POLYMER MODIFIED ASPHALT EMULSIONS
Composition, Uses, and Specifications for Surface Treatments

Publication No. FHWA-CFL/TD-12-004 **January 2012**

U.S. Department
of Transportation
**Federal Highway
Administration**

Federal Lands Highway
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FOREWORD

While guidance, manuals, and specifications exist for conventional asphalt emulsions, the Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) desired further guidance for using high performance modifiers (polymers) for asphalt emulsions, including dosing rates, methods of modification, and benefits derived from their use. Polymer modification increases initial costs, but treatment performance is reportedly improved, and life cycle costs will be lowered with appropriate use.

This study found that performance-related specifications should greatly improve the predictability and performance of the polymer modified asphalt emulsion surface treatments. A series of field trials on FLH projects was conducted, with field samples tested in laboratories according to the draft testing plan developed with input from government, academic, and material supplier experts. The laboratory results are to be compared to evaluations of the field performance, with the expectation that this analysis will continue over the lifespan of the surface treatments. Best practices were used in the specifications for the construction of the experimental field projects, and a draft performance-related asphalt emulsion materials specification was developed. This report includes the knowledge collected over the course of the project including the test plan for the field trials, the draft performance-related specification, and laboratory results. It is intended to aid Federal, State, and local agencies using polymer modified asphalt emulsion pavement preservation treatments.

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Central Federal Lands Highway Division

1. Report No.
FHWA-CFL/TD-12-004

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Polymer Modified Asphalt Emulsions Composition, Uses, and Specifications for Surface Treatments

5. Report Date
January 2012

6. Performing Organization Code:

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8. Performing Organization Report No.

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10. Work Unit No.

11. Contract or Grant No.
DTFH68-05-X-00039

12. Sponsoring Agency Name and Address
Federal Highway Administration
Central Federal Lands Highway Division
12300 W. Dakota Avenue, Suite 210
Lakewood, CO 80228

13. Type of Report and Period Covered
Final Report
September 2005 - December 2009

14. Sponsoring Agency Code
HFTS-16.4

15. Supplementary Notes
COTR: Michael Voth, FHWA FLH. Advisory Panel Members: Gary Evans, FHWA-WFLHD; Jim Sorenson and Joe Gregory, FHWA HIAM; Jack Youtcheff, FHWA-TFHRC; Larry Galehouse, NCPP; Laurand Lewandowski, PRI Asphalt Technologies; Koichi Takamura and Arlis Kadrmas, BASF; and Chris Lubbers, Kraton Polymers. This project was funded under the FHWA Federal Lands Highway Technology Deployment Initiatives and Partnership Program (TDIPP), the Pavement and Materials Functional Discipline Leader (FDL) Initiatives, and the Office of Infrastructure.

16. Abstract

This document gives a comprehensive review of best practices and recommendations for the use of polymer modified asphalt emulsions in surface treatments such as chip seals, slurry seals, micro surfacing and cape seals on low and high volume roadways, trails, paths and parking lots in varying climates. It includes the test plan for field trials using the report-only draft specifications developed during the course of this project, as well as the test results and recommendations for further specification development. It is expected that the laboratory test results and field performance of these projects will be used in the development of performance-related specifications for asphalt emulsions.

17. Key Words

ASPHALT EMULSION; POLYMER; SURFACE TREATMENT; PAVEMENT PRESERVATION; CHIP SEAL; SLURRY SEAL; MICRO SURFACING; CAPE SEAL; POLYMER MODIFIED ASPHALT EMULSION; SBR; SBR LATEX; SBS; MSCR; PERFORMANCE SPECIFICATIONS; SWEEP TEST

18. Distribution Statement

No restriction. This document is available to the public from the sponsoring agency at the website http://www.cflhd.gov.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
250

22. Price

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. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AAPT	Association of Asphalt Paving Technologists
AASHTO	American Association of State Highway and Transportation Officials
ABS	Acrylonitrile-Butadiene-Styrene
AC	Asphalt Concrete
ADT	Average Daily Traffic
AEASC	Asphalt Emulsion Approved Supplier Certification
AEMA	Asphalt Emulsion Manufacturers Association
AI	Asphalt Institute
APWA	American Public Works Association
ARC	Asphalt Research Consortium
ARRA	Asphalt Recycling and Reclamation Association
ASC	Approved Supplier Certification Program
ASTM	American Society for Testing and Materials
BR	Polybutadiene Rubber
BBR	Bending Beam Rheometer
Caltrans	California Department of Transportation
CAM	Christensen-Anderson-Marasteanu
CEN	European Community for Standardization
CFLHD	Central Federal Lands Highway Division
CRM	Crumb Rubber Modifiers
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
DTT	Direct Tension Test
EAC	Equivalent Annual Cost
EBA	Ethyl-Butyl-Acrylate
EGA	Ethylene-Glycidyl-Acrylate
EPA	U.S. Environmental Protection Agency
EPDM	Ethylene-Propylene-Diene-Monomer
ER	Elastic Recovery
EMA	Ethyl-Methacrylate
ETF	Emulsion Task Force
ETG	Expert Task Group
EVA	Ethyl-Vinyl-Acetate
FDO	Forced Draft Oven
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
FLMA	Federal Land Management Agency
HDPE	High Density Polyethylene
HMA	Hot Mix Asphalt
HPGPC	High Performance Gel Permeation Chromatography
HTG	High Temperature Grade
IAA	Impact Absorbing Asphalt
ISSA	International Slurry Surfacing Association
JMF	Job Mix Formula

LASST	Long-Term Asphalt Storage Stability Test
LDPE	Low Density Polyethylene
LTAP	Local Technical Assistance Program
MFI	Melt Flow Index
Mn/DOT	Minnesota Department of Transportation
MSCR	Multi-Step Creep Recovery
NACE	National Association of County Engineers
NCPP	National Center for Pavement Preservation
NMR	Nuclear Magnetic Resonance
NR	Natural Rubber
NRL	Natural Rubber Latex
PAV	Pressure Aging Vessel
PB	Polybutadiene
PCR	Pavement Condition Rating
PE	Polyethylene
PG	Performance Grade
PI	Plasticity Index
PMA	Polymer Modified Asphalt
PME	Polymer Modified Asphalt Emulsion
PVC	Polyvinyl Chloride
QC	Quality Control
RET	Reactive-Ethylene-Terpolymers
RTFO	Rolling Thin Film Oven
RV	Rotational Viscometry
SANRA	South African National Roads Agency
SB	Styrene-Butadiene
SBR	Styrene-Butadiene Rubber
SBS	Styrene-Butadiene-Styrene
SEBS	Styrene-Ethylene-Butylene-Styrene
SHA	State Highway Agency
SHRP	Strategic Highway Research Program
SIS	Styrene-Isoprene-Styrene
SPG	Surface Performance Grading
SSF	Saybolt Seconds Furol
TBD	To Be Determined
TCCC	Transportation Curriculum Coordination Council
TCE	Trichloroethylene
TDIPP	Technology Deployment Initiatives and Partnership Program
TPE	Thermoplastic Elastomer
TPR	Thermoplastic Rubber
TRB	Transportation Research Board
TRIS	Transportation Research Information Service
TSP	Transportation System Preservation
TxDOT	Texas Department of Transportation
UV	Ultraviolet
WFLHD	Western Federal Lands Highway Division

WRI	Western Research Institute
ZSV	Zero Shear Viscosity

ACKNOWLEDGEMENTS

This work was accomplished with the help of many entities.

The authors would especially like to thank the support, guidance, and patience from the staff of the Central Federal Lands Highway Division and the Federal Highway Administration’s Office of Construction and System Preservation who greatly encouraged and facilitated the information sharing among researchers, suppliers, and specifiers.

We also thank the many, many material suppliers, agency users, academic and State Highway researchers and independent testing labs who gave their support, expertise, testing, and materials (much of which was donated) to further the goals of this project.

Members of the Binder Expert Task Group, the newly formed Emulsion Task Force, various Transportation Research Board committees, and the Asphalt Emulsion Manufacturers Association International Technical Committee have also reviewed proposed methods and shared their knowledge.

The authors are excited about the prospects for the future as many researchers and field practitioners are now sharing information and working together to develop polymer modified emulsion specifications that will provide higher quality, longer lasting, and lower cost surfaces for public lands and highway users.

EXECUTIVE SUMMARY

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) initiated this study to provide a guide for the use of polymer modified asphalt emulsions in surface treatment applications, specifically chip seals, slurry surfacings, and cape seals. Although the FLH has much experience with best practices using conventional asphalt emulsions, there was no definitive guide for selecting, specifying, and using polymer modified asphalt emulsions. Based on the experience of many users and producers of polymer-modified asphalt emulsions over the last 25 years, it was generally accepted that polymer modification resulted in better short- and long-term performance, and ultimately cost savings over the life the treated pavements. This study consisted of a comprehensive literature review and information gathering from government, academic, and industry experts. These experts were then called upon to develop recommendations, which are given here and in a related field guide published by FHWA.

During the course of the investigation, it became evident that the industry felt a need for updated test methods, specifications, and recommendations that are better predictors of performance, that is, performance-based specifications. The investigators developed draft specifications based on the best available information from experts on both asphalt emulsions and the performance-based test methods for Superpave hot mix asphalt developed by the Strategic Highway Research Program (SHRP).

Several field trials were run in 2008 and 2009 on FLH projects. Field samples were tested in several laboratories using the draft protocols. This report gives the test plan and results, and comparison with first year field performance, as well as recommendations for future specification development. FLH will continue to evaluate the field performance of these projects over time and the results will be compared to the laboratory test results to determine the applicability of the test methods and the appropriate specification limits. The preliminary results of performance-based rheometry and sweep testing included in this report are very promising. The recommendations and draft materials specifications should be of value to those users and producers wishing to improve performance of asphalt emulsion surface treatments on all types of pavements, and the data is being shared with other researchers to characterize and specify the performance of the modified residue. It is envisioned that performance-based specifications for polymer modified asphalt emulsion surface treatments will be the norm in the not too distant future. Current activities are being fully coordinated with the FHWA Pavement Preservation Expert Task Group’s (ETG’s) Emulsion Task Force and with the FHWA Superpave ETGs to advance recommendations to the American Association of State Highway and Transportation Officials (AASHTO) Highway Subcommittee on Materials, with the goal of an AASHTO pooled-fund study for eventual provisional emulsion performance-based specifications.

1.0 INTRODUCTION

1.1 Background

Polymer modification of asphalt emulsions offers improvements in performance and durability, mitigation of pavement distress, and reduced life cycle costs when compared to unmodified asphalt emulsions or hot mix asphalt surface dressings. Such modifications have exhibited demonstrable reductions in rutting, thermal cracking, and increased resistance to many forms of traffic-induced stress. Conversely, polymer modifiers, when used in chip seal applications, have demonstrated some problems associated with accelerated stripping when placed over a moisture sensitive hot mix. Asphalt emulsions frequently provide a lower cost, efficient, and more environmentally-friendly alternative to hot mixes due to their low energy consumption, reduced hydrocarbon emissions, ease of implementation at remote sites, and preventive maintenance/life-extending benefits when applied to mildly distressed pavements.

Although best-practice manuals and specifications for conventional asphalt emulsions are plentiful, there is no single document available, which offers guidance on the proper use, application techniques, and benefits of high-performance polymer modified asphalt emulsions. Similarly, the preponderance of the published research on polymer modifiers has focused primarily upon their use in hot mix asphalt (HMA) applications.

This research includes an exhaustive review of the literature to collect and analyze polymer modified emulsion practices and specifications, coupled with a laboratory testing and verification program designed to validate the findings and recommendations developed from the literature review. Guidance is provided on proper project selection, polymer dosing rates and methods, applicability under varying traffic load and environmental conditions, and conditions where polymer modifiers may not be recommended.

1.2 Study Objectives

The principal objectives of this study were to:

1.) Compile published research on the types of polymer modifiers, dosage rates, and modification methods.

2.) Compare and contrast the performance, cost, and benefits of polymer modified with non-modified asphalt emulsions.

3.) Determine the applicability of polymer modified asphalt emulsions to low (i.e., generally < 400 average daily traffic [ADT]), medium (400 to 1,000 ADT), and high (> 1,000 ADT) volume roads (as defined by Federal Lands Highway), and varying environmental conditions.

4.) Evaluate the applicability of polymer modified asphalt emulsions to non-roadway applications such as parking lots, hiking and bike trails.

5.) Analyze information obtained from the literature review and develop recommendations and guidelines relating to the proper application, modification, and limitations of polymer modified asphalt emulsions (PMEs).

6.) Perform laboratory testing and verification to evaluate the recommendations and data gaps identified from the analysis of information obtained from the literature review.

7.) Prepare a Federal Lands Highway (FLH) manual of best practices for polymer modified asphalt emulsions.

1.3 Scope

Electronic and physical literature searches were performed using a variety of sources, including the National Center for Pavement Preservation (NCPP) on-line library; the Transportation Research Information Service (TRIS) database; the National Technical Information Service (NTIS); the COMPENDEX engineering research database; the Michigan State University College of Engineering Library; the State Library of Michigan; the websites of the Asphalt Emulsion Manufacturers Association (AEMA), the International Slurry Surfacing Association (ISSA), and the Asphalt Recycling and Reclamation Association (ARRA); the Asphalt Institute's on-line document collection; the Federal Highway Administration's (FHWA) technical document and reference collection; and the Google™ search engine. Numerous pavement and polymer research publications were also examined, including publications of the Transportation Research Board (TRB), the *Journal of the Asphalt Paving Technologists* (AAPT), the *International Journal of Pavement Engineering*, the *Journal of Materials in Civil Engineering*, *Polymer Engineering and Science Journal*, and the *Journal of Applied Polymer Science*.

Although this review focuses principally on polymer modified asphalt emulsions (PMEs), literature and research dealing with polymer modified asphalt (PMA) binders (such as those used in hot mix) have also been used in cases where the results could reasonably be extrapolated. For example, some polymer modifiers occur only in solid form, and must be added directly to the asphalt regardless of whether the binder will be hot-applied, or emulsified; whereas liquid modifiers may be added either to the soap mix; co-milled; or in some cases, post-added to the emulsion mix either at the plant or in the field. Thus, research dealing with the impact of polymer modification on asphalt binders may have some implications with respect to both hot mix and emulsion applications.

Information was also collected from a series of meetings with industry experts, who represented many years of experience with specifying, manufacturing, using and researching many types of polymer modified asphalt emulsions. There was general consensus that current test methods and specifications needed to be updated; and while there has been much work in the field of asphalt (and PMA) characterization in the last decade, little of that has been applied to asphalt emulsions. Further knowledge sharing at a series of industry teleconferences, conferences, and meetings led to development of draft performance-based specifications for PMEs. A series of field projects was constructed by the Federal Lands Highway (FLH) division of the Federal Highway Administration (FHWA). Samples from the field projects were sent to several independent and supplier laboratories for testing with the draft testing protocols. The test results are included here and are being shared with researchers working on related on-going projects.

1.4 Report Organization

Chapter 1 of this report presents an introduction and overview. A discussion of the literature review is provided in Chapter 2. Chapter 3 presents the recommendations for the laboratory testing program and specifications, and a summary of the recommended application guidelines derived from the literature review. Chapter 4 gives the test plan and draft performance-based specifications used for the field and laboratory study. Chapter 5 gives the test results, and Chapter 6 gives the conclusions and recommendations for future work. The compiled meeting notes giving the input of various industry experts consulted are on file in the Central Federal Highway Lands office. Appendix A gives the details of the user and producer survey, and Appendix B gives the materials and construction specifications used for the field trials. The final section gives the references consulted.

2.0 LITERATURE REVIEW OF POLYMER MODIFIED ASPHALT EMULSIONS

This section presents the results of the literature review on the types, modification methods, demonstrated performance, surface treatments, environmental applicability, materials selection, and cost-benefit analysis of polymer modifiers. A brief overview of polymer and emulsion chemistry is provided, as is a discussion of the pavement conditions and applications where polymer modifiers are not needed. Some excellent general information on asphalt emulsions is available in the "Basic Asphalt Emulsion Manual" and the "Recommended Performance Guidelines" published by the Asphalt Institute (AI) and the Asphalt Emulsion Manufacturers Association (AEMA).(1)(109) The California Department of Transportation (Caltrans) Maintenance Technical Advisory Guide is one of the most comprehensive sources for information on using maintenance treatments.(2)

2.1 Basics of Polymers and Asphalt Emulsions

This section introduces and describes some of the basic terms and concepts related to polymers, polymer chemistry, and asphalt emulsions. While the purpose is not to provide a comprehensive narrative of the complexities of polymer chemistry, a grasp of the essential terminology and processes is beneficial in understanding the formulation, advantages, and applications of polymer modified asphalt emulsions.

2.1.1 Polymer Terminology and Chemistry

A polymer is a natural or synthetic high-molecular weight organic compound, which consists of a chain of smaller, simpler repeating units known as monomers. For example, the monomer ethylene may be polymerized (i.e., individual ethylene molecules chained together) to form polyethylene. When two or more distinct types of monomers are combined, the resulting compound is termed a "copolymer."(3)

The structure of copolymers may be random, or may repeat in blocks of polymers (block copolymers) as illustrated in Figure 1. An example of a block copolymer is styrene-butadiene (SB), which consists of blocks of polymerized styrene (a monomer) and polymerized butadiene (another monomer). SB is further categorized as a "diblock" copolymer, because it consists of two different polymerized monomers. Polymer structures include straight, radial, crosslinked, and irregularly branched chains. Factors, which can influence the behavior and performance of polymers include chemistry, structure, bonding types, and the manufacturing process.

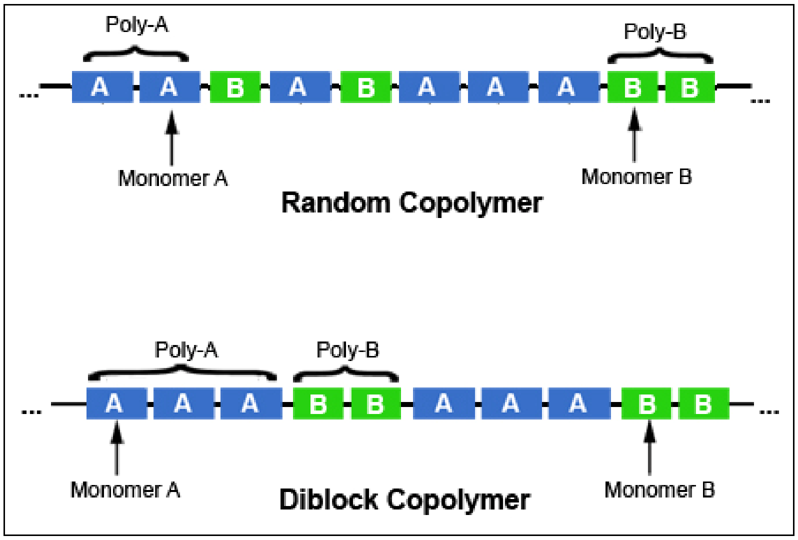


Figure 1. Schematic. Examples of Copolymers.

2.1.2 Asphalt Emulsions

Asphalt emulsions are formed by the milling of raw asphalt into microscopic particles, which are dispersed in water with the aid of a chemical emulsifying agent called a "surfactant" (sometimes referred to as "soap"). In such cases, the dispersed asphalt forms discrete droplets, which are intrinsically insoluble in water. The emulsion is said to be "stabilized" if the asphalt droplets remain well-dispersed such that phase separation does not occur. Stabilization is achieved through the use of surfactants, which consist of polar molecules comprised of a hydrophilic (water loving) "head" and hydrophobic (water avoiding) "tail." The tail of the surfactant molecule is attracted to the asphalt particles, forming a coating around each particle, which consists of the hydrophilic heads of the emulsifying agent. The hydrophilic portions of these surfactants strongly associate with water and aid in keeping the droplets dispersed and in suspension. Formulators can use other additives to enhance properties of the emulsion during storage, shipping, application, and the asphalt's end use.

Surfactants are classified as anionic, cationic, or nonionic based upon the charge of the hydrophilic portion of the molecule. Anionic and cationic emulsifiers are the most commonly used in pavement surface treatment applications. The electrical potential that exists between the surface of the surfactant-coated asphalt particles and the emulsion solution is measured as the Zeta potential. The Zeta potential is determined by measuring the velocity of emulsion particles when an electric field is applied. Some researchers believe high zeta potentials indicate potentially greater electrostatic repulsion between asphalt particles, and therefore greater stability of the emulsion (i.e., less of a propensity to phase-separate). Some suppliers use chemistries, which have confused the issue of classification. For example, nonionic emulsifiers can be used with certain additives to produce materials, which pass specifications for cationic emulsions, and quaternary amines produce cationic emulsions that show behavior more similar to nonionic emulsions.

In cationic asphalt emulsions, the positively charged layer of surfactants coating the asphalt particles are attracted to negatively charged aggregate mixed with the emulsion. Breaking of the emulsion is said to occur when the asphalt separates from the water phase and coalesces to coat the grains of the mineral aggregate. This may occur by 1) simple evaporation of the water; 2) a chemical destabilization of the hydrophilic portion of the surfactant by the aggregate, the existing road surface, or chemical additives; or 3) a combination of evaporation and chemical destabilization. To achieve breaking in anionic asphalt emulsions, the asphalt and aggregate particles must be sufficiently close to overcome the repulsive forces, which exist between the negatively charged outer layer surrounding the asphalt particles and the negatively charged surface of the aggregate (when using aggregates with negatively charged surfaces). The timing and rate of breaking of all asphalt emulsions is controlled by several factors, including the chemistry of the surfactant; type of aggregate used; emulsion formulation; chemical additives; temperatures of the emulsion, air, aggregate, and pavement surface at time of application; and the ambient humidity during application.

Generally, cationic asphalt emulsions maintain their positive charge at low pH but lose the charge at $pH > 8$-10. The emulsion is typically produced, stored, and applied at $pH < 4$. In contrast, anionic asphalt emulsions possess a high negative charge at high pH, but become neutral under acidic conditions. The emulsion pH changes when contacted with aggregate and/or with the addition of other additives, such as Portland cement, which is often added for slurry seals and micro surfacing. This change in the emulsion pH is one of key parameters controlling the timing and range of breaking.

After the break occurs, the water phase of the applied emulsion drains and evaporates, allowing the residual asphalt to coalesce and achieve its full strength (curing). Asphalt is a very viscous liquid, and therefore it flows very slowly. The emulsification process improves flow. Once the water has separated from the asphalt, warm air and surface temperatures facilitate the flowing together of the asphalt particles to form its most stable cohesive and adhesive binder state. Factors influencing the quality and performance of asphalt emulsions include, but are not necessarily limited to:

- Chemical properties, particle size, hardness, and concentration of the base asphalt;
- Chemistry, ionic charge, and concentration of the surfactant;
- Manufacturing conditions such as temperature, pressure, milling shear, and the order in which the ingredients are combined;
- The type of manufacturing equipment used;
- The types and amounts of other chemical modifiers (such as polymers), which are added to the emulsion; and
- Chemistry and quality of the bulk emulsion water solution.(1)

2.1.3 Asphalt Composition

Asphalt emulsions have been characterized as colloids, containing high molecular weight, relatively insoluble and nonvolatile compounds, and associations of lower molecular weight polar molecules known as asphaltenes, which are dispersed within a continuous lower viscosity phase liquid, comprised of low molecular weight compounds called maltenes. Asphaltenes are believed to be the component of asphalt that imparts hardness, while maltenes provide ductility and facilitate adhesion. Maltenes consist predominately of oils (aromatics and saturates) and resins (compounds, which represent a transition between asphaltenes and oils). Typical asphalts normally contain between 5 percent and 25 percent by weight of asphaltenes. Newer theories are a bit more complex, defining sol and gel types of asphalts. The chemistry of the asphalt depends upon the crude oil source and the refining method. The chemistry also determines the stability of the colloidal structure and its physical characteristics, including temperature susceptibility, cohesion, and adhesion.

The asphaltene content of asphalt cements is chiefly responsible for influencing the overall viscosity of the composite system – that is, higher asphaltene contents generally lead to higher composite viscosities. In addition, research has shown that maltene phases possessing a comparatively high aromatic content generally result in better dispersal of the asphaltenes, leading to high ductility, low complex flows, and lower rates of age-dependent hardening.(2)

Conversely, low aromatic maltenes generally lead to the formation of agglomerates of asphaltenes, which form a network-like structure and are referred to as "gel-type" asphalt cement. Asphalts containing high percentages of non-reactive saturated paraffinic, waxy molecules tend to be temperature susceptible; they become fluid at high pavement temperatures causing rutting and bleeding and are brittle at low temperatures causing cracking and shelling. Gel-type asphalt may also be formed from mixtures where the asphaltene to maltene ratio is inordinately high, because maltenes are needed to disperse the asphaltene fractions. Gel-type asphalts are generally characterized by low ductility, increased elastic component content, thixotropic behavior, and rapid age-dependent hardening.(3) In this sense, the addition of polymer modifiers when used in conjunction with compatible asphalts, can lead to improved high and low temperature performance combined with increased flexibility and resistance to deformation. Compatible polymer/asphalt systems produce a two-phase mixture that is characterized by a well dispersed polymer phase that is stable at high temperatures. The most effective polymer networks maintain integrity at both high and low temperatures.

Asphalt's polarity is due to the presence of alcohol, carboxyl, phenolic, amine, thiol, and other functional groups on the various molecules making up the asphalt. As a result of this polarity, the molecules self-assemble to form effectively large, complex structures with molecular weights ranging up to 100,000. The adhesion of asphalt to mineral aggregate particles is also thought to depend on the polar attraction between asphalt particles and the charged surfaces of most aggregates. Although asphalt is not a polymer in the strict sense of the word, it is regarded as a thermoplastic material because it becomes soft when heated and hardens upon cooling. Asphalts also exhibit viscoelastic properties, which can be improved upon with the addition of polymer modifiers.

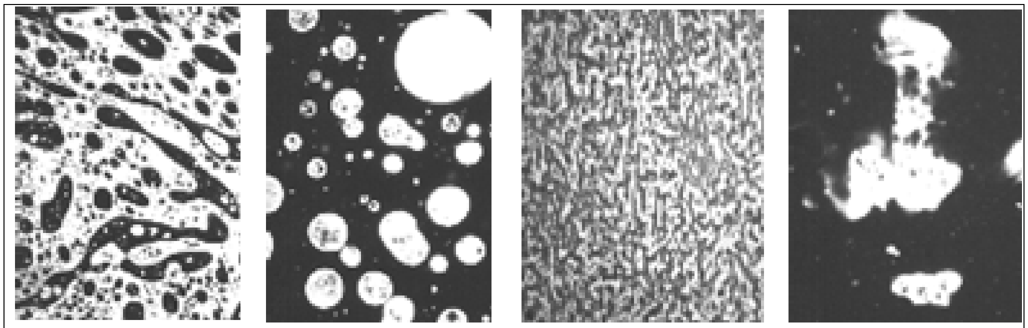
2.1.4 Polymer Modified Asphalt (PMA)

In general terms, the addition of polymers to asphalt binders results in the modification of certain key physical properties including the:

- Elasticity;
- Tensile strength;
- High and low temperature susceptibilities;
- Viscosity; and
- Adhesion and cohesion.

Depending upon the form of modification desired, improvements in pavement longevity can be achieved through the reduction of fatigue and thermal cracking, decreased high temperature susceptibility (e.g., rutting, shoving, bleeding), and enhanced aggregate retention in applications such as chip seals. Polymer modifiers are used to extend the lower and/or upper effective temperature operating ranges of pavements and to add elastic components that allow it to recover from loading stress.

The physical and chemical characteristics of the polymer and its compatibility with the chemistry of the asphalt determine the physical property enhancements. Figure 2 shows ultraviolet (UV) light reflective photomicrographs of two different asphalts modified with differing SB block copolymers, all at the same percent polymer added.(4) The dark is the asphalt and the light colored material is the polymer. In the compatible cases, the polymer is swollen by the oils in the asphalt and entangles itself within the asphalt to form a continuous network. In the incompatible blends, the polymer balls up into itself and is discontinuous. In most cases, the polymer has a lower density than the asphalt, and these polymer particles will rise to the top of the storage tank without constant agitation.



Asphalt G
SB Polymer
Compatible; Good Physical Properties; Homogeneous

Asphalt G
SBS Polymer
Incompatible; Poor Physical Properties; Polymer Separates

Asphalt A
SB Polymer
Compatible; Good Physical Properties; Homogeneous

Asphalt A
SBS' Polymer
Incompatible; Poor Physical Properties; Polymer Separates

Figure 2. Photo. Photomicrographs of 6% of Two Polymers in Two Asphalts.

A variety of testing techniques and equipment are available, which may be used to evaluate and quantify the performance characteristics of polymer modified binders and emulsion residues. A few of the most common are:

- Dynamic shear rheometer (DSR), which is used to measure the shear modulus (resistance and phase angle) of asphalt within intermediate to high operational temperature ranges. DSR testing distinguishes between elastic (recoverable) and viscous (non-recoverable) responses of the test material when placed under stress, and is often used as an indicator of rutting resistance and other forms of permanent deformation. While there is much work with DSR testing and specification of HMAs, there has been relatively little work done with emulsion residues until this study.

- Bending beam rheometer (BBR) and direct tension test (DTT), which are used to determine the stiffness/flexibility of asphalt binders at low temperatures, and thus, their susceptibility to thermal cracking. As with the DSR, there is relatively little in the literature about the use of these tests for asphalt emulsions.

- Ring and ball softening point, which is used to determine the temperature at which an asphalt sample allows a metal ball to fall through the asphalt. This test provides another measure of high temperature susceptibility.

- Direct tensile test, which is a measurement of the force that is required to deform an asphalt sample; tensile strength testing allows the stress applied to the sample to be plotted against its resulting elongation (i.e. strain).

- Elasticity after ductility testing which is a measurement of the recovery that occurs after the sample is elongated into a thread, cut, and a specified time elapses. Elasticity measures have important implications related to the resiliency of the pavement under repeated cycles of loading and unloading.

- Rotational viscometry (RV), which is used to measure the viscosity of modified and unmodified asphalts. It is directly related to the workability of the HMA mixture during field application and may also be used to determine emulsion viscosity.

Modified asphalt emulsion testing can be carried out by either testing the binder prior to emulsification, or by obtaining a sample of the properly cured emulsion residue. A more thorough treatment and evaluation of performance-based testing methodologies and criteria is provided in Section 2.4.

2.2 Types of Polymer Modifiers

2.2.1 Overview and Classification

Based upon their strain characteristics at low temperatures, polymer modifiers are generally separated into two broad categories: elastomers and plastomers. Elastomeric polymers can be stretched up to ten times without breaking, but quickly return to original shape once the load has been removed.(3) Typical elastomeric polymers used to modify asphalt include natural and synthetic rubbers, styrene-butadiene-styrene (SBS) and crumb rubber modifiers (CRM) reclaimed from scrap tires. Worldwide, elastomeric polymers comprise approximately 75 percent of all the asphalt polymer modifiers used (not including recycled crumb rubbers).

Unlike elastomers, plastomeric polymers attain very high strength at a rapid rate, but are brittle and resistant to deformation once set. Examples of plastomeric polymer modifiers include low density polyethylene (LDPE), ethylene-propylene-diene-monomer (EPDM), and ethyl-vinyl-acetate (EVA). Plastomeric polymers currently comprise about 15 percent of the global market for asphalt polymer modifiers.

Elastomeric and plastomeric polymer modifiers are further classified as either thermoset or thermoplastic, based upon their temperature-dependent structural formation and reformation characteristics. When initially heated, thermoset polymers develop a complex, cross-linked structure, which is retained upon cooling, but which cannot be reversed when reheated.(3) In contrast, thermoplastic polymers also develop a well-defined, linked matrix when cooled, but the resultant structures can be reversed or "reset" with reheating.

Thermoplastic rubbers (TPRs) or thermoplastic elastomers (TPEs) such as SBS combine the hard, resistant characteristics and re-settable structure of plastics with the elastic recovery of thermoset elastomers like natural or synthetic rubber. TPEs exhibit this unique blend of properties through the structural integration of rigid, generally steric (i.e., styrene-containing) components with rubbery domains such as found in polybutadiene.

Table 1 presents a summary of the most commonly used polymer modifiers, classified according to their deformational and thermal properties. It is important to note that many of these polymers may be blended with other types to achieve the appropriate combination of thermal and deformational properties. The following subsections provide detailed discussions of the published literature covering each of these polymer modifiers.

Table 1. Types and Classifications of Polymer Modifiers.

Polymer Type	Examples	Classification	References
Natural Rubber (Homopolymers)	Natural Rubber (NR), Polyisoprene, Isoprene, Natural Rubber Latex (NRL)	Thermoset Elastomers	(5) (6)
Synthetic Latex / Rubber (Random Copolymers)	Styrene-Butadiene (SBR)	Thermoset Elastomers	(5) (6)
	Polychloroprene Latex (Neoprene)	Thermoset Elastomers	(3) (6)
	Polybutadiene (PB, BR)	Thermoset Elastomers	(5)
Block Copolymers	Styrene-Butadiene-Styrene (SBS)	Thermoplastic Elastomers	(6)
	Styrene-Isoprene-Styrene (SIS)	Thermoplastic Elastomers	(6) (8)
	Styrene-Butadiene (SB) Diblock	Thermoplastic Elastomers	(3) (5)
	Acrylonitrile-Butadiene-Styrene (ABS)	Thermoplastic Elastomers	(7)
	Reactive-Ethylene-Terpolymers (RET)	Thermoplastic Elastomers	(9)
Reclaimed Rubber	Crumb Rubber Modifiers	Thermoset Elastomers	(5) (6)
Plastics	Low / High Density Polyethylene (LDPE / HDPE), Other Polyolefins.	Thermoplastic Plastomers	(6)
	Ethylene Acrylate Copolymer	Thermoplastic Plastomers	(3) (6)
	Ethyl-Vinyl-Acetate (EVA)	Thermoplastic Plastomers	(6)
	Ethyl-Methacrylate	Thermoplastic Plastomers	(8)
	Polyvinyl Chloride (PVC)	Thermoplastic Plastomers/ Elastomers	(6)
	Ethylene-Propylene-Diene-Monomer (EPDM)	Thermoplastic Elastomers	(6)
	Acrylates, Ethyl-Methacrylate (EMA), Ethyl-Butyl-Acrylate (EBA)	Thermoplastic Plastomers	(4)
Combinations	Blends of Above	Varies	(6)

2.2.2 Natural Rubber and Latex

Natural rubber latex (NRL) is an elastomeric hydrocarbon polymer of the isoprene monomer (polyisoprene) that exists as a natural milky sap produced by several species of plants. The "sap" has a water-based colloidal structure. Natural rubber (NR) is produced from NRL by coagulation to form a solid material.

The first commercial process that was developed to modify asphalt emulsions with NRL was the Ralumac® system. The Ralumac® process involves mixing naturally anionic NRL with cationic surfactants and emulsifying the resulting liquid with asphalt using a colloid mill.(10) This type of NRL modification is usually a two-stage process using a continuous-feed emulsion plant to achieve the desired results. However, when compatible NRL is used (with respect to asphalt microstructure) the process can be reduced to a single stage, and the latex added pre- or post-emulsification as shown in Figure 3.(4)(10)

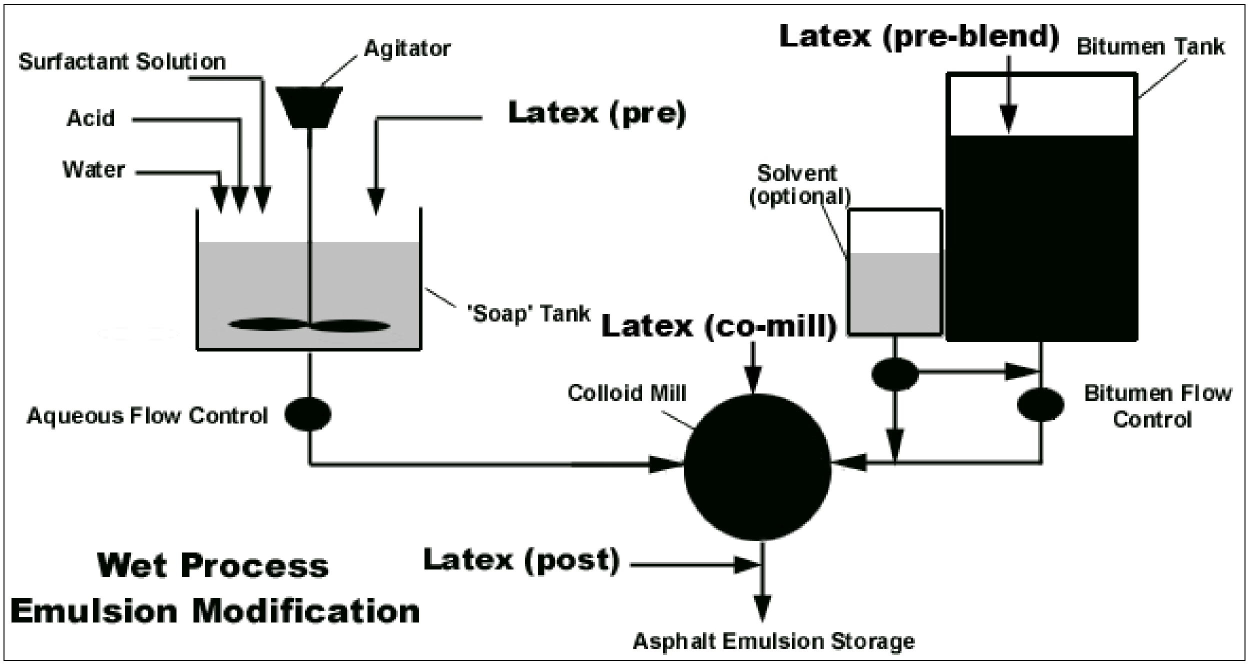


Figure 3. Schematic. Typical Emulsion Modification Processes.(10)

The resulting cationic emulsion is attracted to the anionic surfaces of the aggregate, latex, and filler material; this increases the oil-wettability and ensures better adhesion of the coagulated asphalt to the mineral grains once cured (Figure 4).(11) This breaking process is essential in ensuring rapid adhesion and strength development. The polymer component of a properly formulated and stabilized emulsion is dispersed throughout the bituminous cement to form an elastic, foam-like lattice upon curing (Figure 5).

NRL modification of asphalt yields similar performance benefits to those obtained in hot mix, including increased thermal stability, higher resistance to load deformation, and reduced thermal cracking.(10) The resulting rubberized asphalt acts like an elastic membrane, which holds residual asphalt particles together, thereby retarding crack propagation and increasing stone retention (Figure 5). Crack pinning also contributes to retarding the crack growth.

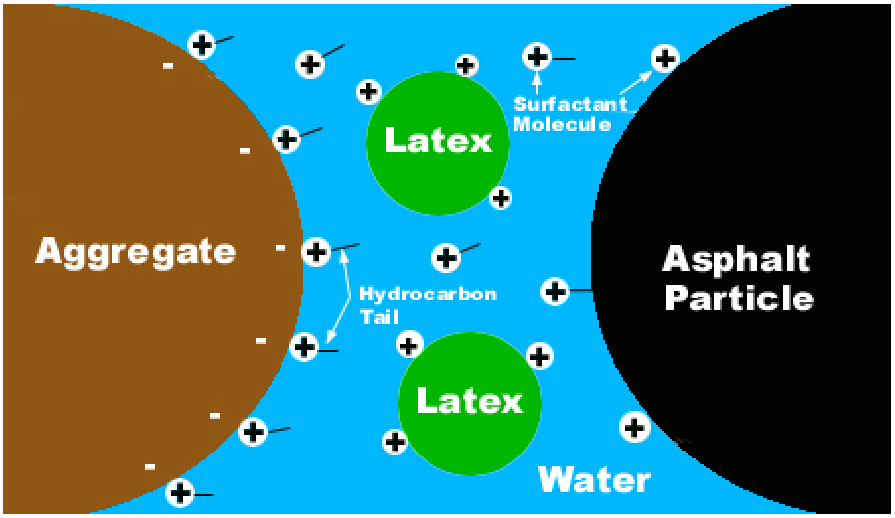


Figure 4. Schematic. Surfactant Action in NRL Modified Asphalt Emulsion.

At higher temperatures, the NRL's lattice resists flow in the asphalt matrix, which increases the pavement's resistance to deformation. Micro surfacing, slurry seals, chip seals, and tack coats all may benefit from the use of NRL modified asphalt emulsions. Figure 5 illustrates the distribution of a latex lattice within the asphalt binder used in a typical chip seal.

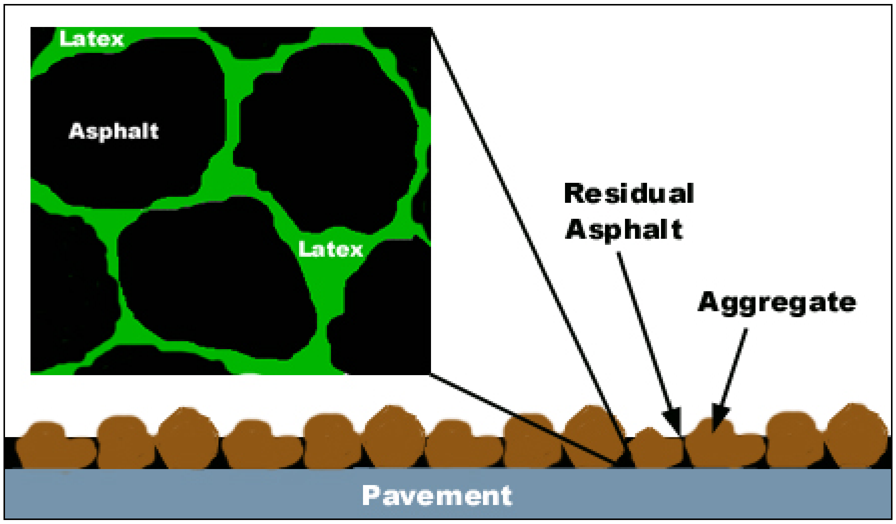


Figure 5. Schematic. Polymer Modified Chip Seal.

2.2.3 Synthetic Rubber and Latex

Synthetic latex is a thermoset elastomer, which consists of a mixture of polymer particles dispersed in water. Commonly used varieties of synthetic latex rubber include styrene-butadiene rubber (SBR), which is a random copolymer; polychloroprene (Neoprene); and polybutadiene (PB). Common uses of latex modified asphalt emulsions include micro surfacings, chip seals, and slurry seals. Lubbers and Watson (2005) note that the handling and blending of SBR latex is particularly facile, and is amenable to a variety of pre- and post-modification methodologies.(5) When sufficient quantities of synthetic latex are added to compatible asphalts, the cured mixture is commonly characterized by a continuous polymer network, which envelops the bitumen particles (see Figure 5). Benefits of properly blended latex polymers include improved stone retention, increased skid-resistance, and improved low temperature performance (i.e., less brittleness, better elasticity, and better adhesion to aggregates).

Like NRL, SBR latex that is uniformly dispersed in the emulsion during blending forms elastic lattices within the bituminous cement when cured. More specifically, as water within an applied emulsion evaporates, droplets containing SBR coalesce along the surfaces of asphalt particles, which results in the formation of a continuous, honeycombed polymer network, which extends throughout the binder.(12) In this way, SBR particles form "welds" between asphalt particles, which results in an increase in tensile strength, stone retention, and resistance to cracking.(12)(13) SBR modification of asphalt emulsions may be accomplished by co-milling at the colloid mill, post-blending after emulsification, or by mixing at the application site through the distributor (a field variation of the post-blending method).(13) Compatibility of the SBR with the asphalt should be verified to ensure the success of single-stage mixing methods.

Takamura (2001) has demonstrated the benefits of SBR modification of asphalt emulsions and micro surfacing mixes, with significant increases in rutting resistance temperatures observed with increasing polymer content, as illustrated in Figure 6. Figure 6 gives test results from laboratory aging at an elevated temperature, in an attempt to simulate long term field aging. Similarly, Takamura shows that a latex modified asphalt chip seal emulsion exhibits better early chip retention than the unmodified emulsion (Figure 7).(14)

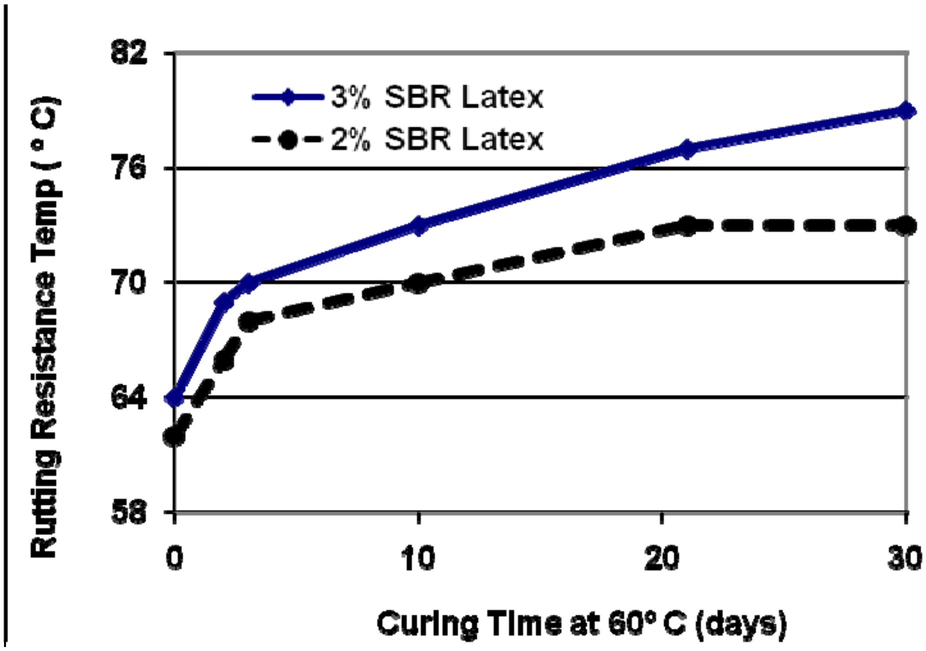


Figure 6. Graph. Curing of a CRS-2P Emulsion.(14)

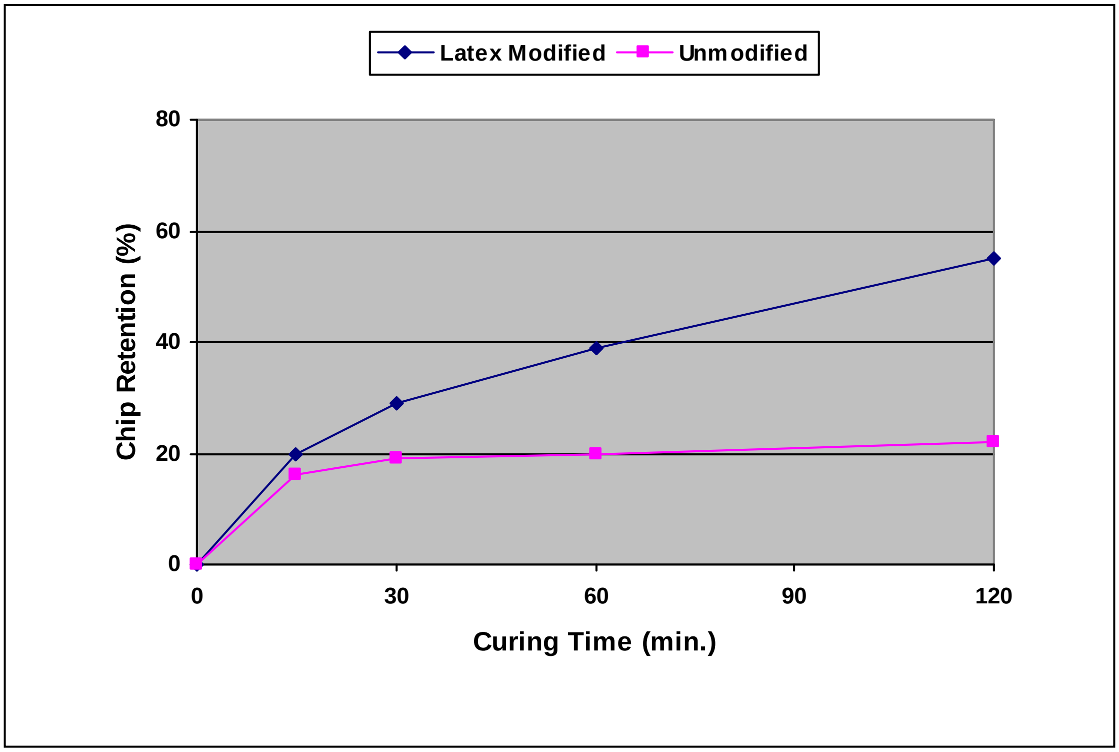


Figure 7. Graph. Stone Retention over Curing Time.(14)

Further, Takamura illustrated that an SBR latex modified micro surfacing mix gave better results than SBS, EVA, or Neoprene (in the same asphalt) in wet track abrasion losses and wheel track deformation, indicating better stone retention and reduced flow characteristics (Figure 8).

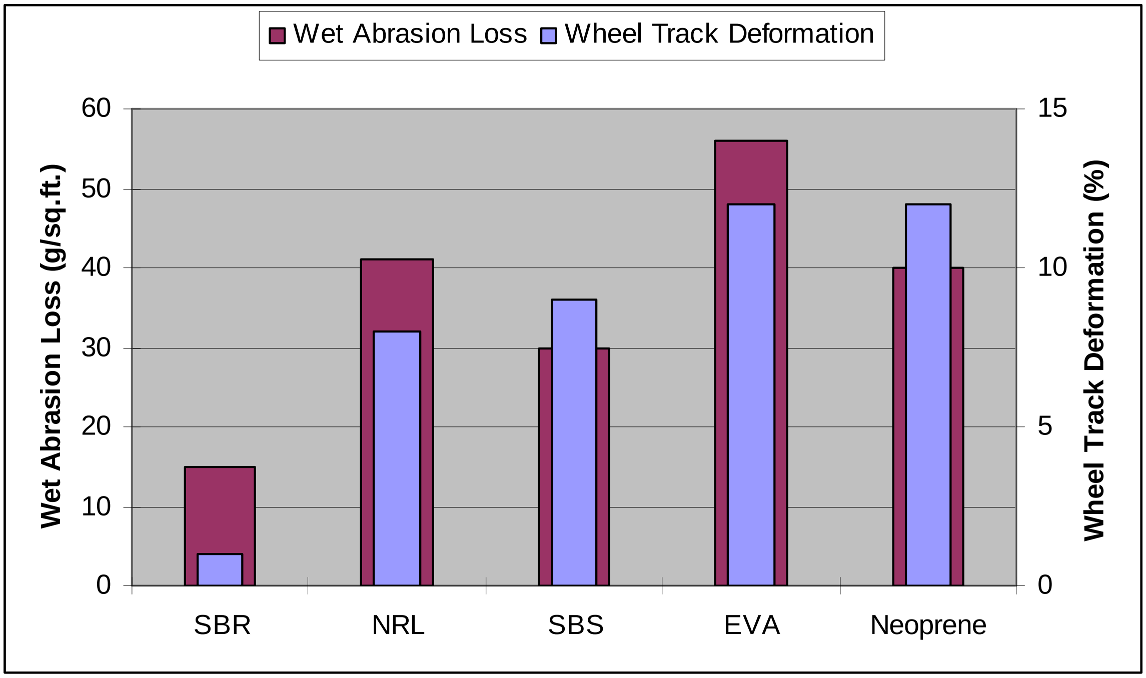


Figure 8. Chart. Wet Track Abrasion and Loaded Wheel Test by Polymer Type.(14)

2.2.4 Block Copolymers

When hard, styrene containing polymers are co-polymerized with small molecules such as butadiene in structurally discrete connected blocks, the result is a block copolymer.(15) Typical examples of block copolymer modifiers include SBS, SIS, SB, ABS, and RET. SBS (a triblock) is the most commonly used because of its desirable properties and comparatively low cost.(16)(17) The elasticity and strength benefits imparted by SBS modifiers are attributable to the molecule's rubbery polybutadiene (PB) "mid-blocks" capped at either end by polystyrene end-blocks, which provide strength and rigidity and increased compatibility with most asphalts.(16) Most block copolymer modifiers behave as thermoplastic elastomers, returning to their original shape upon removal of the loading stress.

Block copolymers are typically lower molecular weight than typical formulations of SBR latex, and generally consist of a comparatively narrow distribution of chains of similar monomer chain lengths. Whereas in SBS or SB, the monomers (building blocks) are randomly positioned and can exhibit a wide variety of regular and well-defined molecular morphologies including linear, star-shaped, and radial structures. Generally, random SBR polymer modified asphalts elongate more (i.e., have better ductility, especially at very low temperatures) than SBS block copolymers because of the double bond structure, but SBS block copolymer modified asphalts show more strength at elongation (i.e., elastic recovery, especially at high temperatures) because of the structure of the styrene blocks.(4) The exact performance, however, depends upon the structure of the specific polymers used and their compatibility with the specific asphalt used, as was illustrated in Figure 2. Formulators have the ability, therefore, to design polymer asphalt blends for specific performance needs, such as for durable micro surfacing and chip seal applications.

When triblock copolymers such as SBS and styrene-ethylene-butylene-styrene (SEBS) are raised above the glass transition temperature of their polystyrene end-blocks, these rigid domains soften, thereby weakening the crosslinked structure of the polymer. At temperatures exceeding 150 ºC, block copolymers are pliable in molten form in contrast to NRL modifiers, which begin to undergo crosslinking at this temperature.(3) Work by Wegan (2001) suggests optimal mixing temperatures of approximately 180 ºC for SBS modifiers.(50) Because block copolymers are workable at higher temperatures, the styrene domains comprising the typical SBS modifier can readily be segregated under shear force during the milling process, promoting the dispersion of individual chains throughout the asphalt binder. Consequently, as the polymer/asphalt blend is cooled, these styrene domains begin to reform, establishing a pervasive polymer network throughout the residual asphalt matrix.(3)

Stroup-Gardiner and Newcomb (1995) report that sufficient quantities of SBS polymer modifiers are required to promote effective crosslinking during the cooling phase to ensure that reactive portions of the styrene domains are close enough together to permit bonding. Termed the "critical concentration" or "c*", Stroup-Gardiner and Newcomb recommend SBS contents of at least 2 percent, and in some cases greater than 4 percent by weight of residual asphalt depending upon the chemistries and compatibility of the specific polymer and asphalt.(3) Additionally, as the ability of the polymer components to be swollen by a given asphalt increases, less polymer additive is needed (by weight) to achieve c*. Polymer swelling is generally believed to be caused via interaction with aromatics contained within maltene fractions, and will eventually lead to the formation of a continuous network.(18)

Factors influencing c* include the quantities of diblock (SB) versus triblock (SBS) copolymer used, mixing temperatures, the chemical compatibility between the asphalt and polymers used, and blending time. Chemical compatibility refers to the degree of molecular interaction occurring between the asphalt and polymer modifier components of the mixture, with more compatible asphalt being characterized by a higher degree of polymer swelling and increased homogeneity and dispersion of the polymer fractions when mixed. Block copolymer modifiers must be matched to a compatible asphalt, which will readily dissolve the end-block styrene domains at typical mixing temperatures to ensure thorough dispersion of the polymer during the emulsification and milling process.(3)

Stroup-Gardiner and Newcomb report that the complex modulus of 6 percent SBS-modified AC-10 decreases significantly with increasing SB diblock content at higher temperatures. Moreover, the researchers note that as the concentration of the diblock SB increases within a particular SBS modifier, the resultant complex modulus decreases substantially, leading to increased pavement rigidity, particularly at higher temperatures.(3)

Studies by Serfass et al. (1992) show that SBS-modified asphalt emulsions exhibit excellent adhesion properties with a diverse variety of aggregate, and they can be applied over a much longer working season than similarly modified hot mixes.(19) Moreover, emulsified asphalt applications were also shown to tolerate higher polymer dosing levels than modified hot mixes, resulting in improved stone retention, cohesion, and viscoelasticity, especially in crack sealing applications.

Investigation into the effects of SBS and SEBS triblock copolymers on asphalt rheology conducted by Gahavari (1997) shows a substantial increase in dynamic shear rheometer complex moduli at low to intermediate testing frequencies as polymer content is increased and when compared to unmodified asphalts. Using time-temperature superposition, the low frequencies correspond to high temperature properties (i.e., resistance to rutting). Gahavari also reports a significant decrease in loss tangent values (i.e., decreased viscous, flow-type behavior) over low to intermediate frequencies with the addition of polymer—an indicator of increased elasticity. However, at higher testing frequencies, it has been shown that the aging condition of modified asphalts may reduce the preferential elastic response effects obtained via the addition of polymer modifiers, which were observed at lower frequencies.(20)

2.2.5 Reclaimed Rubber

With the abundance of used tires and their associated disposal problems, there are undeniable incentives to use reclaimed rubber to improve pavement performance and/or as a means of facilitating disposal. CRM consists of scrap tire rubber that has been mechanically ground and reduced in size to particles generally less than or equal to 6.35 mm (0.25 inches) in diameter. Although most commonly used in HMA applications, reclaimed CRM has been used successfully on a limited basis in asphalt emulsions, particularly in those areas of the world where their lower cost and simplified application in remote locales are viewed favorably as compared to hot mixes.

Reclaimed tire rubbers are not pure polymers, but represent blends of SBR latex, polyisoprene (natural rubber), carbon black, and other additives.(21) CRM is extensively crosslinked and is not very compatible with the asphalt nor is it readily swollen. Devulcanization and use of high shear both reduce molecular weights and open up the polymer structure, thereby improving the solubilization/emulsification. While CRM can be successfully emulsified if particle size is sufficiently fine or if predigested, the cross-linked structure of the compounds in tire rubber generally result in the formation of two distinct phases upon blending (i.e., asphalt and rubber). This makes stabilization of the final emulsion difficult to achieve. Phase separation in CRM modified asphalt emulsions is characterized by two distinct mechanisms: coalescence and creaming.(22) Coalescence occurs when polymer particles aggregate together within the emulsion through the process of molecular diffusion. Creaming occurs when polymer particles rise to the surface of the emulsion due to density differences between the modifier and binder components.

Sabbagh and Lesser (1998) note that the phase stability of CRM modified asphalt emulsions is governed in large part by both particle size and morphology. In unstable modified asphalt emulsions, polymer particles tend to coalesce, gradually increasing in size over time until they become sufficiently large for creaming to occur. Sabbagh and Lesser have experimentally determined the critical particle transition radius (between coalescence and creaming) to be approximately 4 μm at 110 ºC for polyolefins. Polymer particles in unstable asphalt emulsions have a predominately teardrop-shaped morphology, whereas those in stabilized asphalt emulsions are characterized by either spherical and/or cylindrical shapes. The irregular, nonspherical shaped polymer particles, which characterize unstable modified asphalt emulsions are commonly observed under high shear mixing conditions. Additionally, the use of steric stabilizing copolymers has been shown to promote more thermodynamically stable spherical polymer particle shapes. Sabbagh and Lesser have noted that while polymer particle sizes in stabilized asphalt emulsions are generally larger than those in unstable asphalt emulsions, the former are not more susceptible to creaming. The authors attribute this to the increased density of the particles in stabilized asphalt emulsions created by the use of steric stabilizers. Thus, stabilized asphalt emulsions are those which are characteristically stable with respect to both creaming and coalescence. Paradoxically, Sabbagh and Lesser have shown comparable increases in fracture toughness and improved high-temperature viscoelastic behavior with increasing polymer content for both stable and unstable asphalt emulsions. This suggests that actual field performance is relatively insensitive to initial polymer particle morphology.(22)

CRM can be added as a dry ingredient to slurry mixes to avoid problems of phase separation, but in such cases it serves primarily as a filler material. When used as filler, CRM fails to form a pervasive matrix or network, and thus does not impart the cohesive and viscoelastic benefits associated with most other forms of polymer modification.

One solution to the phase separation problems associated with CRM modifiers involves the use of solvents to partially predigest the rubber particles prior to their introduction into the emulsion. High boiling point petroleum-based solvents that are high in aliphatic content are generally preferred because they promote swelling and softening of the rubber, which improves particle wetting and increases adhesion, while also meeting U.S. Environmental Protection Agency (EPA) emissions requirements. RG-1 represents a mixture of 40-50 percent CRM dispersed in a petroleum-based solvent, which is post-added to the emulsion through simple mixing. RG-1 modifiers exhibit good stability when blended with either cationic or anionic asphalt emulsions, with typical treatment applications including chip seals and slurry surfacing.(21)

Laboratory and short-term field testing of RG-1 modified asphalt emulsions indicate improved crack and rut resistance, higher viscosity, lower thermal susceptibility, better stone retention, and improved elasticity when compared to unmodified asphalt emulsions. However, results are generally less impressive than conventional forms of polymer modification. As far as processing RG-1, some research shows that it does not adversely impact setting times for slurries or micro surfacings. When used in chip seals, RG-1 costs are approximately 2 to 5 cents per square foot, and for slurry or micro surfacing the cost is about 1.5 to 3 cents per square foot. No special equipment is required to add RG-1, and standard batch plant transfer pumps are adequate for the task.(21)

Another use of reclaimed rubber and emulsions involves the direct addition of 15-22 percent of CRM to the hot asphalt binder used in some chip seals. In such instances, the modified binder is sprayed on top of the pavement surface followed by an overlay of stone, and then rolled. A fog seal of asphalt emulsion (generally, a 1:1 dilution) may then be applied over the top of the chip seal to improve stone retention.(23) Cape seals may be constructed using CRM in a similar fashion, by modifying the chip seal binder coat prior to the application of the overlying micro surfacing or slurry seal.

2.2.6 Plastics

The plastic polymer modifiers are typically thermoplastic plastomers (and sometimes elastomers), which are commonly based upon the polyolefins or copolymers of ethylene. Typically, polyolefin modifiers include polyethylene and its variants such as high density polyethylene (HDPE) and low density polyethylene (LDPE). Although polypropylenes are also considered part of this group, they are generally not recognized as imparting significant improvements in elasticity or crack resistance in asphalt paving applications.(7)(24) Among the ethylene copolymers, ethyl-vinyl-acetate (EVA), ethylene-propylene-diene-monomer (EPDM), ethyl-butyl-acrylate (EBA), and ethyl-methacrylate (EMA) are the most common.(4)

Characteristically, the plastomers impart rigidity to asphalt pavements leading to rapid early tensile strength and decreased high temperature susceptibility, but depending upon the formulation, may also fail to exhibit the desired elastic response when deformed (i.e., decreased resistance to strain). The Strategic Highway Research Program (SHRP) guidelines call for a maximum fatigue resistance value of 5,000 kPa (as tested at standard temperatures) in order to decrease the propensity of the in-place pavement to crack at intermediate ambient temperatures.(25) Some formulations with these plastomers may fail this parameter. Although many believe the SHRP fatigue parameter may not be the best measure for fatigue resistance, the ability of the material to withstand repeated loadings has a major contribution to its effective life cycle. In general, the higher the degree of crystalline structuring possessed by a plastomer, the higher the resulting tensile strength and the lower the elastic response.(3) While plastomer systems may be somewhat brittle, their plastic polymer structure may give them the ability to resist crack propagation. Additional modifiers may be introduced as copolymers, which can serve to partially disrupt this crystalline structure, thereby increasing the ability of the pavement to flow. The goal of inducing modest increases in flow potential is to reduce excessive binder stiffness at low (less than 10 ºC) temperatures, thereby mitigating the potential for thermal and fatigue cracking.(25) Moreover, the principal function of plastomeric modifiers is usually not to form a pervasive and continuous elastic network as with the block copolymers or latex. It is to produce a dispersal of discrete plastic inclusions throughout the bitumen, which can impart increased rigidity. This provides better resistance to high temperature (greater than 30 ºC) permanent deformation (rutting) and modest improvements in fatigue cracking caused by repeated loading and unloading at intermediate (10 – 30 ºC) temperatures.(25)(26) In addition, these plastic inclusions can also aid in interrupting and therefore arresting the propagation of cracks.(3)

Comparing unmodified binders and those modified with polyethylene plastomers and various elastomers (SBR and CRM), Morrison et al. (1994) have shown that the plastomeric modifiers provide for substantial increases in the penetration index and measures of rutting resistance.(25) These results suggest that the polyethylene-modified binder tested (Dow Chemical Company's Tyrin® 2552) would offer enhanced rheological performance in those environments and during seasons where pavement temperatures meet or exceed 30 ºC.

Some of the plastic modifiers such as EPDM represent hybrid combinations of elastomeric and thermoplastic characteristics. EPDM is often classified as a form of synthetic rubber as well as a plastic, and it can be mixed with plastomeric additives such as HDPE to yield pavements that possess high temperature rutting resistance, and sufficient ductility at low temperatures to inhibit thermal cracking.(27) Greater detail on the use of polymer blends is given below.

Work with polyolefin modifiers indicate asphalt compatibility problems resulting in binder instability (segregation) when stored at temperatures in excess of about 150 ºC. Perez-Lepe et al. (2006) have shown that segregation of the polymer phase occurs at comparatively short storage times in the form of creaming, and that this creaming is immediately preceded by widespread polymer coalescence brought about by the immiscibility between the bitumen and polyethylene fractions.(28) Morrison et al. (1994) have demonstrated that the use of virgin or recycled tire rubber SB as a steric stabilizer in polyethylene modified asphalt emulsions can interrupt this coalescence mechanism, yielding a more stabilized mix.(29)

Yousefi (2003) suggests that as the melt flow index (MFI) of linear polyethylene polymers such as HDPE decreases, instability increases, making thorough dispersal within the bitumen problematic. Moreover, branched polyethylene modifiers such as LDPE are easier to disperse than linearly structured equivalents. While high MFI polymers are easier to disperse, they have less of an effect on high temperature performance, but were shown to significantly improve low temperature behavior.(26)

Hesp and Woodhams (1991) note that polyolefin modifiers impart a wide range of beneficial characteristics to applied asphalt emulsions, including decreased thermal cracking and high temperature rutting, greater fatigue resistance, improved skid-resistance, and increased stone retention. Hesp and Woodhams also observed problems related to gross phase separation at elevated storage temperatures have inhibited the widespread adoption of polyolefin compounds in PMEs. Indeed, the authors note that without the use of a stabilizer, polyolefin-modified asphalt emulsions commonly have stable life-spans of only one hour or less.(30) The findings of Hesp and Woodhams are in general agreement with those of Perez-Lepe, and they indicate that the primary mechanism of instability in polyolefin-modified asphalt emulsions is the coalescence of the polymer phase, which eventually leads to creaming.(28)(30) The most promising and cost-effective method for achieving mixture stability in such cases, is regarded to be the addition of steric stabilizers, which are thought to secure stability by being preferentially absorbed at the polyolefin-asphalt interface.(28)(30)

EVA is a commonly used plastomeric modifier, which represents a copolymer of ethylene and vinyl acetate. By co-polymerizing ethylene and vinyl acetate, the latter serves to reduce the crystalinity of the former, resulting in increased elasticity and better compatibility with the base asphalt. In EMA and ethylene acrylate modifiers, the crystalline structure of polyethylene is similarly reduced via the introduction of acrylic acid.(3) Panda and Mazumdar (1999) report decreased penetration and ductility and improved temperature susceptibility in EVA modified versus unmodified binders. Additionally, EVA modified asphalts have been shown to retain their desirable physical properties even after prolonged periods of storage, and they do not appear to be adversely affected by minor variations in mixing methods or temperatures.(31)

Reclaimed waste plastic modifiers such as HDPE and LDPE have been shown to be somewhat effective in improving fatigue resistance, and in reducing penetration.(24)(32) However, it is noteworthy that some stability problems with these mixes have also been reported, particularly at higher additive concentrations.(24)

Gerard et al. (2001) have compared the performance of plastomer-modified, elastomer-modified, and unmodified asphalt binders with respect to fracture toughness and crack propagation characteristics at low (-20 ºC) temperatures. It has been demonstrated that the use of polymer modifiers generally increases the facture toughness of asphalt binders. However, SB- and SBS-based modifiers exhibited substantially better fracture toughness than did comparable EVA and EMA modified mixtures owing to respective differences in crack propagation behavior as shown in Figure 9. More specifically, Gerard et al. reported that EVA and EMA modified mixes propagate cracks at the interface between the polymer and asphalt phases, leading to brittle behavior and stone pull-out (shelling). In contrast, the continuous polymer network formed in binders modified with elastomeric additives tends to stretch as the energy from the crack propagates through the polymer domains, impeding crack development in a phenomenon referred to as “crack-bridging.” In summation, the results suggest that SB and SBS modifiers provide for diminished low temperature susceptibilities as compared to similar EVA and EMA mixtures.(33)

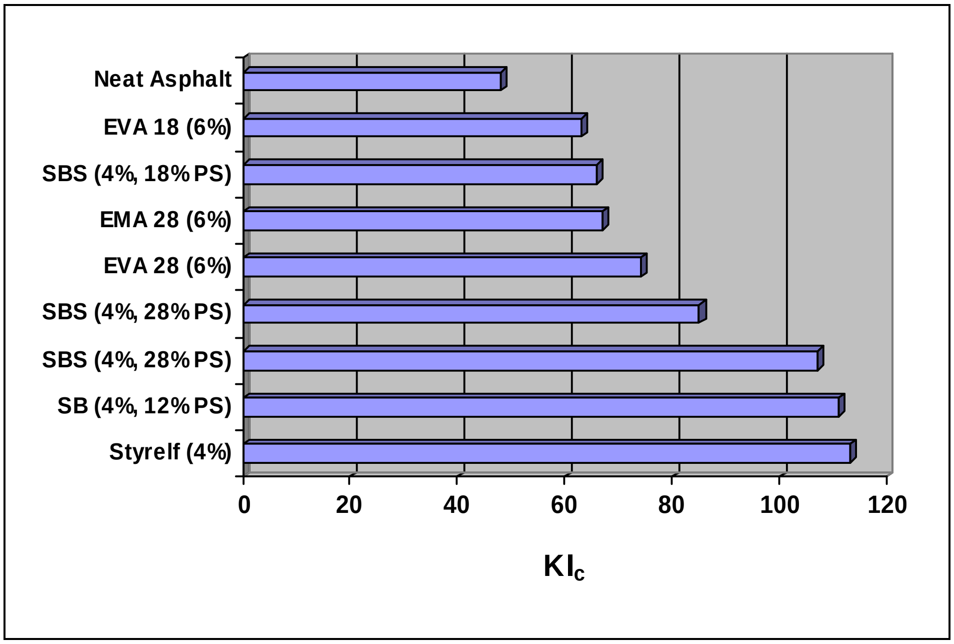


Figure 9. Chart. Fracture Toughness at -20 ºC.(33)

2.2.7 Polymer Blends

Select polymer additives may be blended together to achieve desired composite properties that cannot be obtained from a single polymer modifier alone. Blending may prove a viable option when a particular polymer modifier has attractive availability and costs but does not give the rheological and performance characteristics that satisfy design requirements. In such cases, the addition of complementary modifiers may provide the means to satisfy the design specifications while permitting the use of the desired primary modifier. Additionally, supplemental modifiers are frequently added to improve the overall compatibility between the polymer and bitumen phases and to improve long-term mixture stability. While practical considerations preclude the exhaustive documentation of the numerous potential polymer combinations, examples of some of the most common blends in the literature are presented here.

Applications, which use polyethylene as the primary modifier are frequently augmented via the addition of elastomers such as PB, to improve mixture stability and prevent segregation. Morrison et al. (1994) report that polyethylene-modified asphalt emulsions can be effectively stabilized with either virgin PB or lower-cost de-vulcanized CRM.(29) The mechanism for increasing stability is the attachment of steric stabilizer molecules at the polyethylene-asphalt interface.

Ait-Kadi et al. (1996) reported that blends of HDPE and EPDM produce improved penetration, loss of aromatics (aging), and viscosity when compared to neat asphalt.(27) Comparisons of HDPE/EPDM blends to straight HDPE-modified asphalt in this study indicate little performance difference, although microscopic evaluation suggests that the blends generally yield a better distribution of the polymer phase. This characteristic has important cost and handling implications, since modifiers, which are difficult to disperse translate into significantly higher energy requirements and longer mixing times.(34) More thorough and homogeneous dispersal of the polymer phase within the bitumen generally leads to improved mixture stability and increased potential storage life.

2.3 Polymer Modification Methods and Dosage Rates

The performance of polymer modifiers can be greatly affected by blending techniques, the percentage added, the types of aggregate used, and the methods and temperatures of emulsion storage. This section discusses the impacts of mixing methodologies and conditions, dosing rates, and storage and handling practices on the demonstrable field and laboratory qualities of polymer modified asphalt emulsions.

2.3.1 Polymer Modification Methodology

Table 2 is a summary of representative polymer modification methods and recommended dosage rates found in the literature. Table 2 shows that the modifiers may be added before emulsification to the emulsifying solution or asphalt, added to the finished emulsion product, or "co-milled" at the colloid mill with the various component streams during production (Figure 3). The discussions below on test results of polymer modification methods are generally based on blends of specific polymers and specific asphalts. As mentioned above, the chemical and physical interactions of various polymer/asphalt blends can have significant affects on such results.(4)

Premixing with the soap solution is the generally preferred method of adding liquid latex to asphalt emulsions, followed by co-milling at the colloid mill. Becker et al. (2001) observed that the phase separation and stability problems associated with using solid polymer modifiers generally necessitate preblending the solid polymer in the asphalt at elevated temperatures prior to emulsification.(8)

Post-addition of the modifier to the final emulsion product either at the plant or the application site is sometimes discouraged due to the need for vigorous, continual, and thorough mixing to ensure proper and homogeneous polymer dispersion. One notable commercial exception is the use of CRM-based RG-1, which is predigested with an organic solvent prior to being post-added to the emulsion.

Table 2. Polymer Modification Methods and Dosages.

Type	Method	% Polymer Solids	Application(s)	Ref.(s)
SBR	Soap pre-batching. NO post or field addition.	3 – 4% of residual asphalt content	Slurry seals	(36)
SBR	Not specified	3% of residual asphalt content	Various	(5)
SBR (Ultracoat™)	Dilute with water to 15% latex solids and blend with aggregate at collection hopper	15% of total emulsion weight	Polymer anti-strip increases chip seal stone retention	(37)
SBR (Butonal LS 198®)	Soap pre-batching. NO post or field addition.	2 – 6% of residual asphalt content, usually 3%	Various	(9)(38)
SBR	Soap pre-batching	∃3% of residual asphalt content	Micro surfacing	(39)
SBR, NRL, Neoprene, SBS, EVA	Preblend latex solids with bitumen using a high-shear blender. If latex in form, then use soap pre-batching.	2% of residual asphalt content	Micro surfacing	(40)
SBR, NRL	Soap pre-batch, co-mill, or post add	3 – 5% of residual asphalt content	Various	(41)
SBS	Preblend with asphalt	5 – 12% of residual asphalt content	Various	(42)
SBS	Preblend with asphalt binder	> 5% of residual asphalt content (forms continuous polymer matrix)	Various HMA applications	(17)
SBS, SB	Preblend with asphalt	6% of residual asphalt content	Various	(43)
SBS, SB	Preblend with asphalt	4% by weight of asphalt content	Various low temperature applications	(33)
CRM (RG-1)	Post-blended in-line directly with emulsion at plant and remixed before application	5 – 8% of total emulsion weight	Asphalt rubber slurry surfacing	(44)
NRL (1497C)	Ralumac Process – Soap pre-batching	4% of total emulsion by weight	Various	10
EGA (Elvaloy®)	Preblend directly with binder	1.5 – 2.0% of residual asphalt content	Various HMA applications	(45)
EVA	Preblend with binder	5% by weight of asphalt content	Various	(31)
EVA / EVM	Preblend with binder	6% by weight of asphalt content	Various low temperature applications	(33)
EPDM, LDPE, HDPE	Preblend directly with binder	5% of residual asphalt content	Various HMA applications	(34)
EVA, LDPE	Preblend directly with binder	4 – 8% of asphalt content by weight	Various	(35)
Any Appropriate	Soap pre-batch or preblend with bitumen	3% of residual asphalt content	Micro surfacings	(46)
Polyethylene (Tyrin® 2552)	Preblend directly with binder	3 – 5% of residual asphalt content	Various	(25)
Various	Various	2 – 10% of residual asphalt content, 2 – 3% most commonly	Various	(8)

Forbes et al. (2001) examined the effect of four distinct and commonly used polymer modification techniques on asphalt binder microstructure at high temperatures:

1.) Preblending – The polymer modifier is added directly to the bitumen prior to emulsification. This method is required for solid forms of polymer.

2.) Co-Milling – Separate streams of polymer, bitumen, and emulsifier solution (soap) are co-milled together simultaneously.

3.) Soap Pre-Batching – The polymer modifier is added to the soap solution (water and emulsifier) prior to milling with the bitumen.

4.) Post-Modification – The polymer modifier is added to the final asphalt emulsion either at the plant or in the field.(47)

Properly cured residues from asphalt emulsions prepared using each of these methods were examined using laser-scanning microscopy to ascertain the structural network and distribution of polymer within the test samples. Microstructure comparisons were also performed with non-emulsified polymer-modified HMA binders.(47)

Forbes et al. found that asphalt emulsions produced using either soap pre-batching or co-milling produced a slightly better distribution of the polymer than did post-modification. Bituminous particles created within the colloid mill were found to have polymer modifier droplets layered around their surfaces (Figure 10). When asphalt emulsions are prepared by soap prebatching or co-milling, latex particles are prevented from coalescing in the presence of the soap solution, but result in the formation of a thin film or matrix around the asphalt particles upon drying (Figure 11).(47)

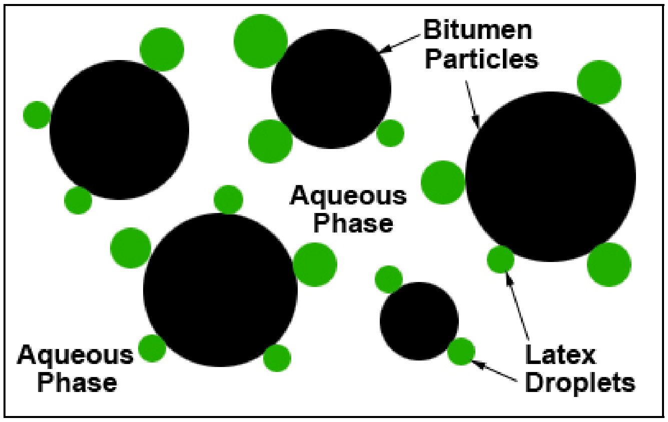


Figure 10. Schematic. Bi-Phase Modified Emulsion.(47)

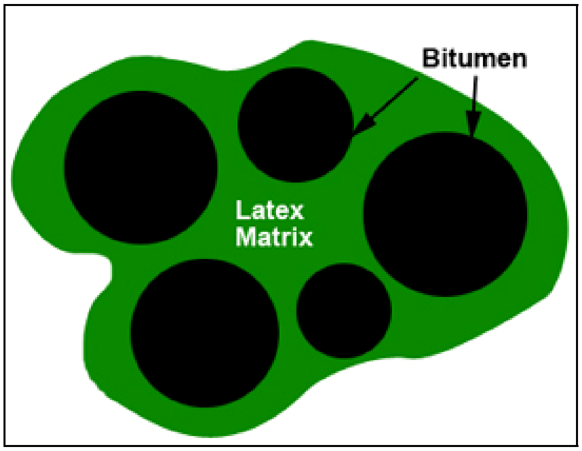


Figure 11. Schematic. Polymer Network in Cured, Co-Milled Emulsion.(47)

Examinations of non-emulsified asphalt binders, which have been subjected to direct polymer modification indicate the presence of widely distributed polymer droplets of varying size, and numerous occurrences of discrete "swollen" polymer particles, indicating incompatibility between the polymer and bitumen phases. However, when preblended asphalts are emulsified, the resulting mixture exhibits well-distributed and discrete fine particles of polymer, areas of swollen polymer, and aggregated asphaltenes, representing a marked improvement in bitumen-polymer compatibility. While co-milling and soap prebatch modification yield a biphase of asphalt and polymer, preblending produces a monophase of asphalt and polymer *after* emulsification as illustrated in Figure 12. Preblending was shown to ultimately yield a much more homogeneous and more thorough distribution of polymer than did modified hot binders, suggesting that preblended polymer-modified asphalt emulsions may lead to more consistent cohesive strength performance, better elasticity, and improved stone retention characteristics than modified hot mix asphalt. When lateral shear stress was applied to a dried preblended modified emulsion sample in the Forbes study, the polymer network was found to predictably elongate and resist deformation. However, Forbes et al. caution that preblended asphalt emulsions do not produce a continuous polymer network as seen in co-milling or soap pre-batching mixes, and they recommend further investigation to determine if this structural difference might impact performance.(47)

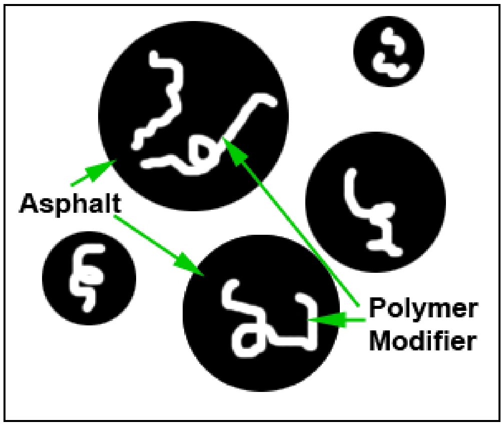


Figure 12. Schematic. Pre-Blended Asphalt-Polymer Monophase.(54)

Lubbers and Watson (2005) presented the results of analyses performed at BASF Corporation using stress-strain testing developed by Dr. Koichi Takamura to gauge the relative fatigue performance of unmodified, preblended, and co-milled asphalt emulsion residues, as well as unmodified hot mixes.(5)(48) The BASF testing consisted of the following steps:

1.) Strain sweep from a low of 0.1 percent to high of 5.0 percent applied for 30 minutes.
2.) Constant strain of 5 percent applied for 30 minutes.
3.) Strain reduced to 0.1 percent for 15 minutes to monitor potential recovery.
4.) Repeated steps 2 and 3 and measured change in residual strength.

A similar test sequence was performed on duplicate samples using a maximal stress of 10 percent. The test results indicate that unmodified asphalt emulsions are substantially weaker than neat hot-mix asphalt, due in large part to the failure of asphalt droplets in the former to fully coalesce, even within a 24-hour period. Conversely, asphalt emulsions modified with 3 percent SBR latex performed significantly better than did unmodified emulsions or neat non-emulsified asphalt cement. Of particular interest was the performance of the preblended SBS-modified emulsion samples, which demonstrated diminished viscoelastic recoveries as compared with conventionally co-milled SBR-modified emulsions. The reduced performance of the preblended asphalt emulsion was especially evident at the higher 10 percent strain level. These results suggest that using preblended modified asphalts without continuous polymer networks in emulsions may yield reduced residual asphalt performance. Figure 13 illustrates fatigue resistance test result comparisons between unmodified, conventionally co-milled, and preblended modified asphalt emulsion residues.(5)

Similarly, an evaluation of preblended and co-milled SBR modified asphalt emulsions in chip seals performed by Takamura (2001) indicates that the formation of a honeycombed polymer network around the asphalt particles, results in a one to two performance grade (PG) improvement in rut resistance as compared to polymer-asphalt monophase mixtures.(14) Figure 14 illustrates a comparison of rutting resistance temperatures for neat asphalt, hot mix, emulsion residue, and cured residue after one week at elevated temperature (60 ºC).

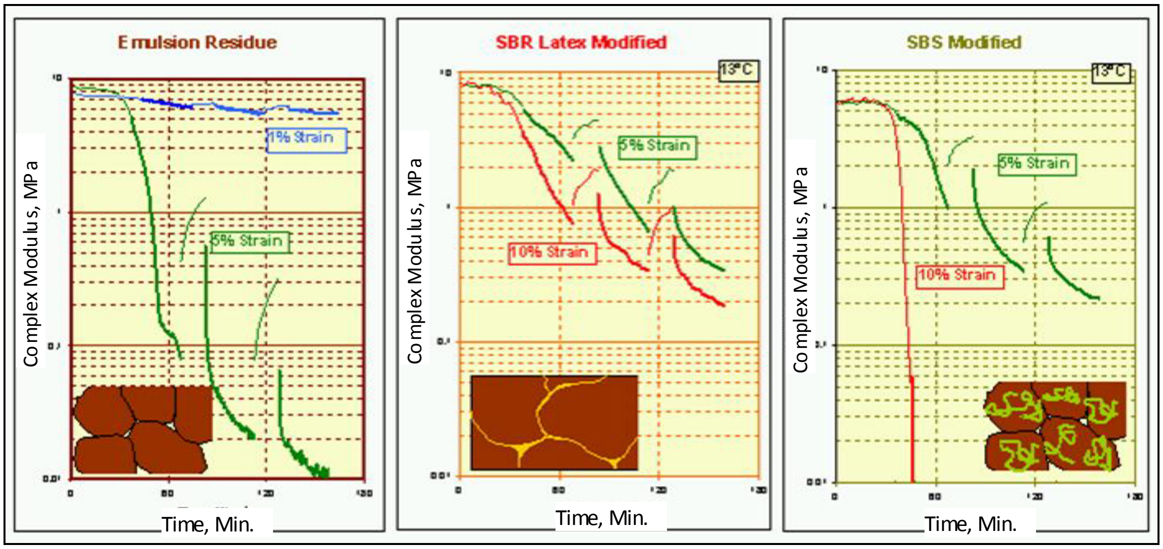


Figure 13. Schematic. (L to R) Unmodified, Co-Milled, and Preblended Emulsion Test Results.(5)

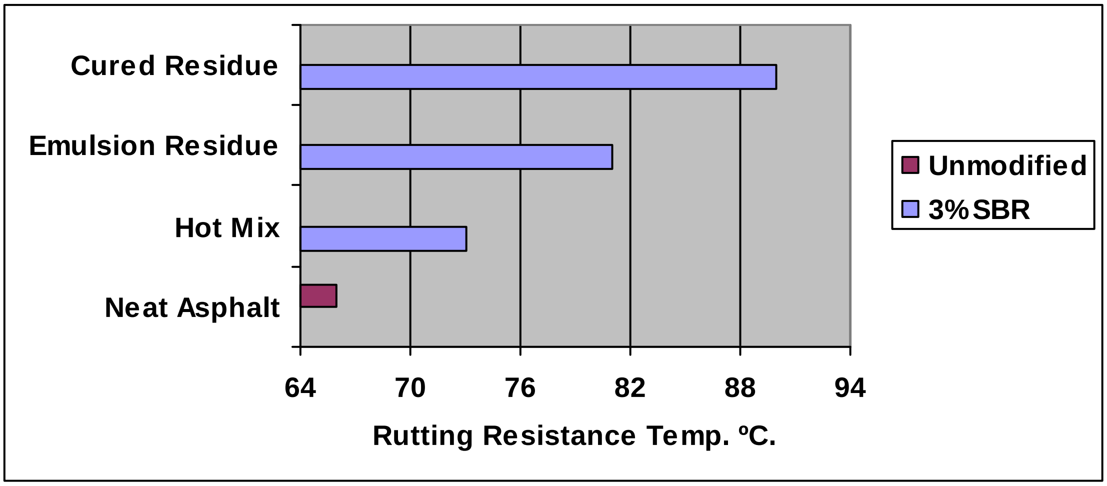


Figure 14. Chart. Advantages of SBR Network.(12)

Takamura and Heckmann (1999) suggest that SBR latex has the advantage over SBS modifiers because SBR latex is able to be successfully added using co-milling, soap pre-batching, or post modification methods, while solid SBS generally must be preblended with hot asphalt before emulsification. The researchers reported observing the successful formation of a continuous polymer network in asphalt emulsions prepared with post-added 3 percent Butonal® NS198 (an SBR modifier), as well as significant improvements in laboratory measures of rutting resistance over unmodified binders, particularly at high (greater than 50 ºC) temperatures. However, no comparisons were provided between the performance characteristics of the various polymer mixing methodologies. Takamura and Heckmann further demonstrated that once formed, the resultant polymer network will remain intact, even when reheated to “hot mix” temperatures (200 ºC).(49)

Wegan (2001) examined the impact of different polymer modification techniques, mixing times and temperatures, and filler and aggregate types on the distribution of polymer additives in modified asphalt binders. This study involved the formulation of a variety of mix designs in the laboratory. Upon curing, samples were cut and prepared as ultrathin sections and subsequently subjected to UV light microscopic analysis. Polymer modifiers tested in the Wegan study included EVA, SBS, and a waste product material based on polyethylene (PE). Results indicate that polymer swelling increases substantially in cases where modifiers are preblended with the binder, versus those which are added directly to the final bituminous mixture (post-modification to asphalt and aggregate mix). Preblended polymer modified asphalt binders were also shown to provide increased contact and adhesion between polymer components and the surfaces of mineral grains in those mixtures where coarse-grained aggregate was used. Polymer was similarly found to be more pervasively distributed and to exhibit better aggregate contact characteristics in cases where mixing times and/or the quantity of the modifier used were increased. Wegan’s temperature-related studies indicated that a mixing temperature of approximately 180 ºC provided for more homogeneous polymer distribution than did substantially cooler (160 ºC) or hotter (200 ºC) temperatures.(50)

In test mixes where 7 percent EVA was preblended with the asphalt binder, Wegan reports observing the formation of a partial, yet distinct polymer network structure. Test samples containing 18 percent preblended EVA exhibited an even greater degree of polymer network formation.(50) These results appear to suggest that in contrast to the findings of the BASF and Forbes studies, modified asphalt binders produced by preblending *may* produce a cross-linked network structure, providing that the polymer content is *sufficiently high*. However, no information is provided by Wegan with respect to comparing the performance of high polymer content preblended binders to conventionally modified lower content mixtures, or whether the increased materials cost of this form of preblend justifies its use. Wegan’s studies were on binders for hot mix asphalt, not asphalt emulsions. The presence of the aqueous phase may account for the differences with the BASF and Forbes studies. The water-based latex emulsion facilitates dispersion of low percentages of polymer among the emulsified asphalt particles.

Hussein (2005) examined the impact of polymer-asphalt blending time on PMA performance for varying molecular weight LDPE and EVA additives. Figure 15 summarizes the change in complex shear modulus for various modified and neat asphalts relative to mixing time. Polymer modified mixes exhibit significant and well-defined increases in complex shear modulus (G*) as mixing time is lengthened, until a critical point is reached whereupon these improvements begin to stabilize (and can decrease). For example, the steady-state points for 8 percent LDPE1, 8 percent EVA1, and 8 percent EVA2 are approximately 30, 15, and 20 minutes, respectively. In contrast, neat asphalt exhibits a virtually flat-line G* response over the same period. Hussein proposes that the point, which represents stabilization in the magnitude of G* is indicative of the optimal blending time for that polymer-modified mixture. Results indicate that the optimal blending time for EVA-modified binders was generally less than for LDPE-modified mixtures, owing in part to the lower weight-average molecular weights of the former. Hussein also found that binders containing low vinyl acetate content EVA additives exhibited the best high temperature susceptibility and long-term storage stability of the mixtures tested. However, little if any benefit was identified for these polymer additives at low temperatures.(35)

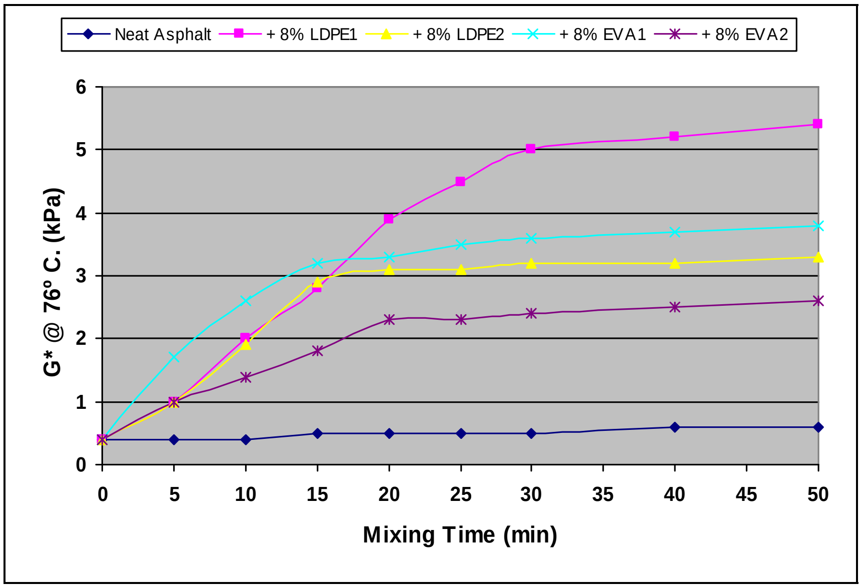


Figure 15. Graph. Complex Modulus over Mixing Time.(35)

2.3.2 Polymer Dosing

As Table 2 illustrates, the range of polymer content dosing recommended for most applications generally varies between about 2 percent and 10 percent by weight of the residual asphalt content with most research, standard, and manufacturer specifications calling for a polymer concentration of approximately 3 percent to 5 percent. The optimal percent depends upon the specific polymer, the specific asphalt, and their interaction.

Chen et al. (2002) examined the effect of SBS polymer content on laboratory-determined PMA performance. SBS contents were varied from 0 percent to 9 percent, and the resulting cured mixtures tested for ring-and-ball softening point, penetration, and complex modulus by dynamic shear rheometer (DSR). In addition, test samples were also subjected to structural analysis via transmission electron microscopy. Results of the Chen et al. study reveal that increasing SBS content resulted in increased polymer swelling, which in turn increased apparent asphaltene percentage (caused by maltene absorption by the polymer phase), leading to a harder matrix. Figure 16 presents the results of the softening point and penetration tests.(17)

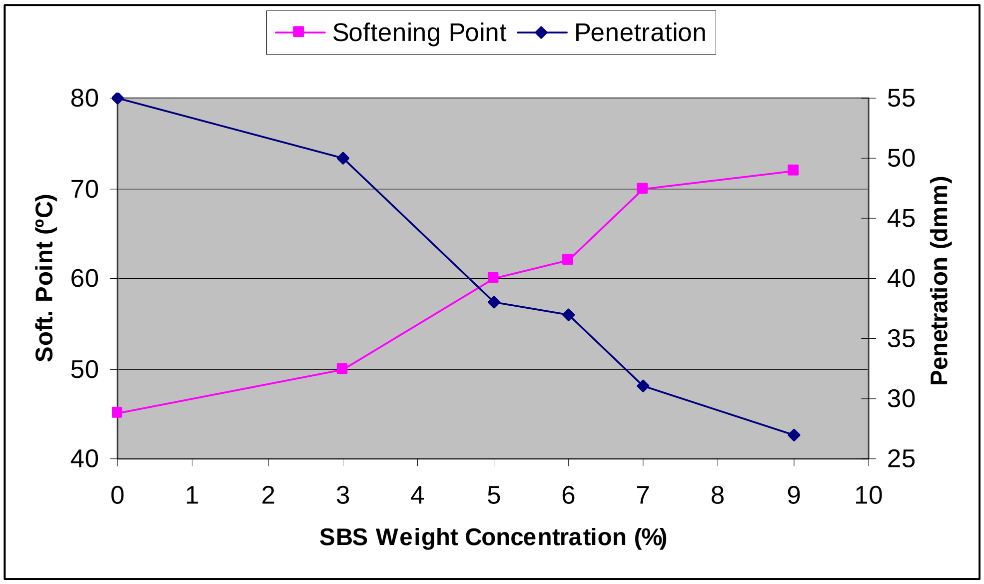


Figure 16. Graph. Effect of SBS Concentration on PMA.(17)

As Figure 16 illustrates, increasing SBS content resulted in substantially increasing softening point and lowering penetration characteristics up to a critical concentration of about 5 percent to 6 percent. Chen et al. noted that as the concentration of polymer reaches about 5 percent, the asphalt and polymer phases both become continuous; each phase forms an interconnected and interwoven matrix. At polymer concentrations in excess of 5 percent, the SBS becomes the dominant matrix, forming a continuous film around droplets of almost pure asphalt. Moreover, because improvements in softening point and penetration begin to stabilize at concentrations higher than about 6 percent, Chen suggests that this level of SBS is optimal for the particular asphalt tested (an AC-30).(17)

Figure 17 depicts the effect of SBS content on the complex shear modulus of test samples as measured using the DSR. As Figure 17 illustrates, adding about 5 percent SBS results in an approximately 6-fold increase in the complex modulus over neat asphalt cement. Furthermore, increasing SBS content from 3 percent to 5 percent yields a proportionally larger increase in complex modulus than do increases in excess of 5 percent.

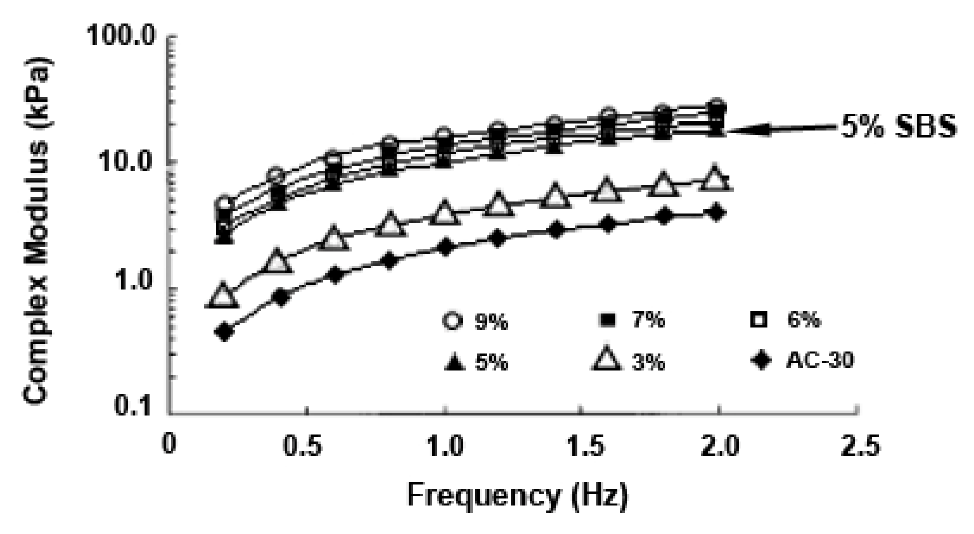


Figure 17. Graph. Effect of SBS Concentration on Complex Modulus at 60 ºC.(18)

Thus, it is suggested that a polymer content of around 6 percent is required to generate the continuous polymer network, which is believed to impart the desirable rubber-like elasticity characteristics associated with polymer modified binders. It should be noted however, that preblending was used to prepare samples for this study. Similar results were obtained by Airey et al. (2002), which indicate that SBS concentrations of 4 percent to 8 percent are required to establish a continuous polymer network with direct bitumen modification.(18) However, as previously discussed, others have shown that preblending certain systems may fail to result in the formation of a continuous polymer network unless the content of polymer added is sufficiently high to promote phase separation and swelling.(5)(12)(50) This would suggest optimal polymer contents presented in the Chen and Airey studies might prove to be higher than necessary than polymer modifiers such as SBR latex, which can be co-milled or soap prebatched in an analogous PME application. It should be noted that at the point where the polymer becomes the sole continuous phase, the blend exhibits more of the physical characteristics of the polymer than the asphalt. That is, it becomes more cohesive and may have a softening point higher than typical use temperatures, making pumping and emulsification difficult for emulsions, and coating of aggregates difficult for HMA.(4)

Chen et al. have also examined the impact of variable SBS concentrations on Brookfield viscosity (American Society for Testing and Materials [ASTM] D789, D4878) as shown in Figure 18.(17) The researchers note that polymer modified binder pumping generally does not become problematic until mixture viscosities begin to exceed about 3,000 cP.(18) Thus, as Figure 18 illustrates, SBS weight concentrations in excess of 6 percent appear to be problematic with respect to the materials handling and placement practicalities for modified AC-10 and A-30 asphalt binders.

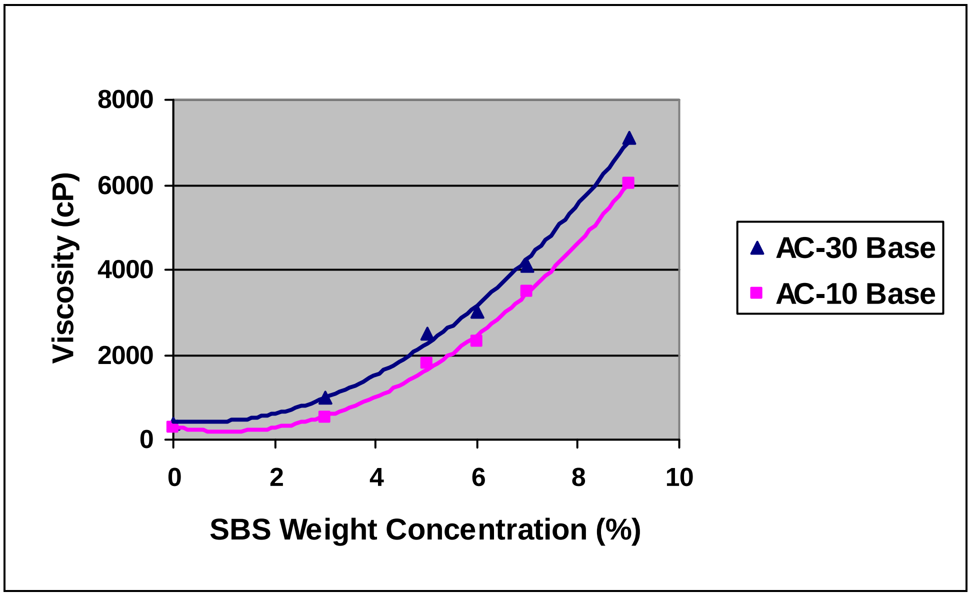


Figure 18. Graph. Viscosity as a Function of SBS Concentration.(17)

Serfass et al. (1992) report that adequate SBS concentrations are required to ensure proper formation of a continuous polymer and asphalt network, and that it is this network, which imparts the most desirable viscoelastic properties to modified asphalt binders. Within this context, the authors note that "adequate" is highly dependent upon asphalt compatibility, but is generally within the range of 3 percent to 5 percent by weight of residual asphalt.(19)

2.3.3 Storage and Handling Considerations

Proper storage conditions represent one of the most common problems associated with the use of PME. The mixing processes used are complex and often proprietary, and as such, modified binders are generally acquired in an already-blended form from the supplier. Once batched, some polymer modified asphalts and some polymer-modified asphalt emulsions must be placed in special holding tanks that can be continuously agitated to prevent phase separation problems. Temperatures during storage also need to be strictly controlled to prevent setting, premature breaking (emulsions), and/or thermal destruction of the polymer modifier. As has already been demonstrated, the effective length of storage of polymer modified asphalt emulsions, even under ideal conditions, can vary widely depending upon the modifier and bitumen types, the degree of polymer-asphalt compatibility, and the surfactant system used. Emulsions formulated for chip seals (rapid-setting) are designed to break quickly for early chip retention, while emulsions for slurry seals and micro surfacing (slow- and quick-setting) are designed to be stable enough to mix with aggregates and additives. Chip seal emulsions are therefore generally less stable than micro surfacing or slurry seal emulsions. When storing and handling prepared asphalt emulsions, the following general guidelines are recommended:(1)(51)(52)

- In general, store the emulsion between 10 and 85 ºC, depending upon the intended use and the particular grade of emulsion. Specifically, rapid setting cationic chip seal emulsions should be stored at temperatures above 50 °C to prevent premature breaking.

- Do not heat the emulsion above 85 ºC during storage as this may cause excess water evaporation. Similarly, excessive and prolonged temperatures above 100 ºC can cause breakdown of the emulsion and/or destruction of its polymer components.

- Avoid prolonged periods of storage, and make sure the mixture is gently and continuously agitated.

- Maintain an accurate temperature history and collect frequent measurements.

- Do not allow the asphalt emulsion to freeze, as this breaks the emulsion and causes phase separation and mixture instability.

- Do not use forced air to agitate the emulsion because it may cause premature breaking.

DSR testing conducted after simulated aging with a rolling thin film oven (RTFO-DSR) of properly cured polymer modified emulsion residue indicates that unmodified asphalt emulsion contamination present within storage tanks or product transfer lines may adversely impact performance.(52) Similarly, some reductions in RTFO-DSR performance were noted with increasing storage times, which, when combined with product contamination, resulted in even more pronounced degradation of RTFO-DSR results.(52)(53)

However, when modified non-emulsified asphalt binders were tested using comparable protocols, results indicate that the impact of prolonged storage, elevated temperatures, and contamination were substantially greater than were found during asphalt emulsion residue trials. It is hypothesized that this performance differential between modified asphalt binders may be due to the evaporation of water from the former, which provides a better barrier to oxidation, and hence aging.(52) Therefore, it is suggested that modified asphalt emulsion storage and handling protocols should focus primarily on preventing excessive water loss and phase separation rather than on aging-related problems.(53)

2.4 Performance

2.4.1 Performance Criteria

The performance enhancing characteristics of polymer additives are generally twofold: increased resistance to permanent deformation such as rutting, shoving, and bleeding (i.e., high temperature susceptibility); and improved durability against load-associated types of pavement distress (e.g., fatigue cracking, aging, and shelling). Polymers can also afford additional benefits by reducing the formation of non-load associated cracks caused by roadway brittleness, which often occur in pavements that become excessively stiff and hard at low temperatures. In this regard, properly modified asphalts demonstrate improved temperature susceptibility characteristics by remaining flexible at low temperatures, while retaining sufficient stiffness at high temperatures to resist flow and permanent deformation.

Some initiatives have been undertaken to develop a “Superpave™-like” specification for surface applied asphalt emulsions. At present, ASTM D977-05 “Standard Specification for Emulsified Asphalt” uses few aspects of Superpave™ in its testing and characterization protocols. Hazlett (1996) asserts that many of the Superpave™ performance-based criteria, such as rutting resistance, thermal cracking, and RTFO aging, are not applicable to surface applied treatments.(55) Moreover, while some forms of Superpave™ testing could be extrapolated to polymer-modified emulsified asphalts, certain specification limits may not be appropriate for pavement surface conditions. However, Clyne et al. (2003) used Superpave™ specifications to test polymer modified asphalt emulsion residue for cold in-place recycling applications, in a manner similar to that of asphalt binder. Comparisons of resulting data trends from emulsified and non-emulsified asphalt binder tests were similar enough to suggest that PG test protocols could be adapted to emulsion characterization, although further investigation is required to establish whether experimental results can be successfully correlated to field performance.(56)

Takamura noted that polymer modified asphalt emulsions can be successfully used in micro surfacing applications for filling ruts up to 5 cm deep.(54) The Portland cement used in micro surfacing significantly improves the rutting resistance of the asphalt binder, as shown in Figure 20. This contradicts the contention by some that rutting resistance is an inconsequential measurement parameter when assessing polymer modified asphalt emulsion performance. Indeed, rutting resistance should prove a valuable indication of a rut-filling mixture's ability to resist future high temperature deformation.

Epps et al. (2001) developed a surface performance grading (SPG) system for asphalt emulsions based upon the modification of existing test protocols used under the standard PG system for HMA.(57) The SPG is designed to take into account the unique forms of distress common to surface course mixes, such as extreme high and low temperature performance, susceptibility to aging, stone loss (from chip seals), storability, and handling characteristics. Modifications to the standard PG system generally include adjustments to constant limiting values, as well as some changes to the actual testing protocols. For example, the PG procedure specifies that the designed high temperature limit should be determined at a depth of 20 mm below the pavement surface—a depth limitation, which is not applicable to surface treatments. Thus, high and low design temperatures under the SPG are taken directly at the pavement surface.

Determinations of in-place asphalt emulsion performance are dependent upon the identification of key performance variables and the measurable physical and chemical properties of the asphalt binder or emulsion residue, which relate to those variables. An extensive literature review conducted by the Strategic Highway Research Program (SHRP) has identified five key variables for assessing pavement performance. These are:

1.) Low temperature cracking (low temperature susceptibility);
2.) Fatigue cracking (repetitive loading/unloading);
3.) Raveling (stone loss);
4.) Rutting (permanent deformation, high temperature susceptibility); and
5.) Aging.(58)

Table 3 presents a matrix adapted from the SHRP review, depicting the reported relationships between various asphalt physical and chemical properties and each of the performance-based variables enumerated above. The arrows in Table 3 indicate whether the performance criteria increases or decreases in magnitude as the corresponding physical or chemical property increases or decreases. For example, when viscosity increases, so do measured fatigue and low temperature cracking.

Table 3. Asphalt Properties and Pavement Performance.(58)

Performance Criteria	Viscosity	Penetration	Ductility	Temperature Susceptibility	Binder or Mix Stiffness	Softening Point	Asphaltene Content	Naphthalene Aromatics
Low Temperature Cracking	↑	↓	↓	↑	↑			↑
Fatigue Cracking	↑	↓	↓					
Raveling	↓		↓				↑	↓
Rutting				↓			↓	
Aging	↑	↓	↓	↓		↑	↑	↓

However, in developing the SPG, Epps generally discounts the importance of rutting and thermal cracking in surface treatments, focusing instead on the more typical emulsion requirements of:

1.) High and low temperature behavior, which can lead to aggregate loss;
2.) Aging performance; and
3.) Application and handling characteristics of the prepared emulsion.(57)

Conversely, rutting resistance can prove a valuable test parameter when assessing the performance of rut-filling mixes such as micro surfacing.(54) Takamura observed that the action of radial truck tires actually produces higher than average critical shear stresses on thin surface treatments such as chip seals and micro surfacing, as compared to full or partial thickness HMA (Figure 19). This underscores the importance and value of estimating the high temperature susceptibility and stone retention capacity of modified surface treatments.

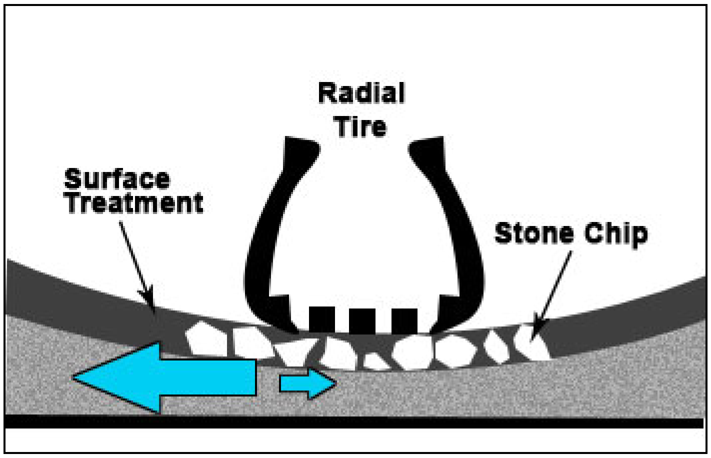


Figure 19. Schematic. Influence of Radial Tire on Surface Treatment.(54)

It is noteworthy that the relationships between laboratory-determined binder physical properties and actual field performance are not always clear, and substantial evidence exists, which is often contradictory. For example, it has been shown through stress-controlled fatigue tests that *stiffer* mixes are more resistant to fatigue cracking, whereas strain-controlled tests indicate that *softer* mixes are more fatigue resistant.(16) Moreover, because polymer modified asphalt binders are used as thinly-applied surface treatments, the physical parameters used to characterize the performance of HMA mixes (such as the PG specification) may not always be applicable.

The search for physical parameters and related laboratory tests, which can be used to accurately characterize the performance of PME is on-going. The following section discusses some of the information obtained from the literature review, which pertains to the use and adaptation of various innovative and routine testing protocols that have been, or may be used, for the analysis of PME residue performance. Section 2.4.2 below gives some protocols developed to use Superpave type methods that more accurately characterize the desired properties of polymer modified asphalt emulsion applications.

2.4.2 Testing Protocols and Considerations

For successful PME applications, the emulsion must exhibit acceptable performance during storage, shipping, and construction. It must remain stable, it must lend itself to effective construction, and it must break (phase separate) at the appropriate time. The cured emulsion residue must also exhibit the expected performance for its end use on the pavement. It is necessary, therefore to test both the emulsion and the residue as it would be on the finished pavement. Analysis of the cured residue properties may be accomplished by directly collecting a sample of the non-emulsified binder or by extracting the properly cured residue from a prepared emulsion sample. Typical residue extraction techniques include:

- Stirred Can Method – This method involves constantly stirring a sample of the emulsion for 170 minutes at a temperature of 163 ºC to evaporate and drive off the water. A blanket of nitrogen gas is used to dampen the effects of oxidation. Although this method yields abundant quantities of testable residue in fairly short-order, it has been criticized as not accurately representing actual field conditions due to the high continuous temperatures, which are used.(59)

- RTFO Method – This methodology described by Takamura (2000) is a variation on the RTFO test used to simulate aging in the hot mix plant. Samples of the emulsion are rolled in bottles in a temperature-controlled environment at 85 ºC for 75 minutes with a stream of heated nitrogen gas jetted over the emulsion film to facilitate water evaporation.(60) This method has also received criticism because it can lead to incomplete water evaporation in certain asphalt emulsions such as CRS-2P, producing inconsistent follow-up test results.(59) However, some suggest that this method may be useful for quality control purposes at emulsion production sites since it permits for the rapid extraction of testable quantities of residue.(60)

- Forced Air-Drying Method – This extraction technique uses forced air flow at ambient (22 ºC) temperatures to facilitate water evaporation. Although this method is generally regarded as the most representative of actual field conditions, it is a lengthy process to complete (300 to 360 minutes) and approximately one day is required to prepare the sample for extraction.(59)

- Vacuum Distillation Method – The sample is placed into a vacuum distillation unit at a temperature of 115 ºC. Takamura (2000) has noted that microscopic examinations of samples extracted through distillation exhibit undesirable changes in polymer network morphology including cross-linking and polymer decomposition owing to the application of excessive heat.(60) These changes can lead to viscosity inconsistencies and the degradation of other performance-based measures. Thus, it is suggested that vacuum distillation may only be appropriate for determining the presence of polymer, not for ascertaining the placed network structure.

- Forced Draft Oven – This technique is described in more detail in Chapter 3. It has the advantage of obtaining cured emulsion residue at a temperature closer to field temperature, but it also takes longer than traditional residue recovery methods. This method has been adopted as ASTM D7497-09, "Standard Practice for Recovering Residue from Emulsified Asphalt Using Low Temperature Evaporative Technique."

- Moisture Analyzer – A technique used to determine asphalt content, but currently yielding very little residue.

Key factors, which should be considered when selecting a residue extraction methodology include:

- Reproducibility – Residue samples repeatedly extracted from the same emulsion mix should yield statistically similar results when subjected to testing techniques such as DSR, softening point, penetration, etc. Extraction techniques that tend to yield widely divergent physical property test results are not suitable for insuring accurate characterization of modified emulsion performance.

- Time – Various extraction methods have different processing time requirements, which must be considered from a logistical standpoint. For example, lengthy extraction techniques may not be appropriate for use at the emulsion production site if accurate test results cannot be obtained in a timely manner prior to field placement.

- Cost – Differences in sample preparation time, extraction time, and equipment requirements can translate into varying costs between methods.

- Accuracy and Representativeness – A balance must be achieved between time/cost considerations, and the testing accuracy that can be realized with an associated extraction methodology. Similar consideration should also be given to how representative an extraction technique is relative to actual field evaporation and curing conditions and whether a particular method might fundamentally alter the character of the residue in a way that distorts physical property test results.

As discussed previously, extracted residues or samples of non-emulsified binder material may be subjected to a wide variety of testing modalities to estimate field performance. Typical forms of performance-based testing include (but are not necessarily limited to):

- DSR – to predict rutting resistance and high temperature susceptibility. Useful for polymer modified asphalt emulsions employed in rut-filling applications.
- RTFO – to simulate the effects of aging/oxidation.
- Pressure Aging Vessel (PAV) – to simulate the effects of long term field aging.
- Ductility – to estimate the potential for fatigue and thermal cracking and/or raveling.
- RV – used to gauge cracking susceptibility, and raveling potential through viscosity measurements.
- BBR – low temperature susceptibility and thermal cracking potential.
- Vialit – measures stone retention characteristics.
- Penetration – to estimate cracking potential and mixture consistency.
- Wheel-Track Test – used to simulate wheel traffic loading and unloading to ascertain rutting-resistance.
- Loaded Wheel Test – used for slurry seals and micro surfacings to compact the sample as a means of assessing the mixture's susceptibility to flushing.
- Wet Track Abrasion Loss – used to measure the wearing characteristics of slurry seals and micro surfacings under wet track abrasion conditions.
- Ring and Ball – to determine stiffness failure at high temperature. Usually used as a consistency check on polymer modified asphalts.
- Schulze-Breuer-Ruck – used to evaluate the compatibility between bitumen, aggregate, filler, and polymer modifier in micro surfacing.
- Zero Shear Viscosity – proposed as an alternative to $G^*/\sin\delta$ as a measure of rut-resistance. Also used in highly modified mixtures to estimate the degree of polymer network formation.
- Infrared Spectroscopy and Nuclear Magnetic Resonance (NMR) – used to verify the presence and relative abundance of polymer modifiers.(4)
- High Performance Gel Permeation Chromatography (HPGPC) – used to characterize the molecular weight and physical size of polymer modifiers.(4)

Emulsion recovery tests are run to determine asphalt content and the properties of the cured material on the pavement. The former can be evaluated using one of the extraction procedures described previously to determine residual asphalt content. The Long-Term Asphalt Storage

Stability Test (LASST) was proposed to estimate thermal degradation and phase separation potential.(4)

Typical physical property testing techniques for asphalt binders and emulsion residue have traditionally focused on determinations of viscosity, penetration, ductility, and softening point temperature. However, these tests often fail to accurately and comprehensively characterize the performance characteristics associated with PME.(16)(48) Most researchers now advocate oscillatory DSR testing as the method of choice for characterizing the viscoelastic properties of modified residue and binders.(16) In this procedure, the binder or emulsion residue sample is placed between two plates in a DSR device and subjected to oscillating shear stress and strain for the purpose of determining the complex modulus (G*, a relative measure of stiffness) and the phase angle (δ, the elastic response) of the material. Takamura (2005) has further proposed a variation on the DSR procedure specifically for modified emulsion residues, which consists of the following sequence of three testing intervals:

1.) <u>Strain Sweep</u> – Strain is gradually increased from 0.1 to 5.0 percent in 35 minutes and is used to evaluate rheological properties of the binder at wide strain levels.

2.) <u>High-Constant Strain</u> – constant strain (1 percent, 5 percent, or 10 percent) is applied immediately after the first period of strain sweep for a period of 30 minutes.

3.) <u>Relaxation</u> – After the end of the period of high-constant strain, the sample is permitted to relax for a period of 15 minutes with only a minimal strain of 0.1 percent. This is used to observe the recovery of G*.(48)

The sequence above is typically repeated at least two more times on the same sample to illustrate the progressive loss of G* as shown in the example provided in Figure 13. The results of this test provide an indication of the relative fatigue resistance of various mixtures under the high-strain deformation forces, which might be created by radial truck tires and/or snowplow blades.(48)

In contrast, Airey (2004) reports that the phase angle (delta, δ) is usually considered to be much more sensitive to the structure of the binder than is G*, and as such, provides a better indication of the type and extent of polymer modification.(16) Within this context, smaller δ values are indicative of a greater elastic (less viscous) response, and thus, suggest a higher degree of polymer network formation, particularly at higher temperatures.

King et al. (1998) noted that at comparatively high polymer levels, viscosity can increase substantially leading to an over-prediction of rutting resistance, while DSR high temperature parameters and wheel-tracking test results are generally found to be more representative and in good agreement with one another. Moreover, ductility testing on binders modified with elastomeric polymers can exhibit significant variability at low to intermediate temperatures (4 – 25 ºC). In this regard, Neoprene and SBR modifiers generally produce comparatively high ductility, while SB and SBS additives yield much lower ductility values. King characterized the low ductility of the latter as a function of “too much” rather than “too little” strength, as the elongated strands of SB/SBS modified asphalts in the ductility test are comparatively thick and snap back much in the way a thick rubber band does when pulled too far.(4) This suggests that with some SB and SBS modified mixes, ductility testing could under-predict performance-based measures of strength.

Desmazes et al. (2000) have developed a testing protocol for measuring the zero shear viscosity (ZSV), which the authors assert provides for a more accurate estimate of rut-resistance in binders modified with certain elastomeric polymers (e.g., SBS). Conceptually, ZSV represents the viscosity of a fluid, which is at rest. In elastic mixes at very low shear rates, the structures of the fluid deform slowly enough to reach equilibrium. Measurements are collected at lower and lower shear rates, and the results are extrapolated to yield the zero shear viscosity. Demazes observes that rutting is a demonstrably slow process, and, as such, the "resting" viscosity of a modified binder more closely approximates its capacity to resist permanent deformation.(61) In contrast, studies have shown that conventional DSR testing tends to underestimate high temperature performance in modified binders characterized by high delayed elasticity.

The SPG developed by Epps (2001) uses the following modified testing program:

- Residue Recovery – the researchers use the stirred can method.

- Aging – pavements located at the surface are most susceptible to aging. RTFOs developed for simulating aging in a hot mix plant were discarded due to the comparatively low application temperatures associated with emulsion surface treatment applications. A PAV test was used instead for long-term aging only.

- RV – viscosity was determined for unaged binders, as this parameter generally reflects how easily the resulting asphalt emulsion can be pumped and sprayed. Multiple temperatures were used to simulate the wide range of typical surface treatment application temperatures, as opposed to the single temperature (135 ºC) used to determine workability for HMA binders under the standard Superpave PG protocol.

- DSR – DSR testing was performed in accordance with AASHTO TP 5 on the unaged binders to determine G* and δ values to assess early, high temperature performance. The researchers believe aggregate loss is of greater significance for surface treatments than are rutting or shoving at high temperatures.

- PAV-DSR – residues were long-term aged using PAV and then tested using the DSR to assess intermediate temperature range performance. More specifically, this test was intended to evaluate the potential for aggregate loss rather than fatigue cracking.

- BBR – BBR testing was performed on long-term aged residues to evaluate low temperature behavior. For this test, the fastest BBR loading time (8 sec.) was used to simulate critical traffic loading conditions, rather than to gauge thermal cracking.(57)

The final recommended limiting values proposed for the SPG are presented in Table 4.(57)

Table 4. Recommended SPG Limiting Values.(57)

Viscosity	DSR	BBR
ASTM D4402 Max.: 0.15; Min.: 0.1 Pas	G*/sin δ , Min.: 0.750 kPa Test Temp. @ 10 rad/s, °C	Creep Stiffness, TP1 S, Max.: 500 MPa m-value, Min.: 0.240 Test Temp., @ 8 s, °C

2.4.3 Evaluation of Existing Federal Lands Standards

The *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects* (FP-03) calls for cationic and anionic emulsified asphalts to conform to AASHTO M 208 and AASHTO M 140, respectively. Polymer modified emulsions are to conform to AASHTO M 316.(62)

Polymer modified asphalt emulsions used for micro surfacing are further specified to meet the requirements of AASHTO M 208 as well as the following:

Residue by distillation:	62 percent minimum.
Softening point:	57 ºC minimum.
Penetration at 25 ºC:	40-90.

Current Federal Lands Highway (FLH) specifications direct that polymer additives are to be blended either into the asphalt directly or into the emulsifier prior to emulsification.

Table 5 presents the key physical property parameter requirements specified under AASHTO M 208 and M 140 (i.e., ASTM D2397-05 and ASTM D977-05, respectively), as well as M 316 for comparison and discussion purposes.

Table 5. Summary of M 208/140/316 Specifications.

Emulsion Type	Viscosity, Saybolt at 22 ºC†	Viscosity, Saybolt at 50 ºC†	Demul-sibility†	Min. Residue by Distillation†	Penetration at 25 ºC‡	Ductility at 25 ºC‡ (cm)
Anionic Emulsions and Residues (M 140-86)						
RS-1	20 – 100	--	60	55%	100 – 200	40
RS-2	--	75 – 400	60	63%	100 – 200	40
MS-1	20 – 100	--	--	55%	100 – 200	40
MS-2	100	--	--	65%	100 – 200	40
MS-2h	100	--	--	65%	40 – 90	40
HFMS-1	20 – 100	--	--	55%	100 – 200	40
HFMS-2	100	--	--	65%	100 – 200	40
HFMS-2h	100	--	--	65%	40 – 90	40
HFMS-2s	50	--	--	65%	200	40
SS-1	20 – 100	--	--	57%	100 – 200	40
SS-1h	20 – 100	--	--	57%	40 – 90	40
Cationic Emulsions and Residues (M 208-86)						
CRS-1	--	20 – 100	40	60%	100 – 250	40
CRS-2	--	100 – 400	40	65%	100 – 250	40
CMS-2	--	50 – 450	--	65%	100 – 250	40
CMS-2h	--	50 – 450	--	65%	40 – 90	40
CSS-1	20 – 100	--	--	57%	100 – 250	40
CSS-1h	20 – 100	--	--	57%	40 – 90	40

Polymer Modified Cationic Emulsified Asphalt (M 316-99)

	Viscos-ity 50 °C†	Demul-sibility (DSS)†	Min. Residue by Evap-oration‡	Pene-tration 25 °C	Ductil-ity 4 °C‡	Ductil-ity 25 °C‡	Force Ratio‡	Elastic Recov-ery‡	Poly-mer Solids‡	Solu-bility in TCE‡
CRS-2P	100 – 400	40+	65	100 – 175	30+	125+	0.3+	50+	2.5+	97.5+
CRS-2L	100 – 400	40+	65	100 – 175	30+	125+	NA	NA	2.5+	97.5+

† Applies to liquid asphalt emulsion

‡ Applies to asphalt emulsion residue

As has already been covered in some detail, the literature review unequivocally illustrates that polymer modified asphalt binders (i.e., PME and PMA) exhibit significant performance benefits over unmodified equivalents.(4)(5)(12)(14)(20)(21)(24)(25)(31)(33)(48)(49) Demonstrable benefits include increased rutting resistance, improved chip/stone retention, improved elasticity and ductility, increased fracture toughness, improvements in the penetration index, decreased low and high temperature susceptibility, and improved fatigue resistance. Although polymer blending techniques appear to impact mixture performance, all of the methods examined performed better when compared to unmodified binders.

2.4.4 Modified versus Unmodified Asphalts

Khosla and Zahran (1988) compared the performance of unmodified and Styrelf® polymer modified mixtures of three commonly used asphalt cements: AC-5, AC-10, and AC-20. Styrelf® is a proprietary blended modified asphalt product produced by Total™, which uses a cross-linked SB elastomeric polymer additive. Khosla and Zahran evaluated each asphalt preparation under varying load conditions and operating temperatures using the resilient modulus test, and reported that they were able to predict the fatigue, deformation, and brittleness of each of the binders. These test results were then used to simulate the predicted service life using the VESYS III computer model in each of the four major climatic regions as shown below in Table 6.(63)

Table 6. Predicted Service Life (Years).(63)

Region	Temp. Range	AC-5	AC-5 Styrelf®	AC-10	AC-10 Styrelf®	AC-20	AC-20 Styrelf®
1	18 – 30 ºC (0 – 90 ºF)	9.83	15.90	11.96	17.13	15.10	19.01
2	4 – 30 ºC (40 – 90 ºF)	6.24	14.39	8.04	16.55	11.94	18.53
3	4 – 49 ºC (40 – 120 ºF)	5.02	12.81	6.04	14.92	10.40	16.39
4	4 – 60 ºC (40 – 140 ºF)	NA	10.32	NA	12.76	6.63	14.21

As Table 6 suggests, in each case the Styrelf® asphalt mixtures appeared to yield significant improvements in overall predicted service life as compared to their unmodified parent asphalts. The performance impacts of polymer modified binders were further evaluated specifically with respect to predicted rut depth, fatigue cracking, and low temperature cracking for various service year benchmarks. Quantitatively, Khosla and Zahran estimated the approximate resulting magnitude of rut depth and the degree of fatigue cracking (using cracking indices) over time. Additionally, low temperature cracking susceptibility was determined by a stiffness value that was formulated based upon creep tests conducted at temperature benchmarks of -29 ºC (-20 ºF), -18 ºC (0 ºF), -7 ºC (20 ºF), and 4 ºC (40 ºF), respectively. Khosla and Zahran conclude that:

- Styrelf® mixtures have better low temperature susceptibility than their unmodified counterparts and are therefore less brittle.
- Styrelf® asphalts are more resistant to low temperature cracking.
- The Styrelf® samples exhibited a reduced propensity for rutting deformation at higher temperatures than the unmodified asphalts.
- Polymer modification of Styrelf® asphalts results in improved fatigue life.(63)

In Figure 20, Takamura (2002) compares the high temperature performance of modified and unmodified asphalt emulsions in micro surfacing applications, as shown by the temperatures where Superpave rut failure criteria are met. The modified asphalt emulsion residues show significantly better rutting resistance than unmodified mixtures.(54)

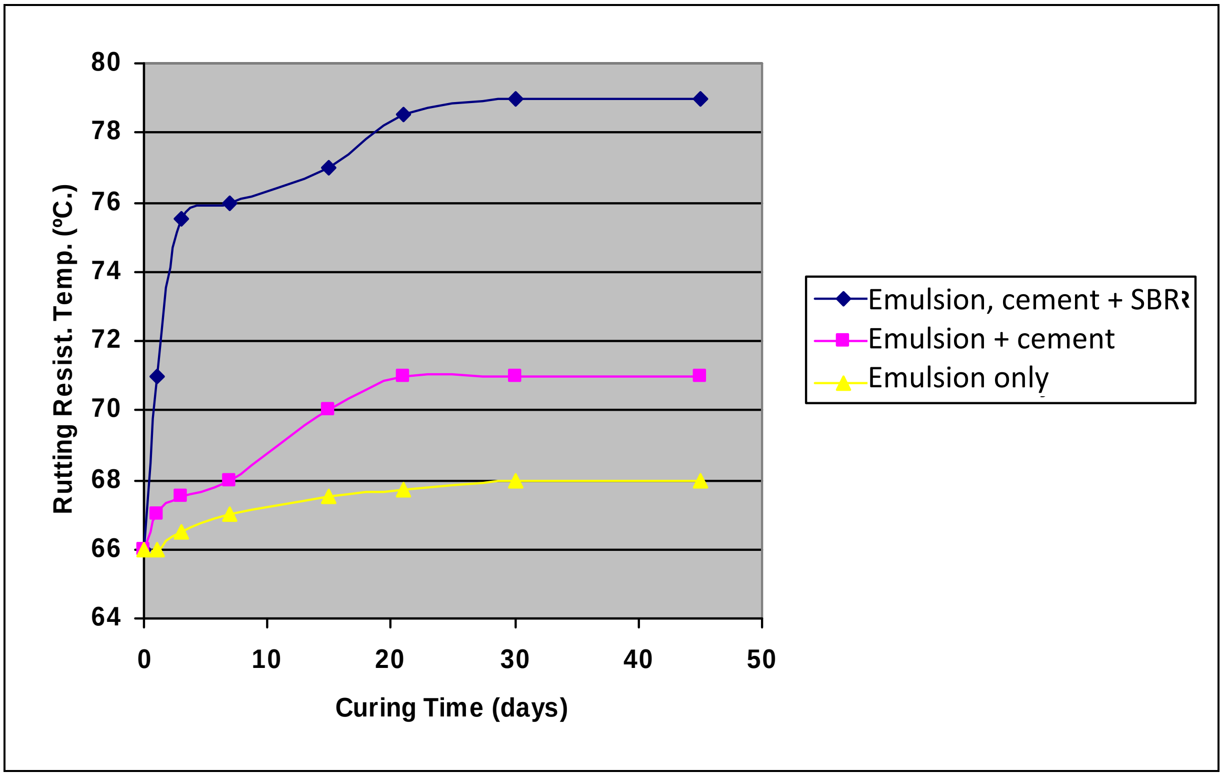


Figure 20. Graph. Micro Surfacing Emulsion Residue Curing Time.(54)

2.4.5 Modified Emulsion versus Modified Hot Mix Binders

Serfass et al. (1992) have compared the performance of SBS modified hot mix and emulsified asphalt in thin surface treatments using laboratory tested rheological properties, cohesion, stone retention, tensile strength, and durability. Results from this study indicate that the studied SBS modified hot mixes exhibit poor adhesion to the study aggregate and require the use of an anti-stripping agent. Moreover, the use of anti-stripping agents in SBS modified hot mixes yields only modest improvements, which decline under more adverse climatic conditions. In this regard, Serfass et al. report that SBS modified hot mixes are not recommended in cooler environs, and that SBS modified asphalt emulsions offer a longer application season, performing well under cool and even damp conditions. The authors also note however, that SBS-modified asphalt emulsions require a much longer set time than do their hot mix counterparts. In addition, Serfass et al. report that higher SBS contents may be used in asphalt emulsions, since modified hot mixes exhibit decreased adhesion and problematically high viscosities when higher SBS concentrations are used.(19)

Gransberg and Zaman (2005) examined the relative performance and cost effectiveness of 342 chip seal projects in the State of Texas to compare the efficacy of hot mix binders to asphalt emulsions. The results of this study indicate that PME performs at least as well as modified hot mix binders, and that the former does so at a lower cost while offering modest improvements in skid resistance and ride quality.(64) The Texas Department of Transportation (TxDOT) generally uses asphalt emulsions in their chip seals on lower volume (< 2,000 ADT) roadways. Moreover, these asphalt emulsions are typically applied to pavements that are generally in poorer condition as compared to hot applied chip seal projects. In such cases, TxDOT differentiates between asphalt emulsion and hot applied chip seal applications based primarily on traffic volumes, because the latter requires a shorter curing time and as such, reduces lane closure times and traffic delays.

2.5 Surface Application Types

2.5.1 General

This section presents those findings of the literature review specific to common surface treatment applications where polymer modified asphalt emulsions may be employed. Among the treatment applications examined are chip seals, slurry seals/micro surfacing, and cape seals. The benefits and limitations of PME are examined with respect to each specific treatment type, and where applicable, compared to the performance of non-modified asphalt emulsions.

2.5.2 Chip Seals

Chip seals (sometimes called seal coats or bituminous surface treatments) consist of an asphalt emulsion, which is spray applied to the pavement surface and then immediately covered with a layer of aggregate (chips) and rolled to seat the aggregate. Chips seals are commonly employed as an inexpensive treatment for minor forms of pavement surface distress such as cracking or raveling and as a cost-effective preventive maintenance (pavement preservation) treatment.

The advantages of using polymer modified asphalt emulsions in chip seal applications over non-modified mixtures include:

- Better early and long-term stone retention;
- Quicker traffic return;
- Reduced rates of flushing and bleeding;
- Increased durability on higher volume roadways (due to improved stone retention); and
- Greater design tolerance for chip and asphalt emulsion quantities and aggregate embedment factor.(14)

Takamura (2003) demonstrates the impact of polymer modifiers on improving stone retention in chip seals.(65) Figure 21 presents a comparison of retained aggregate percentages between modified and unmodified variants of eight mixtures—each containing different aggregates—from an early strength sweep test. As Figure 21 illustrates, improvements in aggregate retention range from modest to dramatic in the polymer modified (BASF's Butonal™ NX1118) chip seal mixes in all eight test cases, with percentages near or above 90 percent.

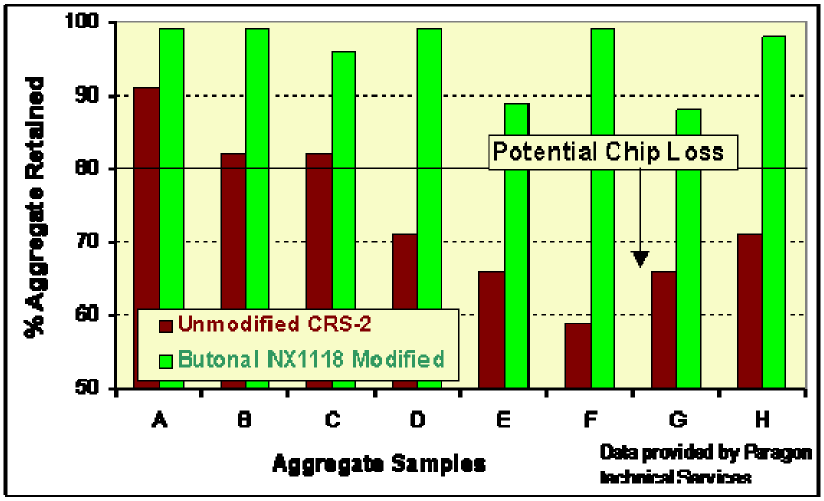


Figure 21. Chart. Chip Seal Aggregate Retention with SBR Latex Polymer.(65)

Windshield damage caused by the displacement of stone is perhaps the most widely reported early difficulty with chip seals. For this reason, many agencies restrict the use of chip seals to relatively low volume (< 2,000 ADT) roadway pavements. Therefore, because polymers offer demonstrably improved rates of aggregate retention, it is suggested that modified chip seals could provide acceptable performance on higher volume roads. Several field studies have shown excellent performance of chip seals on very high volume roads.(4)(66)

Moreover, Lubbers and Watson have also shown that Vialit chip retention test results are markedly better in modified chip seals at low temperatures than are comparable unmodified mixtures, indicating polymers may similarly prove valuable in cold weather climates (Figure 22).(5)

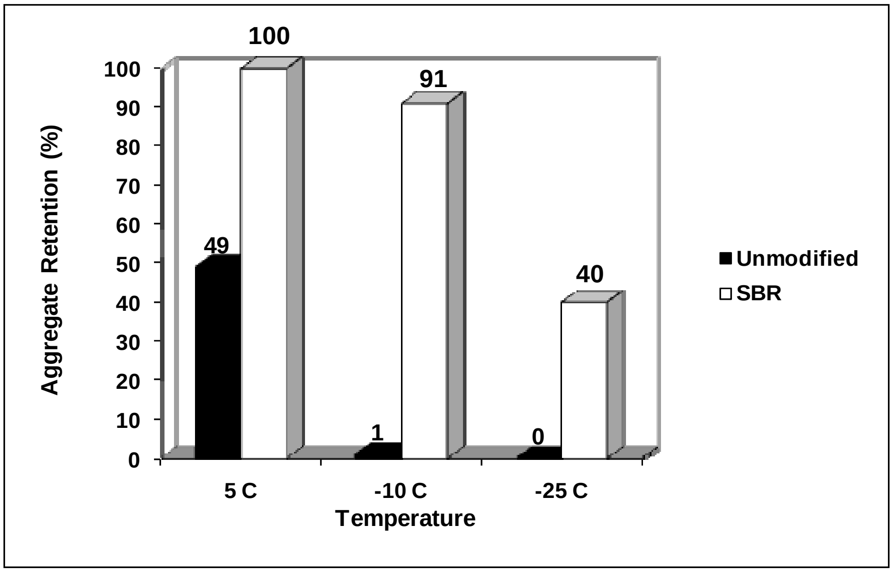


Figure 22. Chart. Vialit Chip Retention at Low Temperatures Chip Seals.(5)

Wegman (1991) notes that the improved early chip retention offered by polymer additives when used in chip seals allows for greater variation in aggregate and emulsion application rates. It also permits earlier sweeping of the applied surface, which serves to mitigate windshield damage.(67)

A survey of chip seal best practices by Gransberg and James (2005) indicates that early brooming of chip seals immediately after rolling to remove loose stone may be ill-advised since curing at this stage is generally insufficient to permit proper binder to aggregate bonding.(68) More specifically, although polymer modifiers can significantly enhance stone retention, research has shown that adequate cure times are needed to realize this benefit (Figures 7 and 21).(14)(65) Gransberg observes that chip seals can be successfully applied to high volume roads, providing allowances are made for adequate curing time, and that the underlying pavement condition of the roadways selected for treatment are fundamentally sound. Moreover, detailed assessment of chip seal performance nationwide indicates that the best performing chip seals are those where design specifications are meticulously prescribed, implemented, and verified by the highway agency.(68)

2.5.3 Slurry Seals and Micro Surfacing

Slurry seals consist of a homogeneous mix of crushed aggregate and an asphalt emulsion, which is applied to the pavement surface as a single-pass monolayer. Some slurry seals contain polymers; others do not. Curing of the slurry seal coat occurs as the water evaporates, leaving only the residual asphalt to coat the aggregate surfaces. In general, slurry seals contain a high proportion of fines, which generally improves skid-resistance and water-resistance. Slurry seals are generally applied to only lower-volume (< 1,000 ADT) roads.

Micro surfacing is a commonly used form of slurry sealing consisting of a combination of mineral aggregate and fillers, a polymer modified asphalt emulsion, and other additives. The primary difference between micro surfacing and other forms of slurry sealing is the chemical formulation, which generally yields an instantaneous, chemical break. Generally, the specifications and design procedures for micro surfacing are more stringent than those for slurry seals. By definition, micro surfacing contains polymers, while slurry seals may or may not contain polymers. Slurry seals are generally laid at thicknesses of 1 to 1.5 cm, whereas micro surfacing can be thickly applied in multiple layers. Slower breaking slurry seals cure on the surface "skinning over" and preventing thorough breaking and curing when they are applied at greater thicknesses. The PME used in micro surfacing breaks chemically instead of through evaporation, which occurs in slurry seals and some other asphalt emulsion applications. This permits the micro surfacing to gain cohesive strength rapidly, thereby minimizing lane closures and traffic delays.(69) Micro surfacing is commonly used to correct wheel-path rutting and improve skid-resistance, can be applied to either high or low volume roadway pavements, and may be used over both asphalt and Portland cement concrete pavements.(40)(70) Takamura (2002) reports that polymer enhanced micro surfacings can be used to fill ruts up to 5 cm in depth using a rut-box.(54) When applied in rut-filling applications, it is desirable to assess the rut-resistance potential of the PME (at a minimum) through the performance of DSR testing on the extracted asphalt residue.(48)(49)(54)

Takamura (2000) also provides comparisons of varying latex polymer concentrations. As stated earlier, achieving a fine, networked structure of polymer within the asphalt provides a stronger and more elastic binder and is dependent upon the type and concentration of polymer, the asphalt source, and the compatibility between polymer and asphalt. Figure 23 illustrates the change in rutting resistance temperature versus percent polymer over a prolonged laboratory curing period at an elevated temperature. The rutting resistance temperature for the 5 percent micro surfacing mixture is improved over the 3 percent mix with prolonged curing, but exhibits little initial difference. As with all asphalt surfaces, the strength (rutting resistance) of micro surfacing continues to increase with time. The 5 percent polymer asphalt binder provides the strength equivalent of PG-76 rutting resistance within a few days of curing.(54)

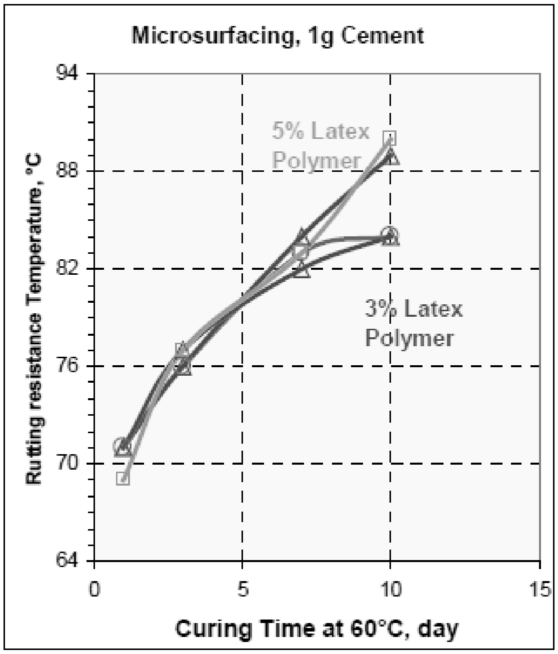


Figure 23. Graph. Curing Time and Rut-Resistance.(54)

Micro surfacing curing times are highly dependent upon a number of factors, including the pH of the asphalt emulsion, the type and amount of surfactant, the type of bitumen and aggregate, and the application temperature.(71) Most manufacturers advise that micro surfacing has developed sufficient strength and is ready for full traffic return within an hour of construction.

Takamura used the same method to test latex polymer chip seal binders, as shown in Figure 24. Although rutting is not usually associated with CRS-2P chip seal emulsions, this is a measure of the strength of the binder, and its ability to resist flushing. As would be expected, the 3 percent polymer binder is consistently stronger than the 2 percent.

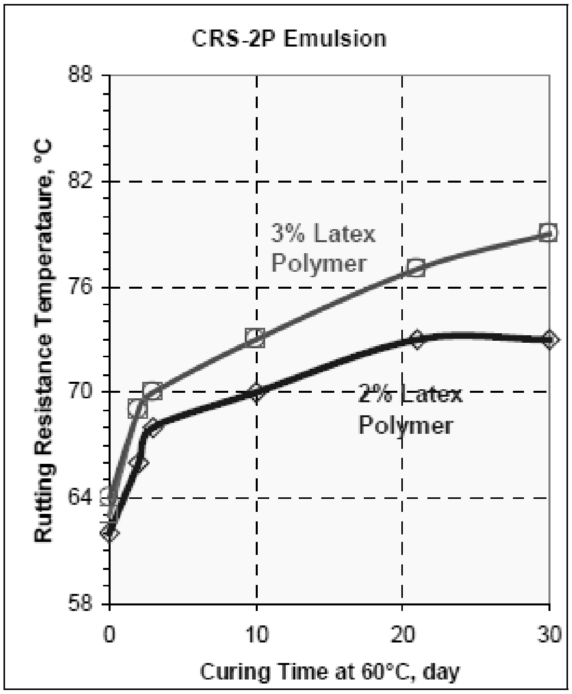


Figure 24. Graph. Prolonged Laboratory Curing of Latex CRS-2P at Elevated Temperature.(54)

Setting agents such as Portland cement or lime can be added to micro surfacing mixes to control curing time by reducing the rate at which water evaporates and the asphalt emulsion breaks. When used with polymer modifiers, these setting agents aid in promoting the formation of the continuous polymer networks associated with quantifiable improvements in the viscoelastic characteristics of thin surface treatments discussed previously. Work by Takamura (2001) proposes substituting aqueous-phase alkali metal hydroxides or salts in place of Portland cement to facilitate independent control of curing and mixing times based upon aggregate and bitumen type.(71) In addition, mixing accuracy is improved and handling made much easier owing to the difficulty in metering powdered Portland cement on the paving machine.

Holleran (1996) recommends using SBR or EVA in micro surfacings at a concentration of 1-5 percent depending upon the application; noting that 3-5 percent polymer concentrations will offer the most significant improvements.(70) Figure 25 presents wet track abrasion losses for 3 percent SBR, SBS, Neoprene, and NRL modified surfacing treatments in comparison to an unmodified asphalt emulsion. A mixture modified with 3 percent SBR can reduce abrasion losses by up to 67 percent over unmodified asphalt after a 6 day soaking period. Similarly, Neoprene and SBS modifiers improve abrasion losses by 40-50 percent. These results indicate that PMEs offer significantly increased adhesion (translating into better stone retention) and water resistance than unmodified asphalt emulsions in slurry seal applications.

With respect to flushing, Holleran has shown that loaded wheel test results produce significant improvements in vertical displacement for 3 percent PME over neat asphalt, particularly for SBR and EVA modified mixtures (Figure 26).(70)

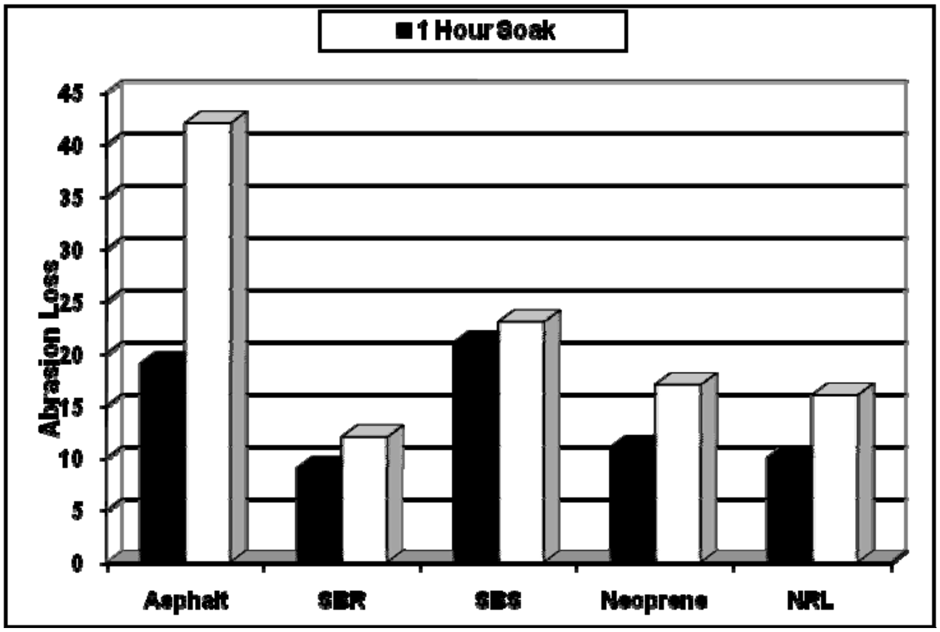


Figure 25. Chart. Wet Track Abrasion Losses.(70)

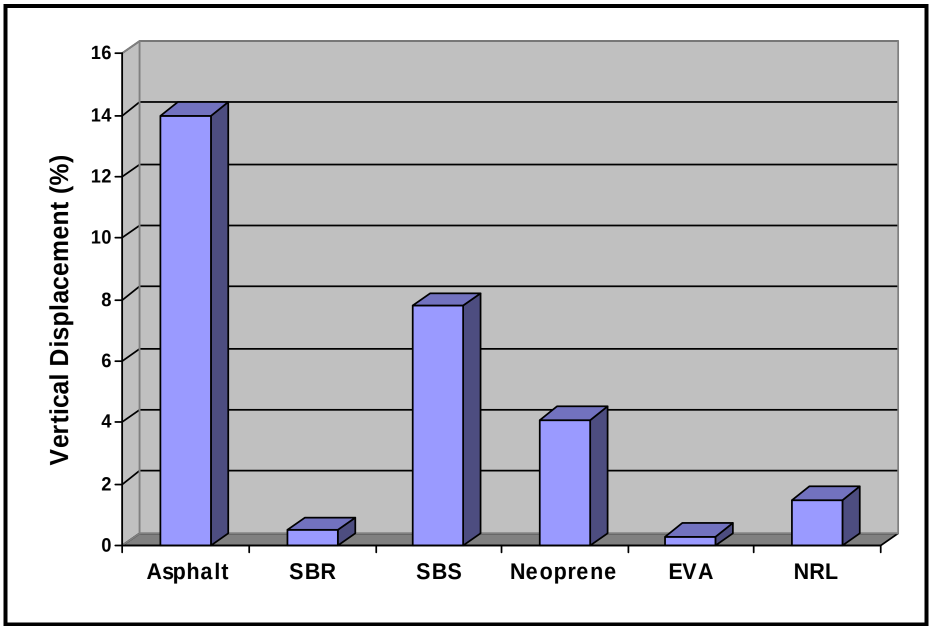


Figure 26. Chart. Loaded Wheel Test Results.(70)

Jones and Ng (1989) have demonstrated similar results, with SBR, NRL, and SBS modifiers offering the greatest improvement in vertical displacement for micro surfacing emulsions as shown in Figure 27. Jones further subjected these same mixtures to the Schulze-Breuer-Ruck abrasion test, which provides estimates of water absorption (soaking), loss (rotary tumbling), adhesion (water boiling), and integrity (largest remaining fragment after tumbling). Measurement parameters from Schulze-Breuer-Ruck are used to derive an overall numerical grade or rating for each test sample, with higher values representing greater compatibility (and thus better adhesion) between the aggregate, binder, filler, and polymer components. Schulze-

Breuer-Ruck results from the Jones study are provided in Table 7. As Table 7 illustrates, SBR and SBS modifiers provide for the most significant improvements in abrasion loss. Moreover, SBR demonstrates the highest degree of integrity and the highest overall grade for the micro surfacing mixtures tested.(40)

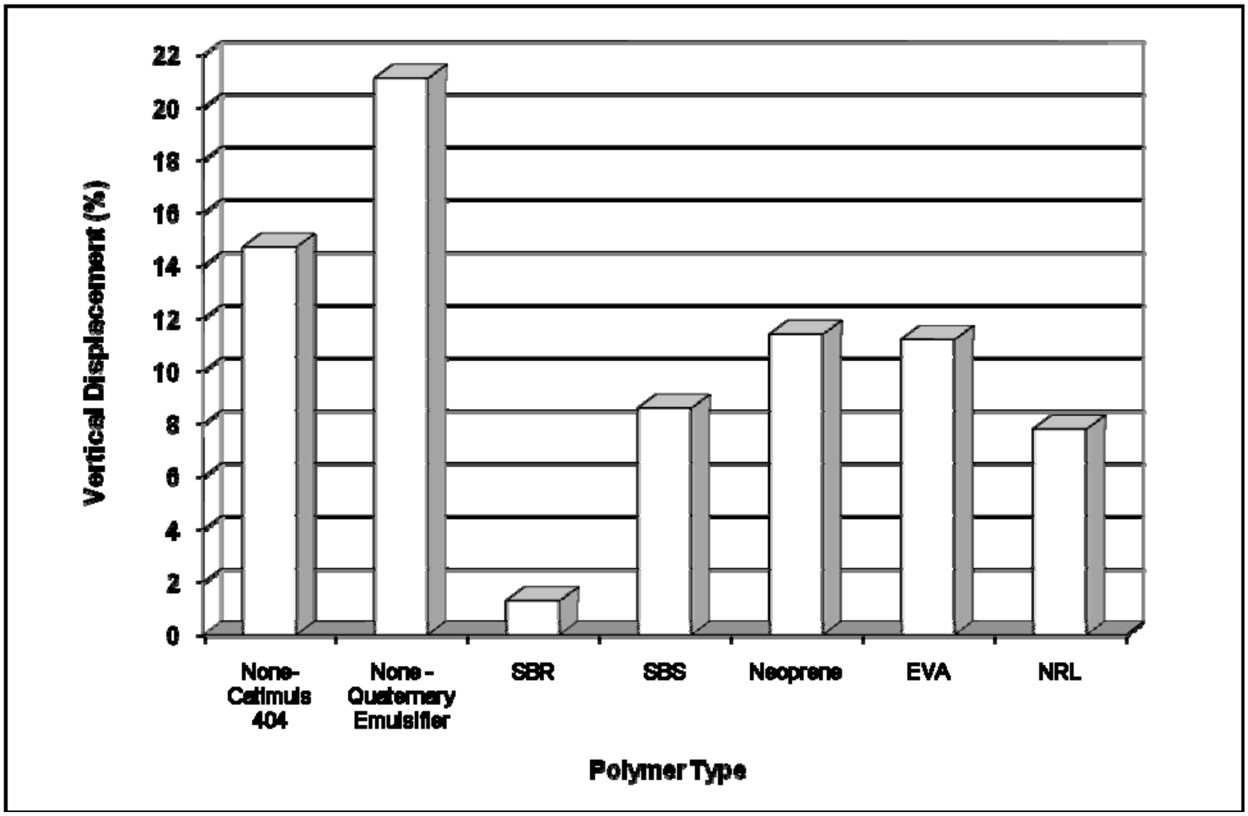


Figure 27. Chart. Loaded Wheel Test Results.(40)

Table 7. Schulze-Breuer-Ruck Test Results.(40)

Polymer	Absorption (g)	Loss (g)	Adhesion (g)	Integrity (percent)	Rating
SBR	1.25	0.96	99	98	11
NRL	2.30	1.49	99	95	9
SBS (Fina 416)	2.18	0.82	99	40	8
EVA (150W)	1.64	1.13	99	67	8
Neoprene (671 A)	2.06	1.51	99	96	9
None Catimuls 404	1.35	1.97	99	62	7
None EM26	1.59	2.01	99	33	5

Jones concludes that among the modifiers tested, SBR offers the best laboratory and long-term field performance in micro surfacing applications. While the Schulze-Breuer-Ruck test appears to be a promising method of assessing the performance of polymer modifiers, it is noted that resulting measures of adhesion and absorption provide little or no correlation or distinction between modified and unmodified mixes (Table 7). Jones also notes that latex modifiers were generally found to outperform solid polymers in micro surfacings.(40) This likely relates both to the necessitated differences in mixing methodology (preblending for solids) and the manner and relative efficiency with which latex may be dispersed relative to bituminous fractions.(5)(7)(12)(47)(54) In addition, it has been shown that preblending of solid polymers may necessitate the addition of higher polymer concentrations than in soap batching or co-milling in order to achieve the formation of a continuous polymer network.

2.5.4 Cape Seals

Cape seals represent a combination of a large aggregate chip seal topped by a slurry seal coat (or micro surfacing), which is applied approximately 4 to 10 days later. Cape seals provide a dense, water-resistant surface, which exhibits superior ride quality and skid resistance.

Solaimanian and Kennedy (1998) evaluated the field performance and design characteristics of 20 cape seal projects in the State of Texas over a period of one year. During this study, bleeding, shoving, and flushing were identified as the most significant forms of distress in cape seals. Insufficient binder stiffness and failure at the interface between the chip seal and underlying pavement surface were generally found to be the primary causes of permanent deformation. Moreover, the infiltration and entrapment of water were indicated to be substantially involved in early cape seal failure.(72)

It has been demonstrated that resistance to deformation can be increased significantly through the addition of polymer modifiers to surface applied asphalt emulsion treatments.(12)(14)(47)(48)(54) This indicates that the use of polymers in the surface seal or micro surfacing overlays of cape seals can increase pavement life and high temperature performance. PME slurry seal overlays are also useful to increase chip seal stone retention and to provide a more water-resistant, smoother riding surface. Polymer modifiers in general have been shown to improve water resistance.(69)(70) However, Solaimanian notes that micro surfacing cannot be used to correct an underlying water problem present in an incorrectly constructed chip seal or deficient base pavement. Indeed, in such cases the use of polymers in surface treatments can actually exacerbate underlying deficiencies, entrapping water, which can lead to stripping and freeze-thaw related damage.(72)

2.6 Polymers and Traffic Volumes

The *Context Sensitive Roadway Surfacing Selection Guide* (2005) specifies roadway volume classifications based upon ADT used in practice by CFLHD.(73) Table 8 presents this classification system for reference.

Table 8. Federal Lands Traffic Volume Classification.(73)

Design Volume (vehicles/day)	Suggested Descriptive Term	Design Speed (mph) Preferred	Design Speed (mph) Minimum
< 200	Very Low	40	30
200 – 400	Low	50	40
400 – 1,000	Medium	50	40
1,000 – 4,000	High	55	45
4,000 – 8,000	High	60	50
> 8,000	High	60	50

A survey of chip seal best practices performed by Gransberg and James (2005) reveals that many U.S. highway agencies restrict their use of chip seals to roadways with maximum traffic volumes of < 2,000 ADT.(68) The primary reason cited for confining chip seal applications to lower volume roads is the loss of stone, which can result in inordinately high levels of windshield damage. It has been well-established, however, that when properly formulated, applied, and cured, polymer modifiers can substantially increase stone retention and allow for earlier brooming without excessive losses.(4)(5)(12)(13)(14)(23)(30)(51)(65)(68) This suggests that polymer modifiers are an essential (though not the only) component in the successful application of chip seals to high volume roads. Table 9 presents a summary of the maximum ADT volumes used for chip seal construction projects, which were reported by U.S. and select international highway agencies surveyed during the Gransberg study.

Table 9. Chip Seal Maximum Traffic Volumes.(68)

Maximum ADT	U.S.	Canada	Australia	New Zealand	South Africa	U.K.
< 500	2	1	0	0	0	0
< 1,000	1	1	0	0	0	0
< 2,000	12	2	0	0	0	0
< 5,000	11	2	0	0	0	0
< 20,000	12	3	3	1	0	0
> 20,000	7	0	1	1	1	1
Agencies Reporting	45	9	4	2	1	1

Of the U.S. state agencies surveyed, approximately 64 percent specify the use of polymer-modified asphalt emulsions in all chip seal applications. Moreover, Gransberg indicates that of the states self-reporting “excellent” levels of chip seal performance (32 percent for in-house, 17 percent for contractors), all were found to use polymer modifiers (including CRM), and all generally prescribe chip seals for only those roads attaining a pavement condition rating (PCR) of “fair” or better.(68) Chip seals are indicated to work best when they are applied as part of the regular pavement maintenance cycle, and they are not a suitable replacement for roads requiring rehabilitation even when polymer modifiers are used.

Micro surfacing applications by definition always include the use of polymer modifiers and are widely regarded as appropriate for use on medium to high volume traffic (> 1,000 ADT) roadway pavements.(40)(70) Because micro surfacing treatments are augmented with setting additives such as Portland cement, breaking can be controlled even at significant layer depths of up to 5 cm. This chemically-controlled curing mechanism allows micro surfacing to be used for comparatively "deep" treatment applications such as rut-filling, and permits expedited opening of the roadway to vehicular traffic.(54)(71)

The South African National Roads Agency (SANRA) states that traffic volumes are important to ensuring proper stone embedment and to keeping the binder "alive and flexible," particularly in chip seal applications. It is noted that since polymers impart increased rigidity to the binder, the demands for an appropriate level of traffic loading are even higher in PME based surface treatments and base pavements. However, SANRA also observes that polymer modified binders offer superior stone retention in the early stages of seal placement, thereby having the additional benefit of reducing asphalt bleeding. This latter benefit of PME is especially relevant on steep grades and at intersections where bleeding problems are most frequently encountered.(74)

2.7 Non-Roadway Applications

One of FLH's objectives is to determine the applicability of PMEs for non-roadway applications such as parking areas, hiking trails, and bike paths. Although the authors could find no directly pertinent literature, the evidence of effectiveness of PME in addressing the same distresses encountered on both roadway and non-roadway pavements leads to the conclusion that judicious selection of PME applications can provide the same enhanced performance.

For example, prevalent forms of pavement distress, deformation, and weathering observed in FLH parking areas include:

- Block cracking;
- Rutting (caused by high pavement temperatures in combination with tight, relatively stationary wheel turns); and
- Oxidation.

Cracking and oxidation are also found on hiking trails and bike paths, with the former representing the most common and problematic form of distress.

FLH reports that slurry seals in particular, are the favored preventive maintenance treatment applied to parking lot pavements, owing to their ability to waterproof the underlying base pavement while reducing closed-to-traffic times, reducing energy consumption, and minimizing environmental impacts. Slurry seals are also easier to construct on odd-shaped parking areas, and they have less loose aggregate.

As the research presented elsewhere in this report clearly illustrates, the use of PMEs in thin surface treatments does appear to enhance stone retention, improve low temperature susceptibility, and reduce the effects of high temperature deformation (rutting). Moreover, PME-based slurry has been anecdotally found to cure at a somewhat faster rate than its non-modified counterparts (thereby reducing closed-to-traffic times). Thus, it is reasonable to conclude that the use of PMEs could be expected to provide similar benefits in non-roadway applications, although it is not possible at this time to assess the resulting cost-benefit implications.

2.8 Climate, Environmental, and Timing Considerations

Serfass et al. (1992) examined the impact of climate on stone retention in surface treatments using SBS modified hot applied and emulsified asphalt. In modified hot applied chip seals, the researchers noted that an adequate period of warm weather is required to facilitate the evaporation of volatiles to allow aggregate to "firm" into its final position. The researchers recommend an application period extending from late May to late August in northern or mountainous climates, and mid-May to mid-September in southern regions for modified hot applied asphalt binders.(19) Conversely, SBS-modified emulsions were found to exhibit good stone retention characteristics even at relatively cool temperatures and high humidity as determined through Vialit cohesive testing. Thus, the cohesive properties of SBS modified emulsions appear to offer a longer application season when used for surface treatments, although Serfass does not provide a specific application calendar.

For chip seals, minimum ambient air and pavement application temperatures of at least 10 ºC and 21 ºC, respectively, are generally accepted standards to prevent excessive and prolonged stone loss.(75)(68) Indeed, early stone loss as a result of late season application under cool temperatures is perhaps the most common reason for chip seal failure. Not only does the emulsion need to break, but the asphalt also needs to cure. For complete curing, the temperature needs to be high enough for a long enough period to allow the asphalt particles to fully flow together and coat the aggregate in a continuous, cohesive, and adhesive binder. In general, low application ambient and/or pavement temperatures can result in high binder viscosity, which hampers bitumen-to-aggregate adhesion.(68) At very high ambient air and pavement temperatures, problems have been reported with emulsions curing on the surface ("skinning over"), leaving emulsion trapped beneath the skin. The trapped water based emulsion does not bind to the surface or aggregate and causes problems when it bleeds through and releases chips under early traffic. Also, cured, low viscosity or solvent extended asphalt residues can bleed on very hot days. There is little consensus concerning maximum pavement temperatures for chip seal application projects, but most recommendations vary between approximately 54 ºC and 60 ºC. Typically, a maximum ambient air temperature of approximately 43 ºC is recommended for most chip seals.(68)

In hot climates, the primary issues that impact bituminous pavements and surface treatments are deformation caused by high temperature susceptibility and binder oxidative aging. Vonk and Hartemink (2004) have shown that when comparing the accuracy of ring-and-ball softening point and zero shear viscosity (ZSV) test results, the latter produces a much more reliable measure of high temperature deformation potential in modified binders than does the former, as illustrated in Table 10.(76)

Table 10. Physical Properties and Deformation Results.(76)

Binder	Ring & Ball Temp. ºC	ZSV Pa-s 40 ºC	ZSV Pa-s 50 ºC	Deformation Rate in Test Road, 40 ºC	Deformation Rate in Test Road, 50 ºC
100 pen	45.5	2.5×10^3	6.3×10^2	24.0	56.2
100 pen + 3% SBS	49.5	3.2×10^5	1.0×10^4	4.0	12.6
60 pen	51.0	7.9×10^3	2.0×10^3	10.1	23.6

The results in Table 10 show:

- The ring and ball test results do not correlate with the test road deformation for the polymer modified binder.
- The ZSV results do correlate with the test road deformation.
- The reduced high temperature susceptibility imparted by the polymer modifier translates into reduced rutting.

In high temperature applications, Vonk recommends SBS concentrations of at least 5 percent to ensure that the polymer phase forms a resilient and continuous network throughout the mixture.(76) As has been suggested previously, it is this network that ultimately imparts the elastic response desired to resist permanent deformation.(4)(12)(14) Vonk's work focuses primarily on the modification of asphalt binders for HMA, and as such, the implications for desirable polymer concentrations in soap pre-batched or co-milled emulsions are uncertain. However, this research undoubtedly has valid implications in emulsion applications where the bitumen is subjected to direct forms of modification (i.e., preblending) prior to emulsification. Moreover, the interplay between polymer concentration, ZSV, and the measurement of high temperature deformation potential have significance in emulsion treatments such as micro surfacing, which are commonly used to fill wheel rut paths.

Vonk (2004) and Demazes et al. (2000) note that the measurement of ZSV in binders with a substantial polymer network is inaccurate because one requirement of this test is the development of steady-state viscosity under constant stress—a state which the elastic components of such a mix cannot attain (viscosity appears to grow infinitely). Although Desmazes offers an extended ZSV testing protocol that may yield improved accuracy and reliability, Vonk suggests that this phenomenon could be used to evaluate proper polymer dosing. More specifically, as ZSV begins to trend toward infinity, this provides a solid indication that a pervasive, 3-dimensional polymer network is present within the mixture, thereby ensuring that the optimal modifier content has been achieved.(61)(76)

Vonk notes that accelerated binder aging in hot climates is dominated by the following characteristics:

- The binder becomes harder and less compatible.
- There is polymer-polymer cross-linking, polymer chain-scission, and reactions between bituminous components.(76)

Vonk observes that even in cases where polymer chains are shortened through age-related scission, the smaller polymer segments still contribute to maintaining elastic flexibility, albeit to a lesser degree than in unaged modified binders.(76) Indeed, work by Davies and Laitinen (1995) demonstrates that aged SBS modified binders harden less than unmodified/differently-modified mixtures as measured via the wheel tracking test.(77)

Vonk asserts that SBS modified binders used for chip seal applications also offer demonstrable benefits in hot climates: increased stone retention, and high ZSV, which indicates the presence of a continuous polymer network to retard permanent deformation and aggregate displacement.(76)

In arid climates however, the potential for hydrogenesis can pose a significant challenge to the use of PMEs. Hydrogenesis is defined as "the upward migration of water vapor in the road pavement, which, under certain climatic conditions, condenses under the road surfacing."(78) In such cases, ambient air, which penetrates through the roadway shoulders into the pavement aggregate layer may transfer water to the stone surfaces via condensation to form a thin film. Although the full implications of hydrogenesis are not yet fully understood, anecdotal evidence provided by State highway agency (SHA) practitioners suggests that PMEs used in thin surface treatments may inhibit this trapped water from evaporating, thereby hastening the development of stripping, surface distress, and/or structural failure.

2.9 Impact of Materials Selection

2.9.1 Polymer Type

A review of the available research indicates no clear empirical evidence that one type of polymer modifier is inherently superior to another with respect to performance, at least between the most commonly used types (SBR and SBS). A recent study of stone retention in chip seals performed by Kucharek et al. (2006) indicates that while latex-based PMEs may require more curing time than preblended PMEs to fully achieve the aggregate retention benefits associated with polymer modification, performance between the two binder types is comparable after only 24 hours. Moreover, Kucharek concludes that "no special benefit has been observed so far from having the SBR polymer both inside and around the asphalt binder;" citing the need for additional research.(80) With a correct design with compatible materials, quality aggregates, and best-practice construction methods, research has shown that a number of different polymers will yield successful pavements.

2.9.2 Surfactants and Emulsion Type

Surfactant chemistry is a complex and multifaceted area of study and as such, is well beyond the scope of the current review. Although published literature on the variation in PME thin surface treatment performance with respect to surfactant types is relatively scant (much of these data are proprietary in nature), a few researchers have attempted to identify high level differences between modified anionic and cationic emulsions.

Kucharek et al. (2006) assessed the chip retention characteristics of a variety of anionic and cationic emulsions modified with different polymers. In this study, emulsion and whole system (i.e., chip seal) performance evaluations were accomplished using DSR, the frosted marble cohesion test, and the sweep test for thin surface treatments. Overall, cationic PME mixes demonstrated considerably higher moduli during the first few hours of curing than did similarly modified anionic preparations. Moreover, although the moduli of the anionic group did gain some ground on the cationic test samples as curing progressed, the modulus values of the anionic mixes were not found to reach the same levels as the cationic group, even after a 24 hour cure period.(80)

Kucharek reports that cationic emulsions consistently demonstrated better chip retention characteristics (as measured in the sweep tests) than anionic emulsions for all the aggregate types studied. Cationic mixes also showed less sensitivity towards the varying chemical composition of the aggregates tested than did those prepared using anionic emulsions.(80)

2.9.3 Aggregates

One of the few issues identified during the literature review with respect to aggregate-polymer interactions pertains to the use of moisture-sensitive aggregate in thin surface treatments. In this regard, aggregates such as moisture-sensitive gravels may exacerbate the effects of hydrogenesis in arid climates, leading to water film buildup beneath a relatively impermeable polymer modified surface treatment.(78) Moreover, in cooler climates pre-existing excess water retention problems can lead to freeze-thaw damage.(72) Arguably, these potentially negative interactions are representative of an indirect relationship between aggregates and polymers. That is, the use of PMEs may not be recommended in certain climates when placed atop a base course containing moisture-sensitive aggregate or one that already has a pre-existing water retention problem.

Overall, the impact of polymers on moisture sensitivity is not well understood at this time. In fact, some polymers are used as adhesion promoters. Moreover, chemical sensitivity issues between aggregate and various types of polymers could also present some challenges in certain cases. But the literature review presented herein turned-up little to no information regarding chemically sensitive aggregates and the use of PMEs. Indeed, the available research points overwhelmingly toward the ability of polymers to impede moisture penetration, enhance stone retention, and increase overall pavement durability. However, caution should be used to determine whether the base course has a fundamental water retention problem prior to the application of any PME based thin surface treatment.

2.9.4 Fillers

Airey et al. (2002) present the findings of a laboratory investigation into the effects of mixing SBS modifier with CRM to produce impact absorbing asphalt (IAA) surfaces.(17) The results of this study show that the polymeric viscoelastic characteristics of the SBS are lost due to precipitation and phase-separation caused by the absorption of light aromatics contained within the maltene fractions by the CRM particles. In properly mixed SBS PMA, which does not contain CRM, the SBS particles absorb these light maltene fractions, which results in the swelling of the polymer phase, thereby producing a continuous elastic network.

Other types of fillers have proven very effective in polymer modified stone matrix HMA serving to increase the film thickness of the binder mastic on aggregates, improving adhesion, cohesion, strength and resistance to oxidative aging.(4) The fillers used in micro surfacing serve similar purposes.

2.10 Surface Treatments, Distress, and Cost-Effectiveness

The selection of appropriate surface treatments and the decision on whether or not to use polymer modifiers are dependent upon a number of factors, including:

- The effectiveness of a given treatment in rectifying a particular form of pavement distress.
- The cost-effectiveness of a particular treatment relative to the benefits and cost of other alternatives (including material, construction, life cycle, and user delay costs).
- The environmental conditions under which the treatment is to be applied.

- The functional classification and/or traffic loading conditions of the roadway to be treated.
- The current condition of the underlying roadway, the type of pavement involved, and its construction and maintenance history.
- The availability of appropriate materials, equipment, and well-trained maintenance forces to ensure proper placement.

Numerous decision tools and best practices have been developed by state highway agencies and industry trade organizations for matching the type and degree of pavement distress with the appropriate form of surface treatment. Hicks et al. (2000) provide a review of some of the best known of these practices, and present a framework, which can be used to determine the most cost-effective treatment alternative.(79) This section of the report focuses on those treatments, which are regularly employed using PMEs including chip, slurry, cape seals, and micro surfacing.

One of the simplest and best known approaches to determining cost-effectiveness is the equivalent annual cost method or EAC. EAC is determined as follows:

EAC = (unit cost of treatment) / (expected life of treatment in years).

Table 11 is from the Hicks et al. (2000) paper and presents the cost-effectiveness of various treatments using the EAC method. Because of changing economics and supply as well as the improved materials and construction of recent times, the numbers given here may not be representative of those today. However, they provide information for comparisons. While the cost of the polymer emulsion may be thirty percent higher than an unmodified emulsion, the relative cost increase is much less when considering the total costs—including materials, construction, traffic control, user delay, and increased service life. More recent data from the Minnesota Department of Transportation (Mn/DOT) has found the total project cost of chip seals is seven percent higher with polymers, and Mn/DOT now uses only PME chip seals statewide, citing better early chip retention, faster traffic return (sweep and open in one hour), significantly reduced claims to the state for windshield damage, and significantly reduced damage from snow plows. They believe that “properly constructed chip seals are the most cost effective application we use to preserve our highways.”

Table 11. Examples of Cost-Effectiveness Using the EAC Method.[(79)]

Treatment	Approx. Average Cost per yd^2 (*)	Avg. Longevity (years) < 100 ADT	Avg. Longevity (years) 100 – 500 ADT	EAC (100 – 500 ADT)
Chip Seal	$1.30	8	5	$0.26
Chip Seal Modified	$1.69	--	6.5 (**)	$0.26
Slurry Seal	$1.08	7	5	$0.22
Slurry Seal Modified	$1.40	--	6.5 (**)	$0.22
Cape Seal	$2.08	11	7	$0.30
Cape Seal Modified	$2.70	--	9 (**)	$0.30
Micro Surfacing	$1.40	11	6	$0.23
*Costs may vary widely depending on materials used, location, etc. **Number of years of longevity needed to achieve EAC break-even point assuming average cost increase of 30 percent for PMEs.				

While it was hoped that the field projects in this study would provide additional cost effectiveness information, they were bid and placed during an unprecedented asphalt and polymer shortage and spike in asphalt and fuel prices, further emphasizing the difficulty in estimating cost differential. Most agencies estimate that a typical PME project costs less than ten percent more than an emulsion project without polymer, when all project costs are considered (including materials, construction, traffic control, striping, etc.). Table 12, which gives the costs of PME FLH projects in 2007 and 2008, is further verification of this figure, and shows the spike that occurred in 2008. The information gathered led to the conclusion when best practices are used for specification and construction, the additional cost of the polymers is more than offset by the improvements in performance both during and after construction.

Table 12. Federal Lands Highway Projects' Cost of PME for 2007-2008.

Project	PME Cost	Chips & Placement	Total Project Cost	PME % of Total Costs	Cost Increase by Polymer*
Chickasaw National Recreation Area Oklahoma (2007)	$147,525	$579,530	$1,152,750	13%	4%
Yosemite National Park California (2007)	$395,568	$457,957	$1,986,451	20%	6%
Joshua Tree National Park California (2007)	$252,000	$374,100	$1,221,159	21%	6%
Death Valley National Park California (2008)	$243,338	$204,978	$741,130	33%	10%
Arches National Park Utah (2008)	$605,475	$345,540	$1,619,535	37%	11%
Dinosaur National Monument Colorado/Utah (2008)	$274,565	$222,750	$797,858	34%	10%
*Assuming PME cost is 30% higher than unmodified.					

Other forms of determining cost-effectiveness include life-cycle costing, longevity cost index, and cost-effectiveness analysis using pavement performance curves.

As Table 11 suggests, the increased longevity realized through the appropriate use of PME in thin surface treatments can offset somewhat higher initial material costs associated with the addition of polymer modifiers. This table assumes a 30 percent higher cost for polymer versus unmodified emulsions, which is fairly typical. However, that translates to approximately a 10 percent higher overall project cost when considering total costs (including aggregate, construction, traffic control, striping, etc.).

In 2007 and 2008, the FHWA developed the Transportation System Preservation (TSP) Research Roadmap by garnering the input of numerous State highway agencies, private industry and academia at three workshops held across the U.S. Several of the resulting problem statements generated by the Roadmap working groups were purposely targeted at identifying research needs that would better quantify the cost-effectiveness of preventive maintenance treatments in general and of individual material components more specifically. The literature review contained herein serves to further emphasize the need for additional research in the area of assessing the cost-benefit relationships between polymer modifiers and thin surface treatments. However, it is worthwhile to note that the comparatively small cost of polymer modifiers relative to overall material and construction costs, coupled with the demonstrable benefits of polymer modification illustrated throughout this report, indicate that the benefits of PMEs likely far outweigh its additional cost.

3.0 LABORATORY TESTING AND SPECIFICATION RECOMMENDATIONS

Task 2 in the statement of work articulated four areas for recommendations. Following the literature search, there were several industry outreach initiatives to collect information from current practitioners. Presently, there are several other in-progress research projects addressing some of the same issues as this work, and the principal investigators of those projects were contacted for idea sharing and possible coordination of on-going and future efforts.

There is a general consensus that current test methods and specifications can be greatly improved, and there are several performance-based protocols and methods currently being evaluated that look very promising. Because the proposed performance-based tests are not yet ASTM or AASHTO approved, and because there are still major data gaps, these protocols are not yet ready for full implementation by FLH.

Based on the findings of this investigation, it is recommended that FLH continue to use the best practices of existing specifications for acceptance and pay supplemented with the performance-based tests listed in Chapter 6. It is further recommended that the data thus reported be combined with field performance evaluations, and that those results be used to gain statistical validation and acceptance as AASHTO/ASTM standards. More detailed information on the background for these recommendations is given in the following sections.

3.1 Industry Outreach Initiatives

3.1.1 Initial Discussions with Industry Representatives

Asphalt emulsion material suppliers, study participants from the NCPP, and FLH representatives participated in an initial information gathering session on September 25, 2006, in St. Louis, Missouri. Koichi Takamura and Chris Lubbers of BASF Corporation, Joe Thrasher and Barry Baughman of Ultrapave, Dennis Muncy and Jon Wingo of SemMaterials, Paul Morris of Ergon, and Roger Hayner of Terry Industries represented the industry viewpoint. Gary Evans, Scott Saunders, and Mike Voth represented FLH, and the NCPP participants were Larry Galehouse and John Johnston. Following this meeting, Gayle and Helen King were brought into the project as consultants to contribute asphalt emulsion materials expertise and a better understanding of supplier needs and concerns. Several teleconference calls and meetings have followed since the initial meeting in St. Louis to garner relevant input from other industry representatives, academics and FHWA personnel. A summary list of these meetings includes:

- September 2006 meeting in St. Louis, Missouri;
- March 2008 meeting in Okemos, Michigan; and
- Teleconference calls with industry and FLH representatives in October, November, and December 2007 and July 2008.

Discussions of the input received during these meetings are presented in the following subsections, and detailed meeting minutes are on file at the Central Federal Lands Highway Division office.

3.1.2 Survey and Follow-up Communication

Based on comments gathered from the previously referenced meetings, the study participants developed a survey for the industry at large. Invitations were sent to members of the Binder Expert Task Group; the Transportation Research Board (TRB) committee AFK20 (Asphalt Binders); the TRB Pavement Preservation Task Force; and the International Technical Committees of the American Emulsion Manufacturers Association (AEMA), the Asphalt Recycling and Reclaiming Association (ARRA), and the International Slurry Surfacing Association (ISSA) to respond to a web-based questionnaire. Appendix A contains the full survey results. In support of the survey, numerous research resources and proposed test procedures were posted on the NCPP website. While a majority of the 33 survey respondents were technical people, there was a good cross-section of industry leaders and experts representing State highway agencies (SHAs), suppliers, contractors, academics, and consultants involved in regulatory, technical, construction, marketing, management, and business roles. Industry had previously opposed innovative ideas for polymer modified emulsion testing and performance-based specifications, often because of concerns about shipping and payment delays or extensive testing requirements. The survey indicates that the private sector of the asphalt emulsion industry would be willing to accept more performance-based methods and specifications, so long as emulsion suppliers and contractors are included in the change process and their existing operations can continue to produce and place products efficiently. To make this happen, emulsion suppliers generally support a standardized certified pre-compliance testing and acceptance program. Overall, there was a mandate for contractor, supplier, and laboratory certification, but not individual certification. Representative samples of the specific comments on test protocols are given below. All of the experts consulted agreed that the ASTM D-244 specification covering test procedures for asphalt emulsions needs to be updated. Changes discussed in the survey are addressed in the following sections.

3.1.2.1 Emulsion Viscosity—Lab Test

Experts agree the Saybolt-Furol method for measuring asphalt emulsion viscosity is antiquated and unable to measure shear rate. Brookfield rheometers are used to determine asphalt viscosities at high temperatures for prediction of HMA mix and compaction temperatures, and are therefore standard equipment in asphalt laboratories. Although asphalt emulsion viscosity can be measured with this same rheometer, survey comments revealed that recent work by Salomon indicates some problems with Brookfield testing that might be overcome with a paddle rheometer as used by the paint industry.(81) Survey comments on the paddle method were generally favorable, but a follow-up phone call indicated that one lab (Flint Hills Resources) conducting work in support of the ASTM committee on asphalt emulsion test methods had problems with temperature control and suggested that additional work is required to validate the method. Improving the method for measuring asphalt emulsion viscosity in the lab remains a data gap. Although not critical for the improvement of FLH PME specifications as outlined in this study, it would be appropriate to include any new viscosity test methods under review by ASTM in the report-only field study.

3.1.2.2 Asphalt Emulsion Viscosity—Field Test

Many respondents feel there are problems with measuring emulsion viscosity in a laboratory some time after the emulsion has been used in the field. The emulsion particle size (and resulting viscosity) change with storage and agitation, particularly when asphalt emulsions are kept at ambient temperatures. Another data gap recognized by many experts is the need for a field viscosity test to be run on an asphalt emulsion at the time of delivery to the project. The Wyoming Department of Transportation (DOT) has already implemented such a field test.(82) The Wyoming procedure should be considered for the report-only field study.

3.1.2.3 Optimizing Emulsion Viscosity

Respondents from cooler climates do not want chip seal emulsion viscosities raised from the standard 100-400 Saybolt Seconds Furol (SSF), but a number of agency and industry representatives from hot climates expressed concern that the 100-400 SSF minimum is too low. Other comments referenced problems with lower viscosity asphalt emulsions on pavements with steep slopes. It is important for the viscosity to be such that the asphalt emulsion sprays uniformly through the distributor and stays in a thick enough film on the pavement for optimal chip embedment. Another data gap revealed by the literature review is that optimum seal coat emulsion viscosity may need to vary with climate and pavement slope.

3.1.2.4 Residue Recovery Method

There was strong support for a low temperature asphalt emulsion residue recovery procedure, but a significantly longer testing time for product certification may only be practical in combination with a delayed acceptance or a pre-certification program to overcome shipping delays. A 2008 presentation by Kadrmas to the AEMA Annual Meeting emphasized the need to eliminate distillation methods with recovery temperatures of 177 °C (350 °F) and higher.(83) He showed that binder moduli for PME micro surfacing residues as recovered using a forced draft oven (FDO) procedure at 60 °C (140 °F) were consistently twice as high as the moduli for the same residues as recovered using 177 °C (350 °F) distillations. This data shows conclusively that asphalt emulsion residue performance-based specifications must not be based on current residue recovery practices. This conclusion is consistent with findings obtained from several European studies. During follow-up discussions, Dr. Didier Lesueur, an asphalt emulsion research manager for Eurovia and participant on European Normalization Committees for asphalt emulsion specification, shared new European Community for Standardization (CEN) standards for residue recovery and a framework for cationic emulsion specifications based on performance parameters.(84)(85) CEN also has a third relevant specification for recovery of emulsion residues, which contain solvent.(86) The CEN standard for emulsion recovery is very similar to the FDO procedure that Takamura and Kadrmas submitted to ASTM. A low temperature (140 °F, 60 °C) FDO using a silicone mold is preferred, because the residue can be easily removed from the mold without reheating; it is run at conditions most closely simulating field conditions; and it has given acceptable results according to inter-laboratory reliability testing and comparison of residue and base asphalt properties. The method was adopted in 2009 by ASTM, as D7497-09 "Standard Practice for Recovering Residue from Emulsified Asphalt Using Low Temperature Evaporative Technique."

The CEN and ASTM methods both first evaporate the asphalt emulsion at ambient temperature for 24 hours and then place the residue in a forced draft oven for another 24 hours. The only major difference is that the CEN standard uses an oven temperature of 50 °C (122 °F), whereas ASTM D7497 uses 60 °C (140 °F). Although many lower temperature recovery methods have been proposed, the FDO procedure has the advantage of curing materials at conditions that most closely simulate conditions on the pavement. Furthermore, residue can be removed from the silicone mold without reheating. Although other potential recovery methods such as stirred can, vacuum recovery, microwave moisture analyzer and others may be faster or may yield more emulsion residue, forced draft oven will remain the method of choice until other methods are proven to match all resulting residue performance-based properties. The ASTM method includes two procedures. Procedure A is the aforementioned 24 hrs at 25 °C (77 °F), and 24 hours at 60 °C (140 °F). Procedure B significantly shortens testing time, with a thinner film evaporated for 6 hours at 60 °C (140 °F).

3.1.2.5 Residue Testing Using Superpave Binder Technology

There is strong support for using Superpave binder tools to specify performance-based properties of asphalt emulsion residues, with an accompanying climate-driven grading system. However, legitimate concerns were expressed regarding additional equipment costs, extended testing time, lack of aging protocols, and the need for a residue recovery method that yields a binder consistency equal to that of a pavement-cured material. More importantly, there is little consensus regarding the definition of performance parameters and specific testing conditions for PME chip seal and PME micro surfacing/slurry applications. Unfortunately, current practice is only loosely tied to variability in climate and traffic. For example, the penetration range for a binder in current micro surfacing specifications is 40 to 90 dmm, a range that would typically represent three full grades in the PG grading system for HMA binders (i.e., PG 58, PG 64, and PG 70). Implementation of performance-based specifications is a huge data gap that remains to be filled.

Although many issues remain to be resolved before asphalt emulsion residues can be characterized with reliable performance-based tests, a number of guidelines for future research can be established based on input received during the survey and related discussions. Residue performance-based properties to be characterized include:

- High temperature grade based upon climate, traffic, and appropriate failure parameters (rutting, bleeding);
- Low temperature grade based upon climate and appropriate failure parameters (cracking, aggregate loss);
- Polymer identifier, which is able to rank performance at different levels of polymer modification; and
- High float gel identifier.

3.1.2.6 Aging Protocol and Handling during Sample Preparation

Because asphalt emulsions are applied at ambient temperatures, and high temperatures are known to change the physical properties of many polymers, PME residues should not be exposed to elevated temperatures during recovery or sample preparation. Any procedure requiring curing or reheating temperatures above 60 ºC (140 °F) must be validated by showing performance-based properties comparable to those from FDO residues.

The rolling thin film oven (RTFO) procedure was definitively rejected by all respondents, since hot mix plants are not used for cold emulsion applications. The pressure aging vessel (PAV) is clearly the aging tool of choice, but it has a number of limitations.

One concern is polymer/asphalt compatibility and stability during aging. It is known that certain polymer/asphalt blends are incompatible, such that the polymer will tend to separate or lose its elastic network over time. For modified HMA binders, such unstable systems are typically eliminated by specifying heat stability tests such as the long-term asphalt storage stability (LASST) test or the separation test. Because there is no heated storage of emulsion residue, experts reject these methods as performance-based indicators. Another good indication of compatibility comes from various microscopic methods such as fluorescence or scanning electron microscopy. Again, experts suggest such methods are useful to the formulator, but should not be adopted for specifications. As another data gap, a method is needed to ensure polymer network stability under the conditions experienced by aging emulsion residues on the pavement surface.

3.1.2.7 Optimization of Testing Time, Cost, and Reliability

Several respondents emphasized the need to minimize the quantity of residue needed for performance-based testing, ideally completing all residue tests with the recovered binder from a single silicone mold as cured in the FDO recovery method.

It was also thought important to minimize equipment costs and testing time, using common tools wherever possible. Survey comments and AEMA discussions emphasized the concern that there are many small companies supplying emulsion from one or two plants, and those facilities only manufacture approximately 10 to 20 percent of volumes shipped by refineries or liquid asphalt terminals supplying PG binders. Amortizing expensive laboratory equipment and testing costs over small volumes can significantly increase product cost and disadvantage smaller producers.

Several comments emphasized the need to maximize the use of the DSR. The DSR appears to be a critical tool for defining performance-based standards based upon rheology. One goal of the planned FLH report-only field study was to maximize the capabilities of this instrument. Conversations with other research teams lead project leaders to believe it may be possible to use DSR to meet each of the four critical residue performance-based properties, as well as determine polymer-asphalt compatibility after aging. DSR also offers other important advantages including small sample size and no reheating for sample preparation. As discussed later in this report, the DSR methods developed by the Binder ETG and adapted by Kadrmas will be used for high temperature residue properties and for polymer identification.(87) Although most experts consider it logical to use the BBR for low temperature performance-based testing, several disadvantages make its use problematic for asphalt emulsion residues. For example, BBR would necessitate reheating recovered residue to pour relatively large test specimens. Additionally the equipment itself is costly, requires significant lab space for testing and temperature control units, and needs volatile solvents that often require access to fume hoods or vents.

An ongoing field-aging study led by Harnsberger and Huang at the Western Research Institute (WRI) encountered similar problems with the need to reduce sample sizes and consequently developed DSR protocols that include rheological measurements around 0-20 °C (32-68 °F).(87) The WRI researchers then fit and extrapolate rheological Christensen-Anderson-Marasteanu (CAM) models to predict binder modulus and phase angle at the lowest pavement temperatures.(88) Full details of Harnsberger's and Huang's work have not yet been published. WRI has significant funding within their current FHWA "Fundamental Properties" contract for development of rheological methods. Discussions are ongoing with project managers to determine whether WRI work plans and resources can be modified to develop specific DSR methods for testing emulsion residues at low temperatures. Of particular interest is a new DSR test method using 4-mm parallel plate geometry to directly measure G* and phase angle at the low pavement temperatures usually tested using BBR. Results to date are encouraging, and these methods will be evaluated as part of ongoing report-only field studies. With the recent addition of a second rheologist to their staff, WRI may also be willing to take on the task of developing a DSR test method to characterize the non-linear gel-like characteristics of anionic high float residues. John Casola of Malvern Instruments has also expressed interest in pursuing rheological studies of gelled asphalts. He cites classic criteria such as yield stress or non-linear response to strain rate can be used, but newer DSR techniques enable more sophisticated analyses such as using harmonics to define gels. An emulsion supplier provided a series of gelled emulsion residues for testing.

3.1.2.8 Defining Polymer Content

Industry experts overwhelmingly favor physical performance-based tests over analytical chemistry methods to define the amount of polymer in various PME residues. Performance-based testing should give better information on predicted performance than recipe specifications. Elastic recovery (ER) in a ductilometer, the most common method used by FLH and most AASHTO agencies, received lukewarm support as the preferred method. However, there was no strong support for other currently available alternatives such as force ductility, toughness and tenacity, torsional recovery, or DSR phase angle. Most industry experts would prefer DSR testing if equipment costs could be controlled and the right parameters selected. Most of the survey comments favored use of a strain recovery parameter from the newly developed DSR Multi-Step Creep Recovery (MSCR) procedure as recommended by the Binder Expert Task Group and recently adopted as AASHTO test method 7405-08.(89) Kadrmas' research presented to AEMA in February 2008 outlines a path forward that should satisfy the many comments received in this area. His results also showed the importance of physical testing rather than polymer quantification to ensure equal performance. This study was discussed in some detail at the Okemos, Michigan meeting, and further testing plans to identify polymer for the FLH report-only study will be based on Kadrmas' recommendations.(83)

3.1.2.9 Polymer/Asphalt Compatibility

Although widely used by suppliers as a formulation tool, there was very little support for the use of microscopy in product specifications to verify polymer network formation or asphalt/polymer compatibility. The increased equipment acquisition and training costs, as well as potential delays in testing were among the primary objections to microscopy. If such a tool were to be included, it should be used as part of product qualification in a certified supplier program rather than as a PME specification tool.

3.1.2.10 PAV Tests to Simulate Field Aging of Emulsion Residues

It is easy to reject RTFO tests since this laboratory aging procedure is meant to simulate oxidation occurring at elevated temperatures in the hot mix plant. The PAV is clearly the tool of choice for asphalt emulsion residue aging, but the direct translation of PAV procedures from asphalt concrete (AC) binders to PME residues is not as straightforward as most experts might expect. AASHTO R 28, "Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)," is believed to be the best alternative for simulating long-term aging because it is run at a reasonable temperature simulating field conditions, and because it is a proven AASHTO test method. Rheological tests on PAV residue should characterize low-temperature behavior after aging (i.e., brittleness, cracking, aggregate loss, and raveling potential) and characterize the modified binder as it ages. Issues to be considered include:

- Residue Recovery for PAV Testing – In order to avoid reheating the recovered residue to pour the sample into the PAV pan, it would be preferable to pour asphalt emulsion directly into the PAV pan and then cure the pan using methods established for the FDO. The cured residue would then be placed into the PAV oven for a defined time and temperature. Although seemingly straightforward, such a method has not yet been developed.

- PAV Aging Time and Temperature – It would be ideal to hold PAV temperatures to 60 °C (140 °F) so that polymer modified residues would never be damaged by temperatures higher than those encountered in the field. The problem is that oxidation reaction rates double for each 10 °C increase in temperature. Therefore the rate of oxidation in the PAV should be approximately 16 times slower at 60 °C than at the 100 °C (212 °F) condition used for most Superpave binders. To reach an equivalent level of oxidation, the PAV testing time would have to be increased from 20 hours to 320 hours if the temperature were reduced to 60 °C. Extensive time-temperature PAV aging studies were conducted at WRI during SHRP. Such data would be valuable in evaluating alternatives for asphalt emulsion residues. Further research will be needed to determine the maximum temperature to which residues can be heated without damaging latex-induced polymer networks.

Performance-based tests to be run on PAV aged residues should include:

- Low Temperature Performance-Based Specification – As asphalt ages, it becomes more brittle and prone to cracking and raveling at low pavement temperatures. Hence, low temperature physical properties should ideally be measured on appropriately aged residues. For surface applications such as slurry/micro surfacing or chip seals, the level of asphalt oxidation should be comparable to that observed near the surface of the HMA. Physical tests on the aged residue should report both a hardness parameter and a relaxation parameter. For example, low temperature specifications could be based upon stiffness (S) and “m-value” as measured by the BBR or dynamic modulus (G*) and phase angle as measured by a DSR.

- PAV Aging to Control Polymer Compatibility/Degradation – Because standard test methods, which control polymer/asphalt compatibility have been removed, there is some risk that unstable polymer/asphalt blends might prematurely degrade or separate. One possible means to control this could be to evaluate the polymer’s contribution to physical properties both before and after aging. For example, if the strain recovery in the MSCR test falls off rapidly with PAV aging, there would be some concern that the polymer system is unstable. Such a test method has not been considered in the literature, and this issue remains a data gap yet to be defined.

3.1.2.11 Aggregate Specifications

It is clear from the survey responses that aggregate requirements must fit the asphalt emulsion application. For example, chip seal experts typically prefer to specify fines by assigning a maximum P-200 percent, while micro surfacing designers want a methylene blue test to control the surface activity of those fines. Although survey respondents generally favor LA Abrasion over MicroDeval, the few who have actually used the latter think it is a much better test, particularly for surface applications where more moisture is present. It is also generally believed that more aggregate and aggregate/emulsion compatibility testing will yield better performance. A recent study by Kim has shown how to optimize aggregate gradation for surface treatments.(90)

Although the primary objective of this study relates to the use and specification of polymer-modified asphalt emulsions, some effort was also directed towards reviewing FLH aggregate specifications for chip seal and slurry/micro surfacing applications. Tables 13 through 20 show how current FLH standards compare to other agency specifications (specifically, TxDOT and Caltrans), as well as recommendations coming from active research projects and unique industry sources. A quick inspection indicates that FLH aggregate specifications use ASTM/AASHTO standard versions of common test procedures. Overall aggregate quality requirements are consistent with or exceed those of most state agencies. Specification of the adherent coating test to control the quantity of P-200 washed from the aggregate is particularly notable as a less common procedure that plays a very important role for ensuring early aggregate adhesion to the emulsion residue.

Because the industry survey and other discussions led to a consensus belief that aggregate quality should be tied to traffic, some effort was made to identify aggregate quality standards that might be used to differentiate such use of materials.

3.1.2.12 Aggregate Specifications for PME Chip Seals

Table 13 compares current and proposed chip seal aggregate specifications from five sources.

Table 13. Comparison of Chip Seal Aggregate Quality Specs.

Agency/Organization	**FLH (703.10)**	**Caltrans**	**TxDOT (Not AASHTO Standards)**	**Colorado State Study**	**RoadArmor® Recommendations (High Performance)**
General Specifications	Furnish hard, durable particles or fragments of crushed stone, crushed slag, or crushed gravel. Use only one type of aggregate on a project.	Screenings shall consist of broken stone, crushed gravel or both. >90% by weight of the screenings shall be crushed particles as per Cal Test 205. Screenings shall be clean & free from dirt & deleterious substances.	Uncontaminated materials of uniform quality meeting plans & specifications. Special requirements for lightweight ag: pressure slaking, freeze-thaw loss, water absorption		
Gradation	Table 703-7	See below	See below		1/2 inch 100 min. 3/8 inch 97 min. #4 12 max. #200 1 max.
Los Angeles Abrasion, AASHTO T 96	40% max.		35 max. 40 max. limestone rock asphalt	<25 for high volume	
Los Angeles Rattler, CA 211 Loss at 100 Rev. Loss at 500 Rev.		10% max. 40% max.			
Sodium sulfate soundness loss, AASHTO T 104	12% max.				
Mg sulfate soundness, 5 cycle, %, Tex-411-A			25 max.		
Fractured faces, one or more, ASTM D5821	90% min.		2 faces >85%		1 face >98% 2+ >95%
Flat and elongated particles, 1:3 ratio, +⅜ inch sieve, by mass, average, ASTM D4791	10% max.				
Clay lumps and friable particles, AASHTO T 112	1.0% max.				
Deleterious Materials Tex-217-F, P-200			2.0 max.		0.5% max. 1.0% max.
Cleanness Value, CA 227		80 min.			
Decantation, %, Tex-406A			1.5 max.		
Adherent Coating, ASTM D5711	0.5% max.				
Film Stripping CA 302		25% max.			
	No lightweight aggregate; AASHTO M 195	Samples for grading & Cleanness Value from spreader conveyor belt prior to application			
Micro-Deval			For screening, not for acceptance		17% max.
Flakiness index Tex-224F			17 max.		17 max.
Absorption					2% max.

Tables 14, 15, and 16 give several agencies' requirements for size, grade, and combinations of the aggregate fractions in the given mix proportions.

Table 14. FLH Table 703-7 Ranges for Surface Treatment Aggregate Gradation.(62)

Sieve Size	Percent by Mass Passing Designated Sieve, (AASHTO T 27 & T 11)					
	Grading Designation					
	A	B	C	D	E	F
1½ inch	100 (1)					
1 inch	90 – 100 (3)	100 (1)				
¾ inch	0 – 35 (5)	90 – 100 (3)	100 (1)			
½ inch	0 – 8 (3)	0 – 35 (5)	90 – 100 (3)	100 (1)		
⅜ inch	---	0 – 12 (3)	0 – 35 (5)	85 – 100 (3)	100 (1)	100 (1)
No. 4	---	---	0 – 12 (3)	0 – 35 (5)	85 – 100 (3)	85 – 100 (1)
No. 8	---	---	---	0 – 8 (3)	0 – 23 (4)	---
No. 200	0 – 1 (1)	0 – 1 (1)	0 – 1 (1)	0 – 1 (1)	0 – 1 (1)	0 - 10 (1)

(1) Statistical procedures do not apply.
( ) The value in parentheses is the allowable deviation (±) from the target value.

Table 15. Caltrans Chip Seal Screenings Sizing.

Seal Coat Types	Size of Screenings
Fine	1/4" x No. 10
Medium fine	5/16" x No. 8
Medium	3/8" x No. 6
Coarse	1/2" x No. 4
Double	
1st application	1/2" x No. 4
2nd application	1/4" x No. 10

Sieve Size	Percentage Passing			
	Coarse	Medium	Medium Fine	Fine
	1/2" x No. 4	3/8" x No. 6	5/16" x No. 8	1/4" x No. 10
3/4"	100	---	---	---
1/2"	95 – 100	100	---	---
3/8"	50 – 80	90 – 100	100	100
No. 4	0 – 15	5 – 30	30 – 60	60 – 85
No. 8	0 – 5	0 – 10	0 – 15	0 – 25
No. 16	---	0 – 5	0 – 5	0 – 5
No. 30	---	---	0 – 3	0 – 3
No. 200	0-2	0-2	0 – 2	0 – 2

Table 16. TxDOT Aggregate Gradation Requirements (Cumulative Percent Retained).

Sieve Size	Grade 1	2	3S2	3 Non-lightweight	3 Lightweight	4S2	4	5S2	5
1"	---	---	---	---	---	---	---	---	---
7/8"	0 – 2	0	---	---	---	---	---	---	---
3/4"	20 – 35	0 – 2	0	0	0	---	---	---	---
5/8"	85 – 100	20 – 40	0 – 5	0 – 2	0 – 2	0	0	---	---
1/2"	–	80 – 100	55 – 85	20 – 40	10 – 25	0 – 5	0 – 5	0	0
3/8"	95 – 100	95 – 100	95 – 100	80 – 100	60 – 80	60 – 85	20 – 40	0 – 5	0 – 5
1/4"	---	---	---	95 – 100	95 – 100	---	---	65 – 85	---
#4	---	---	---	---	---	95 – 100	95 – 100	95 – 100	50 – 80
#8	99 – 100	99 – 100	99 – 100	99 – 100	98 – 100	98 – 100	98 – 100	98 – 100	98 – 100

Notes: Round test results to the nearest whole number; Single-size gradation.

Aggregate specifications for chip seals vary widely, and not all agencies differentiate aggregate quality and traffic. Even the definition of high-volume traffic for chip seals varies markedly, with experts somewhat arbitrarily choosing anywhere from 1,000 ADT to 10,000 ADT as a minimum level, which might require higher quality materials. A high volume chip seal study by Shuler elected to construct field test sections with ADT exceeding 7,500 vehicles.(66) Recommendations from that study, and the new NCHRP project also led by Shuler (Manual for Emulsion-Based Chip Seals for Pavement Preservation: NCHRP 14-17) should be considered. Since FLH has graciously agreed to support this latter NCHRP project with field trials, Shuler's results and recommendations should be available and pertinent to FLH needs. Although the study is ongoing, Shuler has already made some recommendations to the FLH research team based upon earlier work. One example of note is to reduce the LA Abrasion maximum from 40 percent to 25 percent for high volume traffic.

As another example, SemMaterials (formerly Koch Materials) developed a high performance chip seal system under the trademark RoadArmor® for higher volume traffic. This system includes a new piece of construction equipment, which applies both emulsion and then aggregate in a single pass. It also includes upgraded emulsion and aggregate specification recommendations consistent with faster curing and longer wear. RoadArmor® was actually developed for chip seal applications that needed a quick return to traffic, a concept, which may be more appropriate than ADT to FLH needs on pavements such as narrow mountain roads or isolated areas where detours are unavailable and traffic control is difficult. Hence, RoadArmor® guidelines do not define high volume traffic with a specific ADT. However, the aggregate guidelines supplied with this system offer some insight as to recent trends applicable to differentiating material quality. As can be seen on the comparative table for chip seal aggregates (Table 13), RoadArmor® guidelines reduce P-200 fines and deleterious materials and require more crushed faces than most agency specifications. Interestingly, this guideline specification also appears to be among the first in the U.S. to replace LA Abrasion with Micro-Deval.

Although the industry survey received more favorable votes for LA Abrasion, the respondents who actually had experience with using Micro-Deval to screen aggregate durability strongly favored it. Since FLH has the Micro-Deval apparatus available in the Denver lab, it is recommended that Micro-Deval be required in the report-only portion of the experimental materials testing plan. Results should be compared against the RoadArmor guideline of 17 percent maximum loss to determine whether similar limits might fit FLH needs on higher volume chip sealed pavements.

3.1.2.13 Aggregate Specifications for PME Micro Surfacing/Slurry

ISSA offers separate aggregate quality guidelines for slurry seal and micro surfacing applications. The industry survey indicated that ISSA guidelines represent best current practice, and should be adopted where possible as minimum requirements. More recent research for Caltrans, led by Fugro Consultants, proposes that all slurry systems be redefined in essentially three categories based upon traffic, climate, and application. These three classifications should provide better definition for use of micro surfacing, PME slurry seals, and conventional unmodified slurry seal emulsions. Aggregate and mix design guidelines should be adjusted accordingly for these three distinct uses. Preliminary information on aggregate quality guidelines was provided by Fugro on the Caltrans study for slurry seals and micro surfacing. These data are compared to both the ISSA guidelines and existing FLH specifications in Tables 17 and 18.

Table 17. Comparison of Slurry Seal Aggregate Quality Specifications.

Test Method	FLH	ISSA	Fugro/Caltrans Study
General	Furnish natural or manufactured sand, slag, crushed fines, or other mineral aggregate conforming to AASHTO M 29 and the following:	The mineral aggregate used shall be the type and grade specified for the particular use of the slurry seal. The aggregate shall be manufactured crushed stone such as granite, slag, limestone, chat, or other high-quality aggregate, or combination thereof. To ensure that the material is totally crushed, 100% of the parent aggregate will be larger than the largest stone in the gradation to be used.	
Los Angeles Abrasion, AASHTO T 96	35% max.	35% max. Abrasion test run on aggregate before it is crushed	30% max. high traffic 35% max. low traffic
Sand equivalent value, AASHTO T 176, alternate method no. 2, reference method	45 min.	45 min.	45 min. low traffic 65 min. high traffic
Smooth textured sand with < 1.25% water absorption content by weight of total combined aggregate	50% max.		
Soundness, AASHTO T 104		15% max. using Na_2SO_4 25% max. using $MgSO_4$	20% max. using $MgSO_4$
Polishing		Meet approved polishing values	
Gradation	See below	See below	See below

Table 18. Comparison of Micro Surfacing Aggregate Quality Specifications.

Test Method	FLH	ISSA	Fugro/Caltrans Study	TxDOT
General	Furnish natural or manufactured sand, slag, crushed fines, or other mineral aggregate conforming to AASHTO M 29 and the following:	The mineral aggregate used shall be of the type and grade specified for the particular use of the micro surfacing. The aggregate shall be a manufactured crushed stone such as granite, slag, limestone, chat, or other high-quality aggregate, or combination thereof. To ensure that the material is totally crushed, 100% of the parent aggregate will be larger than the largest stone in the gradation to be used.		
Los Angeles abrasion, AASHTO T 96	30% max.	30% max. To be run on parent aggregate	30% max. high traffic 35% max. low traffic	
Sand equivalent value, AASHTO T 176, alternate method no. 2, reference method	65 min.	65 min.	45 min. low traffic 65 min. high traffic	70 min.
Sodium sulfate soundness, AASHTO T 104	15 max. using Na_2SO_4 25 max. using $MgSO_4$	15 max. using Na_2SO_4 25 max. using $MgSO_4$	20 max. using $MgSO_4$	30 max.
Polishing		Meet state-approved polishing values		
		Proven performance may justify the use of aggregates that may not pass all of the above tests.		
Gradation, type II or III	Table 703-8 (See below)	See below	See below	

Recommended aggregate gradation comparisons for slurry seals and micro surfacing applications are provided below in Tables 19 and 20.

Table 19. Slurry Seal and Micro Surfacing Aggregate Gradation and Application Rates.(62)(39)(110)

Sieve Size	Percent by Mass Passing Designated Sieve, (AASHTO T 27 & T 11), Slurry Seal Type					
	I (Slurry Only)		II		III	
	FLH	ISSA	FLH	ISSA	FLH	ISSA
3/8 inch	---	100	100	100	100	100
No. 4	100	100	90 – 100	90 – 100	70 – 90	70 – 90
No. 8	90 – 100	90 – 100	65 – 90	65 – 90	45 – 70	45 – 70
No. 16	65 – 90	65 – 90	45 – 70	45 – 70	28 – 50	28 – 50
No. 30	40 – 65	40 – 65	30 – 50	30 – 50	19 – 34	19 – 34
No. 50	25 – 42	25 – 42	18 – 30	18 – 30	12 – 25	12 – 25
No. 100	15 – 30	15 – 30	10 – 21	10 – 21	7 – 18	7 – 18
No. 200	10 – 20	10 – 20	5 – 15	5 – 15	5 – 15	5 – 15
Application rate, pounds per square yard	6 – 10	8 – 12	10 – 15	10 – 18 slurry 10 – 20 micro	15 or more	15 – 22 slurry 15 – 30 micro

Note: Statistical procedures do not apply to gradations. Application rates are based on the dry mass of the aggregate.

Table 20. TxDOT Micro Surfacing Aggregate Gradation Requirements (Washed).

Sieve Size	Cumulative Percent Retained
1/2 in.	0
3/8 in.	0 – 1
#4	6 – 14
#8	35 – 55
#16	54 – 75
#30	65 – 85
#50	75 – 90
#100	82 – 93
#200	85 – 95

TxDOT Micro Surfacing Job Mix Formula (JMF) Requirements have been provided for comparison purposes in Table 21.

Table 21. TxDOT Micro Surfacing JMF Requirements.

Property	Test Method	Requirements
Wet track abrasion, g/sq. ft., max. wear value	Tex-240-F, Part IV	75
Gradation (aggregate and mineral filler)	Tex-200-F, Part II (Washed)	Table 1
Mix time, controlled to 120 sec.	Tex-240-F, Part I	Pass

3.1.2.14 Emulsion/Aggregate Performance-Related Tests

It is widely recognized that asphalt emulsion and residue properties alone cannot define performance. Similarly, mixture performance-based parameters as typically measured using Superpave mix design and performance-based tools are not sufficient to describe most pavement preservation applications. As pointed out by Leach and Blankenship, asphalt emulsions require time to cure.(91) Therefore, one critical performance issue is establishing the amount of time an asphalt emulsion system must cure before a road can be reopened to traffic.

3.1.2.15 Sweep Test—Chip Seal Curing Time for Traffic—ASTM 7000(92)

The survey indicated some concerns with the sweep test, particularly with respect to repeatability of the standard ASTM method. Takamura has investigated this test in some detail, and reports that three minor revisions to the procedure can reduce variability from 20 percent to 5 percent.(93) Such improvement would almost certainly overcome expressed concerns if these results can be duplicated in multi-lab round-robin studies. The survey also indicates that confusion exists as to the performance-related characteristics being measured. As originally developed by Barnat, the sweep test was intended to rank emulsion/aggregate systems for curing time before a chip seal can be opened to traffic.(94)(95) Since temperature and humidity play an important role in curing, the predictive value of this test is only accurate when the conditioning protocol is able to simulate field conditions at the time of placement. However, when conditioning occurs under the constant environmental conditions designated by the ASTM procedure, the test does seem to provide a reasonably correct rank-ordering of curing times as needed for purchase specifications. It is important to further clarify that the sweep test might predict aggregate loss or potential for windshield damage as the emulsion cures, but it is not intended to be a predictive tool for long term chip loss.

3.1.2.16 Chip Seal—Long Term Aggregate Loss

There was no expert agreement on a good test for evaluating long-term chip loss. Suggestions from Davidson at McAsphalt included the Vialit Plate Shock Test (96) and the Frosted Marble Test,(80)(97) whereas French experts recommended the Vialit Pendulum Test.(98) The best tool to date appears to be the MMLS3 procedures as developed by Dr. Richard Kim's group at N.C. State for the North Carolina DOT.(99)(100) Although too expensive to advance for specification purposes, it remains an excellent research tool against which the predictive capabilities of less expensive performance-based tests can be compared. This subject remains a significant data gap, with no specific project recommendations at this time.

3.1.2.17 Micro Surfacing vs. Polymer Modified Slurry

Micro surfacing is formulated to provide significantly higher performance than slurry seals either with or without polymer. From a use perspective, micro surfacing should be used for rut-fill applications and for high-traffic pavements with ADT exceeding 1,000. Micro surfacing also contains emulsifier packages that break quickly so that traffic can usually be returned in one hour or less. Where traffic control is a problem due to urban traffic, narrow roads, or long detours, the faster curing micro surfacing might be specified for lower volume roads.

3.1.2.18 Micro Surfacing Performance-Related Tests

The ISSA document A143 "Recommended Performance Guidelines for Micro-Surfacing" was cited by survey respondents as the best available current practice for performance-related test procedures.(39) Performance-related tests include wet cohesion, Excess Asphalt by LWT Sand

Adhesion, Wet Stripping, and Wet Track Abrasion Loss after one day soak and after six day soak. These tests should be used as pay items.

3.1.2.19 Newly Proposed Tests for Mix Design and Performance

Moulthrop and Hicks are updating mix design methods for micro surfacing, under Caltrans Contract 65A0151, Slurry/Micro-Surface Mix Design Procedure.(101) Significant contributions from this study include an automated test for cohesion, a German method to predict mixing time by measuring mixer torque, and a French adaptation of the wet track abrasion test using wheels in place of the rubber tube. It is recommended the FLH report-only format be used to evaluate new tools recommended by the Fugro study.

3.1.2.20 Polymer Modified Slurry Seal

Since polymer modified slurry seal asphalt emulsions will only be used on roads carrying lower traffic levels (< 1,000 ADT), the wet-track abrasion test is probably sufficient as a specification parameter for mixture performance-based testing. However, it will be important to ensure an adequate amount of polymer has been added for PME slurry applications. This can best be done with a residue polymer identification test. Elastic recovery should remain in formal specifications for now, but Kadrmas' DSR MSCR protocol reporting recoverable strain initially appeared to be the best choice for report-only criteria.(83) The ultimate strain recovery for a PME slurry seal residue would be significantly less than that expected for micro surfacing. From limited data, Kadrmas tentatively proposed the following test conditions and limits to illustrate differentiation of micro surfacing from PME slurry as shown in Table 22.

While Table 22 was an important first step in the development of performance specifications for polymer slurry seals and micro surfacing, more recent laboratory data with a larger data set of polymer emulsions (as discussed in Chapter 5 of this report) show the test protocols and limits given in Table 22 need further revisions.

Table 22. Tentative Micro Surfacing and PME Slurry Performance-Related Tests.(83)

Testing Protocol	Tentatively Proposed Latex/Polymer Modified Slurry	Tentatively Proposed Micro Surfacing
Original DSR, G*/sin δ	3 (minimum)	5 (minimum)
Original DSR, Phase Angle	80 (maximum)	75 (maximum)
MSCR, % recovery at 3,200 Pa	15 (minimum)	25 (minimum)

3.1.2.21 Manufacturing and Construction: Construction Controls on Climate

Because of problems with curing when asphalt emulsions are applied at lower temperatures, the application window should be carefully restricted. Pavement temperatures continue to be important until the emulsion residue is fully cured.

Chip seals frequently fail if freezing occurs while the binder still holds some moisture. Controlling pavement temperature at time of application may not be sufficient to ensure full curing. Given improvements in weather forecasting, it might be more appropriate to stop projects based upon predicted freezing temperatures for a few succeeding nights rather than raising pavement temperature requirements or narrowing seasonal limits for construction.

Because excess water dilutes and displaces emulsions, break time should be tied to requirements to stop construction for pending inclement weather.

It is also known that sealing high concentrations of moisture into a pavement can result in catastrophic stripping failures. Therefore, entrapped water resulting from recent rainfall before construction or other sources of subsurface moisture can lead to unexpectedly poor performance of sealed pavements.

Use of fog seals over new chip seals can improve short- and long-term aggregate retention, perhaps even to the point of extending the construction season modestly.

Each of these observations, although obvious to the experienced practitioner, represent data gaps needing further research so that effective construction controls can be objectively managed.

3.1.2.22 Manufacturing and Construction: Rolling/Compaction

Recent research by Kim evaluated the effect of compactor type and roller pattern on the performance of chip seals.(100) Recommendations from this work should be included in FLH guidelines.

3.1.2.23 Manufacturing and Construction: Controls on Polymer Addition

Good support was noted in the survey for preblending/co-milling polymers at the emulsion plant. Based on field practice, almost no one indicated support for adding polymer latex to the emulsion distributor or field tanks, with comments noting viscosity drop, polymer latex separation, and lack of uniformity leading the negatives. If post-blending latex is to be allowed at all, specification language should ensure controlled metering and complete blending of latex and asphalt emulsion at the supplier's plant to attain a uniform consistency that continues to meet minimum viscosity requirements.

3.2 Follow-up Discussions with Larger Industry Audience

The goals of the FLH project and the need for industry response to the survey were introduced to several Transportation Research Board (TRB) committees at the January 2008 annual meeting in Washington, D.C., including the following:

- AFK10 – General Issues in Asphalt Technology;
- AFK20 – Asphalt Binders;
- Task Force on Roadway Pavement Preservation; and
- AHD20 – Pavement Maintenance.

Survey results and suggested specification test methods were presented to several groups who were then solicited for their comments. These groups included:

- Joint Annual Meeting of the Asphalt Emulsion Manufacturers Association (AEMA), the Asphalt Recycling and Reclaiming Association (ARRA), and the International Slurry Seal Association (ISSA) in February, 2008, including two presentations and a one-hour breakfast meeting with the International Technical Committee. By the end of the joint meeting, industry response was sufficiently positive for Jim Sorenson of the FHWA Office of Asset Management to form the ETG Emulsions Task Force.

- Asphalt Binder Expert Task Group in February, 2008.

- Emulsion Task Force of the FHWA Pavement Preservation ETG in April, 2008.

- TRB Committee AFK10 (General Issues in Asphalt Technology) in April 2008.

- Discussions with Dr. Scott Shuler, principal investigator of NCHRP Project 14-17, Manual for Emulsion-Based Chip Seals for Pavement Preservation.

- Discussions with Drs. Hussein Bahia and Peter Sebaaly of the Asphalt Research Consortium (ARC).

- Discussions with Dr. Richard Kim, Principal Investigator of an on-going chip seal performance study for the North Carolina DOT (Project HWY 2004-04). Dr. Kim summarized his research at the project review meeting in Okemos, Michigan. He reported that many North Carolina DOT districts are already converting all chip seals to polymer modified asphalt emulsions based upon their own experience and Dr. Kim's findings to date, even though research is not complete and no state mandate requiring polymers has been published.

- Discussions with European emulsion experts and Standards Committee members, including Didier Lesueur of Eurovia and Francois Chaignon of Colas.

- Discussions with Darren Hazlett (TxDOT) and Dr. Amy Epps (Texas Transportation Institute) on their efforts to develop Superpave PG-type performance-based emulsion specifications.

- Discussions with Jim Moulthrop regarding progress with Fugro's pooled-fund micro surfacing mix design study.

- Discussions with McGraw (Mn/DOT), Maurer (Pennsylvania DOT), Hosseinzadeh (Caltrans) and other SHA personnel on the status of delayed acceptance for certified asphalt emulsion suppliers and modified asphalt emulsion performance-based specification development.

- Discussion with Roger Olson (Mn/DOT) regarding an upcoming pooled-fund pavement preservation study for MnROAD that may provide a second opportunity to evaluate performance-based testing protocols as recommended for this FLH study.

- Discussions with Dr. Jack Youtcheff, leader of FHWA's asphalt research team at Turner-Fairbanks. [Note: Dr. Youtcheff oversaw the asphalt chemistry research and the development of Superpave binder specs as a member of the SHRP staff, and now has responsibility for approving research projects and work plans developed by the WRI/ARC, as well as defining asphalt research to be conducted at Turner-Fairbanks. He is also a member of the Binder ETG and the Emulsions Task Force.] Dr. Youtcheff states that he is interested in funding studies that would advance performance-based asphalt emulsion specifications. He has some ideas as to how the WRI and ARC work plans can be reworked to fit identified research needs, and is prepared to pursue money to support some related activities within FHWA's labs at Turner-Fairbanks. However, Youtcheff feels it is important that any defined research needs for asphalt emulsion applications come from the newly-formed FHWA ETG Emulsion Task Force, rather than from individuals or single projects. Dr. King chairs the emulsion residue testing subcommittee of the Emulsion Task Force (ETF), and will initiate efforts accordingly. Further discussions with Dr. Youtcheff, WRI/ARC investigators, and ETF subcommittee members took place at the Association of Asphalt Paving Technologists (AAPT) meeting in April, 2008.

- Recommendations from the FHWA/FP^2 "Spray Applied Polymer Surface Seals Study." The recently completed FHWA/FP^2 study "Spray Applied Polymer Surface Seals" recommends that new chip seals be fog-sealed immediately after brooming if problems from windshield damage or long term chip loss are anticipated.(102) Roger Olsen of Mn/DOT reports that they now fog seal almost all new chip seals, and as a result, windshield and snowplow damage have been reduced, and customer acceptance is unusually high because the black color leads to a perception among the driving public that a new HMA overlay has just been placed. To maintain optimal embedment, the initial application of CRS-2P chip seal emulsion should be reduced by the amount of asphalt to be applied during the ensuing fog seal.

- At the International Symposium on Asphalt Emulsion Technology, in Washington D.C. in 2008, two presentations were given during the technical sessions on the ETF scope and framework and this FLH study.

- In May, 2009 the results to date from this study were presented to the Southeast Pavement Preservation Partnership, the FHWA-sponsored Pavement Preservation Expert Task Group, and the Emulsion Task Force.

- In August 2009, the results were presented to AASHTO's Subcommittee on Materials, where a follow-up pooled fund study was suggested for collecting additional data for developing specification test conditions and limits.

3.3 Specific Recommendations

To specifically address the four items enumerated in the statement of work, recommendations are made in the following subsections. A summary of these recommendations, *Field Guide for Polymer Modified Emulsions: Composition, Uses and Specifications for Surface Treatments*, has been published by FHWA. This is recommended reading for all maintenance engineers.

3.3.1 Task 2A. Use of Modified vs. Unmodified Asphalt Emulsions

Polymer modified asphalt emulsions should be used for chip seal and slurry seal/micro surfacing applications for all traffic and climate conditions. While non-modified materials are less expensive than modified products, the construction, mobilization, traffic control costs, and the improved initial and long-term performance of PMEs usually justify the higher costs.

Moreover, specifications for traffic conditions should be differentiated as follows:

- Micro Surfacing vs. PME Slurry – When slurry seals are polymer modified, the polymer increases the elasticity and durability of the slurry binder. Micro surfacing not only has the benefits of polymer modification, but also has superior quality aggregates, emulsifiers, and additives to give a much faster chemical cure rather than atmospheric evaporation emulsion break typical of most slurry seals. The advantages of micro surfacing are the quick break for thicker application in ruts, the quick break for faster traffic return, generally higher quality aggregates, and slightly higher polymer contents for durability. This study recommends micro surfacing for rut-filling, high traffic areas (> 1,000 ADT), roads that require quick return to traffic, and for high durability needs. PME slurry specifications typically require less polymer, but still significantly upgrade the performance above that expected from conventional slurry. PME slurry emulsions are recommended for low-volume roads (< 1,000) for which micro surfacing is not otherwise justified. The quick cure and superior quality aggregates justify micro surfacing on high traffic areas.

- PME Chip Seals – As mentioned above, cationic or anionic polymer modified chip seal asphalt emulsions are justified regardless of traffic level, as demonstrated by a recent study performed Gransberg et al. (2005) on the cost-effectiveness of CRS-2P on low volume roads, as well as Dr. Kim's research results discussed previously.(64) Traffic levels and speed should be considered when selecting aggregates and performance-based criteria. A quick cure and return to traffic, as potentially differentiated by the sweep test, are particularly desirable for high traffic areas, as are durable, polish-resistant aggregates. It is common to have individual asphalt emulsion specifications for cationic (CRS-2P), anionic (RS-2P), and high float anionic (HFRS-2P) PMEs. Local agency names for these emulsions will vary throughout the country.

For climate considerations, it is recommended that strict windows for application temperatures be specified, but this area also needs further investigation as there is clear evidence that curing, shelling and bleeding of chip seals are associated with climatic conditions occurring well after the time of application. Superpave PG-type specifications for HMA are based on climatic temperature ranges, which may also be useful for asphalt emulsion surface treatments, especially micro surfacing. Although the concept of 6 °C grade increments based upon LTPPBind climate maps is attractive to practitioners, failure properties have not yet been defined and failure limits have not been established. For this reason, the FLH report-only lab testing format will only be useful if measured physical properties can be tied to actual performance on the pavement. It will be important to have longer-term pavement management data and frequent video tapes of pavement condition so that field performance can ultimately be used to set specification limits on promising laboratory performance-based measures.

As discussed in the literature review, polymers are believed to be advantageous for use on hiking or biking trails and parking lots because of resistance to permanent deformation, raveling surface aggregate, oxidative aging, and damage caused in parking lots when front wheels are turned with no concurrent forward motion. Polymer modified materials have also been shown to retard cracking, particularly the block cracking typically seen in older parking areas. Bikers prefer micro surfacing/slurry seals over rougher chip seals for trails. Small-sized aggregates should be used, and loose chips avoided. Although micro surfacing and slurry seals are not typically compacted for paving applications, they are compacted on airport runways and taxiways to eliminate foreign object damage caused by raveling surface aggregate.

If loose aggregate is perceived to be a problem on trails, use of small rollers on slurry/micro surfacing applications should be evaluated. Also, polymerized seals generally cure faster, meaning faster reopening for its intended use. However, there is not much data in the literature on the use of polymerized asphalt emulsions on trails and parking lots, as noted previously.

3.3.2 Task 2B. Identifying and Specifying Polymer Percentages

Experience has shown that specifying polymer percentage does not necessarily result in the expected performance because of differences in compatibilities between asphalt and polymers from different sources. Moreover, feedback received from industry participants at the St. Louis meeting in 2006 clearly indicates that suppliers view polymer quantity specifications as a practice, which serves to inhibit innovation, a problem, which can be remedied with the adoption of appropriate performance-based specifications.

Thus, performance-based testing rather than recipe specifications should result in the longest lasting, most cost-effective treatments, affording suppliers the opportunity to prescribe the polymer types, formulation methods, and mix design flexibility to meet agency and end-user requirements. Specific methods, which are currently under consideration are discussed in Chapters 4 and 5 in this report. Because of the importance of uniformity and compatibility to performance, it is recommended that the polymer not be post-blended with the asphalt emulsion in the field, particularly since both SHA and industry stakeholders have openly discouraged this practice.

Low temperature recovery of asphalt emulsion residues will simulate emulsion curing much more effectively than current recovery methods, which are performed at temperatures that are far higher than these products will ever experience in the field. SemMaterials testing showed the high temperatures associated with currently used recovery methods can change the residue rheological properties, since the modulus is usually cut in half by heating the sample to 350 ºC, as opposed to using a low temperature FDO method.[83] Also, phase angles from high temperature distillation suggest that heating can cause cross-linking and damage to polymer additives. Therefore, it is recommended that a low-temperature method be adopted, which is more representative of field curing conditions. Several such methods are under investigation by various researchers, with the leading candidate being a FDO procedure that is similar to a recent European standard and which has been adopted by ASTM as D 7497-09.

Rheological performance-based tests on the residue should identify the polymeric properties as well as high-float gel structures. While there is some concern that performance-based testing will be more time-consuming and result in shipping, construction, and acceptance delays, a supplier pre-certification or delayed-acceptance program should facilitate the process.

3.3.3 Task 2C. Projected Performance and Cost

Costs vary significantly from region to region, depending upon the local costs and local availability of emulsified asphalt and aggregate materials, contractors, and expertise. Section 2.10 and Tables 11 and 12 above give more information on the projected cost-effectiveness and extended performance of PMEs. For the field projects completed in this study, the emulsion costs were atypical because of an unprecedented shortage and spike in costs of asphalt, fuel, and polymers in 2008. Costs vary according to geographical location, project size, mobilization, time of year, and availability of materials and contractors.

3.3.4 Task 2D. Further Investigation

There are several data gaps in the available information. Nearly everyone in the industry believes that specifications for PME chip and slurry seals need to be changed so that they better predict field performance. While Superpave greatly improved the specifications for HMA, the tests and specifications developed are not necessarily the same criteria needed to specify performance for PME applications, but the tools may prove useful, albeit in some modified form. In fact, there are several studies independently investigating these. A "PG-type" system consistent with the base asphalts used by the binder industry and dependent upon binder rheology and climatic and traffic conditions would be generally acceptable, if it does not disrupt the supply and truly relates to PME surface treatment performance.

The "Strawman" specification given in Table 23 suggests a promising series of protocols, but data gaps are significant. When collected for "report-only," this data will be used to validate or adjust these methods as related pavement performance dictates. FLH routinely evaluates pavements as part of its Pavement Management System. The laboratory data and field performance information collected was evaluated to prescribe tests that are effective, repeatable, and have definable physical properties that can be tied to pavement performance. Hence, there is an ongoing need for project oversight beyond the conclusion of the current study. An AASHTO pooled-fund study is envisioned, and has received widespread support.

3.4 Delayed Acceptance—Approved Supplier Certification

One of the reasons earlier attempts at emulsion performance-based specifications have failed is the concern that performance-based testing will be more time-consuming (two or more days) and result in shipping, construction, and acceptance delays. Suppliers also do not want different specifications and pre-certification requirements for different geographic regions or markets. Similar concerns with Superpave technology resulted in an Approved Supplier Certification Program for allowing the shipment of binder from authorized suppliers before testing is completed. The FHWA Pavement Preservation ETG has assigned a sub-committee, which is in the process of writing a supplier pre-certification or delayed-acceptance program for emulsions. This will be fully coordinated with the Superpave binder and mix ETGs, and advanced to the AASHTO Highway Subcommittee on Materials and AEMA/ARRA/ISSA for their consideration.

Due to unique purchasing requirements for FLH, this program would be written under guidelines for "Delayed Acceptance" rather than in the format of an Approved Supplier Program as preferred by AASHTO.

Replacing the BBR with one of the DSR methods discussed above for low temperature characterization, as well as running the DSR strain sweep for adhesion loss, will reduce equipment and testing costs as well as testing time. Work is also in progress to use DSR methods to characterize polymer elasticity and to define the non-linear rheological behavior typical of high float emulsion residues.

3.5 Strawman "Report-Only" Draft Specification

To simulate field performance, all protocols ideally avoid heating to temperatures above possible field conditions. That means a low-temperature recovery method should be used, and the residue recovered should not be reheated for further testing. A FDO procedure using a silicone mold is preferred, because the residue can be easily removed from the mold without reheating.

Table 23 illustrates a draft Strawman "report-only" testing protocol for recovery and eventual specification of PME residues. The table has both an early draft before the data from this study was collected and analyzed and a draft after the data analysis.

The first version includes rheological testing using a DSR for a minimum G*/sin δ and a maximum phase angle to determine polymer properties. The DSR is further used in the MSCR mode to determine recoverable strain and J_{nr}. High temperature testing will be done at the high temperature (T_h) grade for the base asphalt if known, and two additional temperatures in 6 ºC increments above that. It is suggested that new DSR test methods be developed to predict low temperature physical properties so that the BBR would not be needed for specification of asphalt emulsion residues. One logical approach to this problem is to use cone and plate geometry in the DSR to evaluate G* and phase angle at temperatures ranging from 0-20 ºC, and then use the CAM model to predict low temperature properties.

The second version includes suggested testing based on the results from the field and lab study, discussed in Chapter 5.

If DSR extrapolation methods cannot achieve sufficient accuracy, then new sample preparation procedures would be needed to make BBR a viable tool for classifying asphalt emulsion residues. The quantity of material needed for BBR testing may make the proposed residue recovery procedure time-consuming and inefficient. The temperature needed to heat and pour BBR samples may damage the polymer/asphalt morphology. High-float gel characteristics will be captured through some yet-to-be-determined method of defining non-linear pseudo-plastic behavior. DSR plots of ln(G*) versus shear rate or determination of a yield stress should be able to replace the antiquated float test with more quantitative measures of gel strength.

Table 23. Strawman "Report-Only" Draft Specifications—PME Residue.

Strawman First Draft – Prior to Field Trials			
Purpose	**Test**	**Conditions**	**Report**
Residue Recovery	Forced Draft Oven	24 hrs @ ambient + 24 hrs @ 60 ºC	% Residue
Tests on Residue from Forced Draft Oven			
High Temperature (Rutting/Bleeding)	DSR-MSCR DSR Freq. Sweep	T_h T_h	J_{nr} G* & Phase Angle
Polymer Identifier (Elasticity/Durability)	DSR-MSCR	T_h @ 3,200 Pa	% Recoverable Strain
High Float Identifier (Bleeding)	DSR–Non-Linearity	T_h	*Test to be developed*
Tests on PAV (run on emulsions evaporated in the PAV pan using the Forced Draft Oven procedure)			
Low Temperature (Aged Brittleness)	DSR Freq. Sweep	10 ºC & 20 ºC Model Low Temperature	G* Phase Angle
Polymer Degradation (Before/After PAV)	DSR-MSCR	T_h @ 3,200 Pa	Recoverable Strain Ratio
Strawman Revised Version after 2008 & 2009 Field Test Results			
Purpose	**Test**	**Conditions**	**Report**
Residue Recovery	Forced Draft Oven	A)24 hrs @ ambient + 24 hrs @ 60 ºC, or B)6 hrs @ 60 ºC	% Residue
Tests on Residue from Forced Draft Oven			
High Temperature (Rutting/Bleeding)	DSR	T_h (with an offset to be determined)	G*/sin δ
Polymer Identifier (Elasticity/Durability)	Single Stress DSR Creep Recovery	To be determined	% Recoverable Strain
High Float Identifier (Bleeding)	DSR–Non-Linearity	To be determined	*Test to be developed*
Tests on Aged Residue – Method To Be Determined			
Low Temperature (Aged Brittleness)	DSR Freq. Sweep	10 ºC & 20 ºC Model Low Temperature	G* Phase Angle
Polymer Degradation (Before/After PAV)	Single Stress DSR Creep Recovery	To be determined	Recoverable Strain Ratio
Aged Brittleness	Sweep Test on Aged Sample	To be determined	% Mass Loss

For long-term residue aging, the PAV is the only current standardized alternative, but questions remain about the effects on polymer modified asphalt emulsion physical properties of high temperatures never seen in the field. Although questions remain as to a specific aging protocol, rheological tests on PAV residue should characterize low-temperature behavior after aging (i.e., brittleness, raveling potential) and answer the question of what happens to the modified binder as it ages. Other research teams at WRI and ARC are developing methods for the DSR low-temperature specifications. The samples collected and tested from the four FLH field projects are a test run of the report-only concept.

3.6 Design and Performance-Based Testing

This section presents guidance on design and performance-based testing. Covered areas include aggregate-asphalt interactions and laboratory design procedures.

3.6.1 Aggregate-Asphalt Interactions

Both the short and long term performance (curing time, adhesion, skid resistance, long term chip retention and durability) are dependent upon the aggregate physical properties and the asphalt-aggregate compatibility as well as the physical properties of the emulsion. Performance-related testing is needed on both aggregates and the combination of PME and aggregate.

There are several well-accepted performance-related tests for aggregates. It is clear that cleanliness, shape and durability (as tested by MicroDeval or LA abrasion) are directly related to performance. Aggregate surface chemistry becomes increasingly more important when cure-time-to-traffic is critical to performance.

3.6.2 Laboratory Design Procedures

Chip Seals: The literature review mentions a few of the many design procedures for chip seals, most of which have evolved from McCloud's original work. Dr. Kim's recent studies for the North Carolina DOT specifically address aggregate quality, evaluate various design procedures for chip seals, and offer excellent recommendations that should be considered for FLH guidelines.(103) Although the current ASTM method needs modest revision, the sweep test is viable for ranking curing time, and should be included in the FLH field study. While there are several laboratory test methods for long-term chip seal performance, none has universal acceptance. This is an area where further study is needed, and that is currently being investigated by other research projects such as NCHRP 14-17. The MMLS3, as developed in South Africa and as investigated by Dr. Kim and Dr. Epps, remains a valuable performance-based testing tool.(100) It can be run wet or dry and its rubber tires simulate unidirectional traffic loading on samples. At approximately $100,000, the machine cost is prohibitive as a specification tool, but it can serve as an accelerated simulator for field performance to accelerate validation of other methods.

Micro Surfacing/PME Slurry: Current ISSA mix design and performance-related testing guidelines offer acceptable performance-related standards for micro surfacing.(39) However, better residue specifications and improved mix design protocols are still needed. As discussed elsewhere, the Caltrans pooled-fund study should serve as a source for new tests and methods applicable to micro surfacing mix design.(101)

4.0 PME TEST PLAN AND STRAWMAN SPECIFICATION

4.1 Strawman Specification for Emulsion Residues

With input from a number of researchers and users and approbation from Federal Lands Highway, the initial suggested Strawman specification was developed (see Table 23). Note that it is hoped that the BBR will be replaced by low temperature parameters G* and phase angle (δ) as modeled from intermediate temperature DSR results, or possibly as directly measured using a DSR equipped with 4 mm plates.

4.2 Testing Plan

To verify the format of the Strawman specification, a testing plan was developed as part of this study for use as report-only for several Federal Lands Highway field projects constructed in 2008 and 2009. The tests were run at several temperatures and stress levels to better define the test conditions and limits. Laurand Lewandowski of PRI Asphalt Technologies, Inc. worked closely with the project research team to develop the proposed testing plan presented herein.

PRI was equipped to run all proposed tests for those suppliers or agencies that did not have the capability. PRI Asphalt Tecnologies, Inc., BASF Corp., Paragon Technical Services, Inc., and SemMaterials, LLC ran tests on split samples from the 2008 projects; PRI, BASF, Paragon, Ultrapave, and Kraton Performance Polymers, Inc. ran tests on the samples from the 2009 project at Crater Lake National Park. While the testing during this evaluation has an estimated cost of $2,000 to $3,000 per asphalt emulsion, it is expected that the final specification tests will cost approximately $1,000.

The full list of PME Testing Plan protocols for the 2008 evaluations is provided below in Table 24. The labs used the proposed ASTM low temperature FDO method modified by Lubbers, Takamura, and Kadrmas to recover original residue, and a newly developed method using PAV pans to recover residue prior to PAV-aging. To determine resistance to rutting and bleeding, G* and sin delta were obtained from DSR frequency sweeps on the residues using standard Superpave protocols. Creep compliance and percent residue recovery were determined via MSCR testing. Three rheological tests were planned to measure resistance to low temperature cracking, including:

1.) Frequency sweeps at 0, 10, and 20 °C;
2.) DSR using 4-mm plates at the low pavement temperature (performed by WRI); and
3.) Low temperature BBR.

Unfortunately, the procedure for the low temperature DSR test required further development, and is only now reaching the accuracy and reproducibility needed for application to emulsion residues. Items 1 and 2 above were not completed.

For resistance to aggregate loss (shelling) on original and PAV-aged residue, participants ran strain sweep tests at 25 °C and measured loss in G*. Further, sweep testing (ASTM D7000) using project aggregates and emulsions was used to determine chip seal curing time. FLH will use their road rating trailer to track initial and long-term field performance over a minimum three year interval. These field results will be correlated with lab data to validate the test procedures and to determine appropriate failure limits to allow for the development of performance-based specifications for polymer-modified emulsion pavement preservation applications for FLH projects.

The test plan was altered for tests on the 2009 Crater Lake National Park project. The proposed low temperature recovery procedure was adopted in 2009 by ASTM as D7497 ("Standard Practice for Recovering Residue from Emulsified Asphalt Using Low Temperature Evaporative Technique"), which included two alternative procedures. Procedure A requires two days to run the test (24 hours at 25 °C and 24 hours at 60 °C), while Procedure B is a six-hour test (at 60 °C) using a thinner application of emulsion. Results reported from the series of tests run in 2008 indicated that significant oxidative aging may be occurring during Procedure A's 48-hour recovery period. The shorter exposure to oxygen and faster test turnaround led researchers to believe Procedure B might be preferred, so both of these recovery methods were used for the 2009 testing. Also, because of the information gained from the results of 2008, residue testing protocols were altered for the 2009 Crater Lake project. The MSCR was initially run at two temperatures, 25 and 64 °C; and at two stress levels, 100 and 3,200 kPa. Because the percent recovery values were so low, and sometimes even negative at 3,200 kPa and 64 °C, some tests were also run at 3,200 kPa and 58 °C, and temperatures were further reduced to 52 °C for the final samples. Additionally, standard PG tests were run to determine where temperatures meet the SuperPave $G^*/\sin \delta$ criteria of 1 MPa, as well as the 0.65 MPa limit proposed by Hoyt, Epps Martin, and Shuler as the optimal stiffness for chip seal binders.(105) To ensure all labs used the same protocols, PRI coordinated their efforts. Emulsions were kept in 60 °C (140 °F) ovens. ASTM D7497 was used to recover material for DSR testing; the residue was scraped off of the silicone mat without additional heat for testing in the DSR. For the PAV testing, 50 g of emulsion was placed in the PAV pan for the forced draft oven emulsion curing, followed by the standard PAV aging test. Following the test, the samples were heated for a maximum of 15 minutes at 135 °C to prepare them for the BBR tests after PAV.

For the sweep testing on the 2009 Crater Lake samples, the aggregates were prepared and distributed by PRI. Chris Lubbers of Kraton coordinated and gathered the sweep test data.

Table 25 is a summary of the field project information and assigned responsibilities.

Table 24. Testing Plan Protocols for 2008 Evaluations.†

PROPERTY	TEST METHOD		SPEC	RESULT
Asphalt Emulsion as Received				
Standard AASHTO or ASTM tests:	AASHTO M 140 Emulsified Asphalt or AASHTO M 208 Cationic Emulsified Asphalt			
Field Viscosity Test	WYDOT 538.0		Report	
Evaporative Method Residue (24 hours @ 25 °C, 24 hours @ 60 °C, Forced Draft Oven)				
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 10% Strain)	HTG†	AASHTO T 315	Report	Frequency Sweep (G*, delta, etc…)
Multiple Stress Creep Recovery (MSCR) (100, 1,000, 3,200 & 10,000 Pa)		TP 70-08		% Recovery & J_{nr} at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 10% Strain)	HTG - 6 °C	AASHTO T 315		Frequency Sweep (G*, delta, etc…)
Multiple Stress Creep Recovery (100, 1,000, 3,200 & 10,000 Pa)		TP 70-08		% Recovery & J_{nr} at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 10% Strain)	HTG -12 °C	AASHTO T 315		Frequency Sweep (G*, delta, etc…)
Multiple Stress Creep Recovery (100, 1,000, 3,200 & 10,000 Pa)		TP 70-08		% Recovery & J_{nr} at each stress level
Test Strain Sweep, 1 – 50% strain, 10rad/s	25 °C			Resist to Deformation: G*/sin δ @ 12% Strain Strain Tolerance: Strain Level at G* <90%G*ini Failure Properties: Strain Level at G* <50%G*ini
Pressure Aging Residue (100 °C, 300 psi, 20 hours) R 28 (PAV run on residue obtained by FDO method run in PAV pan)				
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 1% Strain)	HTG†	AASHTO T 315	Report	Frequency Sweep (G*, delta, etc…)
Multiple Stress Creep Recovery (100, 1,000, 3,200 & 10,000 Pa)		TP 70-08		% Recovery & J_{nr} at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 1% Strain)	HTG - 6 °C	AASHTO T 315		Frequency Sweep (G*, delta, etc…)
Multiple Stress Creep Recovery (100, 1,000, 3,200 & 10,000 Pa)		TP 70-08		% Recovery & J_{nr} at each stress level
Frequency Sweep (25 mm, 0.1 – 100 rad/sec, 1% Strain)	HTG -12 °C	AASHTO T 315		Frequency Sweep (G*, delta, etc…)
Multiple Stress Creep Recovery (100, 1,000, 3,200 & 10,000 Pa)		TP 70-08		% Recovery & J_{nr} at each stress level
Frequency Sweep (8 mm, 0.1-100 rad/sec, % Strain TBD)	0 °C	AASHTO T 315		Frequency Sweep (G*, delta, etc…)
Frequency Sweep (8 mm, 0.1-100 rad/sec, % Strain TBD)	10 °C			Frequency Sweep (G*, delta, etc…)
Frequency Sweep (8 mm, 0.1-100 rad/sec, % Strain TBD)	20 °C			Frequency Sweep (G*, delta, etc…)
Test Strain Sweep, 1 – 50% strain, 10 rad/s	25 °C			Resist to Deformation: G*/sin δ @ 12% Strain Strain Tolerance: Strain Level at G* <90%G*ini Failure Properties: Strain Level at G* <50%G*ini
Bending Beam Rheometer	-12 °C + -18 °C	AASHTO T 313		Stiffness + m-value
Performance-Related Tests for Chip Seals				
Sweep Test	Modified ASTM D7000			Report
Performance-Related Tests for Polymer Modified Slurry Seals and Micro Surfacing				
Recommended Performance Guidelines for Emulsified Asphalt Slurry Seal Surfaces Recommended Performance Guidelines for Polymer Modified Micro Surfacing Tests recommended by Caltrans Slurry/Micro Surface Mix Design Procedure Project/Contract 65A0151	ISSA A105 ISSA A143 TBD		ISSA ISSA	

†2009 changes to test plan: Residue recovery following ASTM D7497-09, both procedures A and B.
MSCR tests were run at two temperatures and stress levels: 25 and 64 °C; 100 and 3,200 kPa.

The field projects constructed for this study include numerous project sites, six emulsion suppliers, and multiple contractors. Climates ranged from very hot and dry (Death Valley National Park) to cold and wet, as well as extreme temperature ranges. Construction information on the projects is given in Table 25, and the test plan is in Table 24. The test results are in Chapter 5. The specifications used to construct the projects are in Appendix B.

In late September, 2008, an 11-mile neoprene modified asphalt emulsion chip seal was placed at Dinosaur National Monument, which spans the borders of Utah and Colorado.

The “Utah Parks” project included 90 miles of application of SBR latex modified CRS-2L (henceforth called CRS-2L-UT in this report) and natural rubber modified micro surfacing to locations in Arches National Park, Canyonlands National Park, Natural Bridge National Monument, and Hovenweep National Monument in September and October 2008.

Death Valley National Park was the site of a 21-mile SBR latex modified asphalt (referred to herein as CRS-2L-DV) chip seal project in November, 2008.

A chip seal was applied to Crater Lake National Park in Oregon in 2009. It is important to include the most commonly used and available polymer modified technologies. Because of the unusual industry supply situation during the oil crisis of 2008, it was not possible to include an SBS modified emulsion chip seal in the 2008 projects. The Crater Lake project included both SBR latex and SBS block co-polymer modified chip seal sections. A sample of unmodified emulsion was also obtained from the emulsion supplier, to be tested as a control for the polymer modified emulsions. The SBR latex modified emulsion is designated CRS-2L-CL, the SBS modified emulsion as CRS-2P-CL, and the unmodified emulsion as CRS-2.

Photos of the projects are shown in Figures 28-49.

Table 25. Project Construction Information and Testing Responsibilities.

Project and Status	Contractor	Supplier / Technology	Project Quantities & Costs	Lab Testing
Dinosaur Project #: UT NPS DINO-PRES-1(08) Contract signed (8a small business negotiated). Production 9/23/08- 9/30/08 Project Engineer: Nick Maximoff	Hardrives Construction, Inc. 4800A Helfrick Rd, Billings, MT 59101	Chip seal emulsion: PASS® (neoprene-modified emulsion) Asphalt Systems, Inc. –Salt Lake City	~ 11.4 mile project ~ 165 tons of emulsion @ \$1664/ton ~135,000 yd^{2} chip sealing @ \$1.65 per yd^{2}	PRI: emulsion & aggregates CFLHD Lab: acceptance testing only
Utah Parks Project #: CO IMR-PRES-1(08) ARCH, CANY, NABR, & HOVE Production 9/6/08 - 10/17/08 Project Engineer: Joe Kosine	Intermountain Slurry Seal, Inc 585 W. Beach St. Watsonville, CA 95075 Paul Foster, contact	CRS-2L-UT Chip Seal Emulsion: CRS-Latex modified (SBR) Ergon – Snowflake, AZ Micro Surfacing: Ralumac® (natural rubber) SemMaterials – Salt Lake City	~90 mile project ~1290 tons of CRS-LM @ \$1495/ton ~1,140,000 yd^{2} chip sealing @ \$0.95 to \$1.85 per yd^{2} ~60,000 yd^{2} micro surfacing @ \$4 to \$5.75 per yd^{2}	PRI: Testing chip, micro emulsion & aggregates. Paragon: chip emulsion & aggregates BASF: chip emulsion & aggregates SemMaterials: Micro emulsion NCHRP study (Shuler): chip emulsion & aggregates CFLHD Lab: acceptance testing only
Death Valley Project #: CA NPS DEVA 15(3). Contract signed (8a small business negotiated). Production started 11/11/08, completed 11/14/08 Project Engineer: Nick Maximoff	Hardrives Construction, Inc. 4800A Helfrick Rd, Billings, MT 59101	CRS-2L-DV Chip Seal Emulsion: CRS-Latex modified (SBR) Western Emulsions – Irwindale, CA	~ 21 mile project ~ 290 tons of emulsion @ \$1,350/ton ~271,000 yd^{2} chip sealing @ \$1.27 per yd^{2}	PRI: emulsion & aggregates Paragon: emulsion & aggregates BASF: emulsion & aggregates CFLHD Lab: acceptance testing only
Crater Lake Project #: CA PWR –PRES-1(08) Contract signed (8a small business negotiated). Production started 9/28/09, completed 10/9/09 Project Engineer: Kahaa Rezantes	De Los Santos 444 SE Maple Dr. North Bend, WA 98045-9421	CRS-2L-CL SBR Latex Chip Seal Emulsion CRS-2P-CL SBS Block Copolymer Chip Seal Emulsion	~23 mile project ~420 tons of emulsion @ \$1497/ton ~367,000 yd^{2} chip sealing @ \$1.98 per yd^{2}	PRI: emulsion and sweep Paragon: emulsion and Sweep Ultrapave: emulsion and Sweep BASF: emulsion and Sweep Kraton: emulsion CFLHD Lab: acceptance testing only

Figure 28. Photo. Dinosaur Project—Route 10 Park Pay Station.

Figure 29. Photo. Dinosaur Project—Green River Campground, Loop 'B.'

Figure 30. Photo. Dinosaur Project—Pay Station Chipsealing.

Figure 31. Photo. Dinosaur Project—Loop 'B' After Completion.

Figure 32. Photo. Dinosaur Project—Green River Access Road after Completion.

Figure 33. Photo. Dinosaur Project—Route 10 after Completion.

Figure 34. Photo. Utah Parks Project—Micro Surfacing at Arches National Park.

Figure 35. Photo. Utah Parks Project—Arches NP Partially Fogged.

Figure 36. Photo. Utah Parks Project—Canyonlands NP Chip Seal Emulsion Application.

Figure 37. Photo. Utah Parks Project—Canyonlands NP Chip Seal Chip Application.

Figure 38. Photo. Utah Parks Project—Canyonlands NP Chip Seal Construction.

Figure 39. Photo. Utah Parks Project—Canyonlands NP Finished Chip Seal after Fog and Striping.

Figure 40. Photo. Utah Parks Project—Hovenweep National Monument Micro Surfacing.

Figure 41. Photo. Utah Parks Project—Natural Bridges National Monument Chip Seal.

Figure 42. Photo. Death Valley Project—Chip Seal Emulsion Application.

Figure 43. Photo. Death Valley Project—Chip Seal Aggregate Application.

Figure 44. Photo. Death Valley Project—Chip Seal Construction.

Figure 45. Photo. Death Valley Project—Rolling the Chip Seal.

Figure 46. Photo. Crater Lake Project Chip Seal Application.

Figure 47. Photo. Crater Lake Project Showing Road Condition.

Figure 48. Photo. Crater Lake Project Chip Seal Texture.

Figure 49. Photo. Crater Lake Project Construction and Traffic Control.

5.0 FIELD TRIAL TEST RESULTS AND DISCUSSION

The tests were run according to the protocol in Table 24. The 2008 emulsions tested were Ralumac (natural rubber latex modified), CRS-2L-DV (SBR latex modified), CRS-2L-UT (SBR latex modified), and PASS Emulsion (neoprene modified). The 2009 emulsions were tested with an improved protocol and included the CRS-2L-CL (SBR latex), CRS-2P-CL (SBS block co-polymer) applied on the Crater Lake project, as well as a sample of a standard CRS-2 emulsion. While the CRS-2 was not used on any of the projects, the test results show the difference between the unmodified and polymer modified emulsions.

5.1 Tests on 2008 Projects

One of the primary goals of the testing on emulsions sampled from the 2008 projects was to verify the proposed test methods and conditions. Some of the inter-laboratory residue tests did not give acceptable agreement. Further investigation revealed the testing labs used slightly different procedures for the FDO. Some labs used a silicone mold for obtaining residue for all residue tests, while at least one lab used PAV pans for all testing. While the results may not be as accurate as hoped, they did give information needed to tweak the test methods and temperature and stress conditions for testing on samples from the 2009 project. Based on the results, it was determined that better control of the sample conditioning and preparation would be beneficial, and the researchers were able to improve test temperatures and stresses, as noted above.

5.1.1 Conventional Test Results

The Central Federal Lands Highway Division laboratory conducted conventional emulsion testing on field samples from all four projects. Paragon Technical Services, Inc. evaluated the CRS-2L-UT from the Utah Arches National Park project and the CRS-2L-DV from the Death Valley National Park project. Paragon then tested these same emulsion samples using the full report-only protocol. The results of the conventional emulsion tests run by the Central Federal Lands Highway Division laboratory and Paragon are given in Table 26. The micro surfacing tests run on the Ralumac project are in Table 27. Other project quality control data, including aggregate testing, is available on the National Center for Pavement Preservation website at www.pavementpreservation.org.

All emulsions exceeded the minimum residue requirement of 65 percent, although many lab samples failed the minimum viscosity requirement of 100 SFS. This was not unexpected, as late season emulsions are often manufactured at the low end of the viscosity range, and emulsions viscosities tend to fall rapidly in unheated sample bottles. These failing results emphasize the previously recommended need for a field test for emulsion viscosity. No problems typical of low emulsion viscosity such as run-off or pooling were reported from the field trials, so there is no reason to believe these emulsions were not delivered to the project in specification. Similarly, no problems were reported with sieve or particle charge.

The three key residue tests in current PME specifications are penetration (25 °C or 4 °C), ductility (25 °C and 4 °C), and elastic recovery in a ductilometer. As noted in Table 26, 25 °C penetrations were 54 dm for Ralumac, 49 dm for CRS-2L-UT, and ranged from 57 to 77dm for CRS-2L-DV. The penetrations for the Ralumac and CRS-2L-UT are typical of a PG 64-22 or AC-20, and the penetration of the CRS-2L-DV is in the range that would be expected for a softer

PG 58-28 or AC-10. PASS Emulsion typically contains a blend of asphalt and rejuvenator oils, so the residue is typically much softer than conventional PME specifications would allow. It is therefore sold under its own proprietary specification and uses penetration at the lower 4 °C to control consistency. Ductility at 25 °C means very little for PME residues, because the strength of the polymer network can actually decrease ductility at higher temperatures. Ductility at 4 °C is much more relevant for PMEs. Results for the CRS-2L-DV emulsion supplied to Death Valley were quite erratic. Three field samples pulled from 10-18 cm, but the other two failed almost immediately. No other emulsions were tested for low temperature ductility. The CRS-2L-DV was also the only emulsion tested for elastic recovery. Results for four field samples ranged from 48 to 68 percent, with two of those samples passing and two failing the specification minimum of 58 percent.

Like the FLH lab results, the Paragon emulsion viscosities for the two products tested were marginal to failing, but the long interval between application and testing renders these results relatively useless. Sieve, storage, settlement, demulsibility, and particle charge results were all well within specification. Penetrations were somewhat softer than those reported by FLH (60 and 90 dm respectively), but the difference in consistency between these two residues remains about one full grade as defined by penetration grading systems. Paragon used the California Torsional Recovery test (CA 332) as required by Utah specifications to define elastomeric properties of the polymer. The CRS-2L-UT residue recovery of 23.5 percent exceeded the 18 percent minimum required by the Utah specification; the Death Valley product would have failed this specification with a recovery of 15.7 percent, but torsional recovery was not part of the specification for this location. The torsional recovery test is regarded by the research team to be a very poor indicator for polymer content because it arbitrarily eliminates the early part of the recovery period from total relaxation.

Table 26. Conventional Emulsion Test Results on Field Trial Samples.

Tests on Emulsion, T 59	Speci-fications	Death Valley CRS-2L-DV						Dinosaur PASS Emulsion			Utah CRS-2L-UT Field #1	Utah Ralumac
		Field #1	Field #2	Field #3	Field #5	Field #12	Field #16	9/23 sample	9/24 sample	Supplier QC		
Saybolt Furol Viscosity at 25 °C, s										120		
Saybolt Furol Viscosity at 50 °C, s	100-400	68.2	54.8	58.5	178	268	222	50.8	41.8		258	
Sieve Test, %	<0.1									<0.1%		
Particle Charge Test	Positive	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	pH 2.81	Pass	
Residue by Evaporation, %	>65	69.5	69.8	69.7	69.6	67.5	69.2			66	70.9	64.9
Tests on Residue												
Penetration at 25 °C (100 g, 5s)T49	<86	67	67	77	72	57					49	54
Penetration at 4 °C (100 g, 5s) T49								20	19			
Ductility at 25 °C, cm T51		132	122	113	150+	150+	150+	62	59		150+	
Ductility at 4 °C, cm T51		8	1	10	18	17	1					
Elastic Recovery at 25 °C, %, ASTM D6085	<58	58	55	68	68	48						
Rotational Viscosity, 275 °F, cPa T316												2517
Paragon Test Results (T-59)		**Utah Specs**				**CRS-2L-DV**					**CRS-2L-UT**	
Sieve, %		<0.3				0.02					0.01	
50 °C SFS Viscosity, Seconds		140-400				125					90.7	
24 Hour Storage, %		<1				0.03					0.06	
5 Day Settlement, %		<5				0.1					0.37	
Demulsibility, %		>40-				91.25					100	
Particle Charge		Positive				Positive					Positive	
Distillation:												
Residue, %		>65				69.15					70.68	
Oil Distillate, % by volume		<0				0.25					0.125	
Test on Distillation Residue:												
25 °C Penetration, dmm		40-200				93					60	
25 °C Ductility, cm		>125				150					150	
Torsional Recovery (CA 332)		>18				15.7					23.5	

Table 27. Micro Surfacing Test Results.

Test	Results	Min.	Max.
ISSA TB 113 Mix time	180 sec +	180 sec	
ISSA TB 139 Wet Cohesion	12 kg-cm @ 30 min. 20 kg-cm @ 60 min.	12@ 30 20(NS) @ 60	
ISSA TB 114 Wet Stripping	>95%	90%	
ISSA TB 100 Wet Track Abrasion, 1 hour	80.5 @ 9% emuls 26.9 @ 11% emuls 25.7 @ 13% emuls 22.6 @ 15% emuls		75 g/ft^2
ISSA TB 106 Slurry Seal Consistency	2.9 cm	2 cm	3 cm
ISSA TB 102 Set Time	45 minutes		60 minutes
AASHTO T 176 Sand Equivalent	66	45	
AASHTO T 27/T 11 Gradation			
3/8"	100	100	100
No. 4	85	70	90
No. 8	55	45	70
No. 16	39	28	50
No. 30	29	19	34
No. 50	21	12	25
No. 100	15	7	18
No. 200	10.4	5	15

5.1.2 Report-Only Test Results and Discussion

The proposed test plan protocols given in Table 24 were run on samples from the field projects. This plan included more testing than would be expected for a performance-based specification (such as the Strawman specification given in Table 23), in order to gather information useful to determine the effectiveness, reliability, optimal test conditions, and potential specification limits of the proposed tests. PRI Asphalt Technologies, Inc. led the lab testing phase of the performance-based report-only testing program. Laboratories at Paragon Technical Services and BASF also supported the study by providing results for the FDO recovery method, sweep test, and other procedures that needed multi-lab results to evaluate test reproducibility. The goals are to tie the test results to the performance of specific emulsion applications, minimize the exposure of emulsion residue to excess heat and agitation (which are not present in the field), and maximize the use of the DSR to replace all other emulsion residue test equipment. The results are given below.

5.1.2.1 Recovery of Emulsion Residue by Forced Draft Oven

There is general agreement that conventional emulsion residue recovery tests do not simulate field curing. The high distillation and evaporation temperatures are not seen in the field; they break down some polymers and cause additional cross-linking with others. The agitation of the hot, cured residue does not occur in the field. Such industry groups as AEMA, ASTM, and European agencies have all been evaluating alternative methods, including the FDO procedure (ASTM D7497-09 “Standard Practice for Recovering Residue from Emulsified Asphalt Using Low Temperature Evaporative Technique”), the stirred can test, and the moisture analyzer. ASTM D7497 was selected for the Strawman (Table 23) because it is run at conditions most closely simulating field conditions, and has given acceptable results with interlab reliability testing and comparison of residue properties with the properties of the base asphalt. At the time, it was a proposed ASTM standard (which was accepted midway through this study). Table 28 compares the results of the percent residue from the proposed and conventional tests.

Table 28. Comparison of Residue Recovery Test Methods.

Test	Test Temp., °C	Procedure	Spec	Ralumac LMCQS-1H	CRS-2L-DV, Death Valley Project	CRS-2L-UT, Utah Arches	PASS Emulsion
Evaporative Method Residue (24 hours @ 25 °C, 24 hours @ 60 °C, Forced Draft Oven)							
Residue by Evaporation, %	25, 60	ASTM D7497	Report	64.8	68.9	70.2	66.4
Conventional AASHTO Method							
Residue by Evaporation, %		T 59		64.9	67.5-69.7	70.9	66.0

The FDO was run by Paragon Testing Laboratories, with slight modifications to the procedure currently under consideration by ASTM. There is still work to be done to determine how much aging the FDO procedure produces, i.e., if the FDO alters the initial base asphalt and polymer properties.

5.1.2.2 Residue Aging by Pressure Aging Vessel (PAV)

The aging protocol for performance-graded testing on asphalts for hot mix includes a RTFO test to simulate aging in the hot mix plant and the PAV test (on residue obtained by RTFO) to simulate long term on-the-road aging. The RTFO is obviously not applicable to emulsions, but the PAV is now standard for long term field aging. This study prepared the samples for PAV by running the 48-hour FDO in the same PAV pans to be placed in the PAV. The residue from the completed PAV was then scraped and tested in the DSR, with minimal to no reheating or agitation required.

There are still some issues. Sufficient emulsion must be placed in the PAV pan to allow adequate film thickness of the FDO cured emulsion for the standard PAV test. There is some question if all the water is evaporated during the FDO run in the PAV pans. Thinner films age faster, but they should also dry more quickly. The 100 °C standard PAV temperature exceeds high pavement temperatures, which may alter cured polymer structure and/or cause temperature-induced coalescence of recovered asphalt droplets in the residue. The procedure as outlined here appears to be viable, but more data needs to be collected to determine the optimal conditions for film thickness, aging time, and temperature for a given application.

5.1.2.3 Residue Testing—Residue Before and After PAV Aging

As mentioned above, the goal is a performance-based specification using a testing protocol that is efficient, reliable, and accurately characterizes field behavior. The report-only testing (Table 24) performed in this study is meant to collect data over a broad range of temperature and loading conditions at a cost of approximately $4,000 per sample. The ultimate specification will only use the test conditions needed for a specific application with a target testing cost of $1,000 per individual certification. The results of the testing are given in Table 29.

Table 29. Test Results from Test Plan Protocol.

Test	Test Temp., °C	Procedure	Spec	Ralumac LMCQS-1H	CRS-2L-DV, Death Valley Project	CRS-2L-UT, Utah Arches	PASS Emulsion
Evaporative Method Residue (24 hours @ 25 °C, 24 hours @ 60 °C, Forced Draft Oven)							
Residue by Evaporation, %		Draft Method	Report	64.8	68.9	70.2	66.4
Water Content, %		ASTM D95	Report	0	0	0	0
Frequency Sweep (25 mm, 0.1 - 100 rad/sec, 12% Strain		AASHTO T 315	Report	*	*	*	*
MSCR - % Rec (100 Pa)	70	TP 70-08	Report	31.46	16	21.9	10.72
MSCR - % Rec (1,000 Pa)	70	TP 70-08	Report	16.17	7.5	12.51	0.85
MSCR - % Rec (3,200 Pa)	70	TP 70-08	Report	11.12	5.85	7.26	0.11
MSCR - % Rec (10,000 Pa)	70	TP 70-08	Report	7.07	0.9	7.08	0.03
MSCR - J_{nr} (1,000 Pa) kPa-1	70	TP 70-08	Report	3.53	12.26	2.11	53.46
MSCR - J_{nr} (10,000 Pa) kPa^{-1}	70	TP 70-08	Report	4.71	16.2	2.89	74.06
MSCR - J_{nr} (100 Pa) kPa-1	70	TP 70-08	Report	2.7	10.32	1.81	40.53
MSCR - J_{nr} (3,200 Pa) kPa-1	70	TP 70-08	Report	4.09	13.12	2.52	60.09
Frequency Sweep (25 mm, 0.1 - 100 rad/sec, 12% Strain		AASHTO T 315	Report	*	*	*	*
MSCR - % Rec (100 Pa)	64	TP 70-08	Report	34.75	17.24	21.94	28.66
MSCR - J_{nr} (100 Pa) kPa^{-1}	64	TP 70-08	Report	1.34	4.67	0.94	16.48
MSCR - % Rec (1,000 Pa)	64	TP 70-08	Report	24.59	7.39	17.59	3.79
MSCR - J_{nr} (1,000 Pa) kPa^{-1}	64	TP 70-08	Report	1.59	5.5	1.01	27.06
MSCR - % Rec (3,200 Pa)	64	TP 70-08	Report	17.25	8.65	10.14	0.71
MSCR - J_{nr} (3,200 Pa) kPa^{-1}	64	TP 70-08	Report	1.92	5.74	1.19	32.09
MSCR - % Rec (10,000 Pa)	64	TP 70-08	Report	13.86	4.45	9.39	0.05
MSCR - J_{nr} (10,000 Pa) kPa^{-1}	64	TP 70-08	Report	2.2	6.59	1.38	39.25
Frequency Sweep (25 mm, 0.1 - 100 rad/sec, 12% Strain		AASHTO T 315	Report	*	*	*	*
MSCR - % Rec (100 Pa)	58	TP 70-08	Report	38.05	16.93	25.81	37.27
MSCR - J_{nr} (100 Pa) kPa^{-1}	58	TP 70-08	Report	0.63	2.068	0.45	7.29
MSCR - % Rec (1,000 Pa)	58	TP 70-08	Report	33.3	10	22.69	12.39
MSCR - J_{nr} (1,000 Pa) kPa^{-1}	58	TP 70-08	Report	0.68	2.3	0.46	11.78
MSCR - % Rec (3,200 Pa)	58	TP 70-08	Report	25.88	7.36	16.56	3.73
MSCR - J_{nr} (3,200 Pa) kPa^{-1}	58	TP 70-08	Report	0.81	2.53	0.52	14.68
MSCR - % Rec (10,000 Pa)	58	TP 70-08	Report	18.86	8.06	10.92	0.57
MSCR - J_{nr} (10,000 Pa) kPa^{-1}	58	TP 70-08	Report	0.99	2.71	0.63	18.63

Table 29. Test Results from Test Plan Protocol, Cont.

Test	Test Temp., °C	Procedure	Spec	Ralumac LMCQS-1H	CRS-2L-DV, Death Valley Project	CRS-2L-UT, Utah Arches	PASS Emulsion
PRESSURE AGING RESIDUE (100 °C, 300 psi, 20 hr)							
Frequency Sweep (8 mm, 0.1 – 100 rad/sec, 1% Strain)		AASHTO T 315	Report	*	*	*	*
MSCR - % Rec (100 Pa)	70	TP 70-08	Report	N/A	N/A	-	N/A
MSCR - J_{nr} (100 Pa) kPa-1	70	TP 70-08	Report			-	
MSCR - % Rec (1,000 Pa)	70	TP 70-08	Report	36.16	8.58	23.67	
MSCR - J_{nr} (1,000 Pa) kPa-1	70	TP 70-08	Report	0.54	1.55	0.75	
MSCR - % Rec (3,200 Pa)	70	TP 70-08	Report	23.36	0.56	10.25	
MSCR - J_{nr} (3,200 Pa) kPa-1	70	TP 70-08	Report	0.72	1.818	1.05	
MSCR - % Rec (10,000 Pa)	70	TP 70-08	Report	12.98	0	5.5	
MSCR - J_{nr} (10,000 Pa) kPa^{-1}	70	TP 70-08	Report	1.01	2.804	1.52	
Frequency Sweep (8 mm, 0.1 – 100 rad/sec, 1% Strain)	64	AASHTO T 315	Report	*	*	*	*
MSCR - % Rec (100 Pa)	64	TP 70-08	Report	N/A	N/A	-	N/A
MSCR - J_{nr} (100 Pa) kPa^{-1}	64	TP 70-08	Report			-	
MSCR - % Rec (1,000 Pa)	64	TP 70-08	Report	33.9	19.43	42.55	
MSCR - J_{nr} (1,000 Pa) kPa^{-1}	64	TP 70-08	Report	0.24	0.574	0.15	
MSCR - % Rec (3,200 Pa)	64	TP 70-08	Report	32.97	11.68	31.42	
MSCR - J_{nr} (3,200 Pa) kPa^{-1}	64	TP 70-08	Report	0.25	0.657	0.19	
MSCR - % Rec (10,000 Pa)	64	TP 70-08	Report	19.89	3.43	19.8	
MSCR - J_{nr} (10,000 Pa) kPa^{-1}	64	TP 70-08	Report	0.36	1.106	0.25	
Frequency Sweep (8 mm, 0.1 – 100 rad/sec, 1% Strain)	58	AASHTO T 315	Report	*	*	*	*
MSCR - % Rec (100 Pa)	58	TP 70-08	Report	N/A	N/A		N/A
MSCR - J_{nr} (100 Pa) kPa^{-1}	58	TP 70-08	Report				
MSCR - % Rec (1,000 Pa)	58	TP 70-08	Report	43.33	30.52	44	
MSCR - J_{nr} (1,000 Pa) kPa^{-1}	58	TP 70-08	Report	0.099	0.211	0.06	
MSCR - % Rec (3,200 Pa)	58	TP 70-08	Report	42.54	24.04	43.24	
MSCR - J_{nr} (3,200 Pa) kPa^{-1}	58	TP 70-08	Report	0.1	0.236	0.06	
MSCR - % Rec (10,000 Pa)	58	TP 70-08	Report	33.26	14.29	36.61	
MSCR - Jnr (10,000 Pa) kPa-1	58	TP 70-08		0.12	0.299	0.07	
Frequency Sweep (8 mm, 0.1 – 100 rad/sec, 1% Strain)	10	AASHTO T 315	Report	*	*	*	*
Frequency Sweep (8 mm, 0.1 – 100 rad/sec, 1% Strain)	20	AASHTO T 315	Report	*	*	*	*
Strain Sweep(8 mm, 1 – 50% Strain, 10 rad/sec	25	New Method	Report	*	*	*	*
Stiffness, MPa (60 sec.) -18 °C	-18	AASHTO T 313	300 max.	272	243	315	68
m-value -18 °C	-18	AASHTO T 313	0.300 min.	0.308	0.228	0.282	0.338
Stiffness, MPa (60 sec.) -12 °C	-12	AASHTO T 313	300 max.	120	100	142	18
m-value -12 °C	-12	AASHTO T 313	0.300 min.	0.371	0.384	0.348	0.376

* These results are data sets currently under analysis by researchers working on related on-going projects. It is expected this data will be useful in combination with the data from those projects in developing future specifications and limits.

5.1.2.4 Report-Only Testing—MSCR

The AASHTO "Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)" TP 70-1 was selected to define the high temperature flow and the elasticity of PME residues. This procedure has been under development by FHWA, and has been published by AASHTO. The FHWA sponsored Binder ETG is currently evaluating target test criteria for hot mix asphalt binders. The current AASHTO test can be run on the original binder or on residue from either the RTFO or PAV aging tests. For these emulsion tests, it was run on FDO residues with as little manipulation of the sample as possible. Specimens are placed directly on the DSR plate without reheating. The results are listed in Table 29 above. Figures 50 through 52 are plots of the J_{nr} (compliance) versus the four tested stress levels at the three test temperatures

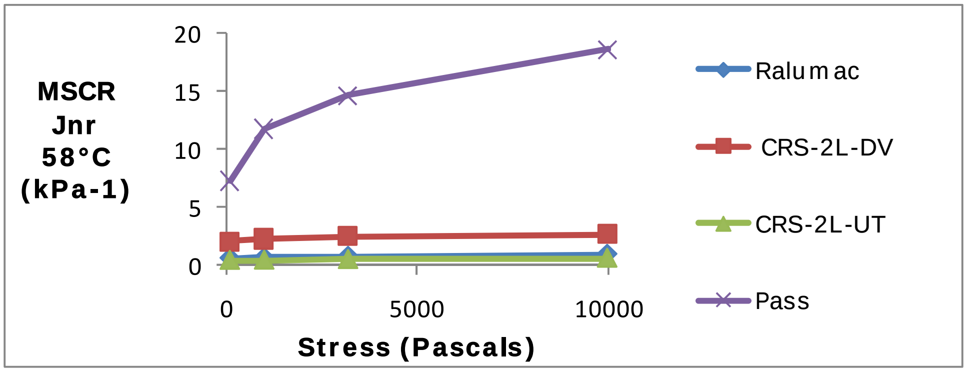


Figure 50. Graph. MSCR—J_{nr} vs. Stress for FDO Residues at 58 °C.

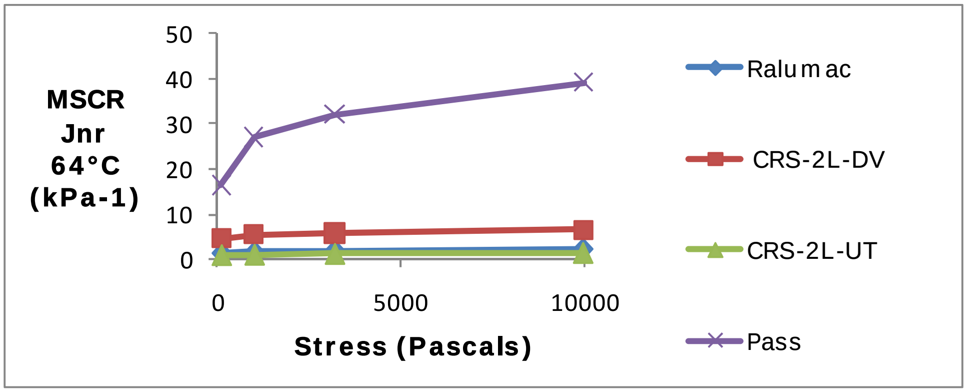


Figure 51. Graph. MSCR—J_{nr} vs. Stress for FDO Residues at 64 °C.

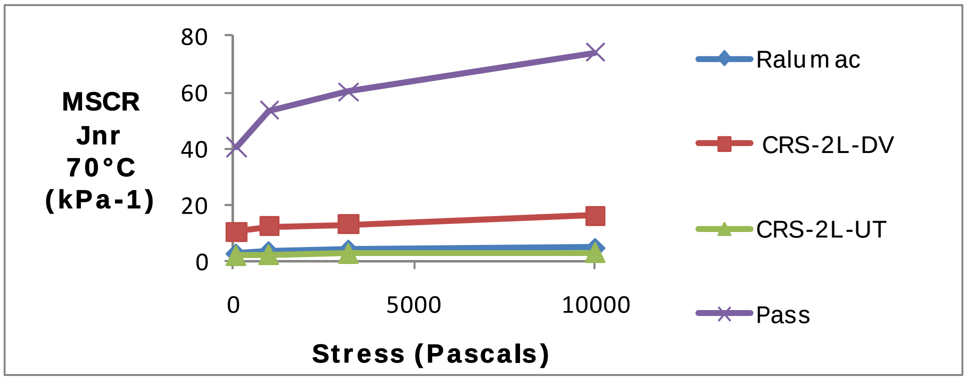


Figure 52. Graph. MSCR—J_{nr} vs. Stress for FDO Residues at 70 °C.

Low J_{nr} indicates resistance to flow—rutting and bleeding. The differences in J_{nr} for the three chip seal emulsion residues were extremely high. For a stress of 3,200 kPa applied at 64 °C, J_{nr} values were 1.2 for Utah Arches (CRS-2L-UT), 5.7 for Death Valley (CRS-2L-DV), and 32.1 for Dinosaur National Monument (PASS Emulsion). When grading HMA binders, a doubling of the J_{nr} represents a softening by approximately one full binder grade. This rule of thumb would suggest that the CRS-2L-DV (Death Valley) is more than two grades softer than the CRS-2L-UT (Utah Arches) residue, and the Dinosaur National Monument PASS emulsion residue another two or three grades softer yet. This range seems excessive, and the hardest binder was not used in the hotter desert climate. In short, these grades as used have no relation to the high temperatures for the respective climates. These surprising results accentuate the need for urgency in developing performance-based emulsion specifications, which more closely tie binder rheology to local climatic conditions.

Figures 53 through 55 give the test results for the MSCR percent recovery versus the four tested stress levels at the three test temperatures.

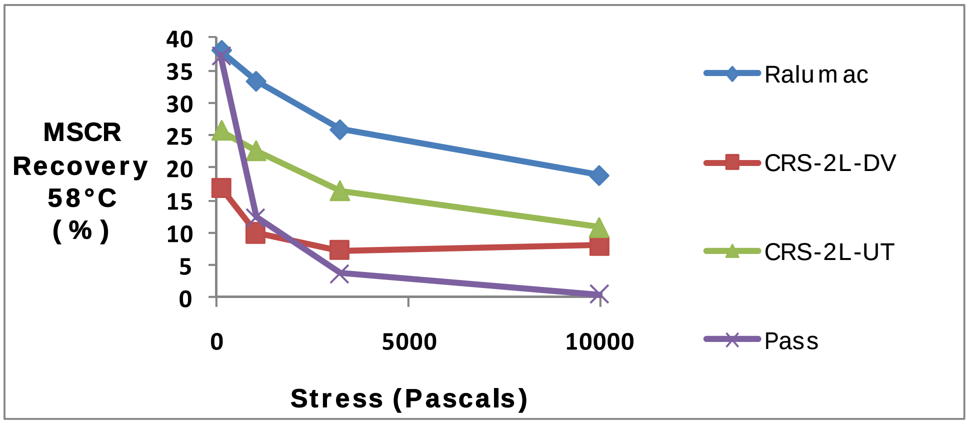


Figure 53. Graph. MSCR—Percent Recovery vs. Stress for FDO Residues at 58 °C.

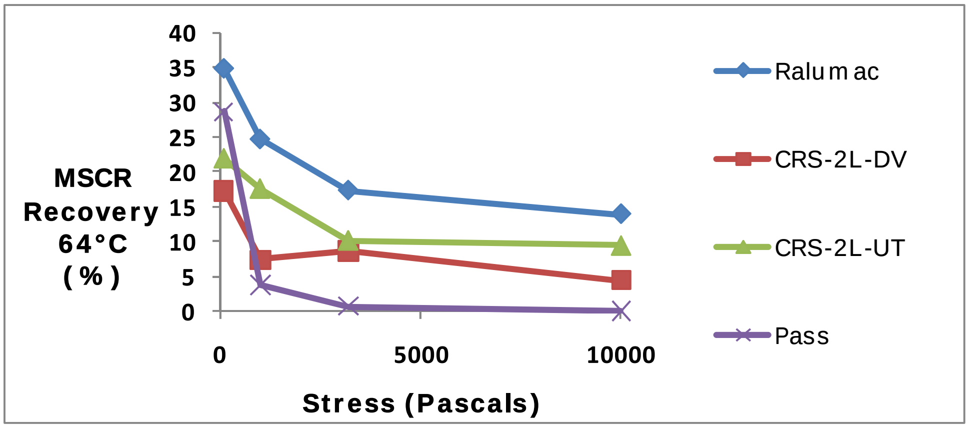


Figure 54. Graph. MSCR—Percent Recovery vs. Stress for FDO Residues at 64 °C.

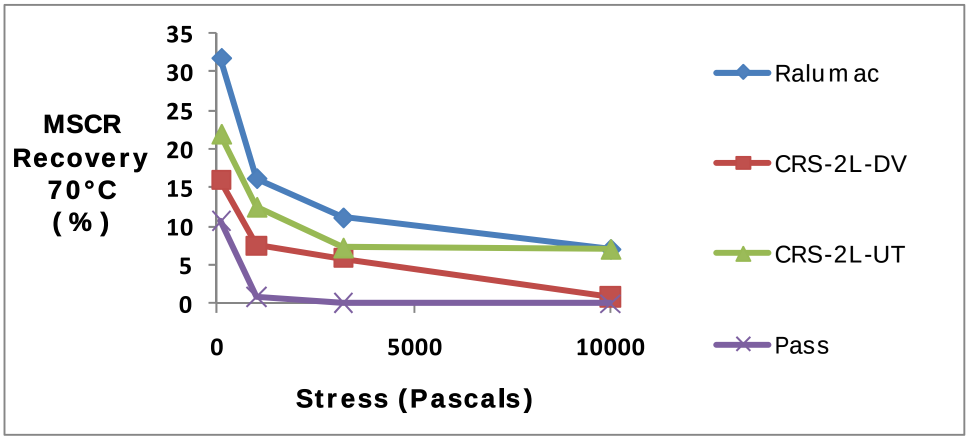


Figure 55. Graph. MSCR—Percent Recovery vs. Stress for FDO Residues at 70 °C.

There were huge differences in performance, particularly at the higher stress levels and temperatures as recommended by FHWA for hot mix asphalt binders. Using a stress level of 3,200 Pa at 64 °C, the recoveries were 0.7% for PASS (Dinosaur), 8.6% for CRS-2L-DV (Death Valley), 10.1% for CRS-2L-UT (Utah Arches), and 17.2% for Ralumac micro surfacing (Utah).

The rejuvenator/elastomer polychloroprene (Neoprene) product used for the Dinosaur project (PASS) is not only very soft, but it also exhibits an almost gel-like tendency to completely lose elasticity as the stress increases. In fact, the emulsion contains an oil designed to soften (rejuvenate) the underlying oxidized pavement surface and a polymer designed not to be swollen by the rejuvenator oil. At 100 Pa and lower test temperatures (58 and 64 °C), it has the best recovery of the three chip seal emulsions; however, at 3,200 Pa, PASS exhibits virtually no elasticity at any test temperature. It seems probable at this time that no single performance-based specification for emulsion chip seal residues could possibly cover the breadth of consistency and elasticity as evidenced by the elastomeric styrene-butadiene latex emulsions (CRS-2L) and the rejuvenating elastomeric Neoprene product (PASS). Independent performance-based specifications will be needed to define their respective residues.

For the PAV aged residues, the J_{nr} (compliance) results were consistent and ranked in the same order as their unaged counterparts, with the exception of the PASS emulsion, which was unable to be tested at the given conditions because it was still very soft after aging. Lab work is ongoing to understand testing issues that resulted in problematic data. In particular, recommendations for the 2009 trials include a reduction in testing temperatures for MSCR testing of chip seal products, because residues can be too soft at 64 °C to keep DSR parameters within the optimum operating range of current equipment. Figures 56 through 58 are plots of the J_{nr} (compliance) versus the four tested stress levels at the three test temperatures for the PAV aged residues of the products.

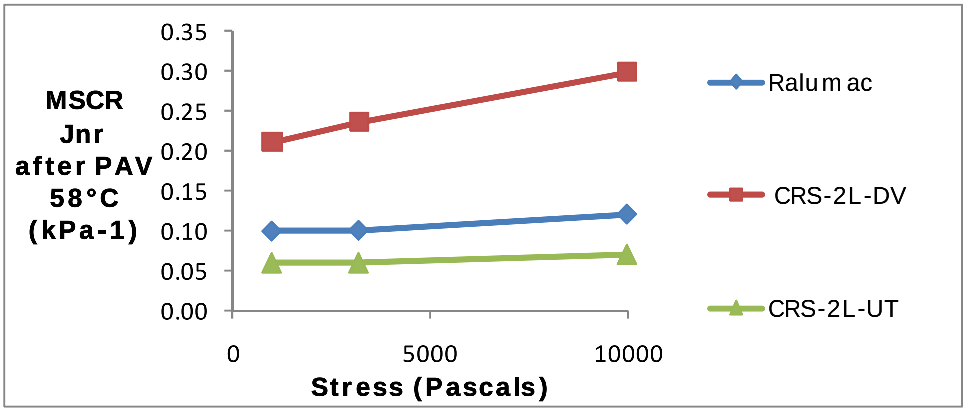


Figure 56. Graph. MSCR—J_{nr} vs. Stress for PAV Residues at 58 °C.

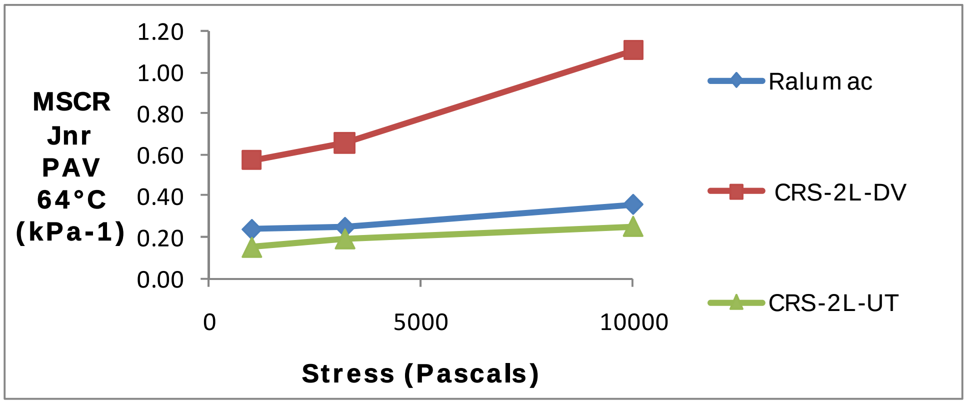


Figure 57. Graph. MSCR—J_{nr} vs. Stress for PAV Residues at 64 °C.

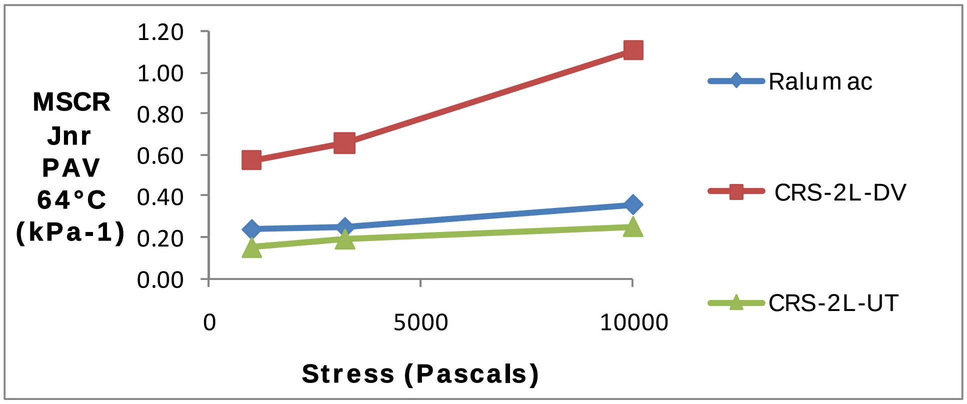


Figure 58. Graph. MSCR—J_{nr} vs. Stress for PAV Residues at 70 °C.

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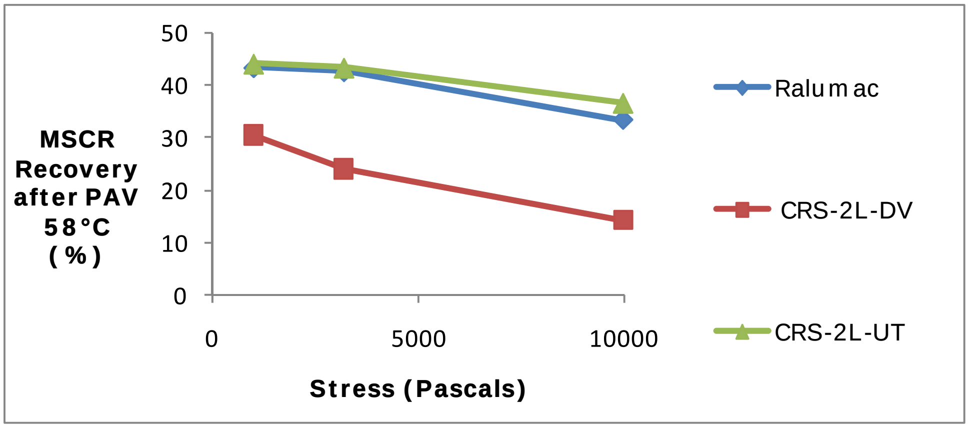

Figure 59. Graph. MSCR—Percent Recovery vs. Stress for PAV Residues at 58 °C.

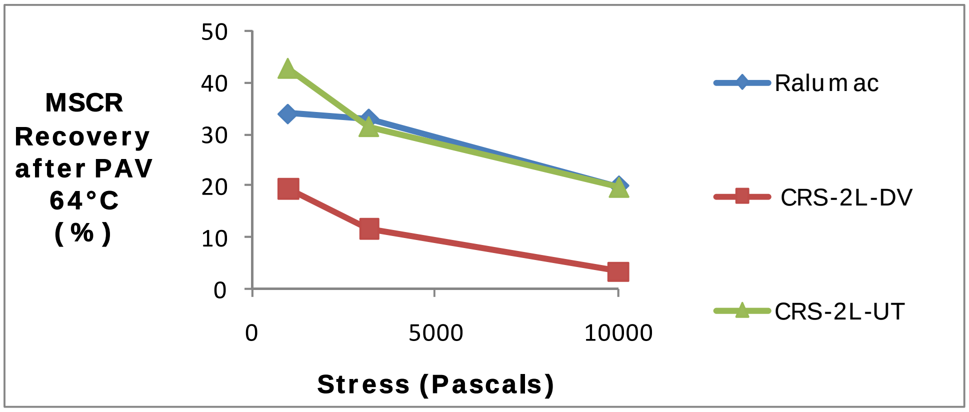

Figure 60. Graph. MSCR—Percent Recovery vs. Stress for PAV Residues at 64 °C.

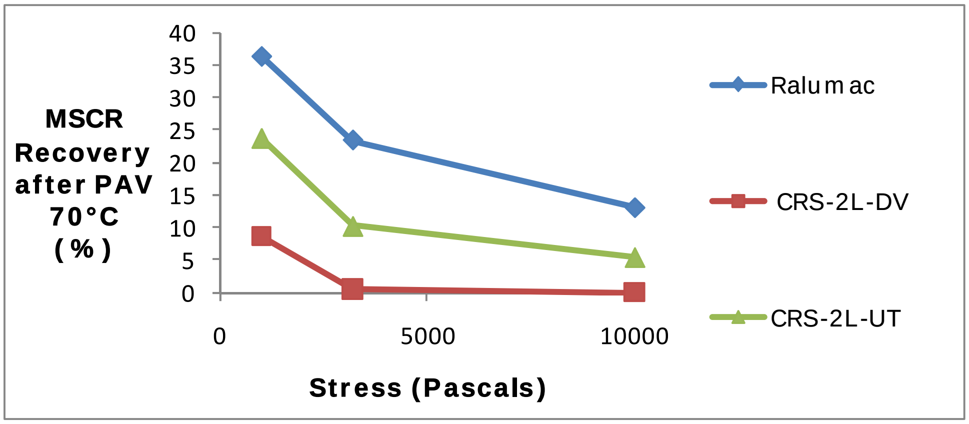

Figure 61. Graph. MSCR—Percent Recovery vs. Stress for PAV Residues at 70 °C.

As can be seen in Figures 59-61, recoverable strain improves following PAV aging. First, harder residues produced through the aging process naturally exhibit better recovery at a given temperature. Secondly, some elastomeric polymers may cross-link to some degree during aging. This cross-linking should strengthen the polymer network and improve elasticity. The CRS-2L-UT product improved in elasticity relatively more than the other latex-modified products. It should be noted that polymers composed of butadiene cross-link (increase in molecular weight) during thermal and oxidative aging while isoprene containing polymers (natural rubber latex) will undergo chain scission by breaking into smaller molecules during thermal and oxidative aging.

To explore test variability, MSCR recoverable strain and J_{nr} were determined by 3 different laboratories, as shown in Figures 62 and 63. There was some question on the labeling of samples from the Utah parks project, which included both micro surfacing and chip seal emulsions. While the Ralumac results from SemMaterials and BASF are in agreement, they do not agree with PRI's results. As mentioned above, there was also some question that the residues were recovered and aged using exactly the same protocols. Further discussion of these variable results among participating labs led to changes in handling and testing protocols for the 2009 projects.

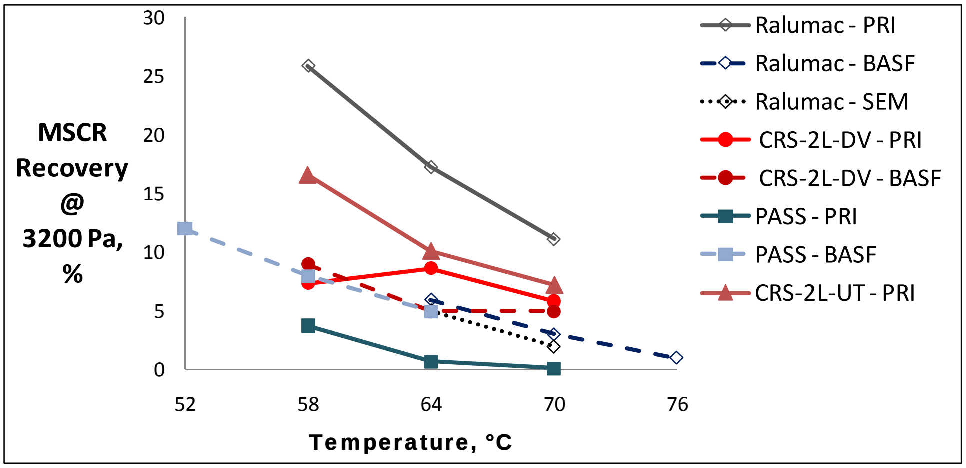

Figure 62. Graph. MSCR Recovery Results From 3 Laboratories.

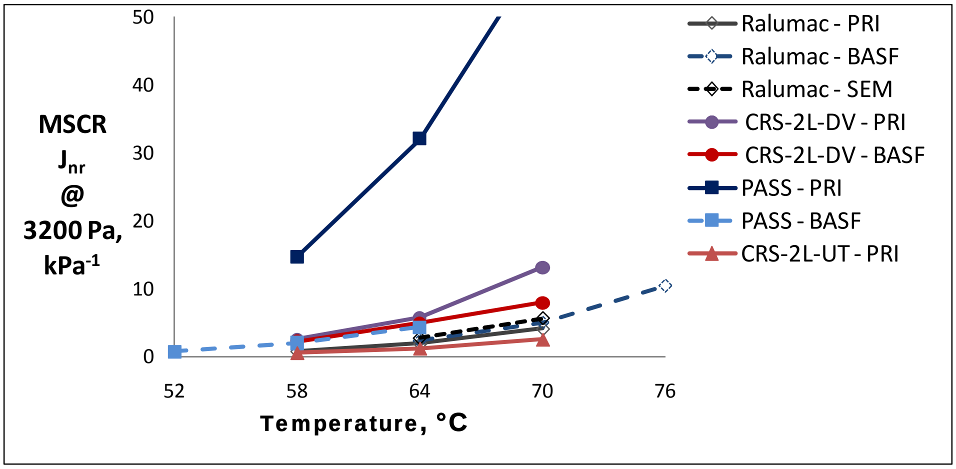

Figure 63. Graph. MSCR J_{nr} Results From 3 Laboratories.

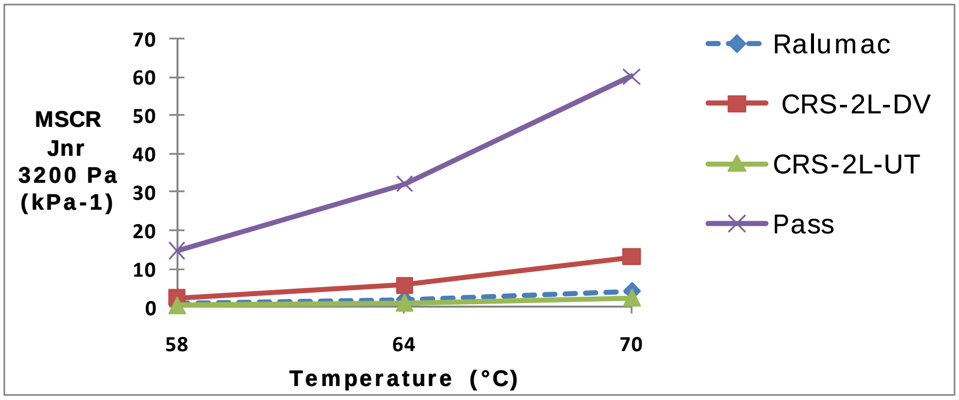

Figure 64. Graph. MSCR—Effect of Temperature on J_{nr} at 3,200 Pa.

As expected from newly developed HMA binder grading protocols, Figure 64 confirms that the residue J_{nr} approximately doubles with each 6 °C incremental increase in test temperature. There is every reason to believe it will be possible to use the climate maps created in LTPPBind to define and select appropriate emulsion grades for a given locale. However, the test conditions and specification limits must be adjusted to best fit the application.

Figure 65 shows the effect of temperature on MSCR recovery for the emulsion residues.

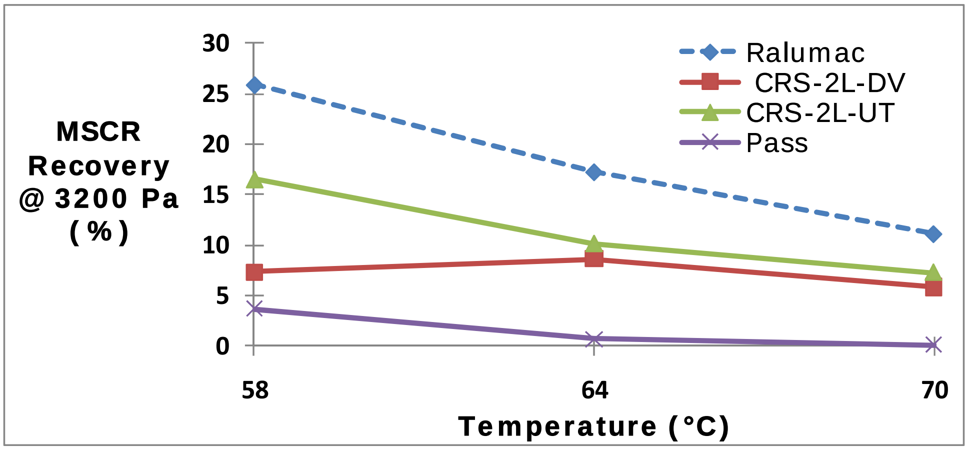

Figure 65. Graph. MSCR—Effect of Temperature on Percent Recovery at 3,200 Pa.

At high test temperatures, MSCR recoverable strain has a very strong dependence on the compliance (inverse modulus), or J_{nr} of the residue. For example, the micro surfacing emulsion (Ralumac) has a recovery of 25.9 percent at 58 °C, 17.2 percent at 64 °C, and 11.1 percent at 70 °C. The high susceptibility of the MSCR percent recovery to binder modulus or temperature is a disadvantage for specifications; it will always be possible to improve acceptance results somewhat by making the residue harder rather than by adding polymer to improve recovery. Although temperature-dependence results in testing variability for other methods currently used to define polymer elasticity, such as ASTM D6084 "Standard Test Method for Elastic Recovery of Bituminous Materials by Ductilometer Elastic Recovery (ER)," the higher imposed strains and a rest period before cutting tend to better differentiate polymer elasticity from binder modulus. New performance-based specifications could change the test temperature at some standard increment based on climate temperature, but it may be necessary to alter the MSCR test conditions significantly if it is to be used as a polymer identification test for PME specifications. It was decided to run MSCR tests for the 2009 trials at lower temperatures. The testing plan was modified to consider three lower testing temperatures:

- T_h-6 °C
- T_h-12 °C
- 25 °C

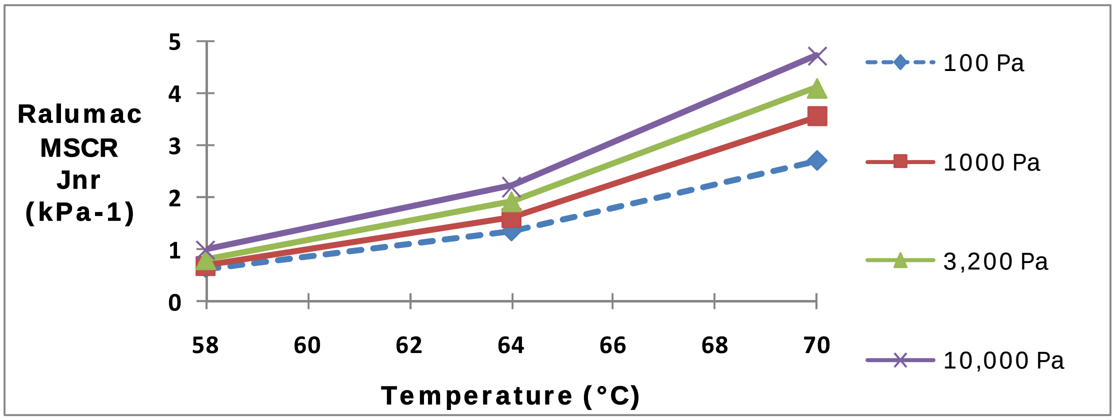

Figure 66. Graph. MSCR—Effect of Stress on J_{nr} for Ralumac.

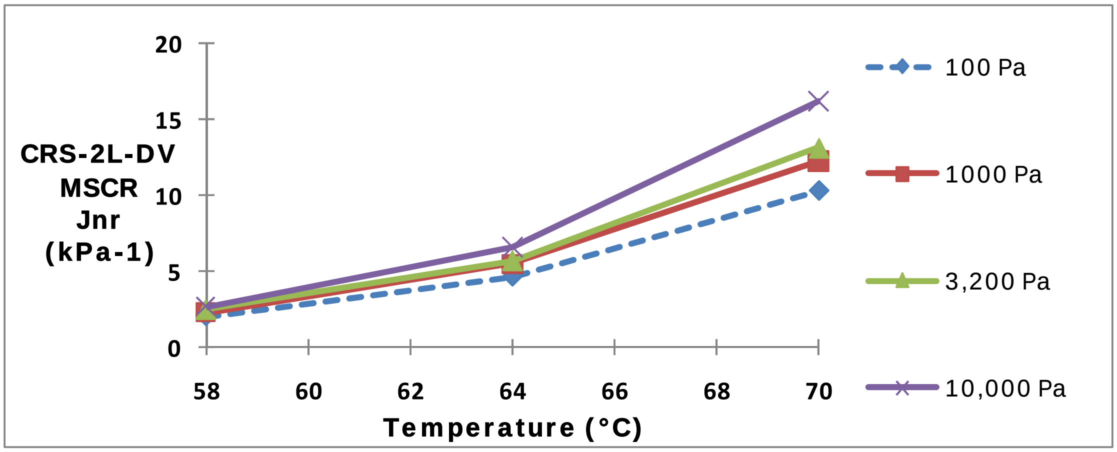

Figure 67. Graph. MSCR—Effect of Stress on J_{nr} for CRS-2L-DV.

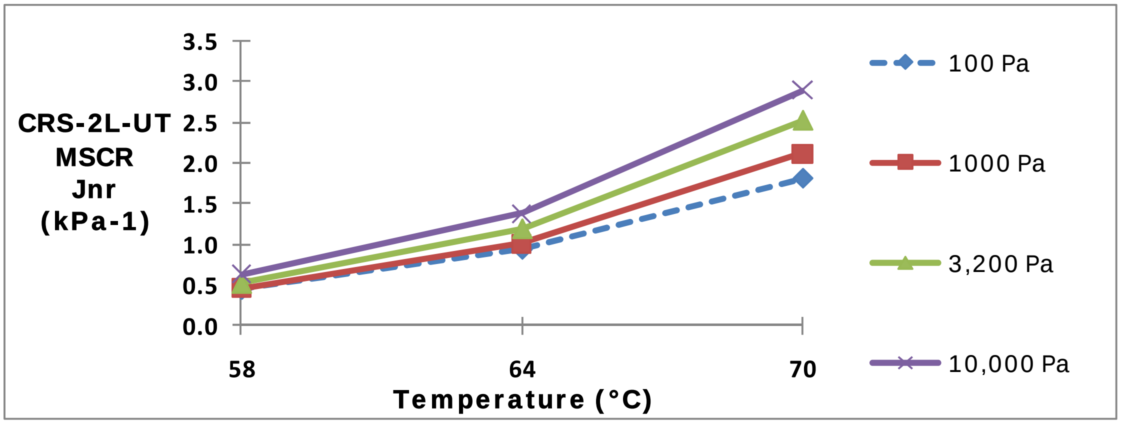

Figure 68. Graph. MSCR—Effect of Stress on J_{nr} for CRS-2L-UT.

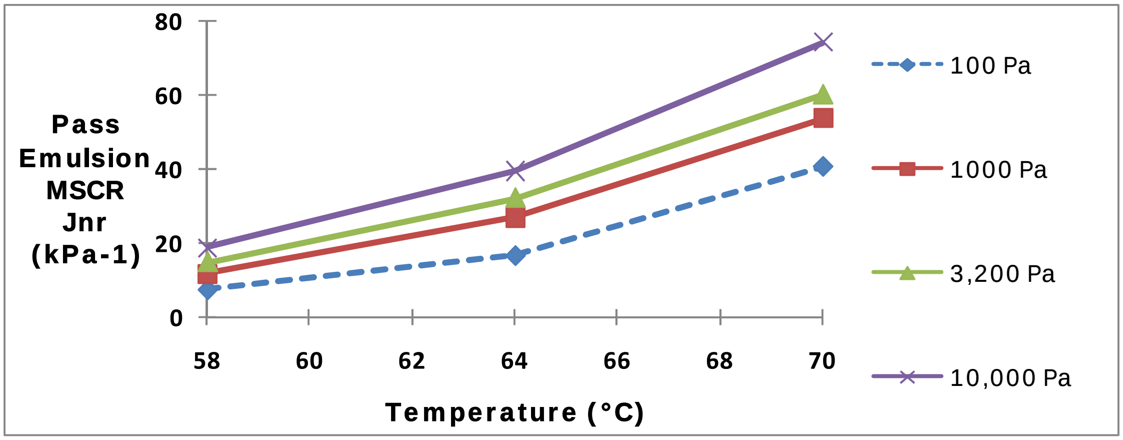

Figure 69. Graph. MSCR—Effect of Stress on J_{nr} for PASS Emulsion.

The MSCR test as developed during NCHRP 9-10 showed clearly that fundamental assumptions regarding linear viscous flow do not apply to highly polymer modified asphalts. As previously noted on Figures 50 through 52, Figures 66 through 69 verify that the binder compliance (modulus) of PME residues also varies greatly with applied stress for each of the products studied.

Although the J_{nr} for all products increases with applied stress at all temperatures, the relative non-linearity as expressed by the slopes varies dramatically from one PME residue to another. All PME residues get softer as increasing load is applied, but the amount of load-induced softening is highly dependent upon the amount and type of polymer, as well as the grade of the base asphalt. Just as FHWA reported for a series of HMA binders used for their Accelerated Loading Facility (ALF II) rutting/fatigue study, nonlinearity is particularly evident for the softest, most highly modified materials.(106) Because the PASS emulsion residue is very soft, it is most sensitive to this stress-induced softening effect at high temperatures. Two examples from the field study are worth noting. First, CRS-2L-UT at 58 °C represents the hardest base residue at the lowest test temperature, and PASS emulsion at 64 °C represents the softest base residue at the next higher test temperature. Under these respective conditions, the CRS-2L-UT J_{nr} changed from 0.45 to 0.52 when applied stress was increased from 100 Pa to 3,200 Pa. With the same stress change, J_{nr} for the much softer PASS residue increased from 16 to 32. On a temperature grading scale typical of the PG system, the CRS-2L-UT in a PG 58 climate would lose two degrees and the PASS emulsion in a PG 64 climate would lose 6 °C, or one full high temperature grade, due to non-linearity at the higher 3,200 Pa stress level recommended by the FHWA's Binder Expert Task Group. The widening gap in J_{nr} as temperature increases is consistent with the fact that softer materials exhibit more non-linearity. Higher applied stress results in higher strains, while softer materials or hotter liquids yield more at any given stress. Hence, increasing stress, increasing temperature, or softening of the base binder all push the results further into the non-linear region.

This effect, when viewed from a chemist's point of view, is really a strain dependent issue related to the polymer structure. Very long polymer molecules entangle much like long hair tangles. These entanglements enable the polymer network to resist flow to a degree much higher than its molecular weight alone would imply. However, as these tangled chains are stretched and unwound, the additional elasticity provided through chain entanglement (increased entropy) is lost. Hence, the polymer network becomes weaker and less elastic as it is stretched to the point that chains begin to disentangle. These effects are tied to the higher applied strains, regardless of cause (higher stress, higher temperatures, or softer base asphalts). Since polymers can vary widely in molecular weight, chain length, branching and molecular structure, the strain at which these effects become important can vary dramatically. This is not surprising; the behavior is much the same as woven fabric being much stronger than the individual threads.

From a maintenance engineer's perspective, softening under heavy stress/strain conditions means less binder strength and more chip loss for intersections, uphill/downhill grades, braking areas, work zones, parking lots, or other locations where turning tires or heavy traffic impose higher strains on the chip seal binder.

Figures 70 through 73 illustrate the effect of stress level on MSCR recovery percent.

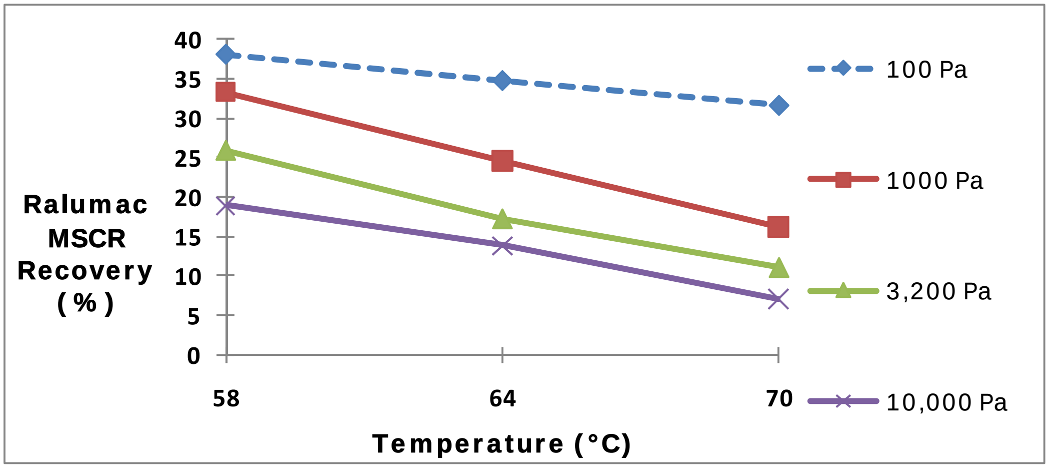

Figure 70. Graph. MSCR—Effect of Stress on Recovery for Ralumac.

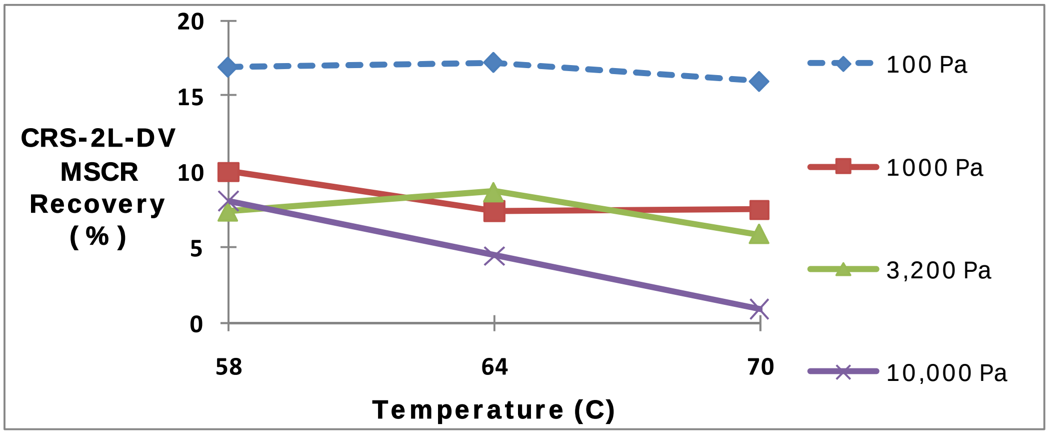

Figure 71. Graph. MSCR—Effect of Stress on Recovery for CRS-2L-DV.

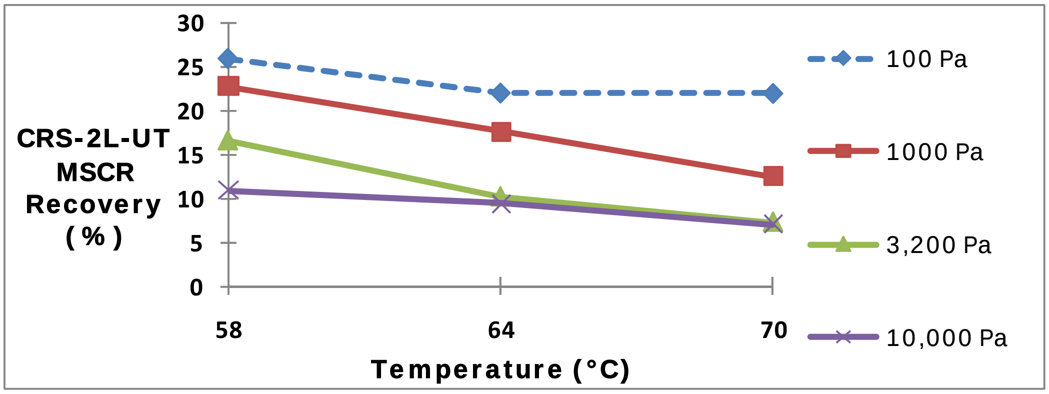

Figure 72. Graph. MSCR—Effect of Stress on Recovery for CRS-2L-UT.

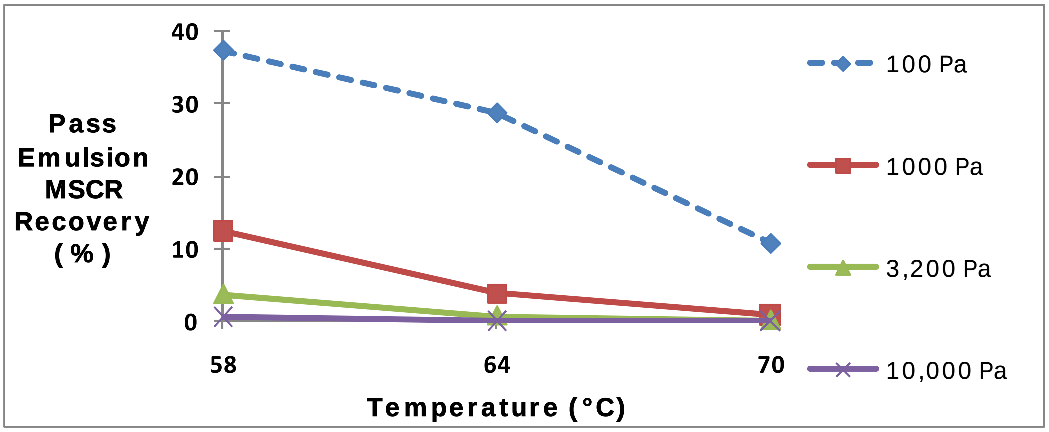

Figure 73. Graph. MSCR—Effect of Stress on Recovery for PASS Emulsion.

The effects of increasing applied stress on strain recovery are considerably more dramatic than those impacting J_{nr}. As mentioned above, recovery is always reduced when higher stresses result in higher strains, which dislodge polymer chain entanglements. However, the percent recovery for the PASS emulsion at 64 °C fell from a relatively high 28.8 percent to less than 1 percent when the applied stress was increased from 100 to 3,200 Pa. The SBR latex modified CRS-2L residues were also highly sensitive to stress, but maintained reasonable elasticity even at the highest stress levels. It is also interesting to note from Figures 70, 71, 72, and 73 that the percent recovery for CRS-2L-DV at different temperatures is surprisingly insensitive to applied stress up to 3,200 Pa. CRS-2L-UT and Ralumac show moderate declines in percent recovery as temperature increases, while percent recovery for the PASS emulsion is extremely sensitive to both temperature and applied stress. It seems most logical to compare recoveries of different products using an equivalent-stiffness approach. Unfortunately, lab procedures would be too time consuming and costly for product specifications. A simpler climate-based grading system for strain recovery could be one possible solution.

Figures 74 through 76 show the change in J_{nr} at 64 °C after PAV aging.

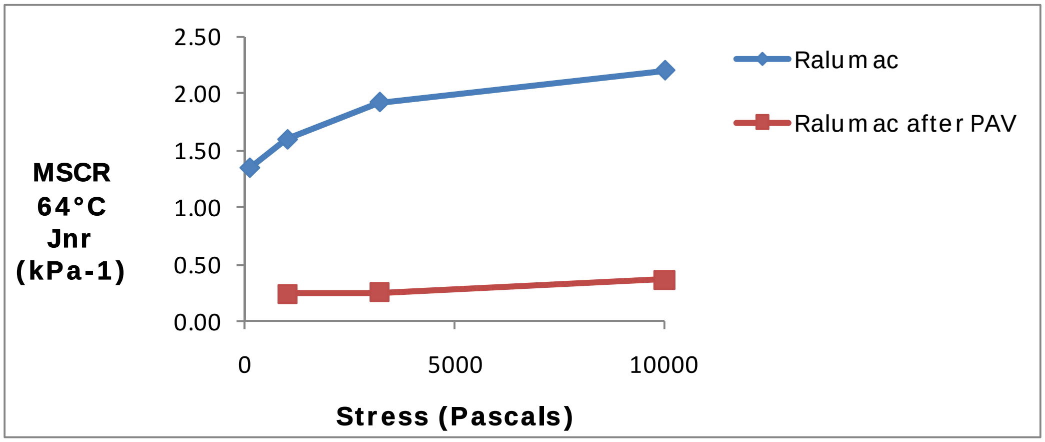

Figure 74. Graph. MSCR—Effect of Aging on 64 °C J_{nr} for Ralumac.

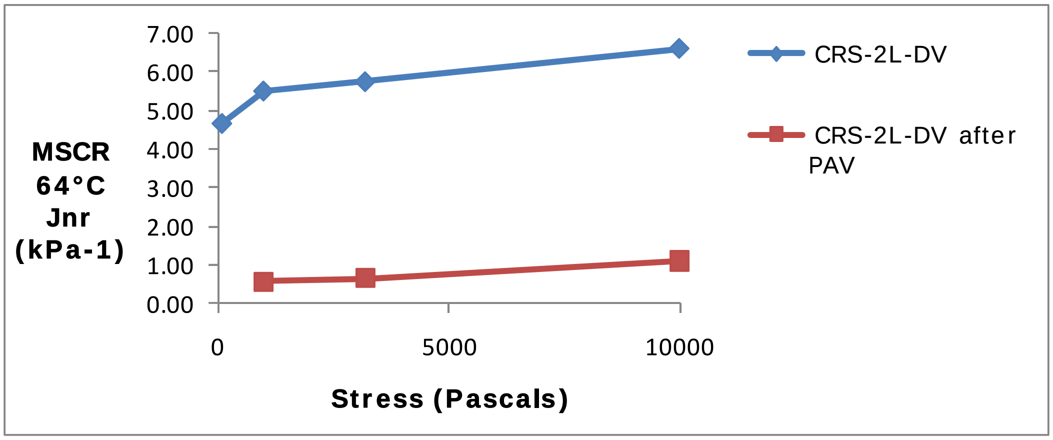

Figure 75. Graph. MSCR—Effect of Aging on 64 °C J_{nr} for CRS-2L-DV.

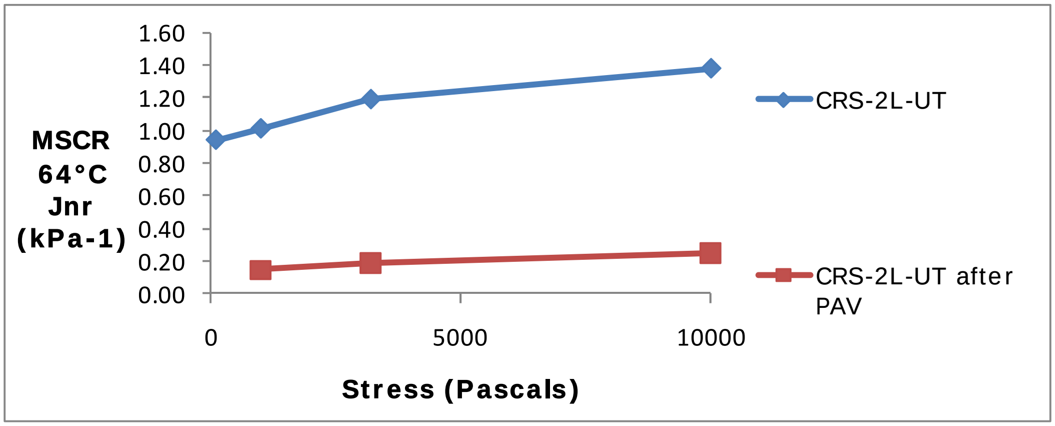

Figure 76. Graph. MSCR—Effect of Aging on 64 °C J_{nr} for CRS-2L-UT.

The evolution in J_{nr} with PAV aging (20 hr, 100 °C) was evaluated for three of the four products. For the intermediate test conditions of 64 °C and 3,200 Pa, the J_{nr} fell with aging as follows:

PAV Aging Ratio

- Ralumac: from 1.92 to 0.25 (7.7 PAV aging ratio)
- CRS-2L-DV: from 5.5 to 0.66 (8.3 PAV aging ratio)
- CRS-2L-UT: from 1.19 to 0.19 (7.6 PAV aging ratio)

Because J_{nr} is inversely proportional to modulus, it may be useful to rank these changes by calculating ratios of J_{nr} before and after aging. The PAV Aging Ratio for the CRS-2L-DV residue would suggest it may have experienced some changes in the polymer network structure and/or more severe asphalt oxidative aging during the PAV procedure. More work is needed to understand how the variables of time and temperature impact aged properties in the PAV oven as compared to field aging. Based upon previously cited rules of thumb that binder stiffness doubles with each grade change, a PAV aging ratio of 8.0 should represent an increase of three high-temperature PG grades during PAV aging.

The PAV aging induced change in percent recovery was evaluated for the same three products at all three test temperatures and all four stress levels, as shown in Figures 77 through 79.

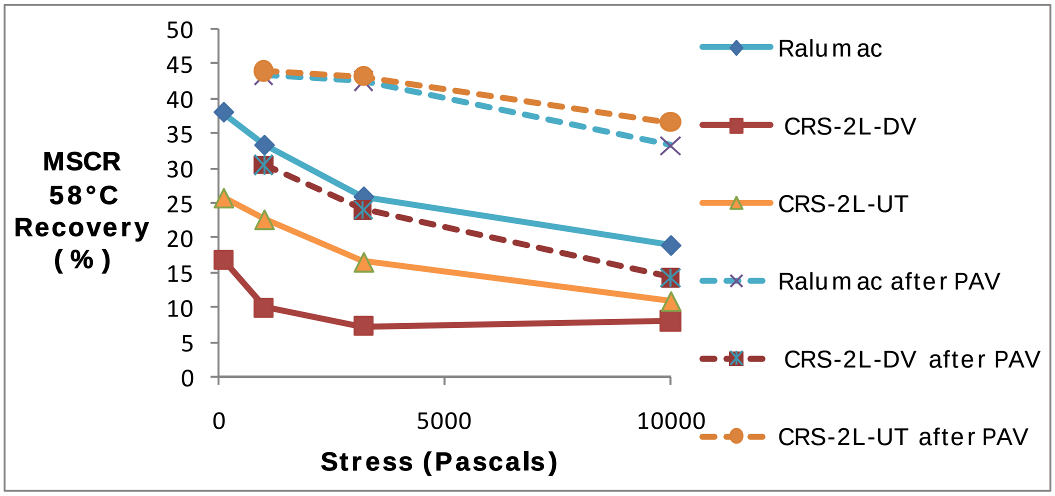

Figure 77. Graph. MSCR—Effect of Aging on Recovery at 58 °C.

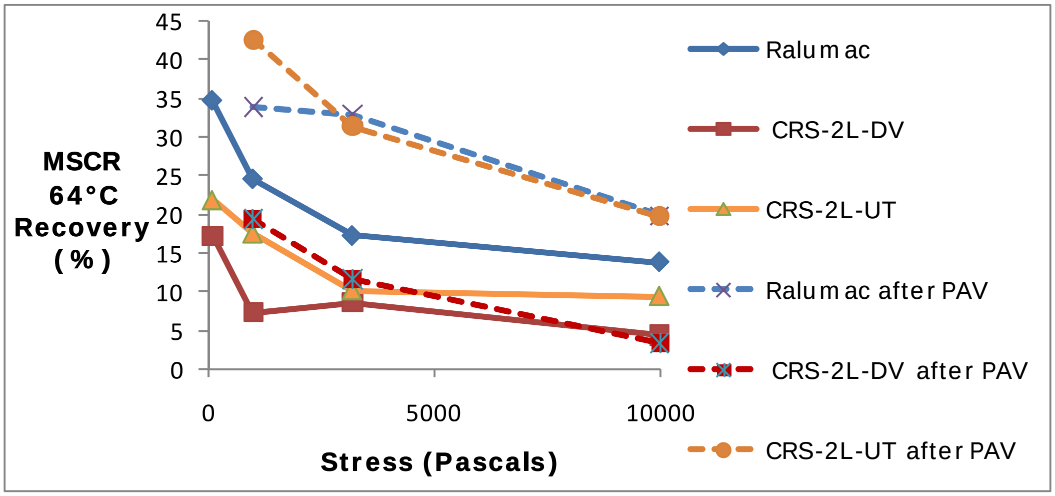

Figure 78. Graph. MSCR—Effect of Aging on Recovery at 64 °C.

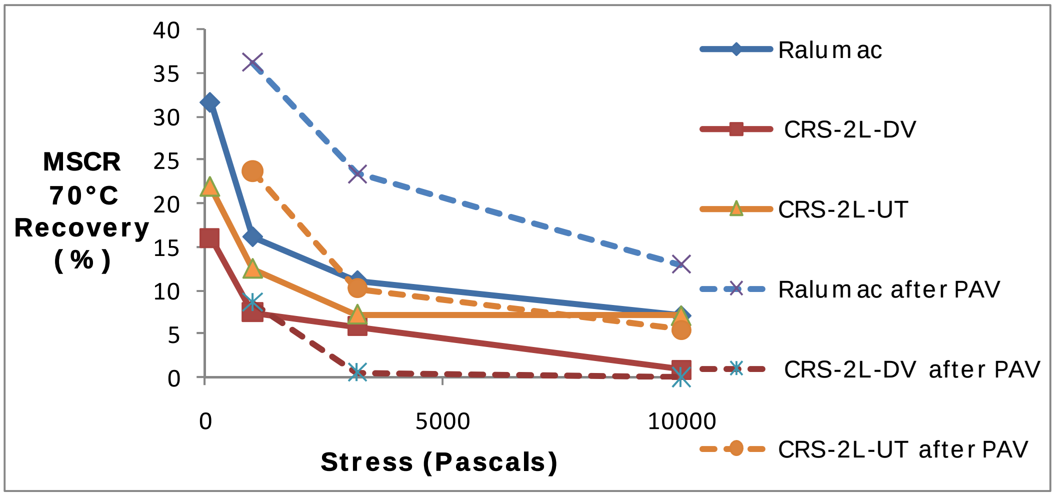

Figure 79. Graph. MSCR—Effect of Aging on Recovery at 70 °C.

Each of the products show significant increases in the percent recovery with aging, but the relative change is quite different. For example, unaged recoveries for the Ralumac micro surfacing residue with its higher polymer content are considerably higher than those from the CRS-2L-UT. However, after aging, the percent recoveries of the two products are almost equal under most test conditions. As discussed earlier, recoveries should increase as the binder stiffens. Although both residues experience very similar relative increases in J_{nr} as measured on a log scale, the CRS-2L-UT exhibited a much higher increase in recovery than did the Ralumac. This would suggest that at least one of these two products may have experienced some changes in the polymer network structure with PAV aging. More work is needed to understand how the variables of time and temperature impact aged properties in the PAV oven as compared to field aging.

5.1.2.5 Bending Beam Rheometer Testing and Continuous Grading

AASHTO T 313 BBR tests were run at two temperatures on the FDO residue. The tests were then used to predict the temperature at which the passing criteria of 300 MPa S and 0.300 m-value were met. The results, given in Table 30, show that the low temperature grading of the SBR and natural rubber latex-modified emulsions were similar, meeting the specification requirements at -28.8, -30.6, and -26.3 °C. The neoprene latex-modified PASS emulsion is much softer, as was indicated in the MSCR testing, with a low temperature of -34.7 °C.

Table 30. Bending Beam Tests and Rheology Limiting Temperatures.

Test	Procedure	Specification	Ralumac LMCQS-1H	CRS-2L-DV, Death Valley Project	CRS-2L-UT, Utah Arches	PASS Emulsion
Stiffness, MPa (60 sec.) -18 °C	AASHTO T 313	300 max.	272	243	315	68
m-value -18 °C	AASHTO T 313	0.300 min.	0.308	0.228	0.282	0.338
Stiffness, MPa (60 sec.) -12 °C	AASHTO T 313	300 max.	120	100	142	18
m-value -12 °C	AASHTO T 313	0.300 min.	0.371	0.384	0.348	0.376
Temperature at Which FDO Residue Meets SHRP PG Grading Specification Limits						
Temperature where residue meets G*/sin delta of 1.0, kPa (°C)		AASHTO T 315	76.9	67.6	81.8	54.6
Temperature where residue meets G* X sin delta of 3,000 Pa		AASHTO T 315	20.7	19.3	21.7	9.3
Temperature where residue meets BBR Stiffness of 300 MPa (°C)		AASHTO T 313	-28.7	-29.3	-27.6	-34.7
Temperature where residue meets BBR m-value of 0.300 (°C)		AASHTO T 313	-28.8	-30.6	-26.3	-34.7
SHRP PG Temperature Grade (continuous grading)		AASHTO MP 1	76-28	67-29	81-26	54-34

Because PG binders are graded in 6 °C temperature increments, it is easiest to understand differences in asphalt consistency by comparing the temperatures at which materials have the same consistency as measured by the current PG standard, G*/sin delta. Because those using PG specifications are familiar with the temperature as defined for HMA applications using a frequency of 10 radians per second and a specification limiting modulus of 1.0 kPa for unaged binders, these test conditions were used to define comparable limiting temperatures for the emulsion residues. Although not in this report, it should be emphasized that full frequency sweep data is available on the FLH project website for all unaged and aged samples at high and intermediate temperatures, so rheological master curves can be constructed and/or limiting temperatures can be determined at other test conditions ultimately deemed appropriate for chip seal applications. As can be seen from the data in Table 30, limiting temperatures for the unaged residue from the three chip seal emulsions ranged from 54.6 °C (PASS) to 81.8 °C (CRS2-LM), a difference of 27.2 °C or 4½ PG binder grades. It is quite surprising that the two extreme binders were both applied to Utah National Parks during the late fall of 2008. The emulsion (CRS-2L-DV) applied during the same period in Death Valley, CA, one of the hottest locations in the U.S., had a consistency near the mid-point of the range between the two Utah projects. This range of consistencies seems illogical and accentuates the need for improved emulsion residue specifications. From a research point of view, though, the broad range of properties might accelerate differences in performance, which could aid in better selecting specification limits in the future.

5.1.2.6 Dynamic Shear Rheometer Frequency Sweep at Intermediate Temperature

The intermediate temperature at which the specification parameter (G* x sin delta) reaches 5,000 kPa for the PAV aged residues from all four emulsions is reported in Table 30. As expected, there were large differences in the critical intermediate temperatures, with the PASS residue appearing to be much softer than the others. This parameter measures dissipated energy per cycle, which was once thought to rank binders for fatigue resistance. It would not be appropriate for inclusion in chip seal specifications. Chip seal residues are not subjected to classic fatigue cracking, and the parameter itself has not been validated to predict cracking damage.

Christensen, Anderson, and Marasteanu showed that rheological master curves of modulus (G*) versus temperature and phase angle versus temperature can be mathematically modeled using the now well-accepted CAM model. If measured data is precise, and if the CAM model appropriately fits both master curves for a given binder over a broad range of temperatures, it is possible to make rheological measurements in one temperature range and then extrapolate using the model to predict rheological properties at a very different temperature. For reasons discussed earlier, it is the goal of this project to investigate the use of these intermediate temperature frequency sweeps as a means of replacing the BBR as the preferred method for specifying the low temperature performance-based properties of emulsion residues.

Because low temperature properties are best defined in performance-based specifications after the binder is subjected to laboratory aging protocols, frequency sweeps were run on all PAV residues at 10 °C and 20 °C using procedures as designated for intermediate temperature PG binder grading (8 mm plates, 2 mm gap, 5 percent strain, 0.1 to 100 radians/second). All frequency sweep data tables can be found on the National Center for Pavement Preservation's website (http://www.pavementpreservation.org) under the document titled "Polymer Modified Emulsion Study Test Data Available."

5.1.2.7 Dynamic Shear Rheometer Strain Sweep

Takamura suggests that asphaltic binders that lose strength when tire contact moves an embedded chip are a major cause of chip loss and raveling.(48) Recent collaborative research between the University of Wisconsin and the University of Stellenboch in South Africa support this. Polymers are a very effective means of creating additional tensile strength with elongation, such that the chip is pulled back to its original position when the tire has passed. This is particularly important for problem areas such as intersections or driveway exits where turning tires are most prone to dislodge chips. Rather than adding an expensive tensile test to the specification, it has been theorized that this property can be captured by determining how much strain can be applied to a binder in a dynamic shear rheometer before it loses a significant percentage of its modulus.

DSR strain sweeps were run on all PAV residues using the test conditions recommended by Bahia (25 °C, 8 mm plates, 2 mm gap, 10 radians/second, 0.01 to 50 percent strain). As can be seen in Figure 80, logarithmic plots of modulus (G*) versus percent strain indicate that the modulus remains relatively constant as strain increases, and then weakens dramatically as the strain exceeds some critical limit. The only apparent difference, however, among all the samples tested (including the unmodified CRS-2) is the amplitude of the G*, which appears to be dependent upon the modulus of the material. Full strain sweep data is available on the National Center for Pavement Preservation’s website mentioned earlier, and detailed data tables have been forwarded to the University of Wisconsin for further analysis.

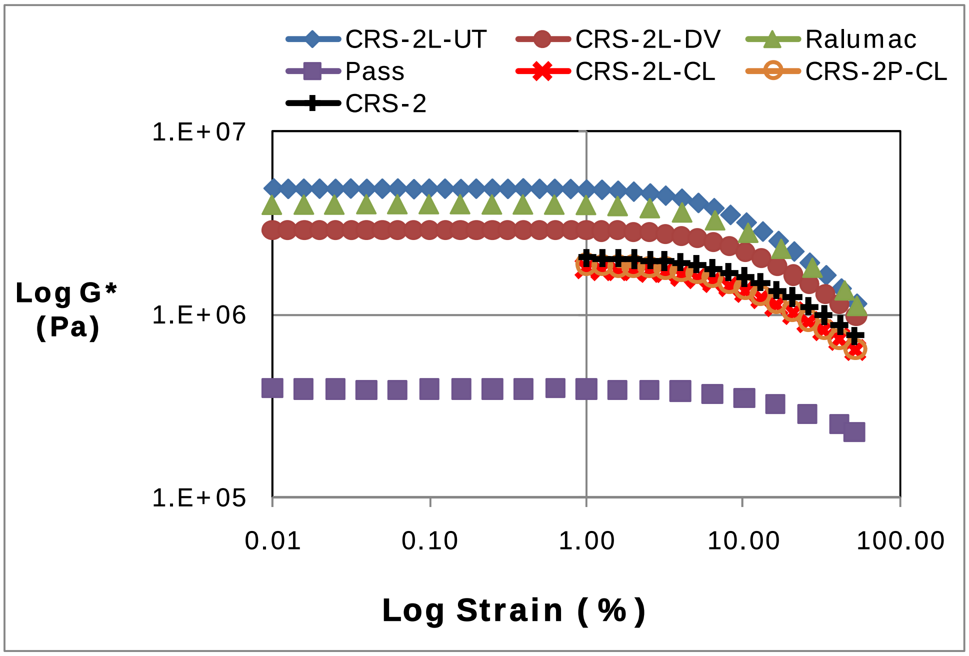

Figure 80. Graph. Strain Sweeps on PME Residues.

5.1.2.8 Sweep Test

ASTM D7000, “Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples,” uses project aggregate and emulsion to determine compatibility of the chip seal emulsion and aggregate, and give an indication of how quickly the emulsion cures to retain chips. Following recommendations from Takamura, the ASTM procedure was modified slightly to improve reproducibility. Changes include:

- Preheating the felt pad to 35 °C in an oven prior to use;
- Dampening the aggregate surface with about 4 grams of water prior to spreading into the emulsion on the sweep test pad; and

- BASF also uses rectangular felt pads, (12 in X 14 in) rather than the circular pads.

Samples of emulsion and aggregate from the Utah Arches, Death Valley, and Dinosaur Monument chip seal projects were sent to all three participating laboratories for sweep testing. Five single-lab replicates were run using a two-hour curing period for every trial. Split samples of the emulsion and aggregates from some of the projects were sent to three labs, Paragon Technical Services, Inc., PRI Asphalt Technologies, Inc., and BASF. The results are given in Table 31.

Table 31. 2008 Sweep Test Results.

Project/Emulsion	Test Lab	Average Mass Loss	Standard Deviation	Range
Arches/CRS-2L-UT	BASF	11.1%	2.0	5.3
Arches/CRS-2L-UT	Paragon	16.5%	0.4	0.9
Arches/CRS-2L-UT	PRI	13.1%	1.0	2.4
Arches/CRS-2L-UT	**All labs**	**13.5%**	**2.7**	**5.4**
Death Valley/CRS-2L-DV	BASF	9.7%	1.5	3.2
Death Valley/CRS-2L-DV	Paragon	26.0%	0.4	1.0
Death Valley/CRS-2L-DV	PRI	11.9%	1.1	3.0
Death Valley/CRS-2L-DV	**All labs**	**15.9%**	**8.8**	**16.3**
Dinosaur NM/PASS emulsion	PRI	Insufficient curing @ 2hrs, all chips lost		

Results from inter-laboratory sweep tests were encouraging, but some questions remain. As can be seen from Table 31, intra-laboratory results for the Arches CRS-2L-UT and the Death Valley CRS-2L-DV were very consistent, with 5-replicate standard deviations ranging from 0.4 to 2.0 percent mass loss. The inter-laboratory agreement for the Death Valley emulsion was not as good. Participating laboratories reviewed results and procedures, and recommended further sample preparation requirements for the 2009 trials.

Finally, the PASS emulsion did not cure sufficiently in two hours to hold any chips, so mass loss was essentially 100 percent and testing was abandoned. It should be understood that the residue from PASS emulsion contains rejuvenator oils, and is therefore very soft. Furthermore, the emulsifier is designed to break more slowly than typical CRS-2P emulsions. This kind of product has found an important niche in the marketplace, particularly when applied to low ADT, highly aged bituminous surfaces that need rejuvenation to prevent further surface-initiated cracking. On the other hand, PASS in this particular formulation may not be an appropriate emulsion for chip sealing roads with high volume traffic or for projects that need early cures to minimize traffic control issues. Hence, such a product would need independent performance-based specifications written for the applications where it is found to be successful.

5.1.3 Field Results on 2009 Projects

Performance reviews of the 2008 Utah Parks and Dinosaur National Monument projects were completed in July, 2009. Generally, the projects all looked good, with a few areas of distress as summarized in Table 32.

Table 32. July 2009 Evaluations of Field Projects.

Park	**Arches**	**Canyonlands**	**Dinosaur**
Emulsion	CRS-2L-UT	CRS-2L-UT	PASS
Pre-construction condition	Transverse cracking	Good	Very good; 2-yr old pavement
Milepost (location)	2.76 (Rt 10)	8.84 (Rt 11)	Park entrance (Rt 10)
Cracking (unsealed)	27 feet (3%)	None	390 sq ft (3.5%)
Raveling (loss of chips)	None	None	Very minor
Flushing/ Bleeding	None	Very minor (not in wheel paths)	None
Observations	• Fog seal has worn off surface of aggregates • Bleeding at most intersections within park • Some raveling of the micro surfacing (Ralumac) • Snow plow damage and scrapes were noted, particularly around the centerline		• Fog seal has worn off surface of aggregates • Some minor bleeding at intersections within park • Chips were easily dislodged by fingers during heat of day; stiffer at early morning colder temperatures • Residue asphalt not as "stretchy" as Arches and Canyonlands in heat of day • Areas of severe damage where heavy equipment had been used for ditch repairs and other work

Figure 73 demonstrated that the MSCR percent recovery of the project sample of PASS (neoprene modified emulsion containing rejuvenator oil) was much more dependent upon temperature and stress than the other materials tested. This result was evidenced in the field; the chip seal was very tight at low morning temperature, but in the hot afternoon sun lost its "stretchiness" and strength. The supplier offers a complete line of PASS products; the product used here includes a very soft rejuvenator and, according to manufacturer literature, is "designed for asphalt surfaces showing signs of cracking, raveling or more severe surface deterioration."(104) The pre-existing pavement was only two years old, in very good condition. The general performance was good (as illustrated in Figure 85) with the exception of areas where heavy equipment used for ditch work had caused heavy wearing and chip loss (Figure 86).

Figures 81 through 86 are photos demonstrating the performance of the surfaces after one winter.

Figure 81. Photo. Arches National Park Chip Seal in July 2009.

Figure 82. Photo. Canyonlands National Park Chip Seal in July 2009.

Figure 83. Photo. Utah Parks Micro Surfacing in July 2009.

Figure 84. Photo. Utah Parks Snow Plow Damage in July 2009.

Figure 85. Photo. Dinosaur National Monument PASS Chip Seal in July 2009.

Figure 86. Photo. Wearing and Chip Loss on Dinosaur Project in July 2009.

5.2 Test Results from 2009 Crater Lake Project

The test procedures for the 2009 project were refined as discussed above. A total of five laboratories participated in the testing; however, not all labs ran all the tests.

5.2.1 Residue Recovery Results from Crater Lake

It was hoped that a shorter test could be run to recover residues for testing; the 6-hour, 60 °C (140 °F) Procedure B is that shorter test. There was some concern that 24 hours at 60 °C would age the residue more than typical field curing. There is acceptable repeatability (0.9%) for the percent residue from Procedure A, as shown in Table 33. (CRS-2L-CL is the SBR latex modified emulsion and CRS-2P-CL is the SBS polymer modified emulsion.) The high temperature DSR testing gave excellent repeatability among 5 labs running the residue recovery and AASHTO T 315, "Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)" on the recovered samples. Table 33 shows that the multi-laboratory results of T 315 have excellent agreement, well within the 6 percent multi-laboratory precision required by the AASHTO test procedure.

Table 33. Repeatability of Residue Recovery Testing.

Emulsion		**CRS-2L-CL**		**CRS-2P-CL**	
ASTM D7497-09 Recovery Procedure		**A**	**B**	**A**	**B**
% Residue	Average	70.05		70.60	
	Standard Deviation	0.63		0.57	
	Coefficient of Variation	**0.9%**		**0.8%**	
G*/Sin Delta @ 64 °C AASHTO T 315	PRI	1.064	0.994	1.130	1.100
	Paragon	1.048	1.020	1.147	1.125
	BASF	1.067	1.038	1.161	1.117
	Ultrapave	1.073	1.047	1.158	1.129
	Kraton	1.041		1.130	
	Average	1.059	1.025	1.145	1.118
	Standard Deviation	0.014	0.023	0.015	0.013
	Coefficient of Variation (T 315 limit = 6%)	**1.3%**	**2.3%**	**1.3%**	**1.2%**

Figure 87 shows the limiting stiffness temperatures of the two emulsions used at Crater Lake, comparing residues obtained with the two forced draft oven (ASTM D7497) procedures. As mentioned above, the agreement among laboratories for each procedure is excellent. There is, however, a statistically significant difference between the two procedures, indicating Procedure A does harden the residue more than Procedure B.

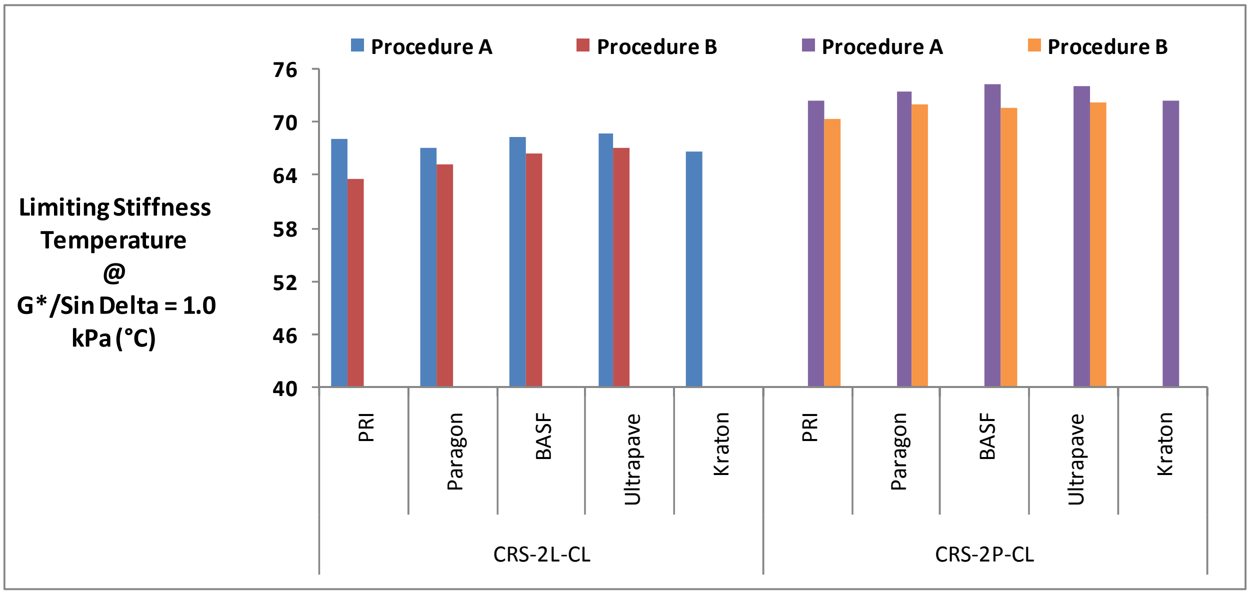

Figure 87. Chart. Repeatability and Effect of Recovery Procedures A and B.

Figure 88 compares the high temperature DSR parameters on the CRS-2L-CL residue for recovery procedures A and B. In all cases, the Procedure A tests on the CRS-2L resulted in stiffer residues; when the temperature where Superpave criteria are met are higher, the J_{nr} values are lower and the percent recoveries are higher.

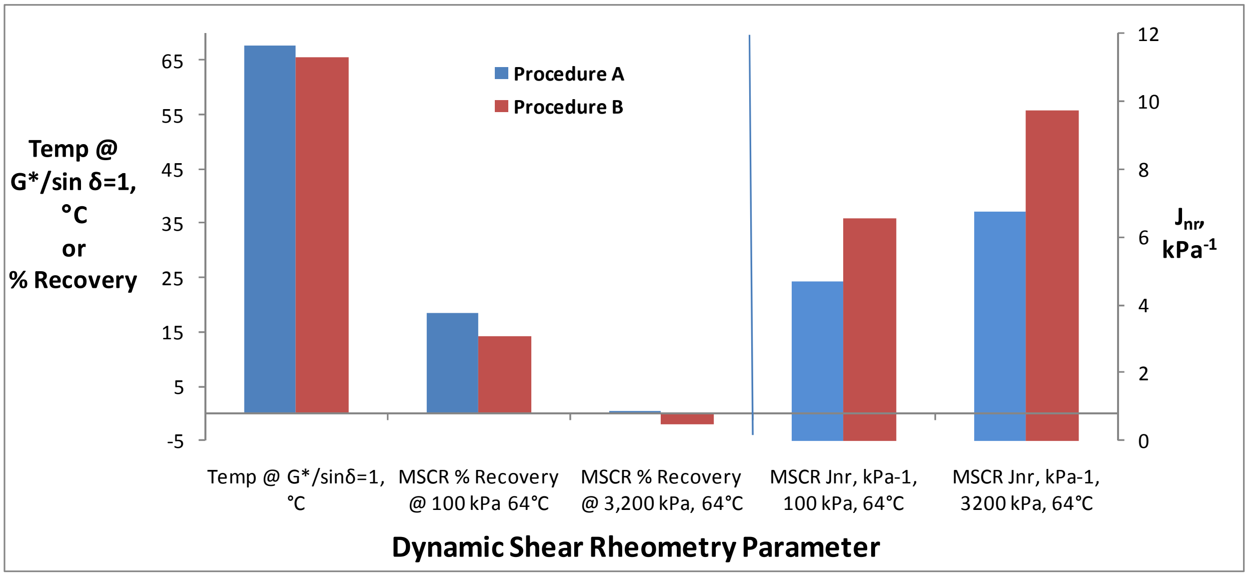

Figure 88. Chart. Recovery Procedures A and B Effect on CRS-2L-CL DSR Parameters.

5.2.2 Rheology Test Results from Crater Lake

All emulsion residue recovery and testing was coordinated by PRI Asphalt Technologies, Inc. As mentioned above, early results showed very low values for MSCR recoveries at 3,200 kPa and 64 °C, so some tests were also run at 25 °C and 58 °C; later single lab tests were collected at 52 °C. When run at 64 °C, results for the MSCR recoverable strain at 3,200 kPa were frequently reported to be negative. This result should be impossible, but occurs when the binder is so soft that the spindle continues to spin in the original direction even after the load is turned off. This problem was most prevalent with one type of instrument used in two of the labs. The DSR supplier has been contacted and asked to rectify the problem. However, it is very clear that a statistically reliable recoverable strain cannot be measured by any of the instruments for the CRS-2L-CL at the climate temperature of 64 °C and 3,200 kPa. These findings confirm the anomalous results previously noted when testing the soft PASS emulsion residue. It seems clear that chip seal emulsion residues may be considerably softer than their HMA counterparts in a given climate. DSR protocols have maximized rheometer performance for testing HMA binders. DSR testing protocols should be adapted for emulsion residues so that instrument response remains within optimum operating parameters. One possibility is to reduce stress levels, but a preferred choice is probably to reduce testing temperatures by 6 to 10 °C below the designated high climate temperature.

Standard Superpave protocols were run to determine the exact temperature PG of the residues. Figure 89 shows the temperatures where high and low temperature failure criteria are met for the emulsions from all 2008 and 2009 projects. While these parameters were designed for hot mix asphalt and not surface treatment emulsion residues, they are helpful in comparing the relative moduli of the materials. The CRS-2L-CL qualifies as a PG 64-28, the CRS-2P-CL as a PG 70-28 (although both are close to meeting -34 criteria), and the CRS-2 residue is a PG 64-28, having a lower total temperature range, as would be expected from an unmodified asphalt binder.

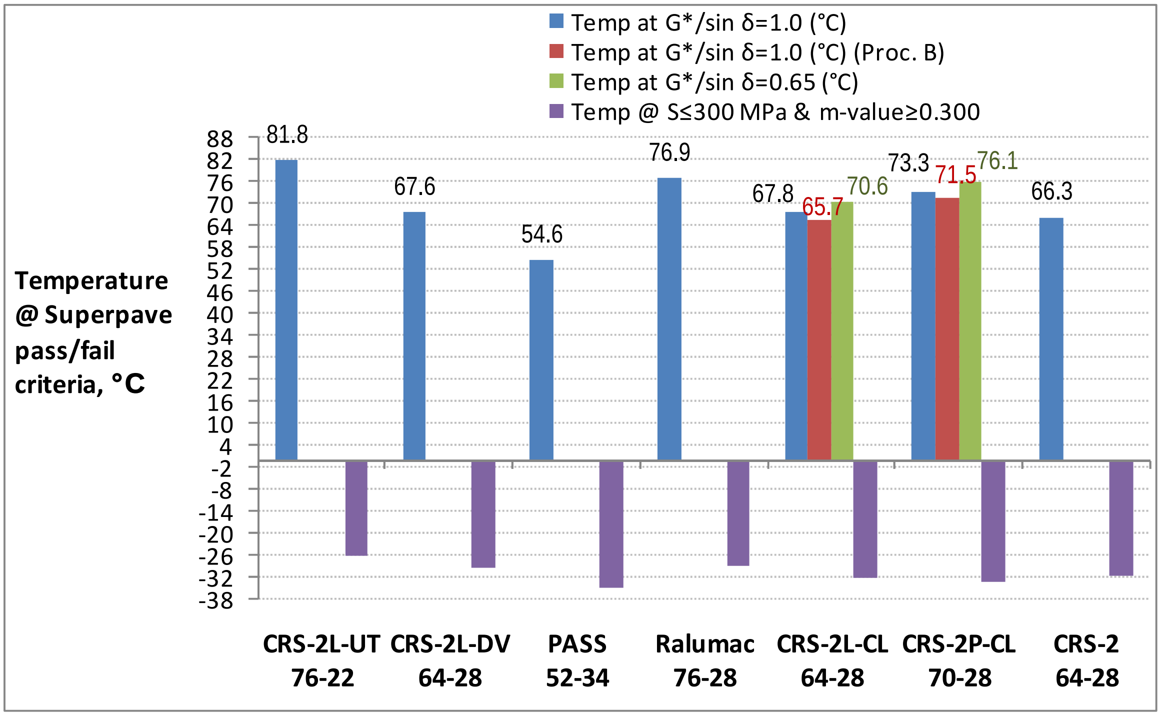

Figure 89: Superpave PG Testing Results of Recovered Emulsion Residues

Hoyt, Epps Martin, and Shuler very recently proposed a new performance grading system (SPG) for chip seal emulsion residues.$^{(105)}$ They suggest that the passing high temperature criteria for emulsion residues should be set at G*/sin δ ≥ 0.65 kPa at 10 radians/second. Figure 89 shows that this modulus is reached at 70.6 °C for the CRS-2L-CL and at 76.1 °C for the CRS-2P-CL, or temperatures approximately two degrees below those for 1.0 kPa. Both tests were run on residues recovered using Procedure A.

Table 34 shows the inter-laboratory repeatability of the various rheology tests. While some of these represent the average of 5 laboratories, some of the tests were run by only two, three, or four labs. The repeatability of the standard Superpave tests to determine the temperature at G*/sin δ = 1 is excellent, as would be expected. The MSCR results are less so, especially at higher temperatures (64 and 70 °C). This problem with MSCR is thought to be related to running the DSR at sub-optimal conditions, and should be correctable by lowering test temperatures.

Table 34. Repeatability of Rheometry Testing.

	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
	CRS-2L-CL Procedure A			**CRS-2P-CL Procedure A**		
Temp @ G*/sin δ = 1.0 kPa, °C	67.76	0.88	1.3%	73.28	0.95	1.3%
MSCR % Recovery @ 100 kPa, 25 °C	53.05	8.45	15.9%	70.20	8.83	12.6%
MSCR % Recovery @ 100 kPa 64 °C	18.32	2.94	16.0%	13.88	8.13	58.6%
MSCR % Recovery @ 3,200 kPa, 25 °C	51.50	5.11	9.9%	65.82	6.56	10.0%
MSCR % Recovery @ 3,200 kPa, 64 °C	0.06	3.42	5459.6%	3.8406	2.4436	63.6%
MSCR J_{nr}, kPa-1, 100 kPa, 25 °C	0.079	0.160	202.2%	0.004	0.001	32.9%
MSCR J_{nr}, kPa-1, 100 kPa, 64 °C	4.706	0.870	18.5%	2.566	0.257	10.0%
MSCR J_{nr}, kPa-1, 3,200 kPa, 25 °C	0.105	0.220	208.6%	0.004	0.001	19.3%
MSCR J_{nr}, kPa-1, 3,200 kPa, 64 °C	6.748	1.392	20.6%	4.47	2.54	56.8%
PAV MSCR % Recovery, 100 kPa, 64 °C	39.37	14.11	35.8%	38.62	8.29	21.5%
PAV MSCR % Recovery @ 3,200 kPa, 64 °C	31.58	11.44	36.2%	25.56	8.04	31.4%
PAV J_{nr}, kPa-1, 100 kPa. 64 °C	0.37	0.18	47.3%	0.46	0.20	44.3%
PAV J_{nr}, kPa-1, 3,200 kPa, 64 °C	0.50	0.29	56.9%	0.66	0.42	64.1%
	CRS-2L-CL Procedure B			**CRS-2P-CL Procedure B**		
Temp @ G*/sin δ = 1, °C	65.58	1.49	2.3%	71.54	0.83	1.2%
MSCR % Recovery @ 100 kPa, 25 °C	54.02	6.46	12.0%	62.09	4.81	7.8%
MSCR % Recovery @ 100 kPa 64 °C	14.12	11.35	80.4%	20.18	3.76	18.6%
MSCR % Recovery @ 3,200 kPa, 25 °C	49.56	7.28	14.7%	66.85	5.48	8.2%
MSCR % Recovery @ 3,200 kPa, 64 °C	-2.02	3.77	187.0%	3.4068	3.8455	112.9%
MSCR J_{nr}, kPa-1, 100 kPa, 25 ° C	0.008	0.003	35.5%	0.004	0.002	36.5%
MSCR J_{nr}, kPa-1, 100 kPa, 64 °C	6.529	1.739	26.6%	2.928	0.235	8.0%
MSCR J_{nr}, kPa-1, 3,200 kPa, 25 °C	0.008	0.003	38.5%	0.004	0.002	39.9%
MSCR J_{nr}, kPa-1, 3,200 kPa, 64 °C	9.752	2.374	24.3%	3.555	2.064	58.1%

A Rocky Mountain User-Producer Group study recommended that HMA binders should be tested within 8 hours of pouring samples into the silicone molds.(107) In the course of compiling data for Table 34, Kraton's lab recovered the residue and placed it in a closed tin, but was unable to complete rheological testing for three weeks. To satisfy agreed upon protocols, they recovered a second emulsion residue and reported results as included above. However, as a side experiment, they also tested the residue recovered three weeks earlier. Results between the two experiments varied to a degree far in excess of any differences that could be explained by the inter-lab study shown here. PRI is undertaking an investigation to define the amount of time that can be allowed between recovery and testing. Results are outside the scope of this study and were not available for this report, but will be forwarded to the emulsion task force.

Table 35 shows the results from all the laboratories. Because binder stiffness is much higher at 25 °C than at 64 °C, the measured strains for the MSCR protocol are very low even at the higher 3,200 kPa applied stress. If further research for specification development is to be done at ambient temperatures, higher applied stresses or longer loading times may be needed to increase the total strain. This is particularly important if the test is used specifically to identify polymers by monitoring recoverable strain.

Table 35. Compiled MSCR Results on Crater Lake Samples.

Sample Recovery Procedure	**Temperature, °C**	**70**	**70**	**64**	**64**	**58**	**58**	**52**	**52**	**25**	**25**	**64**	**64**
	Stress, kPa	**100**	**3,200**	**100**	**3,200**	**100**	**3,200**	**100**	**3,200**	**100**	**3,200**	**100**	**3,200**
	MSCR J_{nr}, kPa-1											**J_{nr} After PAV**	
CRS-2L-CL Procedure A	PRI			5.37	8.41	2.70	3.36	1.19	1.40	0.0073	0.0073	0.60	0.73
	Paragon			5.37	7.83					0.0060	0.0060	0.17	0.20
	BASF			3.34	5.44					0.0050	0.0050	0.37	0.76
	Kraton			5.10	5.30					0.0120	0.0100		
	Ultrapave			4.35	6.76					0.3648	0.4988	0.35	0.32
	Average			**4.71**	**6.75**					**0.0790**	**0.1054**	**0.37**	**0.50**
CRS-2L-CL Procedure B	PRI			8.96	12.08					0.0121	0.0121		
	Paragon			5.86	11.31					0.0080	0.0070		
	BASF			4.88	6.93					0.0050	0.0060		
	Ultrapave			6.42	8.69					0.0078	0.0058		
	Average			**6.53**	**9.75**					**0.0082**	**0.0077**		
CRS-2P-CL Procedure A	PRI			2.40	3.44	1.25	2.07	0.53	0.77	0.0030	0.0040	0.47	0.61
	Paragon			2.48	3.52					0.0040	0.0050	0.19	0.23
	BASF			2.36	3.27					0.0020	0.0030	0.67	1.31
	Kraton			3.00	9.00					0.0044	0.0048	0.64	0.77
	Ultrapave			2.58	3.11					0.0051	0.0039	0.32	0.37
	Average			**2.57**	**4.47**					**0.0037**	**0.0041**	**0.46**	**0.66**
CRS-2P-CL Procedure B	PRI			3.13	5.07					0.0050	0.0060		
	Paragon			2.97	4.37					0.0040	0.0040		
	BASF									0.0060	0.0030		
	Kraton			2.59	3.58								
	Ultrapave			3.02	4.76					0.0023	0.0025		
	Average			**2.93**	**4.44**					**0.0043**	**0.0039**		
CRS-2 Proc. A	PRI	11.05	13.22	6.17	7.14	2.07	2.48			0.0076	0.0077	1.03	1.24
	MSCR % Recovery											**% Rec – PAV**	
CRS-2L-CL Procedure A	PRI			18.8	-3.1	8.0	-0.8	11.3	3.2	54.3	54.1	26.9	16.1
	Paragon			13.3	-4.0					54.2	54.2	48.9	43.0
	BASF			20.0	2.0					60.0	57.0	54.0	31.0
	Kraton			18.7	3.9					38.6	47.1		
	Ultrapave			20.8	1.5					58.1	45.1	27.7	36.2
	Average			**18.3**	**0.1**	**8.0**	**-0.8**	**11.3**	**3.2**	**53.0**	**51.5**	**39.4**	**31.6**
CRS-2L-CL Procedure B	PRI			3.5	-5.1					47.6	47.1		
	Paragon			22.8	-5.4					52.4	52.2		
	BASF			25.0	2.0					63.0	58.0		
	Ultrapave			5.2	0.4					53.1	40.9		
	Average			**14.1**	**-2.0**					**54.0**	**49.6**		
CRS-2P-CL Procedure A	PRI			20.1	4.9	26.8	9.2	34.2	20.5	66.3	65.7	36.2	23.5
	Paragon			15.9	1.6					66.0	64.2	47.8	39.7
	BASF			22.0	7.0					86.0	77.0	47.0	21.0
	Kraton			2.4	1.2					66.6	60.8	31.1	23.4
	Ultrapave			9.0	4.5					66.1	61.4	31.1	20.2
	Average			**13.9**	**3.8**					**70.2**	**65.8**	**38.6**	**25.6**
CRS-2P-CL Procedure B	PRI			20.8	1.9					63.4	63.1		
	Paragon			15.0	-1.0					64.3	64.6		
	BASF									55.0	75.0		
	Kraton			24.0	8.0								
	Ultrapave			20.9	4.7					65.7	64.7		
	Average			20.2	3.4					62.1	66.9		
CRS-2 Proc. A	PRI	**-0.5**	**-5.6**	**-0.6**	**-4.0**	**6.3**	**-1.2**			**47.3**	**47.3**	**14.3**	**4.2**

Figure 90 combines data from 2008 and 2009 testing (MSCR percent recovery at 3,200 kPa, all materials recovered using ASTM D7497, Procedure A), and confirms previous findings that the MSCR percent recovery is strongly dependent upon temperature.

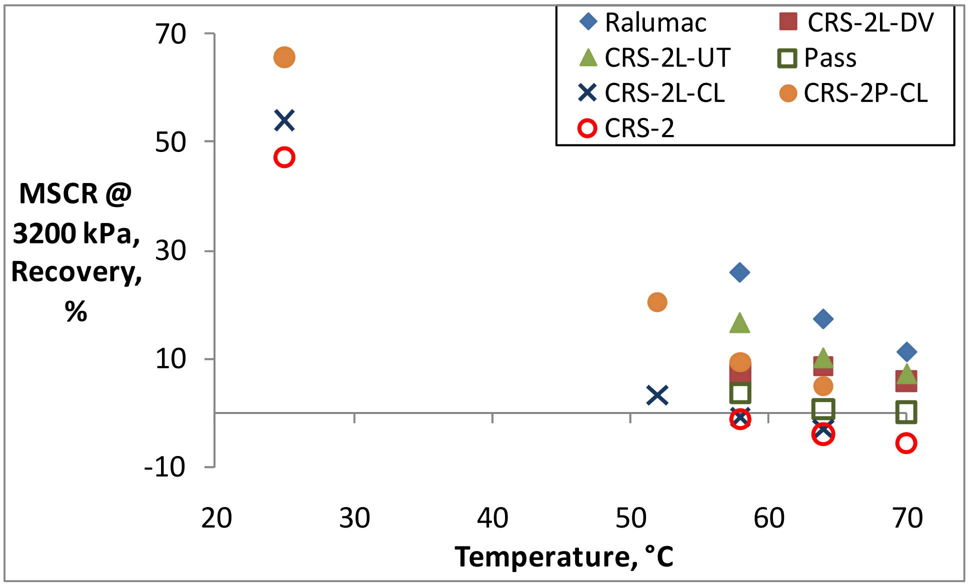

Figure 90. Chart. Effect of Temperature on MSCR Percent Recovery for All Samples.

Figure 90 shows that CRS-2P-CL, which tested as a PG 70-28, has a slightly higher recovery at 64 °C than the CRS-2L-CL, which tested as a PG 64-28. The unmodified CRS-2 has a significant MSCR recovery at 25 °C. In fact, under the conditions of the current MSCR test, the inverse relationship between J_{nr} and percent recovery (Figure 91) is so strong that it almost masks the effect of polymers when viewed over a range of four orders of magnitude in modulus (i.e., 25 to 64 °C). This figure includes data for unmodified CRS-2 as well as the many modified residues. Further research and test modifications will be needed before MSCR strain recovery can reliably replace current polymer identifiers in PME specifications. Some combination of lower temperatures, longer loading times, higher stresses, and longer recovery times will probably be needed to separate the delayed elastic response of polymers from the immediate elastic response of stiffer binders.

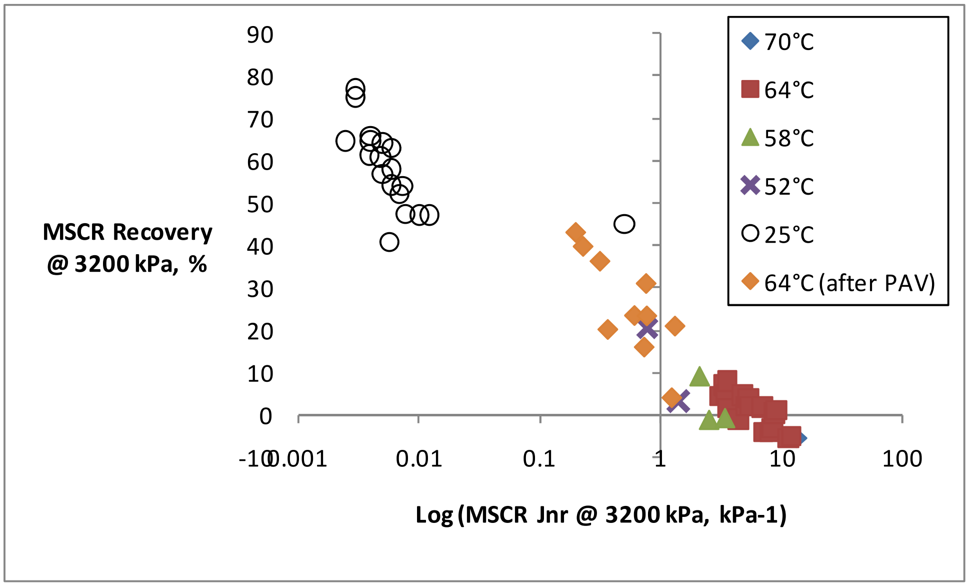

Figure 91. Chart. Relationship of MSCR J_{nr} and Percent Recovery for All Samples.

There was some question about the applicability of aging protocols. Figures 92 and 93 show the MSCR J_{nr} and percent recovery (at 3,200 kPa and 64 °C) results before and after PAV testing. The test results are the averages of multiple labs, with the exception of the PASS, which was tested after PAV only by BASF, and the CRS-2, which was tested only by PRI.

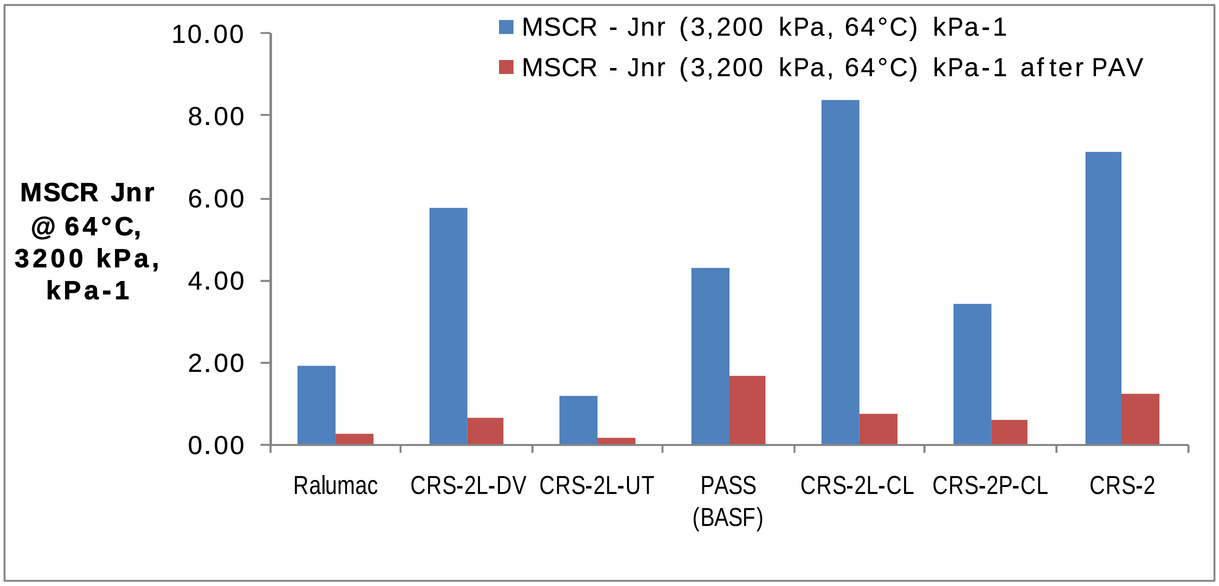

Figure 92. Chart. MSCR J_{nr} Before and After PAV Aging.

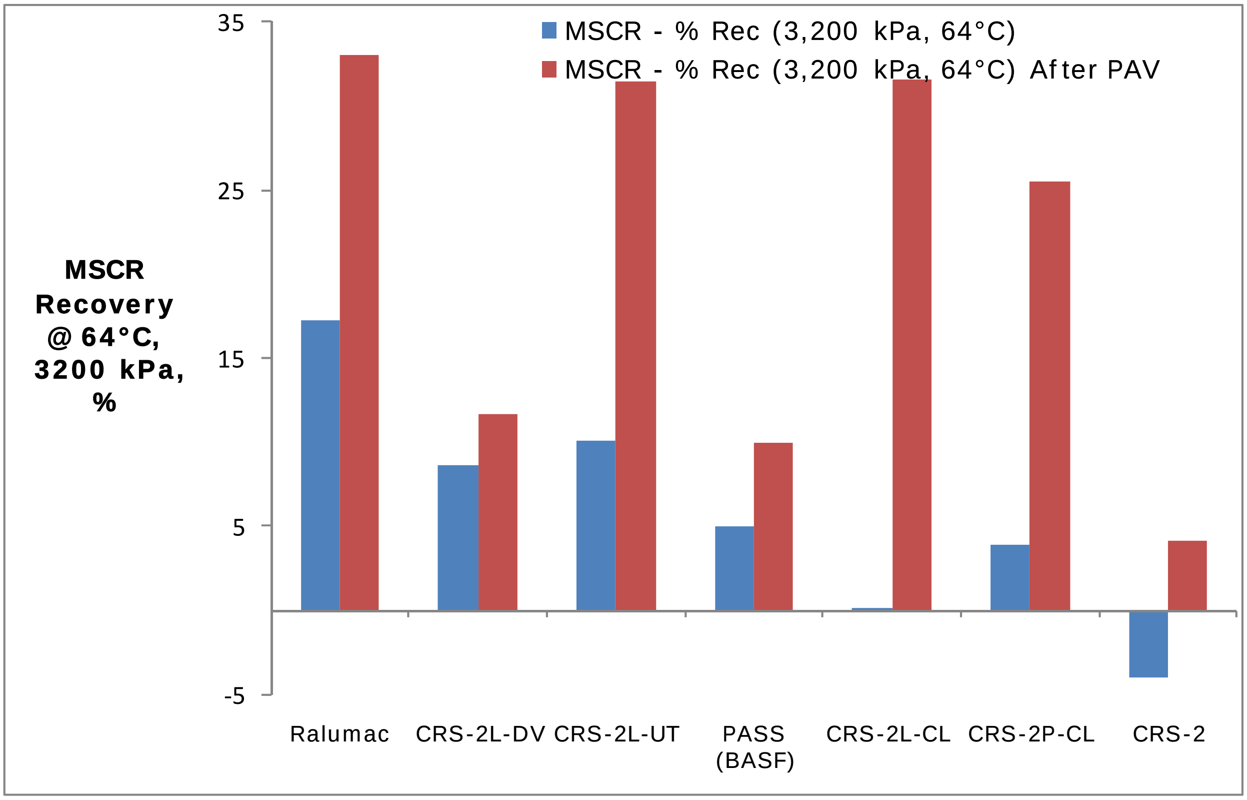

Figure 93. Chart. MSCR Percent Recovery Before and After PAV Aging.

The aging indices are shown in Figure 94 as the inverse of J_{nr} (tested at 64 °C) after aging divided by J_{nr} before aging. They are surprisingly high—ranging from over 2 to more than 11 times as stiff after PAV aging. The results at 100 kPa are very different from those at 3,200 kPa, possibly because of the high testing error at 64 °C.

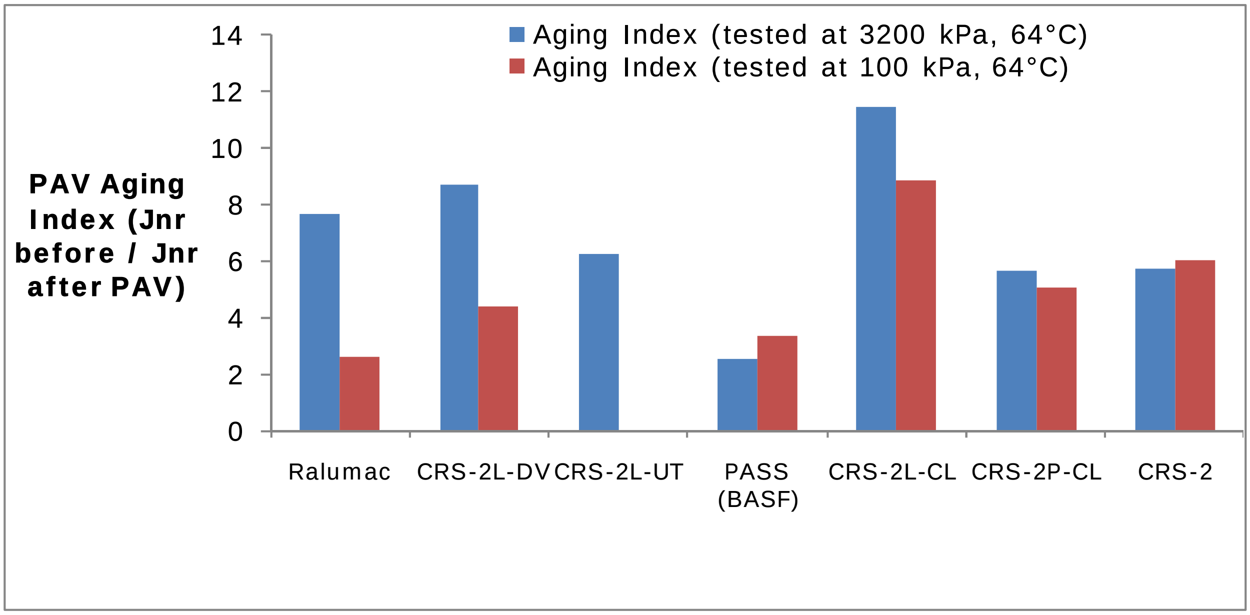

Figure 94. Chart. PAV Aging Indices.

5.2.3 Sweep Test Results from Crater Lake

Table 36 shows the results from the ASTM D7000 sweep tests run on the Crater Lake emulsion samples. Each test represents five replicates; the standard deviation and range given in Table 36 for individual tests are for those five replicates. The “All Labs” percent mass loss results are the averages of the result for each laboratory, and the “All Labs” statistical analyses are for the inter-laboratory test agreement. While the intra-laboratory agreement was generally good, the reliability among the labs was not as good. Because of the discrepancy among the laboratories, a sample of the CRS-2P-CL was re-split and tested by three labs, as shown in the bottom section of Table 36. Both Ultrapave and Paragon labs had a low mass loss this time. They also reported the viscosity of the emulsion (which had been sampled from the field months before) had risen significantly and was difficult to spread on the felt. BASF, however, saw no viscosity rise on storage, and had an identical result to the earlier test. There is still work to be done on improving the inter-laboratory reliability.

Table 36. Compiled Sweep Test Results on Crater Lake Samples.

Initial Test Results						
Emulsion	Test Lab	% Mass Loss	Standard Deviation	Range	Coefficient of Variation	Felt Configuration
CRS-2L-CL	Ultrapave	7.2	1.8	4.6	25.3%	≈ 12.5" diameter circular
	Paragon	18.6	1.1	3.0	6.1%	≈ 12.5" diameter circular
	BASF	13.6	2.8	7.7	20.9%	12" X 14" rectangular
	PRI	11.4	1.3	3.3	11.1%	≈ 12.5" diameter circular
	All Labs	**12.7**	**4.7**	**11.3**	**37.1%**	
CRS-2P-CL	Ultrapave	4.2	0.9	2.0	20.5%	≈ 12.5" diameter circular
	Paragon	18.3	1.2	2.8	6.4%	≈ 12.5" diameter circular
	BASF	16.3	2.1	5.1	12.8%	12" X 14" rectangular
	PRI	12.0	1.1	2.8	9.5%	≈ 12.5" diameter circular
	All Labs	**12.7**	**6.2**	**14.1**	**49.0%**	
Retest—Split Sample						
CRS-2P-CL	Ultrapave	5.0	1.5	2.2	30.0%	
	BASF	16.3	3.7	5.9	22.7%	
	Paragon	6.9	0.04	0.1	0.5%	
	All Labs	**9.4**	**6.1**	**11.3**	**64.3%**	

6.0 CONCLUSIONS AND NEXT STEPS

Polymer-modified asphalt emulsions can be very effective in a number of paving applications for all types of pavement. When properly formulated, they resist deformation and bleeding at high temperatures; resist cracking, raveling, and shelling at low temperatures; are more durable; and they exhibit improved behavior during construction, allowing quicker traffic return and reducing early failure. The best results are obtained when the polymer and asphalt are compatible and the polymer is well dispersed and networked throughout the asphalt. Literature searches; information gathering from industry, academic, and government experts; and a survey confirmed there is a need for performance-based specifications of PMEs. Performance-based specifications, versus recipe specifications for type and content of polymer, will improve the quality of the asphalt emulsion residue remaining on the pavement. The Strawman specification was developed using newly developed techniques for setting time (sweep test), emulsion recovery (FDO test), and rheological characterization (DSR-compliance and recovery in MSCR and BBR). Samples from field trials placed on Federal Highway Administration projects in 2008 were tested using the new protocols. Based on the results of the 2008 tests, the protocols were revised and run on samples from a 2009 field project in Crater Lake National Park. Data was collected with the proposed method of using intermediate temperature rheology testing with mastercurve analysis to characterize low temperature, eliminating the need for expensive and time-consuming BBR testing. Preliminary results are very promising, and the data collected is being shared with other researchers to characterize and specify the performance of the modified residue. There is still work to be done. The information learned from the 2008 and 2009 testing has led to the conclusion that further revisions are needed, as discussed below. It is hoped that other researchers, suppliers, and users should benefit from the results obtained by this testing plan, and it is envisioned that performance-based specifications for polymer modified asphalt emulsion surface treatments will be the norm in the not too distant future.

6.1 Suggestions for Furthering Emulsion Performance Tests and Specifications

While the laboratory test results were informative in narrowing test methods and conditions, there is still work to be done before a PME performance-based specification can be written. Based on what has been learned through this project, test methods can be classified as: those that are recommended for implementation, those that show promise but need additional validation, and those that gave problematic results and probably should be abandoned. Additionally, the results have led to recommendations for areas where further work would be beneficial.

A revised Strawman protocol is given in Table 37.

Table 37. Revised Emulsion Performance Strawman Protocol.

Purpose	**Test**	**Conditions**	**Report**
Residue Recovery	Forced Draft Oven	A)24 hrs @ambient + 24 hrs @60 ºC, or B)6 hrs @60 ºC	% Residue
Tests on Residue from Forced Draft Oven			
High Temperature (Rutting/Bleeding)	DSR	T_h (with an offset to be determined)	G*/sin δ
Polymer Identifier (Elasticity/Durability)	Single Stress DSR Creep Recovery	To be determined	% Recoverable Strain
High Float Identifier (Bleeding)	DSR–Non-Linearity	To be determined	*Test to be developed*
Tests on Aged Residue – Method To Be Determined			
Low Temperature (Aged Brittleness)	DSR Freq. Sweep	10 ºC & 20 ºC Model Low Temperature	G* Phase Angle
Polymer Degradation (Before/After PAV)	Single Stress DSR Creep Recovery	To be determined	Recoverable Strain Ratio
Aged Brittleness	Sweep Test on Aged Sample	To be determined	% Mass Loss

6.1.1 *Performance Tests with Problematic Results*

The test plan protocol (Table 24) included some methods and test conditions that gave unacceptable results. The problems encountered led to the conclusion that these methods should be abandoned, and other methods would be more useful in differentiating and specifying polymer emulsions. These include AASHTO TP 70-08, the Multiple Stress Creep Recovery (MSCR) J_{nr} (compliance) and percent recovery. The J_{nr} is an inverse of the complex modulus. Although results for J_{nr} were reasonable at test temperatures slightly below maximum pavement temperatures, most practitioners are more familiar with G*/sin δ as tested by AASHTO T 315, and its statistical reliability was significantly better. The J_{nr} results in this study had unacceptable multi-laboratory precision, particularly at higher test temperatures, and had very small differences among the materials tested, as discussed in Section 5.1.2.4. Similarly, Figure 91 demonstrated that the MSCR percent recovery results were too dependent upon the stiffness of the materials tested to be effective at differentiating the elasticity of a polymer network in the asphalt. Two DSR instruments sold by the same manufacturer were particularly prone to bias strain recovery results when binder specimens were soft. This project has shown that recoverable strain at the high pavement temperature is too low to measure accurately in the DSR, and at higher temperatures and defined conditions, recoverable strain is too sensitive to binder modulus to be an effective polymer identifier. Although data is limited, the project results suggest that:

- Recoverable strain should be measured at an intermediate temperature tied to the climate temperature range;
- Much longer loading and recovery times should be used; and
- Multiple cycles may not be needed.

The strain sweep results on the recovered residues for resistance to aggregate loss (shelling) on original and PAV residue were also disappointing. Figure 80 shows there was no clear differentiation in curve shape among polymer modified and non-modified emulsions, and the only difference noted was the dependence upon binder stiffness. This study included only one non-modified material, so further confirmation of this finding should be made.

6.1.2 Performance Tests Recommended for Specifications

Multiple labs have shown that these tests are repeatable and, with the limited data currently available, show no discrepancies with field performance.

6.1.2.1 The Sweep Test

The sweep test (ASTM D7000: Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples) is the best indicator of emulsion breaking and chip retention in the field. Demulsibility should be abandoned in favor of the sweep test. The results given in sections 5.1.2.8 and 5.2.3 show that the intra-laboratory sweep test results were generally very good, but inter-laboratory agreement needs to be improved. Even so, most emulsions tested fell within the suggested 30% mass loss maximum, with the exception of the PASS emulsion, which is known to have a slower curing emulsifier. The PASS also had some reported chip loss problems in the field. If the sweep test is specified, determination of whether an emulsion is anionic or cationic is important only to performance to prevent problems with contamination and mixing in tanks, trucks and in the field.

6.1.2.2 Forced Draft Oven (FDO) Emulsion Residue Recovery

ASTM D7497 - 09 “Standard Practice for Recovering Residue from Emulsified Asphalt Using Low Temperature Evaporative Technique,” using the FDO is recommended for recovering emulsion residue for performance tests. The recovered residue is easy to peel from the silicone molds to prepare rheometry test samples without reheating. As illustrated in Table 33 and Figures 87 and 88, both ASTM D7497 Procedure A (24 hrs at 25°C and 24 hours at 60°C) and Procedure B (6 hours at 60°C with a thinner film than A) gave excellent multi-laboratory precision in residue percent and standard Superpave $G^*/\sin\delta$ tests on the residues. Figure 87 shows, however, that Procedure A hardens the residue more than Procedure B. Both procedures are acceptable, but the residues obtained will not be equivalent, so any specification limits on tests run on the residues should specify how the residue is obtained. Procedure B looks especially promising because it significantly shortens testing time and yields less hardening of the residue. However, a single recovery using procedure B yields less residue for testing, so residue specification protocols must minimize sample size. Procedure B is particularly attractive if all residue tests can be completed using various DSR protocols.

ASTM D7497 is not recommended, however, with conventional emulsion residue specifications. The residue properties may be different from those obtained by conventional AASHTO M208/140/316 evaporation or distillation protocols, and specification limits may need to be adjusted.

6.1.3 Performance Tests Warranting Further Investigation

The experimentation in this study has shown that the testing parameters in the originally proposed Strawman protocol (including stress, temperature, etc.) for some test methods are not ideal for the emulsions applied during field trials. In some cases, the conditions are outside acceptable tolerances of the test equipment (especially the rheometry), and in others they do not accurately characterize and show differences among the materials tested. The tests themselves, however, show promise. There are also some tests that have been proposed by other researchers that were outside the scope of this study. Further investigation of these tests should prove useful to the eventual development of emulsion performance-based specifications.

6.1.2.1 Emulsion Viscosity Testing and Specifications

A field viscosity test and specification is more indicative of performance during application than a laboratory test run long after construction; if viscosity is to be measured in the laboratory, an improved lab method of measuring emulsion viscosity should be selected.

6.1.2.2 Residue Rheometry Testing and Specifications

As mentioned above, the MSCR gave disappointing results. DSR testing, however, did show the surprising result that there was no correlation between climatic temperature and the materials used in the field. As discussed in Section 5.1.2.4, conventional AASHTO T 315 DSR tests should be used so that emulsion residue stiffness is appropriate for the climate and project location. While test conditions and limits still need definition, G*/sin δ is an acceptable parameter for determining resistance to bleeding and to differentiate materials that are too soft to retain chips and resist deformation of slurry seals and micro surfacing. G*/sin δ results in this study were repeatable, and the test method is well-developed, understood, and accepted. Parameters used for HMA (e.g., stress levels, temperatures, limits), however, will probably need to be adjusted for emulsions. Chip seal emulsion residues may be considerably softer than their HMA counterparts in a given climate. Using existing nomographs showing relationships between penetration and G*/sin δ could be used to develop the parameters needed for performance specifications for materials that currently give acceptable field performance. Correlation of test conditions and specification limits with field performance is still needed.

The MSCR recoverable strains (percent recoveries) were not within tolerances of most commonly used dynamic shear rheometers. The results suggested, however, that a single cycle creep recovery test at higher strain, longer loading, lower temperature, and higher stresses might give better results. This study recommends investigation of a single stress creep recovery test. Most rheometers would be capable of running this test, and it would take less time to run.
For determining low temperature mechanical properties, the DSR should be used to measure or predict low temperature G* and phase angle. While this testing was outside the scope of this study, field samples from this study have been sent to other researchers for their analysis. Some options for this include:

- Frequency sweep at two intermediate temperatures used with the CAM model to predict G* and phase angle at low temperatures;
- Direct measurement of G* and phase angle at low temperature on 4-mm plates in the DSR; and
- BBR per standard protocols only if DSR methods prove unworkable.

There are several reasons to replace the BBR with DSR testing for low temperature specifications. They include:

- Single instrument for all residue tests to lower cost and reduce laboratory footprint;
- No use of volatile solvents and therefore no need for fume hood;
- No need to reheat (and age) to pour test specimens; and

- Much smaller sample size used, enabling the use of the much faster recovery Procedure B, thinner films to be cured in PAV pan, and allows study of aged binders scraped from pavements in the field.

Performance-based DSR tests and specifications for high float emulsion residues were not addressed in this project, but need to be developed.

6.1.2.3 Long Term Aging

This study only included PAV for long term aging. Before the residue is placed in the PAV, the sample must be free of moisture. Thinner films should be investigated to ensure water vapor loss during the FDO recovery step. The aging ratios from the pressure aging vessel testing in this study seemed high compared to standard asphalt binder results. Research in Australia reported aging to the brittle failure point (chip raveling) correlated to eight years in the Australian outback desert.(108) It may be useful to determine the length of time needed in the PAV that would be required to reach this brittle failure point. There is concern that the PAV temperature and pressure have an affect on the polymer/asphalt morphology that would not be encountered under field conditions. Further, UV light is believed to be one of the most damaging effects on surface treatment binders, and the PAV does not address that. Some type of aging test on the sweep test samples may be useful. More work is needed.

6.1.2.4 Time Lapse between Residue Recovery and Testing

The time lapse between the residue recovery and residue testing appears to have a significant effect on the test results, possibly because of the unique microstructure of polymer modified asphalt emulsion residues. At this time, it is recommended that materials be tested within 24 hours after residue recovery. More work needs to be done to determine optimal conditioning time.

6.2 Leveraging Resources and Information Sharing

This project has begun leveraging available knowledge and pooling information (e.g., test methods, data, and pavement performance) with suppliers and other researchers and agencies (Federal, State, City, and County). The recently released *TSP Preservation Research Roadmap* also recognizes the need for improved, performance-related specifications for asphalt emulsions. Because of the high interest by several entities in developing improved emulsion test methods and specifications, an expert task force of the Pavement Preservation ETG has been formed by FHWA, with the first meeting held in April 2008. By cooperating on testing procedures and round robin testing, researchers from several projects will be more effective in developing standard procedures. Because funding for this FLH PME study has ended, it is hoped that the ETG task force in combination with these other ongoing research efforts will continue to monitor and update the report-only testing program and eventually recommend pertinent performance-based specifications to FLH and to the broader paving industry. It is further expected that the guidelines delivered by this FLH project will be applicable not only to FLH personnel, but to the industry as a whole. It is recommended that governmental agencies support the creation of a recently proposed pooled fund study to continue the performance-based testing using AASHTO agency field projects.

6.3 Other Data Gaps and Future Work

Specific areas identified as currently needing more investigation are detailed in Section 6.1.3 of this report. Other possible extensions include:

- Develop performance and specification recommendations for hiking and biking trails and parking lots.
- Provide clearer differentiation of material performance given variability in climate (temperature, humidity) and traffic. The 6 °C grade increments at both high and low temperatures should be maintained, as this represents a doubling of binder stiffness and fits well with the use of LTPPBind climate software.
- Update asphalt emulsion test methods in ASTM D244, including measures for laboratory and field viscosity and low-temperature residue recovery.
- Continue developing standard asphalt emulsion residue test methods and specifications that correlate with performance.
- Continue the development of rheological methods to ensure the presence of optimum levels of polymer modification or gel (high float) formation in the residue.
- Develop aging procedures and polymer/asphalt compatibility or stability tests for asphalt emulsion residues.
- Improve materials selection, including aggregate specifications and mix-design procedures.
- Develop improved performance-based methods for PME applications to include interactions between modified asphalt emulsion and aggregate. These should include curing tests establishing time-to-traffic, moisture damage, and longer term performance under specified traffic and environmental conditions.
- Improve controls on environmental and pavement conditions at time of construction.
- Create Delayed-Acceptance or Certified Supplier Programs for asphalt emulsions.
- Conduct formal cost-benefit analyses with and without modifiers for specific asphalt emulsion applications.
- Develop decision models for use of single chip seals, double and triple bituminous surface treatments, cape seals, slurry seals, micro surfacing, PASS, etc.
- Develop triggers for timing of surface treatments based upon measures of evolving material properties in the pavement.

There were several FLH chip seal and micro surfacing projects constructed in the summer and fall of 2008 and another placed during early summer of 2009. All materials were tested using the suggested Strawman protocols; 2009 testing was adjusted to reflect what was learned from the tests run in 2008. Multi-lab participation enabled researchers to identify and modify weaknesses in the proposed test procedures. The data presented here is a very promising start in support of the Strawman, and is a beginning of a database of performance-based test results on polymer modified asphalt emulsions. Hopefully these results will be used and expanded by other researchers to optimize test conditions and specification limits.

Although problems with curing might be visible shortly after construction, ultimate performance cannot be analyzed until many years later. FLH typically collects video pavement management data every three years. More frequent field inspection may be needed as the Strawman tests and ranges are compared to field performance with time. Tying the field performance information over time to the test results should be an on-going process. A materials library of the tested materials should also be maintained, so that materials may be retested as the test methods are perfected and pavement performance is known.

In conclusion, current activities are being fully coordinated with the FHWA Pavement Preservation ETG's Emulsion Task Force and with the FHWA Superpave ETGs to advance recommendations to the AASHTO Highway Subcommittee on Materials.