrain: None.

Soil Type: Cement stabilization should not be used for soils with high organic content or containing sulfates.

Other: None.

Other Comments: Portland cement can be used for soil modification (e.g. decrease plasticity of marginal aggregate to make it acceptable for use as a base material) or soil stabilization (e.g. increase strength of existing soft subgrade material). Portland cement binds the surface particles and reduces dust generation when used as a temporary road surfacing.

DESIGN

SLC: 0.12 to 0.25 (increases with increasing compressive strength).

Other Design Values: For fine-grained soils, unconfined compressive strengths of 860 to 3,450 kPa (125 to 500 psi) are common. CBR values for weak soils (CBR of 2) can be increased to a CBR of 40.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support. For cement stabilized subgrades, a subbase layer is usually not required and a bound base should be used. Where cement is used to provide a treated base, the surfacing can consist of a range of materials including PCCP and HACP.

Other Comments: The road surface should be sloped to promote surface runoff and prevent ponding on the road surface that can lead to softening of the treated materials. The base thickness and appropriate road surfacing should be selected based on anticipated traffic volumes.

CONSTRUCTION

Availability of Experienced Personnel: Portland cement stabilization is a commonly used soil stabilizer and experienced contractors are, in general, widely available.

Materials: Portland cement and water are required for cement stabilization.

Equipment: Equipment required for portland cement stabilization includes: tanker or water truck with spray bar, pulverizer, grading equipment (i.e. bulldozer or motor grader), and roller. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Portland cement is typically mixed with base materials at the aggregate plant; stabilization of subgrade soils with cement is normally achieved by in-place mixing.

Placement Process: For new construction projects where aggregate must be hauled to the site, the cement can be mixed with the aggregate in a pugmill before transporting to site. This method provides the most uniform mixing. Alternatively, if the soil/aggregate is in place, the cement is uniformly applied to the existing surface and then mixed into the surface using a rotary mixer. Subgrade soils are usually treated to a depth of 150 mm (6 in.). For deeper mixing and stabilization, the material should be mixed and compacted in 150 mm (6 in.) lifts. Once mixed, the loose surface is sprayed with water using a water truck and then graded and compacted. The compacted surface should be sprayed with water again to ensure that enough water is provided for cement hydration.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the subgrade is frozen.

Construction Rate: Portland cement application rates are on the order of 2,950 to 4,200 m^2/day (3,500 to 5,000 yd^2/day).

Lane Closure Requirements: The roadway lane should be closed during construction, but can be opened to light traffic once construction is complete.

Other Comments: The required application rate will vary based on the characteristics of the material to be treated and the degree of stabilization desired; typical application rates are 3% to 5% by weight. Laboratory testing is recommended to determine/verify the appropriate application rate.

SERVICEABILITY

Reliability and Performance History: Portland cement is a commonly used product for soil/aggregate modification and stabilization and has been used for well over 50 years. Significant research, design and construction information, and documented project experience are available.

Life Expectancy: Life expectancy varies depending on traffic, weather conditions, and surfacing type. Cement stabilized materials can be used as a temporary road surfacing, but should not be used as a permanent surfacing material because they can become brittle and crack under traffic loads. Typical life expectancy for cement stabilized subgrade or base materials, assuming that the roadway has a proper structural design, is more than 20 years and can be greater than 45 years for some projects.

Ride Quality: Portland cement-treated materials can provide fair to good ride quality, depending on the material characteristics, when used as a temporary road surfacing.

Main Distress / Failure Modes: Cracking (due to nonuniform subgrade support and frost action, when used as a road base layer)

Preservation Needs: None.

SAFETY

Hazards: None.

Skid Resistance: Cement-stabilized materials can provide adequate skid resistance when used as a temporary road surfacing.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Portland cement and water are required for cement stabilization. Portland cement is manufactured from limestone through a very energy intensive process. In addition to significant energy consumption during the manufacturing process, portland cement manufacturing produces large amounts of carbon dioxide (CO_2); various reports claim that cement manufacturing is responsible for 2% to 7% of CO_2 produced by humans.

Delivery and Haul Requirements: Portland cement must be transported to the site from the distributor. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Construction process can damage vegetation adjacent to the road, but off-site impacts can be mitigated by careful handling.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: None.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: The treated soil/aggregate can be crushed/pulverized and reused a general construction fill material.

Other Environmental Considerations: None.

AESTHETICS

Appearance: Cement stabilization does not significantly alter the appearance of a soil/aggregate material. The appearance will be of a soil/aggregate surface with the overall color determined by the material type and source. However, the cement-stabilized subgrade and base layers are typically not visible once the roadway is constructed.

Appearance Degradation Over Time: N/A

COST

Supply Price: N/A

Supply+Install Price: \$3.30 to \$4.10/m^2 (\$2.80 to \$3.40/yd^2) for 150 mm (6 in.) mixing depth.

EXAMPLE PROJECTS

Joshua Tree National Park, CA.

SELECT RESOURCES

Portland Cement Association (2003). *Soil-Cement Information: Properties and Uses of Cement-Modified Soils*, IS 411.02, Portland Cement Association, 12 pp.

UNIT SURFACES

UNIT SURFACINGS

BRICK PAVERS

GENERAL INFORMATION

Generic Name(s): Brick Pavers, Paving Brick, Clay Pavers

Trade Names: Numerous products available.

Product Description: Brick pavers are accurately dimensioned blocks constructed of kiln-fired clay, shale, or other similar earthy substance. Brick pavers fit snugly together to form a road surfacing. The brick pavers transfer traffic loads to supporting pavement layers like other flexible pavements and can handle differential settlements without cracking or losing surface integrity. They are similar to rigid pavements because they are resistant to point loads and fuel spills and are not affected by high temperatures. Brick pavers are typically supported on a layer of bedding sand, which is also used to fill the spaces between the pavers. Brick pavers come in a wide range of natural colors, such as brown, red, buff, gray, etc., and can be installed in a range of patterns. Different types of brick are available for use, depending on weather and traffic conditions.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Brick Industry Association, 11490 Commerce Park Drive, Reston, VA 20191, (703) 620-0010, www.gobrick.com.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: Brick pavers can be designed to support a wide range of traffic loading conditions. Brick pavers are normally limited to low speed traffic applications with speeds less than about 60 km/hr (37 mph).

Climate: None.

Weather: None.

Terrain: Brick pavers can be used for roadway gradients up to 20% for slow moving traffic or pedestrians. However, for general traffic applications, it is recommended that brick pavers be limited to applications with roadway gradients less than 10%. At roadway gradients greater than 10%, joint sand washout can become a problem and braking vehicles will increase pavement creep.

Soil Type: N/A

Other: None.

Other Comments: Brick pavers are commonly used at historical sites and visitor's centers. Brick pavers can also be used as a traffic calming measure.

DESIGN

SLC: 0.35 (for paver and bedding sand combined).

Other Design Values: None.

Base/Subbase Requirements: Brick pavers are placed on top of a 25 to 37 mm (1 to 1.5 in.) thick sand bedding layer. Base/subbase course(s) is (are) located under the sand bedding layer. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to placement of sand bedding layer and pavers. In addition, adequate drainage should be provided by the base to minimize infiltration into and softening of the subgrade.

Other Comments: The base/subbase course(s) is (are) the major structural element for the pavement system. Specific design guidelines are available from the various brick industry organizations. The road surface should be graded to promote surface drainage and prevent ponding on the road surface that can reduce tire traction and wash out sand located between the pavers. Brick pavers can be installed in various patterns; however, a herringbone pattern is most durable and stable and is universally recommended for vehicular traffic loadings.

CONSTRUCTION

Availability of Experienced Personnel: Specialty contractors are widely available in or near large urban areas. In remote areas, contractor availability may be limited and require mobilization of a work crew and equipment from a distant location.

Materials: Brick pavers are manufactured from clay, shale, or other similar earthy substance and come in various shapes, colors, and dimensions. Graded sand is required for the bedding layer.

Equipment: Equipment required for brick paver road construction includes: sand spreading equipment, vibratory plate compactor, hydraulic cutter or saw, and broom. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Brick pavers are manufactured in plants and shipped to the site for placement. Some paver cutting may be required on site for pavers placed along the roadway edge.

Placement Process: Brick pavers are placed on top of a 25 to 37 mm (1 to 1.5 in.) thick sand bedding layer. The bedding sand should conform to ASTM C 33, be clean, well-graded, and have a maximum particle size of 4.75 mm (#4 sieve.). The pavers can be placed by hand or using special placement equipment. Pavers should be placed with uniform spacing; spacers can be used to ensure that the pavers are placed at the appropriate spacing. Edge restraints are placed along the roadway edge to prevent block movement and raveling at the road surfacing edge. Once placed, a vibratory plate compactor is used to seat the pavers in the bedding sand layer. Once the pavers are seated, sand is spread over the pavers and the vibratory plate compactor is used to vibrate the sand into the paver joints. This process may be repeated as necessary until the joints are filled. Once the joints are filled, excess sand is swept from the paver surface.

Weather Restrictions: Do not install brick pavers during rain or snow or place pavers over frozen base materials or bedding sands.

Construction Rate: Brick paver installation rates vary from 17 to 125 m^2/man-day (20 to 150 yd^2/man-day) for manual placement to 210 to 420 m^2/man-day (250 to 500 yd^2/man-day) for mechanical equipment placement.

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The brick paver surface can be opened to traffic as soon as it is constructed. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Brick pavers have been used as a roadway surfacing in the United States since the late 1800s. Brick paver use decreased in the early 1900s as vehicle speeds increased; however, use has increased in recent years. A fair amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 20 to 25 years or more. If the brick paver surface is reconstructed at the end of its serviceable life, the same brick paver units can typically be reused.

Ride Quality: Ride quality is typically fair to good and inferior to most paved surfaces. The smoothness level is a function of workmanship and is usually adequate for low-speed applications. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Rutting, differential settlement, paver distortion.

Preservation Needs: Periodic removal and replacement of pavers may be required in distorted areas. In addition, additional joint sand may be needed as well. Initial maintenance may be needed after the first year of service. Thereafter, maintenance is typically needed every 8 to 10 years.

SAFETY

Hazards: Brick pavers are occasionally used for mixed pedestrian and vehicular traffic. They provide a rough surface for pedestrians and can constitute a tripping hazard if not properly maintained.

Skid Resistance: Brick pavers provide adequate skid resistance for low speed applications.

Road Striping Possible?: Yes.

Other Comments: Different surface colors, patterns, and/or textures can be used to delineate specific areas, such as crosswalks or "No Parking" zones. Because low ride quality is typically associated with brick pavers, they can be used as a traffic calming tool.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Brick pavers are manufactured from naturally-occurring clay, shale, or other similar earthy substance. Sands are naturally occurring.

Delivery and Haul Requirements: Brick pavers must be hauled to the site. Depending on local availability, sand may need to be hauled to the site as well.

Potential Short-Term Construction Impacts: If clean aggregate is not used, dust can be a problem during construction and sweeping. Excess sand can be thrown/brushed/washed from the surface into the surrounding environment during construction.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Brick paver surfacings are permeable with infiltration through the joint sand (approximately 10% infiltration); however, there is still significant surface runoff. The amount of infiltration can decrease, leading to increased surface runoff, over time with clogging of the joint sand.

Erosion: Brick pavers are not susceptible to surface erosion. Some sand loss can occur from the paver joints.

Water quality: Water quality could be affected by sediment loading from sand washed from paver joints.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Brick pavers can be reused or crushed for use as an unbound or stabilized material.

Other Environmental Considerations: Light-colored brick pavers can be used to reduce surface heat reflectivity. For brick pavers, tire/road noise is typically moderate to high with a higher noise level than HACP.

AESTHETICS

Appearance: Brick pavers are available in numerous shapes and natural colors, such as brown, red, buff, gray, etc., and can be placed in various patterns to create a visually pleasing surface. Bricks can be "tumbled" to produce a rougher and more antique appearance.

Appearance Degradation Over Time: Brick pavers will maintain their general appearance over time with small changes. Surface polishing and staining are possible over time. The brick paver coloring is natural, so the color does not fade with use and wear.

COST

Supply Price: \$14 to \$48/m^2 (\$12 to \$40/yd^2).

Supply+Install Price: \$145 to \$185/m^2 (\$120 to \$155/yd^2).

EXAMPLE PROJECTS
Nationwide Boulevard, Columbus, OH. Main Street, Celebration, FL.
SELECT RESOURCES
Brick Industry Association, (703) 620-0010, www.gobrick.com. Brick Industry Association (2003). *Flexible Vehicular Brick Paving: Heavy Duty Applications Guide*, Brick Industry Association, 48 pp.

NATURAL STONE PAVERS

GENERAL INFORMATION

Generic Name(s): Natural Stone Pavers, Cobblestones, Sett Paved Surface, Flagstones, Natural Stone Pavements

Trade Names: N/A

Product Description: Natural stone cobbles, or cobblestones, are irregularly sized, smooth, natural stones obtained from river or beach sources. Typical unit cobblestone size ranges from 75 to 200 mm (3 to 8 in.). They are hand placed on a layer of bedding sand and are selected and fitted together to avoid large gaps between adjacent stones. Setts are natural stone pavers that are cut and shaped into regular sizes. Setts are typically rectangular, 100 mm (4 in.) by 200 mm (8 in.) by 150 mm (6 in.) deep. They can be supported on a sand bedding layer or on a layer of lean mix concrete. Flagstones are larger natural stone paving units, typically at least 300 mm (12 in.) by 450 mm (18 in.) and a minimum of 75 mm (3 in.) thick. They are rarely used as a road surfacing, but are occasionally used for sidewalks or decorative courtyards.

Product Suppliers: Natural stone pavers are produced by a small number of specialty rock product suppliers and are typically only produced by special order.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to Low.

Restrictions:

Traffic: Typically not used for heavy traffic loading applications. Natural stone pavers are normally limited to low speed traffic applications with speeds less than about 24 km/hr (15 mph).

Climate: None.

Weather: None.

Terrain: Stone pavers can be used on roadway gradients up to 20% for slow moving traffic or pedestrians. However, for general traffic applications, it is recommended that stone pavers be limited to applications with roadway gradients less than 10%. At roadway gradients greater than 10%, joint sand washout can become a problem and braking vehicles can dislodge paver units. Joint sand can be stabilized to prevent washout.

Soil Type: N/A

Other: None.

Other Comments: Natural stone paver road surfacings are typically only justified for historic sites. The general appearance of natural stone paver surfacings can be reproduced at a lower cost by the use of decorative concrete pavers, brick pavers, or by imprinted HACP or stamped PCCP.

DESIGN

SLC: 0.35 (for paver and bedding sand combined).

Other Design Values: None.

Base/Subbase Requirements: Natural stone pavers are placed on top of a 25 to 50 mm (1 to 2 in.) thick, compacted sand bedding layer. A thicker bedding layer may be needed for random sized cobblestones. Lean mix concrete can also be used for a bedding layer, but sand will still be needed to fill joints between paving units. Base/subbase course(s) is (are) located under the bedding layer. Subgrade and base materials should be compacted and graded to provide a stable working surface prior to placement of bedding layer and pavers. In addition, adequate drainage should be provided for the bedding and base layers to minimize infiltration into and softening of the subgrade.

Other Comments: The base/subbase course(s) is (are) the major structural element for the pavement system. Specific design guidelines are available from the various concrete paver supplier organizations, which are generally applicable for use with natural paver stones. The road surface should be graded to promote surface runoff and prevent ponding on the road surface that can reduce tire traction and wash out the sand between the pavers.

CONSTRUCTION

Availability of Experienced Personnel: Specialty contractor availability is limited in most areas. Installing natural stone pavers is tedious and highly labor-intensive work and requires experienced personnel. Natural stone cobbles require greater skill to lay than stone setts.

Materials: Natural stone cobbles, are irregularly sized, smooth, natural stones obtained from river, beach or pit sources. Typical unit cobblestone size ranges from 75 to 200 mm (3 to 8 in.). Setts are natural stone pavers that are shaped into regular sizes. Setts are typically rectangular, 100 mm (4 in.) by 200 mm (8 in.) by 150 mm (6 in.) deep. Flagstones are larger natural stone paving units, typically at least 300 mm (12 in.) by 450 mm (18 in.) and a minimum of 75 mm (3 in.) thick. Graded sand is required for the bedding layer.

Equipment: Equipment required for unit paver road construction includes: sand spreading equipment, vibratory plate compactor, hydraulic cutter or saw, and a broom. Equipment is widely available in most areas, but availability may be limited in remote areas.

Manufacturing/Mixing Process: Natural stone cobbles can be obtained from some aggregate producers. Setts or flagstones are typically shaped by specialty suppliers into a particular size or thickness prior to shipment to the site. Some stone cutting may be required on site for pavers placed along the roadway edge.

Placement Process: Natural stone pavers are placed on top of a 25 to 50 mm (1 to 2 in.) thick sand bedding layer. Lean mix concrete can also be used for a bedding layer for pavers of uniform thickness, but sand will still be needed to fill joints between paving units. The pavers are placed by hand and arranged to avoid large gaps between pavers. For regular shaped paver units, a uniform spacing should be achieved. Once placed, a vibratory plate compactor is used to seat the pavers in the bedding sand layer. Once the pavers are seated, sand is spread over the pavers and the vibratory plate compactor is used to vibrate the sand into the voids between pavers. This process may be repeated as necessary until the voids are filled. Once the voids are filled, excess sand is swept from the paver surface.

Weather Restrictions: Do not install natural stone pavers during rain or snow or place pavers over frozen base materials.

Construction Rate: The construction rate for natural stone pavers is very slow. Natural stone paver installation rates can average 20 m^2/day (24 yd^2/day) for a three-person crew.

Lane Closure Requirements: The roadway being constructed is closed during construction. Because of the slow rate of construction, temporary traffic diversions are needed during construction. The natural stone paver surface can be opened to traffic as soon as a sufficiently long section is constructed. Road surface striping is technically feasible, but given the slow traffic speeds and typically short paved road sections, may not be necessary.

Other Comments: Fitting stone pavers around utility access covers and other street furniture is problematic and usually source locations for higher maintenance.

SERVICEABILITY

Reliability and Performance History: Natural stone pavers have been used as a roadway surfacing for centuries. However, natural stone pavers are rarely used in the United States at this time due to the high cost and labor-intensive nature of construction. A significant amount of research, design and construction information, and project experience is available for unit pavers and brick pavers, which are similar to natural stone pavers in many aspects.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. If properly installed using durable natural stone, typical life expectancy is more than 100 years.

Ride Quality: Ride quality is typically very poor and inferior to most paved surfaces. Nonetheless, the ride quality is usually accepted for low-speed applications. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Differential settlement, depressions, paver distortion.

Preservation Needs: Periodic removal and replacement of pavers may be required in distorted areas. In addition, additional joint sand may be needed as well. Initial maintenance may be needed after the first year of service. Thereafter, maintenance is typically needed every 8 to 10 years.

SAFETY

Hazards: Unit pavers are occasionally used for mixed pedestrian and vehicular traffic. They provide a rough surface for pedestrians and can constitute a tripping hazard if not properly maintained.

Skid Resistance: The natural stone surfaces become polished with wear and can be a skid hazard in wet weather. However, the hazard is mitigated by slow driving speeds.

Road Striping Possible?: Yes.

Other Comments: Different surface colors or patterns can be used to delineate specific areas. Natural stone pavers can be used in conjunction with brick pavers, for example. Because very low ride quality is typically associated with natural stone pavers, they can be used as a traffic calming tool.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Cobble stones and sand are naturally occurring.

Delivery and Haul Requirements: Natural stone pavers must be hauled to the site. Depending on local availability, sand may need to be hauled to the site as well.

Potential Short-Term Construction Impacts: If clean sand is not used, dust can be a problem during construction and sweeping. Excess sand that is brushed or washed from the surface can impact the surrounding environment during construction.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Natural stone paver surfacings are permeable with infiltration through the joint sand (10-30% infiltration); however, there is still significant surface runoff. The amount of infiltration can decrease, leading to increased surface runoff, over time with clogging of the joint sand.

Erosion: Natural stone pavers are not susceptible to surface erosion. Some sand loss can occur from the paver joints.

Water quality: Natural stone pavers have a minimal impact on water quality, assuming clean, inert sand is used. Water quality could be affected by sediment loading from sand washed from paver joints.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Natural stone pavers can be salvaged and reused or crushed for use as an unbound or stabilized material.

Other Environmental Considerations: Light-colored natural stone pavers can be used to reduce surface heat reflectivity. For natural stone pavers, tire/road noise is typically high with a higher noise level than HACP.

AESTHETICS
Appearance: Natural stone pavers can be produced in numerous shapes and colors, depending on the parent rock type and source. They can be placed in various patterns to create a visually pleasing surface. **Appearance Degradation Over Time:** Natural stone pavers will maintain their general appearance over time with small changes.
COST
Supply Price: \$85 to \$100/m^2 (\$70 to \$100/yd$^{2.}$) **Supply+Install Price**: \$300 to \$360/m^2 (\$250 to \$300/yd^2).
EXAMPLE PROJECTS
Downtown Streets, Nantucket, MA.
SELECT RESOURCES
www.pavingexpert.com.

UNIT PAVERS

GENERAL INFORMATION

Generic Name(s): Concrete Paving Blocks, Concrete Unit Pavers, Paving Stones, Interlocking Concrete Pavement, Segmental Pavers

Trade Names: Numerous products available.

Product Description: Unit pavers are accurately dimensioned, dense concrete products that fit snugly together to form a road surfacing. They transfer traffic loads similarly to flexible pavements and can handle differential settlements without cracking or losing surface integrity. They are similar to rigid pavements because they are resistant to point loads and fuel spills and are not affected by high temperatures. Unit pavers are typically supported on a layer of bedding sand, which is also used to fill the spaces between the pavers. Unit pavers are available in numerous shapes and colors.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Interlocking Concrete Pavement Institute, 1444 I Street NW, Suite 700, Washington, D.C. 20005-6542, (202) 712-9036, www.icpi.org

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to High.

Restrictions:

Traffic: Unit pavers can be designed to support a wide range of traffic loading conditions; they are frequently used for heavy duty industrial pavements. Unit pavers are normally limited to low speed traffic applications with speeds less than about 80 km/hr (50 mph). Minimum 80 mm (3.125 in.) thick pavers are recommended for all road applications.

Climate: None.

Weather: None.

Terrain: Unit pavers can be used roadway gradients up to 20% for slow moving traffic or pedestrians. However, for general traffic applications, it is recommended that unit pavers be limited to applications with roadway gradients less than 10%. At roadway gradients greater than 10%, joint sand washout can become a problem unless stabilized and braking vehicles may increase pavement creep. Joint sand can be stabilized to prevent washout.

Soil Type: N/A

Other: None.

Other Comments: None.

DESIGN

SLC: 0.44 (for 80 mm (3.125 in.) thick paver and 25 mm (1 in.) of bedding sand combined).

Other Design Values: None.

Base/Subbase Requirements: Unit pavers are placed on top of a 25 mm (1 in.) thick sand bedding layer. Base/subbase course(s) is (are) located under the bedding layer. Subgrade and aggregate base materials should be compacted to a minimum of 98% modified Proctor density and graded to provide a stable working surface prior to placement of the sand bedding layer and pavers. In addition, adequate drainage should be provided by the base to minimize infiltration into and softening of the subgrade.

Other Comments: The base/subbase course(s) is (are) the major structural element for the pavement system. Specific design guidelines are available from the various concrete paver supplier organizations. The road surface should be graded to promote surface runoff and prevent ponding on the road surface, typically a minimum 1.5% with similar cross slopes. This will maintain tire traction and help prevent wash out sand located between the pavers. Unit pavers can be installed in various patterns; however, a herringbone pattern is recommended for vehicular traffic.

CONSTRUCTION

Availability of Experienced Personnel: Specialty contractors are widely available in or near large urban areas. In remote areas, contractor availability may be limited and require mobilization of a work crew and equipment from a distant location.

Materials: Unit pavers are manufactured from portland cement concrete (PCC) and come in various shapes, colors, and dimensions. A graded sand conforming to the gradation of ASTM C 33 for concrete sand with no greater than 1% passing the 0.075 mm (No. 200) sieve is required for the bedding layer. Joint sand gradations typically conform to ASTM C 144.

Equipment: Equipment required for unit paver road construction includes: sand spreading equipment, vibratory plate compactor, hydraulic cutter or saw, and a broom. Equipment is widely available in most areas, but availability may be limited in remote areas. Special paver laying machines can be used to place multiple pavers at one time, but equipment availability may be limited outside of large urban areas. Paver laying equipment is economical when large, uniform areas of pavers must be placed.

Manufacturing/Mixing Process: Unit pavers are manufactured in plants and shipped to the site for placement. If paver laying machines are to be used for paver placement, the pavers must be stacked in the final laying pattern at the manufacturing plant prior to shipment. Some paver cutting may be required on site for pavers placed along the roadway edge.

Placement Process: Unit pavers are placed on top of a 25 mm (1 in.) thick sand bedding layer. The bedding sand should be clean, well-graded, and have a maximum particle size of 9.5 mm (0.375 in.). The pavers can be placed by hand or using special placement equipment. Pavers should be placed with uniform joint spacing; spacers can be used to ensure that the pavers are placed at the appropriate spacing. Edge restraints are placed along the roadway edge to prevent block movement and raveling at the road surfacing edge. Once placed, a vibratory plate compactor is used to seat the pavers in the bedding sand layer. Once the pavers are seated, sand is spread over the pavers and the vibratory plate compactor is used to vibrate the sand into the paver joints. This process may be repeated as necessary until the joints are filled. Once the joints are filled, excess sand is swept from the paver surface.

Weather Restrictions: Do not install unit pavers during rain or snow or place pavers over frozen base or bedding sand materials.

Construction Rate: Unit paver installation rates vary from 30 to 40 m^2/man-day (36 to 48 yd^2/man-day) for manual placement to 400 to 600 m^2/man-day (476 to 714 yd^2/man-day) for mechanical equipment placement. This includes screeding sand, placing and compacting the pavers, filling the joints with sand, a second compaction and removal of excess sand.

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The unit paver surface can be opened to traffic as soon as it is constructed. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Similar to unit pavers, stone and brick paver roadways have been used for centuries. Manufactured concrete unit pavers have been used as a roadway surfacing since the 1960s; unit paver use grew rapidly in the 1980s. A significant amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 20 to 40 years.

Ride Quality: Ride quality is typically fair to good but not as smooth as paved surfaces. The smoothness level is a function of workmanship and is usually adequate for low-speed applications. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Rutting, differential settlement, paver distortion.

Preservation Needs: Periodic removal and replacement of pavers may be required in distorted areas. In addition, additional joint sand may be needed as well. Initial maintenance may be needed after the first year of service. Thereafter, maintenance is typically needed every 8 to 10 years.

SAFETY

Hazards: Rutting can lead to water accumulation on the pavement surface, causing a driving hazard. Unit pavers are occasionally used for mixed pedestrian and vehicular traffic. Regular inspection of the surface is required to identify and correct tripping hazards.

Skid Resistance: Provided high quality aggregates are used in paver construction, unit pavers provide adequate skid resistance for low speed applications.

Road Striping Possible?: Yes.

Other Comments: Different surface colors or patterns can be used to delineate specific areas, such as crosswalks or “No Parking” zones. Because low ride quality is typically associated with unit pavers, they can be used as a traffic calming tool.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Unit pavers are constructed of portland cement and aggregates. Recycled materials such as fly ash are used to replace a portion of the cement content.

Delivery and Haul Requirements: Unit pavers must be hauled to the site. Depending on local availability, sand may need to be hauled to the site as well.

Potential Short-Term Construction Impacts: If clean aggregate is not used, dust can be a problem during construction and sweeping. Excess sand can be thrown/brushed/washed from the surface into the surrounding environment during construction.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Unit paver surfacings are permeable with infiltration through the joint sand (10-30% infiltration); however, there is still significant surface runoff. The amount of infiltration can decrease, leading to increased surface runoff, over time with clogging of the joint sand with sediment and detritus. Joint sand stabilization materials applied during construction significantly reduce water infiltration.

Erosion: Unit pavers are not susceptible to surface erosion. Some sand loss can occur from the paver joints.

Water quality: Unit pavers have a minimal impact on water quality. Water quality could be affected by sediment loading from sand washed from paver joints.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Unit pavers can be reused or crushed for use as an unbound or stabilized material.

Other Environmental Considerations: Light-colored unit pavers can be used to reduce surface heat reflectivity. For unit pavers, tire/road noise is typically moderate to high. Noise levels can be controlled by selection of shape, pattern, and chamfer size.

AESTHETICS

Appearance: Unit pavers are available in numerous shapes and colors and can be placed in various patterns to create a visually pleasing surface.

Appearance Degradation Over Time: Unit pavers will maintain their general appearance over time with small changes. Surface polishing, color fading, and staining are possible over time.

COST

Supply Price: \$12 to \$15/m^2 (\$14 to \$18/yd^2) for paving units.

Supply+Install Price: \$36 to \$48/m^2 (\$30 to \$40/yd^2) for paving units, bedding and joint sand.

EXAMPLE PROJECTS

11th Avenue Streetscape, Altoona, PA.
Iowa Avenue Streetscape, Iowa City, IA.

SELECT RESOURCES

Interlocking Concrete Pavement Institute, (202) 712-9036, www.icpi.org
Rollings, R.S., and Rollings, M.P. (1992). *Applications for Concrete Paving Block in the United States Market*, Uni-Group USA., 114 pp.
Smith, D.R. (2000). *Permeable Interlocking Concrete Pavements*, Interlocking Concrete Pavement Institute, 44 pp.

POROUS UNIT PAVERS

GENERAL INFORMATION

Generic Name(s): Porous Unit Pavers, Permeable Interlocking Concrete Pavement, Porous Pavement, Permeable Segmental Pavers

Trade Names: Numerous products available.

Product Description: Porous unit pavers have an interlocking geometry that results in regular void spacing through the completed pavement system. While the voids are filled with sand, they allow good stormwater infiltration while maintaining a driveable surface. The infiltrated water can be collected in a drainage layer and outlet to a storm collection system or can be stored in a specially designed reservoir layer within the pavement structure that allows the water to infiltrate downwards into the subgrade. In some designs, a sand-topsoil mix can be used in the paver openings to support grass. The unit pavers are accurately dimensioned dense concrete products that fit together to form a road surfacing. They transfer traffic loads similarly to flexible pavements and can handle differential settlements without cracking or losing surface integrity. Porous pavers are also similar to rigid pavements because they are resistant to point loads and are not affected by high temperatures. Pavers are available in numerous shapes and colors.

Porous unit pavers can also be constructed of high strength plastic. Plastic pavers typically have more void space than concrete unit pavers and are commonly filled with gravel, sand, or sand-topsoil mix.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Interlocking Concrete Pavement Institute, 1444 I Street NW, Suite 700, Washington, D.C. 20005-2210, (202) 712-9036, www.icpi.org

Representative product suppliers and trade names are provided for informational purposes only. Inclusion of this information is not an endorsement of any product or company. Additional suppliers and unit paver products are available.

APPLICATION

Typical Use: Road surfacing.

Traffic Range: Very Low to Low.

Restrictions:

Traffic: Porous unit pavers are normally limited to low speed traffic applications with speeds less than about 30 km/hr (20 mph).

Climate: None.

Weather: None.

Terrain: Porous pavers are not recommended for roadway gradients steeper than 5%; roadway gradients as flat as possible are desired.

Soil Type: Porous pavers are mainly used in areas with permeable soils with an infiltration rate greater than 1.3 cm/hr (0.5 in./hr). Where soils have low permeability, the base thickness should be increased to provide additional storage. With soils composed of clay or silt, additional drainage may be required.

Other: Depth to seasonal high groundwater levels and bedrock should be greater than 1.2 m (4 ft.).

Other Comments: Porous pavers have mainly been used for low volume parking lots and roads and recreational areas. They are also used for fire or emergency access lanes and for occasional use parking. For low use areas, many pavers can support grass growth and will maintain the appearance of a natural surface.

DESIGN

SLC: 0.44 (for paver and bedding sand combined)

Other Design Values: None.

Base/Subbase Requirements: Unit pavers are placed on top of a 25 to 50 mm (1 to 2 in.) thick sand bedding course, which is the same material used to fill the spaces between the pavers. The bedding sand is usually 100% passing 9.5 mm (0.375 in). Base/subbase course(s) is (are) located under the bedding sand layer. The base/subbase course(s) is (are) the major structural element for the pavement system. Specific design guidelines are available from the various concrete paver supplier organizations. Unless high permeability subgrade soils are present, a permeable base layer needs to be provided below the bedding layer to detain infiltrated stormwater and allow it to infiltrate into the subgrade. The infiltrated stormwater is filtered to some degree as it passes through the drainage layer.

The depth of the permeable base layer should be such that it drains completely within 72 hours. This allows the underlying soils to dry out between storms and also provides capacity for the next storm. If frost penetrates deeper than the thickness of the paver and base course, and the subgrade has potential for frost heaving, additional material should be added to the base course to below the frost zone. The base course should be deep enough to provide sufficient water storage volume. A minimum residence time of 12 hours should be a target for the design storm to provide exfiltration for pollutants removal.

Other Comments: When fine-grained natural soils are present, a geosynthetic separation/filtration layer is typically placed at the bottom of the reservoir layer.

CONSTRUCTION

Availability of Experienced Personnel: Specialty contractors are widely available in or near large urban areas. In remote areas, contractor availability may be limited and require mobilization of a work crew and equipment from a distant location.

Materials: Unit pavers are manufactured from portland cement concrete (PCC) and come in various shapes, colors, and dimensions. Graded sand is required for the bedding layer. Permeable base materials are required for structural support and stormwater storage. Unit pavers manufactured of high strength plastic are also available.

Equipment: Equipment required for unit paver road construction includes: sand spreading equipment, vibratory plate compactor, hydraulic cutter or saw, and a broom. Equipment is widely available in most areas, but availability may be limited in remote areas. Special block laying machines can be used to place multiple pavers at one time, but equipment availability may be limited outside of large urban areas. Block laying equipment is economical when large, uniform areas of pavers must be placed.

Manufacturing/Mixing Process: Unit pavers are manufactured in plants and shipped to the site for placement. If block laying machines are to be used for paver placement, the pavers must be stacked in the appropriate pattern at the manufacturing plant prior to shipment. Some paver cutting may be required on site for pavers placed along the roadway edge.

Placement Process: If needed, the site is excavated to design subgrade depth and graded using light equipment to minimize compaction of the subgrade surface. If the subgrade soils are fine-grained, a geosynthetic separation/filtration layer is placed on the subgrade prior to construction of the base/subbase layer. Then, the base layer and 25 to 50 mm (1 to 2 in.) thick sand bedding course are placed and compacted. Porous unit pavers are placed on top of a sand bedding course. The bedding sand should be clean, well-graded, and have a maximum particle size of 9.5 mm (3/8 in.). The pavers can be placed by hand or using special placement equipment. Pavers should be placed with uniform spacing; spacers can be used to ensure that the pavers are placed at the appropriate spacing. Edge restraints are placed along the roadway edge to prevent block movement and raveling at the road surfacing edge. Once placed, a vibratory plate compactor is used to seat the pavers in the bedding sand layer. Once the pavers are seated, sand is spread over the pavers and the vibratory plate compactor is used to vibrate the sand into the paver joints. This process may be repeated as necessary until the joints are filled. Once the joints are filled, excess sand is swept from the paver surface.

Weather Restrictions: Do not install unit pavers during rain or snow or place pavers over frozen base materials.

Construction Rate: Unit paver installation rates vary from 17 to 125 m^2/man-day (20 to 150 yd^2/man-day) for manual placement to 210 to 420 m^2/man-day (250 to 500 yd^2/man-day) for mechanical equipment placement.

Lane Closure Requirements: The roadway lane(s) being constructed is closed during construction, so adequate traffic control is needed. The unit paver surface can be opened to traffic as soon as it is constructed. Road surface striping may be performed after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Manufactured concrete unit pavers have been used as a roadway surfacing since the 1960s; unit paver use grew rapidly in the 1980s. A significant amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on construction materials used, environmental conditions, and traffic volumes. Typical serviceable lives range from 20 to 25 years for porous concrete pavers.

Ride Quality: Ride quality is typically fair to good and inferior to most paved surfaces. The smoothness level is a function of workmanship and void space and is usually adequate for low-speed applications. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Differential settlement, paver distortion, loss of sand and gravel from voids.

Preservation Needs: Periodic removal and replacement of pavers may be required in distorted areas. Additional joint sand may be needed as well to fill the paver voids. Initial maintenance may be needed after the first year of service. Thereafter, maintenance is typically needed every 8 to 10 years, except for the addition of sand in the voids every 1 or 2 years.

SAFETY

Hazards: Porous pavers are occasionally used for mixed pedestrian and vehicular traffic. They provide a rough surface for pedestrians and can constitute a tripping hazard if not properly maintained.

Skid Resistance: Porous unit pavers provide good skid resistance for low speed applications.

Road Striping Possible?: No.

Other Comments: Different surface colors or patterns can be used to delineate specific areas, such as crosswalks or “No Parking” zones. Because low ride quality is typically associated with unit pavers, they can be used as a traffic calming tool.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Porous concrete pavers are constructed of PCC. Plastic pavers are constructed of high strength, high density polyethylene (HDPE). Sands are naturally occurring.

Delivery and Haul Requirements: Unit pavers must be hauled to the site. Depending on local availability, sand may need to be hauled to the site as well.

Potential Short-Term Construction Impacts: If clean aggregate is not used, dust can be a problem during construction and sweeping. Excess sand can be thrown/brushed/washed from the surface into the surrounding environment during construction.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Porous unit paver surfacings are permeable with significant infiltration through the paver voids; however, there may still be a small amount of surface runoff. The amount of infiltration can decrease, leading to increased surface runoff, over time with clogging of the void sand and vegetation growth.

Erosion: The material in the porous paver voids is susceptible to surface erosion. However, porous paver infiltration rates should be high enough to prevent significant surface runoff (leading to erosion), except during heavy storms.

Water quality: None. However, if the surface water infiltrating the pavement surface contains contaminates that are not easily trapped or reduced, the contaminants will flow through the pavement structure and be introduced into the surrounding soil and potentially into the groundwater.

Aquatic species: None. However, porous pavers can be a vehicle for contaminates to be introduced into nearby bodies of water by infiltrating into the surrounding soils and groundwater. Therefore, porous pavers are not recommended for areas near groundwater dinking supplies or other sensitive bodies of water.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Porous unit pavers can be reused if they are not damaged.

Other Environmental Considerations: Light-colored unit pavers can be used to reduce surface heat reflectivity.

AESTHETICS

Appearance: Unit pavers are available in numerous shapes and colors and can be placed in various patterns to create a visually pleasing surface. For low use applications, some pavers can support grass growth, which can result in the surfacing looking like a grass field from a distance.

Appearance Degradation Over Time: Unit pavers will maintain their general appearance over time with small changes. Surface polishing, color fading, and staining are possible over time.

COST

Supply Price: \$18 to \$21/m^2 (\$15 to \$18/yd^2).

Supply+Install Price: \$36 to \$48/m^2 (\$30 to \$40/yd^2).

EXAMPLE PROJECTS

Parking Area, Reliant Stadium, Houston, TX.

SELECT RESOURCES

Interlocking Concrete Pavement Institute, (202) 712-9036, www.icpi.org

Smith, D.R. (2000). *Permeable Interlocking Concrete Pavements*, Interlocking Concrete Pavement Institute, 44 pp.

RECYCLING AND RECLAMATION ALTERNATIVES

RECYCLING ALTERNATIVES

COLD IN-PLACE RECYCLING

GENERAL INFORMATION

Generic Name(s): Cold In-Place Recycling (CIR)

Trade Names: N/A

Product Description: In-Place Recycling is an in situ process used to recycle 100% of an existing asphalt concrete pavement to construct a new asphalt concrete layer. Cold In-Place Recycling (CIR) is the rehabilitation of asphalt pavements without the application of heat during the recycling process.

In the CIR process, the existing asphalt is cold milled, mixed with about 1.5 to 2.0 percent of emulsified asphalt, and then placed on the road and compacted. The CIR material requires about 1 week of curing. The depth of treatment is typically 50 to 100 mm (2 to 4 in.) but 125 to 150 mm (5 to 6 in.) is also possible. Chemical additives (i.e., lime, cement, fly ash, etc.) are sometimes used to decrease the initial cure time (i.e. promote a more rapid strength gain) and also increase the ultimate strength of the material. New aggregate can also be added to the CIR, not exceeding 25% by weight of RAP, to improve the characteristics of the mix or to address a prior flushing problem.

CIR is commonly overlaid with HACP; however, on low volume roads, slurry seals, chip seals, or other surface treatments are used.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Recycling & Reclaiming Association (ARRA), #3 Church Circle, PMB 250, Annapolis, MD 21401, (410) 267-0023, www.arra.org.

APPLICATION

Typical Use: Binder or base course with HACP or thin cold surfacing.

Traffic Range: Very Low to Medium. CIR use on higher volume roads typically requires thick HACP overlays.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: Constructability can be limited on steep grades or tightly curved roads due to the physical size of the equipment and process.

Soil Type: N/A

Other: As CIR depth is limited, it is not suitable for fixing problems with lower asphalt courses or granular base/ subbase. Pavements with major or extensive structural deficiencies (severe alligator cracking and severe structural rutting) are not good candidates for CIR.

Other Comments: Detailed pavement evaluation is required before designing the CIR pavement rehabilitation. The evaluation should include visual condition survey and evaluation of pavement structural condition, using pavement coring or the Falling Weight Deflectometer (FWD). Pavements exhibiting minor distresses (i.e. cracking, minor rutting) are excellent candidates for CIR.

When recycling material in-place, the depth of milling should be carefully examined to make sure that the underlying granular material is not introduced into the mix. Unless the base material is sound and very stable, the depth of milling is adjusted so that about 25 to 40 mm (1 to 1.6 in.) of the existing asphalt pavement is left in place; this will prevent the contamination of the recycled material with the granular base and will provide structural support for the CIR train during recycling.

The pavement to be CIR treated should be relatively homogenous. If the pavement structure or surface type within the project length changes, new mix design(s) may be required.

As the CIR equipment is relatively wide and long, short road sections particularly in urban setting are not suitable for CIR treatment, or may require special CIR equipment

DESIGN

SLC: 0.28 to 0.35.

Other Design Values: None.

Base/Subbase Requirements: Only the upper part of existing asphalt pavement is treated in the CIR process. Aggregate base and subbase layers are typically not included in the CIR process.

Other Comments: Asphalt pavements in poor structural condition are not considered to be suitable candidates for CIR treatment. If the pavement exhibits localized structural failures, full depth repairs including granular base and subbase may be required, as well as providing efficient surface and subsurface drainage. One of the major advantages of CIR is the mitigation of reflective cracking; in order to achieve this, at least 70 percent of the existing asphalt pavement thickness needs to be treated.

CONSTRUCTION

Availability of Experienced Personnel: Successful CIR processing requires experienced personnel. Experienced CIR contractors are, in general, regionally available in the United States.

Materials: New aggregates, emulsified asphalt, recycling agents and chemical additives such as portland cement or lime are added on an as-required basis. Chemical additives can be used to improve the strength of the material and decrease the initial cure time. Cationic and anionic mixing grade emulsions, both medium setting and slow setting, and high float emulsions, with and without modifiers are used in the CIR process.

Equipment: The CIR process uses a number of pieces of equipment including tanker trucks, milling machines, crushing and screening units, mixers, pavers and rollers. Single, two-unit and multi-unit trains are used in the CIR process. With the single unit train, the milling machine cutting head removes the pavement to the required depth and cross-slope, sizes the RAP and blends the recycling additive with the RAP. However, it does not contain screening and crushing units, making control of the maximum particle size more difficult.

Two-unit trains incorporate pugmill mix-pavers (cold mix pavers) as an integral part of the train. Multi-unit trailers include a trailer mounted screening and crushing unit and a trailer mounted pugmill mixer.

Equipment is available in urban areas, but availability may be limited in remote areas.

Cold In-Place Recycling Process: CIR is an in situ process. In the CIR process, a portion of the existing pavement is milled typically to a depth of 2 to 4 inches (50 to 100 mm). The reclaimed material is thoroughly mixed with emulsified asphalt and recycling agent to restore the properties of the asphalt binder in the mix. In the modified CIR process, new aggregates are also added. The resulting mixture is then placed back on the pavement as the base/binder course, with new wearing course (e.g., asphalt concrete, chip seal, slurry seal, etc.) placed later. Densification of the CIR mixes typically requires more compactive effort than conventional HACP and large pneumatic-tired rollers and vibratory steel drum rollers are used. Well compacted CIR mixes could have 9 to 14 percent Voids in Total Mix (VTM). Rolling with a steel roller several days after initial compaction (re-rolling) is used to remove minor consolidation in the wheel paths. The compacted CIR layers must be cured for a period of about 1 to 2 weeks of good weather before the wearing course is placed.

Weather Restrictions: CIR should not be performed at temperatures below 10 °C (50 °F) or when it is raining. It takes 1 to 2 weeks of good weather for the CIR material to cure.

Construction Rate: Modern CIR multi-unit trains can produce up to 3.2 lane km (2 lane miles) per day.

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The CIR surface can be opened to traffic during the curing period but heavy traffic should be avoided. When the CIR is cured, the roadway lane(s) must be closed for the surface course application (surface treatment or HACP overlay).

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: CIR is a proven recycling technology. Research, design and construction information, and project experience is available. Performance depends on proper pavement evaluation, mix design and quality of construction.

Life Expectancy: CIR with surface treatment generally lasts from 6 and 8 years. HACP overlays extend the CIR life expectancy to 12 to 20 years.

Ride Quality: CIR provides good ride quality after construction depending on the type of wearing course used. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling.

Preservation Needs: No preventative maintenance is typically required because CIR is not commonly used as a surfacing.

SAFETY

Hazards: None.

Skid Resistance: N/A; CIR is not normally used as a surfacing.

Road Striping Possible?: N/A; not used as a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Emulsified asphalt is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: In the typical CIR process no material hauling is required (in situ process). In the modified CIR process, new aggregate must be hauled.

Potential Short-Term Construction Impacts: A certain amount of noise is associated with the CIR construction process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: CIR is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by CIR present in a roadway.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: CIR pavement can be fully recycled as a pavement construction material.

Other Environmental Considerations: CIR’s characteristic black surface will absorb heat from sunlight; since it is an in situ process there is little opportunity to modify its appearance. For CIR, tire/road noise is typically similar to HACP or surface treated pavement, depending on the type of wearing course used.

Environmental Benefits: As CIR does not require pre-heating; CIP results in total energy savings of 40% to 50% compared to conventional HACP.

AESTHETICS

Appearance: Immediately after placement, CIR is generally black with a smooth surface.

Appearance Degradation Over Time: Over time, the layer(s) overlaying CIR can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing and patching, the surface appearance deteriorates further. Where special mixes are used, the future availability of similar mixes should be assured for maintenance purposes to lessen the aesthetic degradation.

COST

Supply Price: N/A

Supply+Install Price: \$4.20 to \$4.80/m^2 (\$3.50 to \$4.00/yd^2) for 75 mm (3 in.) recycling depth.

EXAMPLE PROJECTS

Mooney Road, Lassen National Forest, Lassen County, CA.
Grand Tetons National Park, WY.
Badlands National Park, SD.

SELECT RESOURCES

Asphalt Recycling & Reclaiming Association (ARRA), (410) 267-0023, www.arra.org
ARRA (2001). *Basic Asphalt Recycling Manual*, Publication No. NHI01-022, American Recycling and Reclaiming Association, 270 pp.

HOT IN-PLACE RECYCLING

GENERAL INFORMATION

Generic Name(s): Hot In-Place Recycling (HIR)

Trade Names: N/A

Product Description: The Hot In-Place Recycling (HIR) process consists of (1) heating and softening the existing asphalt pavement so it can be scarified or hot rotary milled to the specified depth, (2) mixing the loosened asphalt pavement with a recycling (rejuvenating) agent and possibly additional virgin asphalt and (3) placing and compacting the mixture with conventional hot mix asphalt paving equipment. This process is called heater-scarification (or reshaping). In the HIR repaving process, heater-scarification is simultaneously combined with an overlay of HACP. When additional materials are needed to recycle the pavement, such as mineral aggregate or virgin hot mix asphalt concrete, the remixing process is used. Typical treatments depths range from 19 to 50 mm (0.75 to 2 in.). HIR is usually surfaced with a hot mix asphalt concrete overlay or chip seal, but is sometimes used as a surface course on low volume roads.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Recycling & Reclaiming Association (ARRA), #3 Church Circle, PMB 250, Annapolis, MD 21401 www.arra.org.

APPLICATION

Typical Use: Road surfacing, binder course.

Traffic Range: Very Low to High. Heater-scarification process should be used only for low volume traffic. Remixing and repaving processes can be used on high traffic volume roads.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: Constructability can be limited on steep grades or tightly curved roads due to the physical size of the equipment and process.

Soil Type: N/A

Other: As HIR depth is limited, it is not suitable for fixing material or performance problems with lower asphalt courses or with the granular base. Pavements with major or extensive structural failures (severe alligator cracking and severe structural rutting) are not good candidates for HIR. As the HIR equipment is relatively wide and long, short road sections particularly in urban settings are not suitable for HIR treatment.

Other Comments: The typical HIR process requires a minimum of 75 mm (3 in.) of existing asphalt pavement. Detailed pavement evaluation is required before designing the HIR pavement rehabilitation. The evaluation should include visual condition survey and evaluation of pavement structural condition, using the Falling Weight Deflectometer (FWD) for instance.

If required strengthening is less than 19 mm (0.75 in.) of HACP, the pavement can be treated with remixing or repaving. If required strengthening is greater than 19 mm (0.75 in.) of HACP, but less than 50 mm (2 in.), the repaving process can be used. HIR is not suitable if required strengthening is greater than 50 mm (2 in.) of HACP. The pavement to be HIR treated should be relatively homogenous. If surface treatments, crack sealants, etc. are present, they should be removed. Large patches may require their own specific mix designs.

DESIGN

SLC: 0.30 to 0.35.

Other Design Values: None.

Base/Subbase Requirements: Only the upper part of existing asphalt pavement is treated in the HIR process. Base and subbase layers are not included in the HIR process. Existing base/subbase support must provide adequate structural support.

Other Comments: If the pavement exhibits severe or extensive structural failures, full depth repairs including granular base and subbase may be required, as well as providing efficient surface and subsurface drainage.

CONSTRUCTION

Availability of Experienced Personnel: Successful HIR process requires experienced personnel. Experienced HIR contractors are, in general, regionally available in the United States.

Materials: New aggregates, new asphalt binder, recycling/rejuvenating agents and/or new hot mix asphalt concrete can be added on an as-required basis. Typically, new aggregates or HMA additions are limited to 30 percent by mass of HIR mix.

Equipment: The HIR process uses a number of pieces of equipment, including pre-heaters, heaters, heater-scarifiers, mixers, pavers and rollers. The HIR equipment, called a recycling "train", has a length of approximately 45 m (150 ft).

Equipment is available in urban areas, but availability may be limited in remote areas. Mobilization costs may make small projects uneconomical.

Hot In-Place Recycling Process: There are three sub-categories within HIR: heater-scarification (also called surface recycling); remixing; and repaving.

Heater-scarification is the process in which softening of the asphalt pavement surface is achieved with heat from a series of pre-heating and heating units. The heated and softened surface layer is then scarified to a predetermined depth, a recycling (rejuvenating) agent is added, the loose recycled material is thoroughly mixed, and then placed with a standard paver screed. The depth of treatment typically ranges from 12 to 20 mm (0.5 to 0.75 in.), although treatments as deep as 50 mm (2 in.) have been used. No new aggregate or HACP are added in the heater-scarification process. Compaction of the recycled mix is with conventional rollers. A chip seal or HACP overlay is generally placed in a subsequent operation.

Remixing is the HIR process in which the existing asphalt pavement is heated, softened, scarified, and new aggregate, new asphalt binder, recycling agent, and/or new HACP is added and the resultant blend is thoroughly mixed. The recycled mix is then placed and compacted in one layer. The remixing process is used when the existing asphalt pavement requires significant modification. The recycled mix is usually left as the wearing course, although chip seal or HACP overlay are sometimes placed as a separate operation. Treatment depth is 25 to 50 mm (1 to 2 in.).

Repaving combines the heater-scarification or remixing process with the placement of an 'integral' overlay of new HACP. The recycled mix and new HACP overlay are compacted together. The thickness of the HACP wearing course ranges from 20 to 75 mm (0.75 to 3 in.).

Weather Restrictions: HIR should not be performed at temperatures below 10 °C (50 °F) or when it is raining.

Construction Rate: For heater-scarification HIR process, construction rates depend on ambient temperature, characteristics of the asphalt pavement being treated, moisture content of the pavement and the heat output of the equipment. Construction rates range from 1.5 to 15 m/min. (5 to 50 ft/min).

In the remixing process, construction rates depend on the same variables as for the heater-scarification plus the amount of admixture being added and the remixing treatment depth. Construction rates range from 1.5 to 10 m/min. (5 to 35 ft/min).

Lane Closure Requirements: The roadway lane being constructed is closed during construction, so adequate traffic control is needed. The HIR surface can be opened to traffic as soon as the HIR has cooled and construction equipment is cleared from the roadway.

Other Comments: It is critical that the rejuvenating agent is applied uniformly and the depth of HIR treatment is consistent during the HIR process.

SERVICEABILITY

Reliability and Performance History: HIR is considered to be a proven recycling technology. Research, design and construction information, and project experience is available. Performance depends on proper pavement evaluation, mix design and quality of construction.

Life Expectancy: Life expectancy varies depending on the type of HIR process, mix types, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives are: heater-scarification process with no subsequent surface treatment - 2 to 4 years; heater scarification with surface treatment - 6 to 10 years; remixing - 7 to 14 years; and, remixing with subsequent HACP overlay - 6 to 15 years.

Ride Quality: HIR provides good to very good ride quality after construction, depending on the type of wearing course used. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Raveling, cracking, rutting. Cracks in the untreated part of the pavement will reflect through the recycled layer within 1 to 2 years in colder climates.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching every 7 to 9 years. Thin surface treatments can be applied to extend the serviceable life of HACP.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided high quality aggregates are used in the recycled mix or HACP overlay, HIR provides good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: In the heater-scarification process no material hauling is required. In the remixing and repaving processes, hot mix asphalt concrete must be hauled from a stationary asphalt plant unless a mobile asphalt plant is assembled. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the HIR process. "Flare-ups" can occur if excessive pre-heater temperatures are used, especially where there is existing crack sealant. Construction processes may impact vegetation adjacent to the roadway. HIR has the potential to create fugitive emissions in the form of blue or white smoke depending on the type of equipment, type of pavement material recycled and the ambient conditions, including temperature, wind velocity and direction. A certain amount of noise is associated with the process. Immediately prior to HIR, road utilities should be checked for the presence of any flammable vapors/gases and should be cleared by the Fire Marshal.

Some rejuvenating agents may be carcinogenic and their application during construction requires special care. A health and safety plan as well as a spill prevention and containment plan should be in place prior to handling carcinogenic rejuvenating agents to protect the health of personnel and the environment.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: HIR is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by HIR roadways.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: HIR can be fully recycled as a pavement construction material.

Other Environmental Considerations: HIR's characteristic black surface will absorb heat from sunlight. Since HIR is essentially an in situ processing, there is limited scope to modify the finished product appearance, except by the addition of a surface treatment. HIR does improve the appearance of an old, deteriorated asphalt surfaces. For HIR, tire/road noise is typically similar to a HACP or surface treated pavement, depending on the type of wearing course used.

AESTHETICS

Appearance: Immediately after placement, HIR is generally black with a very smooth surface.

Appearance Degradation Over Time: Over time, HIR can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing and patching, the surface appearance deteriorates further. Where special mixes are used, the future availability of similar mixes should be assured for maintenance purposes to lessen the aesthetic degradation.

COST

Supply Price: N/A

Supply+Install Price: *Heater-scarification*: \$0.90 to \$1.60/m^2 (\$0.75 to \$1.35/yd^2).

Remixing: \$1.50 to \$2.40/m^2 (\$1.25 to \$2.00/yd^2).

Repaving: \$2.40 to \$3.90/m^2 (\$2.00 to \$3.25/yd^2).

EXAMPLE PROJECTS

Route 58, Lowell to Irasburg, VT.

SELECT RESOURCES

Asphalt Recycling & Reclaiming Association (ARRA), (410) 267-0023, www.arra.org
ARRA (2001). *Basic Asphalt Recycling Manual*, Publication No. NHI01-022, American Recycling and Reclaiming Association, 270 pp.

PORTLAND CEMENT CONCRETE PAVEMENT (PCCP) RECYCLING AND REHABILITATION

GENERAL INFORMATION

Generic Name(s): Reclaimed Concrete Aggregate (RCA), Rubblized Concrete, Crack and Seat

Trade Names: N/A

Product Description: Reclaimed Concrete Aggregate (RCA) is a well graded high quality aggregate produced by crushing old PCC or PCCP. The RCA is generated through the demolition of existing PCCP, PCC curbs, sidewalks, and/or driveways. It can be used by itself as an unbound pavement base or subbase layer in a pavement structure or can be blended with virgin aggregate or RAP.

Rubblization is the process of fracturing concrete slabs in situ, usually by impact with a resonating beam; the fractured slabs are used to form a base layer for an asphalt concrete overlay. Resonant breakers typically operate at a high frequency (44 Hz) and low amplitude (12 mm [0.5 in.]). Ideally, the concrete is broken into 25 to 75 mm (1 to 3 in.) chunks at the top and into 75 to 150 mm (3 to 6 in.) chunks towards the bottom.

Crack and Seat is a process where PCCP slabs are broken in situ using guillotine hammers or multi-head breakers, into relatively large chunks (300 mm [12 in.]) and above. The broken concrete is then rolled to bed it into the underlying base so that it can form the base layer of a reconstructed pavement.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors who can supply RCA can be obtained from: National Stone, Sand, and Gravel Association (NSSGA), 1605 King Street, Alexandria, VA 22314, (800) 342-1415, www.nssga.org.

Information on contractors who perform rubblization can be obtained from Resonant Machines Inc. Tulsa, OK, www.resonantmachines.com.

APPLICATION

Typical Use: Base course. RCA is not recommended for unbound road surfacing due to surface dusting problems and the alkaline nature of water runoff.

Traffic Range: Very Low to High, depending on thickness of HACP added.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Many agencies do not allow the use of RCA within 1 m (3 ft) of the water table because of its potential impact on water quality. Rubblizing has proved to be very effective even on very thick airfield pavements (over 330 mm [13 in.]). With the use of resonant breakers, the concrete slabs need to have adequate structural support to facilitate fracturing of the concrete.

Other Comments: Recycling of PCCP requires removal of steel reinforcing and mesh.

DESIGN

SLC: 0.14 for RCA; 0.14 to 0.25 for rubblized concrete.

Other Design Values: None.

Base/Subbase Requirements: The RCA, rubblized concrete, or crack and seat concrete forms the new base for the reconstructed road; any underlying old base or subbase materials can be treated as subbase in design.

Additional granular base may be needed in the case of rubblization and crack and seat.

Other Comments: RCA may become less permeable over time. Pavement designs incorporating rubblized concrete generally need the addition of edge drains.

CONSTRUCTION

Availability of Experienced Personnel: Contractors capable of producing and placing RCA are available throughout the United States. Rubblizing and crack and seat technology are limited to more specialized contractors with limited availability outside urban centers.

Materials: RCA consists of PCC derived from deteriorated rigid pavements or associated old concrete infrastructure.

Equipment: PCCP recycling requires several pieces of equipment, including combinations of a resonant pavement breaker, multi-head breaker, crushers; front end loaders; rear or bottom dump trucks for hauling material, water trucks, graders, and compactors or rollers. Availability of specialized breaker equipment may be limited in remote areas.

PCCP Recycling and Rehabilitation Process: RCA is produced through crushing and screening of concrete chunks derived from demolition. The process is similar to any aggregate production operation, although steel will need to be removed and caution needs to be exercised in avoiding the inclusion of lower quality materials, such as bricks, wood, and organics. The RCA is placed in a similar manner to other aggregate materials. RCA has higher water absorption properties than virgin aggregates and this may impact compaction characteristics and may require the addition of more water than for conventional aggregates.

Rubblization involves reducing an old PCCP to rubble or relatively small aggregate-sized particles. It is performed by dedicated equipment referred to as resonant breakers. The rubble is then used as an unbound base course to support a flexible pavement.

Crack and Seat is performed by repeated blows of a multi-head breaker or by drop weights or guillotine hammers. The hammers are dropped from variable heights between 0.3 and 1.5 m (1 to 5 ft) to create impact energies between 2,700 and 16, 300 N-m (2,000 to 12,000 ft-lb). The PCCP slabs are broken into pieces in the size range of 0.3 to 0.6 m^2 (1 to 2 ft^2). The pieces are then seated by 2 or 3 passes of a large rubber tired roller.

Weather Restrictions: Avoid construction during heavy rain or snow events and when the soil is frozen.

Construction Rate: RCA construction rates are in the range of 300 to 1,200 m^3/day (400 to 1,500 yd^3/day). Rubblization rates range from 5,000 to 8,400 m^2 /day (6,000 to 10,000 yd^2/day). Crack and seat rates are in the range of 10,000 to 15,000 m^2 /day (12,000 to 18,000 yd^2/day).

Lane Closure Requirements: The roadway lane being constructed is closed during construction, so adequate traffic control is needed. The RCA surface can generally be opened to temporary traffic as soon as construction is complete and construction equipment is cleared from the roadway. Rubblized surfaces could be used temporarily for slow moving traffic, but it is not recommended. Crack and seat surfaces are not suitable for temporary traffic unless additional granular is placed or the first lift of HACP is in place.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: RCA used as a replacement for conventional granular base or subbase is very effective. Rubblizing has been found to be more effective than crack and seat in minimizing reflection cracking. However, even with rubblizing, reflection cracking can possibly occur as a result of larger concrete chunks near the pavement edge or under existing reinforcing steel.

Life Expectancy: Life expectancy with the use of RCA for base or subbase layers would be similar to virgin aggregate. HACP or hot mix overlays above rubblized or crack and seat concrete should have life expectancies of 15 to 20 years.

Ride Quality: If overlaid with hot mix asphalt concrete, RCA, rubblized, and crack and seat concrete can provide very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Rutting, cracking.

Preservation Needs: No preventative maintenance is typically required to the recycled concrete products because these layers are not used as a surfacing.

SAFETY

Hazards: None.

Skid Resistance: When used as a temporary road surfacing, RCA layers can provide adequate skid resistance.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Recycled and processed PCCP is constructed of coarse and fine aggregates, portland cement, water, and chemical admixtures. The aggregates in the mix are naturally occurring and are obtained through mining or dredging. Portland cement is manufactured from limestone through a very energy intensive process.

Delivery and Haul Requirements: RCA is produced at an aggregate plant and hauled to the site. The raw material is concrete chunks obtained from demolition sites or from old PCCP removal. Rubblizing and crack and seat are both in situ processes and no hauling is required.

Potential Short-Term Construction Impacts: Noise is associated with the operation of resonant breakers and even more so with the crack and seat process. This latter process may not be suitable in highly residential locations. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: The leachate from RCA has a number of potential concerns, including highly alkaline runoff, a potential to clog drainage systems (especially those consisting of geotextiles), and potential to cause corrosion of nearby metal pipes. The pH of the leachate is generally in the 11 to 12 range. RCA may also contain some contaminants depending on the source of the original PCCP. Rubblized and crack and seat concrete would not give rise to leachate.

Surface Runoff: None, when used as a base layer.

Erosion: None.

Water quality: RCA can potentially impact the pH of surrounding waters due to the high pH of the leachate.

Aquatic species: RCA impacts water quality and so may be detrimental to aquatic species.

Plant quality: RCA does not directly impact plant quality but the leachate can impinge on plant quality.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: RCA and rubblized PCCP can be fully recycled and reused as a pavement construction material. Crack and seat concrete would have limited ability for economic recycling.

Other Environmental Considerations: None.

AESTHETICS

Appearance: RCA, rubblized PCCP, and crack and seat PCCP are generally not left exposed. The appearance of RCA and rubblized concrete is similar to a light colored crushed aggregate. Crack and seat concrete has an appearance of embedded concrete chunks.

Appearance Degradation Over Time: N/A; RCA is not exposed as a surfacing.

COST

Supply Price: N/A

Supply+Install Price: RCA costs will be location specific but can range from \$15.00 to \$30.00/m^3 (\$12.50 to \$25.00/yd^3). The cost of rubblizing and crack and seat varies widely depending on location, and size of project.

EXAMPLE PROJECTS

East-West Tollway (I-88) Pavement Rehabilitation (Rubblization), DeKalb and Kane Counties, IL.
Wright-Patterson Air Force Base, Fairborn, OH (Rubblization).

SELECT RESOURCES

AASHTO, *Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course*, AASHTO Designation: M 319-02
FHWA, *User Guidelines for Waste and By-Product Materials in Pavement Construction*, USDOT, FHWA Pub No. FHWA-RD-97-148, 1997.

RECYCLED HACP

GENERAL INFORMATION

Generic Name(s): Recycled HACP, Recycled Hot Mix Asphalt, Recycled Hot Asphalt Concrete Pavement.

Trade Names: N/A

Product Description:

Recycled hot asphalt concrete pavement is HACP that contains a mixture of virgin asphalt binder and aggregate combined with cold milled HACP from old pavement structures. This cold milled product is generally referred to as Reclaimed Asphalt Product (RAP). Recycled HACP mixtures typically can contain up to 30% by mass of cold milled HACP (RAP), although higher amounts can be used depending on the proposed use. Surface course mixtures generally will use less or no recycled HACP, and binder courses will use more. The asphalt mix proportions need to be designed to suit the particular application.

HACP is a high quality pavement material that is hot mixed at a plant and then hot laid. It is the most common surfacing for paved roads in the U.S., accounting for more than 90% of paved roads.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706, (888) HOT-MIXX, www.hotmix.org.

APPLICATION

Typical Use: Road surfacing, binder course.

Traffic Range: Very Low to High.

Restrictions:

Traffic: A high stability mix should be used for high traffic volumes and for heavy industrial loading conditions (i.e. slow moving trucks, frequent braking, etc.)

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: None.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges, traffic volumes and amount of RAP to be added to the mixture. Traditionally, asphalt cement grades have been designated as penetration grade (60/70, 85/100, etc.) or by viscosity grades (AC-10, AC-20, AR-4000, etc.). Currently, asphalt cements are specified by Performance Grades (PG), such as PG 64-22, indicating the high and low temperature range in °C. With the use of modifiers, the serviceable temperature range is extended so rutting can be avoided at high temperatures and transverse cracking can be avoided at low temperatures. Typically the addition of up to 20% RAP will not change the grade of asphalt binder required for a mixture. When RAP contents exceed 20%, typically a softer grade of asphalt binder is used to offset the stiffer, oxidized asphalt binder present in the RAP.

For very low to low traffic applications, recycled HACP mixes should be designed so that compaction from traffic is not relied upon to help achieve the target mix air void content as is commonly done for high volume applications. Inadequately compacted recycled HACP will have a higher air void content, making it more permeable and susceptible to oxidation. When recycled HACP oxidizes, it becomes brittle, which leads to cracking. Modifiers can be used in the asphalt cement to improve ductility and reduce the effects of oxidation.

DESIGN
SLC: 0.35 to 0.40.
Other Design Values: None.
Base/Subbase Requirements: Recycled HACP is usually constructed over an aggregate base course, but may be placed directly over a prepared subgrade of native materials. The required recycled HACP thickness depends on the design traffic and the level of base/subbase support provided. Subgrade and base materials should be graded and compacted to provide a stable working surface prior to recycled HACP placement. A prime coat is sometimes used above the aggregate base prior to paving. Tack coats can be used to improve the bond between hot mix layers.
Other Comments: As a general guideline, the minimum recycled HACP lift thickness should be three times the nominal maximum aggregate size.
CONSTRUCTION
Availability of Experienced Personnel: Most HACP paving contractors can also place recycled HACP, so experienced contractors are, in general, widely available. Availability may be limited for projects in remote areas.
Materials: Recycled HACP is composed of a blend of coarse and fine aggregate and mineral filler with asphalt cement as a binder, combined with cold milled HACP from old pavement structures. Modified asphalt cement and/or additives can be used to enhance certain performance characteristics.
Equipment: Equipment required for recycled HACP construction includes: haul vehicles, asphalt distributor (if prime or tack coats are applied), asphalt paver machine, and compaction equipment (static steel wheel roller, pneumatic tire roller, or vibratory roller). Where high a quality finish and smoothness are required, a material transfer vehicle (MTV) can be used to provide more uniform feed of hot mix to the paver. The use of an MTV also reduces the potential for mix segregation. Equipment is widely available in urban areas, but availability may be limited in remote areas.
Manufacturing/Mixing Process: HACP is hot mixed at a stationary asphalt plant by mixing specified proportions of the heated material components together to form a uniform mixture. For recycled HACP, an additional step is added; the cold milled HACP is fed by a conveyor system into a hot mixing chamber. The RAP, which is essentially asphalt binder coated aggregate, is mixed together with the virgin aggregate in the hot mixing chamber to form a homogeneous mixture. HACP mixes are normally mixed at temperatures between 132 to 163 °C (270 to 325 °F). However, depending on the content of RAP to be added, the temperatures may need to be increased. After mixing, the product is placed in haul vehicles to be transported to the project site. The asphalt concrete mix must arrive on-site and be placed before it cools. When transported in insulated vehicles with a tarp cover, the asphalt mixture can remain at an adequate temperature for up to 2 or 3 hours. When the project site is far from an asphalt plant, a portable asphalt plant can be assembled near the project site. When selecting a site for a portable asphalt plant, impacts to the environment and local residents and businesses must be considered.
Placement Process: Upon arrival at the site, the asphalt concrete mixture is transferred from the haul vehicles into the paver hopper, spread onto the prepared working surface by the paver, and leveled by a screed at the rear of the asphalt paver. The recycled HACP is then rolled with compaction equipment to achieve the required density. The compaction process should be completed before the asphalt binder stiffens to a point where additional compactive effort will damage the mat. Typically, this range is from 150 °C (300 °F) down to 85 °C (185 °F). This temperature range may not apply to modified binders. Experience has shown that the compaction process may continue to temperatures below 85 °C (185 °F) when modified binders have been used. The time available for compaction before the mix has cooled will depend on the mix temperature when it is placed, layer thickness, air temperature, and wind, but can range from several minutes to more than 30 minutes.
Weather Restrictions: Do not place recycled HACP if it is raining or there is ponded water on the prepared paving surface or if the surface is frozen. The specified minimum air temperature for recycled HACP placement varies between different agencies, but is normally about 7 °C (45 °F).

Construction Rate: Recycled HACP placement rates are similar to those for HACP, and will depend on the speed that the asphalt concrete mixture is delivered, layer thickness, and paving width. Placement rates can be 0.2 m/sec (40 ft/min) or higher. Compactor speeds are normally limited to 4.8 km/hr (3 mph), so overall construction rates are often dictated by the number of compactors on site. Typical production rates are 900 to 4,500 Mg/day (1,000 to 5,000 tons/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The recycled HACP surface can be opened to traffic as soon as it has cooled and construction equipment is cleared from the roadway. Road surface striping may be performed before or after the lane is opened.

Other Comments: None.

SERVICEABILITY

Reliability and Performance History: Recycled HACP is a very common roadway surfacing. With the increased use of cold milling / cold planing, paving contractors generate significant quantities of RAP. Since, in general, the RAP contains good quality aggregates and old asphalt binder, it is cost-effective to include it in HACP. Provided the percentage of RAP is kept below about 30%, it does not significantly impact the overall quality of the mix. With properly prepared mix designs, recycled HACP is found to perform as well as HACP. However, most agencies forbid or strictly limit the inclusion of RAP in premium wearing course mixes, because of the fact that it is a component of the mix that is not subject to strict quality control verification. Some agencies will only allow RAP that has been milled from their project site to be used, in an effort to control the quality of the RAP component. An extensive amount of research, design and construction information, and project experience is available.

Life Expectancy: Life expectancy varies depending on mix types, environmental conditions, traffic volumes, degree of routine maintenance and amount of RAP added to the mixture. Typical serviceable lives are similar to HACP and range from 15 to 20 years.

Ride Quality: Very good ride quality after construction. Ride quality deteriorates over the serviceable life.

Main Distress / Failure Modes: Cracking, rutting, raveling, loss of surface friction.

Preservation Needs: Preventative maintenance includes periodic crack sealing and localized patching every 7 to 9 years. Thin surface treatments can be applied to extend the serviceable life of recycled HACP.

SAFETY

Hazards: Road splash/spray can reduce visibility during periods of higher traffic volume.

Skid Resistance: Provided only RAP from known sources is used in the asphalt concrete mix, recycled HACP provides good to excellent skid resistance.

Road Striping Possible?: Yes.

Other Comments: Because recycled HACP provides a high-quality road surfacing, there is a tendency for higher road usage and speeding.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Recycled asphalt concrete must be hauled from a stationary asphalt plant unless a mobile asphalt plant is assembled, in which case the cold milled HACP and virgin mix materials must be hauled to the mobile plant. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: Significant heat is generated during the mixing and placement process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Recycled HACP is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by recycled HACP roadways.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Recycled HACP can be fully recycled as a pavement construction material.

Other Environmental Considerations: The use of large amounts of RAP in a mixture may increase the energy requirements of recycled HACP production at the asphalt plant. In addition if the RAP source is unknown, there is the potential to introduce some contaminants into the mix.

Recycled HACP's characteristic black surface will absorb heat from sunlight; select aggregates and pigments can be used to lighten the color and increase heat reflectivity of the surface. For recycled HACP, tire/road noise is similar to conventional HACP and is typically in the range of 66.5 to 77.5 dB(A) inside a car (80 km/hr [50 mph]) and 72 to 79.5 dB(A) at a distance 7.5 m (25 ft) from the vehicle.

AESTHETICS

Appearance: Immediately after placement, recycled HACP is generally black with a very smooth surface. Where a pigmented HACP is desired, RAP should not be added to the mix since it would introduce an unknown aggregate type and the old asphalt binder may compromise the effectiveness of the pigment. Recycled HACP could still be used for the binder course.

Appearance Degradation Over Time: Over time, recycled HACP can change color to a wide range of gray-blacks and occasionally has a brown or red sheen, depending on the predominant aggregate color. With maintenance activities, such as crack sealing and patching, the surface appearance deteriorates further. Short or medium term improvements in appearance can be achieved by the use of thin surface treatments, such as fog seals and slurry seals.

COST

Supply Price: $7.70 to $11.00/Mg ($7.00 to $10.00/ton) for RAP.

Supply+Install Price: $28 to $39/Mg ($25 to $35/ton) for recycled HACP.

EXAMPLE PROJECTS

Recycled HACP is used extensively throughout the United States, and most paving contractors routinely include RAP in hot mix production.

SELECT RESOURCES

Asphalt Institute, (859) 288-4960, www.asphaltinstitute.org
National Asphalt Pavement Association (NAPA), (888) HOT-MIXX, www.hotmix.org

FULL DEPTH RECLAMATION (FDR)

FDR - CEMENTITIOUS

GENERAL INFORMATION

Generic Name(s): Full Depth Reclamation, with Chemical Stabilization

Trade Names: N/A

Product Description: Full Depth Reclamation (FDR) is a rehabilitation technique in which the full thickness of the asphalt pavement and predetermined portion of the underlying materials (base, and sometimes, subbase) are uniformly pulverized and blended to provide an upgraded, homogenous base material. The reclaimed layer is then compacted to provide a uniform platform for the subsequent asphalt base course or surface course. FDR is an in situ process without the addition of heat. Stabilizing additives can be applied to enhance the properties of the reclaimed layer.

Three different types of stabilization can be used: bituminous (using emulsified asphalt or foamed asphalt); chemical (using portland cement, hydrated lime, cement kiln dust or lime kiln dust); and mechanical (using new granular material, RAP or crushed PCC). FDR with mechanical, bituminous and with foamed asphalt stabilizations are covered in detail in separate product summaries.

FDR with chemical stabilization is not the most commonly used form of FDR.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Recycling & Reclaiming Association (ARRA), #3 Church Circle, PMB 250, Annapolis, MD 21401, (410) 267-0023, www.arra.org.

APPLICATION

Typical Use: Base course.

Traffic Range: Very Low to High for stabilized base applications.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Typical FDR equipment can in situ process up to 125 to 150 mm (5 to 6 in.) of existing asphalt. Where existing asphalt thickness is greater than this, prior cold milling is required. Where there is extensive hot mix patching, the variation in asphalt thickness can pose construction problems for the FDR operation.

Other Comments: Full depth stabilized layers are commonly overlaid with HACP or covered with chip seals. FDR material has been used as a temporary road surfacing, but is not generally used as a permanent surfacing.

DESIGN

SLC: 0.15 to 0.22 depending on type of stabilizer used and quality of pulverized material.

Other Design Values: None.

Base/Subbase Requirements: The pulverized and blended material forms the new base for the reconstructed road, any underlying old base or subbase materials can be treated as subbase in design.

Other Comments: Detailed pavement evaluation is recommended before designing the FDR pavement rehabilitation. The evaluation should include visual condition survey and evaluation of pavement structural condition, using the Falling Weight Deflectometer (FWD) for instance. Pavements exhibiting major or extensive structural failures (severe alligator cracking and severe structural rutting) may require full depth base repairs.

FDR stabilization with portland cement, Type C fly ash or lime provides a significant structural component; however, it does not utilize the value of the asphalt binder in the reclaimed asphalt material. Localized full depth base repairs may be necessary in areas exhibiting severe alligator cracking and structural rutting.

CONSTRUCTION

Availability of Experienced Personnel: FDR techniques are considered to be proven in the United States; however, availability of experienced contractors for chemical stabilization is limited. Expertise is required in the preparation of the mix design for the chemical stabilization.

Materials: FDR is constructed with pulverized asphalt pavement and underlying granular material, and stabilizing additives. The additives can be portland cement, lime, fly ash, cement kiln dust and lime kiln dust. New granular materials are sometimes added for structural enhancement or for grade corrections. A bituminous sealer is generally used during the intermediate curing period where cementitious stabilizers are used.

Equipment: On typical FDR projects basic construction equipment is used: self-propelled reclaimer; motor grader; and rollers. On FDR projects including the application of a chemical stabilizing agent, additional equipment is required: haul trucks; water truck with spray bar; bulk spreader for the stabilizing agent; mixers; and tankers for slurry application.

Equipment availability may be limited in remote areas.

Full Depth Reclamation Process: Pulverization may be limited to the existing asphalt concrete or may also include a predetermined depth of the underlying granular material. Additional granular material, RAP or crushed PCC can also be added. The initial shaping of the roadway after the stabilizing additive has been added and mixed by the reclaimer, is performed with a motor grader. This is then followed with initial compaction using large pneumatic-tired or vibratory drum rollers. Final compaction and shaping to the required longitudinal profile and cross–slope is followed by a curing period. Initially moist curing is required to avoid excessive shrinkage cracking. This is followed by a period of intermediate curing when excessive drying of the mix is prevented by the use of a bituminous seal coat. The intermediate curing period is typically seven days. Heavy vehicles should be kept off the stabilized road during the curing period. A chip seal or hot mix asphalt concrete overlay is placed at the end of the curing period.

Weather Restrictions: FDR with chemical stabilization should not be performed at temperatures below freezing (0 °C [32 °F]) or when it is raining.

Construction Rate: FDR rates are on the order of 4,000 to 8,000 m^2/day (4,800 to 9,500 yd^2/day).

Lane Closure Requirements: The roadway lane being constructed is closed during construction, so adequate traffic control is needed. The FDR surface with stabilization additive can be opened to temporary traffic after an initial curing period of 12 to 24 hours. Truck traffic is not allowed until the riding surface is placed unless approved by the Contracting Officer.

Other Comments: When stabilizing granular/recycled asphalt product in-place, mixing should be limited to the depth of the granular material to prevent subgrade soils from being introduced into the mix.

With cementitious stabilization, care must be taken to avoid excessive strength being developed. Experience has shown that excessively stiff cement treated bases are prone to brittle cracking that very quickly impacts ride quality.

SERVICEABILITY

Reliability and Performance History: FDR techniques have been used for a number of years and are still gaining popularity. Research, design and construction information, and project experience is available. Case studies in the literature have reported numerous successful projects with FDR. With the use of stabilization additives, the risks are increased, since a higher structural contribution from the stabilized layer will have been assumed in design. All in situ processes have an inherent degree of risk from variation in the existing materials quality and layer thickness.

Life Expectancy: Life expectancy varies depending on treated material type, environmental conditions, traffic volumes and degree of routine maintenance. The general life expectancy falls within the following ranges: FDR with surface treatment - 7 to 10 years; and FDR with HACP overlay - 15 to 20 years.

Ride Quality: If overlaid with HACP, FDR stabilized pavement can provide very good ride quality after construction.

Main Distress / Failure Modes: Rutting, cracking, similar to the distress modes for conventional flexible pavements provided the stabilized layer is not excessively stiff.

Preservation Needs: No preventative maintenance is typically required because FDR layers are not used as a surfacing.

SAFETY

Hazards: None.

Skid Resistance: When used as a temporary road surfacing, FDR layers can provide adequate skid resistance.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: FDR is generally performed on in situ road materials. Cementitious and chemical stabilizers are manufactured or produced as byproducts of other industries. Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Portland cement, lime and other stabilizing additives must be hauled from manufacturers or suppliers. Haul distances may be significant for remote sites. The cost effectiveness of this type of FDR stabilization can be largely controlled by the haul distances of the stabilization agents.

Potential Short-Term Construction Impacts: A certain amount of noise is associated with the process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Portland cement and lime stabilized layers are considered to be impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by FDR.

Erosion: FDR is generally protected with a surfacing layer and thus is not susceptible to erosion.

Water quality: FDR does not impact water quality.

Aquatic species: FDR does not impact aquatic species.

Plant quality: FDR does not impact plant quality.

Air Quality: FDR does not impact air quality.

Other: None.

Ability to Recycle/Reuse: It is generally assumed that FDR with cementitious or chemical stabilization can be fully recycled and reused as a pavement construction material. However, there are few documented case studies of the practicalities of this form of secondary recycling.

Other Environmental Considerations: None.
AESTHETICS
Appearance: The pulverized pavement resulting from FDR is generally not left exposed. The appearance is similar to a stabilized aggregate base material. **Appearance Degradation Over Time:** N/A; FDR pavement layers are not exposed as a surfacing.
COST
Supply Price: N/A **Supply+Install Price**: \$4.00 to \$7.00/m^2 (\$3.30 to \$5.90/yd^2), depending on the application rate of cement, for a mixing depth of 150 to 200 mm (6 to 8 in.).
EXAMPLE PROJECTS
South Loop Road, Theodore Roosevelt National Park, ND.
SELECT RESOURCES
Asphalt Recycling & Reclaiming Association (ARRA), (410) 267-0023, www.arra.org ARRA (2001). *Basic Asphalt Recycling Manual*, Publication No. NHI01-022, American Recycling and Reclaiming Association, 270 pp.

FDR- EMULSIFIED ASPHALT

GENERAL INFORMATION

Generic Name(s): Full Depth Reclamation, with Bituminous Stabilization

Trade Names: N/A

Product Description: Full Depth Reclamation (FDR) is a rehabilitation technique in which the full thickness of the asphalt pavement and predetermined portion of the underlying materials (base, and sometimes, subbase) are uniformly pulverized and blended to provide an upgraded, homogenous base material. The reclaimed layer is then compacted to provide a uniform platform for the subsequent asphalt base course or surface course. FDR is an in situ process without the addition of heat. Stabilizing additives can be applied to enhance the properties of the reclaimed layer.

Three different types of stabilization can be used: bituminous (using emulsified asphalt or foamed asphalt); chemical (using portland cement, hydrated lime, cement kiln dust or lime kiln dust); and mechanical (using new granular material, RAP or crushed PCC). FDR without stabilization, with mechanical, chemical, and foamed asphalt stabilizations are covered in detail in separate product summaries.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Recycling & Reclaiming Association (ARRA), #3 Church Circle, PMB 250, Annapolis, MD 21401, (410) 267-0023, www.arra.org.

APPLICATION

Typical Use: Base course.

Traffic Range: Very Low to High for stabilized base applications.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Typical FDR equipment can in situ process up to 125 to 150 mm (5 to 6 in.) of existing asphalt. Where existing asphalt thickness is greater than this, prior cold milling is required. Where there is extensive hot mix patching, the variation in asphalt thickness can pose construction problems for the FDR operation.

Other Comments: Full depth stabilized layers are commonly overlaid with hot mix asphalt concrete or covered with chip seals. FDR and stabilized FDR can be used as a temporary road surfacing, but are not generally suitable for permanent road surfacing.

DESIGN

SLC: 0.20 to 0.30 for full depth emulsified asphalt stabilization.

Other Design Values: None.

Base/Subbase Requirements: The pulverized and blended material forms the new base for the reconstructed road, any underlying old base or subbase materials can be treated as subbase in design.

Other Comments: Detailed pavement evaluation is recommended before designing the FDR pavement rehabilitation. The evaluation should include visual condition survey and evaluation of pavement structural condition, using the Falling Weight Deflectometer (FWD) for instance. Pavements exhibiting major or extensive structural failures (severe alligator cracking and severe structural rutting) may require full depth base repairs.

FDR bituminous stabilization provides a significant structural component and it utilizes the value of the asphalt binder in the reclaimed asphalt material. However, where the existing road is determined to have structural deficiencies, the FDR process may not be adequate for rehabilitation. If the pavement exhibits severe structural distresses such as alligator cracking and structural rutting, full depth base or subgrade repairs and drainage improvements/installations may be necessary.

CONSTRUCTION

Availability of Experienced Personnel: FDR techniques are considered to be proven in the United States. Expertise is required in establishing the appropriate mix design based on the properties of the in situ materials to be pulverized and stabilized.

Materials: FDR is constructed with pulverized asphalt pavement and underlying granular material, and stabilizing additives. The emulsified asphalt is sometimes added in conjunction with other additives, such as portland cement or Type C fly ash slurry, to reduce initial curing period, accelerate strength gain and reduce moisture susceptibility. New granular materials are sometimes added for structural enhancement or for grade corrections.

Equipment: On typical FDR projects basic construction equipment is used: self-propelled reclaimer; motor grader; and rollers. On FDR projects including the application of a stabilizing agent, additional equipment is required: haul trucks; aggregate spreader; water truck with spray bar; bulk spreader for the stabilizing agent; mixers and tankers for slurry application; and emulsion tanker and distributor truck.

Equipment availability may be limited in remote areas.

Full Depth Reclamation Process: Pulverization may be limited to the existing asphalt concrete or may also include a predetermined depth of the underlying granular material. Additional granular material, RAP or crushed PCC can also be added. The initial shaping of the roadway after the stabilizing additive has been added and mixed by the reclaimer, is performed with a motor grader. This is then followed with initial compaction using large pneumatic-tired or vibratory drum rollers. Final compaction and shaping to the required longitudinal profile and cross–slope is followed by a curing period, if a stabilizing agent has been used. The initial curing period depends on the type of stabilizing additives used and the ambient conditions; but it typically ranges from a few hours to a day, after which the road can be opened to traffic. Where possible, heavy vehicles should be kept off the stabilized base until the surfacing has been added. The intermediate curing period, prior to placement of surfacing, can take up to 14 days depending on weather conditions. A chip seal or HACP overlay is placed at the end of the intermediate curing period.

Weather Restrictions: FDR should not be performed at temperatures below freezing (0 °C [32 °F]) or when it is raining. Full depth emulsion stabilization should not be used during cold (temperature less than 10 °C [50 °F]) and/or rainy weather.

Construction Rate: FDR rates are on the order of 4,000 to 8,000 m^2/day (4,800 to 9,500 yd^2/day).

Lane Closure Requirements: The roadway lane being constructed is closed during construction, so adequate traffic control is needed. The FDR surface, even without stabilization additive, can generally be opened to vehicular traffic at reduced speeds as soon as construction is complete and construction equipment is cleared from the roadway.

Other Comments: When stabilizing granular/recycled asphalt product in-place, mixing should be limited to the depth of the granular material to prevent subgrade soils from being introduced into the mix.

With asphalt emulsion stabilization, traffic will have to run on the stabilized surface until curing is complete. A surfacing layer applied before the completion of the curing period will be prone to debonding from the stabilized layer.

SERVICEABILITY

Reliability and Performance History: FDR techniques have been used for a number of years and are still gaining popularity. Research, design and construction information, and project experience is available. Case studies in the literature have reported numerous successful projects with FDR. All in situ processes have an inherent degree of risk from variation in the existing materials quality and layer thickness. With the use of stabilization additives, the risks are increased, since a higher structural contribution from the stabilized layer will have been assumed in design.

Life Expectancy: Life expectancy varies depending on treated material type, environmental conditions, traffic volumes and degree of routine maintenance. The general life expectancy falls within the following ranges: FDR with surface treatment - 7 to 10 years; and FDR with HACP overlay - 15 to 20 years.

Ride Quality: If overlaid with HACP, FDR stabilized pavement can provide very good ride quality after construction.

Main Distress / Failure Modes: Rutting, cracking, similar to conventional flexible pavements. The stabilized base layer can be prone to stripping if not adequately protected.

Preservation Needs: No preventative maintenance is typically required because FDR layers are not used as a surfacing.

SAFETY

Hazards: None.

Skid Resistance: When used as a temporary road surfacing, FDR layers can provide adequate skid resistance.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: FDR is generally performed on in situ road materials. Asphalt cement is an asphalt product produced by distillation of crude oil. Emulsifying agents (for emulsified asphalt) are manufactured products. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Emulsified asphalt must be hauled from an asphalt plant. Portland cement, lime and other stabilizing additives must be hauled from manufacturers. Haul distances may be significant for remote sites.

Potential Short-Term Construction Impacts: A certain amount of noise is associated with the process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Bituminous stabilized layers are considered to be impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by FDR.

Erosion: FDR is generally protected with a surfacing layer and thus is not susceptible to erosion.

Water quality: FDR does not impact water quality.

Aquatic species: FDR does not impact aquatic species.

Plant quality: FDR does not impact plant quality.

Air Quality: FDR does not impact air quality.

Other: None.

Ability to Recycle/Reuse: FDR can be fully recycled and reused as a pavement construction material.

Other Environmental Considerations: None.

AESTHETICS

Appearance: The pulverized pavement resulting from FDR is generally not left exposed. The appearance of the asphalt stabilized base is darker than conventional aggregate base material, but lighter than HACP. It presents a stabilized surface with a relatively rough finish.

Appearance Degradation Over Time: N/A; FDR pavement layers are not exposed as a surfacing.

COST

Supply Price: N/A

Supply+Install Price: \$5.00 to \$8.00/m^2 (\$4.20 to \$6.70/yd^2), depending on the quantity of asphalt emulsion needed, for a mixing depth of 150 to 200 mm (6 to 8 in.).

EXAMPLE PROJECTS

Point Road, Chickasaw National Recreation Area, OK.
Rockcreek & New Market Drives, City of Delaware, OH.

SELECT RESOURCES

Asphalt Recycling & Reclaiming Association (ARRA), (410) 267-0023, www.arra.org.
ARRA (2001). *Basic Asphalt Recycling Manual*, Publication No. NHI01-022, American Recycling and Reclaiming Association, 270 pp.

FOAMED ASPHALT

GENERAL INFORMATION

Generic Name(s): Foamed Asphalt, Expanded Asphalt, Foamed Bitumen

Trade Names: N/A

Product Description: Foamed asphalt is a stabilization technique where asphalt cement is used to bind existing or new granular material into a flexible base or subbase layer. Foamed asphalt is constructed with hot asphalt cement and cold water as a foaming agent. When the hot asphalt cement, typically 160 to 200 °C (320 to 390 °F), comes in contact with cold water, typically 15 to 25 °C (60 to 77 °F), the mixture expands to more than ten times its original volume and is separated into very fine droplets. The foamed material is mixed with the granular material to be stabilized and coats the fines in the granular material to form a mortar that binds the coarse particles together. The resulting product is a well mixed stabilized base material.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: National Asphalt Pavement Association, 5100 Forbes Blvd., Lanham, MD 20706, (888) HOT-MIXX, www.hotmix.org; and

Asphalt Recycling & Reclaiming Association (ARRA), #3 Church Circle, PMB 250, Annapolis, MD 21401 www.arra.org.

APPLICATION

Typical Use: Base stabilization, binder course.

Traffic Range: Very Low to High for base stabilization applications.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: Foamed asphalt can be used to stabilize sand, coarse aggregates, or milled asphalt products. The material to be stabilized must have enough fines content (5% to 20%) for the foamed asphalt to bind with to adequately stabilize the material. If the material contains high plasticity fines, additives (e.g. lime, cement, etc.) are often mixed with the material prior to foamed asphalt stabilization.

Other: None.

Other Comments: Compared to other asphalt stabilization techniques, foamed asphalt requires less water and asphalt cement and is better suited for use with marginal materials containing large amounts of fines. Foamed asphalt-stabilized base is commonly overlaid with a thin asphalt concrete layer; fog seals, slurry seals, and chip seals have also been used as a surfacing. Foamed asphalt-stabilized material has been used as a temporary road surfacing, but is not generally used as a permanent surfacing.

DESIGN

SLC: 0.25 (sands and marginal quality aggregates) to 0.40 (high quality granular aggregates).

Other Design Values: None.

Base/Subbase Requirements: Roadway should be designed with adequate base and/or subbase support.

Other Comments: The grade of asphalt cement needs to be selected based on service temperature ranges. Generally, a neat (unmodified) asphalt is necessary to attain the proper foaming characteristics. Highly modified asphalts will often not be able to achieve the proper expansion and half-life (i.e. a measure of the working life of the foam before it dissipates). Typical application rates for foamed asphalt are 2% to 4%.

No long-term durability issues (e.g. freeze-thaw or moisture susceptibility) have been identified to this point. Additional research is needed in this area.

CONSTRUCTION

Availability of Experienced Personnel: Foamed asphalt is a fairly new stabilization technique and availability of experienced contractors is, in general, limited.

Materials: Foamed asphalt is constructed with hot asphalt cement and cold water as a foaming agent.

Equipment: Equipment required for foamed asphalt stabilization construction includes: tanker truck for asphalt, specialized pulverizer (reclaimer) with a foamed asphalt injection system, water truck, compaction equipment, and a motor grader. Equipment availability may be limited in remote areas.

Manufacturing/Mixing Process: Foamed asphalt can be plant-mixed or mixed in place. In-place mixing typically occurs when a granular material is already located on site or when existing pavements in need of complete reconstruction are pulverized into a granular material and cold recycled to create a stabilized base for a new road surfacing.

Placement Process: Foamed asphalt is constructed with hot asphalt cement and cold water as a foaming agent. The foamed asphalt is mixed with the material to be treated using a specialized pulverizer (reclaimer) with a foamed asphalt injection system. Depending on the reclaimer used, the process can either be completed in a single pass or the material may be pre-pulverized prior to foamed asphalt stabilization. The hot asphalt, typically 160 to 200 °C (320 to 390 °F), and cold water are combined at a controlled rate on board the reclaimer. This causes the asphalt cement to foam and expand to more than ten times its normal value. The foamed asphalt is then introduced to the pulverized material in the mixing chamber of the reclaimer through a spray bar mounted on the hood of the mixing chamber. The foamed material mixes with the granular material and coats the fines in the granular material to form a mortar that binds the coarse particles together. Most of the water in the mixture is released as steam and the remaining stabilizer, consisting mainly of asphalt cement, returns to its original volume. The resulting product is a well mixed stabilized base material. A high quality road surface can be achieved with only the application of a thin surfacing.

Weather Restrictions: Foamed asphalt stabilization should not be performed at temperatures below freezing (0 °C [32 °F]) or when it is raining.

Construction Rate: Foamed asphalt stabilization rates are on the order of 4,000 to 6,500 m^2/day (4,800 to 7,800 yd^2/day).

Lane Closure Requirements: The roadway lane(s) being constructed are closed during construction, so adequate traffic control is needed. The foamed asphalt-stabilized surface can be opened to traffic on a temporary basis as soon as construction is complete and construction equipment is cleared from the roadway.

Other Comments: When stabilizing granular/recycled asphalt product in-place, mixing should be limited to the depth of the granular material to prevent subgrade soils from being introduced into the mix. The typical processing depth is 150 mm (6 in.).

SERVICEABILITY

Reliability and Performance History: Foamed asphalt stabilization is a relatively recent stabilization technique in North America, but has gained popularity over the past several years, because of its cost-effectiveness. Research, design and construction information, and project experience is available. Case studies in the literature have reported very good success with foamed asphalt.

Life Expectancy: Life expectancy varies depending on treated material type, environmental conditions, traffic volumes and degree of routine maintenance. Typical serviceable lives range from 15 to 20 years or longer for foamed asphalt-stabilized base with a HACP surfacing. When covered by a thin surface treatment, typical serviceable lives for the foamed asphalt-stabilized base layer are 8 to 12 years for low volume applications.

Ride Quality: Foamed asphalt can provide good to very good ride quality after construction.

Main Distress / Failure Modes: Cracking (within the stabilized layer).

Preservation Needs: No preventative maintenance is typically required because foamed asphalt is not used as a surfacing.

SAFETY

Hazards: None.

Skid Resistance: When used as a temporary road surfacing, foamed asphalt provides adequate skid resistance.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: Foamed asphalt is an in situ treatment. Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: Asphalt cement must be hauled from a stationary asphalt plant. However, the quantities are relatively small since only 2 to 4% asphalt cement needs to be added. Haul distances may be significant for remote sites. When foamed asphalt is used to stabilize existing in-place materials, no aggregate hauling is required.

Potential Short-Term Construction Impacts: None.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Foamed asphalt is impermeable, which promotes surface runoff. However, surface runoff water quality is not generally impacted by foamed asphalt stabilization.

Erosion: None.

Water quality: None.

Aquatic species: None.

Plant quality: None.

Air Quality: None.

Other: None.

Ability to Recycle/Reuse: Foamed asphalt can be fully recycled as a pavement construction material.

Other Environmental Considerations: None.

AESTHETICS

Appearance: Immediately after construction, foamed asphalt generally takes on the color characteristics of the material being treated.

Appearance Degradation Over Time: Foamed asphalt is not exposed as a surfacing material.

COST

Supply Price: N/A

Supply+Install Price: \$4.80 to \$8.40/m^2 (\$4.00 to \$7.00/yd^2) for a mixing depth of 150 mm (6 in.).

EXAMPLE PROJECTS
Marysville Road, Yuba County, CA. Trail Ridge Road, Rocky Mountain National Park, CO. Canyon de Chelly National Monument, AZ.
SELECT RESOURCES
Wirtgen, *Wirtgen Cold Recycling Manual,* Wirtgen GmbH, ISBN 3-00-003577-X, 1998

PULVERIZATION

GENERAL INFORMATION

Generic Name(s): Full Depth Reclamation

Trade Names: N/A

Product Description: Full Depth Reclamation (FDR) is a rehabilitation technique in which the full thickness of the asphalt pavement and predetermined portion of the underlying materials (base, and sometimes, subbase) are uniformly pulverized and blended to provide an upgraded, homogenous base material. The reclaimed layer is then compacted to provide a uniform platform for the subsequent asphalt base course or surface course. FDR is an in situ process without the addition of heat. Stabilizing additives can be applied to enhance the properties of the reclaimed layer. FDR with bituminous and chemical stabilization are covered in detail in separate product summaries.

The structural support of the pulverized in situ pavement materials can be enhanced by the addition of granular materials such as virgin aggregates, reclaimed granular materials, crushed/reclaimed PCC, or reclaimed asphalt pavement (RAP). These additional granular materials can improve gradation deficiencies and drainage characteristics of the compacted base.

Product Suppliers: Representative list of manufacturers, suppliers, and contractors can be obtained from: Asphalt Recycling & Reclaiming Association (ARRA), #3 Church Circle, PMB 250, Annapolis, MD 21401, (410) 267-0023, www.arra.org.

APPLICATION

Typical Use: Base course.

Traffic Range: Very Low to High, similar to any aggregate road base application.

Restrictions:

Traffic: None.

Climate: None.

Weather: None.

Terrain: None.

Soil Type: N/A

Other: Typical FDR equipment can in situ process up to 125 to 150 mm (5 to 6 ins.) of existing asphalt. Where existing asphalt thickness is greater than this, prior cold milling is required. Where there is extensive hot mix patching, the variation in asphalt thickness can pose construction problems for the FDR operation.

Other Comments: Pulverized pavement will perform as an unbound granular surface and can be used for temporary construction traffic without additional surfacing, but is not generally suitable for use as a permanent surfacing.

DESIGN

SLC: 0.10 to 0.15 for pulverized asphalt pavement mixed with existing granular material.

Other Design Values: None.

Base/Subbase Requirements: The pulverized and blended material forms the new base for the reconstructed road, any underlying old base or subbase materials can be treated as subbase in design. New base aggregates can be added to achieve increased base structural support or for geometric adjustments.

Other Comments: Detailed pavement evaluation is recommended before designing the FDR pavement rehabilitation. The evaluation should include visual condition survey and evaluation of pavement structural condition, using the Falling Weight Deflectometer (FWD) for instance. Pavements exhibiting major or extensive structural failures (severe alligator cracking and severe structural rutting) may require full depth base repairs.

CONSTRUCTION

Availability of Experienced Personnel: FDR techniques are considered to be proven in the United States. FDR without bituminous or chemical stabilization is a low risk process.

Materials: FDR is constructed with pulverized asphalt pavement and underlying granular materials. New granular materials, RAP, or crushed PCC can be used in mechanical stabilization and added to enhance the structural quality of the completed base.

Equipment: On typical FDR projects basic construction equipment is used: self-propelled reclaimer; motor grader; and rollers. Other equipment that may be needed includes haul trucks; aggregate spreader; and water trucks to aid in achieving compaction.

Equipment availability may be limited in remote areas.

Full Depth Reclamation Process: Pulverization may be limited to the existing asphalt concrete or may also include a predetermined depth of the underlying granular material. Additional granular material, RAP or crushed PCC can also be added. The initial shaping of the roadway after pulverization and blending is performed with a motor grader. This is then followed with initial compaction using large pneumatic-tired or vibratory drum rollers and final compaction and shaping to achieve the required longitudinal profile and cross–slope. A chip seal or HACP overlay can be placed as soon as the specified compaction is achieved.

Weather Restrictions: FDR should not be performed at temperatures below freezing (0 °C [32 °F]) or when it is raining, due to the difficulties of achieving compaction.

Construction Rate: FDR rates are on the order of 4,000 to 8,000 m^2/day (4,800 to 9,500 yd^2/day).

Lane Closure Requirements: The roadway lane being constructed is closed during construction, so adequate traffic control is needed. The FDR surface can generally be opened to temporary traffic as soon as construction is complete and construction equipment is cleared from the roadway.

Other Comments: Generally, FDR equipment can process to the edge of a curb and gutter section, however, for straight-faced concrete sections (with no gutter), a portion of roadway will have to be removed with smaller equipment.

SERVICEABILITY

Reliability and Performance History: FDR techniques have been used for a number of years and are still gaining popularity. Research, design and construction information, and project experience is available. Case studies in the literature have reported numerous successful projects with FDR. FDR without stabilization is very low risk and the existing granular base is enhanced by the addition of the RAP. All in situ processes have an inherent degree of risk from variation in the existing materials quality and layer thickness.

Life Expectancy: Life expectancy varies depending on treated material type, environmental conditions, traffic volumes and degree of routine maintenance. The general life expectancy falls within the following ranges: FDR with surface treatment - 7 to 10 years; and FDR with HACP - 15 to 20 years.

Ride Quality: If overlaid with HACP, pavements with full depth reclaimed bases provide very good ride quality after construction.

Main Distress / Failure Modes: Rutting and cracking, as for conventional flexible pavements.

Preservation Needs: No preventative maintenance is typically required because FDR layers are not used as a surfacing.

SAFETY

Hazards: None.

Skid Resistance: When used as a temporary road surfacing, FDR layers can provide adequate skid resistance.

Road Striping Possible?: N/A; not a surfacing.

Other Comments: None.

ENVIRONMENTAL CONCERNS

Source of Raw Materials: FDR is generally performed on in situ granular and bituminous bound road materials. Asphalt cement is an asphalt product produced by distillation of crude oil. Aggregates may be naturally occurring or quarried, but either requires mechanical processing (crushing, sizing) before they can be used.

Delivery and Haul Requirements: When FDR is used to treat existing in-place materials, no aggregate hauling is required. Additional aggregates to enhance the in situ properties, where required, would need to be hauled to site from commercial sources.

Potential Short-Term Construction Impacts: A certain amount of noise is associated with the process. Construction processes may impact vegetation adjacent to the roadway.

Potential Long-Term Environmental Impacts:

Leachate: None.

Surface Runoff: Surface runoff water quality is not generally impacted by FDR.

Erosion: FDR is generally protected with a surfacing layer and thus is not susceptible to erosion.

Water quality: FDR does not impact water quality.

Aquatic species: FDR does not impact aquatic species.

Plant quality: FDR does not impact plant quality.

Air Quality: FDR does not impact air quality.

Other: None.

Ability to Recycle/Reuse: FDR can be fully recycled and reused as a pavement construction material.

Other Environmental Considerations: None.

AESTHETICS

Appearance: The pulverized pavement resulting from FDR is generally not left exposed. The appearance is similar to a dark aggregate base material, with the asphalt coated particles visible on close examination.

Appearance Degradation Over Time: N/A; the pulverized pavement is not exposed as a surfacing material.

COST

Supply Price: N/A

Supply+Install Price: \$2.00 to \$4.00/m^2 (\$1.70 to \$3.30/yd^2), for a typical 200 mm (8 inch) processing depth.

EXAMPLE PROJECTS

Used extensively for municipal road rehabilitation throughout the United States.

SELECT RESOURCES

Asphalt Recycling & Reclaiming Association (ARRA), (410) 267-0023, www.arra.org.
ARRA (2001). *Basic Asphalt Recycling Manual*, Publication No. NHI01-022, American Recycling and Reclaiming Association, 270 pp.

APPENDIX B — SURFACING SELECTION ANALYSIS WORKSHEET

Surfacing Selection Analysis Worksheet

Surfacing Type ______________________________

WEIGHTING FACTOR		SCORING FACTOR		WEIGHTING FACTOR		SCORE
PERFORMANCE AND DURABLITY ATTRIBUTES _______						
_______ %	Durability	_______	x	_______	=	_______
_______ %	Life Expectancy	_______	x	_______	=	_______
_______ %	Maintenance Requirements	_______	x	_______	=	_______
_______ %	Safety/Surface Characteristics	_______	x	_______	=	_______
CONSTRUCTABILITY AND COST ATTRIBUTES _______						
_______ %	Life-Cycle Cost	_______	x	_______	=	_______
_______ %	Availability	_______	x	_______	=	_______
_______ %	Construction Impacts	_______	x	_______	=	_______
_______ %	Weather Limitations	_______	x	_______	=	_______
CONTEXT SENSITIVITY ATTRIBUTES _______						
_______ %	Environmental Impacts	_______	x	_______	=	_______
_______ %	Visual Quality	_______	x	_______	=	_______
_______ %	Context Compatability	_______	x	_______	=	_______
100 %				**TOTAL RATING**		_______

WEIGHTING FACTOR: PERCENT OF IMPACT ON SURFACING SELECTION (TOTAL = 100%)
SCORING FACTOR: 1 = POOR OR NOT DESIRABLE; 5 = EXCELLENT OR HIGHLY DESIRABLE

FOR MOST SITUATIONS, NO CATEGORY SHOULD HAVE A WEIGHTING FACTOR LESS THAN 20% OR GREATER THAN 50% AND NO INDIVIDUAL ATTRIBUTE SHOULD HAVE A WEIGHTING FACTOR GREATER THAN 20%.

Figure 4. Worksheet. Surfacing Selection Analysis Worksheet.

APPENDIX C — EXAMPLE PROJECTS

To illustrate the roadway surfacing selection process, three example projects are presented below. The example projects have been developed using information from actual sites and include a historic parkway, a scenic byway, and a local rural road. Although the example projects are based on actual sites, the selection process has not been used in conjunction with roadway projects at any of these sites, and the output from these examples should not be used to infer the appropriate strategy for these actual sites, since many assumptions have been made for the purposes of illustrating the process. These example projects are fictitious and are provided only to show how the selection process could be utilized, based on typical project situations.

EXAMPLE 1 – HISTORIC SITE

Project Description

Project: "Historic Parkway" in the Eastern U.S.

***Traffic (estimate)*:** AADT = 1,800 (with 2% RVs/buses/trucks)

***History*:** The Colonial Parkway connects some of the most historically significant sites in North America. The Parkway connects Jamestown, Yorktown Battlefield, and Williamsburg. Jamestown is the site of the first permanent English settlement in North America in 1607. The Yorktown Battlefield is the site of the final major battle of the American Revolutionary War and the British surrender. Williamsburg was the capital of colonial Virginia and a hotbed for the colonies liberty movement. Preservationists consider this historic triangle of Williamsburg, Jamestown, and Yorktown to be "sacred shrines of national life and liberty".

***Context/Setting*:** The 37 km (23 mile) parkway is situated on the Virginia peninsula and it connects the above and several other significant historical sites. Here are some excerpts from the Historic American Engineering Record (HAER):

"Colonial Parkway is a meticulously crafted landscape that integrates the region's natural and cultural resources into a memorial roadway of the American colonial experience. It marks an important change in the history of National Park Service (NPS) road-building traditions as the first NPS-designated parkway that unifies dispersed sites as part of a cohesive national park."

The Colonial Parkway Outline of Development from 1933 indicated: "Its function as a unifying factor transcends mere considerations of transportation. Its location and design should contribute, as far as practicable, to the general commemorative purposes of the Monument."

Central to the legislation that created the Colonial NHP and Parkway was a plan for a scenic highway that would link the sites and be free of any modern commercial development. The HAER says, "The parkway was designed to provide continuity to the visitor experience of motoring through nearly 400 years of American colonial history. Traversing a diverse environment, the parkway provides visitors with dramatic open vistas of rivers and tidal estuaries as well as shady passageways through pine and hardwood forests."

U.S. Representative Louis Cramton, a major supporter and champion of the parkway, had the following vision for the roadway, "I would like the new highway as part of the new park, on a strip sufficiently wide to protect it by trees shutting out all conflicting modern development, this highway not to be a glaring modern pavement but as much as feasible giving the impression of an old-time road."

Because of WWII, restricted funding, and other issues, the construction of the Colonial Parkway stretched out over a 26-year period from 1931 to 1957.

***Stakeholders*:** Stakeholders include numerous historical and environmental preservation groups, the local Chamber of Commerce, the NPS, tourist industry organizations, and the local traveling public that uses the parkway as a daily commuting route.

The NPS has aggressively fought to limit access and visual encroachments along the road. However, rapid regional population growth is placing new demands upon the parkway and its context-sensitive environment. Despite objections by numerous stakeholder groups, the parkway has become a popular commuting route. Safety, durability, and performance of the exposed aggregate concrete pavement have become more significant issues due to the increased traffic. In selecting a roadway surface, a difficult balancing act of retaining the integrity of the parkway's original design as a scenic, rustic, and rural parkway with the necessity to be a safe, efficient, and durable roadway must be accomplished.

***Design Guidelines*:** The roadway section should be designed for a 20 year design life. Design speeds will be 50 km/hr (31 mph). The current vertical alignment has maximum grades of 3%.

Initial Screening Criteria

***Traffic*:** AADT=1,800, so traffic level is classified as High.

Decorative Setting: No information was provided indicating that a decorative surfacing is required; therefore, this screening criterion is not used.

***Historic Setting*:** The roadway is surrounded by a significant historical setting and efforts are being made to preserve the historical context of the area; therefore the historical criterion should be applied.

***Urban or Rural Setting*:** The historical context is the overriding issue with this project, so urban or rural criteria are not used.

***Low Cost*:** Given the historical significance of this section of road and its uniqueness, low cost is not considered to be a relevant initial screening criterion.

Unbound or Paved: With the traffic level and the existing paved surface, the selected option must be paved, so this criterion is applied. However, in this instance, it eliminates the same options eliminated by the High traffic requirement.

3R or 4R Project: It is assumed that this is a 4R project, especially considering it is more than 45 years old.

Screening Stage

Applying the five initial screening criteria, a total of 32 surfacings can be eliminated, as shown in Table 7, leaving potentially 15 for the selection stage.

Table 7. Example 1 Screening Criteria.

Screening Criteria	High Traffic	Historic	Paved	R4
Number of Surfacings Eliminated	16	17	13	3

In order to rank the 15 remaining surfacings, numerical values were assigned to the scores for each category (A=3, B=2, C=1) and the values for all categories were summed for each surfacing to obtain a total numerical score for each surfacing. The surfacings were then ranked according to the numerical score. A score of 10 was selected as a cutoff for additional evaluation because it reduces the number of qualified surfacings down to a manageable number. Five surfacings had a score of 10 or greater and will be analyzed in the selection stage (Table 8).

Table 8. Example 1 Screening Stage Ranking.

Option No.	Product	Score
1	Synthetic Binder Concrete Pavement	12
2	Unit Pavers	11
3	Exposed Aggregate PCCP	10
4	Pigmented HACP	10
5	Pigmented PCCP	10

Selection Stage

The weighting factors have been assigned to each category and attribute as follows:

Performance and Durability**:** This road has a high traffic volume, so safety and durability are important. Assign Weighting Factor = 35%.

1. Durability = 9%
2. Life Expectancy = 9%
3. Maintenance Requirements = 5%
4. Safety/Surface Characteristics = 12%

Constructability and Cost**:** These factors are of secondary importance. The site is close to major urban areas, so experienced contractors and quality materials should be readily available. Lane closures can be managed without significant disruption to users. The project climate is moderate, so there are no unusual climatic conditions to consider. Assign Weighting Factor = 20%.

5. LCC = 10%
6. Availability = 3%
7. Construction Impacts = 4%
8. Weather Limitations = 3%

Context Sensitivity: Over-riding importance is given to the historic context and uniqueness of the site. Therefore, assign Weighting Factor = 45%.

9. Environmental impacts = 9%
10. Visual quality = 18%
11. Context Compatibility = 18%

After weighting factors have been developed for each attribute, assign scoring factors. Rate and compare the 5 surfacing options for the 11 surfacing attributes. The scoring factors have been applied by comparing the 5 options for each attribute (Table 9).

Table 9. Example 1 Scoring Factors.

Option	Scoring Factor										
	1	2	3	4	5	6	7	8	9	10	11
Synthetic Binder Concrete Pavement	3	4	3	5	1	1	4	3	5	5	5
Unit Paver	3	3	3	2	2	4	2	5	4	3	3
Exposed Aggregate PCCP	3	4	3	3	3	4	3	4	5	4	3
Pigmented HACP	3	4	1	5	3	4	4	3	5	3	2
Pigmented PCCP	4	4	1	5	2	3	3	4	5	3	2
Note: Initial cost used instead of LCC for convenience since LCC information was not available for all alternatives.											

Applying the weighting factors to these scores the following total scores are obtained for each surfacing (Table 10).

Table 10. Example 1 Selection Stage Rating.

Option No.	Product	Total Rating	Rank
1	Synthetic Binder Concrete Pavement	4.01	1
2	Unit Paver	2.83	5
3	Exposed Aggregate PCCP	3.51	2
4	Pigmented HACP	3.30	3
5	Pigmented PCCP	3.25	4

The preferred option is synthetic binder concrete pavement because it has the highest total rating, 4.01, which is significantly higher than the rating for exposed aggregate PCCP. The analysis worksheet for synthetic binder concrete pavement is shown in Figure 5.

Surfacing Selection Analysis Worksheet

Surfacing Type Synthetic Binder Concrete Pavement

WEIGHTING FACTOR				SCORING FACTOR		WEIGHTING FACTOR		SCORE
PERFORMANCE AND DURABLITY ATTRIBUTES			**35%**					
9	%	Durability		3	x	0.09	=	0.27
9	%	Life Expectancy		4	x	0.09	=	0.36
5	%	Maintenance Requirements		3	x	0.05	=	0.15
12	%	Safety/Surface Characteristics		5	x	0.12	=	0.60
CONSTRUCTABILITY AND COST ATTRIBUTES			**20%**					
10	%	Life-Cycle Cost		1	x	0.10	=	0.10
3	%	Availability		1	x	0.03	=	0.03
4	%	Construction Impacts		4	x	0.04	=	0.16
3	%	Weather Limitations		3	x	0.03	=	0.09
CONTEXT SENSITIVITY ATTRIBUTES			**45%**					
9	%	Environmental Impacts		5	x	0.09	=	0.45
18	%	Visual Quality		5	x	0.18	=	0.90
18	%	Context Compatability		5	x	0.18	=	0.90
100	%					**TOTAL RATING**		**4.01**

WEIGHTING FACTOR: PERCENT OF IMPACT ON SURFACING SELECTION (TOTAL = 100%)
SCORING FACTOR: 1 = POOR OR NOT DESIRABLE; 5 = EXCELLENT OR HIGHLY DESIRABLE

FOR MOST SITUATIONS, NO CATEGORY SHOULD HAVE A WEIGHTING FACTOR LESS THAN 20% OR GREATER THAN 50% AND NO INDIVIDUAL ATTRIBUTE SHOULD HAVE A WEIGHTING FACTOR GREATER THAN 20%.

Figure 5. Worksheet. Example 1 Synthetic Binder Concrete Pavement Worksheet.

EXAMPLE #2 – NORTHWEST SITE

Project Description

Project: "Scenic Byway/All-American Road" in the Northwestern U.S.

Traffic (estimate): SADT (Seasonal Average Daily Traffic) = Currently, 1,000 vehicles (with 5% RVs/buses/trucks). Twenty year design traffic is 2,000 vehicles.

History: The highway, designated as a "Scenic Byway/All-American Road," was initially constructed as a National Park approach road in the 1930s. The original surfacing was hot asphalt concrete pavement with a crushed aggregate base. The section proposed for reconstruction was resurfaced with hot-mix asphalt concrete in the 1960s and a thin layer of microsurfacing was applied in 2000. All other segments of the highway were reconstructed in the 1960s to 1980s. The highway section presently serves as a transportation link between a nearby town and National Park and Forest Service Lands. The highway is also a recreational destination and a scenic driving route.

Context/Setting:
The 29 km (18 mile) highway section provides access to National Park and Forest Service Lands from nearby towns and is designated as a "Scenic Byway/All-American Road." The road is functionally classified as a rural minor arterial. The highway section is in need of reconstruction to improve alignments, grades, and widths to FHWA and state guidelines. The existing highway currently has inadequate drainage features and structural deficiencies. The highway section had a Pavement Condition Index of 40 in 1994, indicating that the pavement is in need of major reconstruction. The reconstructed highway section is expected to generally follow the existing alignment in most areas; alternative alignments may be considered along parts of the highway to avoid wetlands or provide a more consistent alignment.

The identified "Purpose and Need" of the highway section is to: (1) support management of National Forest lands adjacent to the road, including maintaining the Scenic Byway/All-American road qualities; (2) maintain an efficient transportation link between the nearby town and National Park that can safely accommodate projected traffic levels in twenty years; and (3) provide a roadway that could be reasonably maintained by a maintaining agency.

The highway corridor is in a management area that emphasizes rural and roaded natural recreational activities; recreational activities include: driving for pleasure, viewing scenery, picnicking, fishing, hiking, camping, snowmobiling, and cross-country skiing. The "All-American Road" designation under the Scenic Byways program indicates that the road has one-of-a-kind features that do not exist elsewhere. "The … Highway is considered one of the most beautiful drives in the country …" The highway segment has natural and scenic qualities of national significance. Based on the "All-American Road" designation, driving along the highway corridor is often the primary reason for the trip. The highway must also accommodate vehicles whose primary destination is the National Park. In addition, the highway section is used by tour buses and cyclists.

Alpine vegetation, along with rare plant species, is located along the road corridor. The existing alignment runs along or over local streams, lakes, and wetland areas. Surface water quality is generally very high and nearby streams are important trout waters. The road is visible from other recreational areas, making the roadway part of the visual landscape.

Tourism and recreation are significant components of the local economy.

The road is generally open from June to mid-October. The road is closed during the winter and early spring months due to harsh winter weather conditions. Some snow plowing can be required every month that the road is open. The current lane width is 0.3 m (1 ft) narrower than standard snowplow blades, making it unsafe to plow the roads when they are open to traffic.

***Stakeholders*:** Stakeholders include numerous historical and environmental preservation groups, the local Chamber of Commerce, the NPS, Forest Service, tourist industry organizations, recreational users, and the local traveling public that uses the highway as a daily commuting route.

***Design Guidelines*:** The highway section should be designed for a 20 year design life. Design speeds will be 50 or 60 km/hr (31 to 37 mph), except at switchback curves where the design speed will be 30 km/hr (20 mph). Vertical alignment should have maximum grades of 8%.

Initial Screening Criteria

***Traffic*:** Design AADT=2,000, so traffic level is classified as High.

***Decorative Setting*:** No information was provided indicating that a decorative surfacing is required; therefore, this screening criterion is not used.

***Historic Setting*:** The setting does not have substantial historic significance, so this screening criterion is not used.

***Urban or Rural Setting*:** Since the setting is rural and significance is placed on the special natural surroundings, the rural criterion should be used.

***Low Cost*:** Based on the location, length of roadway to be reconstructed, and available funding, apply low cost criterion.

***Unbound or Paved*:** No specific requirements or preferences with regard to unbound or paved were provided, therefore, this criterion is not used. However, the High design traffic level will eliminate all unpaved surfaces from consideration.

***3R or 4R Project*:** It is assumed that this is a 4R project since pavement condition index data indicated that major reconstruction is needed.

Applying the five initial screening criteria in order, a total of 24 surfacings can be eliminated (Table 11), leaving potentially 23 for the selection stage.

Table 11. Example 2 Screening Criteria.

Screening Criteria	High Traffic	Rural	Low Cost	R4
No. of Surfacings Eliminated	16	3	6	3

In order to rank the 23 surfacings, numerical values were assigned to the scores for each category (A=3, B=2, C=1) and the values for all categories were summed for each surfacing to obtain a total numerical score for each surfacing. The surfacings were then ranked according to the numerical score. A score of 10 was selected as a cutoff for additional evaluation because it reduces the number of qualified surfacings down to a manageable number. Eight surfacings had a score of 10 or greater and will be analyzed in the selection stage.

Table 12. Example 2 Screening Stage Ranking.

Option No.	Product	Score
1	Chip Seal	11
2	Multiple Surface Treatments	11
3	Cape Seal	10
4	Open Graded Friction Course	10
5	HACP	10
6	Pigmented HACP	10
7	Resin Modified Pavement	10
8	Recycled HACP	10

Chip seal over HACP was not listed as a separate surfacing in the initial screening table, but will be analyzed in the Stage 2 Selection since both chip seal and HACP are being considered individually; combining the two surfacings may take advantage of desirable properties from each.

Selection Stage

The weighting factors for the categories and individual attributes are as follows:

Performance and Durability: This road has a high traffic volume, so safety and durability are very important. Assign Weighting Factor = 38%.

1. Durability = 9%
2. Life Expectancy = 9%
3. Maintenance Requirements = 7%
4. Safety/Surface Characteristics = 13%

***Constructability and Cost*:** These factors are of lesser importance in relation to the other categories. Assign Weighting Factor = 25%.

5. LCC = 11%
6. Availability = 3%
7. Construction Impacts = 8%
8. Weather Limitations = 3%

***Context Sensitivity*:** Since the highway is designated as a “Scenic Byway/All-American Road” with scenic and environmental value, context sensitivity and environmental impacts are very important. Assign Weighting Factor = 37%.

9. Environmental Impacts = 14%
10. Visual Quality = 14%
11. Context Compatibility = 9%

Rate and compare the 10 options for the 11 surfacing attributes. The scoring factors have been applied by comparing the eight options for each attribute (Table 13).

Table 13. Example 2 Scoring Factors.

	Scoring Factor										
Option	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Chip Seal	1	2	2	3	3	3	4	3	4	4	3
Multiple Surface Treatments	2	2	2	3	3	3	4	3	4	4	3
Cape Seal	2	3	2	4	3	2	4	3	4	3	3
Open Graded Friction Course	2	3	1	4	2	1	3	3	5	2	2
HACP	4	4	3	5	2	1	3	3	5	2	2
Pigmented HACP	3	4	3	5	1	1	3	3	5	4	3
Resin Modified Pavement	5	5	4	2	2	1	2	3	4	1	1
Recycled HACP	4	4	3	5	3	1	3	3	5	2	2
Chip Seal over HACP	3	4	4	4	1	1	3	3	4	4	3
Note: Initial cost used instead of LCC for convenience since LCC information was not available for all alternatives.											

By applying the weighting factors to these scores, the following total ratings are obtained for each surfacing:

Table 14. Example 2 Selection Stage Rating.

Option No.	Product	Total Score	Rank
1	Chip Seal	3.02	7
2	Multiple Surface Treatments	3.11	6
3	Cape Seal	3.16	5
4	Open Graded Friction Course	2.78	8
5	HACP	3.32	3
6	Pigmented HACP	3.49	1
7	Resin Modified Pavement	2.73	9
8	Recycled HACP	3.43	2
9	Chip Seal over HACP	3.29	4

The preferred option is Pigmented HACP with a rating of 3.49. The analysis worksheet for this product is shown in Figure 6. Recycled HACP is a close second with a rating of 3.43.

Surfacing Selection Analysis Worksheet

Surfacing Type Pigmented HACP

WEIGHTING FACTOR			SCORING FACTOR		WEIGHTING FACTOR		SCORE
PERFORMANCE AND DURABLITY ATTRIBUTES		**38%**					
9 %	Durability		**3**	**x**	**0.09**	**=**	**0.27**
9 %	Life Expectancy		**4**	**x**	**0.09**	**=**	**0.36**
7 %	Maintenance Requirements		**3**	**x**	**0.07**	**=**	**0.21**
13 %	Safety/Surface Characteristics		**5**	**x**	**0.13**	**=**	**0.65**
CONSTRUCTABILITY AND COST ATTRIBUTES		**25%**					
11 %	Life-Cycle Cost		**1**	**x**	**0.11**	**=**	**0.11**
3 %	Availability		**1**	**x**	**0.03**	**=**	**0.03**
8 %	Construction Impacts		**3**	**x**	**0.08**	**=**	**0.24**
3 %	Weather Limitations		**3**	**x**	**0.03**	**=**	**0.09**
CONTEXT SENSITIVITY ATTRIBUTES		**37%**					
14 %	Environmental Impacts		**5**	**x**	**0.14**	**=**	**0.70**
14 %	Visual Quality		**4**	**x**	**0.14**	**=**	**0.56**
9 %	Context Compatability		**3**	**x**	**0.09**	**=**	**0.27**
100 %					**TOTAL RATING**		**3.49**

WEIGHTING FACTOR: PERCENT OF IMPACT ON SURFACING SELECTION (TOTAL = 100%)
SCORING FACTOR: 1 = POOR OR NOT DESIRABLE; 5 = EXCELLENT OR HIGHLY DESIRABLE

FOR MOST SITUATIONS, NO CATEGORY SHOULD HAVE A WEIGHTING FACTOR LESS THAN 20% OR GREATER THAN 50% AND NO INDIVIDUAL ATTRIBUTE SHOULD HAVE A WEIGHTING FACTOR GREATER THAN 20%.

Figure 6. Worksheet. Example 2 Pigmented HACP Worksheet.

EXAMPLE 3 – RURAL HIGHWAY

Project Description

***Project*:** "Rural Local Road" in the Western U.S.

***Traffic (estimate)*:** Current AADT of 200 vehicles (with 5% RVs/buses/trucks). Twenty-year design AADT is 300. Peak use occurs from June to September with traffic levels double the AADT. Summer weekend traffic levels are 3.5 times the AADT.

***History*:** The last major construction work on the road was completed in the 1960s. The roadway surfacing of the segment being considered is currently gravel/dirt. Adjacent sections of the roadway have gravel/dirt, chip seal, or asphalt concrete surfacings. The road has been designated as a State Scenic and Historic Byway and as a National Forest Scenic Byway.

***Context/Setting*:** The 5-km (3-mile) roadway section provides access to Forest Service Lands from nearby towns and is designated as a "Scenic Byway." The primary use of the roadway is recreational (90% of traffic) with secondary use for short, local trips and local access. The road is functionally classified as a rural local road. The roadway section is in need of reconstruction to improve alignments, grades, and widths to FHWA and state guidelines. The existing roadway currently has inadequate drainage features and structural deficiencies. The reconstructed road section is expected to generally follow the existing alignment in most areas.

The identified objectives of the project are: (1) provide a roadway width and surface capable of accommodating the 20-year design traffic volumes; (2) improve safety by providing consistent roadway geometry and providing reasonable protection from unsafe conditions; (3) accommodate and control access to Forest Service facilities located along the road; (4) reduce the anticipated maintenance costs to the counties and town maintaining the road; (5) repair roadway drainage problems; (6) repair existing unvegetated slopes; (7) avoid, minimize, or mitigate adverse impacts to the environment by considering key issues identified through the public and agency involvement process (social environment, water resources, visual quality, recreational resources, plants and animals, and construction impacts); and (8) maintain the rural and scenic character of the road.

The road provides primary access to National Forest Lands and Forest Service facilities and a privately owned resort. The area is used for sightseeing, hiking, hunting, fishing, camping, wildlife viewing, bicycling, cross country skiing, and other recreational activities. The road is a popular destination for viewing fall foliage.

The road corridor consists of alpine and montane forests with meadows and wetlands. It passes through rock and talus slopes and areas rich in wildlife. The existing road section runs along a creek. During high runoff years, the creek can overflow its banks and inundate portions of the roadway. Surface water quality is generally very high. The existing gravel road surface leads to significant amounts of dust generated from traffic and spreading and erosion of gravel material into adjacent environmentally sensitive areas. The road is visible from other recreational areas, making the roadway part of the visual landscape.

Tourism and recreation are significant components of the local economy.

The roadway is not snowplowed year-round and will be closed for portions of the winter. Local maintaining agencies do not have the funds for frequent dust suppressant application or regrading the road surface.

***Stakeholders*:** Stakeholders include numerous environmental preservation groups, the local Chamber of Commerce, Forest Service, tourist industry organizations, recreational users, and the local traveling public that uses the roadway as a daily commuting route.

***Design Guidelines*:** The roadway section should be designed for a 20 year design life. Design speeds will be 50 km/hr (31 mph), except at switchback curves where the design speed will be 20 km/hr (13 mph). The current vertical alignment has maximum grades of 3%.

Initial Screening Criteria

***Traffic*:** Design AADT=300, so traffic level is classified as Low, although summer traffic levels are Medium. Low traffic level criterion is used, keeping in mind that unbound surfaces may have higher maintenance requirements due to summer traffic levels.

***Decorative Setting*:** No information was provided indicating that a decorative surfacing is required; therefore, this screening criterion is not used.

***Historic Setting*:** The setting does not have substantial historical significance, so this screening criterion is not used.

***Urban or Rural Setting*:** Since the setting is rural and significance is placed on the special natural surroundings, the rural criterion should be used.

***Low Cost*:** Based on available funding, apply low cost criterion.

***Unbound or Paved*:** Do not apply this criterion; allow for either bound or unbound surfacing.

***3R or 4R*:** It is assumed that this is a 4R project.

***Climate*:** The climate is damp to dry with significant frost depth.

***% Fines in Unbound Material*:** Assume that unbound materials contain 5% to 30% fines.

Applying the 6 initial screening criteria in order, only 10 surfacings can be eliminated (Table 15), leaving potentially 37 for the selection stage, as follows:

Table 15. Example 3 Screening Criteria.

Screening Criteria	Low Traffic	Rural	Low Cost	R4	Damp to Dry	5 -30% Fines
No. of Surfacings Eliminated	1	3	6	3	0	0

In order to rank the 37 surfacings, numerical values were assigned to the scores for each category (A=3, B=2, C=1) and the values for all categories were summed for each surfacing to obtain a total numerical score for each surfacing. Bound surfacings were given a score of 3 for the "Climate" and "% Fines in Unbound Material" categories. The surfacings were then ranked according to the numerical score. Four surfacings had a score of 17 or above and 12 surfacings had a score of 16. All surfacings with a score of 17 or above were selected for additional evaluation. To select more surfacings for detailed evaluation without choosing all 12 surfacings with a score of 16, only the products with a score of 16 and with an "A" score for the Rural Setting screening criteria were considered. The Rural Setting screening criteria was chosen due to its importance to the project's context/setting and project objectives. This additional consideration added 2 more surfacings, synthetic polymer emulsions and tree resin emulsions, to the list for detailed evaluation. Therefore, 6 surfacings will be analyzed in the selection stage, as shown in Table 16.

Table 16. Example 3 Screening Stage Ranking.

Option No.	Product	Score
1	Chip Seal	18
1	Multiple Surface Treatments	18
3	Cape Seal	17
4	Otta Seal	17
5	Synthetic Polymer Emulsions	16
6	Tree Resin Emulsions	16

Selection Stage

The weighting factors have been assigned to each category and attribute as follows:

***Performance and Durability*:** Safety and durability have been identified as very important parameters. Assign Weighting Factor = 38%.

1. Durability = 9%
2. Life Expectancy = 9%
3. Maintenance Requirements = 7%
4. Safety/Surface Characteristics = 13%

***Constructability and Cost*:** These factors are of secondary importance. Assign Weighting Factor = 24%.

5. LCC = 10%
6. Availability = 3%
7. Construction Impacts = 8%
8. Weather Limitations = 3%

***Context Sensitivity*:** Since the highway is designated as a "Scenic Byway" with scenic and environmental value, context sensitivity and environmental impacts are very important. Assign Weighting Factor = 38%.

9. Environmental Impacts = 14%
10. Visual Quality = 14%
11. Context Compatibility = 10%

Rate and compare the 6 options for the 11 surfacing attributes. The scoring factors have been applied by comparing the seven options for each attribute (Table 17).

Table 17. Example 3 Scoring Factors.

Option	**Scoring Factor**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Chip Seal	3	4	2	4	3	3	4	3	4	3	3
Multiple Surface Treatments	4	4	3	4	3	3	4	3	4	3	3
Cape Seal	4	4	3	4	3	2	4	3	4	1	1
Otta Seal	4	4	3	3	3	3	4	3	4	2	2
Synthetic Polymer Emulsions	2	4	2	3	2	3	3	3	4	5	5
Tree Resin Emulsions	2	3	2	2	1	3	3	3	4	5	5
Note: Initial cost used instead of LCC for convenience since LCC information was not available for all alternatives.											

By applying the weighting factors to these scores, the following total ratings are obtained for each surfacing (Table 18):

Table 18. Example 3 Selection Stage Ranking.

Option No.	Product	Total Rating	Rank
1	Chip Seal	3.37	3
2	Multiple Surface Treatments	3.53	1
3	Cape Seal	3.02	7
4	Otta Seal	3.16	6
5	Synthetic Polymer Emulsions	3.45	2
6	Tree Resin Emulsions	3.22	5

The preferred option is Multiple Surface Treatments with a rating of 3.53. The analysis worksheet for this product is shown in Figure 7. Synthetic Polymer Emulsion is a close second with a rating of 3.45.

Surfacing Selection Analysis Worksheet

Surfacing Type Multiple Surface Treatments

WEIGHTING FACTOR			SCORING FACTOR		WEIGHTING FACTOR		SCORE
PERFORMANCE AND DURABLITY ATTRIBUTES		**38%**					
9 %	Durability		4	x	0.09	=	0.36
9 %	Life Expectancy		4	x	0.09	=	0.36
7 %	Maintenance Requirements		3	x	0.07	=	0.21
13 %	Safety/Surface Characteristics		4	x	0.13	=	0.52
CONSTRUCTABILITY AND COST ATTRIBUTES		**24%**					
10 %	Life-Cycle Cost		3	x	0.10	=	0.30
3 %	Availability		3	x	0.03	=	0.09
8 %	Construction Impacts		4	x	0.08	=	0.32
3 %	Weather Limitations		3	x	0.03	=	0.09
CONTEXT SENSITIVITY ATTRIBUTES		**38%**					
14 %	Environmental Impacts		4	x	0.14	=	0.56
14 %	Visual Quality		3	x	0.14	=	0.42
10 %	Context Compatability		3	x	0.10	=	0.30
100 %					**TOTAL RATING**		**3.53**

WEIGHTING FACTOR: PERCENT OF IMPACT ON SURFACING SELECTION (TOTAL = 100%)
SCORING FACTOR: 1 = POOR OR NOT DESIRABLE; 5 = EXCELLENT OR HIGHLY DESIRABLE

FOR MOST SITUATIONS, NO CATEGORY SHOULD HAVE A WEIGHTING FACTOR LESS THAN 20% OR GREATER THAN 50% AND NO INDIVIDUAL ATTRIBUTE SHOULD HAVE A WEIGHTING FACTOR GREATER THAN 20%.

Figure 7. Worksheet. Example 3 Multiple Surface Treatments Worksheet.

APPENDIX D — ROADWAY SURFACING OPTIONS PHOTO ALBUM

A *Roadway Surfacing Options Photo Album* (Album) has been developed as a supplement to the Guide. This album contains product descriptions, photographs, and presents some advantages and limitations for different roadway surfacing types. The intent of the photo album is to provide a visual resource for users of the Guide who may be unfamiliar with certain surfacings, especially newer or less commonly used surfacings. To help the user evaluate the visual characteristics of each surfacing, the Album includes photographs that show the various surfacings as they appear in context with the surrounding environment and close-up photographs that highlight the surfacing's color and surface texture.

The Album is included in this report as a CD-ROM attachment that can be found on the inside back cover of this report. The Album will also be included in an update to the FHWA's *Roadway Aesthetic Treatments 2001 Photo Album Workbook.*

APPENDIX E – GLOSSARY OF TERMS

Asphalt Binder/ Asphalt Cement – A dark brown to black cementitious material in which the predominant constituents are bituminous which occur in nature or are obtained in petroleum processing.

Asphaltic Concrete Pavement – See Hot Asphalt Concrete Pavement

Base Course – A pavement layer, either bound or unbound, above the subbase or subgrade and below the surfacing.

Binder Course – The layer of asphalt immediately beneath the surfacing in an asphalt pavement, typically with larger size aggregate.

Bleeding – The upward movement of asphalt binder in an asphalt surfacing resulting in the formation of a film of asphalt on the surface. The most common cause is too much asphalt in one or more of the pavement courses.

Cape Seal – A surface treatment where a chip seal is followed by the application of either a slurry seal or microsurfacing.

Cellular Concrete – A cellular geosynthetic in which the voids are filled with concrete to form a flexible pavement mat.

Chip Seal – A surface treatment using one or more layers of aggregate chips and asphalt binding agent.

Cold In-Place Recycling – A rehabilitation treatment involving cold milling of the pavement surface and remixing with the addition of emulsified asphalt, Portland cement or other modifiers to improve the properties, followed by screeding and compaction of the reprocessed material in one continuous operation.

Cold Milling – A process which uses specialized equipment, consisting of a rotating drum with helically placed teeth, to grind up the pavement into pieces to the desired depth.

Cold Mix Asphalt Concrete – A blend of coarse and fine aggregate with emulsified or cutback asphalt as a binder. Cold mix requires no heating during the production process and can be placed directly after mixing or stockpiled for later use.

Context Sensitive Design/Context Sensitive Solutions – The process of selecting a design solution that, while meeting all the functional design requirements, also considers all aspects of the component's surroundings, environment, and overall context.

Corrugation – Type of pavement distortion. Corrugation, or "washboarding" is a form of plastic movement typified by ripples, typically in a transverse direction, across the asphalt pavement surface.

Cross Slope – The slope across the width of a road lane. On a two-lane road, it is the slope measured from the road centerline to the outer edge of the lane.

Crown – The high point at the center of a road's cross section. A road is crowned to promote water flow to the outer edges of the road.

Cutback Asphalt – asphalt cement that has been liquefied by blending with petroleum solvents (also called a diluent). Upon exposure to atmospheric conditions the diluents evaporate, leaving the asphalt cement to perform its function.

Depression – A localized area that has a slightly lower elevation than the surrounding surface.

Dirt Road – A common term used to describe an unbound road surfacing composed of mineral soil or aggregate.

Distortion – Any change of a pavement shape from its originally constructed shape.

Draindown – Process by which asphalt binder drains from the asphalt mix during mix transportation and laydown.

Dust – Fugitive fines generated from an unbound road surfacing as the road dries and particles are carried by wind or passing vehicles. The term dust is also used to describe the very fine component of an asphalt mix aggregate.

Dust Suppressant – A product that is applied to, or blended with, an unbound road surface to control the generation of dust. Also referred to as a dust palliative.

Emulsified Asphalt – A suspension of minute globules of asphalt cement in water or in an aqueous solution.

Equivalent Single Axle Load (ESAL) – A concept developed to permit the cumulative damage of a spectrum of vehicle loading to be quantified. It equates the damage to a pavement structure caused by the passage of any axle load to that of a standard 80 kN (18,000 pound) axle load, in terms of equal conditions of distress or loss of serviceability.

Faulting – A difference in elevation between opposing sides of a crack or joint caused by weak or moisture-sensitive foundation material.

Fines – The fine aggregate component of a gravel or aggregate blend. It generally refers to that component of an aggregate with particle size smaller than 75 microns (0.003 in.). The term fines is also used to describe the silt and clay fraction (smaller than 75 microns) of a subgrade soil.

Foamed/Expanded Asphalt – A stabilization technique where asphalt cement is used through a foaming process to bind existing or new granular material into a flexible base or subbase layer. Foamed asphalt is constructed with hot asphalt cement, cold water and a foaming agent.

Fog Seal – Sprayed on application of low viscosity, slow to medium setting emulsified asphalt, which seals a pavement surface, controls water infiltration, and retards oxidation.

Fly Ash – Residue from coal combustion, which is carried in flue gases, and is used as a pozzolan or cementing material to replace a portion of the Portland cement in concrete.

Geogrid – A geosythetic product that is a coarse meshed polymer grid structure capable of developing high tensile stresses with little deformation.

Geosynthetics – Woven or non-woven man-made materials designed for such applications as drainage, filtration, separation, and strengthening. They can be subdivided into various groups: geotextiles, geowebs, geocomposites, geogrids or geodrains.

Geotextile – A geosynthetic product that is composed of synthetic fabrics having a broad range of applications in the highway and earth related construction industry. Three broad categories of geotextiles are woven, non-woven and knitted.

Haul – The term use to describe the distance to transport road construction materials from their source or point of manufacture to the road site.

Hot In-Place Recycling – A rehabilitation treatment used to correct asphalt pavement surface distress involving heating, removal of old asphalt concrete, processing, mixing with new aggregates, new asphalt binder and/or recycling agents, relaying, and compacting to meet specifications for conventional asphalt concrete.

Hot Mix Asphalt Concrete - A high quality, thoroughly controlled mixture of asphalt cement (binder) and well-graded, high quality aggregate, that is produced hot at a batch or drum-mixing facility and must be spread and compacted while at an elevated temperature.

Hot Asphalt Concrete Pavement – A flexible pavement structure with a surfacing layer consisting of hot mix asphalt concrete and supported on lower layers of hot mix asphalt concrete and/or aggregate layers.

Hydroplaning – A dangerous vehicle action that occurs as a vehicle tire looses direct contact with the pavement surface when a film of water intervenes between the pavement surface and a vehicle tire, reducing the driver's ability to control of the vehicle. Good pavement macrotexture reduces the potential for hydroplaning.

Interlocking Concrete Pavement – A pavement surface comprised of individual concrete paving units, positioned and interlocked together to support vehicular or pedestrian traffic.

Leachate –Solution of material washed from a solid. It is typically used to describe pollutants that are dispersed and transported by water seepage through a material.

Life-Cycle Cost Analysis (LCCA) – An economic analysis technique that allows comparisons of investment alternatives having different cost streams. LCCA involves estimating all costs associated with each alternative over a selected analysis period and conversion of those costs to economically comparable values considering the time-value of money. In addition to initial construction costs, the analysis also includes the costs for routine maintenance and rehabilitation.

Lifts – A layer of roadway material that is placed in one operation.

Microsurfacing – An enhanced slurry seal with a polymer modified binder, very high quality aggregates, and placed using specialized paving equipment.

Open Graded – having a relatively large amount of voids between particles, when expressed as a percentage of the toal volume of a material.

Open Graded Friction Course (OGFC) – A pavement surface layer that consists of a high-void, plant mix asphalt concrete that permits rapid drainage of rainwater through the layer.

Otta Seal – A type of surface treatment constructed using a thick layer of soft asphalt binder covered by graded aggregates.

Oxidation – Process by which organic molecules in asphalt binder react with oxygen from the atmosphere; causing the structure and composition of the asphalt molecules to change and resulting in the asphalt binder becoming harden and more brittle.

PM_{10} – Refers to fine particles suspended in air, consisting of particles with diameter less than approximately 10 micrometers.

Polymer – A synthetic additive that is mixed into asphalt binder to alter and improve performance characteristics.

Porous Pavement – A pavement that is purposely designed and constructed to be permeable to water infiltration. Stormwater that passes through the pavement is allowed to infiltrate into the underlying soil, with the excess being temporarily stored in a gravel filter bed or removed through a subsurface drainage system.

Portland Cement –A product made from limestone (or some other source of lime) and other materials, which are ground up, mixed, burned in a kiln, and subsequently ground to a fine powder which will harden when mixed with water.

Portland Cement Concrete – The product of mixing Portland cement, aggregate, water, and, in some cases, additives (such as an air entraining agent or a water reducing agent) to result in a hardened structural material after hydration occurs.

Portland Cement Concrete Pavement (PCCP) – A road pavement that is constructed with portland cement concrete, also referred to as a rigid pavement.

Potholes – Bowl-shaped holes of various sizes in the pavement resulting from localized disintegration under traffic.

Prime Coat – Low viscosity emulsion applied to an absorbent surface, such as granular base, prior to hot mix asphalt paving.

Pumping – The displacement and ejection of water and suspended fine particles at joints, cracks, and edges.

Raveling – Progressive separation of aggregate particles in a pavement from the surface downward or from the edges inward. Raveling can be caused by lack of compaction, construction of a thin lift during cold weather, dirty or disintegrating aggregate, too little asphalt in the mix, or overheating of the asphalt mix.

Reclaimed Asphalt Pavement (RAP) – Existing asphalt mixture that has been pulverized, usually by milling, and is used like an aggregate in the recycling of asphalt pavements. It can also be blended with virgin aggregates and used as an aggregate base or subbase material.

Resin Modified Pavement – A surfacing alternative that provides many of the performance characteristics of Portland cement concrete (PCC) but which can be constructed similar to a hot asphalt concrete pavement (HACP). The mix is an open graded asphalt mixture with 25-35% voids that are filled with a latex-rubber modified cement grout.

Ride Quality – As observed from within a vehicle, the smoothness of the roadway as impacted by defects and unevenness in the roadway surface.

Roadway Surfacing – The top layer of a road.

Roller Compacted Concrete – A zero slump (i.e. very stiff) mixture of aggregates, cementitious materials, and water that is consolidated by rolling with vibratory compactors.

Rutting – Grooves or longitudinal depressions that develop in the wheel tracks of a road. Channels may result from consolidation or lateral and vertical movement under traffic in one or more of the underlying courses, or by displacement in the asphalt surface layer itself.

Sand Seal – An asphalt surface treatment constructed by spraying emulsified asphalt and immediately spreading and rolling a thin fine aggregate cover. Similar to a chip seal, except that finer aggregate is used in the cover.

Sandwich Seal – Similar to a double chip seal, except the first layer of asphalt binder is omitted.

Scrub Seal – An asphalt surface treatment where an emulsified asphalt is sprayed on an existing asphalt pavement surface followed by a 'brooming' action to force the emulsion into any voids in the surface left after the initial application. Sand is applied over the surface, followed by compaction.

Sett – A paving block or brick.

Shoving – Permanent, longitudinal displacement of a localized area of a road surface caused by traffic-induced shear forces.

Skid Number (SN) – A standard test measure of the friction between a tire and a wetted road surface.

Skid Resistance – That ability of a roadway surface, particularly when wet, to offer resistance to slipping or skidding.

Slurry Seal – A surface treatment of emulsified asphalt, sand, additives, and water, placed as a aqueous mixture.

Soft Spots – Weak areas in the subgrade of a road structure that can lead to pavement performance problems.

Stabilizing Additive – A mechanical, chemical, or bituminous product or material used to increase or maintain the strength, durability, or moisture susceptibility of a material or to improve its engineering properties.

Stone Mastic/Matrix Asphalt (SMA) – An asphalt mix type that provides excellent performance with high stability, durability, rut resistance, and good friction properties for heavy traffic roads. SMA consists of two parts: a coarse aggregate skeleton with an asphalt binder-rich mortar. The mixture has an aggregate skeleton with coarse aggregate stone on stone contact. A fiber is added to the asphalt binder to prevent draindown.

Structural Layer Coefficient – From the AASHTO pavement design procedure, the empirical relationship between Structural Number (SN) and layer thickness which expresses the relative ability of a material to function as a structural component of a pavement.

Structural Number (SN) – An index number derived from an analysis of traffic, roadbed soil conditions, and environment which may be converted to thickness of flexible pavement layers through the use of suitable layer coefficients related to the type of material being used in each layer of the pavement structure.

Subbase – The layer in a flexible pavement structure immediately below the base course. Also used to describe the single aggregate layer above the subgrade in a rigid pavement structure.

Subgrade – The natural soil or rock layer, or placed earth or rock fill layer, prepared to support a pavement structure. It is the foundation of the pavement structure.

Surface Course – The top layer of a flexible or composite pavement, that comes into direct contact with vehicles.

Surface Texture – The roughness or contours of the traveling surface of the road defined in terms of microtexture and macrotexture. Microtexture is what makes an aggregate smooth or rough to the touch. The macrotexture is surface contours that result from the shape, size, and arrangement of the aggregate particles (for flexible pavements), or the surface finish (for concrete surfaces).

Tack Coat – An application of liquid asphalt or emulsified or cutback asphalt to an existing asphalt concrete surface prior to the placement of an asphalt concrete lift or overlay.

Tining – A series of parallel grooves placed in the surface of a concrete pavement that run parallel or transverse to the longitudinal joint of the road. Tining is used to improve frictional characteristics.

Traffic Loading – The dynamic forces imposed on a pavement structure as a result of normal moving traffic operations.

Unit Paver – Accurately dimensioned, dense concrete products that are fitted snugly together to form a road surfacing. (see Sett).

Washboarding – A series of transverse undulations or corrugations that form in a transverse direction in the surface of an unbound road surface.

Weathering – The natural process of deterioration of a road surfacing over time due to exposure to the elements (e.g. sun, rain, and ice).

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REFERENCES

(1) Federal Highway Administration. (1997). Flexibility in Highway Design, Publication No. FHWA-PD-97-062, Federal Highway Administration, Washington, D.C.

(2) AASHTO. (2004). A Guide for Achieving Flexibility in Highway Design, AASHTO, Washington, D.C., 112 pp.

(3) National Park Service (1984). Park Road Standards. U.S. Department of the Interior, Washington, D.C., 53 pp.

(4) AASHTO Center for Environmental Excellence. (2004). *Context Sensitive Solutions*, http://environmental.transportation.org/context_overview.asp.

(5) Walls, J., III, and Smith, M.R. (1998). Life-Cycle Cost Analysis in Pavement Design, Publication No. FHWA-SA-98-079, Federal Highway Administration, Washington, D.C., 107 pp.

(6) Hicks, R.G., Seeds, S.B., and Peshkin, D.G. (2000). Selecting a Preventative Maintenance Treatment for Flexible Pavements, Publication No. FHWA-IF-00-027, Federal Highway Administration, Washington, D.C., 84 pp.

BIBLIOGRAPHY

This bibliography provides a partial list of the resources identified during a literature review of available roadway surfacing options. This bibliography is not exhaustive due to the enormous amount of information available for some of the roadway surfacing options. Instead, this bibliography is intended to be a representative selection of the total body of information available and provide an initial reference list for anyone who would like additional information on a particular type of roadway surfacing.

WEBSITES

Government Agencies and Organizations

Sponsor	Web Address
AASHTO	www.aashto.org
America's Byways	www.byways.org
Austroads	www.austroads.com.au
Bureau of Transportation Statistics	www.bts.gov
Canadian Strategic Highway Research Program	www.cshrp.org
FHWA Context Sensitive Design	www.fhwa.dot.gov/csd/
FHWA – Federal Lands Highway Division	www.fhwa.dot.gov/flh/
FHWA – Pavement Technology	www.fhwa.dot.gov/pavement/
Iowa Department of Transportation	www.dot.state.ia.us/materials/
Local Technical Assistance Program	www.ltapt2.org
Minnesota Department of Transportation	www.dot.state.mn.us/reslib.html
National Park Service	www.nps.gov
New Mexico Environment Department	www.nmenv.state.nm.us/aqb/dust_control.html
Organisation for Economic Co-Operation and Development (OECD)	www.oecd.org
OECD Road Transport Research Program	www.stn-international.de/stndatabases/databases/itrd.html
Transfund (New Zealand)	www.lowvolumeroads.co.nz
Transportation Research Board	www.trb.org
TRIS	199.79.179.82/sundev/about.cfm
Turner-Fairbank Highway Research Center	www.tfhrc.gov
UK Department for International Development	www.transport-links.org
United State Army Corps of Engineers	www.hnd.usace.army.mil/techinfo/engpubs.htm
USDA Forest Service	www.fs.fed.us
U.S. Fish and Wildlife Service	www.fws.gov

U.S. Green Building Council	www.usgbc.org/LEED/LEED_main.asp
Washington Department of Transportation	www.wsdot.wa.gov/biz/mats/pavement/
	www.wsdot.wa.gov/TA/T2Center/T2HP.htm
World Bank	www.worldbank.org

Professional, Research, Technical, and Trade Organizations

Sponsor	Web Address
American Concrete Pavement Association	www.pavement.com
American Society of Civil Engineers	www.asce.org
ARRB Transport Research	www.arrb.org.au
Asphalt Emulsion Manufacturers Association	www.aema.org
Asphalt Institute	www.asphaltinstitute.org
Asphalt Interlayer Association	www.aia-us.org
Australian Asphalt Pavement Association	www.aapa.asn.au
Australian Stabilization Industry Association - (AustStab)	www.auststab.com.au
Brick Industry Association	www.bia.org
Cement Association of Canada	www.cement.ca
Colorado Asphalt Pavement Association	www.co-asphalt.com
Context Sensitive Design Resource Center	www.contextsensitivesolutions.org
European Asphalt Pavement Association	www.eapa.org
Geosynthetic Manufacturers Association	www.gmanow.com
Interlocking Concrete Pavement Institute	www.icpi.org
International Road Federation	www.irfnet.org
International Slurry Surfacing Association	www.slurry.org
Mountain-Plains Consortium	www.mountain-plains.org
National Asphalt Pavement Association	www.hotmix.org
National Center for Asphalt Technology	www.ncat.us
National Lime Association	www.lime.org
National Stone, Sand, and Gravel Association	www.nssga.org
NCSU Center for Transportation and the Environment	www.itre.ncsu.edu/cte
New England Transportation Consortium	www.cti.uconn.edu
Penn State Center for Dirt & Gravel Road Studies	www.dirtandgravelroads.org
Portland Cement Association	www.portcement.org
Project for Public Spaces	www.pps.org/CSS/cssonline/
Road Engineering Association of Asia & Australiasia	www.roads.co.nz
Scenic America	www.scenic.org
Southeast Cement Association	www.secpa.org

Transport Research Laboratory (TRL)	www.trl.co.uk
Washington Asphalt Pavement Association	www.asphaltwa.com
World Road Association (PIARC)	www.aipcr.lcpc.fr

PUBLICATIONS

Context Sensitive Design/Solutions

Danish Road Directorate (2002). Beautiful Roads, A Handbook of Road Architecture. Danish Road Directorate, Copenhagen, 64 pp.

Grob, J. (2003). "How to Beautify Roads with Context Sensitive Design," Better Roads, Vol. 73, No. 9, pp. 38-43.

Neuman, T. R. et al. (2002). A Guide to Best Practices for Achieving Context Sensitive Solutions, NCHRP Report 480, TRB, National Research Council, Washington, D.C., 138 pp.

San Juan County, Washington, "Scenic Road Manual," www.co.san-juan.wa.us/publicworks/sr-manual/scenic-roads.html.

Texas Department of Transportation (2001). Landscape and Aesthetics Design Manual, Texas Department of Transportation, Austin, 206 pp.

Wandall, B., and Torslov, N. (2003). "A Method for Integrating Aesthetics in Road Planning – A Part of a Strategy for Beautiful Roads," 25th International Baltic Roads Conference, Vilnius, Lithuania, 8 pp.

Yamada, A. et al. (2002). Scenic Byways, A Design Guide for Roadway Improvements, FHWA-FLH-02-001, Federal Highway Administration, Washington, D.C., 116 pp.

General Roadway Surfacing Design/Construction/Management

American Society of Civil Engineers (1992). Local Low Volume Roads and Streets, FHWA-SA-93-006, Federal Highway Administration, Washington, D.C.

Austroads (2003a). Guide to the Selection of Road Surfacings, Revised Edition, Publication No. AP-G63/03, Austroads, Sydney, 82 pp.

Beaudry, Terrance M. (1992). Minnesota's Design Guide for Low Volume Aggregate Surfaced Roads, Report MN/RD-92/11, Minnesota Department of Transportation.

Bolander, P., Marocco, D., and Kennedy, R. (1995). Earth and Aggregate Surfacing Design Guide for Low Volume Roads, FHWA-FLP-96-001, Federal Highway Administration, Washington, D.C., 302 pp.

Giummara, G.J. (2003). "Establishment of a Road Classification System and Geometric Design and Maintenance Standards for Low-Volume Roads," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 132-140.

Grobler, J.A., Taute, A., and Joubert, I. (2003). "Pavement Evaluation and Rehabilitation Design Methodology Currently Used in Low-Volume Roads in Southern Africa," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 343-352.

Hall, K., and Bettis, J.W. (2000). Development of Comprehensive Low-Volume Pavement Design Procedures, Final Report, Report No. MBTC 1070, Mack-Blackwell Transportation Center, University of Arkansas, Fayetteville, 34 pp.

Hall, K.T., et al. (2001). Rehabilitation Strategies for Highway Pavements, NCHRP Project 1-38, TRB, National Research Council, Washington, D.C., 152 pp.

Hicks, R. G., Seeds, S.B., and Peshkin, D.G. (2000). Selecting a Preventative Maintenance Treatment for Flexible Pavements, Publication No. FHWA-IF-00-027, Federal Highway Administration, Washington, D.C., 84 pp.

Hudson, S.W., McCullough, B.F., and Carmichael,R.F. (1987). Surface Design and Rehabilitation Guidelines for Low-Volume Roads. Report No. FHWA/TS-87-225, Federal Highway Administration, Washington, D.C., 228 pp.

Jansson, A.H.H. (1993). "Environmental Impact Assessment and Evaluation of Low-Volume Roads in Finland," Transportation Research Record 1426, TRB, National Research Council, Washington, D.C., pp. 3-9.

Kestler, M.A., Knight, T., and Krat, A.S. (2000). Thaw Weakening and Load Restriction Practices on Low Volume Roads, ERDC/CRREL Technical Report 00-6, ERDC/CRREL, U.S. Department of the Army, Hanover, NH, 13 pp.

Kestler, M.A. (2003). "Techniques for Extending the Life of Low-Volume Roads in Seasonal Frost Areas," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 275-284.

Kim, J.R., and Newcomb, B. (1991). Low Volume Road Pavement Design: A Review of Practice in the Upper Midwest, MPC Report No. 91-3, Mountain-Plains Consortium, 141 pp.

Lukanen, Erland O. (1997). An Evaluation of Aggregate and Chip Seal Surfaced Roads at Mn/ROAD, Report 1998-24, Minnesota Department of Transportation.

Madzikigwa, B.B. (2003). "Nature and Effects of Low-Volume Roads in Botswana," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 88-95.

McDonald, T., and Andersen-Wilk, M. (2003). Low Water Stream Crossings in Iowa: A Selection and Design Guide, Center for Transportation Research and Education, Iowa State University, Ames, IA, 27 pp.

Oman, M., Van Deusen, D., and Olson, R. (2001). Scoping Study: Impact of Agricultural Equipment on Minnesota's Low Volume Roads: Draft Final Report, Minnesota Department of Transportation, Maplewood, MN, 42 pp.

Roadex (2000). Road Condition Management of Low Traffic Volume Roads in the Northern Periphery, ERDF, Northern Periphery Program, 75 pp.

Safronetz, J.D., and Sparks, G.A. (2003). "Project-Level Highway Management Model for Secondary Highways in Saskatchewan, Canada," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 297-304.

Sebaaly, P.E., Siddharthan, R., and Huft, D. (2003). "Impact of Heavy Vehicles on Low-Volume Roads," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 228-235.

Skok, E.L. et al. (2002). Best Practices for the Design and Construction of Low Volume Roads, Report No. MN/RC-2002-17, Minnesota Department of Transportation, St. Paul, 191 pp.

Skorseth, K., and Selim, A.A. (2000). Gravel Roads Maintenance and Design Manual, Report No. LTAP-02-002, South Dakota Local Transportation Assistance Program.

Takallou, M.B. et al. (1987a). "An Overview of Alternate Surfacings for Forest Roads," Transportation Research Record 1106, TRB, National Research Council, Washington, D.C., pp. 1-10.

Takallou, M.B. et al. (1987b). "Evaluation of Alternate Surfacings for Forest Roads," Transportation Research Record 1106, TRB, National Research Council, Washington, D.C., pp. 10-22.

Thenoux, G., Gonzalez, A., and Halles, F. (2003). "Chilean Structural Design Guide for Low-Volume Roads," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 306-313.

USDA Forest Service (1995). The Effects of Winter Haul on Low Volume Forest Development Roads, USDA Forest Service, Washington, D.C., 48 pp.

USDA Forest Service (2000). Forest Roads: A Synthesis of Scientific Information. USDA Forest Srevice, Washington, D.C., 117 pp.

U.S. Department of the Army (2000). Paving and Surfacing Operations, Field Manual FM 5-436, 217 pp.

Walls, III, J., and Smith, M.R. (1998). Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin, FHWA-SA-98-079, Federal Highway Administration, Washington, D.C., 123 pp.

Young, Rodger (2003). "When to Pave a Gravel Road," Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

Asphalt Surfaces

Adams, M.C. (2003). "Porous Asphalt Pavement with Recharge Beds: 20 Years and Still Working," Stormwater, Vol. 4, No. 3.

Anderton, G.L. (1996). User's Guide: Resin Modified Pavement, FEAP-UG-96/01, U.S. Army Center for Public Works, Alexandria, VA, 58 pp.

Asphacolor. Asphacolor Technical Instructions and Specifications.

Asphalt Institute. A Basic Asphalt Emulsion Manual, Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 120 pp.

Australian Asphalt Pavement Association. “Warm Mix Asphalt – A State-of-the-Art Review,” Advisory Note 17, AAPA, 2 pp.

Australian Asphalt Pavement Association (2001). “Geotextile Reinforced Sprayed Seals,” Pavement Work Tips – No. 25, AAPA, 2 pp.

Australian Asphalt Pavement Association (2002). “Sprayed Seals – A Brief Description,” Pavement Work Tips – No. 32, AAPA, 2 pp.

Australian Asphalt Pavement Association (2003). “Cape Seals,” Pavement Work Tips – No. 37, AAPA, 2 pp.

Austroads (2001). Austroads Provisional Sprayed Seal Design Method Revision 2000, Publication No. AP-T09, Austroads, Sydney, 58 pp.

Austroads (2003b). The State-of-the-Art of Bitumen Emulsions in Australia and New Zealand, Publication No. AP-T22, Austroads, Sydney, 18 pp.

Austroads Pavement Research Group (1999). “Ultra Thin Asphalt Surfacing,” APRG Technical Note 8, Austroads, Sydney, 2 pp.

Bolander, P., Chitwood, L.A., and Steele, H.M. (1999). “Lessons Learned from the Failure of a Bituminous Surface Treatment in Central Oregon,” Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 51-58.

Brown, D.C. (2003). “Managing Stormwater with Porous Asphalt,” Public Works: Engineering, Construction, & Maintenance, Hanley-Wood, July 2003.

Brown, N.R. (2003). “Solution for Distressed Pavements and Crack Reflection,” Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 313-317.

Colorado Asphalt Pavement Association (2001). “A Guideline for the Design and Construction of Asphalt Pavements for Colorado Trails and Paths”, 2nd Ed., www.co-asphalt.com/advantage/paths/trails.cfm

Colwill, D.M., Mercer, J., and Nicholls, J.C. (1995). “U.K. Design Procedure for Surface Dressing,” Transportation Research Record 1507, TRB, National Research Council, Washington, D.C., pp. 13-22.

Connolly, Una (2001). “Clearing the Air,” Hot Mix Asphalt Technology, July/August 2001.

Emery, S.J. et al. (1992). “Performance limits for bituminous surfacings on low volume roads,” Annual Transportation Conference 1992, Pretoria.

Geoffroy, D.N. (1998). Thin-Surfaced Pavements, NCHRP Synthesis 260, TRB, National Research Council, Washington, D.C., 112 pp.

Gourley, C.S. et al. (2001). “Cost Effective Designs for Low Volume Sealed Roads in Tropical and Subtropical Countries,” XIVth International Road Federation Meeting, Paris, 12 pp.

Gransberg, D.D., and Zaman, M. (2002). Comparing the Performance of Emulsion versus Hot Asphalt Chip Seal Projects in the Texas Department of Transportation's Atlanta District, University of Oklahoma Research Report, 27 pp.

Gunnarsson, R. (2003). "Treated Wearing Course in Iceland, Reinforcement of Roads," 25th International Baltic Roads Conference, Vilnius, Lithuania.

Hicks, R. G., Seeds, S.B., and Peshkin, D.G. (2000). Selecting a Preventative Maintenance Treatment for Flexible Pavements, Publication No. FHWA-IF-00-027, Federal Highway Administration, Washington, D.C., 84 pp.

Hunt, P.D., and Bunker, J.M. (2003). "Study of Site-Specific Roughness Progression for a Bitumen-Sealed Unbound Granular Pavement Network," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 273-281.

Integrated Paving Concepts, Inc. StreetPrint Pavement Texturing Specification Binder.

International Slurry Seal Association (2003). Recommended Performance Guidelines for Emulsified Asphalt Slurry Seal, A105, International Slurry Seal Association, 16 pp.

International Slurry Seal Association (2003). Recommended Performance Guidelines for Micro-Surfacing, A143, International Slurry Seal Association, 16 pp.

Jahren, C.T., Thorius, J.M., and Behling, K.R. (2003). "Quantitative Guidelines for Use of Thin Maintenance Surfaces," Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, IA, 10 pp.

Janisch, D.W., and Gaillard, F.S. (1998). Minnesota Seal Coat Handbook, Draft Report, Minnesota Local Road Research Board, Maplewood, MN, 116 pp.

Johnson, Greg, (2001). "Otta Seal Construction and Evaluation 2001", http://mnroad.dot.state.mn.us/research/MnROAD_Project/m-e_group/Asphalt/Construction_Evaluation_Report_Otta_Seal_2001_files/frame.htm

Johnson, Greg (2003). "Minnesota's Experience with Thin Bituminous Treatments for Low-Volume Roads," Transportation Research Record 1819, TRB, National Research Council, Washington, D.C., pp. 333-337.

Kandhal, P.S. (1990). Large Stone Asphalt Mixes: Design and Construction, NCAT Report No. 90-4, National Center for Asphalt Technology, Auburn, AL, 57 pp.

Kandhal, P.S. (1991). Design of Large Stone Asphalt Mixes for Low-Volume Roads Using Six-Inch Diameter Marshall Specimens, NCAT Report 91-5, National Center for Asphalt Technology, Auburn, AL, 31 pp.

Kandhal, P.S., and Lockett, L. (1997). Construction and Performance of Ultrathin Asphalt Friction Course, NCAT Report No. 97-5, National Center for Asphalt Technology, Auburn, AL, 23 pp.

Kandhal, P.S., and Mallick, R.B. (1998). Open Graded Asphalt Friction Course: State of the Practice, NCAT Report No. 98-7, National Center for Asphalt Technology, Auburn, AL, 31 pp.

Kandhal, P.S., and Mallick, R.B. (1999). Design of New-Generation Open Graded Friction Courses, NCAT Report No. 99-3, National Center for Asphalt Technology, Auburn, AL, 64 pp.

Keating, J. (2001). “Porous Pavements”, Stormwater, Vol.2, No.2.

Koenders, B.G. et al. (2000). “Innovative Process in Asphalt Production and Application to Obtain Lower Operating Temperatures,” Proceedings of the 2nd Eurasphalt and Erbitume Congress, Barcelona, Vol 2, pp. 830-840.

Mallick, R.B. et al (2000). Design, Construction, and Performance of New-Generation Open-Graded Friction Courses, NCAT Report No. 2000-01, National Center for Asphalt Technology, Auburn, AL, 30 pp.

Mandigo, E.J., Johnson, S., and Keller, G. (1991). “Low-Cost Asphalt-Surfaced Roads,” Transportation Research Record 1291, TRB, National Research Council, Washington, D.C., pp. 84-90.

Michael, L. (2003). “SMA in the Superpave System,” Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

Minnesota Technology Transfer (T2) Program (2002). “Cass County Evaluates Otta Seal,” Technology Exchange Newsletter, Summer 2002.

Missouri Department of Transportation (1999). NovaChip, Product Development 98-055, Research Development and Technology Division Brief, Missouri Department of Transportation, Jefferson City, MO.

Norwegian Public Roads Administration (1999). “A Guide to the Use of Otta Seals,” PIARC XXIst World Road Congress, Kuala Lumpur, Malaysia.

Oloo, S., Lindsay, R., and Mothilal, S. (2003). “Otta Seals and Gravseals as Low-Cost Surfacing Alternatives for Low-Volume Roads: Experiences in South Africa,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 338-342.

Paige-Green, Phil (1999). “Materials for Sealed Low-Volume Roads,” Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 163-171.

Pidwerbesky, B.D., and Pollard, J.S. (1991). “Design and Performance of Sprayed Seal Coats for Unbound Granular Pavements Carrying Heavy Logging Trucks,” Transportation Research Record 1291, TRB, National Research Council, Washington, D.C., pp. 66-71.

Preston, N. (2002). “WAM (Warm Asphalt Mixtures) Technology,” Presented at the Austroads Technology Transfer Seminar, July 2002, Christchurch, NZ.

Rosenberg, J. (2000). Thin Pavements with Synthetic Binder used in Denmark, Report 105, Road Directorate, Danish Road Institute, Roskilde, Denmark, 22 pp.

Scott, J.L.M. (1990). Canadian Practice in the Design, Use, and Application of Bituminous Surface Treatments. Reprinted 1995. Canadian Strategic Highway Research Program, Ottawa, 47 pp.

Solaimanian, M., and Kennedy, T.W. (1998). Evaluation of the Cape Seal Process as a Pavement Rehabilitation Alternative, Project Summary Report 1788-S, Center for Transportation Research, The University of Texas at Austin, Austin, 97 pp.

Sullivan, J. (2001). "Stone Matrix Asphalt," Presented at the 41st Idaho Asphalt Conference, Moscow, Idaho.

Tenison, J.H. (2003). "Performance of Nova Chip in New Mexico," Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

Thurmann-Moe, T., and Ruistuen, H. (1983). "Graded Gravel Seal (Otta Surfacing)," Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 333-335.

Transportation Research Laboratory (1993). "A Guide to the Structural Design of Bitumen-Surfaced Roads in Tropical and Sub-Tropical Countries," Overseas Road Note 31, 4th edition, 82 pp.

Transportation Research Laboratory (200). "A Guide to Surface Dressing in Tropical and Sub-Tropical Countries," Overseas Road Note 3, 2nd edition, 46 pp.

USDA Forest Service (1998), USDA Forest Service Chip Seal & BST Class Notes, Unpublished.

USDA Forest Service (1999a), Asphalt Seal Coat Treatments, San Dimas Technology and Development Center.

U.S. Environmental Protection Agency (1999). Stormwater Technology Fact Sheet: Porous Pavement, EPA 832-F-99-023, U.S. EPA, Office of Water, Washington, D.C., 6 pp.

Vischer, W. (2003). "Low-Volume Road Flexible Pavement Design with Geogrid-Reinforced Base," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 247-254.

Washington State Department of Transportation (2003). "The Use of NovaChip as a Surface Treatment," Tech Notes, June 2003, Washington State Department of Transportation, 4 pp.

Wolfe, P.G.L. (1993). "The Use of Geotextile-Reinforced Bituminous Seals to Improve Amenity and Environment of Remote Rural Roads," Transportation Research Record 1426, TRB, National Research Council, Washington, D.C., pp. 19-23.

Wolters, R.O. (2003). "Thin HMA Overlays as a Cost Effective Preventative Maintenance Tool," Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

Portland Cement Concrete Surfaces

ACI Committee 325 (1995). State-of-the-Art Report on Roller-Compacted Concrete Pavements, ACI 325.10R-95, American Concrete Institute, 32 pp.

Brett, David (2000). "The Performance of Roller Compacted Concrete Pavements," Cement and Concrete Association of Australia Seminar on Industrial Floors and Heavy Duty Pavement, Adelaide, June 2000, 14 p.

Burnham, T. (2003). "Seasonal Load Response Behavior of a Thin Portland Cement Concrete Pavement," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 251-261.

Canadian Portland Cement Association. Roller Compacted Concrete (RCC) Pavements Design and Construction, Concrete Info Bulletin CP018.01P, Canadian Portland Cement Association, 4 pp.

Jofre, C., Josa, A., and Molina, F. (1987). "The Paving of Low-Volume Roads in Spain with Roller-Compacted Concrete ,"Transportation Research Record 1106, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 301-308.

Piggott, R.W. (1999). Roller Compacted Concrete Pavements: A Study of Long Term Performance, Report RP366, Portland Cement Association, 65 pp.

Portland Cement Association (1987). Structural Design for Roller-Compacted Concrete for Industrial Pavements, IS233.01, Portland Cement Association, 8 pp.

Portland Cement Association (2001). The Right Choice for Heavy Duty Pavements, Roller-Compacted Concrete Strength and Economy, Brochure PL 397p, Portland Cement Association, 4 pp.

Todres, H.A., Wu, C.L., and Tarr, S.M. (1995). "Improving Roller Compacted Concrete Pavement Technology: Construction," PCA R&D Serial No. 2014, Portland Cement Association, 129 pp.

Visser, A.T., and Hall, S. (1999). "Flexible Portland Cement Concrete Pavement for Low-Volume Roads," Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 121-127.

Wu, C.L., and Todres, H.A. (1995). "Improving Roller Compacted Concrete Pavement Technology: Pavement Evaluation and Thickness Design," PCA R&D Serial No. 2016, Portland Cement Association, 268 pp.

Aggregate and Soil Surfaces

Althouse, J. (2001). "Dust, Washboards, and Deep Stabilization," Erosion Control, March/April 2001.

Anguiano, G., Sandoval, R., and Webb, T. (1997). Evaluation of Dust Suppression Products Conducted for the Marine Corps Air Ground Combat Center, Twentynine Palms, CA, Site Specific Report SSR-2343-ENV, Naval Facilities Engineering Service Center, Port Hueneme, CA, 41 pp.

AustStab (2002a). Lime Stabilisation Practice, AustStab Technical Note No. 1., Australian Stabilization Industry Association, 8 pp.

Austroads (2002). Mix Design for Stabilised Pavement Materials, Publication No. AP-T16, Austroads, Sydney, 43 pp.

Austroads Pavement Research Group (2002). "Effect of Design, Construction, and Environmental Factors for Long Term Performance of Stabilised Materials," APRG Technical Note 12, Austroads, Sydney, 3 pp.

Bassel, J.R. (1992). "A Demonstration of a Dust Palliative," Roads: Tech Tips, U.S. Forest Service Technology and Development Program, May 1992, San Dimas Technology and Development Center, San Dimas, CA, 8 pp.

Beaudry, Terrance M. (1992). Minnesota's Design Guide for Low Volume Aggregate Surfaced Roads, Report MN/RD-92/11, Minnesota Department of Transportation.

Bergeson, K.L., and Brocka, S.G. (1996). "Bentonite Treatment for Fugitive Dust Control," Proceedings of the 1996 Semisesquicentennial Transportation Conference, Ames, IA.

Bergeson, K.L., and Barnes, A.G. (1998). "Iowa Thickness Design Guide for Low Volume Roads Using Reclaimed Hydrated Class C Fly Ash Bases," Proceedings of CROSSROADS 2000 Transportation Conference, Ames, IA, pp. 253-258.

Berkshire Regional Planning Commission (2001). The Massachusetts Unpaved Roads BMP Manual.

Berthelot, C., and Carpentier, A. (2003). "Gravel Loss Characterization and Innovative Preservation Treatments of Gravel Roads: Saskatchewan, Canada," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 180-184.

Birst, S., and Hough, J. (1999). Chemical Additive Usage on Unpaved Roads in Mountain Plains States, UGPTI Department Publication No. 130, Upper Great Plains Transportation Institute, North Dakota State University, 119 pp.

Bolander, P., Marocco, D., and Kennedy, R. (1995). Earth and Aggregate Surfacing Design Guide for Low Volume Roads, FHWA-FLP-96-001, Federal Highway Administration, Washington, D.C., 302 pp.

Bolander, Peter (1999). "Laboratory Testing of Nontraditional Additives for Stabilization of Roads and Trail Surfaces," Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 24-31.

Boresi, A.P. et al. (1996). Physical and Chemical Stability of Admixtures in Unpaved Road Soils, MPC Report No. 96-52, Mountain-Plains Consortium, Laramie, WY, 145 pp.

Bowen, M.M., and Ksaibati, K. (2000). Performance Evaluation of Cement-Treated Roadway Bases, MPC 00-115, Mountain-Plains Consortium, University of Wyoming, Laramie, 92 pp.

Bowman, J.K., Lidell, R.B., and Schulze, G.B. (1987). "The Use of Wood Chips in Low-Volume Road Construction in the Great Lake States," Transportation Research Record 1106, TRB, National Research Council, Washington, D.C., pp. 47-58.

Brown, D.A., and Elton, D.J. (1994). Guidelines for Dust Control on Unsurfaced Roads in Alabama, Report IR-94-02, Alabama Highway Research Center, Auburn, AL, 19 pp.

Bullen, F. (2003a). "Use of Coral-Derived Aggregates for Construction of Low-Volume Roads," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 134-142.

Bullen, F. (2003b). “Design and Construction of Low-Cost, Low-Volume Roads in Australia,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 173-179.

Bureau of Indian Affairs (2002), Interim Road Stabilization Report (Reconditioning of Asphalt Base Course Materials), BIA, Rocky Mountain Region, Northern Cheyenne Reservation.

California Environmental Protection Agency (2000). Evaluation of the Air Quality Performance Claims for Pennzoil-Quaker State Company PennzSuppress D Dust Suppressant, California Air Resources Board Precertification Program, 20 pp.

California Environmental Protection Agency (2002). Evaluation of the Air Quality Performance Claims for the Midwest Industrial Supply, Inc., Soil-Sement Dust Suppressant, California Air Resources Board Precertification Program, 38 pp.

City of Calgary (1999). Dust Abatement Tests: 144 Avenue North from Panorama Road N.W. to 15 Street N.E. Engineering and Environmental Services Department, Streets Division, City of Calgary, 58 pp.

Colbert, W. J. (2003). “Natural Systems Approach to Preventing Environmental Harm from Unpaved Roads,” Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 210-217.

Edgar, T. (1995). “Strength and Density Modification of Unpaved Road Soils Due to Chemical Additives,” Proceedings of the TEL8 Low Volume Road Conference, Upper Great Plains Transportation Institute, North Dakota State University, Fargo, ND, pp 50-62.

Epps, A., and Ehsan, M. (2002). “Laboratory Study of Dust Palliative Effectiveness,” Journal of Materials in Civil Engineering, ASCE, Vol. 14, No. 5, pp. 427-435.

Erickson, H., and Drescher, A. (2001). The Use of Geosynthetics to Reinforce Low Volume Roads, Report No. MN/RC-2001-15, Minnesota Department of Transportation, St. Paul, 125 pp.

Federal Highway Administration (1998). Problems Associated with Gravel Roads, Publication No. FHWA-SA-98-045, Federal Highway Administration, Washington, D.C.

Foltz, R.B., and Truebe, M. (2003). “Locally Available Aggregate and Sediment Production,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 185-193.

Franklin Regional Council of Governments (2001). Answers to Frequently Asked Questions about Gravel Roads.

Geosynthetic Materials Association. Handbook of Geosynthetics, Geosynthetic Materials Association, www.gmanow.com, 64 pp.

Gillies, J.A. (1999). “Long-Term Efficiencies of Dust Suppressants to Reduce PM10 Emissions from Unpaved Roads,”Journal of the Air & Waste Management Association, Vol. 49, pp. 3-16.

Gusey, D.L. (1991). “Trail Hardening Test,” Engineering Field Notes, Vol. 23, May/June 1991, USDA Forest Service, Washington, D.C., pp 53-68.

Heath, A., Theyse, H., and Lea, J. (1999). "Use of Ash in Low-Volume Road Construction in South Africa," Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 196-202.

Hough, J., Smadi, A., and Schulz, L. (1996). Gravel Shortage Options, Upper Great Plains Transportation Institute.

Jahren, C. T. (2001). Best Practices for Maintaining and Upgrading Aggregate Roads in Australia and New Zealand, Report No. MN/RC-P2002-01, Minnesota Department of Transportation.

Jones, D. (1999). "Holistic Approach to Research into Dust and Dust Control on Unsealed Roads," Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 3-9.

Jones, D. (2003). "Toward Fit-for-Purpose Certification of Road Additives," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 208-217.

Jones, D., Paige-Green, P., and Sadzik, E. (2003). "Development of Guidelines for Unsealed Road Assessment," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 287-296.

Keating, J. (2003). "Chemical Soil Stabilization," Erosion Control, January/February 2003.

Legere, G., and Tremblay, H. (2003). "Laboratory and Field Evaluation of Cement Kiln Dust and Lime for Stabilizing Clayey Silt on Low-Volume Unpaved Roads," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 3-10.

Lidell, R.B., and Bowman, J.K. (1987). "The Use of Paper Mill Sludge to Stabilize Sand Roads," Transportation Research Record 1106, TRB, National Research Council, Washington, D.C., pp. 65-70.

Liebenberg, J.J.E., and Visser, A.T. (2003). "Stabilization and Structural Design of Marginal Materials for Use in Low-Volume Roads," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 166-172.

Little, Dallas (1987). Fundamentals of the Stabilization of Soils with Lime, Bulletin No. No. 332, National Lime Association, Arlington, VA, 21 pp.

Little, Dallas (1999). Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates, Volume 1: Summary of Findings, National Lime Association, 97 pp.

Little, Dallas (2000). Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates, Volume 3: Mixture Design and Testing Protocol for Lime Stabilized Soils, National Lime Association, 16 pp.

Lohnes, R.A., and Coree, B.J. (2002). Determination and Evaluation of Alternative Methods for Managing and Controlling Highway-Related Dust, Report TR 449, Iowa Highway Research Board, Iowa Department of Transportation, 32 pp.

Lunsford, Lt. G.D. and Mahoney, J. (2001). Dust Control on Low-Volume Roads: A Review of Techniques and Chemicals Used, Report No. FHWA-LT-01-002, Federal Highway Administration, Washington, D.C., 58 pp.

Mathis, H. (1999). Soil Modification and Stabilization Utilizing Lime, Dravo Lime Company, Butler, Kentucky, 42 pp.

Mathur, S., Soni, S.K., and Murty, A. (1999). "Utilization of Industrial Wastes in Low-Volume Roads," Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp. 246-256.

Monlux, S. (2003). "Stabilizing Unpaved Roads with Calcium Chloride," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 52-56.

Mustonen, J., Lintila, J., and Makio, T. (2003). "Turning Deteriorated Paved Roads Back into Gravel Roads," Transportation Research Record 1819, Vol. 1, TRB, National Research Council, Washington, D.C., pp. 96-103.

National Lime Association (1999). Lime Facts, National Lime Association, Arlington, VA, 31 pp.

N-Viro Resources, Inc. Cement Kiln Dust Soil Stabilization Manual.

Palmer, J.T., Edgar, T.V., and Boresi, A.P. (1995). Strength and Density Modification of Unpaved Road Soils Due to Chemical Additives, MPC Report No. 95-39, Mountain-Plains Consortium.

Phillips, M., Puppala, A.J., and Melton, K. (2003). "Development of Stabilizer Selection Tables for Low-Volume Roads: Arlington, Texas," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 85-94.

Portland Cement Association (2003). Soil-Cement Information: Properties and Uses of Cement-Modified Soils, IS 411.02, Portland Cement Association, 12 pp.

Presto Products Company. Geoblock System General Design and Construction Package, Presto Products Company, Appleton, WI, 18 pp.

Prusinski, J.R., and Battacharja, S. (1999). "Effectiveness of Portland Cement and Lime in Stabilizing Clay Soils," Transportation Research Record 1652, TRB, National Research Council, Washington, D.C., pp 215-227.

Puppala, A.J., and Hanchanloet, S. (1999). "Evaluation of a New Chemical (SA-44/LS-40) Treatment Method on Strength and Resilient Properties of a Cohesive Soil," Preprint, 78th Annual Meeting of the Transportation Research Board, Washington, D.C., 23 pp.

Puppala, A.J., Wattanasanticharoen, E., and Hoyos, L.R. (2003). "Ranking of Four Chemical and Mechanical Stabilization Methods to Treat Low-Volume Road Subgrades in Texas," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 63-71.

Robinson, L. (2003). "Clearing America's Dusty Trails," Erosion Control, March/April 2003.

Rummer, B. et al. (2001). “Improving Stability of Low-Volume Forest Roads Using a Lignin-Based Emulsion,” Proceedings of the 24th Annual Meeting of the Council on Forest Engineering, Corvallis, OR, Council on Forest Engineering, 5 pp.

Sander, T.G., and Addo, J.Q. (1993). Effectiveness and Environmental Impact of Road Dust Suppressants. Report No. MPC 94-28, Mountain Plains Consortium, 40 pp.

Sanders, T.G., et al (1997). "Relative Effectiveness of Road Dust Suppressants", Journal of Transportation Engineering, ASCE, September, 1997, pg. 393- 397.

Santoni, R.L.,Tingle, J.S., and Webster, S.L. (2002). “Stabilization of Silty Sand with Nontraditional Additives,” Transportation Research Record 1787, TRB, National Research Council, Washington, D.C., pp. 61-70.

Santoni, R.L., Tingle, J.S., and Nieves, M. (2003). “Accelerated Strength Improvement of Silty Sand Using Nontraditional Additives,” Presented at the 82nd Annual Meeting, TRB, Washington, D.C., 21 pp.

Scholen, D.E., and Coughlan, S. (1991). “Nonstandard Stabilization of Aggregate Road Surfaces,” Transportation Research Record 1291, TRB, National Research Council, Washington, D.C., pp 285-293.

Scholen, Douglas E. (1992). Non-Standard Stabilizers, FHWA-FLP-92-011, U.S. Department fo Transportation, Washington, D.C.

Selim, A.A., Skoresth, O.K., and Muniandy, R. (2003). “Long-Lasting Gravel Roads: Case Study from the United States,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 161-165.

Sheehy, D. (2002). “Reconditioning and Stabilization of Unpaved Roads for Reducing Road Maintenance and Impacts on Fisheries Habitat,” Proceedings of the International Conference on Ecology and Transportation, Keystone, CO, Center for Transportation and the Environment, North Carolina State University, Raliegh, NC, pp. 121-131.

Skorseth, K., and Selim, A.A. (2000). Gravel Roads Maintenance and Design Manual, Report No. LTAP-02-002, South Dakota Local Transportation Assistance Program.

Spokane County Air Pollution Control Authority (2003). “Controlling Dust in Spokane County,” Spokane County Air Pollution Control Authority, Spokane, WA, www.scapca.org/dust.html.

Taha, R. (2003). “Evaluation of Cement Kiln Dust-Stabilized Reclaimed Asphalt Pavement Aggregate Systems in Road Bases,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 11-17.

Tensar Earth Technologies (1998). “A Review of Geosynthetic Functions and Applications in Paved and Unpaved Roads,” Tensar Technical Note BR11, Tensar Earth Technologies, Atlanta, 48 pp.

Thenoux, G., and Vera, S. (2003). “Evaluation of Hexahydrated Magnesium Chloride Performance as Chemical Stabilizer of Granular Road Surfaces,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 44-51.

Thompson, M. (1968). “Lime-Treated Soils for Pavement Construction,” Journal of the Highway Division, American Society of Civil Engineers, Vol. 94, No. 11, pp 191-213.

Tilton, J.L. (2002). “Corralling Dust and Stabilizing Soil,” Erosion Control, July/August 2002.

Tingle, J.S., and Santoni, R.L. (2003). “Stabilization of Clay Soils With Nontraditional Additives,” Transportation Research Record 1819, Vol.2, TRB, National Research Council, Washington, D.C., pp 72-84.

USDA Forest Service (1999b), Dust Palliative Selection and Application Guide, San Dimas Technology and Development Center, 23 pp.

U.S. Department of the Army (1987). Dust Control for Roads, Airfields, and Adjacent Areas, Technical Manual TM 5-830-3, 42 pp.

U.S. Department of the Army (1990). Design of Aggregate Surfaced Roads and Airfields, Technical Manual TM 5-822-12

U.S. Department of the Army (1992). “Chapter 9: Soil Stabilization for Roads and Airfields,” Military Soils Engineering, Field Manual FM 5-410, 81 pp.

U.S. Department of the Army (1994). Soil Stabilization for Pavements, Technical Manual TM 5-822-14, 57 pp.

Vermont Local Roads (1984). Road Dust Control with Calcium Chloride, Vermont Local Roads Fact Sheet, 4 pp.

Vermont Local Roads (1986). Road Dust Suppressants, Vermont Local Roads Fact Sheet, 8 pp.

Walker, D. (2002). Pavement Surface Evaluation and Rating: Gravel PASER Manual, Wisconsin Transportation Information Center, Madison, WI, 24 pp.

Washington State Department of Ecology (1996). “Techniques for Dust Prevention and Suppression,” Ecology Fact Sheet, Publication No. 96-433, Washington State Department of Ecology, Olympia, 20 pp.

Wheeler Zamaroni. General Notes for Specifying, Estimating, & Installing TerraPave Pavement.

Wisconsin Transportation Information Center (1997). Dust Control on Unpaved Roads, Wisconsin Transportation Bulletin No. 13, Wisconsin Transportation Information Center, Madison, 6 pp.

Unit Surfaces

Interlocking Concrete Pavement Institute (1999). Application Guide for Interlocking Concrete Pavements, Tech Spec No. 10, Interlocking Concrete Pavement Institute, Washington, D.C., 6 pp.

Smith, D.R. (2003). “Stormwater Runoff: Permeable Interlocking Concrete Pavement,” Public Works: Engineering, Construction, & Maintenance, Hanley-Wood, July 2003.

Recycling and Reclamation Alternatives

Acott, S.M., and Myburgh, P.A. (1983). "Design and Performance Study of Sand Bases Treated with Foamed Asphalt," Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 290-296.

Asphalt Recycling and Reclaiming Association (2001). Basic Asphalt Recycling Manual, ARRA, Annapolis, Maryland, 270 pp.

Atherton, Charlie (2003). "Solventless Emulsion to Extend the Performance of Cold-In-Place Recycling," Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

AustStab (2002b). Foamed Bitumen Stabilisation, AustStab Technical Note No. 2., Australian Stabilization Industry Association, 4 pp.

Baker, D. et al. (2000). "Cold In-Place Recycling Using Asphalt Emulsion for Strengthening for Saskatchewan Low Volume Roads," Canadian Technical Asphalt Association Proceedings, Annual Conference, Vol. 47, pp. 145-166.

Berthelot, C., and Gerbrandt, R. (2000). "Full Depth Cold In-Place Recycling/Stabilization for Low Volume Road Strengthening: A Case Study," 2000 Annual Conference of the Transportation Association of Canada, Edmonton, Alberta, 19 pp.

Berthelot, C. et al. (2001). "Cold In Place Rock Crushing and Stabilization of Northern Low Volume Roads: A Case Study," Presented at 80th Annual Meeting, Transportation Research Board, Washington, D.C., 20 pp.

Berthelot, C., and Gerbrandt, R. (2003). "Full-Depth In-Place Recycling and Road Strengthening Systems for Low-Volume Roads: Highway No. 19 Case Study," Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 32-43.

Castedo, L.H., and Wood, L.E. (1983). "Stabilization with Foamed Asphalt of Aggregates Commonly Used in Low-Volume Roads," Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 297-302.

Goldbaum, J. (2003). "Guidelines for Using Hot-In-Place Recycling," Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

Horvath, A. (2003). "Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements," Technical Report, University of California Transportation Center, 29 pp.

Huffman, J. (2003). "Cold In-Place Recycling Evolution / Advances," Presented at the 30th Annual Rocky Mountain Asphalt Conference and Equipment Show, Denver, CO.

Jahren, C.T. et al (1998). "Review of Cold In-Place Asphalt Recycling in Iowa," Proceedings of CROSSROADS 2000 Transportation Conference, Ames, IA, pp. 259-263.

Jones, P. (2002) "Foamed Asphalt," Presented at the 42nd Idaho Asphalt Conference, Moscow, Idaho.

Morton, B.S., Visser, A.T., and Horak, E. (2003). “Use of Foamed Tar for Construction of Flexible Pavement with Existing Unpaved Road Structure,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 314-322.

Romanoschi, S.A., Heitzman, M., and Gisi, A.J. (2003). “Foamed Asphalt Stabilized Reclaimed Asphalt Pavement: A Promising Technology of Mid-Western Roads,” Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, IA, 11 pp.

Scherocman, J.A. (1983). “Cold In-Place Recycling of Low-Volume Roads,” Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 308-315.

Spelman, S.R. (1983). “Rural Cold Recycling,” Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 303-307.

Wen, H., Tharaniyil, M.P., and Ramme, B. (2003). “Investigation of Performance of Asphalt Pavement with Fly-Ash Stabilized Cold In-Place Recycled Base Course,” Transportation Research Record 1819, Vol. 2, TRB, National Research Council, Washington, D.C., pp. 27-31.

Wirtgen (2000). “Caltrans Personnel Hear Benefits of Foamed Asphalt,” Wirtgen Technology, Summer 2000, Wirtgen America, Inc., pp 20-22.

Wirtgen Group. Cold Recycling with Foamed Bitumen in Modern Road Rehabilitation, Wirtgen Group Press Release, 8 pp.