INTERNATIONAL TECHNOLOGY SCANNING PROGRAM

Warm-Mix Asphalt: European Practice

SPONSORED BY:

U.S. Department of Transportation
Federal Highway Administration

IN COOPERATION WITH:

American Association of State Highway and Transportation Officials

National Cooperative Highway Research Program

FEBRUARY 2008

NOTICE

Technical Report Documentation Page

1. Report No.
FHWA-PL-08-007

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Warm-Mix Asphalt: European Practice

5. Report Date
February 2008

6. Performing Organization Code

7. Author(s)
John D'Angelo, Eric Harm, John Bartoszek, Gaylon Baumgardner, Matthew Corrigan, Jack Cowsert, Thomas Harman, Mostafa Jamshidi, Wayne Jones, Dave Newcomb, Brian Prowell, Ron Sines, and Bruce Yeaton

8. Performing Organization Report No.

9. Performing Organization Name and Address
American Trade Initiatives
P.O. Box 8228
Alexandria, VA 22306-8228

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTFH61-99-C-005

12. Sponsoring Agency Name and Address
Office of International Programs
Office of Policy
Federal Highway Administration,
U.S. Department of Transportation
American Association of State Highway and
Transportation Officials
National Cooperative Highway Research Program

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes
FHWA COTR: Hana Maier, Office of International Programs

16. Abstract
Warm-mix asphalt (WMA) is a group of technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt and provide for the complete coating of aggregates at lower temperatures. WMA is produced at temperatures 20 to 55 °C (35 to 100 °F) lower than typical hot-mix asphalt (HMA). In 2007, a team of U.S. materials experts visited Belgium, France, Germany, and Norway to evaluate various WMA technologies through the Federal Highway Administration's International Technology Scanning Program.

The scan team learned that the benefits of WMA technologies include reduced fuel usage and emissions in support of sustainable development, improved field compaction, which can facilitate longer haul distances and cool weather pavement, and better working conditions. A range of technologies is available to produce WMA. European agencies expect WMA performance to be the same as or better than the performance of HMA. Although several areas need to be addressed as these technologies are adapted to U.S. materials and production practices, the scan team believes that the United States has no long-term barriers to WMA use. With additional research and trials, the team expects that highway agencies will allow WMA as an alternative to HMA.

17. Key Words
compaction, emissions, sustainable development, warm-mix asphalt

18. Distribution Statement
No restrictions. This document is available to the public from the:
Office of International Programs,
FHWA-HPIP, Room 3325, U.S. Department of Transportation,
Washington, DC 20590
international@fhwa.dot.gov
www.international.fhwa.dot.gov

19. Security Classify. (of this report)	20. Security Classify. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	68	Free

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Warm-Mix Asphalt: European Practice

PREPARED BY THE INTERNATIONAL TECHNOLOGY SCANNING STUDY TEAM:

JOHN D'ANGELO (Cochair)
FHWA

ERIC HARM (Cochair)
Illinois DOT

JOHN BARTOSZEK
Payne and Dolan, Inc.

GAYLON BAUMGARDNER
Ergon, Inc.

MATTHEW CORRIGAN
FHWA

JACK COWSERT
North Carolina DOT

THOMAS HARMAN
FHWA

MOSTAFA (MOE) JAMSHIDI
Nebraska Department of Roads

WAYNE JONES
Asphalt Institute

DR. DAVE NEWCOMB
National Asphalt Pavement Association

DR. BRIAN PROWELL
(Report Facilitator)
Advanced Materials Services, LLC

RON SINES
P.J. Keating Company

BRUCE YEATON
Maine DOT

FOR:

Federal Highway Administration
U.S. Department of Transportation

American Association of State Highway and Transportation Officials

National Cooperative Highway Research Program

JANUARY 2008

International Technology Scanning Program

The International Technology Scanning Program, sponsored by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP), evaluates innovative foreign technologies and practices that could significantly benefit U.S. highway transportation systems. This approach allows for advanced technology to be adapted and put into practice much more efficiently without spending scarce research funds to re-create advances already developed by other countries.

FHWA and AASHTO, with recommendations from NCHRP, jointly determine priority topics for teams of U.S. experts to study. Teams in the specific areas being investigated are formed and sent to countries where significant advances and innovations have been made in technology, management practices, organizational structure, program delivery, and financing. Scan teams usually include representatives from FHWA, State departments of transportation, local governments, transportation trade and research groups, the private sector, and academia.

After a scan is completed, team members evaluate findings and develop comprehensive reports, including recommendations for further research and pilot projects to verify the value of adapting innovations for U.S. use. Scan reports, as well as the results of pilot programs and research, are circulated throughout the country to State and local transportation officials and the private sector. Since 1990, about 70 international scans have been organized on topics such as pavements, bridge construction and maintenance, contracting, intermodal transport, organizational management, winter road maintenance, safety, intelligent transportation systems, planning, and policy.

The International Technology Scanning Program has resulted in significant improvements and savings in road program technologies and practices throughout the United States. In some cases, scan studies have facilitated joint research and technology-sharing projects with international counterparts, further conserving resources and advancing the state of the art. Scan studies have also exposed transportation professionals to remarkable advancements and inspired implementation of hundreds of innovations. The result: large savings of research dollars and time, as well as significant improvements in the Nation's transportation system.

Scan reports can be obtained through FHWA free of charge by e-mailing *international@fhwa.dot.gov.* Scan reports are also available electronically and can be accessed on the FHWA's Office of International Programs Web site at *www.international.fhwa.dot.gov.*

International Technology Scan Reports

Bringing Global Innovations To U.S. Highways

Safety

Safety Applications of Intelligent Transportation Systems in Europe and Japan (2006)
Traffic Incident Response Practices in Europe (2006)
Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response (2006)
Roadway Human Factors and Behavioral Safety in Europe (2005)
Traffic Safety Information Systems in Europe and Australia (2004)
Signalized Intersection Safety in Europe (2003)
Managing and Organizing Comprehensive Highway Safety in Europe (2003)
European Road Lighting Technologies (2001)
Commercial Vehicle Safety, Technology, and Practice in Europe (2000)
Methods and Procedures to Reduce Motorist Delays in European Work Zones (2000)
Innovative Traffic Control Technology and Practice in Europe (1999)
Road Safety Audits—Final Report and Case Studies (1997)
Speed Management and Enforcement Technology: Europe and Australia (1996)
Safety Management Practices in Japan, Australia, and New Zealand (1995)
Pedestrian and Bicycle Safety in England, Germany, and the Netherlands (1994)

Planning and Environment

Active Travel Management: The Next Step in Congestion Management (2007)
Managing Travel Demand: Applying European Perspectives to U.S. Practice (2006)
Transportation Asset Management in Australia, Canada, England, and New Zealand (2005)
Transportation Performance Measures in Australia, Canada, Japan, and New Zealand (2004)
European Right-of-Way and Utilities Best Practices (2002)
Geometric Design Practices for European Roads (2002)
Wildlife Habitat Connectivity Across European Highways (2002)
Sustainable Transportation Practices in Europe (2001)
Recycled Materials In European Highway Environments (1999)
European Intermodal Programs: Planning, Policy, and Technology (1999)
National Travel Surveys (1994)

Policy and Information

European Practices in Transportation Workforce Development (2003)
Intelligent Transportation Systems and Winter Operations in Japan (2003)
Emerging Models for Delivering Transportation Programs and Services (1999)
National Travel Surveys (1994)
Acquiring Highway Transportation Information from Abroad (1994)
International Guide to Highway Transportation Information (1994)
International Contract Administration Techniques for Quality Enhancement (1994)
European Intermodal Programs: Planning, Policy, and Technology (1994)

Operations

Commercial Motor Vehicle Size and Weight Enforcement in Europe (2007)
Active Travel Management: The Next Step in Congestion Management (2007)
Managing Travel Demand: Applying European Perspectives to U.S. Practice (2006)
Traffic Incident Response Practices in Europe (2006)
Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response (2006)
Superior Materials, Advanced Test Methods, and Specifications in Europe (2004)
Freight Transportation: The Latin American Market (2003)
Meeting 21st Century Challenges of System Performance Through Better Operations (2003)

Traveler Information Systems in Europe (2003)
Freight Transportation: The European Market (2002)
European Road Lighting Technologies (2001)
Methods and Procedures to Reduce Motorist Delays in European Work Zones (2000)
Innovative Traffic Control Technology and Practice in Europe (1999)
European Winter Service Technology (1998)
Traffic Management and Traveler Information Systems (1997)
European Traffic Monitoring (1997)
Highway/Commercial Vehicle Interaction (1996)
Winter Maintenance Technology and Practices—Learning from Abroad (1995)
Advanced Transportation Technology (1994)
Snowbreak Forest Book—Highway Snowstorm Countermeasure Manual (1990)

Infrastructure—*General*

Audit Stewardship and Oversight of Large and Innovatively Funded Projects in Europe (2006)
Construction Management Practices in Canada and Europe (2005)
European Practices in Transportation Workforce Development (2003)
Contract Administration: Technology and Practice in Europe (2002)
European Road Lighting Technologies (2001)
Geometric Design Practices for European Roads (2001)
Geotechnical Engineering Practices in Canada and Europe (1999)
Geotechnology—Soil Nailing (1993)

Infrastructure—*Pavements*

Warm-Mix Asphalt: European Practice (2008)
Long-Life Concrete Pavements in Europe and Canada (2007)
Quiet Pavement Systems in Europe (2005)
Pavement Preservation Technology in France, South Africa, and Australia (2003)
Recycled Materials In European Highway Environments (1999)
South African Pavement and Other Highway Technologies and Practices (1997)
Highway/Commercial Vehicle Interaction (1996)
European Concrete Highways (1992)
European Asphalt Technology (1990)

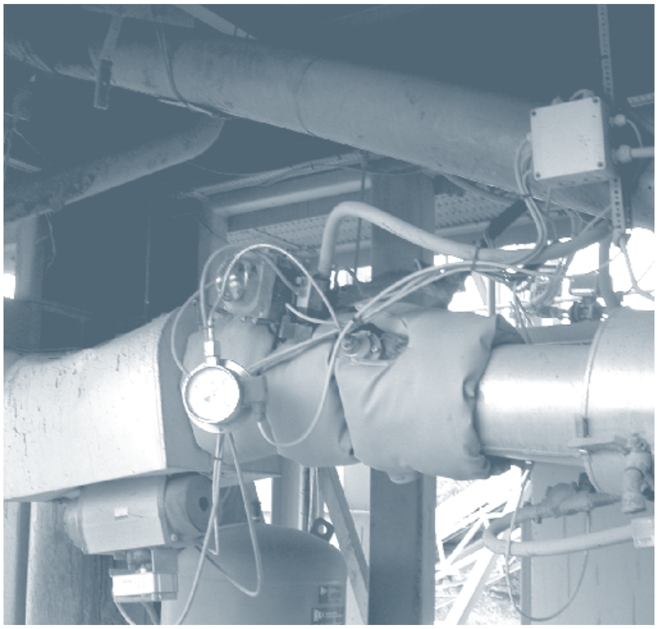
Infrastrucure—*Bridges*

Prefabricated Bridge Elements and Systems in Japan and Europe (2005)
Bridge Preservation and Maintenance in Europe and South Africa (2005)
Performance of Concrete Segmental and Cable-Stayed Bridges in Europe (2001)
Steel Bridge Fabrication Technologies in Europe and Japan (2001)
European Practices for Bridge Scour and Stream Instability Countermeasures (1999)
Advanced Composites in Bridges in Europe and Japan (1997)
Asian Bridge Structures (1997)
Bridge Maintenance Coatings (1997)
Northumberland Strait Crossing Project (1996)
European Bridge Structures (1995)

All publications are available on the Internet at www.international.fhwa.dot.gov.

Contents

Figures



Tables

Executive Summary

A number of new technologies have been developed to lower the production and placement temperatures of hot-mix asphalt (HMA). Generically, these technologies are referred to as warm-mix asphalt (WMA). WMA has been used in all types of asphalt concrete, including dense-graded, stone matrix, porous, and mastic asphalt. It has also been used in a range of layer thicknesses, and sections have been constructed on roadways with a wide variety of traffic levels.

A team of 13 materials experts from the United States visited four European countries—Belgium, France, Germany, and Norway—in May 2007 to assess and evaluate various WMA technologies. The team learned about a wide range of technologies, discussed with various agencies how and why they were implementing these technologies, visited construction sites, and viewed in-service pavements. A number of factors were consistently identified as driving WMA development in Europe:

- Environmental aspects and sustainable development concerns, particularly reduction of energy consumption and resulting reduction in carbon dioxide (CO_2) emissions.
- Improvement in field compaction. Improvements in the compactability of WMA mixes can facilitate an extension of the paving season and allow longer haul distances.
- Welfare of workers, particularly with gussasphalt or mastic asphalt, which is produced at much higher temperatures than HMA.

Benefits

A number of potential benefits from the use of WMA were discussed:

Reduced emissions: Data indicate plant emissions are significantly reduced. Typical expected reductions are 30 to 40 percent for CO_2 and sulfur dioxide (SO_2), 50 percent for volatile organic compounds (VOC), 10 to 30 percent for carbon monoxide (CO), 60 to 70 percent for nitrous oxides (NO_x), and 20 to 25 percent for dust. Actual reductions vary based on a number of factors. Technologies that result in greater temperature reductions are expected to have greater emission reductions.

Reduced fuel usage: Burner fuel savings with WMA typically range from 11 to 35 percent. Fuel savings could be higher (possibly 50 percent of more) with processes such as low-energy asphalt concrete (LEAB) and low-energy asphalt (LEA) in which the aggregates (or a portion of the aggregates) are not heated above the boiling point of water.

Paving benefits: Paving-related benefits discussed included the ability to pave in cooler temperatures and still obtain density, the ability to haul the mix longer distances and still have workability to place and compact, the ability to compact mixture with less effort, and the ability to incorporate higher percentages of reclaimed asphalt paving (RAP) at reduced temperatures.

Reduced worker exposure: Tests for asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) indicated significant reductions compared to HMA, with results showing a 30 to 50 percent reduction. It should be noted that all of the exposure data for conventional HMA were below the current acceptable exposure limits.

WMA Technologies

Before the scanning study, the team members believed that they were aware of all of the processes for producing WMA. However, new processes were identified and more are under development in the United States and abroad. A number of methods are used to classify these technologies. One is classifying the technologies by the degree of temperature reduction. Warm asphalt mixes are separated from half-warm asphalt mixtures by the resulting mix temperature. There is a wide range of production temperatures within warm mix asphalt, from mixes that are 30 to 50 C° (55 to 85 F°) below HMA to temperatures slightly above 100 °C (212 °F).

Another way to classify the technologies is those that use water and those that use some form of organic additive or wax to affect the temperature reduction (this classification method allows for a more descriptive discussion of the processes).

Processes that introduce small amounts of water to hot asphalt, either via a foaming nozzle or a hydrophilic material such as zeolite, or damp aggregate, rely on the fact that when a given volume of water turns to steam at atmospheric pressure, it is dispersed in hot asphalt, which results in an expansion of the binder and a corresponding reduction in the mix viscosity. The amount of expansion depends on a number of factors, including the amount of water added and the temperature of the binder.

The processes that use organic additives (waxes or amides) show a decrease in viscosity above the melting point of the wax. The type of wax must be selected carefully so that the melting point of the wax is higher than expected in-service temperatures (otherwise permanent deformation may occur) and to minimize embrittlement of the asphalt at low temperatures.

Performance

Laboratory and field performance data were presented in three of the countries visited. Based on the laboratory and short-term (3 years or less) field performance data, WMA mixes appear to provide the same performance as or better performance than HMA. Poor performance was observed on limited sections in Norway; the poor performance was not directly attributed to WMA use. Both France and Germany have established procedures for evaluating new products such as WMA that combine laboratory testing and controlled field trials where performance is monitored.

Specification of WMA

WMA technologies have been used with all types of asphalt mixtures, including dense-graded asphalt, stone matrix asphalt (SMA), and porous asphalt. WMA has been used with polymer-modified binders and in mixes containing RAP. WMA has been placed on pavements with high truck traffic, up to 3,500 heavy vehicles per day, which over a 20-year design period would be expected to exceed 30 million 18-kip-equivalent single-axle loads. WMA has also been placed at bus stops, on airfields, and on port facilities.

The European agencies visited during the scan expect the same performance from WMA as HMA. One factor that may affect the willingness of European agencies to allow WMA is that short, 2- to 5-year workmanship warranties are included in most European paving contracts. Further, evaluation systems are in place in France and Germany to assess and approve new products. A similar process, combining laboratory performance tests and controlled field trials, should be developed in the United States for WMA as well as other innovative process. The evaluation process should be implemented on a national level.

Overall, the use of WMA in Europe was not as high as the scan team expected. It should be emphasized that WMA, in most cases, is allowed but not routinely used. Discussions with contractors and agencies suggested two reasons for this. First, many of the oldest WMA sections are just exceeding the period of the workmanship warranty. The contractors who developed these processes want to develop confidence in their long-term performance before using WMA widely. Second, in most cases WMA still costs more than HMA, even when fuel savings are considered. Representatives of the French Department of Eure-et-Loir noted that they were willing to pay more for WMA because they believed it would last longer.

General Observations

During the scanning study, the team noticed several differences between typical European practices for the design, production, and placement of asphalt mixtures. In addition, the team also noticed differences between European and U.S. contractors. The water absorption of aggregates used to produce asphalt mixtures was generally less than 2 percent in the countries visited and less than 1 percent in France. The water absorption of aggregates used to produce asphalt mixtures in parts of the United States is higher, up to 5 percent. The Europeans experienced with the production of WMA repeatedly emphasized that the coarse aggregate must be dry. The higher the aggregate water absorption, the more difficult it may be to completely dry the aggregate at lower production temperatures.

The contractors in the countries visited routinely blend or modify binders. By comparison, the United States has invested heavily in the performance grade (PG) binder system with supplier certification. Several WMA processes modify the binder, and the grading of the binder may be affected in all cases because of reduced aging during production. Throughout Europe, performance tests play a broader role in the mix design process. Performance tests enable European agencies and contractors to better assess innovative products, such as WMA, before conducting field trials.

Based on the countries visited, batch plants and in some cases smaller drum plants appear to be more prevalent in Europe. Increased drying may result at reduced WMA production temperatures in a batch plant, compared to a drum plant at the same reduced temperature. This may be an advantage when producing WMA. Although some differences in placement practices were observed between Europe and the United States, placement practices did not differ between HMA and WMA, with the exception of lower compaction temperatures. Finally, European contractors appear to be better equipped in terms of research and development capabilities than U.S. contractors. This capability aids European contractors in developing and selecting innovative materials like WMA.

Challenges and Recommendations

The scan team identified a number of challenges as the United States moves forward with the implementation of WMA. Challenges include verifying performance, evaluating and approving products, specifying changes, adapting to high production rates, ensuring dry coarse aggregate, and selecting technologies with the widest range of application by contractors. The team considers none of these challenges insurmountable.

The United States has already made great strides in evaluating WMA. A WMA Technical Working Group (TWG) has been established to oversee the implementation of WMA. A large number of trial sections and demonstration projects have been completed. In some cases, WMA has been used in production paving.

Based on the team's experience, the United States has no long-term barriers to WMA use. Many elements of WMA still need to be investigated. The consensus among the scan team members is that WMA is a viable technology and that U.S. highway agencies and the HMA industry need to cooperatively pursue this path. Key implementation goals include the following:

- WMA should be an acceptable alternative to HMA at the contractor's discretion, provided the WMA meets applicable HMA specifications.
- An approval system needs to be developed for new WMA technologies. The approval system must be based on performance testing and supplemented by field trials. The WMA TWG should lead the development of a performance-based evaluation plan for new WMA products. Realistically, such a system is needed for a broader range of modifiers and technologies used in HMA.
- Best practices need to be implemented during WMA production for handling and storing aggregates to minimize moisture content, burner adjustment, and WMA in general or specific technologies.
- More WMA field trials with higher traffic are needed. The field trials need to be large enough to allow a representative sample of the mixture to be produced. The trials should be built in conjunction with a control. The WMA Technical Working Group has developed guidelines that describe minimum test section requirements and data collection guidelines. The guidelines are at *www.warmmixasphalt.com*. Agency commitment is needed to monitor the project for a minimum of 3 years. More information on WMA, upcoming trials, and the WMA Technical Working Group is at *http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm*.

Chapter 1: Introduction

The asphalt industry and its agency partners are constantly looking for ways to improve pavement performance, increase construction efficiency, conserve resources, and advance environmental stewardship.[1] One such technology, now under evaluation, is warm-mix asphalt (WMA). WMA represents a group of technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt and provide complete aggregate coating at lower temperatures. WMA is produced at temperatures 20 to 55 C° (35 to 100 F°) lower than typical hot-mix asphalt (HMA). The same mechanisms that allow WMA to improve workability at lower temperatures also allow WMA technologies to act as compaction aids. Improved compaction or in-place density tends to reduce permeability and binder hardening due to aging, which tends to improve performance in terms of cracking resistance and moisture susceptibility.

WMA technologies also have the potential to be beneficial during cold-weather paving or when mixtures must be hauled long distances before placement. The smaller differential between the mix temperature and ambient temperature results in a slower rate of cooling. Since WMA can be compacted at lower temperatures, more time is available for compaction.

Fuel prices have risen sharply in recent years. It is estimated that if production temperatures are reduced by 28 C° (50 F°), fuel consumption to heat and dry the aggregate will be reduced by 11 percent.[2] Theoretical calculations for one WMA technology, with resulting mix temperatures less than 100 °C (212 °F), indicate a more than 50 percent reduction in fuel consumption to heat and dry the aggregate.[3]

Worldwide, one of the driving factors in the reduction of carbon dioxide (CO_2) and other so-called greenhouse gases is the Kyoto Protocol, adopted by a consensus of the third session of the United Nations Framework Convention on Climatic Change. The Kyoto Protocol is designed to arrest greenhouse gas concentrations that some believe cause global warming. The Kyoto Protocol seeks to cut the production of CO_2 by 5.2 percent of 1990 levels between 2008 and 2012. The European Union (EU) has pledged a 15 percent reduction in CO2 emissions by 2010. Germany pledged a 25 percent reduction of 1990 levels, which was achieved in 2005.[4]

Although the United States has signed but not ratified the Kyoto Protocol, emissions reduction requirements are occurring through other legislation. In March 2005, the U.S. Environmental Protection Agency issued the Clean Air Interstate Rule (CAIR), which is designed to significantly reduce sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions in 28 eastern States and the District of Columbia. SO_2 and NO_x contribute to the formation of fine particles and NO_x contributes to the formation of ground-level ozone, both of which are associated with a variety of health problems. At full implementation, CAIR will reduce SO_2 by 73 percent from 2003 levels and reduce NO_x by 61 percent of 2003 levels. The greatest percentage of these reductions is expected to come from power plants.[5] Figure 1 shows the U.S. States covered by CAIR. Even before CAIR, some State and local regulations required that HMA plants in some nonattainment areas curtail operations during daylight hours during certain times of the year when ozone formation is problematic, or limit production to a certain number of hours per week.[1]

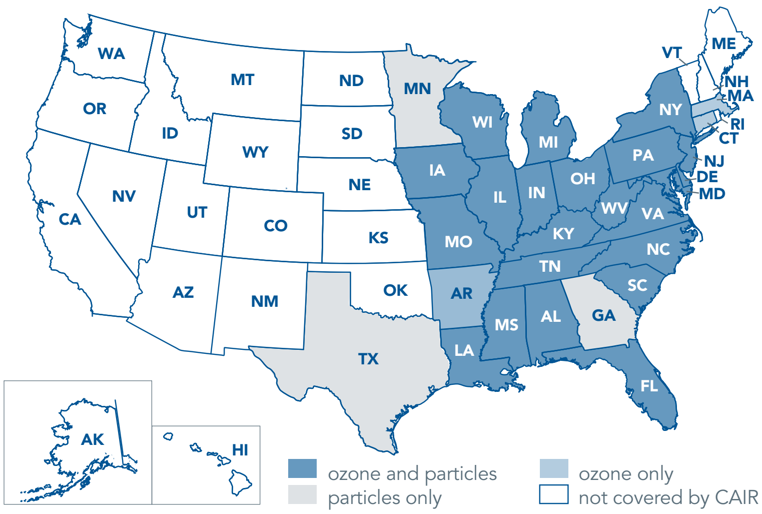


Figure 1. States covered by CAIR.[3]

The concept of sustainable development embraces reduced consumption of raw materials (fuel), reduced emissions, and the possibility of increased recycling while still meeting development needs. The United

Nations' Brundtland Commission defined sustainable development as "development that meets the need of the present without compromising the ability of future generations to meet their own needs."[6] Sustainable development does not focus solely on the environment, but encompasses three interdependent areas: economic development, social development, and environmental protection, as illustrated in figure 2. Both corporations and government agencies in Europe have embraced sustainable development. WMA is consistent with the ideals described by sustainable development.

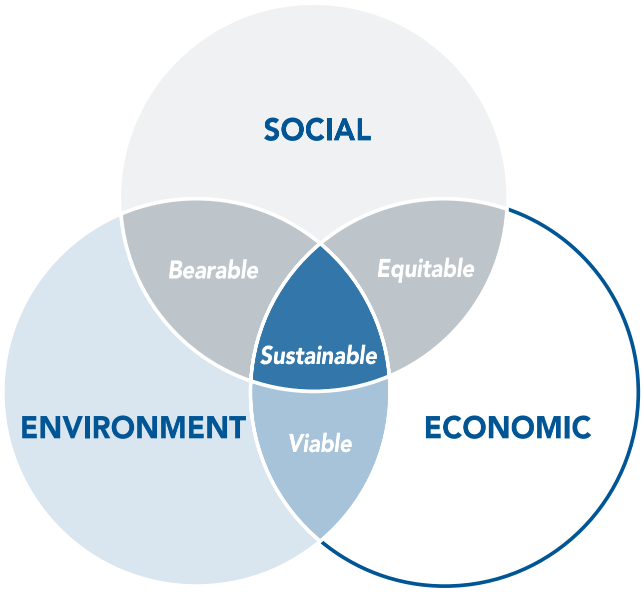


Figure 2. Sustainable development.[6]

Improved working conditions when placing HMA can lead to higher quality work, increased productivity, and greater employee retention. The implementation of engineering controls on asphalt pavers in 1997 was an important step in this direction.[7] Engineering controls remove fumes from the immediate area surrounding the paver and the screed operator. Reductions in HMA temperature reduce the fumes workers are exposed to and provide a cooler working environment.

WMA originated in Europe in response to a variety of concerns. In 2002, the National Asphalt Pavement Association (NAPA) led a study tour to Europe to examine WMA technologies. Since then, interest in these technologies has grown in the United States. The Federal Highway Administration (FHWA) designated WMA as a focus area.[8] FHWA and NAPA formed a WMA Technical Working Group to oversee WMA investigations and field trials in the United States. Research agencies such as the National Center for Asphalt Technology and other universities have conducted laboratory investigations of WMA. A number of State agencies and even some municipalities have placed trial sections of WMA in the United States.

As a continuation of the evaluation process, the American Association of State Highway and Transportation Officials (AASHTO) and FHWA organized a scanning study of Europe, allowing U.S. experts to meet firsthand with the agencies that first used these technologies, the suppliers and contractors that developed them, and the contractors that build WMA pavements. The study also allowed the team to view the performance of some of the oldest WMA projects in Europe.

In May 2007, a team of 13 U.S. materials experts visited four European countries—Belgium, France, German, and Norway—to assess and evaluate various technologies for reducing the temperatures at which hot-mix asphalt (HMA) is mixed and compacted. The scan team represented a wide variety of HMA interests in the United States, including AASHTO representatives from State agencies, FHWA representatives, asphalt supplier and HMA contractor industry representatives, and a consultant.

The purpose of the scan was to gather information on technologies used to produce WMA, with particular emphasis on long-term field performance. The scan team identified the following specific topics of interest pertaining to the use of WMA in Europe:

- **WMA processes**—What processes, materials, and construction practices are being used in the production and placement of WMA?
- **Mix design and construction practices**—How do these processes, materials, and production practices differ from standard mix designs and production?
- **WMA performance**—What are the performance characteristics of WMA in terms of rutting, fatigue cracking, thermal cracking, moisture damage, etc.?
- **Limitations of WMA**—What class of roadway or pavement, traffic volumes, and truck volumes are best suited for WMA use? What are the limitations on temperature reduction?
- **WMA benefits**—What are the benefits of and future plans for using WMA?

The team learned about a wide range of technologies, discussed with various agencies how and why they were implementing these technologies, visited construction sites, and viewed in-service pavements. In addition, the team tried to understand how conventional HMA practice differs between the United States and the various European countries and how these differences might affect potential WMA implementation in the United States. The information obtained during the study identified several implementation items to further the use of WMA in the United States. This report describes the scan, the team's findings, and its recommendations to help forward WMA as a viable alternative to HMA in the United States.

Team Members

The WMA scan team was made up of State agency AASHTO representatives, FHWA representatives, asphalt supplier and HMA contractor industry representatives, and a consultant. The team members were John Bartoszek (Payne and Dolan Inc.), Gaylon Baumgardner (Ergon, Inc.), Matthew Corrigan (FHWA), Jack Cowsert (North Carolina Department of Transportation (DOT)), cochair John D'Angelo (FHWA), cochair Eric Harm (Illinois DOT), Thomas Harman (FHWA), Mostafa (Moe) Jamshidi (Nebraska Department of Roads), H. Wayne Jones (Asphalt Institute), David Newcomb (National Asphalt Pavement Association), Ron Sines (P.J. Keating Company), and Bruce Yeaton (Maine DOT). The report facilitator was Brian Prowell (Advanced Materials Services, LLC). Appendix A contains contact information and biographies of the team members. Figure 3 is a photograph of the team taken during a visit to the Colas Campus near Paris, France.

Scan Preparation

The WMA scanning study began in November 2006 with the completion of a desk scan. The purpose of the desk scan was to review the use of WMA in a number of countries and identify the countries that would provide the most information about WMA technologies, construction practices, and field performance that could be implemented in the United States. The desk scan recommended that the team visit Belgium, France, Germany, and Norway during the study. While other countries have used WMA, France, Germany, and Norway have had the most long-term experience with WMA. Belgium was included to allow a visit to the European Asphalt Pavement Association to gain an overall perspective of WMA and HMA practices in Europe. The initial team meeting took place in November 2006 to identify critical issues to address during the scan and to develop a list of amplifying questions to give the host countries in advance. The amplifying questions, in Appendix B, were intended to help the host countries determine whom to invite to the meetings with the U.S. contingent and what to present to the group.

Team Meetings and Travel Itinerary

The team had an initial meeting in Washington, DC, to plan the scan trip countries and determine the emphasis areas. During the 2-week scan, the team visited representatives in four countries: Belgium, France, Germany, and Norway. After the scan, the team met to review the final report and implementation plan. Table 1 summarizes the team meetings and travel schedule.

Figure 3. Scan team members (left to right) R. Sines, M. Corrigan, W. Jones, J. D'Angelo, D. Newcomb, T. Harman, E. Harm, B. Yeaton, B. Prowell, M. Jamshidi, G. Baumgardner, J. Cowsert, and J. Bartoszek.

Table 1. Team meetings.

Date	Location	Purpose or Host
November 14, 2006	Washington, DC	Initial team meeting to determine emphasis areas and develop amplifying questions
May 20, 2007	Oslo, Norway	Kickoff trip meeting to review travel plan and make note-keeping assignments
May 21–22, 2007	Oslo, Norway	Meet with Norwegian hosts
May 23–25, 2007	Cologne and Frankfurt, Germany	Meet with German hosts
May 27, 2007	Paris, France	Midtrip meeting to review findings to date
May 28, 2007	Brussels, Belgium	Meet with Belgian hosts
May 29–June 1, 2007	Paris and Nantes, France	Meet with French hosts
June 1, 2007	Paris, France	Final trip meeting to identify key findings and develop preliminary recommendations
August 28–29, 2007	Washington, DC	Final team meeting to finalize report and implementation plan

Host Delegations

During the scanning study, the team members met with representatives of about 25 organizations representing a broad range of asphalt pavement stakeholders. The majority of the organizations represented one of the following perspectives: road agency (city, regional, or national), contractor, supplier, academic, or industry association, as indicated in table 2. Lists of individuals the team met with and contact information are in Appendix C. The team participated in meetings and viewed in-service WMA pavements, plants producing WMA, and placement of WMA. The team members also interacted with their hosts on an informal basis during hosted dinners. The sites the team visited are listed in table 3.

Report Organization

The team members learned about many technologies, practices, and experiences during the scan. At the end of the 2-week trip, the team met to review its observations and findings and to develop recommendations for potential implementation in the United States. The benefits of WMA are described in Chapter 2. Chapter 3 provides an overview of WMA technologies and production practices. Chapter 4 covers the performance of WMA. Chapter 5 covers methods European countries have used to specify WMA. Chapter 6 covers the team's general observations on European mix design, construction, and contracting practices. Challenges that need to be addressed for successful implementation in the United States and recommendations for implementation are interspersed throughout Chapters 2 through 6 and summarized in Chapter 7.

Table 2. Types of host organizations represented in meetings.

Type of Agency	Country			
	Norway	Germany	Belgium	France
National or regional road agency	X	X		X
Local road agency				X
Contractor	X	X	X	X
Supplier	X	X		
Industry association			X	X
Academic		X		

Table 3. Sites visited during the scan.

Country	Sites Visited	Location
Norway	Offices of Norwegian Public Roads Administration	Oslo
	Kolo Veidekke asphalt plant and paving site	Ås
	Kolo Veidekke central laboratory and offices	Ås
	Various in-service pavements	
Germany	German Federal Highway Research Institute (BASt)	Cologne
	Wilhelm Schütz Co. asphalt plant	Frankfurt
Belgium	Offices of European Asphalt Pavement Association	Brussels
France	Central Laboratory for Roads and Bridges (LCPC)	Nantes
	Ministry for Transport, Infrastructure, Tourism, and the Sea, Highways General Department (DGR)	Paris
	EIFFAGE Travaux Publics asphalt plant	Near Paris
	FAIRCO paving site	Near Paris
	Routes de France (USIRF)	Paris
	Colas Campus (Research and Development Laboratories)	Magny-les-Hameaux
	Eurovia paving site	Near Paris

Chapter 2: Benefits of WMA

A number of benefits were consistently identified as driving the development of WMA in Europe:

- Environmental aspects and sustainable development concerns, or "green construction," particularly reduction of energy consumption and resulting reduction in CO_2 emissions.
- Improvement in field compaction. Improvements in the compactability of WMA mixes can facilitate an extension of the paving season and allow the possibility for longer haul distances.
- Welfare of workers, particularly with gussasphalt or mastic asphalt, which is produced at much higher temperatures than HMA.

As discussed previously, one pillar of sustainable development is environmental protection. Reduction in the use of natural resources (fuel) and the production of CO_2 is a key element of sustainable development. Reduction of CO_2 emissions is mandated as part of the European Union's ratification of the Kyoto Protocol. It does not appear that the Kyoto Protocol directly impacts the HMA industry in Europe. However, the HMA industry has taken a proactive approach in investigating means of reducing CO_2 emissions. This was apparent in all of the countries visited.

Although they do not consider it a prime factor, some contractors acknowledged that improvement in field compaction was realized when using WMA technology. They saw this as an added benefit in ensuring adequate in-place density for long-term performance. More widely recognized were potential benefits of extending the paving season and potential for longer haul distances. As in the United States, many locations in Europe have climatic conditions that restrict HMA placement to warmer months. Extending the paving season and/or providing for longer haul distances can make the use of HMA more economical.

Contractors noted that reduced temperatures improved workers' comfort and productivity. The European Union is implementing new regulations to address worker exposure to all types of chemicals, including asphalt binder.

Several WMA technologies mentioned in this chapter will be described in Chapter 3.

Reduced Emissions

A number of suppliers' presentations in Norway (Norwegian and Italian data), Belgium (Netherlands data), and France included data that indicated reduced plant emissions. Table 4 presents the ranges in reductions. Reduced emissions were reported in Germany, but no data were presented. Data from the Bitumen Forum relate emissions to temperature: "At temperatures below 80 °C (176 °F), there are virtually no emissions of bitumen; even at about 150 °C (302 °F), emissions are only about 1 mg/h. Significant emissions were recorded at 180 °C (356 °F)."[9]

Problems observed in the United States with increased emissions—particularly CO and VOCs—potentially due to unburned fuel were not reported in Europe. The smaller plants used in most cases in Europe have correspondingly smaller burners, making it easier to adjust the burner to run at lower temperatures.

Table 4. Reported reductions in plant emissions (percent) with WMA.[10, 11, 12]

Emission	Norway	Italy	Netherlands	France
CO_2	31.5	30–40	15–30	23
SO_2	NA	35	NA	18
VOC	NA	50	NA	19
CO	28.5	10–30	NA	NA
NO_x	61.5	60–70	NA	18*
Dust	54.0	25–55	NA	NA

Reported as NO_2
NA—not available

Reduced Fuel and Energy Usage

Reports indicated that burner fuel savings with WMA typically range from 20 to 35 percent. These levels could be higher if burner tuning was completed to allow the burner to run at lower settings. Fuel savings could be higher (possibly 50 percent or more) with processes such as low-energy asphalt concrete (LEAB) and low-energy asphalt (LEA), in which the aggregates (or a portion of the aggregates) are not heated above the boiling point of water. It does not appear that any change in electrical usage to mix and move the material through the plant has been considered in the analysis of potential fuel savings. No specific study was referenced for the suggested fuel savings.

Paving Benefits

Although paving benefits may not have been a driving force in the development of WMA technologies, they may be particularly attractive to U.S. contractors and agencies. Several paving-related benefits were discussed, including the following:

- Ability to pave in cooler temperatures and still obtain density
- Ability to haul the mix longer distances and still have workability to place and compact
- Ability to compact mixture with less effort (assuming typical conditions, not cold weather or long haul)
- Ability to incorporate higher percentages of RAP
- Ability to place thick lifts and open to traffic in a short time period

Case studies were presented in Germany in which paving was completed with various technologies when ambient temperatures were between -3 and 4 °C (27 and 40 °F). Base, binder, and an SMA surface course were placed in Germany using Aspha-min. The base course contained 45 percent RAP. Ambient temperatures during placement ranged from 30 to 37 °F (-1 to 3 °C). The mix temperatures for the WMA behind the paver ranged from 216 to 282 °F (102 to 139 °C). Better density results were obtained with the WMA than the HMA with the same or fewer roller passes.[13] The ability to compact the mix at lower temperatures is achieved through the reduction in viscosity of the binder. Data were presented using Licomont BS 100 on the viscosity reduction effect at lower temperatures. Similar data were presented for Sasobit and Sübit (binder modified with Licomont BS 100). The Department of Eure-et-Loir in France also believes that WMA technologies can be used to extend the paving season. The ability to place and compact WMA at lower temperatures has not been investigated in Norway using the WAM-Foam process.

Actual production temperatures for WMA mixes produced during cool weather vary, depending on the WMA technology, ambient conditions, and haul distance. In most cases the production temperatures will most likely be reduced compared to HMA produced under the same conditions. In some cases, the production temperatures may be closer to that of HMA.

Similar to the potential for extending the paving season using WMA technologies, longer hauls may be facilitated by the reduced rate of cooling of WMA and the reduced viscosity of WMA at lower temperatures. Kolo Veidekke reported that it stored WAM-Foam in a silo for 48 hours and still had the ability to place and compact the mix. HMA containing Sasobit reportedly was hauled up to 9 hours in Australia and the material was still able to be unloaded. The Department of Eure-et-Loir in France also believes that WMA technologies can be used for longer hauls while maintaining workability.

WMA technologies may be beneficial with mixes containing high proportions of RAP in two ways: 1) the viscosity reduction will aid in compaction, and 2) the decreased aging of the binder as a result of the lower production temperatures may help compensate for the aged RAP binder, similar to using a softer binder grade. In Germany, a case study was presented in which 45 percent RAP was used in the base course. In the Netherlands, both LEAB and HMA are routinely produced with 50 percent unfractionated RAP. Trials have been conducted in Germany with 90 to 100 percent RAP using Aspha-min zeolite and Sasobit.

Overall, RAP usage in the United States appears to be higher than that in the countries visited. In Norway, Kolo Veidekke reported that it typically runs 7 to 8 percent RAP in all of its mixes. Milling is not used extensively in Norway, so its RAP supply is limited. Kolo Veidekke tries to run a consistent amount of RAP in all of its mixes. In its annual report, Colas reported that its U.S.-based operations averaged a recycling rate of 14 percent, compared to 3 percent in France.[14] Colas' Northern Europe operations averaged an 11 percent recycling rate.

Several studies provided data to show that the WMA technologies acted as compaction aids and reduced the required compactive effort. Some of the technologies (Sasobit and Licomont BS 100 or Sübit) were initially used for their stiffening effect at high in-service pavement temperatures. During this use it was observed that the materials reduced viscosity at compaction temperatures, particularly when compared to other types of modifiers.

Finally, WMA technologies can be used to facilitate deep patches, such as those placed when repaving the Frankfurt Airport. Sasobit was used in the repaving of Frankfurt Airport. Twenty-four inches of HMA were placed in a 7.5-hour window. The runway was then reopened to jet aircraft at a temperature of 85 °C (185 °F). This may have significant implications either for trench patching or when rehabilitation strategies require multiple lifts to be placed in the same night.

Reduced Worker Exposure

Enforcement of a new European Union regulation called **R**egistration, **E**valuation, **A**uthorization, and **R**estriction of Chemicals (REACH) was implemented in June 2007. It requires chemical suppliers to provide information to workers on potential exposure and to set derived noneffect levels (DNEL). Asphalt binders are included under these regulations. Research has shown a strong correlation between production temperatures and asphalt fume production. It is anticipated the DNEL levels will set asphalt application temperatures at less than 200 °C (392 °F). While this is well above the temperature at which HMA is placed, particularly in the United States, it is lower than temperatures used for the production of mastic asphalt. Although mastic asphalt usage is relatively small, it is a technology that European agencies want to continue to specify. This seems to be a driving force toward WMA in areas where mastic asphalt is routinely used. Mastic asphalt, not used in the United States, should not be confused with stone matrix asphalt. Mastic asphalt is described in Chapter 6.

French, German, and Italian data were presented that indicated reduced worker exposure when placing WMA. Direct comparisons of measurements of fumes and aerosols are difficult since different testing protocols and sampling periods are used in different countries. It should be noted that all of the exposure data for HMA were below the acceptable exposure limits. Tests for asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) indicated significant reductions compared to HMA. Data presented by the Bitumen Forum appear to result in a 30 to 50 percent reduction.[9] Preliminary data from a forthcoming Italian study indicate even larger reductions.

In addition to reducing worker exposure, the lower mix temperatures also provide a more comfortable working environment. This may aid in worker retention. In Germany, one contractor also observed greater worker productivity when placing WMA compared to HMA.

Chapter 3: WMA Technologies

The WMA technologies the team viewed during the scan can be classified a number of ways. One way is by the degree of temperature reduction. Figure 4 shows a classification of various application temperatures for asphaltic concrete, from cold mix to hot mix. The range of production temperatures within warm mix asphalt is wide, from mixes that are 20 to 30 C° (36 to 54 F°) below HMA to temperatures slightly above 100 °C (212 °F). Warm mix asphalt mixes are separated from half-warm asphalt mixtures by the resulting mix temperature. If the resulting temperature of the mix at the plant is less than 100 °C (212 °F), the mix is considered a half-warm mix.

WMA technologies can also be classified by type. Two major types of WMA technologies are those that use water and those that use some form of organic additive or wax to affect the temperature reduction. Processes that introduce small amounts of water to hot asphalt, either via a foaming nozzle or a hydrophilic material such as zeolite, or damp aggregate, rely on the fact that when a given volume of water turns to steam at atmospheric pressure, it expands by a factor of 1,673.[15] When the water is dispersed in hot asphalt and turns to steam (from contact with the hot asphalt), it results in an expansion of the binder phase and corresponding reduction in the mix viscosity. The amount of expansion depends on a number of factors, including the amount of water added and the temperature of the binder.[16]

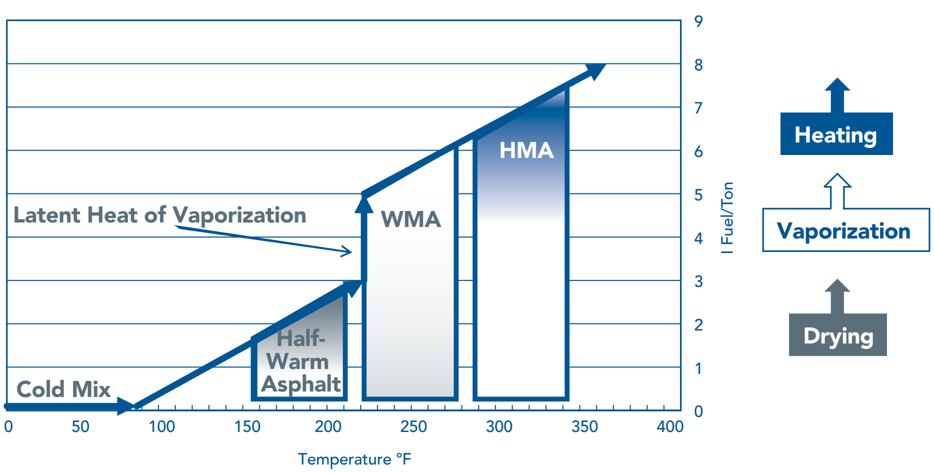


Figure 4. Classification by temperature range, temperatures, and fuel usage are approximations.

The processes that use organic additives (e.g., Fischer-Tropsch wax, Montan wax, or fatty amides) show a decrease in viscosity above the melting point of the wax. The type of wax must be selected carefully so that the melting point of the wax is higher than expected in-service temperatures (otherwise permanent deformation may occur) and to minimize embrittlement of the asphalt at low temperatures.

Additional processes include sequential coating of aggregates. Table 5 (see next page) summarizes the processes observed in Europe. A brief discussion of each process follows; greater detail on each process and necessary plant modifications, if any, is in Appendix D.

Organic Additives

Sasobit is a Fischer-Tropsch wax. Fischer-Tropsch paraffin waxes are produced by treating hot coal with steam in the presence of a catalyst. Fischer-Tropsch waxes are long-chain aliphatic hydrocarbon waxes with a melting point of more than 98 °C (208 °F), high viscosity at lower temperatures, and low viscosity at higher temperatures. They solidify in asphalt between 65 and 115 °C (149 and 239 °F) into regularly distributed, microscopic, stick-shaped particles. They may be used to modify binder or added directly to the mixture.[17,18]

Asphaltan-B is a refined Montan wax blended with a fatty acid amide. Montan wax is a combination of nonglyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins; it is a fossilized plant wax. The melting point is 82 to 95 °C (180 to 200 °F). Also known as lignite wax or OP wax, Montan wax is obtained by solvent extraction of certain types of lignite or brown coal. Montan wax is used to make car and shoe polishes and paints and as a lubricant for molding paper and plastics. About a third of total world production is used in car polishes. Unrefined Montan wax contains asphalt and resins, which can be removed by refining.[18]

Table 5. WMA technologies.

WMA Process	Company	Additive	Production Temperature (at plant) °C	Use Reported in	Approximate Total Tonnage Produced to Date
ORGANIC (WAX) ADDITIVES—ADDED TO BINDER OR MIX					
Sasobit (Fischer-Tropsch wax)	Sasol	Yes, in Germany added on average at 2.5% by weight of binder; lower doses, 1.0–1.5%, used in U.S.	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266 to 338 °F), depending on binder stiffness	Germany and 20 other countries worldwide	>10 million tons worldwide
Asphaltan-B (Montan wax)	Romonta	Yes, in Germany added on average at 2.5% by weight of binder	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	Germany	Unknown
Licomont BS 100 (additive) or Sübit (binder) (fatty acid amides)	Clariant	Yes, about 3% by weight of binder	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–38 °F), depending on binder stiffness	Germany	>322,500 square meters since 1994
3E LT or Ecoflex (proprietary)	Colas	Yes	Varies, 30–40 C° (54–72 F°) drop from HMA	France	Unknown
FOAMING PROCESSES					
Aspha-min (zeolite)	Eurovia and MHI	Yes, about 0.3% by total weight of mix	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	France, Germany, and U.S.	About 300,000 tons
ECOMAC (cold mix warmed before laying)	Screg	Yes (unknown type/ quantity)	Placed at about 45 °C (113 °F)	France	Some trials
LEA, also EBE and EBT (foaming from portion of aggregate fraction)	LEACO, Fairco, and EIFFAGE Travaux Publics	Yes, 0.2–0.5% by weight of binder of a coating and adhesion agent	<100 °C (212 °F)	France, Spain, Italy, and U.S.	>100,000 tons
LEAB® (direct foam with binder additive)	BAM	Yes, added at 0.1% by weight of binder to stabilize foam, aid in coating, and promote adhesion	90 °C (194 °F)	Netherlands	Seven commercial projects

WMA Process	Company	Additive	Production Temperature (at plant) °C	Use Reported in	Approximate Total Tonnage Produced to Date
FOAMING PROCESSES *(continued)*					
LT Asphalt (foamed asphalt with addition of hygroscopic filler to maintain workability	Nynas	Yes, added 0.5–1.0% of a hygroscopic filler	90 °C (194 °F)	Netherlands and Italy	Unknown
WAM-Foam (soft binder coating followed by foamed hard binder)	Kolo Veidekke, Shell Bitumen (patent rights worldwide, except U.S.), and BP (patent rights U.S.)	Not necessary; a surfactant may be added to aid in the foaming of certain binders and an antistripping agent may be added to the soft binder	110–120 °C (230–248 °F)	France and Norway, also Canada, Italy, Luxembourg, Netherlands, Sweden, Switzerland, and United Kingdom	>60,000 tons
EMERGING U.S. TECHNOLOGIES					
Evotherm™ (hot aggregate coated with emulsion)	Mead-Westvaco	Yes	85–115 °C (185–239 °F)	France, also Canada, China, South Africa and U.S.	>17,000 tons
Double-Barrel Green	Astec	Not necessary; an antistripping agent may be added similar to normal HMA	116–135 °C (240–275 °F)	U.S.	>4,000 tons
Advera (zeolite)	PQ Corporation	Yes, about 0.25% by total weight of mix	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	U.S.	>10,000 tons
	Mathy Construction	Dilute surfactant	110 °C (230 °F)	U.S.	Trial sections only

Licomont BS 100 is a fatty acid amide. Fatty acid amides are produced by reacting amines with fatty acids. Typically, the melting point is between 141 and 146 °C (286 and 295 °F). Similar products have been used as viscosity modifiers in asphalt for several years and are available in various forms from a number of suppliers. Fatty acid amides have been used in roofing asphalt since the late 1970s to early 1980s.[18,19]

Foaming Processes

Aspha-min is a synthetic zeolite composed of alumino-silicates of alkalimetals. It contains about 20 percent water of crystallization, which is released by increasing temperature. Typically 0.3 percent zeolite by weight of mixture is added to the mixture shortly before or at the same time as binder. The zeolite releases a very small amount of water, creating a controlled foaming effect that leads to a slight increase in binder volume and reduces the viscosity of the binder. Gradual release of water reportedly provides a 6- to 7-hour period of improved workability, which lasts until the temperature drops below about 100 °C (212 °F).[18, 13]

Little is known about the Ecomac process. It appears that a traditional cold mix is prepared using an emulsion. The cold mix is stored until it is ready to be laid, at which time it is warmed to improve compaction and the overall mechanical properties.[20]

LEA, EBE (enrobé à basse énergie), and EBT (enrobé basse temperature) all use moisture contained in the aggregates to foam the asphalt. In the LEA process, the coarse aggregate is heated to about 150 °C (302 °F) and mixed with the total binder required for the mixture at the normal binder temperature (appropriate for the particular grade). About 0.5 percent by weight of binder of a coating and adhesion additive is added to the binder just before mixing. After the coarse aggregate is coated, it is mixed with the cold, wet fine aggregate. Ideally, the fine aggregate should contain about 3 percent moisture. This moisture turns to steam and causes the asphalt on the coarse aggregate to foam, which in turn encapsulates the fine aggregate. The resulting (equilibrium) mix temperature is less than 100 °C (212 °F). In a drum plant, the fine aggregate is typically added through the reclaimed asphalt pavement (RAP) collar. If the fine aggregate is too wet, a portion of the fine aggregate can be dried with the coarse aggregate.[21]

The LEAB process is a commercialization of the half-warm foamed asphalt work completed by Jenkins.[16] To date, this process has been used only in batch plants. This is the only process, other than ECOMAC, that does not heat at least a portion of the aggregate to temperatures above the boiling point of water. The virgin aggregate is heated to about 95 °C (203 °F). RAP is heated in a separate dryer drum to 110 to 115 °C (230 to 239 °F). Typically, 50 percent RAP is used in the Netherlands. During the trials to assess moisture content of the aggregate, it was noted that the moisture content of the fines/filler going to the baghouse was high, about 2.2 percent. Therefore, the contractor who developed the mix, BAM, added an extra burner (after the pugmill) to heat the air going into the baghouse. An additive is added to the binder immediately before mixing to promote coating and adhesion. This additive also tends to extend the life of the foam, which increases workability.[22]

The Nynas low-temperature asphalt (LT-Asphalt) uses a special foaming process in combination with about 0.5 to 1.0 percent of hydrophilic filler, which helps to hold and control latent moisture from foaming. The aggregates are heated to 90 °C (194 °F), then a special penetration-graded binder is foamed with special nozzles and mixed with the aggregates along with the hygroscopic filler.[20]

WAM-Foam is a process, not an additive or material. It is reportedly a common practice in Norway for the contractor to maintain two asphalt binder grades, one nominally soft and one nominally hard. The soft and hard binders are blended in-line to produce the desired binder grade. The soft binder typically has a viscosity grade of 1,500 centistokes at 60 °C (140 °F); the hard binder is typically a 70/100 penetration grade (pen), or about a PG 58/64-22. The aggregate, minus any filler, is heated to about 130 °C (266 °F) and then coated with the soft binder, which is typically 20 to 30 percent of the total binder. The hard binder is then foamed into the mixture by adding cold water at a rate of 2 to 5 percent by mass of the hard binder at about 180 °C (356 °F). This results in about 1.6 pounds (lb) of water per ton (0.8 kilogram (kg) per metric ton) of mix for a 5 percent total asphalt content mixture. The resulting binder grade for 20 percent of a 1,500 centistoke and 80 percent of a 70/100 Pen binder is a 70/100 Pen binder, unaged. Thus the resulting binder, after going through the plant, is softer than typically expected for a 70/100 Pen binder after short-term aging. Coating the coarse aggregate with the soft binder acts to satisfy the asphalt absorption of the coarse aggregate that may not otherwise occur with a stiffer binder at low temperature.[10,23]

Emerging U.S. Technologies

In addition to the technologies discussed in Europe, the scan team is aware of a number of technologies developed in the United States.

Evotherm™ was developed in the United States. In the original process, an emulsion is mixed with hot aggregates to produce a resulting mix temperature between 85 and 115 °C (185 and 240 °F). The emulsion is produced using a chemical package designed to enhance coating, adhesion, and workability. The majority of the water in the emulsion flashes off as steam when the emulsion is mixed with the aggregates. A new process has been developed called dispersed asphalt technology (DAT), in which the same chemical package diluted with a small amount of water is injected into the asphalt line just before the mixing chamber.

Astec Industries is developing a foaming system that can be retrofitted to some types of existing HMA plants to produce WMA. The system uses a manifold with 10 nozzles to produce the foam. About 1 lb of cold water is introduced through the nozzles per ton (0.5 kg per metric ton) of mix, causing the binder to expand by about 18 times. Typical production temperatures are 135 °C (275 °F), with the mixture being placed as low as 115 °C (240 °F).

PQ Corporation is producing a synthetic zeolite called Advera, which is similar to Aspha-min zeolite, described above. Advera is a finer gradation than Aspha-min, with 100 percent passing the 0.075 millimeter (mm)

(No. 200) sieve. PQ Corporation is working on a process to blend Advera with the binder as it is being introduced into a plant instead of simply blowing it into the mixing chamber like a fiber. This process is believed provide a more consistent WMA.

Mathy Construction Company developed a WMA process in which a diluted surfactant is injected into the asphalt line in conjunction with an expansion chamber to cause foaming and help lubricate the mix. The surfactant reduces the volatility of the foaming process and increases the half-life, or working time, of the resulting foam. WMA using this process is typically produced at 110 °C (230 °F). Trial sections were planned in Minnesota and Wisconsin in 2007.

Summary

Before traveling to Europe, the scan team thought it had identified all of the WMA processes it would see. During the scanning study, the team found that a number of new processes have been developed. In France, each contractor is trying to develop its own process. The number of processes being developed emphasizes the need for an evaluation system for new processes, discussed later in the report. One consistent feature among the processes was that almost every process required some type of additive. However, in some cases the additive was simply an adhesion agent, which may play a more important role in WMA than HMA.

Chapter 4: Performance of WMA

The general consensus in the countries visited during the scanning study was that WMA is expected to provide performance equal to or better than HMA. The scan team was interested in viewing and gathering data on the performance of in-service WMA pavements in Europe, since Europe has WMA sections that have been in service longer than U.S. trial sections.

> **Challenge 1:** Make sure that the overall performance of WMA is truly as good as HMA. On a life-cycle basis, if WMA does not perform as well, there will not be long-term environmental benefits or energy savings.

Norway

The scan team viewed six WAM-Foam pavement sections in Norway with average daily traffic ranging from 3,500 to 25,000 vehicles (figure 5). Four of the pavements were dense-graded mixes and two were stone matrix asphalt (SMA). The pavements generally appeared to be in very good condition. Some rutting was observed, but it was not attributed to the use of WMA technologies. Norway allows the use of studded tires. Studded tires cause significant wear to the pavement, which manifests itself in the form of rutting in both HMA and WMA.

Figure 5. U.S. scan team inspecting a WAM-Foam pavement in Norway.

During the 1970s and 1980s, research was undertaken to identify the factors affecting studded tire wear. Based on these studies, restrictions were implemented to reduce studded tire use in Norway, mainly in the form of user fees. HMA specifications were modified to reduce studded tire wear, including the use of harder aggregate, higher percentages of coarse aggregate, and larger nominal maximum aggregate size mixes. The use of studded tires diminished further in the 1990s with the improvement of nonstudded tires. Although the use of studded tires in Norway is decreasing, it is still the main reason that roads are rehabilitated in Norway.

Since 1990, the Norwegian Public Roads Administration (NPRA) has performed annual pavement condition surveys on its 56,000-kilometer (km) (35,000-mile (mi)) county and national road network. The condition surveys include pavement roughness, texture, profile, rutting, and photos every 20 meters (m) (66 feet (ft)). Rutting measurements are analyzed using a cumulative frequency distribution. When the rut depth represented by the 90 percent cumulative frequency exceeds 25 mm (1 inch (in)) (e.g., 10 percent of the measurements exceed 25 mm (1 in)), the pavement is overlaid.

NPRA provided pavement management data on 28 WAM-Foam sections representing 17,800 metric tons (16,198 tons) of WMA ranging in age from 2 to 8 years.[24] The performance of the sections has been mixed. Where poor performance occurred, it was attributed to factors other than the use of WAM-Foam. The rutting or studded tire wear rate for HMA and WMA appeared to be the same. Overall, the WAM-Foam sections appeared to perform similarly to previous HMA overlays.[24]

Germany

BASt has specific procedures for investigating new materials and construction practices. In the case of new materials, the trial begins with laboratory testing. After a successful laboratory evaluation, field trials are conducted on different roads and under different conditions. The field trials must meet the following conditions:

- High traffic
- Right-hand (travel) lane
- Section length >500 m (1,640 ft)

Contractual conditions are altered to reduce the contractor's risk in the case of a field trial. Field trials are monitored for a minimum of 5 years. For the WMA projects, field data collected at the time of construction included mix temperature monitoring, emissions data, mix samples, and initial profiles. During the 5-year evaluation period, the sections are monitored for transverse profile, layer thickness, and surface condition. The test sections are always constructed in conjunction with a control section, in this case HMA. The scan team viewed a series of WMA mastic asphalt sections being evaluated on the Autobahn between Cologne and Frankfurt (figures 6 and 7).

Figure 6. Transverse profile measurements.

Figure 7. Layer thickness measurements.

In Germany, laboratory and field performance data were presented on seven WMA test sections being monitored by BASt. The seven test sections were constructed between 1998 and 2001. Six of the seven projects were SMA mixes and one was a dense-graded mix. Two of the SMA projects were 8 mm nominal maximum aggregate size (NMAS) and the remainder of the projects were 11 mm NMAS. The seven sections include data from four WMA technologies: Sasobit, Asphaltan-B, Aspha-min, and Sübit (asphalt modified with Licomont BS 100). Table 6 shows the performance comparisons with the control sections. A control section was not available for section number 7. In all cases, the test sections had performance that was the same as or better than the HMA control sections.[13,25]

In addition, several WMA additive suppliers presented performance data on a variety of trial sections, some of them on commercial projects. Again, the performance of the WMA was as good as or better than the HMA (or in some cases HMA that had previously been used at the site). Three of the WMA additives used in Germany—Fischer-Tropsch wax (Sasobit), Montan wax (Asphaltan-B), and fatty acid amides (Licomont BS 100 or Sübit)—have the advantage of increasing the stiffness of the binders at high temperatures. These additives may also affect the low-temperature properties of the binder. The low temperatures in Germany are generally somewhat milder than in the northern United States (PG xx-22 or warmer). Therefore, there is less concern about low-temperature cracking.

France

In France, both laboratory studies and field trials have been conducted on various WMA processes. Laboratory studies have included gyratory tests for workability and estimation of field compaction, wheel-tracking tests for rutting resistance, Duirez test for moisture resistance, and fatigue tests.[11] Workability for the WMA tended to improve. The rutting resistance of the WMA was the same as for HMA. In some cases, the ratio of the conditioned to unconditioned Duirez test results was slightly lower for the WMA. The fatigue tests indicated results similar to HMA. Service of Technical Studies of the Roads and Expressways (SETRA) has conducted field trials as part of the certification process for new products (described in Chapter 5).

The Department of Eure-et-Loir (a department is a road authority district), southwest of Paris, has experimented with Aspha-min zeolite and ECOMAC. Based on the experiences to date, the agency planned to pave 40 km (24 mi) with WMA in 2007. Eure-et-Loir is using WMA because of the environmental benefits, reduction in worker exposure, and safety aspects from reduced steam if it rains while paving. The agency also believes it helps with long haul distances and helps extend the paving season. Finally, it expects the WMA to last longer.[26]

The city of Paris has experimented with several WMA processes in the urban environment, including a dedicated bus lane. The city is evaluating WMA technologies

Table 6. Evaluation of test sections in comparison with control sections.[25]

		SmB 35 B 209 (preblended Sasobit)	50/70 Pen + 4% Sasobit (added at plant) Hamburg	50/70 Pen + Asphaltan B B 193	50/70 Pen + Asphaltan B L 303	50/70 Pen + Aspha-min B3	Sübit VR 45 B283	Sübit VR 35 B 51
Section Number		**1**	**2**	**3**	**4**	**5**	**6**	**7**[3]
Field Measurements	Rutting[1]	Equal	Equal	Equal	Equal	Equal	Equal	Low
Field Measurements	Post-compaction densification in the wheelpaths	Equal	Better	Equal	Better	Better	Equal	None
Field Measurements	Cracking	Equal[2]	Equal[2]	Equal[2]	Equal[2]	Equal[2]	Equal[2]	
Laboratory Investigations	Thermal stability	Better	Better	Equal	Better	Equal	Better	Very Good
Laboratory Investigations	Low-temperature performance	Equal	Equal or Better	Equal	Equal	Equal or Better	Equal or Better	Good
Laboratory Investigations	Aging of the binder	Equal or Better	Equal or Better	Equal or Better	Equal or Better	Equal	Equal	Low
Laboratory Investigations	Adhesion	Equal or Better	Equal or Better	Better	Equal	Equal or Better	Equal or Better	Good

[1]Low level = <10 mm (0.4 in)
[2]Equal = none
[3]No control section available

in response to calls from Parisians concerned about fumes and odors from paving projects. The first projects used WMA in conjunction with mastic asphalt. The city of Paris has also tested six WMA processes in HMA mixes, beginning in 2004. Some of the projects were constructed at night. Projects are monitored for a minimum of 3 years before products are approved.[27]

The private toll road operator Cofiroute, which operates a series of toll roads southwest of Paris, constructed a trial section with Aspha-min zeolite on the A81 in 2003. The A81 carries 21,000 vehicles per day (two directions) with 1,500 trucks per day (one direction). The legal axle limit in France is 13 tonnes. Cofiroute placed 2,500 metric tons (2,275 tons) of a semiopen-graded mix containing Aspha-min in a 2.4-in (6-cm) lift. The mix containing Aspha-min was mixed and compacted at temperatures 30 C° (54 F°) lower than the HMA. The in-place voids were slightly higher for the WMA, 7.3 percent compared to 6.5 percent. The macrotextures of the HMA and WMA were similar, 0.98 and 1.03 mm, respectively. Samples were tested for modulus at 15 °C (59 °F) and 10 hertz (Hz). The modulus of the HMA (10,414 megapascals (MPa)) was slightly lower than the modulus of the WMA (11,376 MPa).[11] Although it sees the same advantages to WMA as described above and is pleased with the performance of the A81 section, Cofiroute has not done additional projects with Aspha-min to date because of the increased cost. Two experiments with other WMA processes were planned for 2007.[28]

Summary

Laboratory and field performance data were presented in three of the countries visited. Based on the laboratory and short-term (3 years or less) field performance data, WMA mixes appear to provide the same performance as or better performance than HMA. Poor performance was observed on limited sections in Norway, but it was not attributed to WMA use. Both France and Germany have established procedures for evaluating new products such as WMA, using a combination of laboratory testing and controlled field trials in which performance is monitored.

Chapter 5: Specifications of WMA

This chapter discusses how different agencies specify or incorporate WMA into their specifications and the applications that WMA has been used for. Across the board, the expectation is that WMA should provide the same performance as or better performance than HMA (i.e., no compromises in performance are acceptable when using WMA). One factor that may affect the willingness of European agencies to allow WMA is the fact that short, 2- to 5-year workmanship warranties are included in most European paving contracts.

WMA has been used in all types of asphalt concrete, including dense-graded, stone matrix, porous, and mastic asphalt. It has also been used in a range of layer thicknesses. WMA sections have been constructed on roadways with a wide variety of traffic levels, from low to high. In Norway, the highest trafficked WAM-Foam section carried about 25,000 average daily traffic (ADT) (two directions) with 2,500 heavy vehicles per day (one direction). ADT values were not reported in Germany, but sections were placed with truck traffic levels of 1,600 heavy vehicles per day. The A81 toll road in France received 21,000 ADT (two directions), with 1,500 heavy vehicles per day (one direction). Legal axle loads vary in the countries visited from 10 metric tons (9.1 tons) in Norway to 13 metric tons (11.8 tons) in France. The ECOMAC process, a warmed cold mix, is recommended for low traffic only.

Norway

The Norwegian Public Roads Administration has allowed WMA to be used in lieu of HMA. The WMA (WAM-Foam) must meet all the applicable specifications for HMA. There are no variances. The blending of a hard and soft binder to meet the specified binder grade, used in the WAM-Foam process, is already allowed. The Norwegian Public Roads Administration does require a 5-year materials and workmanship warranty. Items monitored under the warranty include potholes, longitudinal joints, delamination, voids, and ride.

Germany

The European standards on hot mix asphalt include requirements for constituent materials, which state: "Only constituent materials with established suitability shall be used. The establishment of suitability shall result from one or more of the following: 1) European Standard, 2) European Technical Approval, or 3) specifications for materials based on a demonstrable history of satisfactory use in asphalt. Evidence shall be provided on their suitability. This evidence may be based on research combined with evidence from practice."[29] In the case of WMA, BASt has been gathering data on the performance of Sasobit, Romontan-B, Licomont BS 100 (Sübit), and Aspha-min to meet option 3 using the research and test sites described in Chapter 4. This includes monitoring of field test sections placed under heavy traffic for a minimum of 5 years. Part of the data was gathered from test sections constructed by contractors on commercial projects. A compilation of WMA experiences has been prepared.[25] Germany also requires a materials and workmanship warranty, typically for 4 years after construction.

Based on these experiences, in August 2006, a "Merkblatt," or bulletin, on the use of WMA was issued. The bulletin provides general remarks and references for WMA, and serves as a step toward a standard construction method. The guidelines include information on five additives or modifiers for HMA, including Fischer-Tropsch wax, Montan wax, fatty acid amides, a blend of Montan wax and fatty acid amides, and zeolite. Zeolite is to be used only in HMA, not mastic asphalt. Table 7 presents the recommended mixing and compaction temperatures for WMA presented in the Merkblatt.[30]

The temperatures in table 7 (see next page) represent a reduction of 36 to 54 F° (20 to 30 C°) from conventional HMA paving temperatures. A 70/100 pen binder is about equivalent to a PG 64-22. PmB represents polymer-modified binders. The temperatures in table 7 tend to be somewhat higher than production temperatures used for WMA in the United States.

The Merkblatt provides other notes on the use of WMA. Good tack coats and joints are important with WMA. A homogeneous blend of organic additives must be achieved. The content of organic additives can be determined using differential scanning calorimetry. Longer solvent extraction times are required to measure asphalt content for mixes with organic additives. The ring and ball softening point is required to be determined with organic additives.

France

In France, new innovations for road authorities are evaluated by a partnership between the developer (often

Table 7. Reference temperatures for temperature-reduced asphalt (WMA).[30]

Type of Asphalt	Binder Grade (Pen)	Reference Production Temperature, °C	Reference Temperature Behind Screed, °C
Rolled Asphalt (HMA)	70/100	130 to 150	Minimum 120
	50/70	130 to 150	
	30/45	140 to 160	Minimum 130
	PmB 45 A	140 to 160	
	Pmb 25 A	150 to 170	Minimum 140

a contractor) and the road directorate. SETRA, Service of Technical Studies of the Roads and Expressways, represents the road directorate. Both partners must fund the evaluation. The evaluation process starts with a laboratory evaluation; if successful, field trials are undertaken and then guidance papers are prepared for use of the product. The final step is to incorporate the product into existing standards or develop new ones if no applicable standard exists. Trial sections are constructed along with a control section, each a minimum of 500 meters long. Trial sections are monitored for a minimum of 3 years. Typically, at least three trial sections are used to evaluate a single product, and a certificate is awarded at the end of a successful evaluation. The certificate technically validates the product and provides guidelines for the product's use. Certificates are often used by contractors for marketing. In 2007, SETRA awarded a certificate to Aspha-min zeolite (figure 8). SETRA can recommend, but not mandate, that contractors use certified products. However, a representative from a private toll road company, Cofiroute, said that the company would not use an uncertified product unless it had conducted its own experiments. SETRA is not involved with urban roads. Therefore, municipalities, such as Paris, conduct their own experiments.

Figure 8. SETRA certificate for Aspha-min.


Bagneux, 31 march 2005

MOTORWAY INNOVATION CHARTER

APSA/COFIROUTE/DR/EUROVIA
MEMORANDUM OF AGREEMENT

WARM-MIX PROCESS
EUROVIA

CERTIFICATE

Sétra

LCPC considers WMA to be in conformity with the existing French (soon to be European) performance-related design procedures. Mix designs would be expected to follow the same steps, with type testing of performance parameters to follow the optimization of the job mix formula. Only the field production temperatures would change.[11]

Challenge 2: Address initial product approval. How do we sort out good innovative products from poor products? Accepted performance tests are needed to separate the good from the bad. The traditional practice of products and technologies being approved on a state-by-state basis needs to be changed. Products and technologies should be approved on a national, or at least a regional, basis.

Summary

WMA has been used with all types of asphalt mixtures, including dense-graded asphalt, SMA, and porous asphalt. WMA has been used with polymer-modified binders and in mixes containing RAP. WMA has been placed on pavements with high truck traffic, up to 2,500 heavy vehicles per day, which over a 20-year design period would be expected to exceed 30 million 18-kip-equivalent single-axle loads. WMA has also been placed at bus stops, on airfields, and on port facilities.

As noted in Chapter 4, the European agencies visited during the scan expect the same performance from WMA as HMA. One factor that may affect the willingness of European agencies to allow WMA is the fact that short, 2- to 5-year workmanship warranties are included in most European paving contracts. Further, evaluation systems are in place in France and Germany to assess and approve new products. A similar process combining laboratory performance tests and controlled field trials should be developed in the United States for WMA as well as other innovative processes. The evaluation process should be implemented on a national level.

Overall, the use of WMA in Europe was not as high as the scan team expected. It should be emphasized that in most cases, WMA is allowed but not routinely used. Discussions with contractors and agencies suggested two reasons for this. First, many of the oldest WMA sections are just exceeding the period of the workmanship warranty. The contractors who developed these processes want to develop confidence in their long-term performance before using them widely. Second, in most cases WMA still costs more than HMA, even when fuel savings are considered. In discussing its environmentally friendly, energy-efficient (3E) asphalt mix in its annual report, Colas noted, "Customers who wish to act in support of sustainable development can now opt for this asphalt mix."[14] The French Department of Eure-et-Loir noted that it was willing to pay more for WMA because it believed it would last longer.

Challenge 3: Address issues with existing specifications that may prohibit the use of WMA. Examples include allowing blending of binders, minimum production and placement temperatures, and minimum ambient temperatures or cutoff dates.

Chapter 6: General Observations and Findings

As the team traveled through the four countries, it gained many valuable insights into European practices for asphalt mix design and construction and observed some significant differences between practices in the United States and Europe. To provide a context for the challenges and recommendations presented in this and the preceding chapters, this chapter describes the team's more significant observations. The challenges and recommendations are best appreciated if the reader has an understanding of conventional design and paving practices in Europe.

Materials

A number of differences were observed between European and U.S. practice for selection of materials. As described below, binder blending or modification at the contractor's plant was commonly observed in the countries visited and the aggregates used in asphalt mixtures tended to have lower water absorption values than those used in parts of the United States.

Binders

The contractors in the countries visited regularly blend or modify binders during production. Blending a hard and soft asphalt at the HMA plant has become the industry standard in Norway, whether the plant is making traditional HMA or WMA. The soft binder is typically a binder with a viscosity grade of 1,500 centistokes; the hard binder is typically a 70/100 pen or about a performance grade (PG) 58/64-22. The contractor maintains two separate binder streams containing the hard and soft asphalt materials that are brought together to produce any required penetration grade that may be needed for an individual mix. This eliminates the need for separate tanks for each grade with the adequate amounts of storage in each to properly supply upcoming production demands. Having two separate streams of liquid asphalt eliminates cross contamination when one tank is not completely emptied before a different grade is introduced into that same tank. This also eliminates any financial penalties for nonspecification material when a sample is pulled from a cross-contaminated tank.

In Germany, Wilhelm Schütze Company regularly modifies its binders during production. Similar practices were observed on a previous trip at Norddeutsche Mischwerke GMBH's (NMW) plant in Berlin. The contractor can add binder modifiers, such as Sasobit or Licamont BS 100, during production to produce a modified binder.

In France, hard binders such as 10/20 pen are routinely used to produce high-modulus mixes. Stiffer binders increase the difficulty of producing WMA. However, by adjusting the LEA process, FAIRCO has placed 5,000 metric tons (4,550 tons) of high-modulus LEA with placement temperatures of 90 to 95 °C (194 to 203 °F).

Blending processes to produce a certain grade take place in the asphalt refinery or terminal in the United States. The hard and soft asphalt base stocks are blended to produce the various PG grades required to be inventoried for the local market where the refinery or terminal is located. The material is then stored in separate tanks by binder grade until it is piped to the load-out rack for shipping to the HMA plant. The process of blending to grade at the source, inventorying the grades in separate tanks at the source, transporting the material to the contractor, and storing at the HMA plant allows the material to be sampled and tested for specification compliance anywhere along the supply chain. Blending at the HMA plant, just before mixing with the aggregate, does not allow for specification compliance testing before being introduced into the mix. For all but warranty projects, checking a binder's grade is a critical test for mix acceptance and payment in the United States. The United States has made significant investments in both the PG grading system and accompanying certifications of binders shipped from terminals or refineries.

Aggregates

One concern about implementing WMA in the United States is that the drying of the aggregates may be incomplete because of the lower production temperatures. In the United States, water absorption of aggregates can exceed 5 percent in some areas. In Europe, aggregates used to produce HMA or WMA have relatively low water absorption values. In Norway, the composite moisture content of the aggregates (this is the in-situ water content, which tends to be greater than the water absorption of the aggregates) at Kolo Veidekke's plant near Ås was reported to range between 2 and 3 percent. In Germany, aggregates with low water absorptions, such as gneisses, granites, and quartzite, are generally used. The composite moisture content of virgin aggregates reported by one contractor in the Netherlands was 2.2 percent. The aggregates used in HMA in every region of France have less than 1 percent water absorption. The low water absorption and moisture content of the aggregates make them easier to dry at lower temperatures. In the United States, greater attention to best management practices to minimize aggregate moisture contents, particularly for aggregate sources with water absorptions higher than 2 percent, will be required when producing mixes at lower temperatures. Examples of best management practices are discussed later in this chapter.

Mix Design

European practice for designing HMA, as well as WMA, differs in many respects from U.S. practice. European standards are being developed to standardize test methods and provide broad definitions of mix types. Two goals of the standardization process are the elimination of trade barriers between countries and development of a common technical language for nations of the European Union. Standardized test methods and mix descriptions allow research and experience to be exchanged more freely. Individual countries can develop national application documents to specify exactly what they want within the framework of the European standards. Performance tests tend to play a more dominant role in the European mix design process than in the U.S. The European Union, like the United States, is still searching for a reliable moisture damage test.

Each country now uses a slightly different design procedure, described in table 8. Some of the design parameters and tests are selected to address specific concerns in a given country. For instance, Norway allows the use of studded tires. Norwegian pavements have suffered significant wear because of studded tires. Aggregate test methods, such as the Nordic Abrasion Test, have been developed to identify aggregate sources that are resistant to studded tire wear. The Norwegian and German design procedures share more similarities with the U.S. systems than the French system does, with the exception of the use of the gyratory compactor. In Norway and Germany, minimum requirements for aggregate quality and binder grades are specified for a given mix. Gradation ranges are also specified for various mix types and nominal maximum aggregate size. Both Norway and Germany use the Marshall method to determine volumetric properties and optimum asphalt content. In Norway, Kolo Veidekke was experimenting with the Finnish gyratory compactor. Historically, Germany has used a wet Hamburg loaded-wheel test with a steel wheel at 50 °C (122 °F) to assess both rutting potential and moisture susceptibility. The wet Hamburg test is not included in the new EU standards.

For axle loads less than 13,000 metric tons (11,830 tons), the new EU standards specify a dry Hamburg loaded-wheel test with a hard rubber wheel, referred to as the small-scale wheel-tracking tester (figure 9). This test is now being used by both Norway and Germany. Norway is using a tensile strength ratio (TSR) test for moisture susceptibility, while Germany is investigating its use.

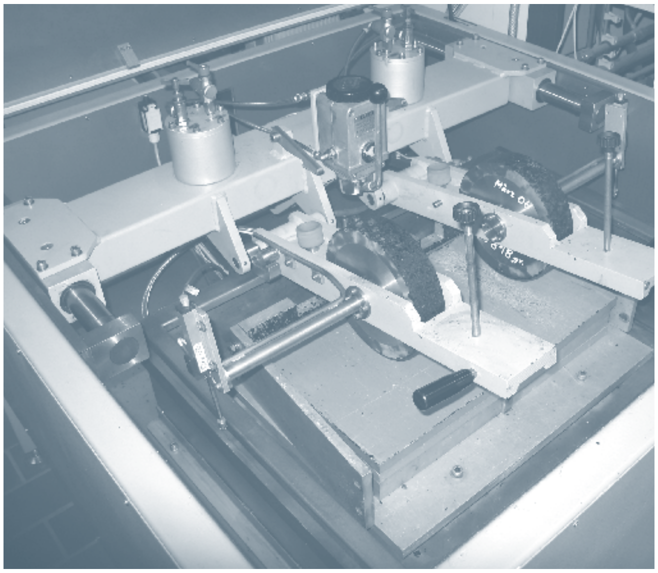


Figure 9. EU small-scale wheel-tracking tester.

The French use a mix design system that combines prescriptive, performance-related, and fundamental components. Figure 10 (see page 30) describes the French mix design procedure.[31] The mix design is divided into two major parts, the optimization of the job mix formula, including selection of materials, grading, and initial asphalt content, and type testing to ascertain compliance with a given mix designation's performance properties. Performance specifications are provided for a range of mix types, including dense-graded, high modulus, thin, ultra-thin, and porous. The mixture specifications do not include gradation bands. They do, however, include nominal maximum aggregate sizes and typical ranges for percent passing the No. 10 (2.0 mm) sieve. Performance specifications include four levels. Level 1 includes gyratory compaction tests for workability (related to field compaction) and moisture sensitivity. Level 2 adds wheel-tracking testing for rutting susceptibility. Level 3 adds modulus tests, and Level 4 adds fatigue tests. Figure 11 (see page 30) shows the French wheel-tracking device and figure 12 (see page 30) shows testing of trapezoidal samples for modulus or fatigue. Additional information on the French design procedure is in Appendix E.

In 1988, the European Union issued the Construction Product Directive (CPD), aimed at eliminating trade

Table 8. Summary of current design practices.

European Standards	Category	Norway	Germany	France
Constitutive Materials	Aggregate Properties	• Polish value for surface mixes • LA abrasion test (25 to 35 limit based on traffic) for coarse aggregate • Nordic abrasion test (maximum 7 to 14 based on traffic) for coarse aggregate • Flakiness index for coarse aggregate • No requirements for fine aggregate	• Polish value for surface mixes • Schlagversuch impact test for coarse aggregate • Flakiness index for coarse aggregate	• Component selection • Check properties (performance class)
	Binder Properties	• Pen at 25 °C (77 °F) (hard) • Viscosity (soft) • Ring & ball softening point	• Pen at 25 °C (77 °F) • Viscosity • Fraaß breaking point (low temperature) • Ring & ball softening point	• Component selection • Check properties (performance class)
Mixture Design	Component Selection	• Gradation bands for each mix type (dense, SMA, porous, etc.)	• Gradation bands for each mix type (dense, SMA, gussasphalt (mastic), porous, etc.)	• Level (1-4) of mix design defined in contract • Choose gradation from experience
	Binder Content Methodology	• Marshall mix design system (75 blows/side)	• Marshall mix design (50 blows/side)	• Minimum binder content defined, k richness modulus (film thickness)
	Workability	• French system using Finnish gyratory	• Gyratory system is not preferred	• French gyratory compactor; criteria is a function of mixture type and lift thickness
	Moisture Resistance	• Tensile strength ratio (TSR) value	• Exploring TSR, EU does not allow wet Hamburg	• Immersion compression (Duriez) test
	Rutting Resistance	• Hamburg-type loaded wheel tester, dry at 50 °C (122 °F)	• Hamburg loaded wheel tester, dry at 50 °C (122 °F)	• French loaded wheel tester
	Mixture Stiffness			• Direct tensile or 2-point bending
	Fatigue Resistance		• 3-point bending test	• 2-point bending test (link to structural design)
Valid Period	Approved Design	2 years	2 years	5 years

barriers for construction materials produced by the various EU nations. The CPD requested the harmonization of standards for a variety of construction materials, including HMA. The harmonization of standards and test methods was overseen by European Committees for Standardization (CEN) Technical Committee 227, which has developed definitions, test methods, product standards, and quality standards for the production of HMA. Product standards have been prepared for dense-graded mixtures, stone matrix asphalt, porous mixtures, and recycled asphalt, as well as other products. For dense-graded mixtures, there is both an empirical and a fundamental design procedure. The fundamental design procedure includes modulus, fatigue, and a cyclic-load, triaxial compression test. However, even the empirical design methodology includes performance-related parameters such as wheel-tracking and moisture resistance tests. The goal is to have HMA, WMA, and half-warm mixes designed the same way to the same standards. The new standards must be implemented by March 2008.[32]

Although test methods and broad definitions of mix types are being standardized, each country can still apply national application documents to narrow the product standards for use in a given country. This is similar to U.S. States modifying AASHTO test practices for local conditions.

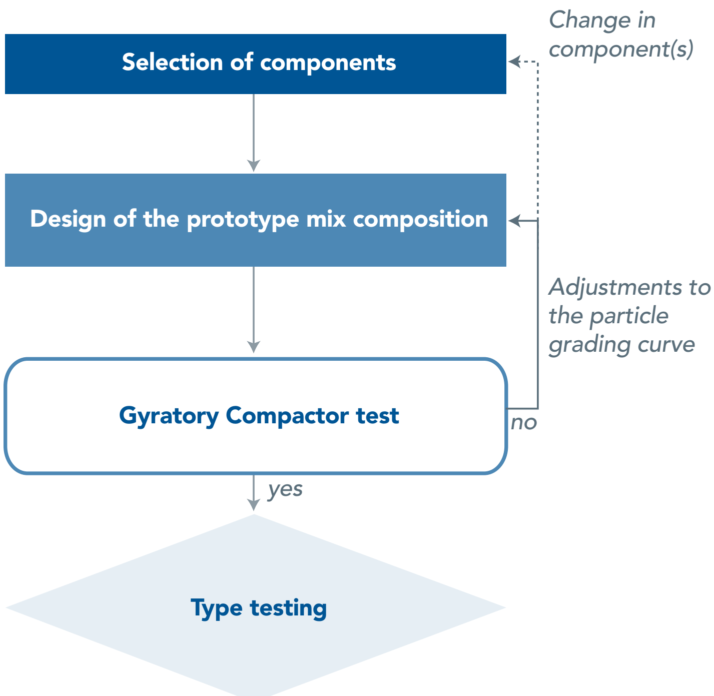


Figure 10. Outline of French design procedure.[31]

Products sold on the European internal market, including construction materials, must carry the CE marking, according to the Construction Products Directive.[32] The CE marking indicates that a product conforms to all of the provisions of the Construction Products Directive. To obtain a CE marking, the manufacturer must conduct initial type testing and factory production control and provide for initial and continuous monitoring of the product by an independent third party. Type testing can be conducted to various degrees, depending on the market demands. Type testing commonly includes testing for moisture resistance or rutting susceptibility, but also can include tests for fuel resistance. An abbreviated CE marking includes a description of the mix type and source, while the full CE marking includes the job-mix formula and type testing results. The CE marking covers only the manufacturing or production of the mix, not the placement and compaction.

The preceding describes the state of practice for mix design in the EU countries visited during the WMA scan (Belgian mix design practices were not discussed). The development of standardized test methods and mixture descriptions began in 1990. However, the current state of implementation represents only the first generation. Development has begun on performance-related standards, with a long-term goal of describing the performance characteristics required by the end user (figure 13). Ultimately, it will not matter how the performance requirements are achieved, whether with HMA, WMA, or half-warm mixtures.[32]

Although a range of mix design procedures is used for asphalt mixtures in the countries visited, all rely on performance tests to one degree or another. Accepted performance tests allow greater innovation, such as the development of WMA, by giving both the agency and the contractor tools to evaluate new additives, processes, and mixes. All of the contractor's labs the scan team visited were equipped with performance test equipment of one sort or another. The adoption of accepted performance tests and criteria is an integral step in evaluating new WMA technologies developed in the United States and abroad. Beyond WMA, the United States has a wider need for accepted performance tests to evaluate new modifiers, increased recycling levels, and new mix types in an accelerated manner.

Construction Practices

The scan team observed a number of construction practices that differ from U.S. practice:

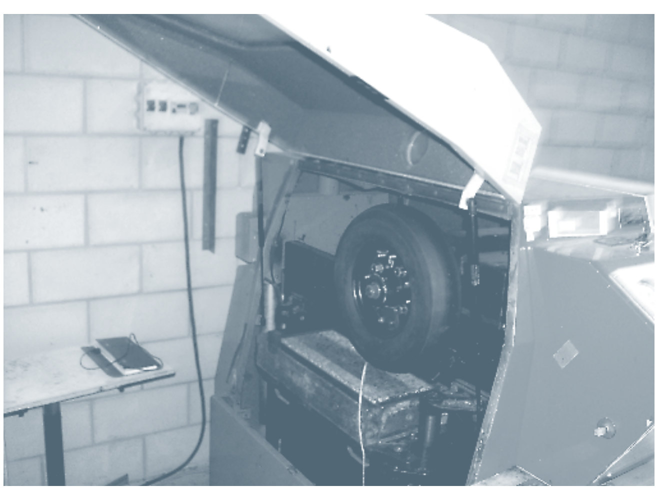


Figure 11. MLPC large-scale wheel-tracking tester.

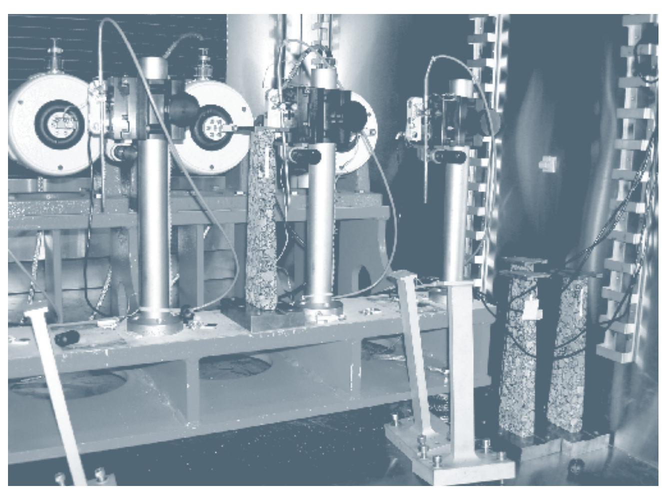


Figure 12. MLPC trapezoidal modulus and fatigue tester.

- Batch plants are more prevalent in Europe than drum plants.
- Production rates tend to be lower.
- Heavy tamping-bar vibratory-screed pavers are commonly used to place mix.

Some of these practices may have an impact on the viability of WMA. In all cases, construction practices for WMA were reported to be the same as construction practices for HMA. The scan team visited three asphalt plants producing WMA, one each in Norway, Germany, and France (figures 14 and 15). All three plants were batch plants. The plants used to produce LEAB in the Netherlands were also batch plants. Kolo Veidekke in Norway operated drum plants in addition to batch plants, and had modified an Amman drum plant to produce WAM-Foam. The drum plant was rated for 250 metric tons per hour, but typically operated in the 125- to 150-metric ton-per-hour range. Drum plants of varying sizes are also reportedly used in France. EIFFAGE Travaux Publics has modified 30 plants, 15 batch and 15 drum, in France and Spain to produce LEA.

Challenge 4: Adapt WMA products and technologies from low-production batch and drum plants frequently used in Europe to higher production plants used in the United States.

It is believed that drier aggregate results from a batch plant operated at lower temperatures than a drum plant operated at the same lower temperature. In a batch plant, the aggregate tends to be stored at an elevated temperature for a longer time period in the hot elevator and hot bins before being coated with asphalt in the pugmill. This increased storage time allows increased drying, even though the temperature is reduced. The smaller drum plants used in some cases have correspondingly smaller burners, making it easier to adjust the burner to run at lower temperatures. No problems with unburned fuel were reported. In Germany, HMA is normally produced at higher temperatures than in the United States. The Merkblatt (guidelines) on WMA recommends that it be produced at between 130 and 150 °C (266 and 302 °F), a 20 to 30 C° (36 to 54 °F) reduction from HMA produced in Germany.[30]

In addition to the prevalence of batch plants, a number of good practices were observed at the plant sites. In figures 14 and 15, note that the cold-feed belts are covered to minimize blowing dust and help keep the aggregate dry in case of rain. Kolo Veidekke's plant in Ås used a portable enclosure to cover its reclaimed asphalt

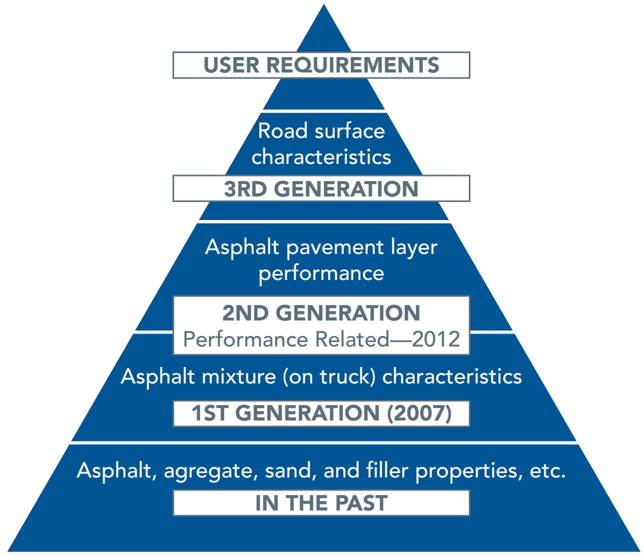


Figure 13. Vision for pyramid of requirements for future asphalt mixture specifications.

Figure 14. Kolo Veidekke batch plant in Norway.

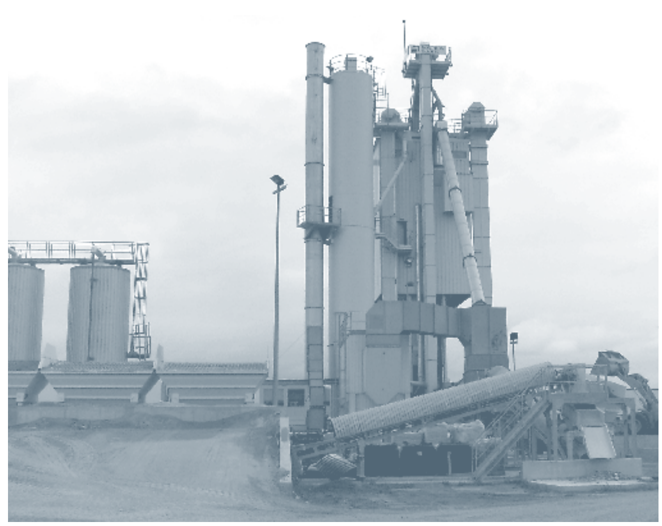


Figure 15. EIFFAGE Travaux Publics batch plant in France.

pavement (RAP) stockpiles (figure 16) to minimize the moisture content. As noted previously, the aggregates used in HMA in Europe generally have low water absorptions. Use of best practices further reduces the amount of moisture in the stockpiles.

Challenge 5: Coarse aggregate must be dry. Aggregates with low water absorption, less than 2 percent, are used to produce both HMA and WMA in Europe. Aggregates with much higher water absorptions are used in parts of the United States. WMA processes must be adapted to produce dry aggregates in the mix. Best practices for drying and minimizing moisture in aggregates should be encouraged, including paving under stockpiles and in certain conditions covering stockpiles.

Figure 16. Kolo Veidekke's covered RAP storage.

Figure 17. Heavy tamping-bar paver.

Four paving operations were observed during the scan. From a placement standpoint, no differences were noticed between the equipment used to place HMA and WMA. In all cases, the HMA or WMA was hauled in end-dump trucks that were unloaded directly into the paver hopper. Heavy tamping-bar vibratory-screed pavers are commonly used to place asphalt in Europe (figure 17). This type of paver tends to produce a high degree of density immediately behind the paver. Kolo Veidekke reportedly uses a more conventional U.S.-style paver for a particular type of paving, referred to as track-paving, described later in the document.

Steel-wheel vibratory rollers were used for compaction on all of the projects visited. Drum widths tended to be narrower than those used in the United States. Although the French gyratory compaction protocol is correlated to passes with a rubber tire roller, rubber tire rollers are used sparingly on HMA and WMA in the countries visited. A Sasol representative stated that there was no observed difference in pick-up with a rubber tire roller when compacting WMA produced with Sasobit. Compaction was reportedly achieved in the same or fewer passes.

It was generally noted that the paving equipment was cleaner when using WMA. Workability seemed to vary, depending on the process, but in most cases it seemed to be good. In Norway, workers were observed paving around a series of manhole covers with WMA produced using the WAM-Foam process. The mix temperature directly behind the screed ranged from 88 to 99 °C (190 to 210 °F). The workers did not appear to have any problems with the handwork and even shimmed the elevation of the manhole covers using WMA (figure 19). Paving crews seemed to prefer WMA, particularly in the hottest part of the summer.

In the European countries visited, the scan team observed no differences in paving practices between HMA and WMA, except that the placement temperatures

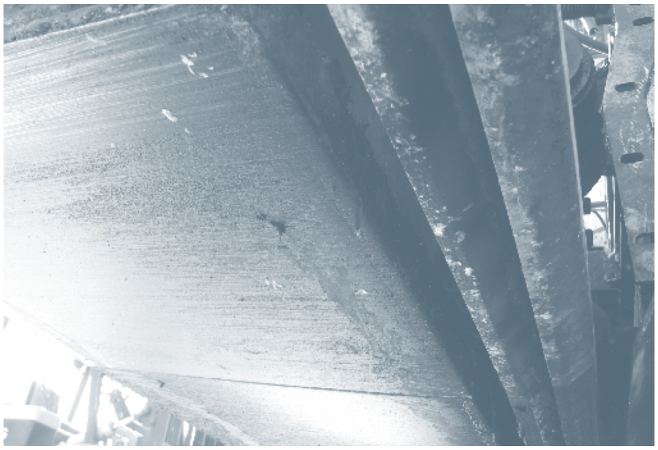


Figure 18. Close-up of tamping bars and vibratory screed.

were lower. Although paving practices vary slightly between the United States and Europe, particularly on the type of pavers used, there are no barriers to the use of WMA in the United States in placement practices. The increased prevalence of higher production drum plants in the United States is not considered a barrier to the implementation of WMA. However, best practice guidelines must be implemented for aggregate storage to minimize composite moisture contents and adjustment of drum plant burners and flighting.

Mastic Asphalt

One type of asphalt observed in France and Germany that is not used in the United States is gussasphalt (mastic asphalt). Mastic asphalt makes up 1.6 percent of the total HMA usage in Germany. In France, it is used mainly in Paris. Although mastic asphalt usage is relatively small, it is a technology that agencies want to continue to specify. Because of the extremely high temperatures used for mastic asphalt, it is a driving force toward WMA in areas where mastic asphalt is routinely used.

Mastic asphalt is reported to be durable, waterproof, and skid resistant. It is used as a wearing course on the Autobahn in rural Germany. In this application, the lifespan is expected to be 30 years.[33] Mastic asphalt is also used as a waterproofing layer for bridge decks and in parking structures. In addition, it is used as a pedestrian surface in Germany and France, particularly Paris, and as an interior flooring material. Only a few mastic asphalt projects have been constructed in the United States.

Mastic asphalt is produced in three nominal maximum aggregate sizes (NMAS) ranging from 5 to 11 mm. Depending on the NMAS, the mixture contains 20 to 34 percent dust, with an asphalt content of 6.5 to 8.5 percent by total weight of mix. Mastic asphalt is mixed in special transports (see figure 20 on next page) at 250 °C (482 °F) and placed by hand (see figure 21 on next page) or mechanical spreader at temperatures exceeding 200 °C (392 °F). Aggregate, typically 2- to 5-mm particles, is broadcast on the surface and embedded to provide skid resistance.

European Contractors

The expanding number of WMA technologies used in Europe is a function of the relationship between the industry and government agencies. Generally speaking, European contractors tend to be larger. In France, the scan team met with three major contractors: Colas, EIFFAGE Travaux Publics, and Eurovia. Each contractor has extensive research capabilities that allow it to lead innovation. Not surprisingly, each has developed one or more WMA technologies. Throughout Europe, industry has led the development of WMA technologies. The

Figure 19. Handwork with WMA around manhole.

Figure 20. Unloading a mastic asphalt transport.

Figure 21. Placing mastic asphalt.

agencies concentrate their efforts on evaluating the technologies. In France, LCPC has actually offered to partner with smaller contractors to help them develop WMA technologies to allow them to compete with the larger contractors. The difference in the size and technological capability of European contractors compared to many U.S. contractors may put U.S. contractors at a disadvantage on evaluating and selecting, let alone developing, WMA technologies.

Challenge 6: Individual contractors need to determine what products and technologies will work over the widest range of applications. In the past, agencies have mandated changes. In Europe, contractors have staffs who routinely conduct research to develop new products and processes. In the United States, contractors generally do not have these resources available in their own organizations. Such resources in the United States are generally found in research institutions and consultancies.

Although contractors tend to be larger in Europe than in the United States, production rates are lower. Kolo Veidekke produced 1.65 million tons in 2006 with 30 plants, or an average of 55,000 tons per plant per year. A large U.S. contractor, by comparison, produces about 137,000 tons per plant per year with individual high-capacity drum plants producing 200,000 to 650,000 tons per year.

Contractors in all of the countries visited as well as agencies in France observed that WMA is a component of sustainable development. In Norway, Kolo Veidekke observed that WMA was a step toward corporate social responsibility.[10] Sections of Colas', Eurovia's, and EIFFAGE's annual reports to shareholders are devoted to their efforts on sustainable development, including the development of WMA technologies.[14,34,35] The range of business practices considered within the framework of sustainable development is much wider than environmental protection and also includes human rights, labor standards, and business ethics. In terms of sustainable development, the main benefit from the use of WMA is the reduction of greenhouse gases and fuel usage. Recycling, reduced energy consumption, and reduced chemical usage, particularly solvents, are other examples of sustainable development practices being implemented by European contractors to address environmental protection.

Summary

During the scanning study, the team noticed several differences between typical European practices for the design, production, and placement of asphalt mixtures. In addition, the team also noticed differences between European and U.S. contractors. The water absorption of aggregates used to produce asphalt mixtures was generally less than 2 percent in the countries visited and less than 1 percent in France. The water absorption of aggregates used to produce asphalt mixtures in parts of the United States is higher, up to 5 percent. The Europeans experienced with the production of WMA repeatedly emphasized that the coarse aggregate must be dry. The higher the aggregate water absorption, the more difficult this may be. The contractors in the countries visited routinely blend or modify binders. By comparison, the United States has invested heavily in the PG binder system with supplier certification. Several WMA processes modify the binder, which may affect the grading of the binder (due to reduced aging). Throughout Europe, performance tests play a broader role in the mix design process. Performance tests enable European agencies and contractors to better assess innovative products, such as WMA, before conducting field trials.

Based on the countries visited, batch plants and in some cases smaller drum plants appear to be more prevalent in Europe. Increased drying is expected to result at the same (lower) temperature in a batch plant as a drum plant. This may be an advantage when producing WMA. Although some differences in placement practices were observed, placement practices did not differ between HMA and WMA; only the temperature was lower. Finally, European contractors appear to be better equipped in terms of research and development capabilities compared to U.S. contractors. This capability helps European contractors develop and select innovative materials like WMA.

Chapter 7: Summary of Challenges and Recommendations

Throughout the scan, the team identified a number of challenges that need to be addressed as WMA is implemented in the United States. These challenges, enumerated throughout the report, are summarized below. Based on the findings of the scanning study and the challenges identified, the team developed a series of recommendations to help move WMA toward implementation in the United States.

Challenges

Based on the summary and the team's experience, the following represents the challenges that need to be addressed as the United States moves forward with WMA:

1. **Make sure that the overall performance of WMA is truly as good as HMA.** On a life-cycle basis, if WMA does not perform as well, there will not be long term environmental benefits or energy savings. A number of test sections have been constructed. Monitoring of these and future sections combined with laboratory performance testing should provide this information.

2. **Address initial product approval.** How do we sort out good innovative products from poor products? Accepted performance tests are needed to separate the good from the bad. The traditional practice of products and technologies being approved on a state-by-state basis needs to be changed. Products and technologies should be approved on a national, or at least a regional, basis.

3. **Address issues with existing specifications that may prohibit the use of WMA.** Examples include allowing blending of binders, minimum production and placement temperatures, and minimum ambient temperatures or cutoff dates.

4. **Adapt WMA products and technologies from low-production batch and drum plants frequently used in Europe to higher production plants used in the United States.** Trial projects have been completed in the United States with higher production plants using the appropriate modifications.

5. **Coarse aggregate must be dry.** Aggregates with low water absorption, less than 2 percent, are used to produce WMA in Europe. Aggregates with much higher water absorptions are used in parts of the United States. WMA processes must be adapted to produce dry aggregates in the mix. Best practices for drying and minimizing moisture in aggregates should be encouraged, including paving under stockpiles and in certain conditions covering stockpiles.

6. **Individual contractors need to determine what products and technologies will work over the widest range of applications. In the past, agencies have mandated changes.** In Europe, contractors have staffs who routinely conduct research to develop new products and processes. In the United States, contractors generally do not have these resources available in their own organizations. Such resources in the United States are generally found in research institutions and consultancies.

Recommendations

The United States has already made great strides in evaluating WMA. A WMA Technical Working Group (TWG) has been established to oversee the implementation of WMA. A large number of trial sections and demonstration projects have been completed. In some cases, WMA has been used in production paving. During the WMA scanning study, the team learned that a wide variety of techniques are used to produce WMA, wider than the team was previously aware. One key element the team observed was that production temperatures were generally higher than expected. In part, this was done to ensure that the coarse aggregate particles were dry.

Based on the team's experience, there are no long-term barriers to the use of WMA in the United States. Many elements of WMA still need to be investigated. The consensus among team members is that WMA is a viable technology and that U.S. agencies and the HMA industry should cooperatively pursue this path. Implementation goals include the following:

- WMA should be an acceptable alternative to HMA at the contractor's discretion, provided the WMA meets applicable HMA specifications.
- An approval system needs to be developed for new WMA technologies. The approval system must be based on performance testing and supplemented by

field trials. The WMA TWG should lead the development of a performance-based evaluation plan for new WMA products. Realistically, such a system is needed for a broader range of modifiers and technologies used in HMA.

- The WMA scan team should provide technology transfer of the information gained through presentations, articles, and reports. An international workshop will be organized to promote WMA in 2008.
- Best practices need to be implemented for production handling and aggregate storage to minimize moisture content, burner adjustment, and WMA in general or specific technologies.
- More WMA field trials with higher traffic are needed. The field trials need to be large enough to allow a representative sample of the mixture to be produced. The trials should be built in conjunction with a control. The WMA Technical Working Group has developed guidelines that describe minimum test section requirements and data collection guidelines. The guidelines are at *www.warmmixasphalt.com*. Agency commitment is needed to monitor the project for a minimum of 3 years. More information on WMA, upcoming trials, and the WMA Technical Working Group is at *www.fhwa.dot.gov/pavement/asphalt/wma.cfm*.
- The factors affecting the economic viability of WMA need to be identified and tracked. Potential factors include additive costs, plant modifications, asphalt costs, fuel costs, costs of emission compliance equipment such as low-NO_X burners and fugitive emissions containment systems, and costs related to worker exposure.

References

1. Newcomb, D. "An Introduction to Warm-Mix Asphalt." National Asphalt Pavement Association. Accessed from *http://fs1.hotmix.org/mbc/Introduction_to_Warm-mix_Asphalt.pdf* August 8, 2007.

2. Cervarich, M. "Foaming the Asphalt: New Warm-Mix Technique Challenges Conventional Wisdom." *Hot Mix Asphalt Technology,* Volume 12, Number 4, National Asphalt Pavement Association, Lanham, MD, July/August 2007, pp 23-24, 42.

3. Romier, A., M. Audeon, J. David, Y. Martineau, and F. Olard. "Low-Energy Asphalt with Performance of Hot-Mix Asphalt." *Journal of Transportation Research Board,* No. 1962, Transportation Research Board, National Academies, Washington, DC, 2006, pp 101-112.

4. von Devivere, M., W. Barthel, and J.P. Marchand. "Warm Asphalt Mixes by Adding a Synthetic Zeolite." Proceedings of the 22nd World Road Congress, PIARC, Durban, South Africa, 2003.

5. U.S. Environmental Protection Agency. "Clean Air Interstate Rule." Accessed from *www.epa.gov/interstateairquality/* October 2006.

6. Brundtland Report. *Our Common Future.* Oxford: Oxford University Press, 1987.

7. National Institute for Occupational Safety and Health. *Engineering Control Guidelines for Hot-Mix Asphalt Pavers, Part I New Highway-Class Pavers.* DHHS (NIOSH) Publication No. 97-105, U.S. Department of Health and Human Services, Cincinnati, Ohio, January 1997. Accessed from *http://www.cdc.gov/niosh/pdfs/97-105.pdf* August 9, 2007.

8. Corrigan, M. "Warm Mix Asphalt Technologies and Research." Federal Highway Administration, last updated August 18, 2006. Accessed from *http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm* August 9, 2007.

9. The German Bitumen Forum, Rühl, R., and B. Lindemeier, Ed. *Progress Report 2006: The German Bitumen Forum.* Edition 2 (in English), Heinrich Lauck GmbH, Germany, 2006.

10. Moen, Ø. "Warm-Mix Asphalt (WMA) International Scanning Tour." Norwegian Public Roads Administration, Norway, Presentation to WMA Scan Team, May 2007.

11. Brosseaud, Y. "Warm Asphalt—Overview in France." LCPC, France, Presentation to WMA Scan Team, May 2007.

12. Andersen, E.O. "WAM-Foam—An Environmentally Friendly Alternative to Hot-Mix Asphalt." Norwegian Public Roads Administration, Oslo, Norway, Presentation to WMA Scan Team, May 2007.

13. Harnischfeger, S. "Aspha-min Retrospectives and Prospects." BASt, Germany, Presentation to WMA Scan Team, May 2007.

14. Colas. *Colas in 2006.* Annual Report, Euro RSCG C&O, 2006.

15. Yunus, Ç., and M. Boles. *Thermodynamics: An Engineering Approach.* 2nd Edition, New York: McGraw-Hill, Inc., 1994.

16. Jenkins, K. *Mix Design Considerations for Cold and Half-Warm Bituminous Mixes with Emphasis on Foamed Bitumen.* Doctoral Dissertation, Stellenbosch University, 2000.

17. Nölting, M. "10 Years of Sasobit Technology Experiences, Applications and Outlook." BASt, Germany, Presentation to WMA Scan Team, May 2007.

18. Hirsch, V. "Warm Mix Asphalt Technologies." BASt, Germany, Presentation to WMA Scan Team, May 2007.

19. Wölfe, H., and K. Orlamünder. "Bitumen Modification with Additives for Road Construction—Technology of Low-Temperature Asphalt." BASt, Germany, Presentation to WMA Scan Team, May 2007.

20. Brosseaud, Y. "Warm Asphalt—Overview in France." LCPC, Nantes, France, Presentation to WMA Scan Team, May 2007.

21. Olard, F. "LEA® (Low Energy Asphalts): A New Generation of Half-Warm Mix Asphalts." USIRF, France, Presentation to WMA Scan Team, May 2007.

22. van den Beemt, C.M.A. "Low-Temperature Asphalt Production Using Foamed Bitumen Technologies." European Asphalt Pavement Association, Belgium, Presentation to WMA Scan Team, May 2007.

23. Andersen, E. "WAM-Foam®: An Environmentally Friendly Alternative to Hot Mix Asphalt." Norwegian Public Roads Administration, Norway, Presentation to WMA Scan Team, May 2007.

24. Berntsen, G. "NPRA's Experience with WAM-Foam Pavements." Norwegian Public Roads Administration, Norway, Presentation to WMA Scan Team, May 2007.

25. *Erfahrungssammlung über die Verwendung von Fertigprodukten und Zusätzen zur Temperaturabsenkung von Asphalt.* BASt, *http://www.bast.de/cln_007/nn_37284/DE/BASt/Organisation/abteilung-s/referat-s5/temperaturreduzierter-asphalt/erfahrungssammlung,templateId=raw,property=publicationFile.pdf/erfahrungssammlung.pdf,* accessed June 2007. Translated in part by Peter Bellin.

26. Sauterey, D. "Les Departements." DGR, France, Presentation to WMA Scan Team, May 2007.

27. Leroy, C. "Warm Mix-Asphalt in Paris." DGR, France, Presentation to WMA Scan Team, May 2007.

28. George, L.A. "Warm-Mix Asphalt in French Toll Motorway Companies." DGR, France, Presentation to WMA Scan Team, May 2007.

29. Bull-Wasser, R. "Presentation of the Federal Highway Research Institute—Part 2." BASt, Cologne, Germany, Presentation to WMA Scan Team, May 2007.

30. FGSV. *Merkblatt für Temeraturabsenkung von Asphalt.* Cologne, Germany, August 2006.

31. The RST Working Group. "Design of Hot Asphalt Mixtures." Under the supervision of Delorme, J.L., C. De La Roche, and L. Wendling, *LPC Bituminous Mixtures Design Guide.* LCPC, Nantes, France 2005.

32. Beuving, E. "Asphalt Mixtures Standardization in Europe." European Asphalt Pavement Association, Brussels, Belgium, Presentation to WMA Scan Team, May 2007.

33. Bommert, F. "Warm-Mix Asphalt (WMA) International Scanning Tour—Implementation of a New Technology in Germany." German Federal Highway Research Institute, Cologne, Germany, Presentation to WMA Scan Team, May 2007.

34. Vinci. *A Responsible Group—Sustainable Development Report.* Vinci 2006 Annual Report, Accessed August 15, 2007, from *http://publi.vinci.com/docs/dd/rapport-dd-vinci-2006-en.pdf.*

35. EIFFAGE. *Eiffage 2006 Annual Report.* Accessed September 18, 2007, from *http://www.eiffage.fr/cms/finances/rapport-annuel.html.*

36. Sasol Wax. "Roads and Trials with Sasobit ." Accessed from *http://www.sasolwax.com/data/sasolwax_/Bitumen%20Modification/Roads%20and%20trials%20e.pdf* May 13, 2005.

37. Hurley, G.C., and B.D. Prowell. *Evaluation of Sasobit® for Use in Warm-Mix Asphalt.* NCAT Report 05-06, National Center for Asphalt Technology, Auburn University, 2005.

38. Hurley, G.C., and B.D. Prowell. *Evaluation of Aspha-min® Zeolite for Use in Warm-Mix Asphalt.* NCAT Report 05-04, National Center for Asphalt Technology, Auburn University, 2005.

39. Brock, D. "Warm-Mix Technology by Astec." PowerPoint® Presentation, June 21, 2007.

40. Brock, D. "Double-Barrel Green Mix Paving Demo." PowerPoint Presentation, June 21, 2007.

Appendix A: Team Members

Contact Information

John A. D'Angelo *(FHWA Cochair)*
Asphalt Materials Engineer
Federal Highway Administration
Office of Pavement Technology
1200 New Jersey Avenue, SE.
HIPT, E73-301
Washington, DC 20590
Telephone: (202) 366-0121
Fax: (202) 493-2070
E-mail: *john.d'angelo@dot.gov*

Eric E. Harm *(AASHTO Cochair)*
Deputy Director/Assistant Chief Engineer
Division of Highways
Illinois Department of Transportation
2300 South Dirksen Parkway
Springfield, IL 62764
Telephone: (217) 785-0888
Fax: (217) 524-2972
E-mail: *eric.harm@illinois.gov*

Dr. Brian D. Prowell *(Report Facilitator)*
Principal Engineer
Advanced Materials Services, LLC
1975 Mall Blvd., Suite 202
Auburn, AL 36830
Telephone: (334) 408-4855
Fax: (334) 408-4854
E-mail: *Brian.AMSLLC@CharterInternet.com*

John C. Bartoszek
Manager, Technical Services and Engineering
Payne & Dolan, Inc.
W6380 Design Drive
Greenville, WI 54942
Telephone: (920) 757-7535
Fax: (920) 757-2906
E-mail: *jbartoszek@payneanddolan.com*

Gaylon L. Baumgardner
Executive Vice President, Paragon Technical Services, Inc.
Ergon, Inc.
PO Box 1639
Jackson, MS 39215-1639
Telephone: (601) 933-3217
Fax: (601) 933-3363
E-mail: *gaylon.baumgardner@ergon.com*

Matthew R. Corrigan
Asphalt Pavement Engineer
Federal Highway Administration
Office of Pavement Technology
1200 New Jersey Avenue, SE.
HIPT, E73-465
Washington, DC 20590
Telephone: (202) 366-1549
Fax: (202) 493-2070
E-mail: *matthew.corrigan@dot.gov*

Jack E. Cowsert
State Materials Quality Engineer
North Carolina Department of Transportation
1801 Blue Ridge Road
Raleigh, NC 27607
Telephone: (919) 329-4030
Fax: (919) 329-4031
E-mail: *jcowsert@dot.state.nc.us*

Thomas P. Harman
Team Leader
Pavements and Materials Technical Service Team (TST)
Federal Highway Administration Resource Center
10 South Howard Street, Suite 4000
Baltimore, MD 21201
Telephone: (410) 962-0134
Fax: (410) 962-3655
E-mail: *tom.harman@dot.gov*

Mostafa (Moe) Jamshidi
Materials and Research Engineer
Nebraska Department of Roads
1400 Highway 2
PO Box 94759
Lincoln, NE 68509-4759
Telephone: (402) 479-4847
Fax: (402) 479-3975
E-mail: *mjamshid@dor.state.ne.us*

H. Wayne Jones
Field Engineer
Asphalt Institute
6113 Bickford Court
Columbus, OH 43230-8376
Telephone: (614) 855-1905
Fax: (614) 855-5384
E-mail: *wjones@asphaltinstitute.org*

Dr. David E. Newcomb
Vice President for Research & Technology
National Asphalt Pavement Association
5100 Forbes Boulevard
Lanham, MD 20706
Telephone: (301) 731-4748
Fax: (301) 731-4621
E-mail: *dnewcomb@hotmix.org*

Ronald A. Sines
Operations Manager
P.J. Keating Co.
998 Reservoir Road
Lunenburg, MA 01462
Telephone: (978) 582 9931
Fax: (978) 423-5590
E-mail: *rsines@pjkeating.com*

Bruce A. Yeaton
Materials Testing Engineer
Maine Department of Transportation
16 State House Station
Augusta, ME 04333-0016
Telephone: (207) 624-3482
Fax: (207) 624-3401
E-mail: *bruce.yeaton@maine.gov*

Biographic Sketches

JOHN A. D'ANGELO is the Asphalt Team leader in the Federal Highway Administration (FHWA) Office of Pavement Technology. He is responsible for establishing policy and guidance for the FHWA programs on asphalt material testing, asphalt pavement construction, materials quality assurance, recycling, and pavement design. He is also responsible for establishing the research needs and direction in the asphalt pavement area. For the past 16 years, he has been involved with the implementation of the Strategic Highway Research Program and the development of the Superpave Asphalt Design System. D'Angelo has been with FHWA for 29 years and has published numerous papers on material testing and quality control. He is a member of the Transportation Research Board (TRB), the Association of Asphalt Pavement Technologists (AAPT), the Canadian Technical Asphalt Association, the American Association of State Highway and Transportation Officials' (AASHTO) Subcommittee on Materials, and the American Society for Testing and Materials (ASTM).

ERIC E. HARM is the assistant chief engineer for the Illinois Department of Transportation in Springfield, Illinois. He is responsible for eight engineering bureaus that develop and issue statewide policies, procedures, standards, and specifications and that interact with local agencies, other regulatory agencies, and the construction industries. Before his present position, his responsibilities were concentrated in the research, materials, and pavement areas. He has served with the Illinois DOT for 26 years. Harm is a graduate of the University of Illinois at Urbana with a bachelor's degree in civil engineering and holds a master's degree in civil engineering from the University of California at Berkeley. He is a licensed engineer in Illinois and serves on several technical research committees at the national level.

BRIAN D. PROWELL is a principal engineer for Advanced Materials Services, LLC (AMS). Before joining AMS, Prowell was an assistant director for the National Center for Asphalt Technology (NCAT) and a senior research scientist for the Virginia Department of Transportation's Research Council. Prowell has conducted a number of laboratory and field evaluations of warm mix asphalt. He received his bachelor of science degree from Pennsylvania State University in 1990, his master of science degree from Virginia Polytechnic Institute and State University in 1992, and his Ph.D. degree from Auburn University in 2006. Prowell is the chair of TRB Committee AFK30 on nonbituminous components of bituminous mixtures, which include warm-mix asphalt additives and processes, a member of the FHWA Warm-Mix Asphalt Technical Working Group, and a member of the Association of Asphalt Paving Technologists. He is a registered professional engineer in Virginia.

JOHN C. BARTOSZEK is the corporate manager of technical services and engineering for Payne and Dolan Inc., headquartered in Waukesha, Wisconsin. Bartoszek is responsible for the engineering and technical aspects of the company's operations, including quality control, mix design, engineering, pavement design, and paving operations. Payne and Dolan Inc. is proactive in research and development and did the first warm-mix paving projects in Michigan and Wisconsin. Bartoszek's paving research areas include intelligent compaction and GPS-integrated control systems to aid in achieving uniform asphalt pavement densities. Bartoszek has a bachelor's degree in geotechnical and civil engineering from Michigan Technological University. He is a licensed professional engineer in Michigan and Wisconsin and serves on technical committees for both States, including the National Asphalt Pavement Association (NAPA).

GAYLON L. BAUMGARDNER is executive vice president of Paragon Technical Services, Inc. (PTSi). A subsidiary of Ergon, Inc., PTSi is a nationally recognized asphalt testing and development laboratory offering services in design and evaluation of hot-, warm-, and cold-mix asphalt, asphalt binders, and emulsions. Baumgardner has 27 years' experience in the petroleum and petroleum-related products industries. He has a bachelor's degree in chemistry and mathematics from Henderson State University in Arkansas. He serves on various American Society for Testing and Materials (ASTM) D04 and D08 task groups. He is chair of the Asphalt Emulsion Manufacturers Association (AEMA) International Symposium on Asphalt Emulsion Technology (ISAET) organizing committee. He cochairs the Binder Expert Task Group and serves on the Asphalt Institute Technical Advisory Committee, the board of directors of the International Bitumen Emulsion Federation (IBEF), the National Center for Asphalt Technology (NCAT) Applications Steering Committee, the American Chemical Society (ACS), and other technical committees in the asphalt and petroleum products industries.

MATTHEW R. CORRIGAN is an asphalt pavement engineer for the FHWA Office of Pavement Technology in Washington, DC. Corrigan is FHWA's principal coordinator for the investigation and implementation of warm-mix asphalt technologies in the United States. He is a cochair of the joint NAPA-FHWA Warm-Mix Asphalt Technical Working Group and operates the FHWA Mobile Asphalt Testing Laboratory Trailer program. His other areas of expertise include quality assurance and statistical acceptance specifications. Before joining the Office of Pavement Technology, he was a construction project engineer with FHWA's Central Federal Lands Highway Division, in charge of road and bridge construction inside U.S. national parks and forests. Corrigan is a graduate of Pennsylvania State University and a licensed professional engineer in Virginia.

JACK E. COWSERT is the state materials quality engineer for the North Carolina Department of Transportation's (NCDOT) Materials and Tests Unit (MTU) in Raleigh, North Carolina. Cowsert manages the four central laboratories (Soils and Aggregate, Chemical, Asphalt, and Physical Testing) and the Structural Members Section of the MTU. Cowsert has served with NCDOT for more than 21 years with responsibilities in materials and testing, pavement design, bridge maintenance, and roadway design. He also served 3 years with the Mississippi Highway Department with responsibilities in construction project inspection. He has a bachelor's degree in civil engineering from North Carolina State University. He is a registered professional engineer in North Carolina and serves on a technical committee and an NCHRP Project Panel of the Transportation Research Board. He chairs and serves on subcommittees of the American Society for Testing and Materials and technical sections of the AASHTO Subcommittee on Materials.

THOMAS P. HARMAN is the senior pavement engineer for the FHWA Resource Center in Baltimore, Maryland. Harman is the team leader for the Pavement and Materials Technical Service Team. Harman's team assists FHWA Divisions on technical issues and supports FHWA program offices in the deployment of new technologies. His activities include the development of a National Asphalt Pavement Roadmap for Research and Technology and accelerated implementation of intelligent compaction technology. Harman has been with FHWA since 1990. He served as pavement engineer and project manager for FHWA's Office of Technology Application from 1990 to 1996, and as team leader for the Pavement and Construction Team for Research and Development from 1996 to 2006. Harman is internationally recognized for his expertise in asphalt materials, including the development and implementation of Superpave® technology. He has a bachelor's degree in civil engineering from the University of Maryland at College Park and a master's degree in civil engineering from the University of Illinois at Urbana-Champaign. Harman and his team work closely with FHWA's program offices in evaluating and implementing warm-mix asphalt technologies.

MOE JAMSHIDI is the materials and research engineer for the Nebraska Department of Roads (NDOR). Jamshidi is responsible for directing the activities related to pavement design, pavement management, and materials testing for Nebraska's 10,000-mile State highway system. He is also in charge of coordinating all the research activities related to pavements and materials for NDOR. Jamshidi has been involved in designing and constructing transportation-related projects for more than 23 years. He has served on numerous technical advisory committees for asphalt-related research projects. Jamshidi is a graduate of the University of Nebraska with a degree in civil engineering and is a registered professional engineer in Nebraska. He is a member of the AASHTO Subcommittee on Materials and the AASHTO Research Advisory Committee, and is NDOR's representative to the Transportation Research Board.

H. WAYNE JONES is a registered professional engineer with 32 years of experience in designing and constructing transportation projects nationwide. He has a strong background in construction and material selection for airport, industrial, and heavy highway applications. Jones is the Asphalt Institute field engineer for Illinois, Indiana, Michigan, and Ohio. In this role he plans, organizes, and conducts asphalt training seminars and serves on several regional technical committees. Before joining the institute, Jones had more than 28 years of experience in the highway construction industry. He has rebuilt sections of interstate highways in four States and has won several State quality paving awards and a national award for quality airport paving. He has paved successfully for such owners as NASA, NASCAR, Disney World, and Universal Studios in Orlando, Florida. Nationally, he is active in the Transportation Research Board and serves as the lead instructor for the National Highway Institute course on "Asphalt Pavement Recycling Technologies."

DAVID E. NEWCOMB is vice president–research and technology for the National Asphalt Pavement Association (NAPA). He represents the interest of the hot-mix asphalt paving industry on research panels and task groups involved with developing asphalt technology. Before that, he was a professor in the Department of Civil Engineering at the University of Minnesota for 10 years. Before moving to Minnesota, he taught at the University of Nevada-Reno. He received his Ph.D. degree at the University of Washington after working at the New Mexico Engineering Research Institute. Newcomb received his bachelor of science and master of science degrees at Texas A&M University. He is a registered professional engineer in Minnesota.

RONALD A. SINES has been employed by the P.J. Keating Company for the past 7 years and is now the operations manager, responsible for overseeing the production operations at P.J. Keating's four quarries and five hot-mix asphalt plants and the equipment and quality assurance divisions. P.J. Keating is a vertically integrated company producing 4 million tons of aggregate and 1.4 million tons of HMA that it supplies to its paving and construction operations in eastern Massachusetts and Rhode Island. Previously, Sines spent 15 years at the New York State Department of Transportation's Materials Bureau, where he managed all aspects of the State's HMA program, including implementation of Superpave and quality assurance specifications for HMA pavement construction. Sines is the former chair and vice chair of the Superpave Mixture and Aggregate Expert Task Group and serves on several NCHRP panels overseeing HMA research. He is a board member of the New England Transportation Technician Certification Program and of the North East Asphalt User-Producer Group, and a member of Oldcastle Materials' Hot-Mix Asphalt Best Practices Committee. Sines received a bachelor's degree in civil engineering from Youngstown State University and is a registered professional engineer in New York.

BRUCE A. YEATON is the State materials testing engineer for the Maine Department of Transportation (Maine DOT) in Augusta, Maine. He is responsible for managing the Central and Regional Laboratories that perform all materials testing, including hot-mix asphalt lab and field testing on highway and bridge construction projects. He also assists the research staff in developing specifications for new products and materials-related technologies. Yeaton has served with the Maine DOT for 29 years and has been involved with HMA mix design, inspection, placement, and compaction, along with the development of quality assurance specifications for hot-mix asphalt. He is a graduate of the University of Maine-Orono with a bachelor's degree in civil engineering. He is a licensed professional engineer in Maine and serves on several AASHTO technical sections that maintain and develop hot-mix asphalt standard specifications. He is also a member of several regional groups that work to solve HMA-related issues, including the New England Transportation Technician Certification Program, North East Asphalt User-Producer Group, and Canadian Technical Asphalt Association.

Appendix B: Amplifying Questions

As part of our information gathering to better understand WMA processes and additives, the team desires to visit highway agencies and active construction projects, talk to contractors and suppliers of these projects, and review older existing projects for field performance.

1. What processes, materials, and construction practices are being used in the production and placement of warm-mix asphalt (WMA)? Expanded areas of interest include the following:

- WMA additives and processes
- Types of mixes using WMA (e.g., dense-graded, SMA, open-graded)
- Use with polymer modifiers
- Use with recycled or reclaimed asphalt pavement (RAP)

2. How do these processes, materials, and production practices differ from standard mix designs and production? Expanded areas of interest include the following:

- Specifications
- Differences in selection of aggregates, bitumen grade, or gradations
- Laboratory testing
- Moisture damage susceptibility
- Workability
- Asphalt plant setup and special equipment required
- Production and placement temperatures
- Tack coat and bond between layers
- Placement and compaction

3. What are the performance characteristics of WMA in terms of rutting, fatigue cracking, thermal cracking, moisture damage, etc.? Expanded areas of interest include the following:

- Comparisons with conventional hot-mix asphalt
- Performance monitoring of in-place sections
- Accelerated laboratory testing or test roads to evaluate performance
- Failures or less-than-expected performance
- Changes in products, practice, or specifications resulting from experience to date

4. What class of roadway or pavement, traffic volumes, and truck volumes are best suited for WMA use? Expanded areas of interest include the following:

- Factors or criteria used to select particular projects
- Use over concrete pavements
- Experience with high-traffic-volume roads or airfields
- Experience with low-volume roads

5. What are the benefits and future plans for using WMA? Expanded areas of interest include the following:

- Studies documenting reduced emissions
- Fuel savings
- Studies documenting reduced worker exposure to fumes
- Cold-weather construction
- Long hauls
- Increased percentages of recycled asphalt pavement
- Cost, cost-benefit analyses, or life-cycle cost analyses

Appendix C: European Hosts

Norway

Øyvind Moen
Project Engineer
Kolo Veidekke
E-mail: *oyvind.moen@veidekke.no*
Telephone: +47 64 97 47 60

Olle R. Larsen
Technical Director
Kolo Veidekke
E-mail: *olle.varsen@veidekke.no*
Telephone: +47 64 97 47 62

Eivind Olav Andersen
Technical Manager Nordics
Shell Bitumen
E-mail: *eivindolav.andersen@shell.com*
Telephone: +47 22 66 50 00

Carl Christian Gabrielsen
Secretary, International Affairs
Norwegian Public Roads Administration
E-mail: *carl.gabrielsen@vegvesen.no*
Telephone: +47 22 07 32 71

Kjell Sture BjØrvig
Deputy Director General
Norwegian Public Roads Administration
E-mail: *kjell.bjorvig@vegvesen.no*
Telephone: +47 22 07 35 04

Leif JØrgen BaklØkk
Technology Department
Norwegian Public Roads Administration
E-mail: *leif.baklokk@vegvesen.no*
Telephone: +47 73 95 46 66

Rabbira Garba Saba
Senior Engineer
Norwegian Public Roads Administration
E-mail: *rabbira.saba@vegvesen.no*

Geir Berntsen
Senior Principal Engineer
Norwegian Public Roads Administration
E-mail: *geir.berntsen@vegvesen.no*
Telephone: +47 24 05 84 28

Germany

Dr. Volker Hirsch
Head of Section, Chemistry
Federal Highway Research Institute (BASt)
E-mail: *hirsch@bast.de*
Telephone: +49 (0)2204 43 760

Rudi Bull-Wasser
Head of Section, Asphalt Pavement
Federal Highway Research Institute (BASt)
E-mail: *bull-wasser@bast.de*
Telephone: +49 (0)2204 43 750

Franz Bommert
Federal Highway Research Institute (BASt)
E-mail: *bommert@bast.de*
Telephone: +49 (22 04) 43 752

Erika Borsberg
Federal Highway Research Institute (BASt)
E-mail: *borsberg@bast.de*
Telephone: +49 (22 04) 43 337

Ottmar W. Schütz
Wilh. Schütz GmbH & Co
Telephone: 0 64 71/9 53 2-0

Walter Barthel
Managing Director
Aspha-min GmbH
E-mail: *w.barthel@aspha-min.com*
Telephone: +49 6181/98 38 898

Stephan Harnischfeger
Sales Manager
Aspha-min GmbH
E-mail: *s.harnischfeger@aspha-min.com*
Telephone: +49 6181/98 38 897

Dr. Reinhold Rühl
BG BAU
E-mail: *reinhold.ruehl@bgbau.de*
Telephone: (0 69) 47 05-213

Dr. Jürge Hutschenreuther
Dr. Hutschenreuther Ingenieurgesellschaft
E-mail: *jh@hutschenreuther.de*
Telephone: +49 (0)-3643-87 149 0

Hans Wölfe
Managing Director
BfB
E-mail: *hans.woelfle@t-online.de*
Telephone: +49 (0) 83 31/66 58

Günther Heiling
Technical Marketing Manager
Clariant Produkte GmbH
E-mail: *guenther.heiling@clariant.com*
Telephone: +49 821 479 2233

Dr. Martin Radenberg
Professor
Ruhr-Universität Bochum
E-mail: *martin.radenberg@rub.de*
Telephone: +49 (0) 234/32 14152

Matthias Nölting
Global Business Unit Manager
Sasol Wax GmbH
E-mail: *matthias.noelting@de.sasol.com*
Telephone: +49 (0) 40 78 11 5-731

Belgium

Jürgen Sturm, LL.M.
Secretary General
European Asphalt Pavement Association
E-mail: *sturm@eapa.org*
Telephone: +32 2 502 58 88

Egbert Beuving, M.Sc.
Technical Director
European Asphalt Pavement Association
E-mail: *ebeuving@eapa.org*
Telephone: +32 2 502 58 88

Jean-Paul Michaut
Technical & Development Director, Europe
COLAS
E-mail: *michaut@siege.colas.fr*
Telephone: +33 (0)6 61 09 34 90

Rémy van den Beemt
BAM Wegen bv
E-mail: *r.vanden.beemt@bamwegen.nl*
Telephone: (030) 287 69 78

France

Michel Boulet
Technical Director Delegate for Transport Infrastructure
LCPC
E-mail: *michel.boulet@lcpc.fr*
Telephone: +33 (0)2 40 84 58 37

Chantal de la Roche
Head, Bituminous Binders and Road Materials Unit
LCPC
E-mail: *chantal.de-la-roche@lcpc.fr*
Telephone: +33 (0)2 40 84 59 29

Yves Brosseaud
Head, Road Management and Pavement Monitoring Unit
LCPC
E-mail: *yves.brosseaud@lcpc.fr*
Telephone: +33 (0)2 40 84 59 28

Vincent Gaudefroy, Ph.D.
Researcher
LCPC
E-mail: *vincent.gaudferoy@lcpc.fr*
Telephone: +33 (0)2 40 84 56 72

Pierre Hornych
LCPC
E-mail: *pierre.hornych@lcpc.fr*
Telephone: +33 (0)2 40 84 58 09

Agnès Jullien
Head, Sustainable Development Unit
LCPC
E-mail: *agnes.jullien@lcpc.fr*
Telephone: +33 (0)2 40 84 59 38

Thomas Caillot
Project Manager, Pavement Materials
SETRA
E-mail: *thomas.caillot@equipement.gouv.fr*
Telephone: +33 (0)1 46 11 33 98

Pierre Dupont
Project Manager, Pavement Materials
SETRA
E-mail: *pierre.dupont@equipement.gouv.fr*

Antoine Averseng
International Area Manager, Office of International Affairs
DGR
E-mail: *antoine.averseng@equipement.gouv.fr*
Telephone: +33 (0)1 40 81 18 71

Samuel Charpentier
Project Manager, Regional Public Works Research Laboratory of Blois
CETE
E-mail: *samuel.charpentier@equipement.gouv.fr*
Telephone: +33 (0)2 54 55 49 47

Denis Sauterey
Director of Road Facilities
Departmental Council of Eure et Loir
E-mail: *denis.sauterey@cg28.fr*
Telephone: +33 (0)2 37 20 11 50

Luc-Amaury George
Asset Management Special Task Manager
Cofiroute
E-mail: *luc-amaury.george@cofiroute.fr*
Telephone: +33 (0)1 41 14 70 68

Christine Leroy
Head of Public Thoroughfare Division, Streets and Moving Department
City of Paris
E-mail: *christine.leroy@paris.fr*
Telephone: +33 (0)1 40 28 75 13

Samir Soliman
Doctor-Engineer, Technical Department
Eurovia Management
E-mail: *ssoliman@eurovia.com*
Telephone: +33 1 47 16 46 70

Max von Devivere
Director for Industrial Business Development and Technical Resources
Eurovia
E-mail: *mvondevivere@eurovia.com*
Telephone: +33 1 47 49 19 70

François Olard
Task Manager, Research and Development Department
EIFFAGE Travaux Publics
E-mail: *folard@travauxpublics.eiffage.fr*
Telephone: +33 (0)4 72 21 24 30

Bernard Heritier
Technical Director
EIFFAGE Travaux Publics
E-mail: *bheritier@travauxpublics.eiffage.fr*
Telephone: +33 (0)1 49 44 98 73

Gregory A. Harder, PE
Vice President
McConnaughay Technologies
E-mail: *gharder@mcconnaughay.com*
Telephone: 1 (866) 622-8324

Jean-Claude Roffé
President
SFERB
E-mail: *jean-claude.roffe@usirf.com*
Telephone: +33 (0)1 44 13 32 87

Alain Le Coroller
President & Director General
RGRA
E-mail: *alecoroller@editions-rgra.com*
Telephone: +33 (0)1 40 73 80 00

Jean-Eric Poirier
Scientific Director of Colas Group
Colas
E-mail: *poirier@campus.colas.fr*
Telephone: +33 (0)1 39 30 93 40

Xavier Carbonneau
Head of Asphalt Service 1, Research and Development Department
Colas
E-mail: *carbonneau@campus.colas.fr*
Telephone: +33 (0)1 39 30 93 63

Appendix D: WMA Technologies

Organic Additives

Most polymers and hydrocarbons have a flexible backbone chain of carbon atoms. The length of the carbon chain is related to the molecular weight of the molecule and is often denoted as Cx, where the C stands for a carbon atom and the subscript x denotes the length of the carbon backbone chain. Organic additives are typically waxes with molecular sizes greater than C45 and melting points greater than 70 °C (158 °F). Longer carbon chain lengths tend to lead to higher melting points. Examples include Fischer-Tropsch wax (Sasobit®), Montan wax, fatty acid amides (Licomont BS 100), and blends of Montan wax and fatty-acid amides (Asphaltan-B). Although straight Montan wax has been used in mastic asphalt, Asphaltan-B is recommended for WMA. In Germany, organic additives are typically added at a rate of 2.5 percent by total weight of binder (e.g., including the weight of binder in any RAP added to the mixture).

Fischer-Tropsch Wax

Fischer-Tropsch wax is produced by heating coal or natural gas with water to 180 to 280 °C (356 to 536 °F) in the presence of a catalyst. Fischer-Tropsch wax is a synthetic aliphatic hydrocarbon wax. Sasobit is a Fischer-Tropsch wax. The molecular lengths of the linear Sasobit hydrocarbon molecule range from C40 to C120. The smaller crystalline structure of Fischer-Tropsch wax reduced brittleness at low temperatures compared to macrocrystalline bituminous paraffin waxes. Sasobit wax has a congealing point of 98 °C (209 °F), with a melting range of 70 to 114 °C (158 to 238 °F). The penetration of the wax at 25 °C (77 °F) is less than 1 dmm. The (melted) wax has a viscosity of 12 mPas at 135 °C (275 °F). As the asphalt-wax combination cools, the wax solidifies into regularly distributed, microscopic, stick-shaped particles. It is believed that the distribution of stick-like particles provides the framework that increases the viscosity of the Sasobit modified binder at in-service pavement temperatures.[17,18]

Sasobit may be preblended with the binder, blended in-line in a molten state, or added during the mixing process as a pellet. In Germany, Sasobit is typically added at 2.5 percent of the total binder mass. Addition rates should not exceed 3 percent because of stiffening effects at low temperatures. Addition rates of 1 to 1.5 percent have been typically used in the United States. Figure 22 shows two forms of Sasobit, flakes and small prills or pellets. The flakes are used for molten addition and the prills can be blown into a plant. Figure 23 shows a pneumatic feeder used to meter Sasobit into a drum plant. The Sasobit is introduced into the mixing chamber at about the same point that the binder is introduced (or where fibers would be introduced).

Figure 22. Sasobit flakes (left) and prills (right).[37]

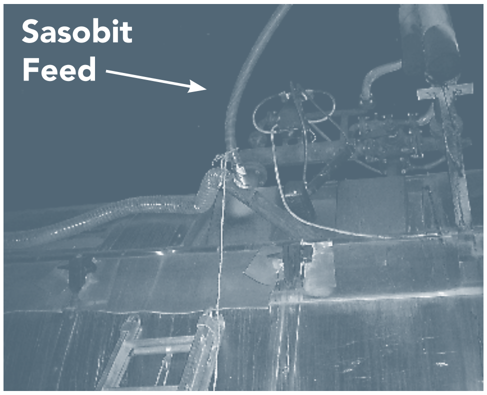


Figure 23. Sasobit pneumatic feed to mixing chamber.[37]

Since 1997, more than 142 projects totaling more than 10 million tons of mix have been paved using Sasobit. Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, Netherlands, New Zealand, Norway, Russia, Slovenia, South Africa, Sweden, Switzerland, the United Kingdom, and the United States. The projects included a wide range of aggregate types and mix types, including dense-graded mixes, stone matrix asphalt, and gussasphalt. Sasobit addition rates ranged from 0.8 to 4 percent by mass of binder.(36)

Montan Wax

No additional information was collected on Montan wax.

Fatty Acid Amide

Fatty acid amides have been used as a viscosity modifier in asphalt for a number of years. These products have been used in the roofing industry since the late 1970s to early 1980s. Fatty acid amides are available in various forms from a number of suppliers. Licomont BS 100 is one form commercially used in WMA in Germany. Sübit is a binder modified with fatty acid amides, and Asphaltan-B is a blend of Montan wax and fatty acid amides. The fatty acid amides used to modify asphalt come from the chemical family of N,N-Ethanol bistearin amides and have a low molecular weight.

Licomont BS 100 is available as a powder or in granular form. Figures 24 and 25 show Licomont BS 100 granules and a weigh hopper for introduction into a batch plant at the Wilhelm Schütz plant near Frankfurt, Germany.

3E-LT/Ecoflex

3E-LT is a proprietary process developed by Colas. No additional information is available.

Foaming Processes

Synthetic Zeolite

Zeolites are framework silicates with large empty spaces in their structures that allow the presence of large cations, such as sodium and calcium. They also allow the presence of large cation groups, such as water molecules. Most zeolites are characterized by their ability to lose and absorb water without damaging their crystal structure. Both naturally occurring and synthetic zeolites are available. Aspha-min® is a synthetic aluminosilicate of alkalimetals with the following chemical formula:(18)

$$M_{2}/_{z}O \bullet Al_2O_3 \bullet x\, SiO_2 \bullet y\, H_2O$$

As noted in the body of the report, Aspha-min contains about 20 percent water of crystallization, which is released at temperatures greater than 100 °C (212 °F). When mixed with hot aggregates or asphalt, the zeolite releases water, creating a very fine mist or water spray in the mixture. The water creates a controlled foaming effect that leads to a slight increase in binder volume, therefore reducing viscosity of the binder. Gradual release of water provides a 6- to 7-hour period of aided compaction.(13)

The Aspha-min distributed in the United States is about a 0.300-mm (No. 50 mesh) powder. Aspha-min should be added at about the same time the binder is added to the mix. It can be added to the pugmill of a batch plant manually or using a small weigh hopper (figure 26). In a drum plant, Aspha-min is blown into the mixing chamber at the same point fibers would be added using a pneumatic feeder (figure 27). Advera is another synthetic zeolite with about 100 percent passing the 0.075-mm sieve (No. 200). It can be added in the same manner as Aspha-min, although PQ Corporation is working on a method to blend it in-line with the binder.

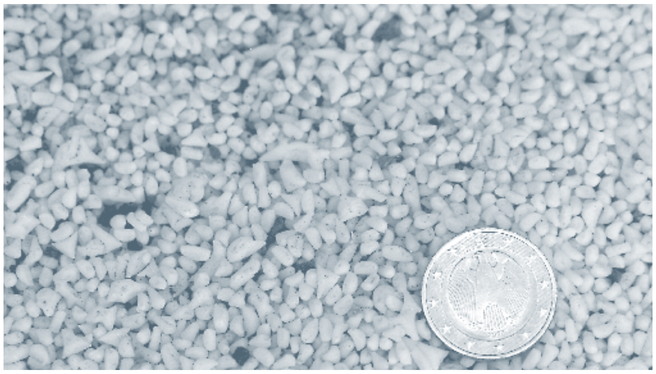


Figure 24. Licomont BS 100 granules.

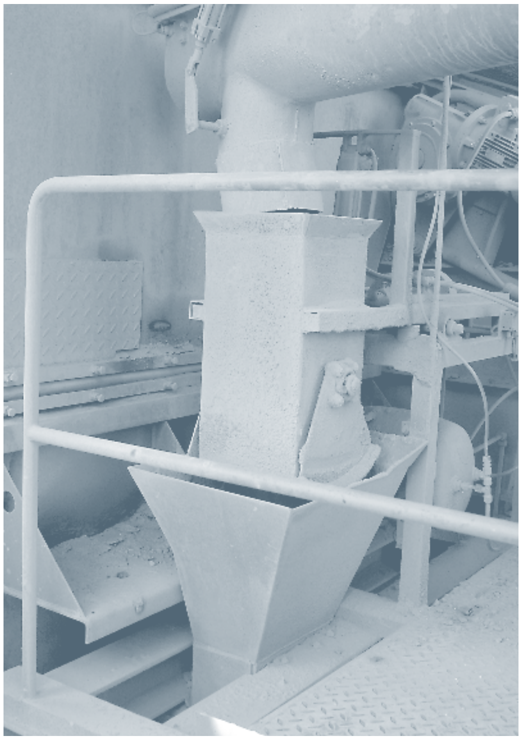


Figure 25. Batching hopper at W. Schütz batch plant in Germany.

Ecomac

Ecomac is a proprietary process developed by Colas. No additional information is available.

Low-Energy Asphalt

Two patented sequential mixing processes, enrobé à basse énergie (EBE) and enrobé basse température (EBT), were developed by Fairco and EIFFAGE Travaux Publics, respectively, to produce WMA. These two companies are cooperating in a joint venture, LEA-CO, to promote and market low-energy asphalt (LEA) in Europe, North America, and some other countries

In one variant of the LEA process, the coarse aggregate is dried and coated with hot asphalt, and then the wet sand is introduced into the mix. The moisture in the sand foams the asphalt, allowing the sand to be coated. The resulting mix temperature is less than 100 °C (212 °F). The process, shown graphically in figure 28, is as follows:[38]

1. The aggregate is split into two fractions: coarse aggregate and sand-size particles without fines, and sand-size particles with fines.

2. The coarse aggregate and sand-size particles without fines are dried and heated to a temperature of about 150 to 160 °C (302 to 320 °F) (about 20 C° (36 F°) cooler than for HMA).

3. The binder is heated to its normal mixing temperature, depending on the grade. Just before injection into the plant, a specially formulated additive is added to the binder using a volumetric pump (see figure 29 on next page) at a rate of about 0.5 percent by weight of binder. The additive is designed to regulate expansion of the foam and to act as an antistripping agent. The additive varies, depending on the aggregate type.

4. The hot, dry coarse aggregate is coated with all of the asphalt to be added to the mixture. The coarse aggregate and any sand-size particles without fines

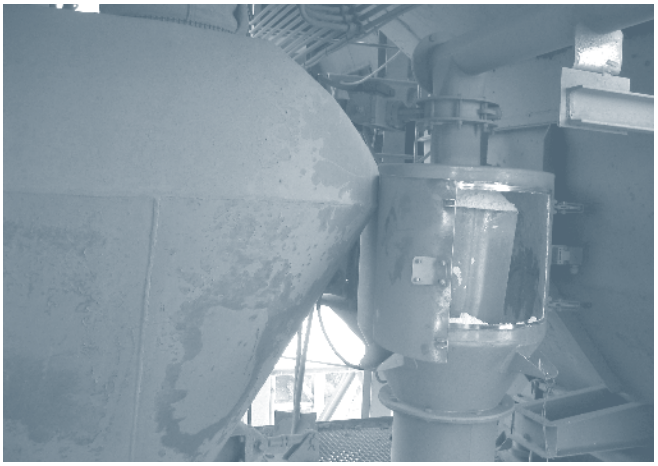


Figure 26. Batch hopper for batch plant.

Figure 27. Pneumatic feeder (right) for drum plant.[38]

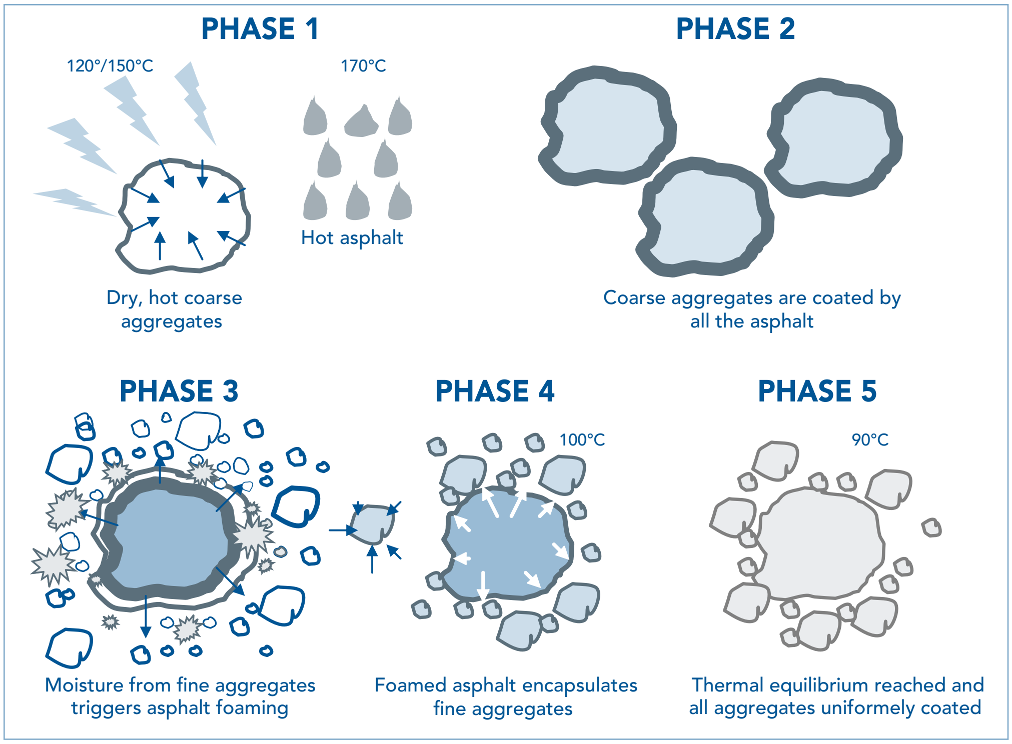


Figure 28. LEA process.[3]

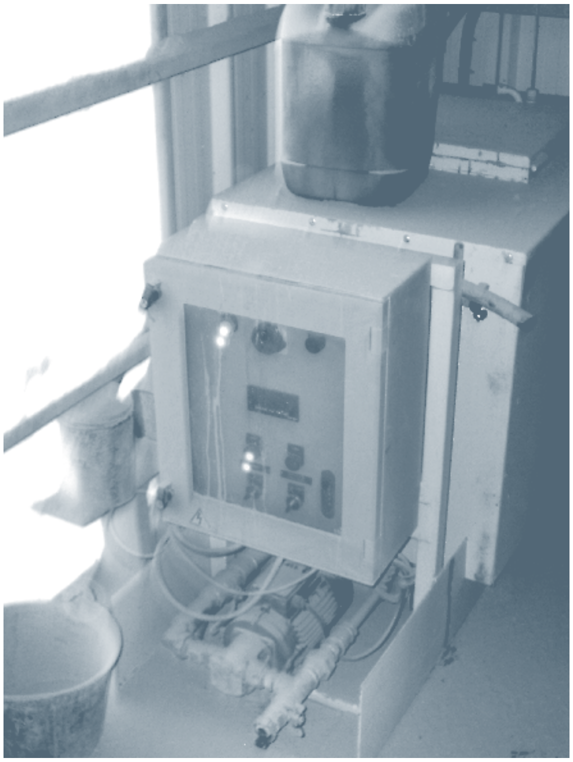


Figure 29. Volumetric pump for LEA additive at the EIFFAGE Travaux Publics batch plant in France.

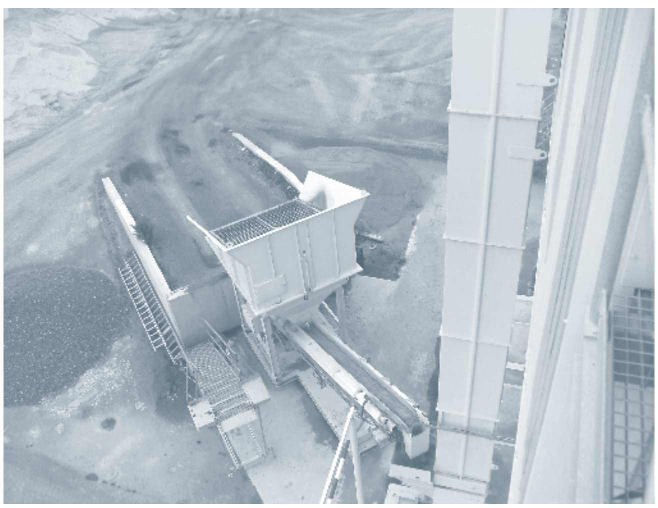


Figure 30. Separate cold-feed bin and elevator for addition of wet fines at the EIFFAGE Travaux Publics batch plant in France.

should make up about 60 percent of the mix.

5. The remaining 40 percent of the aggregate, consisting of wet sand and fines with about 3 percent moisture, is mixed with the coarse aggregate. In both a batch and a drum plant, the wet fine aggregate is added through a separate feed system. The cold-feed bin for a batch plant is shown in figure 30. A patented process pulls steam out of the pugmill. For a drum plant, the wet fine aggregate can be added through the RAP collar. If the fine aggregate is too dry, additional water can be added using a spray bar system. If the fine aggregate is too wet, a portion of the fine aggregate can be diverted to the dryer with the coarse aggregate.

6. When the hot, asphalt-coated coarse aggregate contacts the wet fine aggregate, the asphalt binder foams. This encapsulates the fine aggregate. The cold fine aggregate is heated by contact with the coarse aggregate. The resulting equilibrium mix temperature is less than 100 °C (212 °F).

7. Residual, recondensed moisture in the mix, present in fine droplets, helps to maintain workability, even at low temperatures.

LEAB®

The LEAB® process, which stands for low-energy asphalt concrete, was developed by BAM in the Netherlands. It is a commercialization of the half-warm foam mix research conducted by Kim Jenkins.(13) In laboratory trials, the aggregate was split into coarse and fine fractions, water was added to the aggregate to facilitate coating, and mixing was conducted in a two-stage process. This same process was attempted initially in the field, but failed. In the LEAB process, no additional water is added to the aggregates. The foaming of the binder takes place in a nozzle (figure 31). BAM uses a series of six nozzles to produce LEAB (figure 32, circled). The nozzles are retractable when HMA is being produced. An amine-based additive is added at 0.1 percent by weight of binder, immediately before foaming. The additive aids in the stability of the foam and improves adhesion. The

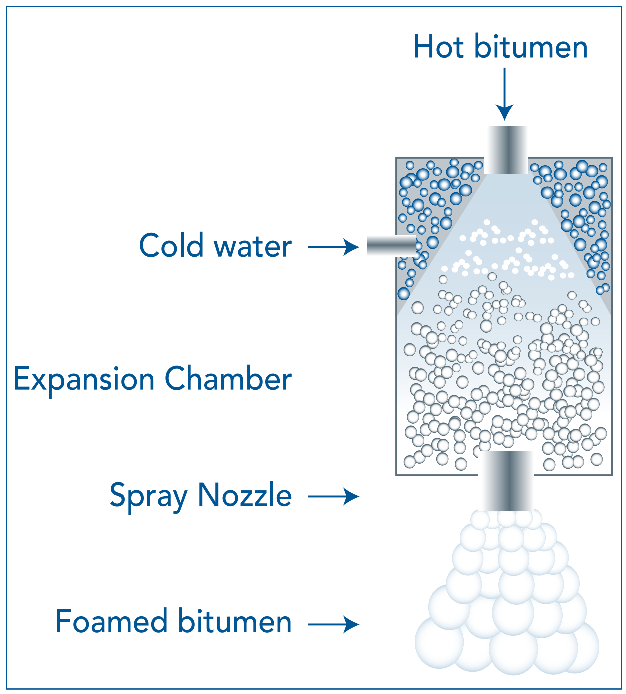


Figure 31. Schematic of foaming nozzle.(22)

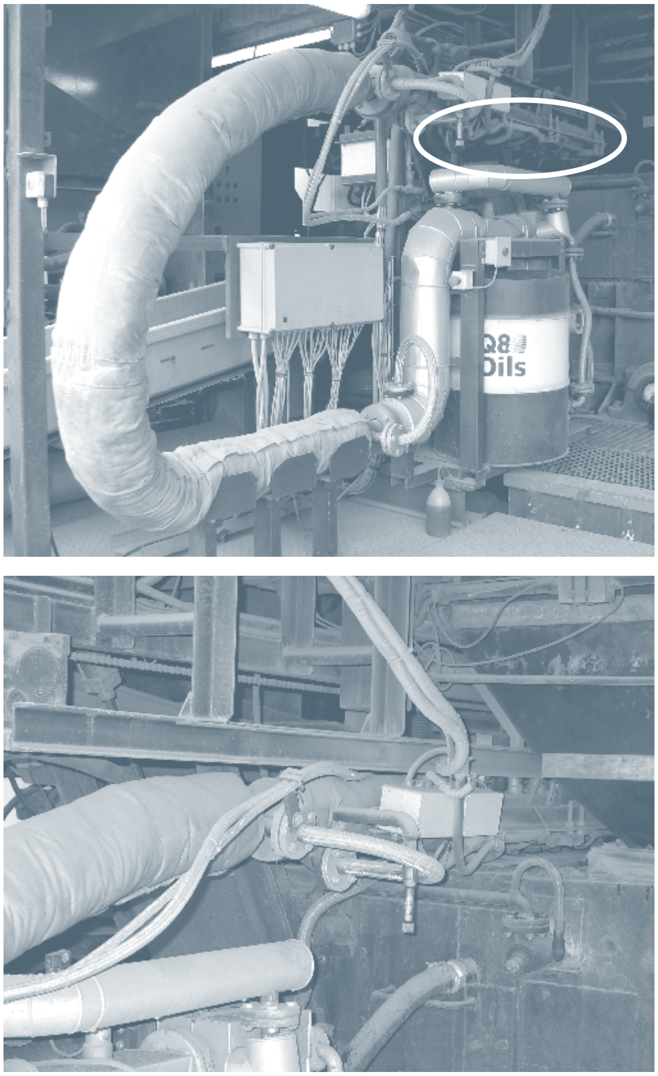


Figure 32. LEAB. The nozzles are retractable when HMA is being produced (top). The nozzle deployed over the pugmill (bottom).[22]

additive is similar to those used to produce emulsions and is believed to be fatty acid amine based.

Typically, 50 percent RAP is run in both WMA and HMA mixes in the Netherlands. BAM heats its RAP in a separate dryer drum to a temperature of 110 to 115 °C (230 to 239 °F).[22] Energy savings of 40 percent are reported with virgin mixes and 30 percent with mixes containing 50 percent RAP.

WAM-Foam

Shell Bitumen developed the warm-asphalt mix (WAM) concept of blending hard and soft binder components to reduce production temperature in 1996. Collaboration with Kolo-Veidekke in Norway led this work in a new direction by adding the hard bitumen component as foam. This led to the development of the WAM-Foam process, which is now patented and marketed worldwide (except in the United States) by Shell Bitumen. BP has patent rights for the technology in the United States.

WAM-Foam is a process, not an additive or material. It is reportedly a common practice in Norway for the contractor to maintain two asphalt binder grades, one nominally soft and one nominally hard. The contractor blends the soft and hard binders in-line to produce the desired binder grade. The soft binder has a viscosity grade of 1,500 centistokes (V1500); the hard binder is typically a 70/100 pen or about a PG 58/64-22.

The soft binder typically represents 20 to 30 percent of the total binder content. The resulting binder grade, assuming 20 percent of a V1500 and 80 percent of a 70/100 pen binder, would be a 70/100 pen binder, unaged. If the resultant binder grade needs to be altered, this should be done by varying the component binder grades because a minimum percentage of the soft binder is required to coat the coarse aggregate. Coating the coarse aggregate with the soft binder should also satisfy the demand of any asphalt absorption of the coarse aggregate that may not otherwise occur with a stiffer binder at low temperature. Antistripping agents could also be added to the soft binder.

Foaming of the hard binder is accomplished by adding ambient temperature water at a rate of 2 to 5 percent by mass of the hard bitumen fraction (about 1.6 pounds (726 grams) of water per ton of mix, assuming 5 percent total asphalt content, 80 percent of which is hard binder) to the hard binder at about 175 to 180 °C (347 to 356°F). The water expands by a factor of about 1,600 when it contacts the hot binder and turns to steam. This causes the resulting binder-water combination to expand by a factor of about 15 times its original volume.

Both batch plants and drum plants have been retrofitted to produce WAM-Foam. The aggregate, minus any added filler, is heated to 130 °C (266 °F). The aggregate is coated with about 20 percent of the total mass of binder in the form of the soft asphalt. The hard asphalt is foamed into the mix. The resulting mix temperature is between 100 and 120 °C (212 and 248 °F).

For a batch plant, the soft binder is added using the plant's existing asphalt line and asphalt weight bucket. A foaming nozzle with an expansion chamber is added above the pugmill. A separate asphalt line is added to the plant to supply the hard asphalt. A mass flow meter controls the rate of addition for the hard asphalt. Since a batch plant is not a continuous process, it is important to clean the nozzle and expansion chamber with compressed air after each introduction of foam. Figure 33 (see next page) shows the expansion chamber and controls for Kolo Veidekke's batch plant in Ås. To keep

Figure 33. Asphalt line, expansion chamber, controls, and transfer pipe for foaming hard asphalt.

the hard asphalt pumpable near the expansion chamber, a three-way valve may be required to recirculate the hard binder to the tank between batches.

Drum mix plants are easier to modify. Like batch plants, the original asphalt system handles the injection of the soft asphalt into the mix. A new asphalt line is needed to deliver the hard asphalt to the mixing area of the drum, along with a well-insulated water line to foam the asphalt. The new hard asphalt line does not extend as far inside the drum, allowing the soft material to fully coat the aggregate before the foamed hard asphalt is added. Because the foaming takes place continuously and the foaming nozzle and expansion chamber are well heated by the hot air stream inside the drum, there is no need for a compressed air line to keep them clean.

Emerging U.S. Technologies

Evotherm™

Evotherm™ is a chemical package designed to promote the adhesion, coating, compaction, and workability of asphalt mixtures at reduced temperatures. Different chemical packages are available for different aggregate types. The main difference between chemical packages is the adhesion agents. One component of the chemical package is a surfactant, which acts as an emulsifier. About 50 percent of the chemical package is derived from renewable resources. Evotherm allows a 50 to 75 °C (100 to 130 °F) reduction in production and placement temperatures compared to HMA.

Initially, the Evotherm chemical package was delivered in the form of an asphalt emulsion with a binder residue of about 70 percent. The emulsion is stored at a temperature of 80 °C (176 °F). The emulsion can be pumped directly off a tanker or be stored in a mobile nurse tank or a dedicated tank at the plant. The plant setting for the target asphalt content needs to be adjusted (increased) to account for the approximately 30 percent water in the emulsion. The majority of the water is liberated as steam during mixing. The resulting WMA is fully coated and black in color like HMA, unlike cold-emulsion mixes. Although the emulsion is still available, a new process, called dispersed asphalt technology (DAT), has been developed to directly inject the chemical package and a small amount of water into the asphalt line, just before it enters the mixing chamber. Figure 34 shows the volumetric pump used to control the DAT addition and figure 35 shows the injection point on an existing asphalt line. A major advantage of the DAT process is that it reduces shipping costs compared to the emulsion and allows the contractor to rapidly switch between HMA and WMA.

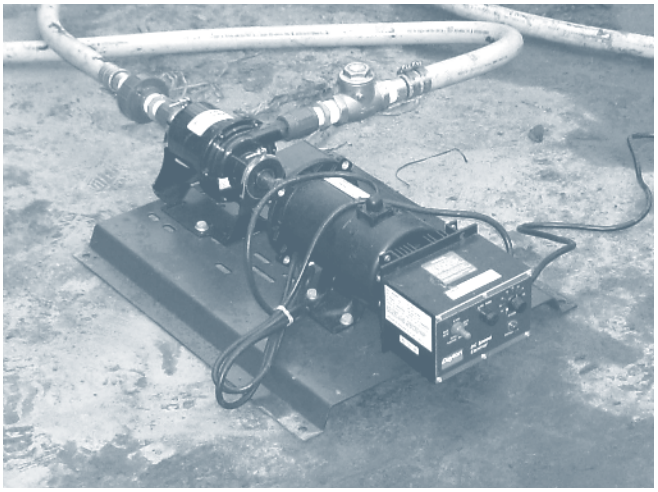


Figure 34. DAT volumetric pump.

Figure 35. DAT injection point.

Double-Barrel® Green

Astec Inc. developed a multinozzle foaming device designed to work with its Double Barrel® plants. The device consists of a series of valves, mixing chambers, and foam nozzles supplied by an asphalt manifold. The asphalt manifold is surrounded by a hot oil jacket. Each nozzle is designed to supply sufficient foam for mixing 50 tons per hour of WMA. A computer-controlled system adjusts the number of nozzles used based on the production rate. A positive displacement pump controls the water injection. The water pump speed is varied with the speed of the asphalt pump. About 1 lb (454 g) of cold water is introduced through the nozzles per ton of mix, causing the binder to expand about 18 times.(39) Typical production temperatures are 135 °C (275 °F), with the mixture being placed as low as 115 °C (240 °F). Testing conducted by Astec indicates that the production of volatile organic compounds can be significantly reduced if temperatures are kept below 141 °C (285 °F).(2) Although liquid antistripping agents can be added to the binder, no additive is required to produce the foam and consequently the WMA. Figure 36 shows a schematic of the Astec nozzle. Figure 37 shows the multinozzle foaming device.

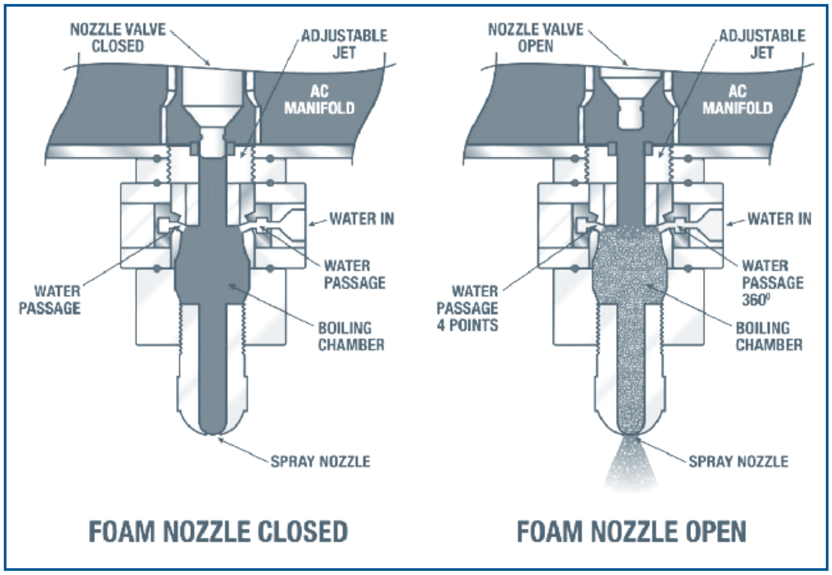


Figure 36. Schematic of Astec nozzle.(39)

Figure 37. Astec multinozzle foaming manifold.(40)

Appendix E: French Mix Design Procedure

Selection of components includes specifications for aggregate quality. Specifications for coarse aggregate include LA Abrasion, micro-Deval, and percentage of crushed faces. Methylene blue tests are specified for fine aggregate and fillers. A minimum fine aggregate angularity, based on a flow test, is specified for surface courses. A maximum rounded sand content of 10 percent is recommended for surface and binder courses. Rigden voids and ring and ball softening point tests (or change in softening point) are also specified for the filler. Binder grades are not specified in the French specifications. The LCPC *Design Manual* notes, "To better prevent against cracking risks under severe traffic and climatic loading conditions, it would be advised to select the softest grade compatible with rutting resistance-based requirements."[9] Penetration grades are recommended for the various mix types, based on traffic loading, but the designer may adjust to meet type testing requirements.

For a Level 1 design, a trial gradation is selected based on the mix designer's experience. A minimum richness modulus, essentially a film thickness, which in turn determines a minimum binder content, is specified for each mixture type. Samples are then prepared in the French gyratory compactor (figure 38) to assess the ability of the mix to be compacted in the field. The French specifications include a minimum void content at 10 gyrations and an acceptable void range at a specified number of gyrations (varies by mix type). It should be noted that the French gyratory compactor has a lower external and internal angle of gyration (1.00 and 0.82 degrees, respectively) than the Superpave gyratory compactor. The pressure used in the French gyratory is the same as that used in the Superpave gyratory compactor. Thus, the French gyratory provides less compaction than the Superpave gyratory for the same number of gyrations.

Level 2 designs add the large-scale wheel-tracking tester developed by LCPC to assess rutting potential. Samples are prepared at either 2 or 4 inches (5 or 10 centimeters) thick, depending on the intended lift thickness. The air void content varies by mix type and represents the anticipated in-place air voids. The samples are tested at 140 °F (60 °C) with a 1,124-lb (5-kN) vertical load, using a pneumatic tire inflated to 87 psi (6 bars). The load is applied at a frequency of 1 Hz.

The Level 3 design adds modulus and Level 4 adds fatigue testing. Modulus testing is conducted either on trapezoidal samples in two-point bending or on uniaxial tension-compression samples. Fatigue testing is conducted in two-point bending mode on trapezoidal samples at 50 °F (10 °C) and 25 Hz. Type test fatigue requirements are a minimum strain level that will provide a fatigue life of 1 million cycles.

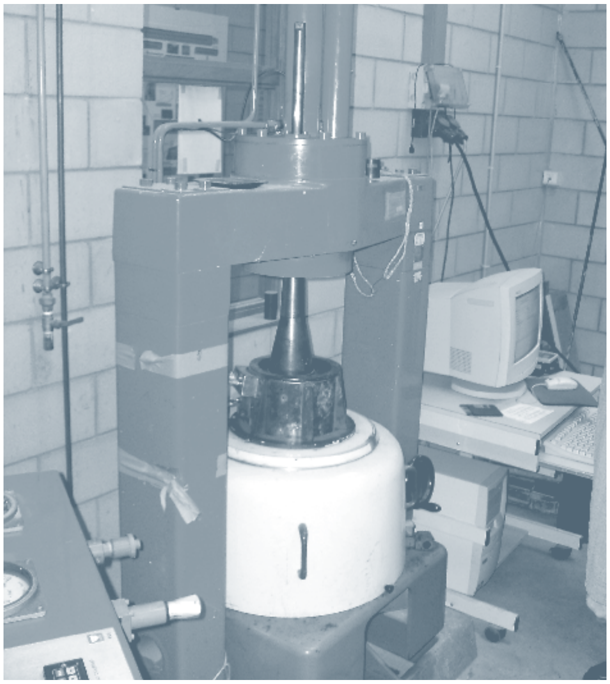


Figure 38. MLPC Type II gyratory compactor.

OFFICE OF INTERNATIONAL PROGRAMS

FHWA/US DOT (HPIP)
1200 New Jersey Ave., SE
Washington, DC 20590
Phone: (202) 366-9636
Fax: (202) 366-9626
international@fhwa.dot.gov
www.international.fhwa.dot.gov

Publication No. FHWA-PL-08-007
HPIP/2-08(3.5)EW