Evaluation of the Moisture Susceptibility of WMA Technologies

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 763

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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents proposed guidelines for identifying potential moisture susceptibility in warm mix asphalt (WMA) and proposed revisions to the Appendix to AASHTO R 35, "Special Mixture Design Considerations and Methods for WMA" to implement the guidelines. Thus, the report will be of immediate interest to materials engineers in state highway agencies and the asphalt pavement construction industry.

Over the past decade, the use of WMA for asphalt pavement construction has dramatically increased in the United States. WMA is seen as an alternative to hot mix asphalt (HMA), which offers the potential to lower energy demand during production and construction, reduce emissions at the plant and the paver, and increase allowable haul distances. However, questions remain about the long-term performance and durability of WMA pavements. One key issue is the moisture susceptibility of WMA pavements. Concerns about WMA moisture susceptibility include the possibility that aggregates will be inadequately dried at lower production temperatures and the fact that several WMA technologies introduce additional moisture in the production process.

The objectives of NCHRP Project 9-49 were to (1) assess whether WMA technologies adversely affect the moisture susceptibility of asphalt pavements and (2) develop guidelines for identifying and limiting moisture susceptibility in WMA pavements. The research was performed by the Texas A&M Transportation Institute, College Station, Texas.

The research was conducted through coordinated laboratory and field experiments that investigated the potential for moisture susceptibility in WMA compared to HMA. Design of the experiments was guided by a survey of the state DOTs and industry on WMA pavement construction and performance. The survey identified no instances of moisture damage to WMA pavements in service through 2010. This negative finding is supported by the results of recently completed NCHRP Project 9-47A, which conducted intensive evaluations of WMA pavements constructed across the United States between 2006 and 2011.

Project 9-49 then focused on development of guidelines for WMA mix design and quality control to identify and minimize any possibility of moisture susceptibility. The laboratory experiments evaluated (1) laboratory-conditioning protocols for WMA before moisture-susceptibility testing, (2) the ability of standard test methods to detect moisture susceptibility of WMA, and (3) potential differences in WMA moisture susceptibility measured on laboratory-mixed and -compacted specimens; plant-mixed, laboratory-compacted specimens; and plant-mixed, field-compacted cores.

The guidelines are presented in the form of a workflow of conditioning protocols and standard test methods that first assess the potential moisture susceptibility of a WMA mix design or field mixture and then recommend remedies to minimize such susceptibility.

Specific test thresholds in the guidelines are based on the results of testing of WMA from field projects in Iowa, Montana, New Mexico, and Texas.

This report fully documents the research and includes the following Appendixes:

- Appendix A. Laboratory Conditioning Experiment
- Appendix B. Moisture Conditioning Experiment
- Appendix C. Performance Evolution Experiment
- Appendix D. Construction Reports and Performance of Field Projects
- Appendix E. Mixture Volumetrics
- Appendix F. Proposed Draft Revisions to the Appendix to AASHTO R 35
- Appendix G. Future Work Plan to Evaluate Moisture Susceptibility of HMA and WMA
- Appendix H. Statistical Results

Appendix F is included herein. Appendixes A—E, G, and H are not provided herein but are available on the TRB website and can be found by searching for *NCHRP Report 763*.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

ABBREVIATIONS, ACRONYMS, AND INITIALISMS

AADT	Annual average daily traffic
AFM	Atomic force microscopy
ANOVA	Analysis of variance
APA	Asphalt pavement analyzer
ASTM	American Society for Testing and Materials
AV	Air voids
BBS	Bitumen Bond Strength
DSR	Dynamic shear rheometer
ESAL	Equivalent single axle loads
FM	Farm-to-market
F/T	Freeze-thaw
FT	Film thickness
HMA	Hot mix asphalt
HSD	Honestly Significant Differences
HWTT	Hamburg Wheel-Tracking Test
IDT	Indirect tensile
LAS	Liquid anti-stripping
LC_R	Remaining life
LEA	Low emission/energy asphalt
LMLC	Laboratory-mixed laboratory-compacted
LTOA	Long-term oven aging
LTPP	Long-term pavement performance
LVDT	Linear variable differential transducers
MIST	Moisture-Induced Stress Tester
NAPA	National Asphalt Paving Association
NCAT	National Center for Asphalt Technology
PG	Performance grade
PHT	Pavement Health Track
PMFC	Plant-mixed field-compacted
PMLC	Plant-mixed plant-compacted
QA	Quality assurance
QC	Quality control
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RDT	Repeated direct tension
RSL	Remaining Service Life
SFE	Surface Free Energy

SGC	Superpave gyratory compactor
SIP	Stripping inflection point
SMA	Stone matrix asphalt
SN	Stripping number
STOA	Short-term oven aging
TSR	Tensile strength ratio
TWG	Technical Working Group
TxDOT	Texas Department of Transportation
WMA	Warm mix asphalt

SUMMARY

Evaluation of the Moisture Susceptibility of WMA Technologies

Economic, environmental, and engineering benefits motivate the reduction of production and placement temperatures for the asphalt concrete paving materials used on most paved roads in the United States. The latest technology that has been rapidly adopted for this purpose is warm mix asphalt (WMA), which is defined as an asphalt concrete paving material produced and placed at temperatures approximately 50°F (28°C) cooler than those used for hot mix asphalt (HMA). WMA was first introduced in Europe in the mid-1990s as a way to reduce greenhouse gas emissions and then transferred to the United States in the early 2000s largely through the effort of the National Asphalt Paving Association (NAPA).

WMA technologies offer several benefits, including decreased energy consumption, reduced emissions and fumes at the plant, improved working conditions at the construction site as a result of reduced fumes and emissions, extended haul distances, longer pavement construction season and reduced construction days, improved workability and compactability, reduced aging, and better resistance to cracking and raveling. However, barriers to the widespread implementation of WMA include (1) the wide variety of WMA technologies and (2) the imprecise correlation between the laboratory and field performance of these technologies. The latter likely results from the lack of standard laboratory conditioning and aging protocols during mix design to better simulate early-life performance, where WMA may be more susceptible to rutting due to reduced aging and moisture susceptibility resulting from incomplete drying of aggregate and differences in aggregate absorption of binder.

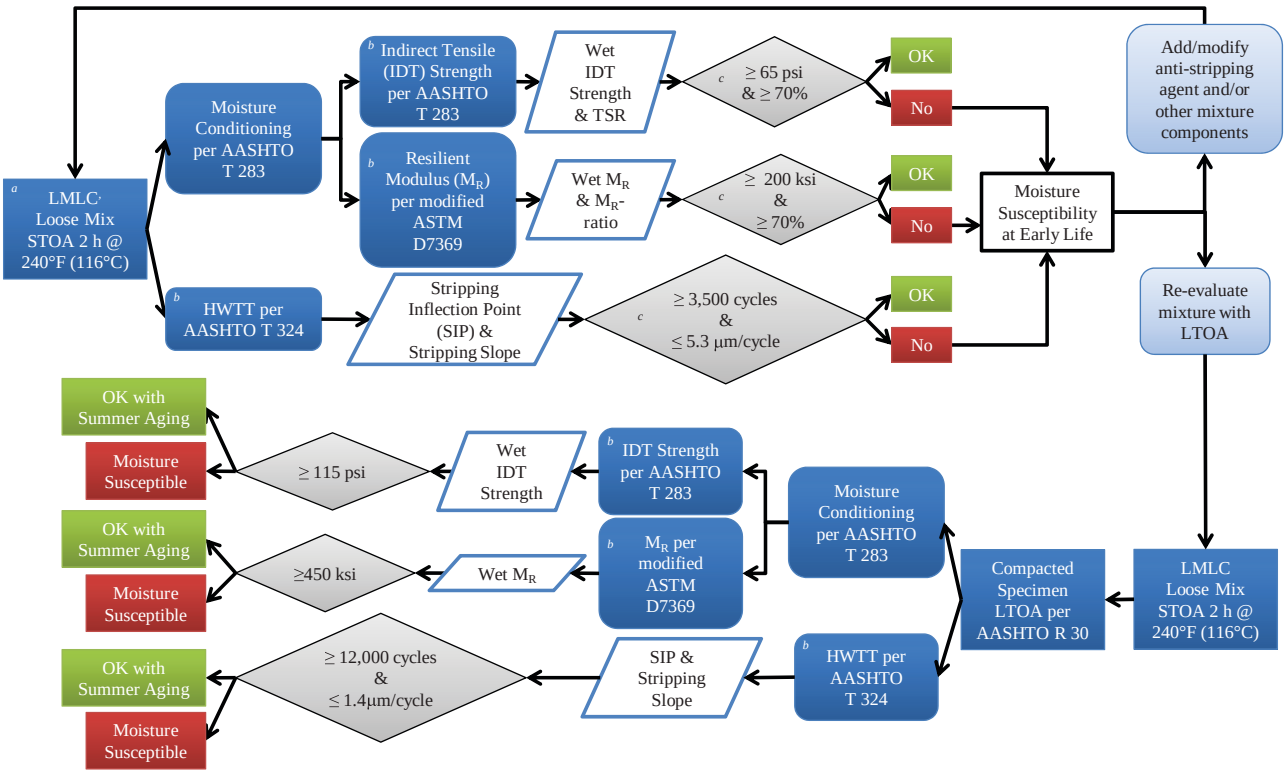
NCHRP Project 9-49 focused on the moisture susceptibility of WMA. Laboratory-mixed laboratory-compacted (LMLC) specimens, plant-mixed laboratory-compacted (PMLC) specimens, and plant-mixed field-compacted (PMFC) cores were evaluated to develop guidelines for identifying and limiting moisture susceptibility in WMA pavements. To meet these objectives, the research conducted in NCHRP Project 9-49 included the following:

- Identification and preliminary assessment of current WMA pavements with evidence of moisture susceptibility and a work plan for further investigation of these pavements.
- Evaluation of laboratory conditioning protocols for WMA prior to moisture-susceptibility testing to propose protocols for WMA and HMA.
- Evaluation of standard test methods to predict moisture susceptibility and ability of materials and methods to minimize this distress.
- Comparison of WMA moisture susceptibility for LMLC specimens, PMLC specimens, and PMFC cores.
- Evaluation of WMA pavements to identify possible reasons and evolution of performance with time.

The results of the experiments on WMA laboratory conditioning, WMA moisture susceptibility, and WMA performance evolution were used to produce the primary products from NCHRP Project 9-49. These products include (1) proposed guidelines for identifying and minimizing moisture susceptibility in WMA, (2) proposed revisions to the appendix of the AASHTO R 35 Special Mixture Design Considerations and Methods for WMA, and (3) a work plan for future research to continue the search for an effective laboratory test method and performance-related criteria for precluding moisture susceptibility in WMA.

The major conclusions from the research completed in NCHRP Project 9-49 are summarized in the figure below, which details the proposed laboratory conditioning and aging protocols and thresholds for three different standard laboratory tests used to assess moisture susceptibility of WMA. These thresholds were developed based on the field and laboratory performance of two of the four field projects used in NCHRP Project 9-49, and then they were verified based on the performance of the other two field projects. This flow chart was produced as a set of guidelines for mix design and quality assurance (QA), and state departments of transportation (DOTs) can modify it to suit their needs based on their experience.

The research conducted in NCHRP Project 9-49, based on a limited number of field projects, showed that the use of WMA that will not sustain a summer of aging prior to multiple freeze-thaw cycles or wet and cold days in the first winter should be approached with caution, especially in extreme climates for moisture susceptibility. The addition of anti-stripping agents compatible with the WMA technology and the component binder and aggregate materials will likely mitigate the potential for moisture susceptibility. Based on the field projects evaluated in this project, the use of either a relatively elevated high-temperature performance grade (PG) binder or a relatively low high-temperature PG binder



Note [a]: if WMA LMLC is not available, use trial batch prior to production for verification: onsite PMLC or offsite PMLC with minimal reheating
Note [b]: select a single test method and use it throughout the mix design verification
Note [c]: If trial batch offsite PMLC specimens are used, employ the following thresholds (TSR and M_R-ratio remain unchanged):
Wet IDT ≥ 100 psi, Wet M_R ≥ 300 ksi, SIP ≥ 6,000 cycles, stripping slope ≤ 2.0 µm/cycle

with reclaimed asphalt pavement (RAP) appears to provide adequate performance in terms of moisture susceptibility with or without an anti-stripping agent. WMA was also shown to improve in terms of moisture susceptibility measured in standard laboratory tests after either summer aging in the field or long-term oven aging (LTOA) in the laboratory that simulated this early-life field aging period.

Before being considered for adoption, the proposed revisions to the appendix to AASHTO R 35 are based on a limited number of field projects and should be used on a trial basis. This will provide additional data to refine the moisture susceptibility criteria and the laboratory-conditioning and aging protocols that capture the time when WMA is most susceptible to this type of distress. Data from additional field projects will provide increased confidence in the guidelines provided and possible revisions to the framework proposed in this report. In addition, further information will be gathered to resolve differences between generally adequate field performance and laboratory assessment that indicates potential for moisture susceptibility for some mixtures. Continued field performance monitoring of the limited number of field projects used in NCHRP Project 9-49 is also suggested so as to further improvement of the guidelines produced.

CHAPTER 1

Background

History and Definition

HMA is a well-established paving material with proven performance used on 94 percent of the more than 2.5 million mi (4.0 million km) of paved roads in the United States (FHWA 2008, NAPA 2010). HMA is produced by mixing asphalt binder and aggregate at an elevated temperature in either batch or drum mix plants and then placed by compacting the mixture at temperatures ranging from 275°F (135°C) to 325°F (163°C) (Kuennen 2004, Newcomb 2005a). These high production and placement temperatures are necessary to ensure complete drying of the aggregate, coating and bonding of the binder with the aggregate, and workability for adequate handling and compaction. All of these processes contribute substantially to good pavement performance in terms of durability and resistance to permanent deformation and cracking. Recent advances in asphalt technology (including polymer-modified binders and stiff HMA mixtures with angular aggregate that improve resistance to permanent deformation—such as stone matrix asphalt [SMA]) and an emphasis on compaction for QA and subsequent good performance have resulted in further increases in HMA mixing and compaction temperatures up to a limit of 350°F (177°C) where polymer breakdown in the binder can occur. These high temperatures are linked to increased emissions and fumes from HMA plants (Stroup-Gardiner et al. 2005). In addition, the HMA production process consumes considerable energy in drying the aggregate and heating all materials prior to mixing and compacting.

Economic, environmental, and engineering benefits motivate the reduction of production and placement temperatures for asphalt concrete paving materials. Past efforts to reduce placement and production temperatures date back to the late 1950s and include binder foaming processes (using either steam or water), asphalt emulsification, and incomplete aggregate drying (Kristjansdottir 2006, Zettler 2006).

The latest technology adopted to reduce placement and production temperatures of asphalt concrete paving materials is WMA. This technology was first introduced in Europe in the mid-1990s in order to reduce gas emissions. The technology was transferred to the United States in the early 2000s, largely through the efforts of the NAPA. WMA is defined as an asphalt concrete paving material produced and placed at temperatures approximately 50°F (28°C) cooler than those used for HMA. Several technologies satisfy this definition through different mechanisms and provide economic, environmental, and engineering benefits in terms of reduced viscosity of the binder, mixture, or both to allow for complete coating of the aggregate by the binder, sufficient adhesion between the aggregate and binder, and mixture compactability at lower temperatures. Widespread use of this technology and realization of its benefits requires production of WMA with similar performance and durability as HMA at substantially reduced production and placement temperatures (Button et al. 2007, Jones 2004, Prowell et al. 2011).

Benefits and Issues

WMA offers the following benefits (Button et al. 2007, Jones 2004, Koenders et al. 2002, McKenzie 2006, National Center for Asphalt Technology [NCAT] 2005, Newcomb 2005a, Newcomb 2005b):

- Short-Term Benefits:
  - Decreased energy consumption of 30 to 40 percent (Jenkins et al. 2002, Kuennen 2004).
  - Reduced emissions and odors at the plant (30 percent reduction in CO_2) (Kuennen 2004).
  - Reduced fumes and improved working conditions at the plant and construction site (fumes below detection limits and significant dust reduction) (Newcomb 2005a).
  - Decreased plant wear and costs.

  - Extended haul distances, a longer pavement construction season, and a longer construction day than if produced at typical HMA temperatures (Kristjansdottir 2006, NCAT 2005).
  - Reduced construction time for pavements with multiple lifts (Kuennen 2004).
  - Improved workability and compactability.
  - Reduced initial costs (in some cases).
- Long-Term Benefits:
  - Reduced aging and subsequent susceptibility to cracking and raveling.
  - Decreased lifecycle costs.

Although WMA technology is successfully used in other countries, where the environmental benefits and high energy costs motivate implementation, many questions remain as it is adopted in the United States, where, in addition to the reduced emissions and lower energy demand benefits, reduced plant wear and associated costs, extended haul distances, and a longer pavement construction season and construction day provide additional driving forces (Barthel et al. 2004, Cervarich 2003, Kuennen 2004, McKenzie 2006). Some technologies result in an increase in initial costs ($3 to $4 per ton premium). However, these costs have decreased (to $0 to $3 per ton premium) as demand has increased and additional equipment required for some WMA technologies has become readily available. Other barriers to implementation include the following specific performance and mix design issues (Kuennen 2004, NCAT 2005, Newcomb 2005a, Rand 2008):

- Short-Term Issues:
  - Conditioning/curing in the laboratory and field prior to compacting specimens.
  - Compaction in the laboratory (including mixing and compaction temperatures) and field.
  - Coating of aggregates with binder (some WMA technologies).
  - Mix design (including selection of binder grade and optimum binder content with or without additives).
  - Possible increased susceptibility to permanent deformation due to reduced aging.
- Long-Term Issue:
  - Possible increased moisture susceptibility due to incomplete drying of aggregate and differences in aggregate absorption of binder.

In summary, although there has been a surge in WMA research and implementation in the United States, the effect of WMA technologies on mixture performance is still being evaluated.

Project Objectives and Scope

NCHRP has committed funding for the following six research projects to address the major remaining issues associated with WMA:

- Mix design (NCHRP Project 9-43—Mix Design Practices for WMA).
- Overall mixture performance, engineering properties, and emissions (NCHRP Project 9-47A—Properties and Performance of WMA Technologies).
- Moisture susceptibility (NCHRP Project 9-49—Performance of WMA Technologies: Stage I—Moisture Susceptibility).
- Overall long-term field performance (NCHRP Project 9-49A—Performance of WMA Technologies: Stage II—Long-Term Field Performance).
- Laboratory specimen preparation for mix design and performance testing (NCHRP Project 9-52—Short-Term Laboratory Conditioning of Asphalt Mixtures).
- Foaming properties of binders and laboratory specimen preparation (NCHRP Project 9-53—Properties of Foamed Asphalt for Warm Mix Asphalt Applications).

NCHRP Project 9-43 is now complete, and the final *NCHRP Reports 691* (Bonaquist 2011a) and *714* (Advanced Asphalt Technologies, LLC 2012) document the results that include laboratory specimen fabrication procedures specific to each WMA technology type and volumetric mix design procedures with selection of optimum binder content at 4 percent air voids (AV). The mixture design is also evaluated based on workability, compactability with new initial numbers of gyrations, aggregate coating, moisture susceptibility in terms of tensile strength ratio (TSR) as defined in AASHTO M 323 with AASHTO T 283 testing, and stability in terms of flow number as defined in AASHTO TP 79. The interim report for NCHRP Project 9-47A is available, and the extensive field experiment to establish relationships between engineering properties of WMA binders and mixtures and corresponding field performance is ongoing. NCHRP Project 9-49A began in spring 2011, and NCHRP Projects 9-52 and 9-53 began in summer 2012. In addition to these WMA projects, NCHRP is also sponsoring NCHRP Project 9-48—Field Versus Laboratory Volumetrics and Mechanical Properties, where different specimen types are being evaluated, including laboratory-mixed laboratory-compacted (LMLC) specimens, PMLC specimens, and PMFC cores. The interim report for NCHRP Project 9-48 is also available (Mohammad and Elseifi 2010).

Information and data between this NCHRP Project 9-49 and these related NCHRP projects were shared through NCHRP quarterly reports and other communication in terms of (1) mix design and specimen fabrication protocols, (2) relationships

between laboratory tests and field performance, and (3) evaluation of the differences in volumetric and mechanical properties measured on different specimen types. Further coordination was facilitated by an invited national workshop in May 2011 and the subsequent *NCHRP Research Results Digest 370: Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Studies* (Harrigan 2012b).

NCHRP Project 9-49 focused on the moisture susceptibility of WMA. LMLC specimens, PMLC specimens, and PMFC cores were evaluated to develop guidelines for identifying and limiting moisture susceptibility in WMA pavements. To meet these objectives, this project designed and completed WMA laboratory conditioning, WMA moisture susceptibility, and WMA performance evolution experiments, as described in Chapter 2, which resulted in a series of technical reports that documented the following:

- Identification and preliminary assessment of current WMA pavements with evidence of moisture susceptibility (as available) and a work plan for further investigation of these pavements (available as an interim report).
- Evaluation of conditioning protocols for WMA prior to moisture susceptibility testing to propose protocols for WMA and HMA (available as an interim report with results available in Appendix A).
- Evaluation of standard test methods to predict moisture susceptibility and ability of materials and methods to minimize this distress (available as an interim report with results available in Appendix B).
- Comparison of WMA moisture susceptibility for LMLC specimens, PMLC specimens, and PMFC cores (available as part of an interim report with results available in Appendix B).
- Evaluation of WMA pavements to identify possible reasons and evolution of performance with time (available as an interim report with results available in Appendix C).

These technical reports are documented in this final project report and its appendices, along with the following:

- Proposed guidelines for identifying and minimizing moisture susceptibility in WMA.
- A work plan for a future research project to search further for an effective laboratory test method and performance-related criteria for precluding moisture susceptibility in WMA.
- Proposed revisions to the appendix of AASHTO R 35.

Relevant Literature and Survey Results

Despite the attractive economic, environmental, and safety advantages of WMA, several changes in the production process as compared to HMA have raised concerns regarding the long-term performance of WMA pavements. Bonaquist (2011b), who evaluated mix design practices for WMA through laboratory and field study, indicated that the effect of WMA processes on moisture susceptibility is mixture and process specific. He pointed out that different WMA processes have different effects on moisture susceptibility and that most of them provide the mixture with less resistance to moisture damage, although some processes, such as low emission/energy asphalt (LEA), may be beneficial in terms of moisture susceptibility. Thus, moisture susceptibility of WMA mixtures should be evaluated comprehensively.

To meet the objectives of this project, the WMA laboratory conditioning, WMA moisture susceptibility, and WMA performance evolution experiments, described in Chapter 2, were designed and completed. Literature relevant to these three experiments is summarized in this section, including a discussion of factors that could increase the moisture susceptibility of WMA, with additional discussion in Appendices A, B, and C. A summary of the national survey conducted at the beginning of this project is also provided.

WMA Laboratory Conditioning

To simulate the binder absorption and aging that occurs during construction, the standard practice for laboratory mix design of asphalt concrete paving materials is to conduct short-term oven aging (STOA) or condition the loose mix prior to compaction for a specified time at a specific temperature. For HMA, the proposed procedure when preparing samples for performance testing is 4 h at 275°F (135°C); for mix design, when aggregate absorption is less than 4 percent, the conditioning time can be reduced to 2 h (AASHTO R 30). In the past few years, several studies were conducted to evaluate the effect of different conditioning protocols on WMA mixture properties. These studies are summarized in Table 1-1.

In general, most studies performed to understand the effect of conditioning prior to compaction on the performance of WMA have concluded that an increase in laboratory conditioning temperature, time, or both may reduce the difference in performance between WMA and HMA. However, no standard conditioning protocol for WMA has been established to date.

WMA Moisture Susceptibility

Several factors are related to the lower production temperature of the WMA and the use of certain foaming and additive technologies that could increase the moisture susceptibility of WMA. These factors include

- Introduction of additional moisture with the WMA technologies that introduce water to produce a foamed binder.
- Use of wet or damp aggregates in the production process.

Table 1-1. Previous research on WMA laboratory conditioning.

Authors	Year	Conditioning Protocols	Laboratory Tests	Conclusions
Al-Qadi et al.	2010	Reheat to Tc for offsite PMLC	E*, Flow Number HWTT IDT Creep and Strength Semi-Circular Bending	- Increased stiffness, strength, and rutting resistance with loose mix reheating - Reheating is sensitive to temperature - Effect of reheating: HM A > WMAs
Bonaquist	2011a	2 h @ Tc (W)	Volumetrics IDT Strength	- Equivalent G_{mm} and dry IDT strength of WMA LMLC with 2 h @ Tc and PMFC cores
Clements	2011	0.5, 2, 4, and 8 h @ 240°F (W) and @ 275°F (H)	Flow Number Disc-Shaped Compact Tension	- Mixture properties: WMA = HMA for each conditioning time
Clements et al.	2012	0.5, 2, 4, and 8 h @ 240°F (W) and @ 275°F (H)	E* Flow Number HWTT Disc-Shaped Compact Tension	- Lower stiffness and resistance to rutting of WMA vs. HMA - Better fracture performance of WMA vs. HMA at 28°F test temperature - Increased stiffness and rutting resistance of WMA and HMA with increased conditioning
Estakhri et al.	2010	2 h @ 220°F (W) 2 h @ 250°F (H) 2 h @ 275°F (H & W) 4 h @ 275°F (H & W)	HWTT	- Increased performance with higher temperature and longer time - Equivalent performance of different WMAs conditioned at 220°F - 4 h @ 275°F is proposed for WMA
Estakhri	2012	2 h @ 275°F (W) 2 h @ Tc-HMA (H & W)	HWTT Overlay	- Increased resistance to rutting for WMA with higher temperature and longer time - Overlay results are sensitive to curing time and temperature - Significant decreased cracking resistance with curing time increased from 2 to 4 h
Jones et al.	2011	No conditioning (H & W) 4 h @ Tc (H & W)	HWTT Full-Scale Accelerated Load Test	- Equivalent resistance to rutting of WMA and HMA after 4 h @ Tc - Resistance to rutting, without conditioning: WMA < HMA

Note: W: WMA; H: HMA; HWTT: Hamburg Wheel-Tracking Test; IDT: Indirect Tensile.

- Reduced binder absorption by the aggregates at lower production temperatures.
- Reduced binder-aggregate coating and bond strength in the presence of certain WMA additives.

Only the first factor has not been addressed extensively in previous research. Table 1-2 summarizes selected research studies on the remaining factors. From the performance evaluation of various WMA technologies, the conclusion of several laboratory studies is that WMA has increased moisture susceptibility as compared to HMA, with mixed conclusions with regard to rutting of WMA as compared to HMA.

WMA Performance Evolution

Results from the laboratory conditioning experiment indicated that the initial stiffness of WMA is less than the stiffness of conventional HMA but that this gap may be reduced over time in the field. In the past few years, several studies were

Table 1-2. Previous research on WMA moisture susceptibility.

Authors	Year	WMA Technologies	Topic	Laboratory Tests	Conclusions
Bennert et al.	2011	Evotherm 3G Sasobit Rediset	Aggregate Moisture Content	Overlay Tester	Fatigue resistance decreased when moisture content increased and decreased as production temperature increased 10°F (5.6°C).
Gong et al.	2012	Sasobit		Resilient Modulus (M_R), Creep Compliance, IDT Strength, Calculated Energy Ratio	Moisture susceptibility is aggravated for mixtures that contained incompletely dried aggregates.
Hurley and Prowell	2006	Aspha-min Sasobit Evotherm		IDT Strength	The use of moist aggregates decreased the IDT strength in all cases versus the HMA control.
Xiao et al.	2009	Aspha-min Sasobit		IDT and TSR	Different WMA technologies do not alter IDT strength values significantly. TSR decreased with increase in aggregates moisture content.
Austerman et al.	2009	Advera Sasobit	Moisture Susceptibility and Rutting Potential	HWTT	WMAs are more moisture susceptible than HMAs. Advera is more susceptible than Sasobit.
Hurley and Prowell	2006	Aspha-min Sasobit			Aspha-min: less rutting resistant than HMA; lime improves rutting resistance. Sasobit: anti-stripping agent improves rutting resistance; improved rutting resistance with limestone but not with granite aggregate.
Mogawer et al.	2012	Sonne Warmix			Use of RAP or polymer-modified binder may improve moisture susceptibility and rutting.

Table 1-2. (Continued).

Authors	Year	WMA Technologies	Topic	Laboratory Tests	Conclusions
Hearon and Diefenderfer	2008	Sasobit	Moisture Susceptibility	IDT Strength and TSR	Improved TSR after long-term aging of the mixtures. TSR improved with higher mixing temp. TSR > 80% in all cases where anti-stripping additives were used.
Hurley and Prowell	2006	Aspha-min Sasobit			All WMA TSR below 0.8 threshold (no anti-stripping agent). Improved IDT and TSR at higher short-term aging temperature. Aspha-min: lime improves TSR. Sasobit: anti-stripping agent improves TSR.
Prowell et al.	2007	Aspha-min Evotherm Sasobit			Aspha-min: shows TSR below 0.8. Sasobit and Evotherm: results depend on aggregate type. Sasobit: increased TSR with limestone. Evotherm: increased TSR with granite.
Alavi et al.	2012	Synthetic Zeolite Surfactants Viscosity Reducers	Bond Strength	Bitumen Bond Strength (BBS) and Dynamic Modulus Ratio	BBS, production at reduced temperatures has the potential to increase moisture susceptibility. Optimize WMA additive/aggregate type combinations for better results in term of moisture resistance, proposed BBS ratio 0.70.
Estakhri et al.	2010	Evotherm		Surface Free Energy (SFE) and	Decreased binder-aggregate bonding with inclusion of WMA

(continued on next page)

Table 1-2. (Continued).

Authors	Year	WMA Technologies	Topic	Laboratory Tests	Conclusions
		Sasobit Rediset		Work of Adhesion	additives. In presence of water, negative work of adhesion meaning de-bonding between materials is likely to occur.
Nazzal and Qtaish	2013	Advera Evotherm M1 Sasobit Foaming		Adhesive and Cohesive Bond from Atomic Force Microscopy (AFM)	For unconditioned samples, all WMAs increase in adhesive bond as compared to HMA. After AASHTO T 283, Evotherm performs better than other WMA and equivalent to HMA.
Wasiuddin et al.	2008	Aspha-min Sasobit		SFE	Aspha-min shows no significant effect on SFE and no improvement in wettability. It shows increased adhesion for PG 70-28 but no effect for PG 64-22. Sasobit shows increased wettability, decrease in dry cohesive strength and binder-aggregate adhesive bond. It reduced total SFE of the binder.

conducted to quantify the evolution of WMA performance-related properties with time in an effort to understand the difference between HMA and WMA and, more importantly, when (or if) the properties of the two types of mixtures converge. This is particularly significant when evaluating moisture susceptibility, which can occur early in the life of the pavement or after several years in service, depending on environmental and loading conditions. These studies are summarized in Table 1-3. In general, most of these studies performed to understand the effect of long-term oven aging (LTOA) on the performance of asphalt mixtures have concluded that LTOA can significantly increase mixture stiffness. In addition, reasonable correlations between laboratory LTOA and field aging have been proposed based on laboratory test results.

Summary of National Survey and Interviews

A web-based survey of state DOTs was conducted at the beginning of the project to (1) document the performance of existing WMA pavements with an emphasis on moisture susceptibility and (2) identify candidate pavements for inclusion in the work plan. Follow-up phone interviews were conducted with state DOTs that indicated availability of information regarding the performance of previously placed WMA pavements, upcoming construction projects, and willingness to participate in the project. Assistance in identifying candidate pavements was also sought from WMA industry groups, including contractors, equipment manufacturers, and additive suppliers. The list of agency representatives and contact information was compiled with input from the NCHRP panel, NCAT, the internal and external advisory groups, the FHWA WMA Technical Working Group (TWG), and the RAP Expert Task Group. This section summarizes the information gathered as a result of the web-based survey and phone interviews.

The detailed survey, interview questionnaires, and responses are documented and available as an interim report.

State DOT Web-Based Survey

To identify WMA pavements with evidence of distress, a brief web-based survey was conducted among the state DOTs. The following information was requested:

- Current use of WMA.
- Quantity of WMA placed.
- WMA use requirements.
- Types of WMA technologies.
- Use of anti-strip additives.
- Moisture susceptibility tests in WMA design practice.
- WMA pavements failure or distress.

Table 1-3. Previous research on WMA performance evolution.

Authors	Year	Aging Stages	Laboratory Tests	Conclusions
Bell et al.	1994	LTOAs (4 days at 212°F and 8 days at 185°F)	M_R	- LTOA on stiffness: 8 days at 85°C = 4 days at 100°C - Equivalent aging: lab 8 days at 85°C; lab 4 days at 100°C; 9-year field aging
Brown and Scholz	2000	LTOA (120 h at 185°F)	IDT Modulus	- Increased mixture stiffness with LTOA
Bueche and Dumont	2011	Long-Term Aging (0, 1, 2, 4, and 12 weeks at room temp)	HWTT IDT Strength	- No effect on mixture resistance to moisture susceptibility
Diefenderfer and Hearon	2008	LTOAs (4 and 8 days at 185°F)	IDT Strength	- Improved TSR of mixtures produced at 110°C and 130°C - Insignificant effect on TSR of mixtures produced at 150°C - Improved moisture resistance of WMA with LTOAs
Estakhri et al.	2009	Field Aging	HWTT Dry IDT Strength	- Initial stiffness: WMA < HMA - Increased stiffness with field aging - HWTT results for 1-year PMFC cores: WMA = HMA - IDT strengths for WMA: 1-month PMFC core > offsite PMLC - IDT strengths for HMA: 1-year PMFC core = 1-month PMFC core = offsite PMLC
Estakhri	2012	Field Aging	HWTT Overlay Dry IDT Strength	- Comparable performance of WMA and HMA - HWTT, Overlay, IDT Strength results: WMA 1-year PMFC core > PMFC at construction - No effect on WMA cracking resistance after 1 year in service
Mogawer et al.	2010	LTOA (16 h at 140°F)	HWTT	- Improved performance in HWTT with LTOA - Increased stiffness with LTOA
Xiao et al.	2011	LTOA (5 days at 185°F)	Dry/Wet IDT Strength	- Insignificant effect on dry IDT strength - Increased wet IDT strength with LTOA - Improved moisture susceptibility of WMA with LTOA

- Availability of technical data.
- Upcoming WMA pavements.
- Availability to further participate in NCHRP 9-49 research activities.

The web-based survey was launched in November 2010 with an invitation e-mail containing a brief description of the objectives of the project and the purpose of the survey. The invitation was sent to DOT representatives from all 50 states in addition to the District of Columbia and Puerto Rico. Thirty-five agencies responded to the survey (i.e., a 67 percent response rate).

In general, more than half of the responding state DOTs (i.e., 54 percent) indicated current use of WMA in trial projects, approximately 40 percent routinely used WMA, and only 6 percent had no experience with WMA. Figure 1-1 shows the distribution of WMA use in the United States based on the responses. In addition, 44 percent of the respondents indicated past or planned use of WMA in 2-5 projects, 21 percent in between 5-10 projects, and 23 percent in more than 10 projects (i.e., routine use). Also, most of the responding state DOTs (i.e., 73 percent) allow the use of WMA as an option; of these, 6 percent require it, 6 percent allow it as a separate bid item, and 12 percent do not allow its use.

With regard to specific WMA technologies, the survey results showed that the preferred types, which accounted for 70 percent of the responses, included Advera® WMA (including former Aspha-min® product), Astec DBG®, Aquablack™, EvothermDAT™, Sasobit®, and Terex®. About 48 percent of the respondents required the use of anti-stripping agents in WMA due to the use of moisture-susceptible aggregates, results of moisture-susceptibility tests, or both.

Concerning moisture-susceptibility testing, 76 percent of the responding state DOTs indicated that their agency specifications included related criteria as part of the HMA or WMA design procedure. The TSR of AASHTO T 283 is the moisture-susceptibility test preferred by 68 percent of the state DOTs. The next preferred test is the HWTT (AASHTO T 324), with 19 percent of the responses. Others tests, such as the Asphalt Pavement Analyzer (APA) (AASHTO TP 63) and the Immersion-Compression Test (AASHTO T 165), accounted for only 10 percent of the responses. Finally, all of the state DOTs indicated that their WMA pavements had not experienced failure or distress from moisture damage.

State DOT Follow-Up Phone Interviews

Based on the knowledge acquired through the web-based survey and input from the internal and external advisory groups, 15 state DOTs were identified as candidates for follow-up phone interviews. These states were selected because of their prior experience with WMA technologies via trial or routine projects, existence of WMA pavements planned dur-

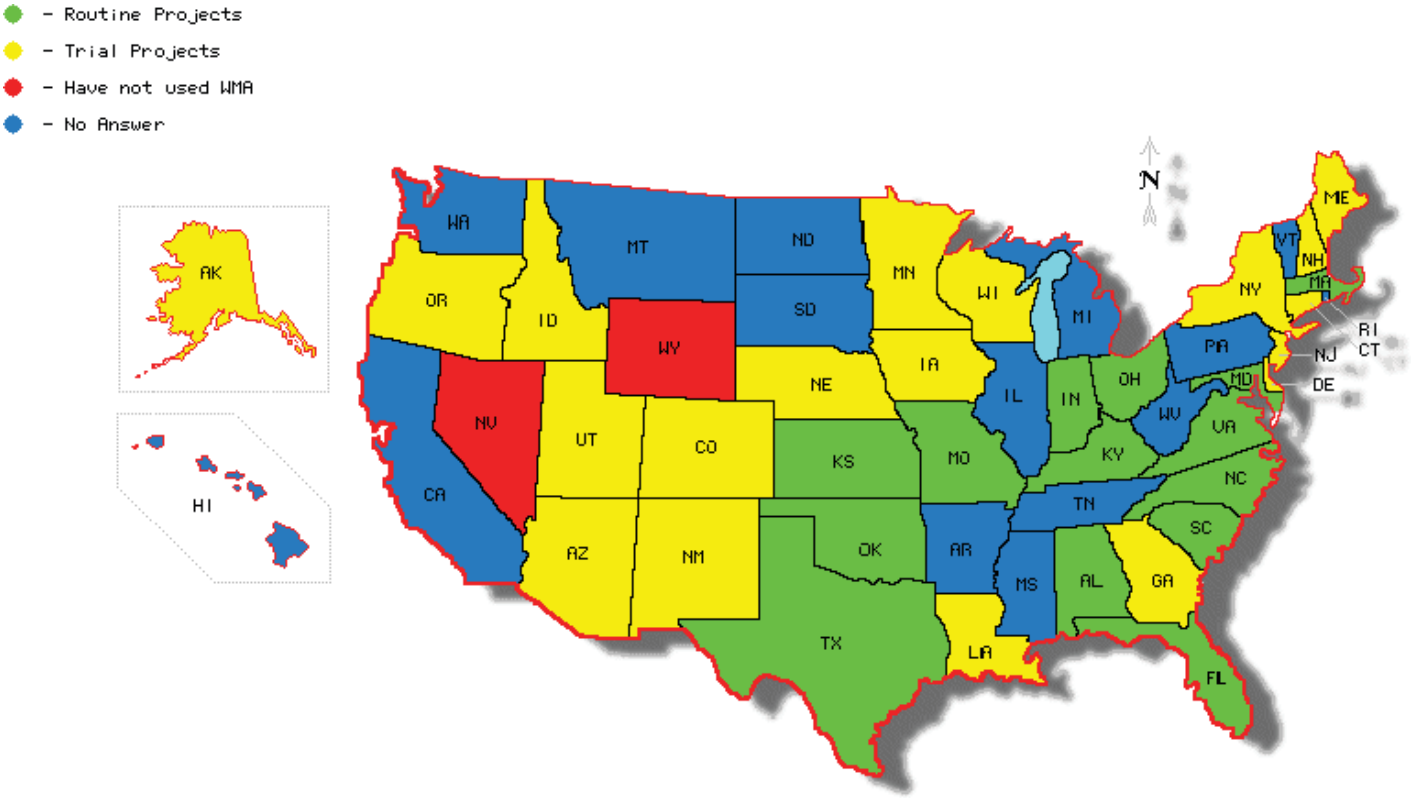


Figure 1-1. WMA use in the United States.

ing the 2011 construction season, and willingness to participate in the NCHRP 9-49 research efforts.

The state DOTs were asked to identify past pavements as part of their responses to the follow-up interview questions. The questions addressed pavement location, structure, traffic level, environmental conditions, type of materials and WMA technologies used, laboratory tests performed, construction procedures, QA measures, pavement performance, planned maintenance and rehabilitation, and WMA quantity and cost. Ten state DOTs were available to complete the follow-up phone interview. Some of these DOTs proposed contacting researchers in charge of studying various performance aspects of the WMA pavements in their respective states. Six researchers were interviewed to complement the answers of the state DOTs. The responses of state DOTs and researchers are summarized next, and the summary is organized by questionnaire topics.

Materials and WMA Technology. The technologies most commonly used in the selected WMA pavements, which were built between 2006 and 2010, were Evotherm™, free water foaming systems, and Sasobit®. The most common aggregate type used in these WMA pavements was limestone with minor use of other materials (e.g., gravel, quartzite, dolomite, and basalt). The quartzite and specific sources of limestone in some states were classified as moisture susceptible. The predominant mixture type used was a 12.5 mm Superpave dense-graded mixture. The types of binders used were all performance graded, including PG 58-28, PG 64-34, PG 64-28, PG 64-22, PG 70-22, PG 76-22, and PG 76-16.

The use of anti-stripping additives was mandatory for three agencies, three agencies did not require it, and the others prescribed use only when employing aggregates prone to stripping or mixtures prone to moisture damage based on moisture-susceptibility test results. With regard to material availability, all the state DOTs indicated that virgin materials (i.e., binder, aggregates, and additives) from past WMA pavements were not available; a few state DOTs had plant loose mix or cores.

Mixture Design and Location. All selected pavements were built during dry and mild to hot weather, except for one done after a heavy rain. Regarding WMA mix design practices, only one state DOT used separate HMA and WMA mix design specifications; the rest of the agencies stated that they followed the Superpave volumetric criteria used for HMA when designing WMA. Thus, the WMA design was done following HMA practices with the only difference being that the mixture was produced at reduced temperatures based on additive producers or equipment manufacturers' recommendations.

Some agencies did not consider any critical distresses as part of the WMA design, and others used the same criteria applied to HMA. Moisture-susceptibility testing during the mix design stage was based primarily on TSR using AASHTO T 283 or the HWTT. Only two agencies indicated using the Immersion-Compression Test (AASHTO T 165). Two agencies did not perform any moisture-susceptibility tests, while one agency required the use of AASHTO T 283 results for mix design approval. Agencies used between three and six Superpave gyratory specimens to determine TSR, with specimens varying from 4 to 6 inches (100 to 150 mm) in diameter and 4 inches (100 mm) in height.

The results of the moisture susceptibility tests varied from agency to agency. For most of the agencies, the WMA TSR test results were lower than for the control HMA. In addition, for one agency, the TSR values of PMFC WMA specimens were less than 80 percent, while for PMLC WMA (i.e., after reheating), the TSR was greater than 80 percent. Another state DOT also indicated observing differences between the WMA TSR results of PMFC versus PMLC specimens. Other agencies indicated that the TSR results of LMLC WMA specimens were above 80 percent for all WMA technologies. One agency used WMA versus HMA (instead of unconditioned versus conditioned) to compute the TSR and required a value greater than 85 percent.

Construction. The reported WMA production temperatures varied from 230 to 270°F (110 to 132°C) depending on the technology being used. The maximum reported production temperature was 280°F. The respondents indicated that the mixing process for WMA was no different than that for HMA. With regard to compaction temperatures, the state DOTs indicated that the usual range was around 230°F (110°C) with special instances being as low as 190°F (88°C) or as high as 275°F (135°C). Besides the temperature, the only other reported difference in compaction was the roller pattern, with the roller positioned closer to the paver for WMA due to the reduced temperature of the mixture. The type and weight of the rollers were the same for both HMA and WMA. The QA measures required on the WMA pavements were the same as the ones prescribed for HMA construction: volumetrics, aggregate gradation, binder content, etc.

Performance. All state DOTs indicated that, to date, no distress related to moisture damage had been observed or reported in the WMA pavements. However, these pavements are relatively new, and yearly condition monitoring is planned to track performance. One agency reported thermal cracking appearing in the WMA pavements during the first winter season after construction. Another two agencies reported problems with compaction. In one case, it was sheen effects and high densities, and in the other, it was poor compaction and difficult handwork after long haul distances. Two other agencies reported observing cracking and other minimal distresses occurring on all pavements, including the HMA control.

All agencies were expecting the same or better service life out of the WMA pavements compared with the HMA pavements. In addition, the maintenance and rehabilitation options being considered for the WMA pavement sections were the same ones being used for HMA pavements.

Other. The cost of WMA was handled in different ways by the various agencies. For some, because the WMA pavements were trial or demonstration projects, the cost was subsidized by the additive supplier, equipment manufacturer, or contractor. For others, the cost was very similar to typical HMA prices. One agency required the contractor to reduce the price per ton of the WMA based on value engineering, under the principle that energy savings generated by producing WMA should be shared with the agency.

General. The state DOTs and researchers were asked to give additional information, ideas, or comments useful to the study of moisture susceptibility of WMA. Input to this final question touched on the following topics of interest:

- Measure the change in WMA performance with time and versus HMA.
- Evaluate the sensitivity of current tests to quantify moisture susceptibility of WMA.
- Validate/calibrate current tests to accurately quantify moisture susceptibility of WMA and reflect field performance.
- Clarify negative aspects associated with the production of foamed asphalt.
- Develop a process to identify well-performing WMA additives and methods in the future.
- Establish a unified laboratory mix design process using WMA additives and foaming.
- Study the effects of wet/moist aggregates on WMA.

Contractors' Phone Interviews

With the input of the internal and external advisory groups and the outcome of the state DOTs' web-based survey and follow-up interviews, a list of contractors was consolidated to collect information via phone interviews regarding candidate WMA pavements as well as current WMA practice. Interviews for contractors included questions about construction practices using specific WMA technologies such as mix design, changes in plant and field operations, QC measures, placement temperatures, compaction, mat thickness, and costs. They were also asked to share information about upcoming construction of WMA pavements.

Six contractors were interviewed. These contractors used technologies that included an array of foaming and additive types. The mix type most commonly used in all instances was dense-graded with minor use of open or gap-graded mixtures, especially when including crumb-rubber modified asphalt. The responses also indicated that the purpose of using WMA in 85 to 90 percent of the pavements built with WMA was to achieve temperature reduction. In the other instances, the purpose stated was to extend haul distances/times, obtain better density, achieve cold in-place recycling, control emissions, provide a cleaner and safer construction environment, achieve cost/fuel savings, or accelerate construction placement. Two contractors indicated that their technology was used in the laboratory as part of the WMA mix design.

As far as changes in plant operations are concerned, the primary modification (besides the temperature reduction) was introducing hardware and controls to introduce the additives. With respect to field operations, the contractors indicated the differences were the lower compaction temperature and the location/timing of the compaction rollers, which were placed closer to the paver because of the reduced temperature of the mixture and thus have limited time to achieve the required density and finish the surface. One contractor answered that when using free water foaming technologies, adjustments to the rolling pattern and timing of the rollers had to be made because placement of the WMA under shaded areas caused the mixture to become tender due to the lower temperatures.

The typical compaction temperatures the respondents had used varied with WMA technology. The reported temperatures were as low as 205°F (96°C) to as high as 275°F (135°C). In terms of QC measures, all contractors followed regular HMA practice (i.e., volumetrics). One contractor allowed the compacted loose mix to cool down before compaction in the laboratory to replicate agency practices. Another contractor included moisture-susceptibility tests as part of its quality assessment and obtained lower TSR for WMA (i.e., 39 percent) versus HMA (i.e., about 90 percent). After reheating the mixture in the laboratory, the TSR of the WMA increased to around 50 percent but was still below the desired threshold of 80 percent.

The respondents reported no significant difference in the layer thicknesses prescribed for WMA versus conventional HMA. Regarding cost, the contractors noted that the major cost difference of producing WMA versus HMA was the initial capital investment on equipment, additives, or both. However, they also indicated that as the use of WMA becomes more prevalent, the capital and production costs will probably be offset by the energy savings obtained by producing at reduced temperatures.

With respect to performance, the contractors indicated that, to date, they had not observed any distresses on any of the pavements, even ones built 3 years ago. The contractor that obtained the low TSR values in the laboratory also observed that this particular WMA pavement had not shown signs of stripping (moisture damage) in the field. Finally, upcoming projects were investigated with the respective state DOTs.

Some topics of interest that the contractors pointed out at the end of the interview included

- Quantify the differences in material properties between WMA versus HMA.
- Improve moisture-susceptibility laboratory tests to correlate with field observations.
- Validate moisture-susceptibility laboratory test criteria for WMA.
- Measure moisture content of WMA in the field and compare with HMA.

WMA Equipment Manufacturers and WMA Additive Suppliers Phone Interviews

Interviews for equipment manufacturers and additive suppliers included questions aimed at identifying primary customers of the equipment/additive, pavements where the equipment/additive was used, technical information on the WMA technology process (e.g., temperature, cost, application time, and quantity produced), and upcoming WMA pavement construction. Two WMA equipment manufacturers of free water foaming systems and one WMA additive supplier were interviewed.

With respect to primary customers, the equipment manufacturers indicated that contractors were their main clients, while the additive supplier's customers consisted primarily of state DOTs. Although the foaming and additive processes have a different approach in lowering the viscosity of the binder, the production temperatures of WMA for both technologies ranged between 260 and 285°F (127 and 141°C) with higher temperatures sometimes required when crumb-rubber asphalt was incorporated in the mixture. When producing WMA using the foaming systems at temperatures below 32°F (0°C), some precautions needed to be taken to prevent the water supply from freezing. In addition, burner adjustments were also necessary when decreasing the temperature and thus increasing the production.

Regarding the cost difference of producing WMA using the equipment/additive versus HMA, the price was comparable, especially for the foaming systems. Some cost savings resulted from using less energy when mixing at reduced temperatures, requiring less compaction effort to achieve density, and being able to open the pavement to traffic sooner. Concerning the quantity produced and application time of WMA versus HMA, all respondents indicated that there was no difference.

No specific list of upcoming pavements was available from the interviewees. However, based on their insight as to which states were likely to use their equipment/additive, additional inquiries were sent to the respective state DOT representatives.

The equipment manufacturers and additive supplier pointed out these topics of interest:

- Improve current laboratory tests to accurately quantify moisture susceptibility of WMA.
- Develop guidelines to limit maximum moisture content of aggregates used in production.
- Dispel negative opinions associated with the production of foamed asphalt.

CHAPTER 2

Research Approach

Field Projects

The following factors were considered in selecting field projects (including a wide spectrum of materials and field conditions in this study): climate (wet and dry, freeze and no-freeze), aggregate type, binder type, inclusion of recycled materials (RAP or recycled asphalt shingles [RAS]), and WMA technology. Materials and cores from four field sections in Iowa, Texas, Montana, and New Mexico were selected based on these considerations. During construction, raw materials and loose plant mix were acquired on site, conditioned and compacted, and evaluated based on the selected performance parameters. PMFC cores were obtained at all four field projects at construction and after 6 months and 12 months in service from the Iowa field project, after 8 months in service from the Texas field project, and after 6 months in service from the Montana field project. The three field projects where performance was monitored with time by taking PMFC cores represent the three extreme climates for moisture susceptibility as follows:

- Iowa = wet and freeze-thaw (F/T) = high rainfall with some F/T cycles = northern and northeastern states that may be susceptible after 1,000 days or 2–3 years.
- Texas = hot and wet = high temperatures, high rainfall, and high relative humidity = southeastern states that may be susceptible after 1,000 days or 2–3 years.
- Montana = cold and multi-F/T = low temperatures, some rainfall, and multiple F/T cycles = intermountain western states that may be susceptible after 100 days or 3–4 months.

In addition to these three extreme climates for moisture susceptibility, a risk to mixture durability and performance is posed by late-season construction in almost all United States climates (where mixtures may be susceptible after 100 days), the use of aggregates prone to moisture damage, and entrapment of moisture beneath an impenetrable surface layer or treatment.

The four field projects are summarized in Table 2-1 and introduced in the following subsections with additional details provided in Appendix D. Climate data, including cumulative plots of degree days (base 32°F [0°C]), freezing days, and wet days and corresponding coring dates throughout March 2013, are summarized in Figures 2-1, 2-2, and 2-3. As shown in Figure 2-1, for cumulative degree days (base 32°F [0°C]), aging over 8 months that included a summer in the hot/wet Texas climate was similar to aging over 12 months that included a summer in the wet/F/T Iowa climate. Aging after 6 months over the winters in the wet/F/T Iowa climate and the cold/multi-F/T Montana climate were also similar in terms of this climatic parameter. In terms of cumulative freezing days, as shown in Figure 2-2, the cold/multi-F/T Montana climate was significantly more severe than the wet/F/T Iowa climate, and the hot/wet Texas climate experienced almost no freezing days. Opposite trends are shown in Figure 2-3 in terms of cumulative wet days, with the hot/wet Texas climate showing the most precipitation followed by the wet/F/T Iowa climate and the essentially dry cold/multi-F/T Montana climate. Even though performance was not monitored with time by taking PMFC cores for the New Mexico field project, the climate is dry like Montana, cold during the winter like Iowa, and relatively hot during the summer with cumulative degree days between Texas and Iowa, as shown in Figures 2-3, 2-2, and 2-1, respectively.

In addition to the climate data, traffic data were also estimated in terms of cumulative equivalent single-axle loads (ESALs) throughout the project, as shown in Figure 2-4 with corresponding coring dates. These estimated cumulative ESALs were determined based on inputs of 2011 annual average daily traffic (AADT), truck percentage (assumed constant), and annual growth rate (used to calculate assumed constant compound monthly growth rate) for each field project and assumed 50-percent directional factor and route type (Major Mixed Truck Route [Type I]) (Titus-Glover et al. 2010). Annual

Table 2-1. Summary of field projects.

Location and Environment Condition	Location	Construction Completion Date	Mixtures	Aggregates	Asphalt Binder	Additives			Field Compaction Temperature (°F)	Coring Dates
						RAP	RAS	Anti-Strip Agent		
Iowa (Wet, Freeze)	US 34, near Corning	Sep. 2011	HMA+RAP	Quartzite, Limestone, Field Sand	PG 58-28	17%	None	None	295-300	Sep. 2011
			Evotherm 3G+RAP						240-248	Mar. 2012
			Sasobit+RAP						235-240	Sep. 2012
Montana (Dry, Freeze)	IH 15, near Dillon	Oct. 2011	HMA	Siliceous	Modified PG 70-28	None	None	1.4% Lime	310-315	Oct. 2011 Apr. 2012
			Evotherm 3G						270-280	
			Sasobit						275-280	
			Foaming						270-275	
Texas (Wet, No-Freeze)	FM 973, near Austin	Jan. 2012	HMA	Limestone, Field Sand	Modified PG 70-22	None	None	None	275-285	Jan. 2012 Sep. 2012
			Evotherm DAT						230-235	
			Foaming						240-250	
New Mexico (Dry, No-Freeze)	IH 25, near Truth or Consequences	Oct. 2012	HMA+RAP	Siliceous Gravel	Modified PG 64-28	35%	None	1% Versabind	285-290	Oct. 2012
			Evotherm 3G+RAP						255-260	
			Foaming+RAP						265-270	

growth rates were not available for Texas and New Mexico, so assumed values of 2.5 percent and 0 percent, respectively, were used. The New Mexico assumed annual growth rate was based on decreasing AADT counts from the New Mexico DOT. As shown in Figure 2-4, there is a significant difference in the traffic between those field projects on interstate highways (Montana and New Mexico) and those on other types of facilities (US highway in Iowa or busy FM road in Texas).

Iowa Field Project

The Iowa field project was in Union and Adams Counties on US Route 34. A quartzite aggregate, two limestone aggregates,

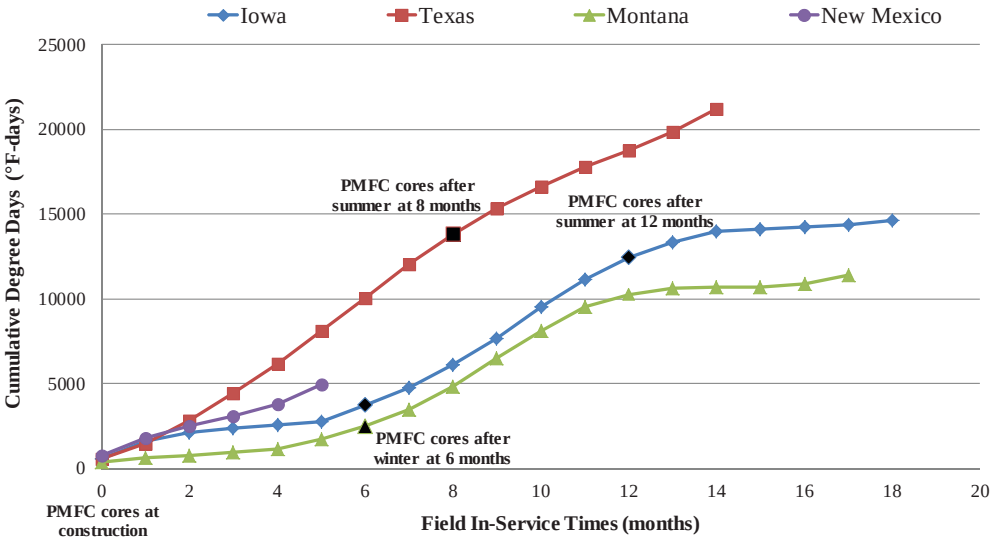


Figure 2-1. Summary of cumulative degree days (base 32°F) for field projects.

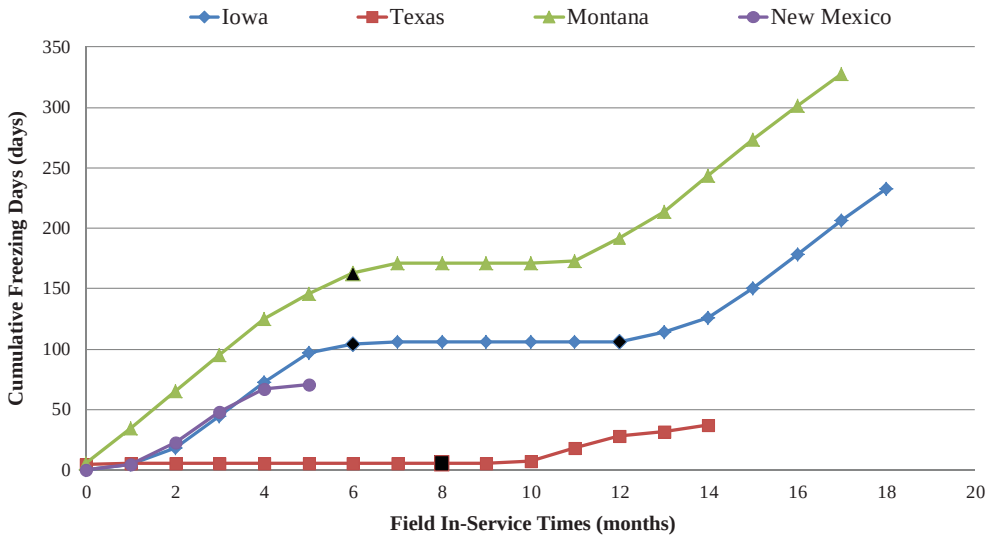


Figure 2-2. Summary of cumulative freezing days for field projects.

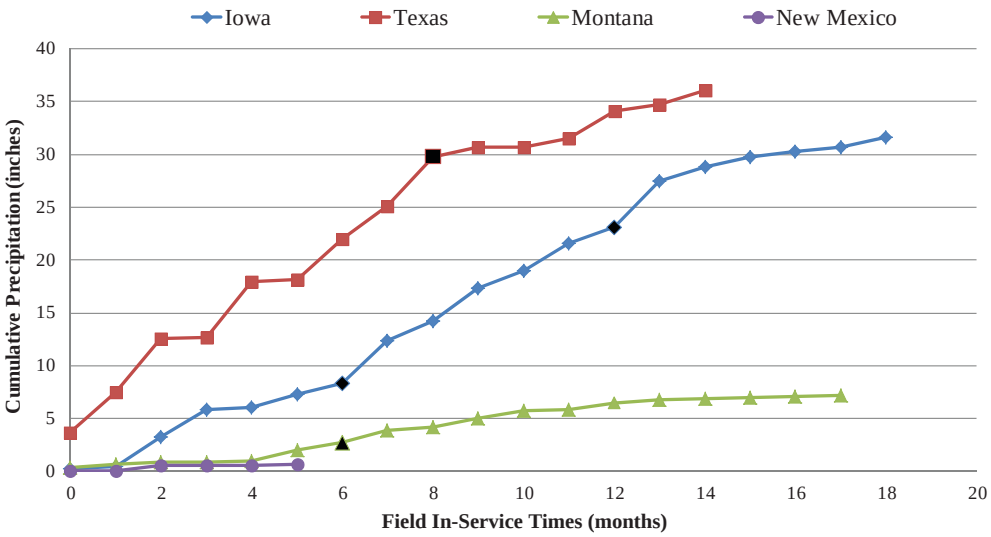


Figure 2-3. Summary of cumulative wet days for field projects.

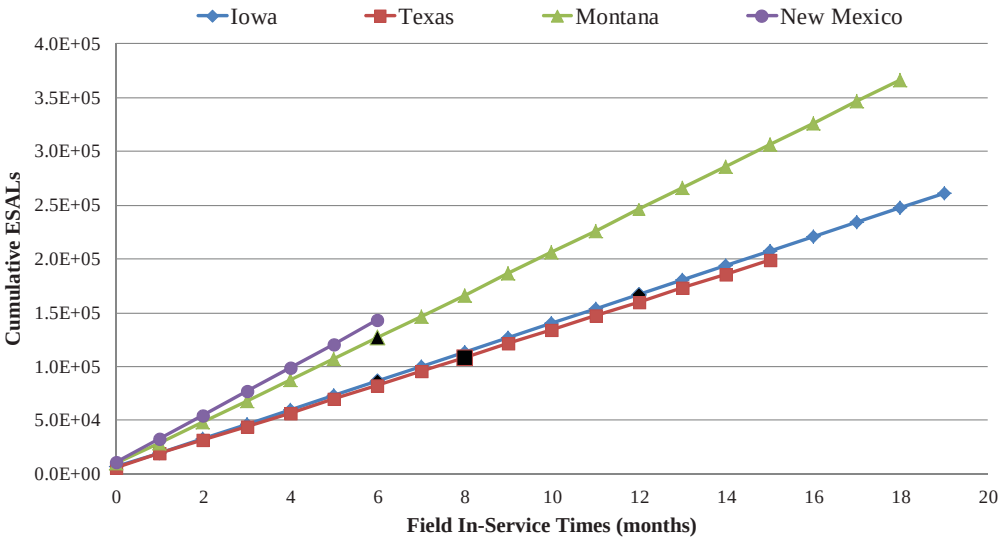


Figure 2-4. Summary of traffic information for field projects.

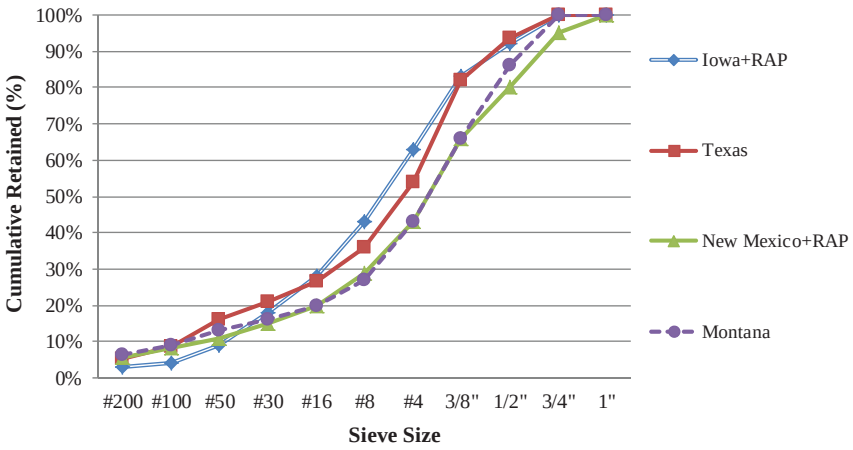


Figure 2-5. Aggregate gradations from field projects.

and field sand and RAP were used and combined. The gradation of the combined aggregate is presented in Figure 2-5. A washed sieve analysis was also conducted to verify the gradation of the combined aggregates, and two trials were again used to adjust the gradation of the combined aggregates. The asphalt binder used in this project was a PG 58-28 binder with a specific gravity of 1.0284. The optimum binder content was determined as 5.4 percent (by weight of the total mixture).

Evotherm® 3G and Sasobit® were selected as the WMA technologies for this project. Evotherm® 3G is a combination of surfactants, waxes, processing aids, polymers, acids, and other materials intended to reduce frictional forces between the binder and aggregate. Sasobit® is a crystalline, long chain aliphatic polymethylene hydrocarbon, identical to paraffin waxes that are found in crude oil, except that it has a higher molecular weight. Given its ability to lower the viscosity of the binder at high temperatures, Sasobit® may improve the binder flow during the mixing process and laydown operations. Both WMA additives were blended at 0.4 percent by weight of binder at the plant.

The construction of the pavements was completed in September 2011, and PMFC cores at construction, after 6 months in service, and after 12 months in service were obtained from this field project. Climate data, including cumulative plots of degree days (base 32°F [0°C]), freezing days, and wet days and corresponding coring dates are summarized in Figures 2-1, 2-2, and 2-3, respectively. This field project represents the wet and F/T extreme climate for moisture susceptibility.

Montana Field Project

The Montana field project was on IH 15, near the Idaho border. Three different fractions of a siliceous gravel aggregate and 1.4 percent lime were used and combined. The gradation of the combined aggregate is presented in Figure 2-5. A PG 70-28 binder with a specific gravity of 1.034 was used in this project, and the optimum binder content was determined as 4.6 percent (by weight of the total mixture). Evotherm® 3G, Sasobit®, and the Madsen Eco-Foam II foaming process were used as WMA technologies in this field project. The compaction temperatures of WMA used in the Montana field project were significantly higher than those in the Iowa and Texas field projects. Thus, offsite PMLC specimens were fabricated following the conditioning protocol proposed based on resilient modulus (M_R) data from the Iowa and Texas field projects and were tested using M_R to validate the laboratory conditioning protocol.

The construction of the pavements was completed in October 2011, and PMFC cores at construction and after 6 months in service were obtained from this field project. Climate data, including cumulative plots of degree days (base 32°F [0°C]), freezing days, and wet days and corresponding coring dates, are summarized in Figures 2-1, 2-2, and 2-3, respectively. This field project represents the cold and multi-F/T extreme climate for moisture susceptibility.

Texas Field Project

The Texas field project was on FM 973, near the Austin Bergstrom International Airport. Four different fractions of a limestone aggregate and a field sand were used and combined. The gradation of combined aggregate is presented in Figure 2-5. A washed sieve analysis was also conducted to verify the gradation of the combined aggregates, and two trials were again used to adjust the gradation of the combined aggregates. A PG 70-22 binder with a specific gravity of 1.033 was used in this project, and the optimum binder content was determined as 5.2 percent (by weight of the total mixture).

Evotherm DAT™ and a foaming process were used as WMA technologies in this field project. Evotherm DAT™ has been designed to enhance coating, adhesion, and workability at lower production temperatures. In order to treat the binder with this chemical additive, the binder was heated to the

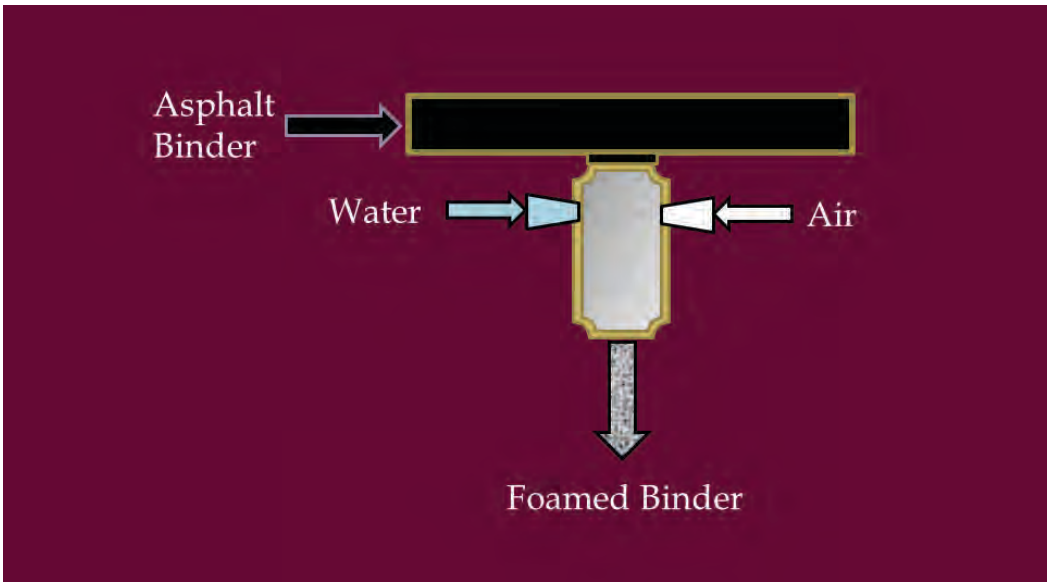


Figure 2-6. Laboratory foaming process.

mixing temperature (T_m) and the additive was blended at 5 percent by weight of binder. Foamed binder was produced on site by injecting 5-percent water and air into the hot binder inside a special expansion chamber. In the laboratory, a foaming device that simulates the air-atomized mixing at the plant was used to produce foamed binder/mixtures with 5% water, as shown in Figure 2-6.

The construction of the pavements was completed in January 2012, and PMFC cores at construction and after 8 months in service were obtained from this field project. Climate data, including cumulative plots of degree days (base 32°F [0°C]), freezing days, and wet days and corresponding coring dates, are summarized in Figures 2-1, 2-2, and 2-3, respectively. This field project represents the hot and wet extreme climate for moisture susceptibility.

New Mexico Field Project

The New Mexico field project was on IH 25, in Sierra County. Three fractions of a siliceous gravel aggregate and 1% Versabind (a low-grade Portland cement) were used and combined. The gradation of the combined aggregate is presented in Figure 2-5. A washed sieve analysis was also conducted to verify the gradation of the combined aggregates, and three trials were used to adjust the gradation of the combined aggregates.

Evotherm® 3G and a foaming process were used as WMA technologies in this field project. Thirty-five percent of RAP was included in the mixture for the control HMA and WMA. In addition, another control HMA without RAP was constructed using the same aggregates to discriminate the effect of recycled materials on mixture performance. For those mixtures with RAP, a PG 64-28 binder with a specific gravity of 1.02 was used, while a PG 76-28 binder with a specific gravity of 1.00 was used for the HMA without RAP, and the total binder content was determined as 5.4% (by weight of the total mixture).

The construction of the pavements was completed in October 2012, and only PMFC cores at construction were obtained from this field project. Climate data including cumulative plots of degree days (base 32°F [0°C]), freezing days, and wet days are summarized in Figures 2-1, 2-2, and 2-3, respectively.

Summary of Compaction Temperatures Used in the Field Projects

Compaction temperatures used in the Iowa, Texas, Montana, and New Mexico field projects are summarized in Table 2-2.

Laboratory Tests and Specimen Fabrication

Laboratory Tests

Based on previous experience in evaluating asphalt mixture stiffness and moisture susceptibility in the laboratory, one nondestructive test and two destructive tests were selected to quantify the mixture stiffness in dry and wet conditions and the loss of strength and stiffness after moisture conditioning. The destructive tests were (1) determination of indirect tensile (IDT) strength in dry conditions and after moisture conditioning to determine TSR and (2) the Hamburg Wheel-Tracking Test (HWTT) that indicates mixture resistance to both moisture susceptibility and rutting. The nondestructive test was

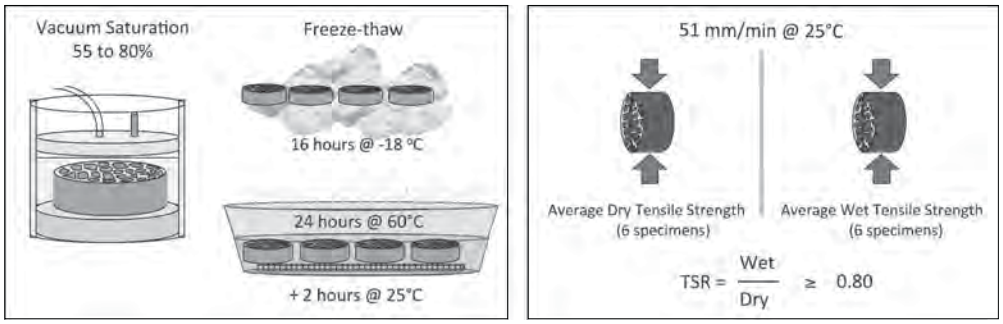
Table 2-2. Summary of compaction temperatures (T_c) from field projects.

Location and Environmental Condition	Mixture Type	Specimen Type				
		PMFC (°F)	Onsite PMLC 0-1 h (°F)	Onsite PMLC 1-2 h (°F)	LMLC (°F)	Offsite PMLC (°F)
Iowa (Wet, Freeze)	HMA+RAP	295-300	N/A	295-300	295	295
	Evotherm 3G+RAP	240-248	N/A	240-248	240	240
	Sasobit+RAP	235-240	N/A	235-240	240	240
Montana (Dry, Freeze)	HMA	310-315	N/A	315	N/A	275
	Evotherm 3G	270-280	N/A	275	N/A	240
	Sasobit	275-280	N/A	279	N/A	240
	Foaming	270-275	N/A	271	N/A	275
Texas (Wet, No-Freeze)	HMA	270-285	275	275	275	275
	Evotherm DAT	230-235	225	225	240	240
	Foaming	240-250	225	250	235	275
New Mexico (Dry, No-Freeze)	HMA+RAP	285-290	N/A	295	275	275
	Evotherm 3G+RAP	255-260	N/A	275	240	240
	Foaming+RAP	265-270	N/A	275	240	275
	HMA	330-335	N/A	320	275	275

determination of M_R with testing conducted in dry conditions and after moisture conditioning to determine M_R-ratio.

IDT Strength and TSR

IDT strength in both wet and dry conditions and the resulting TSR of wet-to-dry IDT strengths was selected as one of the destructive tests given that it is the most common national standard test to evaluate moisture susceptibility of asphalt mixtures. IDT strength at 77°F (25°C) was determined for both dry specimens and for wet specimens moisture conditioned according to AASHTO T 283 with partial vacuum saturation, one freeze-thaw cycle, and soaking in warm water, as shown in Figure 2-7. All laboratory-compacted specimens were fabricated to a diameter of 6 inches (150 mm) and a height of 3.75 inches (95 mm) in the Superpave gyratory compactor to target air void contents of 7±0.5%. In this project, the TSR was determined as the ratio of the average of three IDT strength



(Santucci, 2010)

Figure 2-7. Modified lottman test by AASHTO T 283.

results obtained from three specimens tested in wet condition to the average of three IDT strength results obtained from three specimens tested in dry condition. The TSR values and the wet IDT strengths were considered in this project to compare WMA and HMA in terms of moisture susceptibility. As only one replicate TSR value was produced from each set of six specimens, the TSR results for different mixture types or different specimen types were compared to each other based on the precision and bias statement that indicates a d2s acceptable range of two results with more than a 95% confidence level of 9.3% (Azari 2010).

In AASHTO M 323, the threshold for TSR by AASHTO T 283 is a minimum of 0.80, or 80%. Some agencies also specify a minimum value of dry, wet, or both IDT strength values in addition to or instead of a limit on the TSR. Some of these minimums include

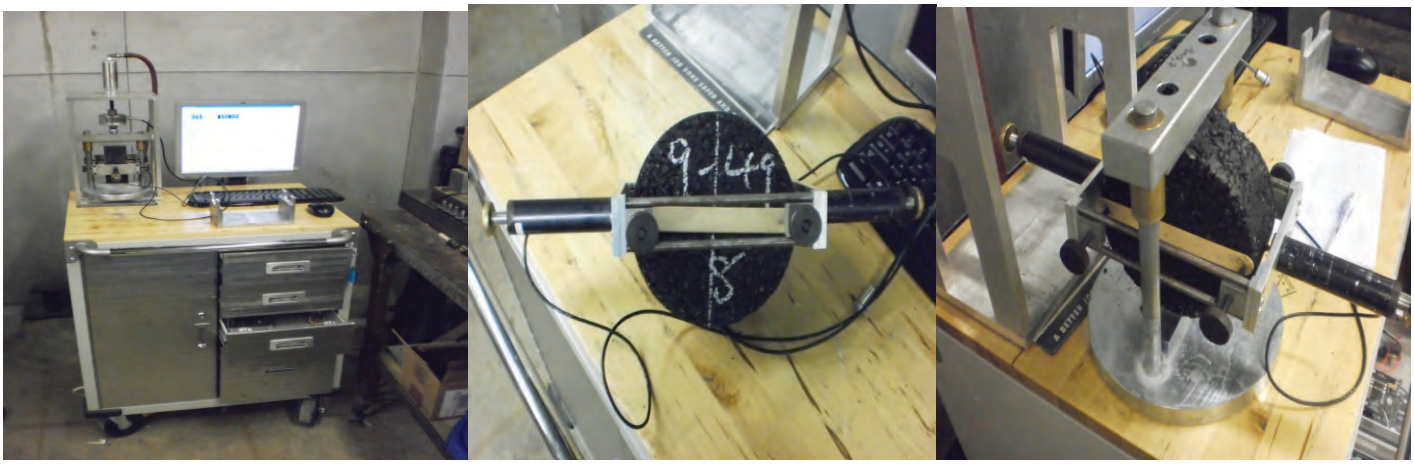
- Nevada:
  - Unmodified binder: 60 psi for dry IDT strength (48 psi wet IDT strength assuming TSR ≥ 80%).
  - Modified binders: 90 psi for dry IDT strength (72 psi wet IDT strength assuming TSR ≥ 80%).
- Tennessee:
  - Unmodified binder: 80 psi for wet IDT strength.
  - Modified binders: 100 psi for wet IDT strength.
- Texas:
  - 85 psi for dry IDT strength (68 psi wet IDT strength assuming TSR ≥ 80%).

Resilient Modulus (M_R) and M_R-ratio

M_R stiffness in both wet and dry conditions and the resulting M_R-ratio of wet-to-dry M_R stiffnesses was selected as the nondestructive test given its cost effectiveness in providing an accurate indicator of moisture susceptibility in terms of stiffness. In this project, M_R stiffness at 77°F (25°C) was measured by ASTM D7369 with the modification of replacing on-specimen linear variable differential transducers (LVDTs) with LVDTs aligned along the horizontal diametral plane (gauge length as a fraction of diameter of the specimen = 1.00) to reduce costs, as shown in Figure 2-8. For each specimen, M_R stiffness was measured twice, rotating the specimen 90 degrees after the first measurement. M_R stiffness was first determined for dry specimens, and then these same specimens were moisture-conditioned according to AASHTO T 283 with partial vacuum saturation, one freeze-thaw cycle, and soaking in warm water, as shown in Figure 2-8, and tested again to determine M_R stiffness for wet specimens. All laboratory-compacted specimens were fabricated to a diameter of 6 inches (150 mm) and a height of 2.4 inches (61 mm) in the Superpave gyratory compactor to target air void contents of 7±0.5%. In this project, the M_R-ratio was determined as the ratio of the average of three M_R stiffness results obtained from three specimens tested in wet condition to the average of three M_R stiffness results obtained from three specimens tested in dry condition. The M_R-ratio values and the wet M_R stiffnesses were considered in this project to compare WMA and HMA in terms of moisture susceptibility. A precision and bias statement was not available for the M_R-ratio, because although the wet and dry stiffness measurements were conducted on the same specimen, the d2s value was not likely any larger than that for TSR (9.3%) (Azari 2010). Therefore, a 10% difference was considered for this project for identifying significant differences between mixture types and specimen types for the M_R-ratio where only one replicate value was produced from each set of six specimens.

HWTT

The HWTT by AASHTO T 324 was selected as the other destructive test because of its recent adoption by several states

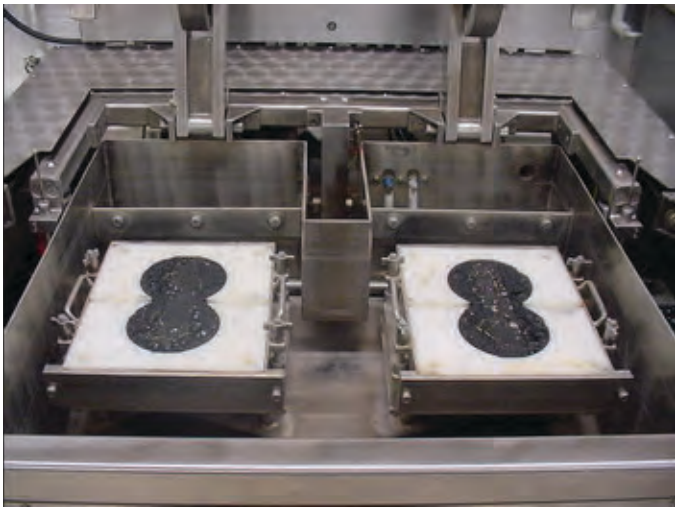


(a) Data Acquisition System **(b) LVDT Setup** **(c) Loading Frame Setup**

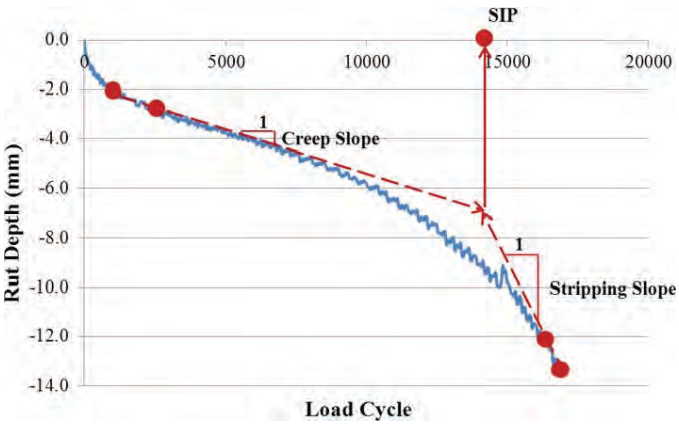
Figure 2-8. M_R test equipment.

to simultaneously evaluate rutting and moisture susceptibility of asphalt mixtures. The HWTT was conducted at 122°F (50°C), and the stripping inflection point (SIP) and stripping slope, as shown in Figure 2-9, were calculated to compare WMA and HMA in terms of moisture susceptibility. All laboratory-compacted specimens were fabricated to a diameter of 6 inches (150 mm) and a height of 2.4 inches (61 mm) in the Superpave gyratory compactor to target air void contents of 7±0.5%, and the cylindrical specimens were tested as shown in Figure 2-9 for a maximum of 20,000 passes or until 0.5 inch (12.5 mm) of deformation occurred.

Because a precision and bias statement was not available for the selected HWTT test results, the average differences in SIP and the stripping slope for all Texas mixtures that exhibited stripping were calculated as approximately 2,000 load cycles and 0.2 µm/cycle, respectively, for use as corresponding d2s values in this analysis. Thus, these thresholds were used for identifying significant differences between mixture types and specimen types for these performance parameters.



(a) Equipment with Loaded Specimens



(b) Typical Deformation Behavior with Load Cycles

Figure 2-9. Hamburg wheel-tracking test.

Current specifications when available for the HWTT for the states where the field projects were located were as follows:

- Iowa:
  - Water temperature during test: 122°F (50°C).
  - Minimum SIP of 10,000 or 14,000 load cycles depending on ESAL level (i.e., <3M or ≥3M, respectively).
- Texas:
  - Water temperature during test: 122°F (50°C).
  - Variable cycles to failure depending on the binder performance grade (PG 64 or lower, 10,000 load cycles; PG 70, 15,000 load cycles; PG 76, 20,000 load cycles).
  - 0.5 inch (12.5 mm) max allowable rut depth.
- Montana:
  - Water temperature depending on the binder performance grade (14°C lower than the high-temperature performance grade).
  - 20,000 cycles to failure; 0.51 inch (13 mm) max allowable rut depth.

For all of these states except Iowa, the HWTT specifications focus on limiting rutting, not moisture susceptibility.

Specimen Fabrication

To fabricate LMLC specimens, aggregates and binder were heated to the specified mixing temperatures independently and then mixed with a portable mixer. Afterwards, HMA and WMA loose mixes were conditioned (1) in the oven with various protocols for the WMA laboratory-conditioning experiment and (2) for 2 h at 275°F (135°C) and 240°F (116°C) for HMA and WMA, respectively, for the WMA moisture-susceptibility (including the effects of anti-stripping agents) and WMA performance-evolution experiments. Specimens were then compacted with the Superpave gyratory compactor (SGC) at the compaction temperatures shown in Table 2-3. Trial specimens were fabricated to ensure specimens were obtained with air void contents of 7±0.5%. To simulate field aging in early life in the WMA performance-evolution experiment, compacted specimens were further conditioned following various aging protocols in an environmental room or oven prior to being tested. In total, almost 500 LMLC specimens with 7±0.5% AV were fabricated for the Iowa, Texas, Montana, and New Mexico field projects that included 13 mixtures (4 HMA and 9 WMA).

PMFC cores were obtained at construction for the Iowa, Texas, Montana, and New Mexico field projects. Additionally, PMFC cores after 6 months and 12 months in service from the Iowa field project, after 8 months in service from the Texas field project, and after 6 months in service from the Montana field project were also acquired. To fabricate onsite PMLC specimens, loose mixes were taken from the trucks before leaving the plant and maintained in the oven for 1–2 h

Table 2-3. WMA laboratory-conditioning test plan for LMLC specimens.

Location and Environmental Condition	Mixture Type	Laboratory-Conditioning Protocols				
		2 h @ T_c	2 h @ 275°F	4 h @ T_c	2 h @ T_c + 16 h @ 140°F + 2 h @ T_c	4 h @ 275°F
Iowa (Wet, Freeze)	HMA+RAP	X	X	X	X	X
	Evotherm 3G+RAP	X	X	X	X	X
	Sasobit+RAP	X	X	X	X	X
Texas (Wet, No-Freeze)	HMA	X	X	X	X	X
	Evotherm DAT	X	X	X	X	X
	Foaming	X	X	X	X	X

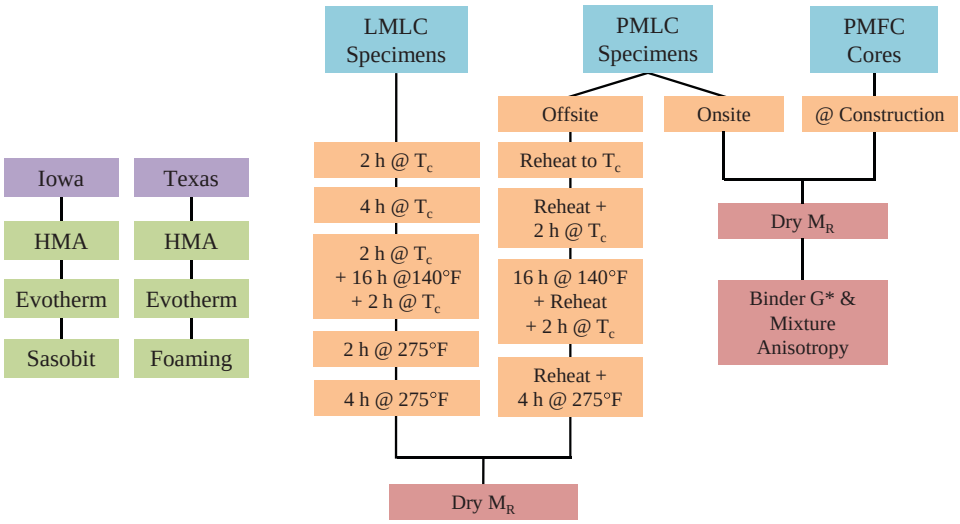
at the temperature shown in Table 2-2 prior to compaction. In total, more than 250 PMFC cores and more than 150 onsite PMLC specimens from the Iowa, Texas, Montana, and New Mexico field projects were tested in this project. To fabricate offsite PMLC specimens, loose mixes were transported to the laboratory in buckets that were then reheated in an oven to the specified conditioning temperature prior to compaction. In total, almost 250 offsite PMLC specimens were fabricated from the four field projects.

For LMLC and offsite PMLC specimens, the total time between fabrication and completion of testing or the beginning of LTOA was approximately 2 weeks. After LTOA of LMLC specimens, testing was also completed within an approximately 2-week period. Such timeframes are also possible for onsite PMLC specimens and PMFC cores when one field project (that includes 3 to 4 mixtures) at a time is arriving at the laboratory. However, when these types of specimens are arriving from more than one field project or other unavoidable delays due to equipment availability or testing schedules are encountered, storage of these specimens at cold temperatures (≤ 68°F [20°C]) is proposed for delays that can stretch from 1 to 4 months. For the Iowa field project, specimens were stored at 77°F (25°C), and average increases of 30% in dry M_R stiffness were noted. For the Montana field project, specimens were stored at 68°F (20°C), and dry M_R stiffnesses did not change.

Experiment Designs

WMA Laboratory Conditioning

The goal of the WMA laboratory-conditioning experiment was to propose conditioning protocols consisting of a combination of time and temperature that produce WMA LMLC and offsite PMLC specimens calibrated to PMFC field cores. Figure 10 presents the research method used for this experiment. In this experiment, LMLC and offsite PMLC specimens with different laboratory-conditioning protocols, PMFC



Note: T_c: compaction temperature.

Figure 2-10. Flowchart for WMA laboratory-conditioning experiment.

cores, and onsite PMLC specimens were tested to determine dry stiffness in terms of M_R, as well as compactability in terms of number of SGC gyrations (N) required in specimen fabrication to achieve 7±0.5% AV.

Analysis of variance (ANOVA) and Tukey-Kramer Honestly Significant Differences (HSD) tests were conducted at a 5% significance level to compare the conditioned LMLC and PMLC specimens (both on site and off site) with the PMFC cores for each mixture type and each selected performance parameter, while accounting for the variability in the M_R stiffness results. Initially, in addition to the main factor of interest conditioning protocol, the effect of orientation (i.e., rotating the specimen 90 degrees after the first measurement) as well as the interaction effect between orientation and conditioning protocol was also tested by using a more sophisticated ANOVA analysis (a split plot design analysis).

As shown in Tables 2-3 and 2-4, five different conditioning protocols were selected for LMLC specimens prior to compaction, and four different ones were applied to offsite PMLC specimens after reheating to the specified conditioning temperature. For LMLC specimens, the conditioning protocol of 2 h at T_c was used because it was proposed by the recently completed NCHRP Project 9-43, and 4 h at 275°F (135°C) was proposed because it is the current standard in the state of Texas. The comprehensive conditioning protocol of 2 h at T_c followed by 16 h at 140°F (60°C) and 2 h at T_c was proposed during a WMA workshop (Harrigan, 2012b) held in May 2011, in Irvine, California. The other two protocols used were derived by combining common conditioning temperatures and times. For offsite PMLC specimens, the conditioning protocol of reheating to T_c was proposed as the least amount of conditioning time/temperature possible prior to compaction. Additionally, three protocols proposed for LMLC specimens were also used to prepare offsite PMLC specimens. The laboratory conditioning protocol for offsite PMLC specimens was proposed based on M_R data from the Iowa and Texas field projects. Because the Montana compaction temperatures for both HMA and WMA were significantly higher than those for Iowa and Texas, offsite PMLC specimens from the Montana field project were fabricated following the proposed protocol, as well as one consisting of the same conditioning time at T_c, and tested with M_R to validate the proposed protocol.

Field cores at construction and onsite PMLC specimens were expected to have similar stiffnesses as they experienced approximately the same level of binder aging. However, their performance in M_R tests was significantly different, as described subsequently, and thus binder was extracted and recovered from these specimens to measure the difference in binder stiffness with the dynamic shear rheometer (DSR). In addition, images were acquired from the same specimens through a novel method (Zhang et al., 2011) to evaluate the effect of aggregate orientation by different compaction methods on mixture stiffness. Finally, the effect of total AV on the stiffness of the specimens was also evaluated.

WMA Moisture Susceptibility

The goal of the moisture-susceptibility experiment was to evaluate moisture susceptibility of WMA in comparison with HMA; Figure 2-11 and Table 2-5 present the research method and test plan, respectively, for this experiment. In this experiment, all laboratory-compacted specimens (LMLC, onsite PMLC, and offsite PMLC) were tested to determine wet and dry M_R stiffness and M_R-ratio, HWTT SIP and stripping slope, and wet and dry IDT strengths and TSR. PMFC cores were also evaluated in terms of all of these same moisture-susceptibility

Table 2-4. WMA laboratory-conditioning test plan for offsite PMLC specimens.

Location and Environmental Condition	Mixture Type	Laboratory-Conditioning Protocols			
		R @ T_c	R + 2 h @ T_c	R + 16 h @ 140°F + 2 h @ T_c	R + 4 h @ 275°F
Iowa (Wet, Freeze)	HMA+RAP	X	X	X	X
	Evotherm 3G+RAP	X	X	X	X
	Sasobit+RAP	X	X	X	X
Texas (Wet, No-Freeze)	HMA	X	X	X	X
	Evotherm DAT	X	X	X	X
	Foaming	X	X	X	X
Montana* (Dry, Freeze)	HMA	X			
	Evotherm 3G	X			
	Sasobit	X			
	Foaming	X			

Note: R: reheat.
*Also included proposed protocol of reheating to 240°F for WMA (except Foaming) and 275°F for HMA and WMA Foaming.

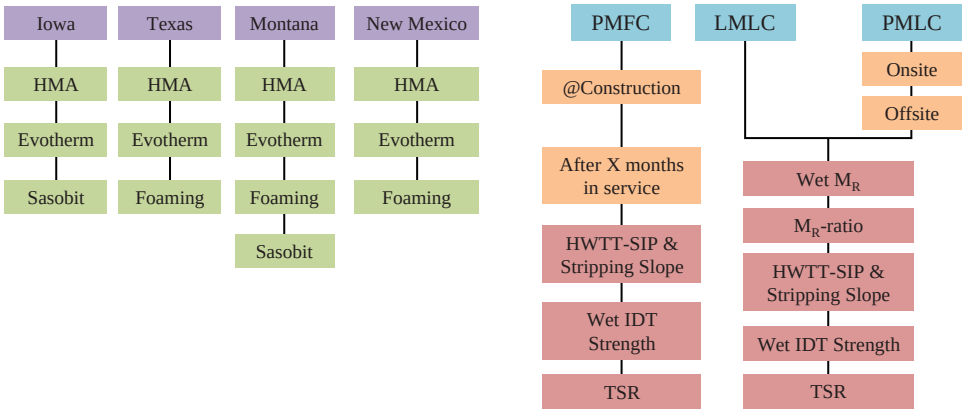


Figure 2-11. Flowchart for WMA moisture-susceptibility experiment.

parameters, except wet M_R stiffness and M_R-ratio. Offsite PMLC and LMLC specimens for moisture testing were fabricated to mimic the early-life behavior of the mixture, based on the results of the laboratory-conditioning experiment.

ANOVA and Tukey's HSD tests were conducted at a 5% significance level to compare WMA with HMA in terms of moisture-susceptibility performance for the same specimen type while accounting for the variability in those tests with multiple replicates. For those tests without multiple replicates, d2s values for the acceptable range of two results or similar values defined based on data from this project as described previously were used in the comparisons.

Table 2-5. WMA moisture-susceptibility test plan.

WMA Field Project	Mixture Type	LMLC As Designed				Onsite & Offsite PMLC				Cores at Construction			Cores after Winter (6 months IA, MT)			Cores after Summer (12 months IA, 8 months TX)		
		Dry M_R	Wet M_R	TSR	HWTT	Dry M_R	Wet M_R	TSR	HWTT	Dry M_R	TSR	HWTT	Dry M_R	TSR	HWTT	Dry M_R	TSR	HWTT
Iowa US 34 (Wet, Freeze) Wet/F/T	Evotherm 3G +RAP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Sasobit +RAP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	HMA +RAP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Montana IH 15 (Dry, Freeze) Cold/multi-F/T	Sasobit	-	-	-	-	X	X	X	X	X	X	X	X	X	X	-	-	-
	Evotherm 3G	-	-	-	-	X	X	X	X	X	X	X	X	X	X	-	-	-
	Foaming	-	-	-	-	X	X	X	X	X	X	X	X	X	X	-	-	-
	HMA	-	-	-	-	X	X	X	X	X	X	X	X	X	X	-	-	-
Texas FM 973 (Wet, No-Freeze) Hot/Wet	Evotherm DAT	X	X	X	X	X	X	X	X	X	X	X	-	-	-	X	X	X
	Foaming	X	X	X	X	X	X	X	X	X	X	X	-	-	-	X	X	X
	HMA	X	X	X	X	X	X	X	X	X	X	X	-	-	-	X	X	X
New Mexico IH 25 (Dry, No-Freeze) Hot/Dry	Evotherm 3G +RAP	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-
	Foaming +RAP	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-
	HMA +RAP	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-

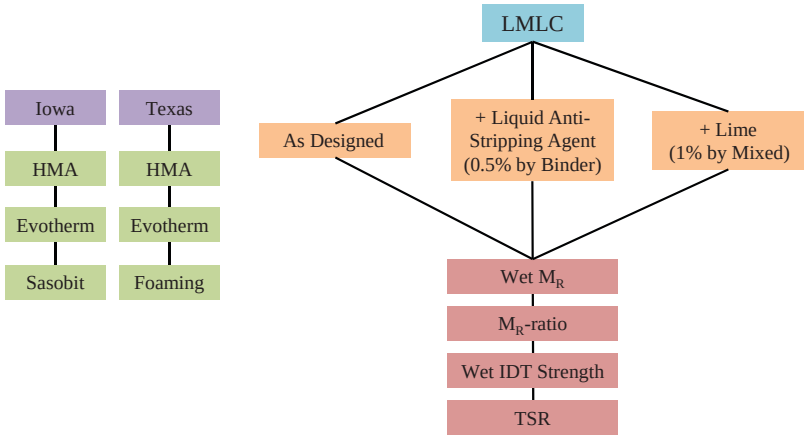


Figure 2-12. Flowchart for anti-stripping agent experiment.

Effect of Anti-Stripping Agents

To evaluate the use of anti-stripping agents as an aid to improve WMA moisture susceptibility, hydrated lime and a common liquid anti-stripping agent were added to Texas and Iowa HMA and WMA in LMLC specimens in a separate experiment. Figure 2-12 presents the method used. Hydrated lime was added through the dry process in a proportion of 1% by the weight of dry aggregates, removing that same 1% of material passing the No. 200 sieve to preserve the gradation of the mix design. A liquid anti-stripping (LAS) agent was added at 0.5% by weight of binder by blending with the binder prior to mixing with the aggregates. In total, an additional 108 LMLC specimens were fabricated to compare with the LMLC specimens designed and used in the WMA moisture-susceptibility experiment. The laboratory test plan for this anti-stripping experiment is shown in Table 2-6.

In this experiment, to assess the effectiveness of the hydrated lime and the LAS agent, dry and wet IDT strength and TSR and dry and wet M_R and M_R-ratio were measured. Moisture conditioning for all wet specimens was done following AASHTO T 283 with one freeze-thaw cycle.

ANOVA and Tukey's HSD tests were conducted at a 5% significance level to compare WMA with HMA in terms of moisture-susceptibility performance for the same specimen type while accounting for the variability in those tests with multiple replicates. For those tests without multiple replicates, d2s values for the acceptable range of two results or similar values defined based on data from this project as described previously were used in the comparisons.

Effect of Specimen Type

Using the same data as the WMA moisture-susceptibility experiment where WMA was compared with HMA for each specimen type, different specimen types were also compared for each mixture type to examine important differences in (1) LMLC specimens used in mix design, (2) PMLC specimens used in QA, (3) PMLC specimens reheated for offsite compaction, and (4) field performance as determined by laboratory testing of PMFC cores. Data used in this analysis were the same as those collected for the WMA moisture-susceptibility experiment but regrouped and reanalyzed for a different comparison.

Table 2-6. Anti-stripping agent test plan for LMLC.

WMA Field Project	Mixture Type	As Designed		+ Hydrated Lime		+ Liquid Anti-Stripping Agent	
		M_R-ratio	TSR	M_R-ratio	TSR	M_R-ratio	TSR
Iowa US 34 (Wet, Freeze) Wet/F/T	Evotherm 3G+RAP	X	X	X	X	X	X
	Sasobit+RAP	X	X	X	X	X	X
	HMA+RAP	X	X	X	X	X	X
Texas FM 973 (Wet, No-Freeze) Hot/Wet	Evotherm DAT	X	X	X	X	X	X
	Foaming	X	X	X	X	X	X
	HMA	X	X	X	X	X	X

ANOVA and Tukey's HSD tests were conducted at a 5% significance level to compare the different specimen types in terms of moisture-susceptibility performance for the same mixture type while accounting for the variability in those tests with multiple replicates. For those tests without multiple replicates, d2s values for the acceptable range of two results or similar values defined based on data from this project as described previously were used in the comparisons.

WMA Performance Evolution

Results from the laboratory-conditioning experiment indicated that the initial stiffness of the WMA is less than the stiffness of conventional HMA and that this gap can be reduced with increased elapsed time in the field. The goal of the WMA performance-evolution experiment was to determine the time when (or if) the properties of HMA and WMA converge and evaluate the performance of WMA as compared with HMA in the early life of the pavement. The hypothesized results in terms of the changes in HMA and WMA stiffness in the field and in the laboratory as long-term aging time increases are shown in Figures 2-13 and 2-14. Figure 2-15 presents the two-phase research method used for this experiment.

In the first phase, as shown in Table 2-7, the vulnerability of WMA in terms of moisture susceptibility was determined in terms of a critical age or time period to reach a dry M_R stiffness equivalent to that of an HMA control section. Changes in HMA and WMA dry M_R stiffness in the field and laboratory were evaluated separately, followed by the correlation of mixture aging in these two conditions. PMFC cores at construction and after 6 or 8 months in service, respectively, from the Iowa and Texas field projects and those after 12 months in service from the Iowa field project were tested to determine dry M_R to evaluate the change in mixture stiffness with aging in the field. Additionally, onsite PMLC specimens from these field projects were tested to indicate the initial stiffness of HMA and WMA pavements in their early life. The same set of LMLC specimens from Iowa and Texas were aged at 140°F (60°C) over a series of aging periods (1 week, 2 weeks, 4 weeks, 8 weeks, and 16 weeks) prior to being tested to determine M_R, with the same specimen tested repeatedly in this nondestructive test to reduce variability and specimen fabrication efforts. These aging periods were selected based on the long-term conditioning for loose mix included in AASHTO T 283 and on previous research in Texas that indicated 4 weeks (1 month) at 140°F (60°C) aged HMA mixtures to stiffnesses similar to those in HMA pavements after approximately 1 year in Texas climate conditions (Glover et al. 2005). Thus, the selected aging times might reflect 1 to 4 years under Texas conditions and likely 2 to 8 years in milder climates in the United States. Results from the first phase were used to define an aging period at which WMA reached a dry M_R stiffness equivalent to that of an HMA control section. This aging time was defined as t_A for use in the second phase.

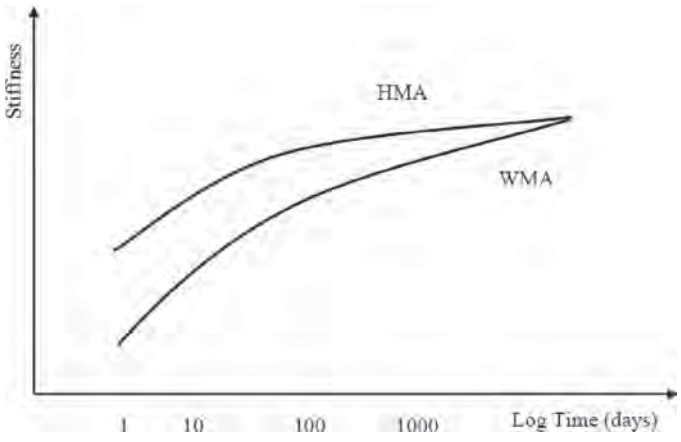


Figure 2-13. Hypothesized evolution of field mixture stiffness with time.

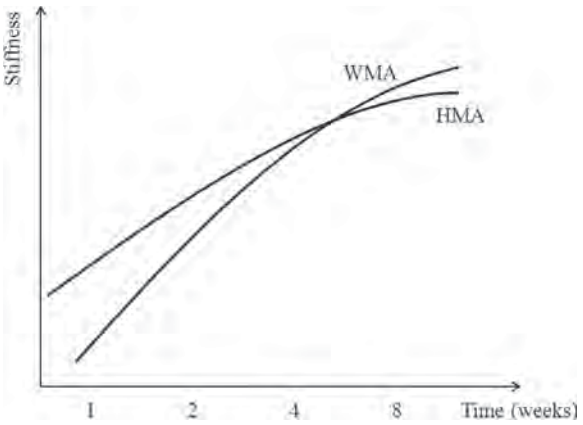


Figure 2-14. Hypothesized evolution of laboratory mixture stiffness with LTOA time.

In the second phase, as shown in Table 2-8, HMA and WMA mixture properties were evaluated after LTOA at different periods in terms of IDT strength in dry and wet condition and TSR, dry and wet M_R and M_R-ratio, and HWTT SIP and stripping slope. Selected LTOA protocols included t_A of 2 weeks at 140°F (60°C), as defined in the first phase of the experiment; a longer aging time, t_B, of 16 weeks, also at 140°F (60°C) to represent several years in service in the field; and the standard LTOA at 185°F (85°C) for 5 days, as is included in AASHTO R 30. Materials from the Iowa, Texas, and New Mexico field projects were used in this phase. LMLC specimens were fabricated following the proposed laboratory-conditioning

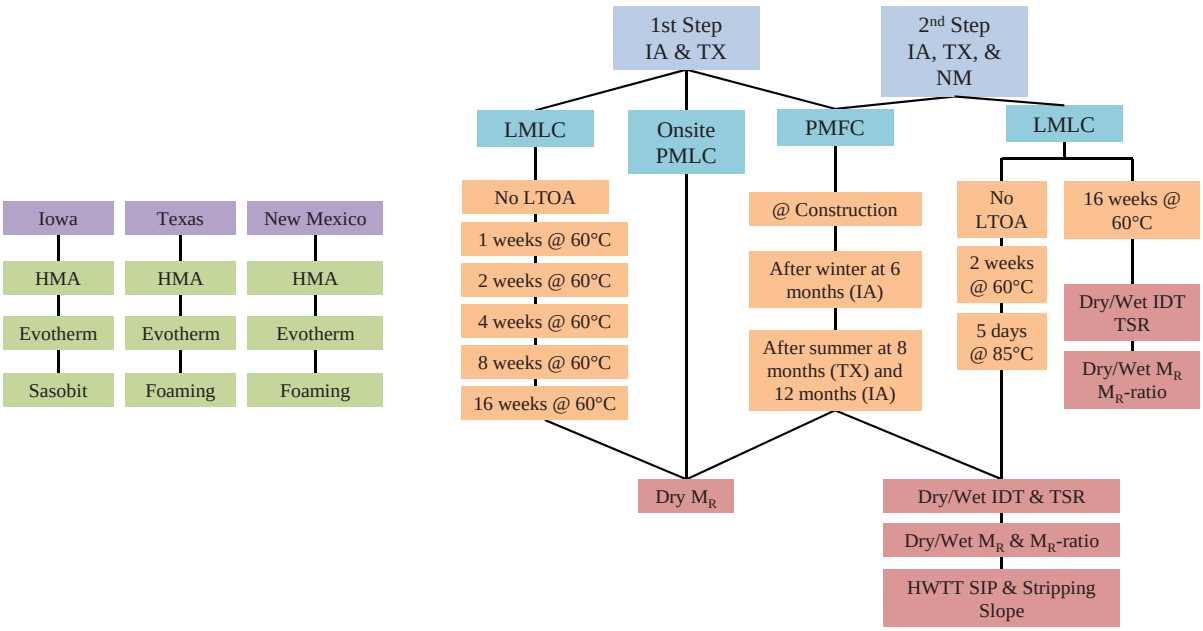


Figure 2-15. Flowchart for WMA performance evolution experiment.

Table 2-7. Phase one of the WMA performance evolution test plan for dry M_R tests of LMLC specimens.

Location and Environmental Condition	Mixture Type	LTOA Protocols @140°F				
		1 week	2 weeks	4 weeks	8 weeks	16 weeks
Iowa US 34 (Wet, Freeze)	HMA+RAP*†	X	X	X	X	X
	Evotherm 3G+RAP*†	X	X	X	X	X
	Sasobit+RAP*†	X	X	X	X	X
Texas FM 973 (Wet, No-Freeze)	HMA*	X	X	X	X	X
	Evotherm DAT*	X	X	X	X	X
	Foaming*	X	X	X	X	X

* Onsite PMLC specimens and PMFC cores at construction and after 6 or 8 months in service were tested for dry M_R.
† PMFC cores after 1 year in service were tested for dry M_R.

Table 2-8. Phase two of the WMA performance evolution test plan for M_R, HWTT, and IDT strength tests of LMLC specimens.

Location and Environmental Condition	Mixture Type	LMLC Specimens		
		t_A = 2 weeks @ 140°F	t_B = 16 weeks @ 140°F*	5 days @ 185°F
Iowa US 34 (Wet, Freeze)	HMA+RAP†‡	-	X	-
	Evotherm 3G+RAP†‡	-	X	-
	Sasobit+RAP†‡	-	X	-
Texas FM 973 (Wet, No-Freeze)	HMA†Δ	X	X	X
	Evotherm DAT†Δ	X	X	X
	Foaming Process†Δ	X	X	X
New Mexico IH 25 (Dry, No-Freeze)	HMA+RAP†	X	-	X
	Evotherm 3G+RAP†	X	-	X
	Foaming+RAP†	X	-	X

* HWTT test was not performed.
† PMFC cores at construction were tested for dry/wet M_R, HWTT, and dry/wet IDT tests.
‡ PMFC cores after winter at 6 months in service were tested for dry M_R, HWTT, and dry/wet IDT tests.
Δ PMFC cores after summer at 8 months in service were tested for dry M_R, HWTT, and dry/wet IDT tests.

protocol prior to compaction defined in the laboratory-conditioning experiment and then long-term aged by the selected protocols after compaction and prior to testing to determine wet and dry M_R stiffness and M_R-ratio, HWTT rut depth at a specific number of load cycles, HWTT SIP, and wet and dry IDT strength and TSR. These moisture-susceptibility parameters were then used to compare WMA and HMA in their early lives.

In both phases, ANOVA and Tukey's HSD tests were conducted at a 5% significance level to compare WMA with HMA in terms of moisture-susceptibility performance for the same specimen type while accounting for the variability in those tests with multiple replicates. For those tests without multiple replicates, d2s values for the acceptable range of two results or similar values defined based on data from this project as described previously were used in the comparisons.

CHAPTER 3

Findings and Applications

Mixture Volumetrics

Appendix E provides detailed volumetric properties by field project with a comparison of mixture types for each field project and a separate comparison of specimen types for each field project. Volumetrics provided include total AV for each group of specimens in terms of the average and range, theoretical maximum mixture specific gravity (G_{mm}), percent binder absorption (P_{ba}), and effective binder film thickness (FT) defined as the effective binder content (P_{be}) coating the surface area of the aggregates with parameters calculated by Saskatchewan Highways and Transportation method STP 204-19. G_{mm} values were measured for LMLC specimens according to AASHTO T 209 and taken from mix design information for onsite PMLC specimens and PMFC cores. The d2s value of 0.014 for single-operator, single-laboratory provided in AASHTO T 209 was used in the comparisons of mixture type (WMA versus HMA) and in the comparisons of specimen type (PMFC cores at construction versus LMLC specimens and versus offsite PMLC specimens) because the other volumetric parameters (i.e., P_{ba} and effective binder FT) were calculated from G_{mm}. Higher G_{mm} values corresponded to higher P_{ba} values and lower effective binder FT values.

The results of these comparisons can be summarized as follows:

- For most mixtures from the four field projects, volumetrics for WMA and HMA were not different for each specimen type based on d2s values. The only exceptions were lower G_{mm} values for both Iowa WMAs with RAP for LMLC specimens and for WMA foaming from the Texas field project for both onsite and offsite PMLC specimens and higher G_{mm} values for two Montana WMAs for offsite PMLC specimens.
- For most Texas, Montana, and New Mexico mixtures, volumetrics for PMFC cores at construction and laboratory mixtures (LMLC and offsite PMLC specimens) were not different for each mixture type based on d2s values. The only exceptions were lower G_{mm} values for offsite PMLC specimens for WMA foaming with RAP from the New Mexico field project and higher G_{mm} values for LMLC specimens for HMA from the Texas field project. For the Iowa mixtures, volumetrics for PMFC cores at construction were not different from those for offsite PMLC specimens, but LMLC specimens had higher G_{mm} values.

As part of the WMA laboratory-conditioning experiment, volumetrics of LMLC specimens and onsite PMLC specimens were also calculated and compared in terms of binder absorption and film thickness (STP 204-19) to further examine factors that may influence moisture susceptibility. This comparison indicated that all onsite PMLC specimens (except for WMA foaming from the Texas field project) had higher G_{mm} values and P_{ba} and lower effective binder FT. Thus, the loose plant mix experienced more conditioning/binder absorption prior to compaction than that mixed in the laboratory. The reduction in mixing and compaction temperatures (T_m and T_c, respectively) and the incorporation of WMA additives resulted in lower G_{mm} values and lower binder absorption as compared with HMA. This phenomenon could reduce the adhesive bond strength between aggregates and binder, possibly making WMA more moisture susceptible in the early life of the pavement.

WMA Laboratory Conditioning

The objective of the WMA laboratory-conditioning experiment was to propose standard laboratory-conditioning protocols for WMA specimens for moisture-susceptibility performance testing. These protocols are intended to be used as part of the WMA mix design procedure or the QA program for WMA. Different conditioning protocols were selected for fabricating WMA LMLC and PMLC specimens, and these specimens were tested to determine the effect of the conditioning protocol on the mixture's dry M_R stiffness. PMFC

cores at construction and after a winter in service were also incorporated in the experimental design to represent HMA and WMA pavements in their early life. In addition to the primary parameter used in this experiment (i.e., dry M_R stiffness), mixture compactability in terms of N to 7% AV was also compared. A small experiment was also completed to evaluate the effects of binder stiffness, aggregate orientation, and AV on M_R stiffness among the different specimen types. Appendix A provides detailed results for HMA and WMA comparing LMLC and PMLC specimens to PMFC cores during the early life of the pavement. Summary results for dry M_R stiffness are presented in this section in addition to brief conclusions from the comparison of other parameters and the small experiment.

Table 3-1 summarizes the results for LMLC specimens, including statistical analysis by Tukey's HSD test at a 5% significance level, to compare the different conditioning protocols. Prior to examining this main factor of interest, neither the effect of orientation (i.e., rotating the specimen 90 degrees after the first measurement, as required by the standard method) nor the interaction effect between orientation and conditioning protocol was shown to be statistically significant by a split plot design analysis. The effect of conditioning protocol was statistically significant for all mixtures, except for Texas HMA.

In Table 3-1, red shading indicates statistically higher M_R stiffness values for LMLC specimens as compared with PMFC cores at construction, green shading indicates statistically equivalent performance for these specimen comparisons, and yellow shading indicates that LMLC specimens exhibited statistically lower M_R stiffness values for the same comparison. As shown, all of the conditioning protocols resulted in HMA LMLC specimens with M_R stiffnesses that were statistically equivalent as compared with PMFC cores for the Texas field project, but only the 2 h at T_c protocol provided the same results for the Iowa field project, with all other protocols resulting in higher M_R stiffnesses for the HMA LMLC specimens. This same conditioning protocol of 2 h at T_c provided the best agreement between M_R stiffnesses for LMLC specimens and corresponding PMFC cores for the WMA mixtures from both the Iowa and Texas field projects with only lower M_R stiffnesses for the LMLC specimens for WMA Evotherm® 3G with RAP from Iowa and the least difference between these specimen types for WMA foaming from Texas. The conditioning protocols at longer times or higher temperatures resulted in LMLC specimens of more mixtures per field project with M_R values that were statistically higher than PMFC cores at construction.

In summary, dry M_R stiffness results showed that the stiffnesses of LMLC specimens increased with higher conditioning temperatures and longer conditioning time and that WMA was more sensitive to conditioning temperature than conditioning time. Among the five selected conditioning protocols for LMLC specimens, 2 h at T_c was most representative in terms of stiffnesses for both HMA and WMA pavements in their early life. Considering the difficulty in accurately defining T_c in the field, the common range of T_c for HMA and WMA (Table for this project) and the current standard temperature for HMA in AASHTO R 30 of 2 h at 275°F (135°C) and 240°F (116°C) instead of 2 h at T_c was proposed as the standard laboratory-conditioning protocol prior to compaction for HMA and WMA LMLC specimens, respectively.

Table 3-2 summarizes the corresponding results for both onsite and offsite PMLC specimens, including statistical analysis by Tukey's HSD test at a 5% significance level to compare the different conditioning protocols with colored shading as described previously. Based on the ANOVA results, the interaction effect between conditioning protocol and orientation was again statistically insignificant for all mixtures. The main effect orientation was statistically insignificant for all mixtures except for Texas WMA Evotherm DAT™, but the difference was practically insignificant. The effect of conditioning protocol was statistically significant for all mixtures.

Table 3-1. Summary trends for WMA laboratory-conditioning experiment for dry M_R stiffness of LMLC specimens vs. PMFC cores at construction.

		LMLC Conditioning Protocols				
Location	Mixture Type	2 h @ Tc	4 h @ Tc	2 + 16 + 2 h @ Tc	2 h @ 275°F	4 h @ 275°F
Iowa	HMA+RAP					
	Evotherm 3G+RAP					
	Sasobit+RAP					
Texas	HMA			N/A		
	Evotherm DAT					
	Foaming	Least Difference				
Key	LMLC = PMFC		LMLC > PMFC		LMLC < PMFC	

Note: T_c: compaction temperature.

Table 3-2. Summary trends for WMA laboratory-conditioning for dry M_R stiffness of PMLC specimens vs. PMFC cores at construction.

		Conditioning Protocols				
		Onsite PMLC	Offsite PMLC			
Location	Mixture Type	1-2 h @ T_c	R to T_c	R + 2 h @ T_c	16 h + R + 2 h @ T_c	R + 4 h @ 275°F
Iowa	HMA+RAP	Least Difference				
	Evotherm 3G+RAP					
	Sasobit+RAP	Least Difference				
Texas	HMA					
	Evotherm DAT					
	Foaming					
		Onsite PMLC	Offsite PMLC			
		1-2 h @ T_c	R to 275°F (HMA) R to 240°F (WMA)		Reheat to T_c	
Montana	HMA					
	Evotherm 3G					
	Sasobit		Least Difference			

Key: PMLC = PMFC; PMLC > PMFC

Note: R: reheat; T_c: compaction temperature.

For all Texas mixtures, onsite PMLC specimens exhibited equivalent M_R stiffnesses to those for PMFC cores at construction. For the Iowa mixtures, this same equivalence was only valid for Iowa WMA Evotherm® 3G with RAP, but the least difference as compared to PMFC cores at construction was shown for onsite PMLC specimens for the other two Iowa mixtures. Generally, conditioning protocols for offsite PMLC specimens yielded statistically higher M_R stiffnesses as compared with those for PMFC cores at construction. Therefore, stabilizing the plant mix to a standard T_c of 240°F (116°C) and 275°F (135°C) for WMA and HMA, respectively, to prepare onsite PMLC specimens is proposed for QA. If onsite PMLC specimens are not available, reheating plant mix to a standard T_c of 240°F (116°C) and 275°F (135°C) is proposed to produce offsite PMLC specimens for WMA with additives and HMA, respectively. Considering the evaporation of water in foamed mixtures and the assumed loss of effectiveness of foaming properties when reheating, conditioning of offsite PMLC specimens for WMA foaming must follow the same protocol as that for HMA, i.e., reheating to 275°F (135°C).

Compaction temperatures for WMA from the Montana field project were significantly higher than those from the Iowa and Texas field projects (Table 3-2). Therefore, to further validate the proposed conditioning protocols for offsite PMLC specimens, offsite PMLC specimens for the Montana field project were fabricated following the proposed protocol as well as reheating to the actual T_c of 315°F (157°C) for HMA and 275°F (135°C) for WMA with additives. Then, the M_R stiffness of these offsite PMLC specimens and corresponding onsite PMLC specimens were compared against PMFC cores at construction. M_R stiffness results and results from the same type of statistical analysis used for LMLC and PMLC specimens from the Iowa and Texas field projects are provided in Appendix A.

The summary comparisons shown in Table 3-2 also include the results from Montana. As shown, for Montana HMA and WMA Evotherm® 3G, both the proposed conditioning protocols and those of reheating to actual T_c yielded offsite PMLC specimens with equivalent M_R stiffnesses to the PMFC cores at construction. In the case of Montana Sasobit®, higher M_R stiffnesses were shown for both sets of offsite PMLC specimens; however, a smaller difference in M_R stiffness was shown using the proposed conditioning protocol. Therefore, the proposed alternative conditioning protocol for offsite PMLC specimens of reheating plant mix to 275°F (135°C) for HMA and WMA foaming and to 240°F (116°C) for all WMA mixtures except WMA foaming was verified.

In addition to the primary parameter of interest in this experiment (i.e., dry M_R stiffness), mixture compactability was compared for specimens fabricated with different conditioning protocols. Mixture compactability data in terms of the number of SGC gyrations (N) to 7% AV agreed with the dry M_R stiffness results. More gyrations were required to achieve the same AV level during compaction for LMLC specimens conditioned with protocols with longer times and at higher temperatures.

Onsite PMLC specimens and PMFC cores taken at construction were expected to have similar dry M_R stiffnesses,

as they experienced approximately the same level of binder aging, with the PMFC cores possibly aging more during transportation to the paving site. Dry M_R stiffness results from the Texas field project verified this expected behavior, while corresponding results from the Iowa field project showed a different trend. For the Iowa field project, the onsite PMLC specimens showed higher dry M_R stiffnesses as compared with those for the PMFC cores at construction. To evaluate these differences with respect to binder stiffness and aggregate orientation, binders were extracted and recovered from HMA and Evotherm WMA onsite PMLC specimens and PMFC cores obtained from both projects. The stiffness of the extracted binders was then evaluated with the DSR in terms of $G^*/\sin\delta$. In addition, the effect of the aggregate orientation was estimated via image analysis techniques, and differences in AV content were considered.

The stiffness of the binder extracted from PMFC cores at construction was higher than the stiffness of the binder extracted from onsite PMLC specimens, as indicated by DSR testing. Thus, the discrepancy in mixture and binder stiffness between PMFC cores at construction and onsite PMLC specimens was likely due to other factors that overcome the difference in binder stiffness, such as mixture anisotropy induced by different compaction methods (i.e., laboratory versus field) and different AV. Based on image analysis techniques, the onsite PMLC specimens showed less horizontal anisotropy as compared with PMFC cores at construction, as expected, resulting in less resistance to the diametral load in the M_R test. Higher AV may also significantly reduce the mixture stiffness in terms of M_R. Therefore, mixture anisotropy and overall AV had a greater effect on mixture stiffness than the increasing binder stiffness.

WMA Moisture Susceptibility

The objectives of the WMA moisture-susceptibility experiment were to (1) evaluate moisture susceptibility of WMA as compared with that of HMA based on standard laboratory tests and (2) examine the effects of anti-stripping agents to improve moisture susceptibility. HMA and WMA performance was compared in terms of moisture susceptibility evaluated on the basis of wet IDT strength and TSR, wet M_R stiffness and M_R-ratio, and HWTT SIP and stripping slope. Different specimen types were also compared within each mixture type to examine important differences in (1) LMLC specimens used in mix design, (2) PMLC specimens used in QA, (3) PMLC specimens reheated for offsite compaction, and (4) field performance as determined by laboratory testing of PMFC cores.

Appendix B provides detailed results for the different performance parameters by mixture type. Summary results are presented in this section for this experiment in tables of the trends observed for the different performance parameters measured in laboratory tests. The comparisons in test results shown in these summary tables are based on the following for each test parameter:

- Wet IDT strength: ANOVA and Tukey's HSD statistical analysis at a 5% significance level.
- TSR: d2s value of 9.3% (Azari 2010).
- Wet M_R stiffnesses: ANOVA and Tukey's HSD statistical analysis at a 5% significance level.
- M_R-ratio: assumed d2s value of 10%.
- HWTT SIP: numerical comparison with an allowable difference of 2,000 load cycles based on data from the Texas field project.
- HWTT stripping slope: numerical comparison with the allowable difference of 0.2 μm/cycle based on data from the Texas field project.

Moisture Susceptibility

Table 3-3 summarizes the comparison of WMA versus HMA mixture performance from the four field projects in terms of wet IDT strength and TSR for PMFC cores at construction and after field aging, onsite and offsite PMLC specimens, and LMLC specimens. This same comparison is shown for HWTT SIP and stripping slope in Table 3-4, and Table 3-5 shows the comparisons for wet M_R stiffness and M_R-ratio for only onsite and offsite PMLC specimens and LMLC specimens. In Tables 3-3, 3-4, and 3-5, red shading indicates decreased WMA performance as compared to HMA, and green shading indicates WMA performance at least equivalent to that of HMA. Tables 3-3, 3-4, and 3-5 also indicate when WMA fails common thresholds even with better or equivalent performance as compared to HMA and when WMA passes common thresholds but exhibits inferior performance as compared to HMA. These common performance thresholds include minimum 80% for TSR and M_R-ratio, minimum SIP of 10,000 based on the Iowa specification, and minimum wet IDT strengths of 65 psi and 80 psi for mixtures with unmodified (Iowa) and modified (Montana, New Mexico, and Texas) binders based on averages from the Nevada, Tennessee, and Texas specifications.

In the Iowa field project, generally inferior performance was exhibited by WMA with RAP in terms of wet IDT strengths and TSR values of PMFC cores at construction and PMFC cores after winter at 6 months in service. However, there was a significant increase in these parameters for PMFC cores after summer at 12 months in service such that WMA with RAP performance was at least equivalent to HMA with RAP. This same trend was shown for the Texas field project when comparing WMA versus HMA PMFC cores at construction to PMFC cores after summer at 8 months in service in terms of

Table 3-3. Summary trends for IDT strength results.

Location	Specimen Type	Wet IDT			TSR		
		Evotherm	Sasobit	Foaming	Evotherm	Sasobit	Foaming
Iowa	Cores at construction	Fail		N/A			N/A
	Cores after winter				Fail		
	Cores after summer						
	Onsite PMLC				Pass	Pass	
	Offsite PMLC				Fail		
	LMLC					Fail	
Montana	Cores at construction						
	Cores after winter						
	Onsite PMLC	Fail	Fail	Fail	Fail	Fail	Fail
	Offsite PMLC	Pass	Pass			Pass	
Texas	Cores at construction	Fail	N/A	Fail	Fail	N/A	
	Cores after summer						
	Onsite PMLC				Fail		Fail
	Offsite PMLC			Pass	Fail		Fail
	LMLC						
New Mexico	Cores at construction	Pass	N/A			N/A	
	Onsite PMLC						
	Offsite PMLC						
	LMLC			Fail	Fail		Fail
Key		WMA ≥ HMA			WMA < HMA		

Table 3-4. Summary trends for HWTT results.

Location	Specimen Type	HWTT SIP			HWTT Stripping Slope		
		Evotherm	Sasobit	Foaming	Evotherm	Sasobit	Foaming
Iowa	Cores at construction	Fail	Fail	N/A			N/A
	Cores after winter	Fail	Fail				
	Cores after summer	Fail	Fail				
	Onsite PMLC	Fail	Fail				
	Offsite PMLC	N/A			N/A		
	LMLC	Fail	Fail				
Montana	Cores at construction						
	Cores after winter			Fail			
	Onsite PMLC						
	Offsite PMLC			Pass			
Texas	Cores at construction		N/A			N/A	
	Cores after summer						
	Onsite PMLC			Fail			
	Offsite PMLC	Pass					
	LMLC						
New Mexico	Cores at construction		N/A			N/A	
	Onsite PMLC						
	Offsite PMLC						
	LMLC						
Key		WMA ≥ HMA			WMA < HMA		

Table 3-5. Summary trends for M_R results.

Location	Specimen Type	Wet M_R			M_R-ratio		
		Evotherm	Sasobit	Foaming	Evotherm	Sasobit	Foaming
Iowa	Onsite PMLC			N/A	Fail	Fail	N/A
	Offsite PMLC				Fail	Fail	
	LMLC				Fail	Fail	
Montana	Onsite PMLC						Pass
	Offsite PMLC						
Texas	Onsite PMLC		N/A		Fail	N/A	Fail
	Offsite PMLC				Fail		
	LMLC						
New Mexico	Onsite PMLC		N/A			N/A	
	Offsite PMLC						
	LMLC				Fail		Fail

Key: WMA ≥ HMA; WMA < HMA

HWTT SIP and stripping slope. For the Montana field project, at least equivalent performance of WMA as compared to HMA was shown for PMFC cores at construction and after winter at 6 months in service for wet IDT strength, TSR, and HWTT performance parameters. This same trend was observed for the Texas field project, but only for wet IDT strength and TSR for all except the WMA foaming PMFC cores at construction. Again, the same trend was shown for the Iowa field project for all PMFC cores in terms of HWTT SIP, but for stripping slope, WMA Sasobit® with RAP exhibited inferior performance as compared to HMA with RAP for all PMFC cores, and WMA Evotherm® 3G with RAP exhibited generally adequate performance for PMFC cores. With only PMFC cores at construction available in the New Mexico project, WMA with RAP had adequate (at least equivalent) performance as compared to HMA with RAP for both HWTT parameters and TSR values; wet IDT strength with inadequate performance was noted for Evotherm® 3G with RAP, but the value was still above the 80 psi common threshold for modified binders.

Comparing onsite and offsite PMLC specimens, there was no difference between WMA with RAP and HMA with RAP for the Iowa field project in terms of wet M_R and M_R-ratio and for the New Mexico field project in terms of wet IDT strength and TSR and HWTT SIP and stripping slope. Generally, there was no difference between WMA and HMA for these specimens for the Texas field project for wet IDT strength and TSR and for the Montana field project for the HWTT parameters. Exceptions were generally seen when reheating WMA foaming mixtures (to 275°F [135°C] as for HMA) that resulted in unexpected inferior performance. For this same comparison in the Iowa field project, adequate (at least equivalent) performance was exhibited by WMA in terms of wet IDT strengths and TSR values only after reheating to compact off site. This same trend was shown in the New Mexico field project for WMA foaming with RAP in terms of wet M_R and M_R-ratio, while WMA Evotherm® 3G with RAP showed no difference. This same increase in performance after reheating was seen for WMA Evotherm DAT™ in the Texas field project for wet M_R and WMA foaming in the Montana field project for M_R-ratio, while most of the other WMA mixtures showed no difference as compared to HMA for these performance parameters.

Exceptions where unexpected inferior performance as compared to HMA was obtained after reheating were observed in the case of WMA foaming in the Texas field project for M_R-ratio and WMA Evotherm® 3G in the Montana field project for wet M_R. This same phenomenon of unexpected inferior performance after reheating the plant mix was exhibited by WMA Sasobit® for both wet IDT strength and TSR and WMA Evotherm® 3G for only wet IDT strength in the Montana field project. WMA foaming in this field project showed no difference with HMA for both of these parameters, and WMA Evotherm® 3G showed no difference for TSR value. For the Texas field project, generally inferior performance of WMA was noted in terms of the HWTT parameters for both onsite and offsite PMLC specimens, with only WMA Evotherm DAT™ showing an increase in performance with reheat-

ing for the stripping slope. Finally, for the Iowa field project where HWTT results were not available for offsite PMLC specimens, inferior performance was shown in terms of stripping slope, but adequate performance was noted for SIP.

LMLC specimens were available for the Iowa, Texas, and New Mexico field projects. For the New Mexico field project, there were no differences noted between WMA with RAP and HMA with RAP for any of the moisture susceptibility parameters evaluated. This same trend was noted for both WMA mixtures with RAP in the Iowa field project for both ratios (TSR and M_R-ratio) and SIP, but inferior performance as compared to HMA with RAP was shown for wet IDT strength, wet M_R, and stripping slope. For the Texas field project, WMA foaming exhibited inferior performance as compared to HMA for all of the moisture-susceptibility parameters evaluated, while WMA Evotherm DAT™ exhibited inferior performance for both HWTT parameters and TSR.

Based on the complete set of laboratory performance tests for all four field projects, WMA can be more moisture susceptible in its early life prior to a summer of aging. However, WMA generally exhibits adequate (at least equivalent) performance as compared to HMA in terms of moisture susceptibility measured in the laboratory after a summer of aging. The use of anti-stripping agents may reduce this susceptibility. Finally, there are differences in offsite and onsite PMLC specimens in terms of laboratory-measured moisture susceptibility, with the artificial aging due to reheating generally producing specimens with improved resistance to moisture damage.

Effect of Anti-Stripping Agents

Tables 3-6 and 3-7 summarize the comparison of WMA and HMA design mixtures with those with added anti-stripping agents. In Tables 3-6 and 3-7, red shading indicates decreased performance as compared to the design mixture, yellow shading indicates equivalent performance as compared to the design mixture, and green shading indicates improved performance as compared to the design mixture. For this experiment, LMLC specimens were produced for the Iowa and Texas field projects to evaluate the effect of adding hydrated lime or LAS in terms of wet IDT strength and TSR and wet M_R stiffness and M_R-ratio. Before compaction, the loose mix was conditioned according to the proposed laboratory-conditioning experiment protocol.

In general, when looking at all of the performance parameters evaluated, the addition of either hydrated lime or LAS did not improve the performance of either WMA or HMA across all parameters (wet IDT strength, wet M_R, and M_R-ratio), although some benefits were noted for some mixtures for some of these parameters. In terms of the traditional parameter for assessing moisture susceptibility (TSR), addition of LAS resulted in improved performance for four out of the six mixtures evaluated. WMA Sasobit® with RAP in the Iowa field project and WMA foaming in the Texas field project also benefitted in terms of this parameter and wet M_R with the addition of hydrated lime. Adding hydrated lime also resulted in improved performance for WMA foaming in the Texas field project for M_R-ratio, and adding LAS resulted in improved performance for WMA Sasobit® with RAP in the Iowa field project for M_R-ratio and for WMA Evotherm DAT™ in the Texas field project for wet IDT strength. HMA with RAP in the Iowa field project also showed improved performance with hydrated lime for wet IDT strength. The most benefits from the addition of anti-stripping agents were shown for the WMA foaming from the Texas project and the WMA Sasobit® with RAP from the Iowa field project. These mixtures were weaker in terms of moisture-susceptibility parameters, as discussed in detail in Appendix B. Finally, the incorporation of additional

Table 3-6. Summary trends for IDT strength results from the anti-stripping agent experiment.

Location	Mixture Type	Wet IDT		TSR	
		Hydrated Lime	LAS	Hydrated Lime	LAS
Iowa	HMA+RAP				
	Evotherm 3G+RAP				
	Sasobit+RAP				
Texas	HMA				
	Evotherm DAT				
	Foaming				

Key: AS = Design; AS < Design; AS > Design

Table 3-7. Summary trends for M_R results from anti-stripping agent experiment.

Location	Mixture Type	Wet M_R		M_R-Ratio	
		Hydrated Lime	LAS	Hydrated Lime	LAS
Iowa	HMA+RAP				
	Evotherm 3G+RAP				
	Sasobit+RAP				
Texas	HMA				
	Evotherm				
	Foaming				

Key: AS = Design; AS < Design; AS > Design

LAS to WMA Evotherm from either the Iowa or Texas field projects showed a counterproductive effect, decreasing performance in four cases. This could be attributed to the incompatibility between the amine compounds in Evotherm with the LAS components used in this study.

Based on the mixed results shown, the selection of an optimum anti-stripping agent does not appear to be related to WMA technology or different from the process used for HMA. As for HMA, an important factor to consider is the aggregate type; LAS agents are likely more sensitive to the compatibility with the aggregate and the WMA additive type than hydrated lime.

Effect of Specimen Type

Tables 3-8 through 3-10 summarize the comparison of specimen types from the four field projects in terms of wet IDT strength and TSR, HWTT SIP and stripping slope, and wet M_R and M_R-ratio, respectively. The analysis focused on these comparisons for the WMA mixtures.

For both WMAs from both the Iowa and Texas field projects, the LMLC specimens successfully represented the early-life field performance (PMFC cores at construction and after winter at 6 months in service for Iowa) in terms of wet IDT strength. For the Iowa field project, the onsite and offsite PMLC specimens for both WMAs with RAP generally represented the PMFC cores after field aging over a summer (12 months in service) for this parameter. For the Texas field project, the PMFC cores after summer at 8 months in service for both WMAs exhibited increased wet IDT strength as compared to onsite and offsite PMLC specimens that also represented the early-life field performance (PMFC cores at construction). For the Montana field project, which did not include LMLC specimens, the offsite PMLC specimens were generally able to represent early-life field performance (PMFC cores at construction and after winter at 6 months in service for WMA Evotherm® 3G); for two WMAs, the onsite PMLC specimens exhibited lower wet IDT strengths. For the third WMA for this field project (i.e., WMA foaming), the PMFC cores at construction and after winter at 6 months in service had wet IDT strengths between the onsite PMLC specimens and the offsite PMLC specimens, with the latter showing the largest IDT strength for the Montana WMA foaming.

When comparing TSR values, the LMLC specimens successfully represented the early-life field performance for the Iowa field project with equivalent values based on the d2s value for this test method for PMFC cores at construction and for the Texas field project with values between the PMFC cores at construction and those after summer at 8 months in service. For the New Mexico project, LMLC specimens did not represent PMFC cores at construction. In addition, onsite and offsite PMLC specimens exhibited equivalent TSR values (based on the d2s value) for both WMAs in both the Iowa and Texas field projects and one WMA in the New Mexico field project. However, for all three WMAs in the Montana field project and the other WMA in the New Mexico field project, these types of specimens were not equivalent in terms of TSR.

For wet M_R, LMLC specimens for the Iowa project were not representative of the onsite or offsite PMLC specimens that exhibited increased wet M_R values for both WMAs. Better representation by the LMLC specimens of the onsite and offsite PMLC specimens was shown for both WMAs in the Texas field project. In addition, the onsite and offsite PMLC specimens produced statistically equivalent wet M_R values for all of the WMAs, except WMA Evotherm in both the Texas and Montana field projects and WMA foaming with RAP in the New Mexico field project. This same general agreement

Table 3-8. Effect of specimen type based on IDT strength results.

Location	Specimen Type	Wet IDT			TSR		
		Evotherm	Sasobit	Foaming	Evotherm	Sasobit	Foaming
Iowa	Cores at construction	B	C	N/A			N/A
	Cores after winter	B	C				
	Cores after summer	A	A				
	Onsite PMLC	A	B				
	Offsite PMLC	A	A				
	LMLC	B	C				
Montana	Cores at construction	A	A-B	B			
	Cores after winter	A	A	B			
	Onsite PMLC	B	C	C			
	Offsite PMLC	A	B	A			
Texas	Cores at construction	C	N/A	B	N/A	N/A	N/A
	Cores after summer	A		A			
	Onsite PMLC	B-C		B			
	Offsite PMLC	B		B			
	LMLC	B-C		B			
New Mexico	Cores at construction	A	N/A	A	N/A	N/A	N/A
	Onsite PMLC	A		B			
	Offsite PMLC	A		C			
	LMLC	B		D			

Key TSR LMLC = Cores Different Offsite = Onsite PMLC

between onsite and offsite PMLC specimens was observed for M_R-ratio for all WMAs, except WMA Evotherm® 3G from the Montana field project and WMA foaming from both the Texas and New Mexico field projects.

For the HWTT parameters (SIP and stripping slope), LMLC specimens successfully represented the early-life field performance (PMFC cores at construction and after winter at 6 months in service for Iowa) in terms of SIP for all WMAs in all field projects, except WMA foaming in the Texas field project. All WMAs, except WMA Evotherm DAT™ in the Texas field project, also showed agreement in this parameter between onsite and offsite PMLC specimens. Agreement between these specimen types was also shown for stripping slope for two WMAs in the Montana field project and both WMAs with RAP in the New Mexico field project. The WMAs in both the Iowa and Texas field projects did not show agreement between onsite and offsite PMLC specimens for this parameter. For stripping slope, only one WMA in the Texas field project and both WMAs in the New Mexico field project showed agreement in terms of LMLC specimens representing early-life field performance (PMFC cores at construction). In general, stripping slope seemed to be a more sensitive parameter than SIP for identifying differences in mixture and specimen types.

WMA Performance Evolution

The objectives of the two-phase WMA performance evolution experiment were to (1) determine when (or if) properties of HMA and WMA converged and (2) evaluate the evolution of performance of WMA as compared to HMA in the early life of the pavement. In the first phase, the moisture susceptibility of WMA was determined in terms of a critical

Table 3-9. Effect of specimen type based on M_R results.

Location	Specimen Type	Wet M_R Evotherm	Wet M_R Sasobit	Wet M_R Foaming	M_R-ratio Evotherm	M_R-ratio Sasobit	M_R-ratio Foaming
Iowa	Onsite PMLC	A	A	N/A			N/A
	Offsite PMLC	A	A				
	LMLC	B	B				
Montana	Onsite PMLC	A	A	A			
	Offsite PMLC	B	A	A			
Texas	Onsite PMLC	B	N/A	A-B		N/A	
	Offsite PMLC	A		A			
	LMLC	A-B		B			
New Mexico	Onsite PMLC	A	N/A	B		N/A	
	Offsite PMLC	A		A			
	LMLC	B		B			

Key M_R-ratio: Different; Offsite = Onsite PMLC

age to reach a dry M_R stiffness equivalent to that of an HMA control mixture. The evolution of dry M_R stiffness in HMA and WMA in the field and laboratory were evaluated separately, followed by the correlation of laboratory and field aging. In the second phase, HMA and WMA performance was compared in terms of dry M_R stiffness and moisture susceptibility evaluated on the basis of wet IDT strength, TSR, wet M_R stiffness, M_R-ratio, HWTT SIP, and stripping slope after LTOA of compacted specimens at different time periods.

Appendix C provides detailed results for the evolution of dry M_R stiffness and moisture susceptibility parameters measured in laboratory tests due to field and laboratory aging of

Table 3-10. Effect of specimen type based on HWTT results.

Location	Specimen Type	HWTT SIP Evotherm	HWTT SIP Sasobit	HWTT SIP Foaming	HWTT Stripping Slope Evotherm	HWTT Stripping Slope Sasobit	HWTT Stripping Slope Foaming
Iowa	Cores at construction			N/A			N/A
	Cores after winter						
	Cores after summer						
	Onsite PMLC						
	Offsite PMLC						
	LMLC						
Montana	Cores at construction						
	Cores after winter						
	Onsite PMLC						
	Offsite PMLC						
Texas	Cores at construction		N/A			N/A	
	Cores after summer						
	Onsite PMLC						
	Offsite PMLC						
	LMLC						
New Mexico	Cores at construction		N/A			N/A	
	Onsite PMLC						
	Offsite PMLC						
	LMLC						

Key: LMLC = Cores; Different; Offsite = Onsite PMLC

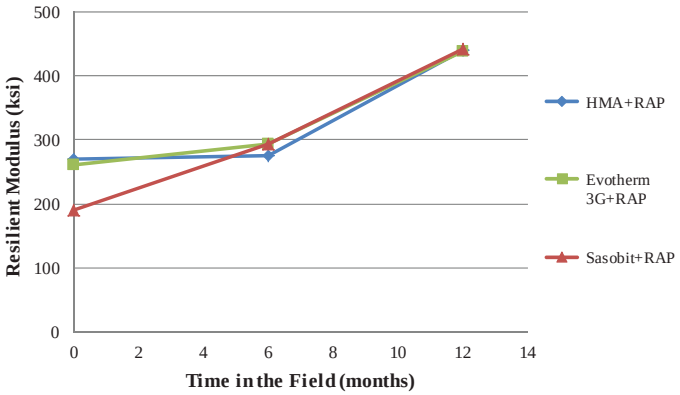


Figure 3-1. Evolution of M_R stiffness with field aging for the Iowa field project.

HMA and WMA. Summary results are presented in this section for both phases of this experiment.

Phase I

Field Aging

The period in the field where equivalent dry M_R stiffness between HMA and WMA was achieved was determined for the Iowa and Texas field projects, respectively, from Figure 3-1 and Figure 3-2. For Iowa (Figure 3-1), the initial stiffness of PMFC cores for HMA with RAP was higher than that for WMA Sasobit® with RAP and equivalent to that for WMA Evotherm® 3G with RAP. For PMFC cores after winter at 6 months in service, equivalent stiffness between HMA with RAP and WMAs with RAP was achieved. For Texas (Figure 3-2), the stiffness of PMFC cores at construction for HMA was higher than both WMA mixtures, while the stiffness of WMA foaming was higher than that of WMA Evotherm DAT™. After summer at 8 months in service, the stiffness of PMFC cores for all mixtures increased significantly, and equivalent stiffness was achieved between HMA and WMA foaming.

In addition, onsite PMLC specimens from the Texas field project conditioned 1–2 h at T_c as compared to those conditioned 0–1 h at the same temperature exhibited equivalent dry M_R stiffnesses. Equivalent stiffnesses were also shown for onsite PMLC specimens and PMFC cores at construction for the Texas field project, indicating the same level of mixture aging as expected. Conversely, for the Iowa field project, onsite PMLC specimens exhibited higher M_R stiffnesses than PMFC cores at construction. These differences were attributed to aggregate anisotropy resulting from different compaction methods and total AV in the specimens.

From the dry M_R stiffness results, it can be inferred that HMA and WMA PMFC cores from both field projects experienced a significant increase in stiffness with aging in the field. The increase in stiffness after a summer was more significant than that after a winter, probably because of the high in-service temperature and substantial aging experienced by the pavement in the summer. Equivalent stiffnesses between HMA with RAP and WMA with RAP were achieved for PMFC cores after winter at 6 months in service for Iowa, while for the Texas field project, PMFC cores of WMA Evotherm DAT™ were less stiff than those of HMA and WMA foaming. Thus, in the case of Texas, PMFC cores over a longer service time in the field would be needed to determine the period necessary for the stiffness of HMA and WMA Evotherm DAT™ to converge. Additionally, a higher rate of increase in M_R stiffness was shown for WMA pavements as compared to HMA pavements for both Iowa and Texas field projects, with the exception of WMA Evotherm® 3G with RAP for the Iowa field project.

Laboratory Aging

Figures 3-3 and 3-4 indicate that, for both the Iowa and Texas field projects, the dry M_R stiffness of HMA and WMA LMLC specimens increased significantly after subjecting

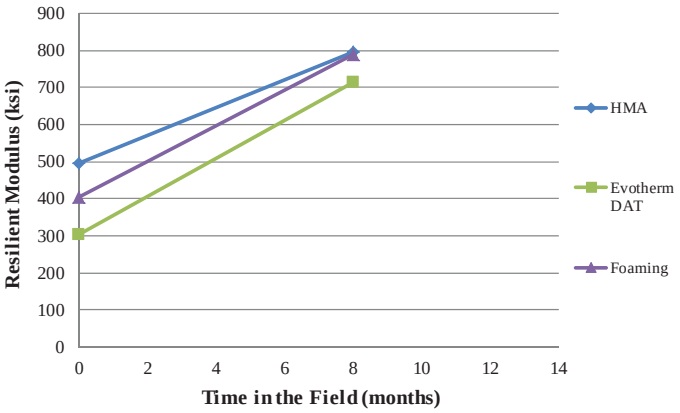


Figure 3-2. Evolution of M_R stiffness with field aging for the Texas field project.

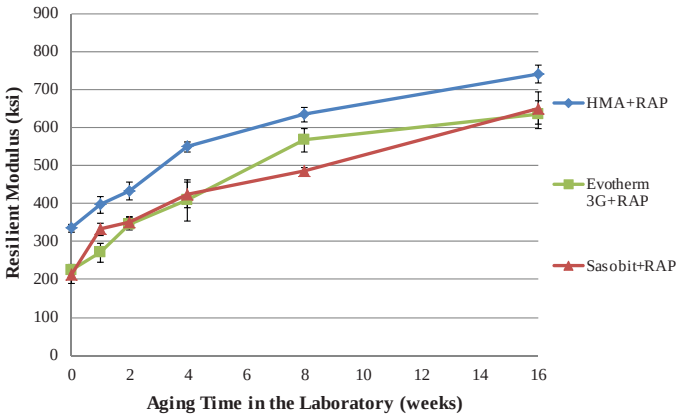


Figure 3-3. Evolution of M_R stiffness with laboratory aging at 140°F (60°C) for the Iowa field project.

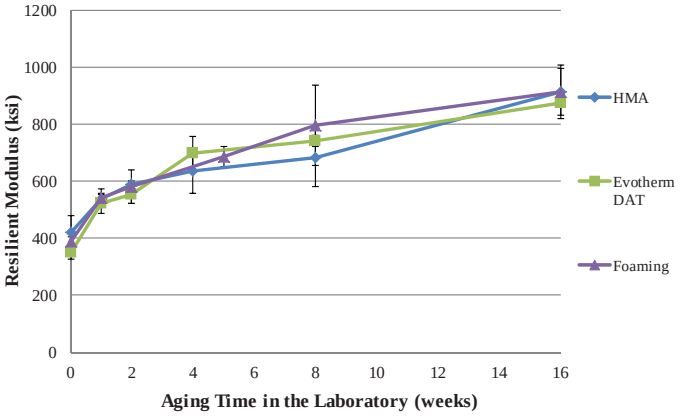


Figure 3-4. Evolution of M_R stiffness with laboratory aging at 140°F (60°C) for the Texas field project.

the compacted specimens to aging in the laboratory at 140°F (60°C). As shown, the rate of aging or slopes of the piecewise linear relationships were similar for HMA and WMA, with steeper slopes for both types of mixtures during the first week of laboratory aging. To further explore the laboratory aging behavior, an exponential curve was fitted to the dry M_R stiffness data. Based on these fitted curves, the laboratory aging protocol of 2 weeks at 140°F (60°C) was selected for Phase II of the WMA performance-evolution experiment. This aging period represented the time at which the stiffness of WMA was similar to the initial stiffness of HMA (Iowa field project) or the stiffness of HMA and WMA converged (Texas field project). Additionally, considering a previous study in Texas on the correlation between laboratory and field aging (Glover et al. 2005), a second laboratory aging protocol of 16 weeks at 140°F (60°C) was selected to characterize the field aging of asphalt pavements approximately 1 to 2 years after construction. The standard laboratory aging protocol of 5 days at 185°F (85°C) by AASHTO R 30 was selected as the third protocol.

Correlation of Laboratory and Field Aging

Table 3-11 summarizes the comparison of dry M_R stiffnesses for LMLC specimens with different laboratory aging protocols versus those for PMFC cores after different in-service times, including statistical analysis by Tukey's HSD test at a 5% significance level to compare the different laboratory aging protocols. In Table 3-11, red shading indicates statistically higher M_R stiffness values for LMLC specimens as compared to PMFC cores, green shading indicates statistically equivalent performance for these specimen comparisons, and yellow shading indicates that LMLC specimens exhibited statistically lower M_R stiffness values for the same comparisons.

As shown in Table 3-11, equivalent dry M_R stiffness between LMLC specimens with LTOA protocols at 140°F (60°C) for up to 2 weeks and PMFC cores at construction and after a winter (at 6 months in service for Iowa) was shown for most of Iowa and Texas mixtures, indicating equivalent initial stiffness in the laboratory and field. In addition, the laboratory LTOA protocols at 140°F (60°C) for 4 to 16 weeks were representative of the field aging experienced by PMFC cores after a summer (at 12 months in service for Iowa and at 8 months in service for Texas).

Phase II

In Phase II of the WMA performance evolution experiment, new sets of LMLC specimens were fabricated and, after compaction, subjected to the three LTOA protocols selected in Phase I prior to being evaluated on performance. The effects of field aging and laboratory LTOA on HMA and WMA performance, the correlation between laboratory

Table 3-11. Summary trends for dry M_R stiffness in Phase I of WMA performance evolution.

		LTOA Protocols – Weeks at 140°F (60°C)															
		0	1	2	4	8	16	0	1	2	4	8	16	0	1	2	4	8	16
Location	Mixture Type	vs. PMFC Cores at Construction						vs. PMFC Cores after 1st Winter						vs. PMFC Cores after 1st Summer					
Iowa	HMA+ RAP																		
	Evotherm 3G+RAP																		
	Sasobit																		
Texas	HMA							N/A											
	Evotherm DAT																		
	Foaming																		
	Key	LMLC > PMFC Cores						LMLC = PMFC Cores						LMLC < PMFC Cores					

and field aging, and a comparison of HMA versus WMA for each aging stage are provided in this section in summary tables of the trends observed for the different performance parameters measured in laboratory tests. The comparisons in test results shown are based on the following for each test parameter:

- Dry and wet IDT strength: ANOVA and Tukey's HSD statistical analysis at a 55% significance level.
- TSR: d2s value of 9.3% (Azari 2010).
- Dry and wet M_R stiffnesses: ANOVA and Tukey's HSD statistical analysis at a 55% significance level.
- M_R-ratio: assumed d2s value of 10%.
- HWTT SIP: numerical comparison with an allowable difference of 2,000 load cycles.
- HWTT stripping slope: numerical comparison with an allowable difference of 0.2 μm/cycle.

Effect of Aging on Mixture Performance

Table 3-12 summarizes the comparison of Iowa and Texas mixture performance in IDT strength, M_R, and HWTT tests for PMFC cores after field aging in the summer and winter versus those at construction. In Table 3-12, red shading indicates decreased performance for aged mixtures as compared to those at construction; green shading indicates increased performance with aging; and yellow shading indicates equivalent performance with aging.

In the Iowa field project for HMA with RAP and two WMAs with RAP, dry and wet IDT strengths of PMFC cores

Table 3-12. Summary trends in field aging of PMFC cores.

Mixture	Test	Parameters	Iowa Winter Aging Cores @ 6 months	Iowa Summer Aging Cores @ 12 months	Texas Summer Aging Cores @ 8 months
Iowa HMA+RAP/ Texas HMA	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R	N/A		
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			
Iowa Evotherm 3G+RAP/ Texas Evotherm DAT	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R	N/A		
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			
Iowa Sasobit+RAP	IDT	Dry IDT Strength			N/A
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R	N/A		
		M_R-ratio			
	HWTT	SIP			
		Stripping Slope			
Texas Foaming	IDT	Dry IDT Strength	N/A		
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R			N/A
		M_R-ratio			
	HWTT	SIP			
		Stripping Slope			

Key: Decreased Performance | Increased Performance | Equivalent Performance

at construction and PMFC cores after winter at 6 months in service were generally statistically equivalent. However, dry and wet IDT strengths and dry M_R stiffnesses for PMFC cores after summer at 12 months in service increased significantly. The TSR values of HMA with RAP for PMFC cores decreased from 91 to 62% as field aging time increased from at construction to after summer at 12 months in service. However, the decrease in TSR values for this same aging period for WMA Evotherm® 3G with RAP and WMA Sasobit® with RAP PMFC cores was insignificant.

In the Texas field project for HMA and two WMAs, PMFC cores after summer at 8 months in service had generally higher dry and wet IDT strengths, dry M_R stiffnesses, and TSR values as compared to those at construction. The TSR values of PMFC cores at construction for HMA and two WMAs were lower than 70%, while those of PMFC cores after summer at 8 months in service were closer to or above 80%. For all mixtures in this field project, PMFC cores at construction did not meet the Texas criteria of 20,000 load cycles with less than 0.5 inch (12.5 mm) rut depth. However, PMFC cores after summer at 8 months in service were shown to have significantly better performance in the HWTT test. For the two WMAs, PMFC cores after summer at 8 months in service had increased SIP values and decreased stripping slopes as compared to those at construction, indicating improved resistance to moisture susceptibility.

In general, PMFC cores after field aging in the summer (Iowa PMFC cores after 12 months in service and Texas PMFC cores after 8 months in service) had significantly better performance in the laboratory tests as compared to PMFC cores at construction. However, the difference between PMFC cores after field aging in the winter (Iowa PMFC cores after 6 months in service) and those at construction was insignificant.

Tables 3-13 through 3-15 summarize the comparison of mixture performance in IDT strength, M_R, and HWTT tests for LMLC specimens with LTOA protocols and those without LTOA, for Iowa, Texas, and New Mexico mixtures, respectively, with colored shading as described previously. For the Iowa field project, the laboratory LTOA protocol of 16 weeks at 140°F (60°C) significantly increased the dry and wet IDT strengths and dry and wet M_R stiffnesses of HMA with RAP and two WMAs with RAP but had no significant effect on

Table 3-13. Summary trends in laboratory aging of LMLC specimens for the Iowa field project.

Mixture	Test	Parameters	LTOA 2 weeks @ 60°C	LTOA 16 weeks @ 60°C	LTOA 5 days @ 85°C
HMA+RAP	IDT	Dry IDT Strength	N/A		N/A
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R	N/A		N/A
		Wet M_R			
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			
Evotherm 3G+RAP	IDT	Dry IDT Strength	N/A		N/A
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R	N/A		N/A
		Wet M_R			
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			
Sasobit+RAP	IDT	Dry IDT Strength	N/A		N/A
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R	N/A		N/A
		Wet M_R			
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			

Key: Decreased Performance | Increased Performance | Equivalent Performance

Table 3-14. Summary trends in laboratory aging of LMLC specimens for the Texas field project.

Mixture	Test	Parameters	LTOA 2 weeks @ 60°C	LTOA 16 weeks @ 60°C	LTOA 5 days @ 85°C
HMA	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R			
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			
Evotherm DAT	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R			
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			
Foaming	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R			
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			

Key: Decreased Performance | Increased Performance | Equivalent Performance

increasing the TSR values or M_R-ratios of LMLC specimens. Additionally, the increase in mixture dry M_R stiffness from the LTOA protocol of 16 weeks at 140°F (60°C) was more significant than that from LTOA protocol of 2 weeks at 140°F (60°C).

For the Texas field project, the same trends as for the Iowa field project were shown for dry and wet IDT strengths and dry and wet M_R stiffnesses (increased with aging) and for TSR values and M_R-ratios (no change with aging) for HMA and two WMAs with the LTOA protocol of 16 weeks at 140°F (60°C), LTOA protocol of 2 weeks at 140°F (60°C), and LTOA protocol of 5 days at 185°F (85°C). The increase in IDT strength and M_R stiffness after the LTOA protocol of 5 days at 185°F (85°C) was significantly greater than or equivalent to that after LTOA protocol of 2 weeks at 140°F (60°C) for HMA. For the two WMAs, the difference between these two aging protocols was less significant. For all mixtures in the Texas field project, LMLC specimens without LTOA did not meet the Texas criteria of 20,000 load cycles with less than 0.5 inch (12.5 mm) rut depth. However, LMLC specimens with laboratory LTOA protocols were shown to have significantly better performance in the HWTT test. For all cases (mixtures and LTOA protocols), LMLC specimens with laboratory LTOA protocols had higher SIP and lower stripping slope than those without LTOA.

For the New Mexico field project, the same trends as for both the Iowa and Texas field projects were shown only for the dry and wet M_R stiffnesses (increased with aging) for HMA with RAP and two WMAs with RAP after LTOA protocols of 2 weeks at 140°F (60°C) and 5 days at 185°F (85°C). M_R-ratios also increased with aging for all three mixtures after the LTOA protocol of 2 weeks at 140°F (60°C) and for HMA with RAP after LTOA protocol of 5 days at 185°F (85°C), but unexpectedly, no significant aging effect was shown for this parameter for the longer LTOA protocol for both WMAs with RAP. All mixtures also exhibited no significant aging effect on either HWTT parameter (SIP and stripping slope) after both LTOA protocols of 2 weeks at 140°F (60°C) and 5 days at 185°F (85°C). For dry and wet IDT strengths, there was a change in the aging effect for LMLC specimens after the LTOA protocol of 2 weeks at 140°F (60°C) and after the LTOA protocol of 5 days at 185°F (85°C) with the HMA with RAP, and one WMA with RAP generally showed no effect after the shorter

Table 3-15. Summary trends in laboratory aging of LMLC specimens for the New Mexico field project.

Mixture	Test	Parameters	LTOA 2 weeks @ 60°C	LTOA 5 days @ 85°C
HMA+RAP	IDT	Dry IDT Strength		
		Wet IDT Strength		
		TSR		
	M_R	Dry M_R		
		Wet M_R		
		M_R-ratio		
	HWTT	SIP		
		Stripping Slope		
Evotherm 3G+RAP	IDT	Dry IDT Strength		
		Wet IDT Strength		
		TSR		
	M_R	Dry M_R		
		Wet M_R		
		M_R-ratio		
	HWTT	SIP		
		Stripping Slope		
Foaming+RAP	IDT	Dry IDT Strength		
		Wet IDT Strength		
		TSR		
	M_R	Dry M_R		
		Wet M_R		
		M_R-ratio		
	HWTT	SIP		
		Stripping Slope		

Key: Decreased Performance | Increased Performance | Equivalent Performance

protocol but increased IDT strengths after the longer protocol. For the other WMA with RAP, there was no aging effect on IDT strengths for either LTOA protocol. The TSR value for this same WMA with RAP also had no aging effect for either LTOA protocol, and the HMA with RAP showed increased TSR values for both LTOA protocols. The other WMA with RAP exhibited an increased TSR value for the shorter LTOA protocol, but unexpectedly, there was no aging effect for the longer protocol.

In general, for all Iowa, Texas, and New Mexico mixtures, LMLC specimens with different LTOA protocols in this study had significantly better performance than those without LTOA, indicating the significant effect of laboratory LTOA in increasing mixture performance.

Tables 3-16 and 3-17 summarize the comparison of mixture performance in IDT strength, M_R, and HWTT tests for PMFC cores after aging in the field and LMLC specimens with LTOA protocols, for Iowa and Texas mixtures, respectively. In these tables, yellow shading indicates decreased performance for LMLC specimens as compared to aged PMFC cores, green shading indicates equivalent performance for these comparisons, and red shading indicates that LMLC specimens exhibited increased performance for the same comparisons.

For the Iowa field project with limited data available, LTOA protocol of 16 weeks at 140°F (60°C) produced LMLC specimens with increased or equivalent performance as compared to PMFC cores after field aging for all performance parameters for both HMA with RAP and two WMAs with RAP. A similar trend was generally shown for dry M_R stiffness for LMLC specimens with LTOA protocol of 2 weeks at 140°F (60°C). For some performance parameters with laboratory aging, increased properties were shown as compared to PMFC cores after winter at 6 months in service, but the laboratory LTOA protocol produced LMLC specimens with equivalent properties with further field aging as compared to PMFC cores after summer at 12 months in service. For TSR values for HMA with RAP and one Evotherm® 3G with RAP, the opposite trend was observed.

For the Texas field project (Table 3-17), the LTOA protocols of 16 weeks at 140°F (60°C) and 5 days at 185°F (85°C) produced LMLC specimens with increased or equivalent performance as

Table 3-16. Summary trends in laboratory vs. field aging for the Iowa field project.

Mixture	Test	Parameters	LTOA 2 weeks @ 60°C	LTOA 16 weeks @ 60°C	LTOA 5 days @ 85°C
HMA+RAP	IDT	Dry IDT Strength	N/A	Increased Performance	N/A
		Wet IDT Strength		Increased Performance	
		TSR		W: Equivalent Performance; S: Increased Performance	
	M_R	Dry M_R	W: Increased Performance; S: Equivalent Performance	Increased Performance	N/A
		Wet M_R	N/A		
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			
Evotherm 3G+RAP	IDT	Dry IDT Strength	N/A	W: Equivalent Performance; S: Increased Performance	N/A
		Wet IDT Strength		Increased Performance	
		TSR		W: Equivalent Performance; S: Increased Performance	
	M_R	Dry M_R	Equivalent Performance	Increased Performance	N/A
		Wet M_R	N/A		
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			
Sasobit+RAP	IDT	Dry IDT Strength	N/A	W: Equivalent Performance; S: Equivalent Performance	N/A
		Wet IDT Strength		W: Equivalent Performance; S: Equivalent Performance	
		TSR		Equivalent Performance	
	M_R	Dry M_R	W: Equivalent Performance; S: Decreased Performance	Increased Performance	N/A
		Wet M_R	N/A		
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			

Key: Increased Performance; Equivalent Performance; Decreased Performance

Note: W: field aging in the winter, PMFC cores after winter at 6 months in service; S: field aging in the summer, PMFC cores after summer at 12 months in service.

compared to PMFC cores after summer at 8 months in service for most of the performance parameters for HMA and both WMAs. Decreased performance as compared to PMFC cores after field aging was shown only for dry IDT strength for HMA after LTOA of 5 days at 185°F (85°C) and for TSR for WMA foaming after LTOA of 16 weeks at 140°F (60°C). Both WMAs after LTOA of 2 weeks at 140°F (60°C) also exhibited decreased performance for most performance parameters, whereas the HMA exhibited increased or equivalent performance for most parameters after this shorter aging protocol.

Based on these results, laboratory LTOA protocols can be used in conjunction with the STOA proposed in this project to capture the evolution of WMA performance in early life. General trends in the test results for both field projects showed that, compared to PMFC cores after field aging, LMLC specimens with LTOA protocols of 16 weeks at 140°F (60°C) and 5 days at 185°F (85°C) exhibited increased or equivalent performance. On the other hand, WMAs with LTOA protocol of 2 weeks at 140°F (60°C) showed decreased performance in the selected laboratory tests.

Comparison of WMA vs. HMA

Table 3-18 summarizes the comparison of WMA and HMA with different field aging times and laboratory LTOA protocols in the Iowa and Texas field projects. Red shading indicates decreased performance for WMA as compared to HMA; green shading indicates increased or equivalent performance for WMA as compared to HMA.

For the Iowa field project, PMFC cores at construction and after winter at 6 months in service for two WMAs with RAP exhibited increased or equivalent performance as compared to those of HMA with RAP for dry M_R stiffness and dry IDT strength. Decreased performance was shown for PMFC cores for wet IDT strength and TSR, and these mixtures improved in terms of both of these performance parameters with field aging after a summer at 12 months in service. All TSR values of PMFC cores except those with WMA Sasobit® with RAP after winter at 6 months in service and HMA with RAP after summer at 12 months in service were higher than 70%. In addition, the LTOA protocol of 16 weeks at 140°F (60°C) produced LMLC specimens with

Table 3-17. Summary trends in laboratory vs. field aging for the Texas field project.

Mixture	Test	Parameters	LTOA 2 weeks @ 60°C	LTOA 16 weeks @ 60°C	LTOA 5 days @ 85°C
HMA	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R		N/A	
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			
Evotherm DAT	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R		N/A	
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			
Foaming	IDT	Dry IDT Strength			
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R		N/A	
		M_R-ratio			
	HWTT	SIP		N/A	
		Stripping Slope			

Key: Increased Performance | Equivalent Performance | Decreased Performance

improved and increased or equivalent performance for both WMAs with RAP as compared to HMA with RAP for all performance parameters except dry M_R stiffness and wet IDT strength for WMA Sasobit® with RAP. These same WMAs with RAP exhibited decreased performance as compared to HMA with RAP for wet and dry IDT strength and wet and dry M_R stiffness with LMLC specimens with no LTOA. Equivalent TSR and M_R-ratio values between HMA with RAP and two WMAs with RAP were obtained for LMLC specimens with no LTOA and with LTOA of 16 weeks at 140°F (60°C).

For the Texas field project, field aging after summer at 8 months in service produced PMFC cores with improved and increased or equivalent performance for both WMAs as compared to HMA for TSR, dry M_R stiffness, SIP, and stripping slope. Increased or equivalent performance for both WMAs as compared to HMA was exhibited for all PMFC cores for wet IDT strength. For most of the performance parameters, LMLC specimens with no LTOA or with LTOA protocol of 2 weeks at 140°F (60°C) for at least one WMA showed decreased performance as compared to HMA. But after LTOA protocols of either 16 weeks at 140°F (60°C) or 5 days at 185°F (85°C), improved and increased or equivalent performance was exhibited by LMLC specimens of both WMAs in terms of wet and dry IDT strength, SIP, and stripping slope. Mixed results in terms of improved WMA performance were shown for these two longer laboratory LTOA protocols for wet and dry M_R stiffness, M_R-ratio, and TSR. All WMA foaming LMLC specimens, except those subjected to the LTOA protocol of 5 days at 185°F (85°C), had the lowest TSR values of all mixture types and lower than the minimum threshold of 80% suggested by AASHTO T 283. WMA foaming also had the lowest M_R ratio values for all LMLC specimens with and without LTOA protocols.

For the New Mexico field project with only PMFC cores at construction available, WMA Evotherm® 3G with RAP generally exhibited decreased performance as compared to HMA with RAP for many of the performance parameters, while WMA foaming with RAP exhibited increased or equivalent performance for the same parameters. For both WMAs, increased or equivalent performance was shown for TSR, SIP, and stripping slope. All laboratory LTOA protocols examined for the New Mexico field project resulted in LMLC specimens with increased or equivalent performance for both WMAs with RAP as compared to HMA with RAP for all performance parameters except TSR for WMA foaming with RAP

Table 3-18. Summary trends of WMA vs. HMA performance evolution.

Aging Stage	Test	Parameters	Iowa WMA vs. HMA		Texas WMA vs. HMA		New Mexico WMA vs. HMA	
PMFC Cores @ Construction	IDT	Dry IDT Strength					E	F
		Wet IDT Strength	E	S			E	F
		TSR			E	F		
	M_R	Dry M_R			E	F	E	F
		Wet M_R	N/A					
		M_R-ratio						
	HWTT	SIP	N/A					
		Stripping Slope			E	F		
PMFC Cores after 1st Summer Field Aging Iowa: after 12 months Texas: after 8 months	IDT	Dry IDT Strength					N/A	
		Wet IDT Strength						
		TSR						
	M_R	Dry M_R						
		Wet M_R	N/A					
		M_R-ratio						
	HWTT	SIP	N/A					
		Stripping Slope						
PMFC Cores after 1st Winter Field Aging Iowa: after 6 months	IDT	Dry IDT Strength			N/A		N/A	
		Wet IDT Strength						
		TSR	E	S				
	M_R	Dry M_R						
		Wet M_R	N/A					
		M_R-ratio						
	HWTT	SIP						
		Stripping Slope						
LMLC No LTOA	IDT	Dry IDT Strength						
		Wet IDT Strength			E	F		
		TSR						
	M_R	Dry M_R			E	F		
		Wet M_R			E	F		
		M_R-ratio			E	F		
	HWTT	SIP	N/A					
		Stripping Slope						
LMLC LTOA 2 weeks @ 60°C	IDT	Dry IDT Strength	N/A		E	F		
		Wet IDT Strength						
		TSR					E	F
	M_R	Dry M_R						
		Wet M_R						
		M_R-ratio			E	F		
	HWTT	SIP						
		Stripping Slope						

(continued on next page)

after LTOA of 2 weeks at 140°F (60°C) and M_R-ratio for WMA Evotherm® 3G with RAP after LTOA of 5 days at 185°F (85°C). In addition, inadequate performance based on the minimum TSR threshold of 80% for TSR was indicated for HMA with RAP and both WMAs with RAP for LMLC specimens without LTOA and after LTOA of 5 days at 185°F (85°C) and for WMA foaming with RAP for all LTOA protocols.

In general, the initial performance of HMA PMFC cores and LMLC specimens without field and laboratory aging was better than the performance of the WMA mixtures. However, the difference was reduced with field aging and laboratory LTOA. Additionally, better or equivalent performance of WMA versus HMA was achieved for several field and laboratory aging conditions.

Table 3-18. (Continued).

Aging Stage	Test	Parameters	Iowa WMA vs. HMA	Texas WMA vs. HMA	New Mexico WMA vs. HMA
LMLC LTOA 16 weeks @ 60°C	IDT	Dry IDT Strength	N/A		N/A
		Wet IDT Strength	E S		
		TSR		E F	
	M_R	Dry M_R			
		Wet M_R			
		M_R-ratio			
	HWTT	SIP	N/A		
		Stripping Slope			
LMLC LTOA 5 days @ 85°C	IDT	Dry IDT Strength	N/A		
		Wet IDT Strength			
		TSR			
	M_R	Dry M_R			
		Wet M_R			
		M_R-ratio		E F	E F
	HWTT	SIP			
		Stripping Slope			

Key: Decreased Performance; Equivalent or Increased Performance

Note: E: Iowa WMA Evotherm® 3G with RAP or Texas WMA Evotherm DAT™ or New Mexico WMA Evotherm® 3G with RAP; S: Iowa WMA Sasobit® with RAP; F: Texas WMA foaming or New Mexico WMA foaming with RAP.

Revisions to Draft AASHTO Standards

Appendix F provides revisions to AASHTO R 35 appendix based on the results generated and analyzed in this project and proposed as described in the next chapter. The following revisions are proposed as noted:

- Preparation of LMLC specimens of WMA mixtures for moisture-susceptibility performance tests to include short-term conditioning of 2 hours at 240°F (116°C) instead of the compaction temperature.
- Preparation of onsite PMLC specimens of WMA mixtures for moisture-susceptibility tests to include stabilizing to 240°F (116°C) instead of the compaction temperature.
- Preparation of offsite PMLC specimens of WMA mixtures for moisture-susceptibility performance tests to include reheating to 240°F (116°C) for all WMA mixtures (except foaming technologies) and to 275°F (135°C) (WMA foaming technologies) instead of the compaction temperature.
- Use of proposed moisture-sensitivity criteria instead of 80% TSR by AASHTO T 283.

  For LMLC specimens or onsite PMLC specimens of WMA mixtures without LTOA by one of the following selected laboratory tests, the following criteria are proposed:

  – Wet IDT strength (AASHTO T 283 with one F/T cycle) ≥ 65 psi and TSR (AASHTO T 283) ≥ 70%.
  – Wet M_R (ASTM D7369, condition by AASHTO T 283 with one F/T cycle) ≥ 200 ksi and M_R-ratio = wet M_R/dry M_R ≥ 70%.
  – HWTT SIP ≥ 3,500 cycles and HWTT stripping slope ≤ 5.3 µm/cycle.

  For offsite PMLC specimens of WMA mixtures without LTOA by one of the following selected laboratory tests, the following criteria are proposed:

  – Wet IDT strength (AASHTO T 283) ≥ 100 psi and TSR (AASHTO T 283 with one F/T cycle) ≥ 70%.
  – Wet M_R (ASTM D7369, condition by AASHTO T 283 with one F/T cycle) ≥ 300 ksi and M_R-ratio = wet M_R/dry M_R ≥ 70%.
  – HWTT SIP ≥ 6,000 cycles and HWTT stripping slope ≤ 2.0 µm/cycle.

  If inadequate resistance is indicated without LTOA, WMA mixtures with LTOA of LMLC compacted specimens of 5 days at 85°C by AASHTO R 30 by same selected laboratory test to evaluate if a summer of aging prior to winter conditions would mitigate early-life moisture susceptibility:

  – Wet IDT strength (AASHTO T 283) ≥ 115 psi.
  – Wet M_R (ASTM D7369, condition by AASHTO T 283) ≥ 450 ksi.
  – HWTT SIP ≥ 12,000 cycles and HWTT stripping slope ≤ 1.4 µm/cycle.

CHAPTER 4

Findings, Discussion and Guidelines, and Suggested Research

This chapter presents overall findings from the three experiments described in the previous chapter, a summary of WMA performance compared to HMA, guidelines for evaluating WMA for moisture susceptibility during mix design and QA, and suggested research based on the results of this project.

Findings

WMA Laboratory Conditioning

The following are findings from the results of the WMA laboratory-conditioning experiment that included evaluation of almost 250 LMLC specimens, onsite and offsite PMLC specimens, and PMFC cores from the Iowa, Texas, and Montana field projects:

- MR results showed that the stiffness of LMLC specimens increased with higher conditioning temperatures and longer conditioning time and that WMA was more sensitive to conditioning temperature than conditioning time. Among the five selected conditioning protocols for LMLC specimens, 2 hours at T_c was more representative in terms of the stiffness of HMA and WMA pavements in their early life. Considering the difficulty in accurately defining T_c in the field and the common range of T_c for HMA and WMA, 2 hours at 275°F (135°C) and 240°F (116°C)—instead of 2 hours at T_c—are proposed as the standard laboratory-conditioning protocol for HMA and WMA LMLC specimens, respectively.
- M_R results for PMLC specimens subjected to different conditioning protocols versus PMFC cores at construction showed that onsite PMLC specimens were more representative in terms of stiffness of HMA and WMA pavements in their early life. In contrast, the conditioning protocols used on the offsite PMLC specimens yielded specimens with statistically higher stiffness as compared to the PMFC cores at construction, showing that reheating loose mix had a significant effect on the stiffness of offsite PMLC specimens. Even in the case of HMA and WMA with only reheating to T_c, the stiffness was higher than the stiffness of PMFC cores at construction. Considering the difficulty in accurately defining T_c in the field and the common range of T_c for HMA and WMA, T_c in the proposed conditioning protocols for preparing PMLC specimens is standardized at 275°F (135°C) and 240°F (116°C), respectively.
- Offsite PMLC specimens of WMA prepared with foaming processes required a different conditioning protocol as compared to WMA with additives because the foaming effect during production was assumed lost after mixing and cooling of the loose mix. Therefore, the conditioning protocols proposed for preparing PMLC specimens onsite are as follows: (1) 1 hour at 275°F (135°C) for HMA, and (2) 1 hour at 240°F (116°C) for WMA. When compacting PMLC specimens on site is not viable, the proposed conditioning protocol for offsite PMLC specimens is to (1) reheat to 275°F (135°C) for HMA and WMA with foaming process, and (2) reheat to 240°F (116°C) for WMA with additives.

WMA Moisture Susceptibility

The following are findings from the results of the WMA moisture-susceptibility experiment that included evaluation of more than 850 LMLC specimens, onsite and offsite PMLC specimens, and PMFC cores from the Iowa, Texas, Montana, and New Mexico field projects:

- The selected laboratory-conditioning protocol simulates the early life of the pavement and produces laboratory-compacted mixtures with performance in terms of moisture susceptibility equivalent to that of PMFC cores at construction, after a winter, or both, as indicated by the selected laboratory tests.
- Based on laboratory moisture-susceptibility tests, WMA can be more moisture susceptible in early life (prior to

summer aging) as compared to HMA, but equivalent performance is shown after a summer of aging.
- WMA may be moisture susceptible in early life (prior to summer aging), and the use of anti-stripping agents may reduce this susceptibility. WMA technologies exhibiting the greatest moisture susceptibility in laboratory tests will show the greatest benefit with the use of anti-stripping agents. Compatibility of the anti-stripping agent with the WMA technology and component materials should be considered.
- Onsite and offsite PMLC specimens differ in terms of laboratory-measured moisture susceptibility, with the artificial aging due to reheating producing offsite PMLC specimens that exhibit improved resistance to moisture damage.
- Agreement between laboratory and field performance based on pavement condition was shown for the Montana and New Mexico field projects with good field performance for all mixtures, and for the Iowa field project with poor field performance for the two WMAs with RAP. Agreement was mixed across specimen types and across the three standard laboratory tests for the Texas field project.

WMA Performance Evolution

The following are findings from the results of the WMA performance-evolution experiment that included evaluation of more than 500 LMLC specimens, onsite PMLC specimens, and PMFC cores from the Iowa, Texas, and New Mexico field projects:

- HMA and WMA PMFC cores experienced significant increase in dry M_R stiffness with field aging. The increase in stiffness during the summer months was more significant than during the winter, probably because of aging during the high in-service temperatures. For both the Iowa and Texas field projects, HMA had a higher initial stiffness than its WMA counterparts at construction, but the WMA experienced an increase in stiffness at a higher rate with field aging than the HMA mixtures for these field projects. Consequently, equivalent dry M_R stiffnesses between WMA and HMA were achieved by Iowa PMFC cores after summer at 12 months in service and by Texas PMFC cores after summer at 8 months in service.
- The comparison in dry M_R stiffness between HMA LMLC specimens with different LTOA times at the same LTOA temperature illustrated the effect of laboratory aging on mixture stiffness. The laboratory aging protocol of 2 weeks at 140°F (60°C) was able to represent the time period where the stiffness of WMA was equivalent to the initial stiffness of HMA without LTOA (for the Iowa pavement) or where the dry stiffness of WMA and HMA converged (for the Texas pavement).
- Equivalent dry M_R stiffnesses between LMLC specimens with up to 2 weeks LTOA at 140°F (60°C) and PMFC cores at construction were shown for most Iowa and Texas mixtures, indicating the similar initial stiffness in the laboratory as compared to the initial field conditions. In addition, the laboratory LTOA protocols at 140°F (60°C) for 4 to 16 weeks were representative of the field aging experienced by PMFC cores after the first summer.
- As with dry M_R stiffness, results from other standard laboratory tests (dry and wet IDT strengths, wet M_R stiffnesses, and HWTT parameters) indicated that PMFC cores acquired after the first summer in service had statistically better performance than those acquired at construction. However, the difference between PMFC cores acquired after the first winter in service versus the ones acquired at construction was not significant. The laboratory LTOA protocols used in this study also had a significant effect on performance, improving the M_R stiffness, IDT strength, and moisture susceptibility of the mixtures. In addition, the comparison of mixture performance measured in the laboratory between PMFC cores after several months in service and LMLC specimens with LTOA indicated that laboratory aging of 16 weeks at 140°F (60°C) as well as 5 days at 185°F (85°C) were representative of the early-life field aging that PMFC cores experienced after construction.
- Based on the dry and wet IDT strengths, dry and wet M_R stiffnesses, and HWTT test results, HMA had higher stiffness and strength and better moisture resistance than its WMA counterparts did at the initial field and laboratory stages. This was indicated by the comparisons of results from these laboratory tests for PMFC cores at construction and LMLC specimens without LTOA. However, the difference between HMA and WMA was reduced as PMFC cores and LMLC specimens experienced field aging and laboratory LTOA, respectively. For most of the cases, after aging, better or equivalent mixture performance in laboratory tests was achieved by WMA. Thus, WMA pavements are more likely to be susceptible to moisture-related distresses during their early life as compared to HMA pavements. Therefore, measures such as adding anti-stripping agents or ensuring summer aging prior to wet and cold winter conditions should be considered to prevent moisture-related pavement distresses from occurring.

Performance Summary

The trends discussed in the previous chapter focus on a comparison of WMA and HMA in terms of the selected laboratory performance parameters, the effects of adding anti-stripping agents, and the differences in results for different specimen types and after different conditioning and LTOA protocols. In this section, a discussion of the overall performance of the

HMA and WMA mixtures from the different field projects in the context of these laboratory results, limited field performance data, traffic, climate, and materials is provided. The laboratory results were compared to common thresholds, including minimum 80% for TSR and M_R-ratio, minimum SIP of 10,000 based on the Iowa specification, and minimum wet IDT strengths of 65 psi and 80 psi for mixtures with unmodified (Iowa) and modified (Montana, New Mexico, and Texas) binders based on averages from the Nevada, Tennessee, and Texas specifications.

In general, as detailed in Appendix D, the four field projects are performing well to date (through March 2013) after 18 months (Iowa), 17 months (Montana), 14 months (Texas), and 5 months (New Mexico). The Montana field project is not exhibiting distress related to moisture susceptibility to date, despite construction in October 2011 without experiencing a summer of aging prior to winter conditions, heavy traffic on an interstate highway (Figure 2-4), and an extreme climate for moisture susceptibility (cold and multi-F/T) (Figure 2-1, Figure 2-2, and Figure 2-3). This field project did not use RAP but did include an anti-stripping agent (lime) and a relatively elevated high-temperature performance grade binder (PG 70-28) (Table 2-1). In addition, this field project was treated with a seal coat friction course in July 2012. The field performance for the HMA and three WMAs from this field project was in agreement with all of the results from the three standard laboratory tests that indicated adequate resistance to moisture susceptibility when compared to common thresholds, with the only exceptions being wet IDT strengths and TSR values for onsite PMLC specimens.

The relatively recently constructed New Mexico field project is also not exhibiting distress related to moisture susceptibility to date, despite construction in October 2012 without experiencing a summer of aging prior to winter conditions, heavy traffic on an interstate highway (Figure 2-4), and a climate that mirrors aspects of different extreme climates for moisture susceptibility (dry, cold during the winter, and relatively hot during the summer, as shown in Figure 2-1, Figure 2-2, and Figure 2-3). This field project used RAP with a relatively low high-temperature performance grade binder (PG 64-28) and included an anti-stripping agent (Versabind) (see Table 2-1). Similar to the Montana field project, agreement was shown between the field performance and the laboratory performance for all three standard laboratory tests for the HMA and two WMAs from this field project. All of these tests indicated adequate resistance to moisture susceptibility when compared to common thresholds, with the only exceptions being wet IDT strengths and TSR values for all LMLC specimens and M_R-ratios for all LMLC specimens and WMA foaming for onsite PMLC specimens.

The Texas field project is also generally performing well to date and not exhibiting distress related to moisture susceptibility, despite winter construction in January 2012 in an extreme climate for moisture susceptibility (hot and wet) (Figure 2-1, Figure 2-2, and Figure 2-3) with heavy truck traffic on a farm-to-market (FM) road (Figure 2-4). This field project did not use RAP or an anti-stripping agent but did use a relatively elevated high-temperature performance grade binder (PG 70-22) with a relatively lower-quality aggregate (SAC-B), as categorized by the Texas Department of Transportation's (TxDOT's) Surface Aggregate Classification System (TxDOT, 2012). For this field project, agreement between the field and laboratory performance as predicted based on common thresholds was not as complete across the different specimen types or across the three standard laboratory tests as it was for the Montana and New Mexico field projects. For example, the HWTT results indicated that the two WMAs may have been moisture susceptible in early life, as indicated by onsite PMLC specimens, LMLC specimens, and PMFC cores at construction but that their resistance improved after a summer of aging. Wet IDT strength and TSR values and wet M_R stiffness and M_R-ratios also indicated that the WMA foaming and WMA Evotherm DAT™ may have been moisture susceptible in their early life based on results for LMLC and some PMLC specimens and PMFC cores at construction.

The Iowa field project also did not include an anti-stripping agent (Table 2-1) and is now exhibiting some distress related to moisture susceptibility for some of the mixtures. The Iowa field project is exhibiting some raveling in both WMAs (WMA Sasobit® with RAP and WMA Evotherm® 3G with RAP) that was likely exacerbated by paver segregation at the crown and subsequent snow plow damage (Appendix D). The Iowa HMA with RAP is not exhibiting raveling to date. In addition to possible construction issues, the Iowa field project was constructed in September 2011 without experiencing a summer of aging prior to winter conditions in an extreme climate for moisture susceptibility (wet and F/T) (see Figure 2-1, Figure 2-2, and Figure 2-3) and sustains moderate traffic on a U.S. highway (Figure 2-4). This field project used RAP with a relatively low high-temperature performance grade binder (PG 58-28). Although part of the aggregate fraction typically requires the use of an anti-stripping agent, the project did not use it (Table 2-1) because adequate TSR results were obtained during mix design. After construction, Iowa DOT QA results did indicate the need for an anti-stripping agent based on TSR results, and these results agree with those obtained herein that an anti-stripping agent would likely have been beneficial and may have been able to offset the moisture susceptibility of this project in its early life.

As for the Montana and New Mexico field projects with good performance for all mixtures, the WMAs with RAP in the Iowa field project indicated inadequate resistance to moisture susceptibility for all tests when compared to common thresholds

based on results from LMLC specimens and PMFC cores in the early life at construction and after winter at 6 months in service. The agreement was not as clear for the HMA with RAP, because all three standard laboratory tests indicated marginal or inadequate performance for some specimen types in contrast to the relatively good field performance. In addition, at least one of the parameters for each of the three standard laboratory tests was able to discriminate this difference in field performance between WMA and HMA by finding that the two WMAs with RAP exhibited reduced performance as compared to HMA with RAP based on PMLC, LMLC, or both types of specimens and PMFC cores in early life at construction or after winter with 6 months in service. For wet IDT strength and TSR values, improved performance of the two WMAs with RAP for PMFC cores after a summer of aging at 12 months in service was exhibited such that equivalent performance as compared to HMA with RAP was attained. WMA Evotherm with RAP also showed this improved performance in terms of the HWTT stripping slope for PMFC cores after a summer of aging at 12 months in service.

Based on the overall laboratory results for specimens that were STOA to represent early life and those that were LTOA to represent the effects of a summer aging period, all of the WMA mixtures from all of the four field projects exhibited either adequate moisture susceptibility initially or after a summer of aging as compared to HMA. Unfortunately, all four field projects were constructed in fall or winter and did not experience a summer of aging prior to winter conditions, and thus the overall hypothesis that WMA will exhibit adequate moisture susceptibility after a summer of aging was not fully tested. In addition, based on the results of the survey, most field sections in the United States are not exhibiting signs of moisture susceptibility.

Based on the data from the few field projects included in NCHRP Project 9-49, construction with WMA technologies that will not sustain a summer of aging prior to multiple freeze/thaw cycles or wet and cold days in the first winter may involve some risk of moisture susceptibility, but the addition of anti-stripping agents may mitigate this risk. The use of either a relatively elevated high-temperature performance grade binder or a relatively low high-temperature performance grade binder with RAP appears to provide adequate performance in terms of moisture susceptibility with or without an anti-stripping agent. Compatibility of the anti-stripping agent with the WMA technology and the component binder and aggregate materials is crucial, and the laboratory results from this project indicate that the use of a liquid anti-stripping agent in concert with Evotherm may be unnecessary or even counterproductive. The guidelines provided in the next section address this issue of changing performance during the early life through a two-step WMA laboratory evaluation process for moisture susceptibility.

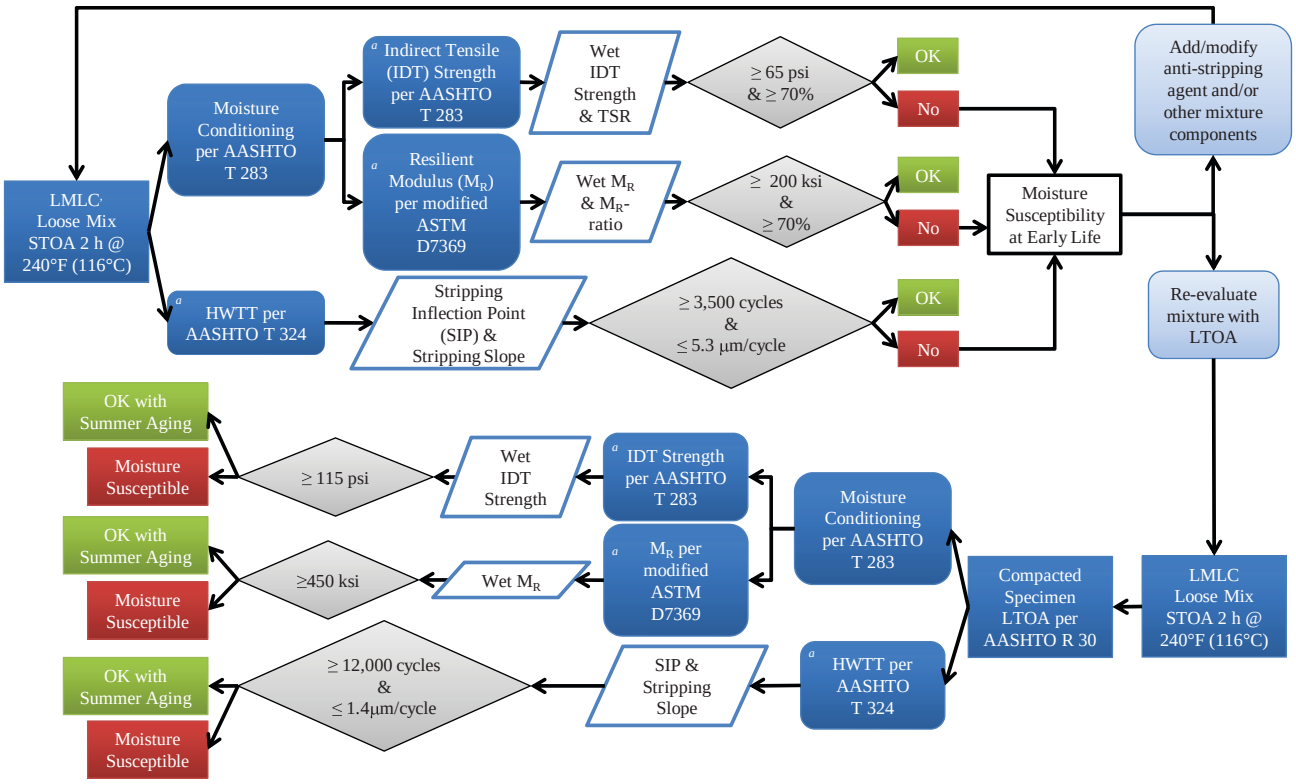
Discussion and Guidelines

Figure 4-1 shows proposed guidelines for evaluating WMA for moisture susceptibility during laboratory mix design based on an analysis of the results of this project. If appropriate laboratory equipment is not available to fabricate LMLC specimens with the WMA technology, testing may be conducted on PMLC specimens fabricated on site or off site with minimal reheating from plant trial batch materials as shown in Figure 4-2 and Figure 4-3, respectively. Figure 4-2 and Figure 4-3 can also be used as guidelines for QA of WMA with respect to moisture susceptibility. All of these proposed guidelines are incorporated in the revised draft AASHTO R 35 appendix presented in Appendix F. Figures 4-1 through 4-3 were produced as a set of guidelines, and state DOTs can modify them to suit their needs based on their experience.

After mixing WMA LMLC specimens according to the AASHTO R 35 appendix, loose mix is subject to STOA for 2 hours at 240°F (116°C) prior to compaction. Next, a test to evaluate moisture susceptibility is selected based on available equipment, costs, and prior experience from the following three choices: wet and dry IDT strengths at 77°F (25°C) and TSR by AASHTO T 283, wet and dry M_R stiffnesses at 77°F (25°C) and M_R-ratio after moisture conditioning by AASHTO T 283, or HWTT SIP and stripping slope per AASHTO T 324 at 122°F (50°C).

Two criteria for each test for these STOA specimens are shown in Figure 4-1. These criteria were developed by separating the results from the relatively good field and laboratory performance of the Texas WMAs and the relatively poor field and laboratory performance of the Iowa WMAs, as shown in Table 4-1. Mixtures from the Iowa field projects contained a relatively low high-temperature performance grade binder (PG 58-34) and RAP, and those from the Texas field project contained a relatively elevated high-temperature performance grade binder (PG 70-22) without RAP. In Table 4-1, red shading indicates that the STOA mixture did not meet the criteria and would likely be moisture susceptible in early life, and green shading indicates that the STOA mixture met the criteria and would likely not be moisture susceptible.

These thresholds were verified through examination of the WMAs from the Montana and New Mexico field projects, as shown in Table 4-2. For the Montana field project where LMLC specimens were not available, onsite PMLC specimens were used as proposed in Figure 4-1. Again, both types of mixtures (with and without RAP) with different high-temperature performance grade binders were used. Mixtures from the New Mexico field project contained a relatively low high-temperature performance grade binder (PG 64-28) and RAP, and those from the Montana field project contained a relatively elevated high-temperature performance grade binder (PG 70-28) without RAP. As shown in Table 4-2, this verification predicted adequate performance in terms of moisture susceptibility for

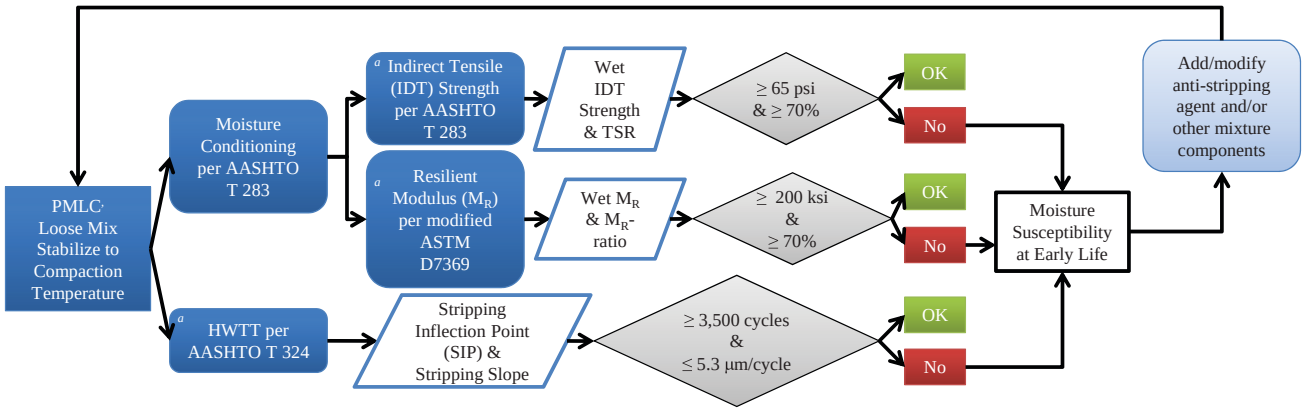


Note [a]: select a single test method and use it throughout the mix design verification

Figure 4-1. Proposed WMA moisture susceptibility evaluation for mix design with LMLC specimens.

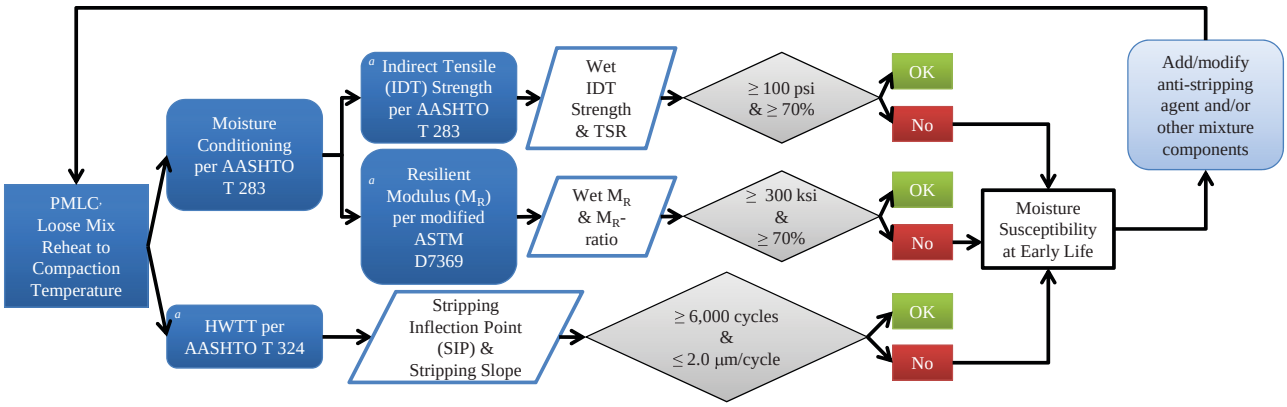
most of the standard laboratory tests for the STOA WMAs from both of the Montana and New Mexico field projects that agrees with field performance to date.

If the WMA passes both criteria for the selected test, the mixture is expected to have adequate performance in terms of moisture susceptibility. If the WMA does not pass one or both criteria for the selected test, early-life moisture susceptibility is probable. Mixture modifications in terms of (1) adding, modifying the dosage of, or changing anti-stripping agents; (2) changing other mixture components (e.g., binder grade or inclusion of RAP); or any combination of these modifications is then proposed prior to a second evaluation of the modified WMA with these same criteria. As shown in Table 4-1, even with the addition of two different anti-stripping agents, most of the Iowa STOA mixtures were likely to be moisture susceptible in early life, while the addition of hydrated lime to the WMA foaming mixture from the Texas field project that failed the criteria without anti-stripping agents exhibited adequate performance in terms of both wet IDT strength and TSR and wet M_R stiffness and M_R-ratio.



Note [a]: select a single test method and use it throughout the mix design verification

Figure 4-2. Proposed WMA moisture susceptibility evaluation for mix design or QA with onsite PMLC specimens.



Note [a]: select a single test method and use it throughout the mix design verification

Figure 4-3. Proposed WMA moisture susceptibility evaluation for mix design or QA with offsite PMLC specimens.

WMA Sasobit® with RAP from the Iowa field project also improved in terms of wet M_R stiffness and M_R-ratio with the addition of hydrated lime. As shown in Table 4-2, two of the three STOA WMAs from the Montana field project (WMA Evotherm® 3G and WMA Sasobit®) did not meet the criteria for wet IDT strength and TSR, and unfortunately, data were not available to assess the effect of anti-stripping agents.

If the original WMA or modified WMA still does not pass one or both criteria for the selected test, early-life moisture susceptibility is probable. To evaluate if the WMA will overcome this vulnerable period, a second evaluation is proposed after LTOA of LMLC compacted specimens for 5 days at 85°C per AASHTO R 30. After long-term aging, the same selected laboratory test is proposed but with changed criteria that reflect the stiffening effects of oxidative aging, as shown in Figure 4-1. For this second evaluation of aged specimens, only wet properties are specified for IDT strength and M_R stiffness, but two criteria remain for the HWTT.

If the WMA passes all criteria for the same selected test, moisture susceptibility in early life is probable and a summer of aging is needed prior to the occurrence of multiple freeze-thaw cycles or wet and cold days. If the WMA does not pass one or both criteria for the selected test, the mixture is considered moisture susceptible. As shown in Table 4-2, two of the three STOA WMAs from the Montana field project (WMA Evotherm® 3G and WMA Sasobit®) did not meet the criteria for wet IDT strength and TSR, and unfortunately data were not available to assess the effect of LTOA in the laboratory or field aging with PMFC cores after a summer to assess if any possible moisture susceptibility was confined to early life. As shown in Table 4-1, one of the two STOA WMAs from the Texas field project (WMA foaming) marginally failed the criteria for M_R-ratio, but after LTOA in the laboratory, this mixture passed the criteria for aged specimens. As shown in Table 4-1, one of the two STOA WMAs from the New Mexico field project (WMA Evotherm® 3G with RAP) also marginally failed the criteria for M_R-ratio, but after LTOA in the laboratory, this mixture also passed the criteria for aged specimens.

Finally, as shown in Figure 4-3, if the alternative offsite PMLC specimens are used to evaluate WMA moisture susceptibility, the thresholds are increased for wet IDT strength, wet M_R stiffness, SIP, and stripping slope.

Suggested Research

This section presents suggestions for future research based on results of this project, additional analyses conducted during the project (see Appendix G), and other ideas for improving moisture susceptibility evaluation of WMA.

Based on the WMA laboratory-conditioning experiment, suggestions for future research are as follows:

- In this study, standard laboratory-conditioning protocols to prepare LMLC specimens and PMLC specimens for performance tests were proposed based on M_R results. Additional mixture properties need to be considered for validation. These properties may include performance-related properties that indicate moisture susceptibility or resistance to rutting or cracking.
- The effect of the total AV in the asphalt mixture specimen on mixture stiffness was verified in this study using LMLC specimens of a single WMA technology prepared with one specific conditioning protocol. Future research into the comprehensive effects of AV on the stiffness of asphalt mixtures prepared with various WMA technologies is necessary, with a particular emphasis on exploring the difference in AV between PMFC cores and LMLC specimens and PMLC specimens.
- Several WMA additives are available to reduce the production temperature of asphalt mixtures. In this study,

Table 4-1. Threshold Development for WMA Moisture Susceptibility Evaluation Based on the Iowa and Texas Field Projects.

Aging Protocol (+anti-stripping)	Conditioning/Testing Protocol	Test Parameter	Iowa		Texas	
			Evotherm	Sasobit	Evotherm	Foaming
LMLC STOA 2 h @ 240°F (116°C)	Moisture Conditioning AASHTO T 283	Wet IDT (psi)	50	47	88	77
		TSR (%)	84	77	79	66
		Conclusion	MS @ Early Life	MS @ Early Life	OK	MS @ Early Life
		Wet M_R (ksi)	133	164	281	239
		M_R-ratio (%)	72	77	80	62
		Conclusion	MS @ Early Life	MS @ Early Life	OK	MS @ Early Life
	HWTT AASHTO T 324	SIP (cycles)	1,677	2,176	6,256	4,111
		Stripping Slope (μm/cycle)	10.0	6.6	1.7	2.9
		Conclusion	MS @ Early Life	MS @ Early Life	OK	OK
LMLC STOA 2 h @ 240°F (116°C) (+ Hydrated Lime)	Moisture Conditioning AASHTO T 283	Wet IDT (psi)	48	55	–	81
		TSR (%)	81	92	–	77
		Conclusion	MS @ Early Life	MS @ Early Life	–	OK
		Wet M_R (ksi)	138	215	–	301
		M_R-ratio (%)	66	79	–	83
		Conclusion	MS @ Early Life	OK	–	OK
LMLC STOA 2 h @ 240°F (116°C) (+ LAS)	Moisture Conditioning AASHTO T 283	Wet IDT (psi)	41	51	–	87
		TSR (%)	72	91	–	84
		Conclusion	MS @ Early Life	MS @ Early Life	–	OK
		Wet M_R (ksi)	93	171	–	238
		M_R-ratio (%)	53	96	–	69
		Conclusion	MS @ Early Life	MS @ Early Life	–	MS @ Early Life
LMLC STOA 2 h @ 240°F + LTOA 5 days @ 185°F (85°C)	Moisture Conditioning AASHTO T 283	Wet IDT (psi)	N/A	N/A	–	–
		Conclusion	–	–	–	–
		Wet M_R (ksi)	N/A	N/A	–	475
		Conclusion	–	–	–	OK
Key	Does Not Meet Criteria				Meets Criteria	

Note: MS: moisture susceptible.

Table 4-2. Threshold verification for WMA moisture susceptibility evaluation based on the Montana and New Mexico field projects.

Aging Protocol	Conditioning/Testing Protocol	Test Parameter	Montana*			New Mexico	
			Evotherm	Sasobit	Foaming	Evotherm	Foaming
LMLC STOA 2 h @ 240°F (116°C)	Moisture Conditioning AASHTO T 283	Wet IDT (psi)	76	74	77	81	72
		TSR (%)	59	57	72	73	70
		Conclusion	MS @ Early Life	MS @ Early Life	OK	OK	OK
		Wet M_R (ksi)	261	321	234	296	320
		M_R-ratio (%)	83	86	80	69	76
		Conclusion	OK	OK	OK	MS @ Early Life	OK
	HWTT AASHTO T 324	SIP (cycles)	>20,000	>20,000	>20,000	>20,000	>20,000
		Stripping Slope (μm/cycle)	0	0	0	0	0
		Conclusion	OK	OK	OK	OK	OK
LMLC STOA 2 h @ 240°F (116°C)+ LTOA 5 days @ 185°F (85°C)	Moisture Conditioning AASHTO T 283	Wet IDT (psi)	N/A	N/A	–	–	–
		Conclusion	–	–	–	–	–
		Wet M_R (ksi)	–	–	–	585	653
		Conclusion	–	–	–	OK	OK
Key	Does Not Meet Criteria				Meets Criteria		

Note: MS: moisture susceptible.
* For Montana, no LMLC specimens were available, and thus values of onsite PMLC specimens are used in lieu of LMLC STOA 2 h @ 240°F.

commonly used WMA additives were used and evaluated. Future research may include other WMA technologies and verify the general applicability of the standard conditioning protocols proposed in this study.

Based on the WMA moisture-susceptibility experiment, several issues regarding WMA remain unclear, and future research is suggested in the following areas:

- Moisture affects mixtures over time, but, if with a summer of aging, WMA that is initially more moisture susceptible as compared to HMA can improve resistance to moisture damage, construction that allows for a summer of aging may result in both mixture types having adequate performance at the onset of freeze-thaw cycles and wet and cold days in the winter. The next step is to characterize any early-life weakness as compared to HMA and tie thresholds for laboratory test parameters to field performance. To date, three of the four field test sections report good performance of WMA in the field over time with respect to moisture susceptibility. LTOA methods need to be evaluated to find better ways to simulate field conditions in the laboratory for WMA with time.
- The moisture-conditioning protocol is critical for characterizing moisture susceptibility, and the most commonly used protocol in AASHTO T 283 is severe due to vacuum saturation. Besides, achieving the target degree of saturation

specified in AASHTO T 283 is sometimes challenging, with some mixtures requiring only a few seconds under vacuum and others several minutes. Further research is proposed to assess the differences in saturation that result from different processes such as high relative humidity, water immersion, and use of the Moisture-Induced Stress Tester (MIST) equipment. The use of a relatively small container and steam could create a more realistic and faster moisture-conditioning method where there would not be concern about pore liquid water pressure in wet specimens during testing.

- Another limitation of AASHTO T 283 is that the moisture-conditioned specimens are tested in a wet condition, and concerns remain that the water still present inside the specimens is a source of error, especially for a repeated load testing such as M_R. Wet specimens may need to be dried before testing so that water does not affect the behavior of the specimens during testing.

Based on the WMA performance-evolution experiment, suggestions for future research are as follows:

- For the Texas field project, compacted LMLC specimens of HMA after LTOA of 5 days at 185°F (85°C) exhibited significantly higher stiffnesses and improved moisture susceptibility in M_R and HWTT tests as compared to corresponding PMFC cores after summer at 8 months in service. Based on this observation, future research on LTOA protocols with shorter periods (less than 5 days) is proposed in order to produce LMLC specimens with properties more representative of those for PMFC cores after summer aging in the field.
- In this project, STOA of loose mix plus LTOA of compacted LMLC specimens was used to represent field aging of PMFC cores after summer aging. Future research on simulating field aging via only STOA of loose mix at higher temperatures is suggested to reduce the time required to evaluate mixtures.

In addition to the suggestions for future research based on the results of the three experiments included in this project, Appendix G discusses other advanced testing and analyses conducted during the project, with promising results shown for the mixtures from the Texas field project that generated the following ideas for improving moisture-susceptibility evaluation of WMA:

- An alternative analysis of the results from a repeated load test in the presence of water (HWTT) can be used to produce a stripping number (SN) and crack speed index that also incorporates IDT strength analysis and AV. Remaining life (LC_R) in terms of number of cycles prior to stripping failure can also be determined from this repeated load test.
- Adhesive bond energy between the binder and aggregate for both dry and wet conditions can be indirectly calculated from a short monotonic load test (IDT strength), a nondestructive load test (M_R), and AV, or directly calculated from cataloged surface energy values of the component materials.
- Both of these alternative analyses produce indices that directly incorporate AV that greatly affects mixture characterization in any of the standard laboratory tests evaluated in this project.
- A different shorter repeated load test (repeated direct tension [RDT] test) in a nondestructive mode followed by a destructive mode allows for the incorporation of healing and determination of an endurance limit. This test and its associated analysis method can also provide input for determining adhesive bond energies in both dry and wet conditions.
- Extensive data generated in this project could be reanalyzed according to these proposed alternative analyses to set thresholds that separate the mixtures from the Iowa field projects with relatively poor performance and those from the Texas field project with relatively good performance as was done in Table 4-1 for the standard laboratory tests. Validation with the mixtures from both the Montana and New Mexico field projects could also be conducted as was done in Table 4-2 for the standard laboratory tests.

Before being considered for adoption, the proposed revisions to the appendix to AASHTO R 35 (suggested on the basis of a limited number of field projects) should be used on a trial basis. This will provide additional data to further refine the moisture-susceptibility criteria and the laboratory-conditioning and -aging protocols that capture the time when WMA may be most susceptible to this type of distress. Data from additional field projects will provide increased confidence in the guidelines provided, along with possible revisions to the framework proposed in this report. In addition, further information will be gathered toward resolving any differences between generally adequate field performance and laboratory assessment that indicates potential for moisture susceptibility for some mixtures. Continued field performance monitoring of the field projects used in NCHRP Project 9-49 is also suggested in order to further improve the guidelines produced.

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APPENDICES A THROUGH E, G, AND H

Appendices A through E, G, and H are available on line and can be accessed by searching the TRB website for NCHRP Report 763.

APPENDIX F

Proposed Draft Revisions to AASHTO R 35

Standard Practice for

Superpave Volumetric Design for Hot Mix Asphalt (HMA)

AASHTO Designation: R 35-12

AASHTO
THE VOICE OF TRANSPORTATION

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

Standard Practice for

Superpave Volumetric Design for Hot Mix Asphalt (HMA)

AASHTO Designation: R 35-12

AASHTO
THE VOICE OF TRANSPORTATION

1. SCOPE

1.1. This standard practice for mix design evaluation uses aggregate and mixture properties to produce a hot mix asphalt (HMA) job-mix formula. The mix design is based on the volumetric properties of the HMA in terms of the air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA).

1.2. This standard practice may also be used to provide a preliminary selection of mix parameters as a starting point for mix analysis and performance prediction analyses that primarily use T 320 and T 322.

1.3. Special mixture design considerations and practices to be used in conjunction with this standard practice for the volumetric design of warm mix asphalt (WMA) are given in Appendix X2.

1.4. *This standard practice may involve hazardous materials, operations, and equipment. This standard practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 320, Performance-Graded Asphalt Binder
- M 323, Superpave Volumetric Mix Design
- PP 60, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)
- R 30, Mixture Conditioning of Hot Mix Asphalt (HMA)
- T 2, Sampling of Aggregates
- T 11, Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
- T 27, Sieve Analysis of Fine and Coarse Aggregates
- T 84, Specific Gravity and Absorption of Fine Aggregate
- T 85, Specific Gravity and Absorption of Coarse Aggregate
- T 100, Specific Gravity of Soils
- T 166, Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens
- T 195, Determining Degree of Particle Coating of Asphalt Mixtures
- T 209, Theoretical Maximum Specific Gravity (G_{mm}) and Density of Hot Mix Asphalt (HMA)
- T 228, Specific Gravity of Semi-Solid Asphalt Materials
- T 248, Reducing Samples of Aggregate to Testing Size

- T 275, Bulk Specific Gravity (*G*mb) of Compacted Hot Mix Asphalt (HMA) Using Paraffin-Coated Specimens
- T 283, Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage
- T 312, Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor
- T 320, Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST)
- T 322, Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device
- TP 79, Determining the Dynamic Modulus and Flow Number of Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)

2.2. *Asphalt Institute Standard*:

- SP-2, Superpave Mix Design

2.3. *Other References*:

- LTPP Seasonal Asphalt Concrete Pavement Temperature Models, LTPPBind 3.1, http://www.ltppbind.com
- NCHRP Report 567: Volumetric Requirements for Superpave Mix Design

3. TERMINOLOGY

3.1. *HMA*—hot mix asphalt.

3.2. *design ESALs*—design equivalent (80 kN) single-axle loads.

3.2.1. *Discussion*—Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. For pavements designed for more or less than 20 years, determine the design ESALs for 20 years when using this standard practice.

3.3. *air voids* (V_a)—the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture (Note 1).

Note 1—Term defined in Asphalt Institute Manual SP-2, Superpave Mix Design.

3.4. *voids in the mineral aggregate (VMA)*—the volume of the intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective binder content, expressed as a percent of the total volume of the specimen (Note 1).

3.5. *absorbed binder volume* (V_{ba})—the volume of binder absorbed into the aggregate (equal to the difference in aggregate volume when calculated with the bulk specific gravity and effective specific gravity).

3.6. *binder content* (P_b)—the percent by mass of binder in the total mixture, including binder and aggregate.

3.7. *effective binder volume* (V_{be})—the volume of binder that is not absorbed into the aggregate.

3.8. *voids filled with asphalt (VFA)*—the percentage of the VMA filled with binder (the effective binder volume divided by the VMA).

3.9. *dust-to-binder ratio* ($P_{0.075}/P_{be}$)—by mass, the ratio between the percent passing the 75-µm (No. 200) sieve ($P_{0.075}$) and the effective binder content (P_{be}).

3.10. *nominal maximum aggregate size*—one size larger than the first sieve that retains more than 10 percent aggregate (Note 2).

3.11. *maximum aggregate size*—one size larger than the nominal maximum aggregate size (Note 2).

Note 2—The definitions given in Sections 3.10 and 3.11 apply to Superpave mixes only and differ from the definitions published in other AASHTO standards.

3.12. *reclaimed asphalt pavement (RAP)*—removed and/or processed pavement materials containing asphalt binder and aggregate.

3.13. *primary control sieve (PCS)*—the sieve defining the break point between fine and coarse-graded mixtures for each nominal maximum aggregate size.

4. SUMMARY OF THE PRACTICE

4.1. *Materials Selection*—Binder, aggregate, and RAP stockpiles are selected that meet the environmental and traffic requirements applicable to the paving project. The bulk specific gravity of all aggregates proposed for blending and the specific gravity of the binder are determined.

Note 3—If RAP is used, the bulk specific gravity of the RAP aggregate may be estimated by determining the theoretical maximum specific gravity (G_{mm}) of the RAP mixture and using an assumed asphalt absorption for the RAP aggregate to back-calculate the RAP aggregate bulk specific gravity, if the absorption can be estimated with confidence. The RAP aggregate effective specific gravity may be used in lieu of the bulk specific gravity at the discretion of the agency. The use of the effective specific gravity may introduce an error into the combined aggregate bulk specific gravity and subsequent VMA calculations. The agency may choose to specify adjustments to the VMA requirements to account for this error based on experience with local aggregates.

4.2. *Design Aggregate Structure*—It is recommended that at least three trial aggregate blend gradations from selected aggregate stockpiles are blended. For each trial gradation, an initial trial binder content is determined, and at least two specimens are compacted in accordance with T 312. A design aggregate structure and an estimated design binder content are selected on the basis of satisfactory conformance of a trial gradation meeting the requirements given in M 323 for V_a, VMA, VFA, dust-to-binder ratio at N_{design}, and relative density at $N_{initial}$.

Note 4—Previous Superpave mix design experience with specific aggregate blends may eliminate the need for three trial blends.

4.3. *Design Binder Content Selection*—Replicate specimens are compacted in accordance with T 312 at the estimated design binder content and at the estimated design binder content ±0.5 percent and +1.0 percent. The design binder content is selected on the basis of satisfactory conformance with the requirements of M 323 for V_a, VMA, VFA, and dust-to-binder ratio at N_{design}, and the relative density at $N_{initial}$ and N_{max}.

4.4. *Evaluating Moisture Susceptibility*—The moisture susceptibility of the design aggregate structure is evaluated at the design binder content: the mixture is conditioned according to the mixture conditioning for the volumetric mixture design procedure in R 30, compacted to 7.0 ± 0.5 percent air voids in accordance with T 312, and evaluated according to T 283. The design shall meet the tensile strength ratio requirement of M 323.

5. SIGNIFICANCE AND USE

5.1. The procedure described in this standard practice is used to produce HMA that satisfies Superpave HMA volumetric mix design requirements.

6. PREPARING AGGREGATE TRIAL BLEND GRADATIONS

6.1. Select a binder in accordance with the requirements of M 323.

6.2. Determine the specific gravity of the binder according to T 228.

6.3. Obtain samples of aggregates proposed to be used for the project from the aggregate stockpiles in accordance with T 2.

Note 5—Each stockpile usually contains a given size of an aggregate fraction. Most projects employ three to five stockpiles to generate a combined gradation conforming to the job-mix formula and M 323.

6.4. Reduce the samples of aggregate fractions according to T 248 to samples of the size specified in T 27.

6.5. Wash and grade each aggregate sample according to T 11 and T 27.

6.6. Determine the bulk and apparent specific gravity for each coarse and fine aggregate fraction in accordance with T 85 and T 84, respectively, and determine the specific gravity of the mineral filler in accordance with T 100.

6.7. Blend the aggregate fractions using Equation 1:

$$P = Aa + Bb + Cc, \text{ etc.} \qquad (1)$$

where:

P = Percentage of material passing a given sieve for the combined aggregates A, B, C, etc.;
A, B, C, etc. = Percentage of material passing a given sieve for aggregates A, B, C, etc.; and
a, b, c, etc. = Proportions of aggregates A, B, C, etc., used in the combination, and where the total = 1.00.

6.8. Prepare a minimum of three trial aggregate blend gradations; plot the gradation of each trial blend on a 0.45-power gradation analysis chart, and confirm that each trial blend meets M 323 gradation controls (see Table 3 of M 323). Gradation control is based on four control sieve sizes: the sieve for the maximum aggregate size, the sieve for the nominal maximum aggregate size, the 4.75- or 2.36-mm sieve, and the 0.075-mm sieve. An example of three acceptable trial blends in the form of a gradation plot is given in Figure 1.

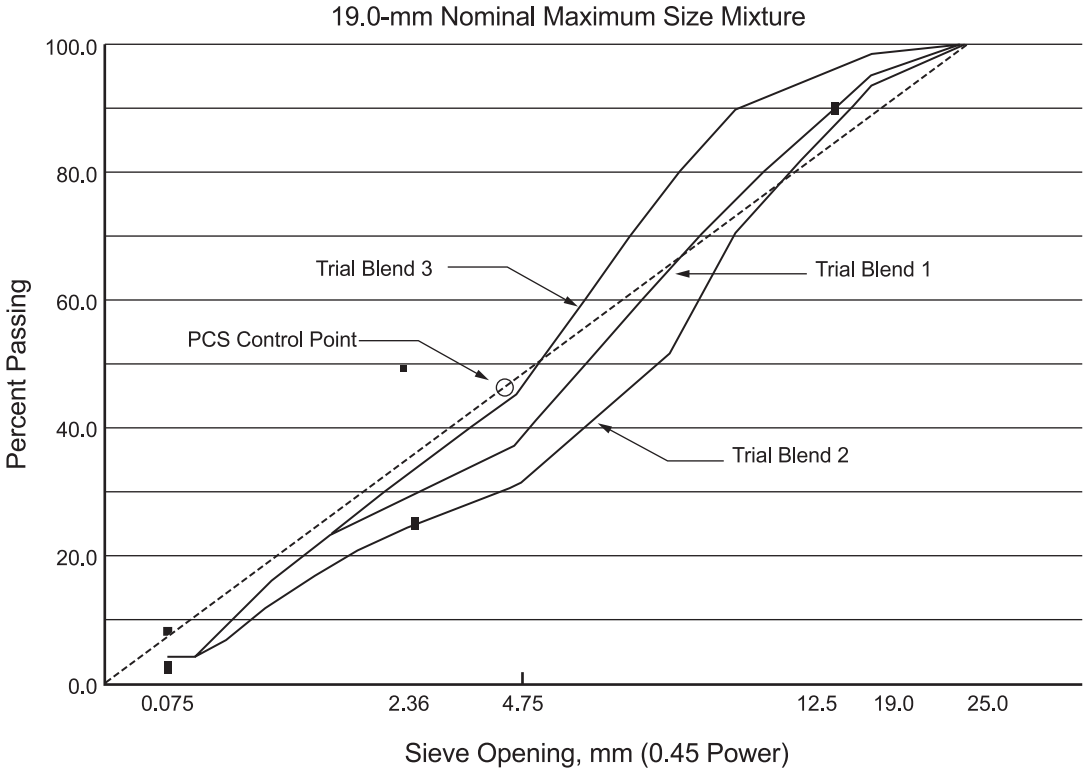


Figure 1—Evaluation of the Gradations of Three Trial Blends (Example)

6.9. Obtain a test specimen from each of the trial blends according to T 248, and conduct the quality tests specified in Section 6 of M 323 to confirm that the aggregate in the trial blends meets the minimum quality requirements specified in M 323.

Note 6—The designer has an option of performing the quality tests on each stockpile instead of the trial aggregate blend. The test results from each stockpile can be used to estimate the results for a given combination of materials.

7. DETERMINING AN INITIAL TRIAL BINDER CONTENT FOR EACH TRIAL AGGREGATE GRADATION

7.1. Designers can either use their experience with the materials or the procedure given in Appendix X1 to determine an initial trial binder content for each trial aggregate blend gradation.

Note 7—When using RAP, the initial trial asphalt content should be reduced by an amount equal to that provided by the RAP.

8. COMPACTING SPECIMENS OF EACH TRIAL GRADATION

8.1. Prepare replicate mixtures (Note 8) at the initial trial binder content for each of the chosen trial aggregate trial blend gradations. From Table 1, determine the number of gyrations based on the design ESALs for the project.

Note 8—At least two replicate specimens are required, but three or more may be prepared if desired. Generally, 4,500 to 4,700 g of aggregate is sufficient for each compacted specimen with a height of 110 to 120 mm for aggregates with combined bulk specific gravities of 2.55 to 2.70, respectively.

8.2. Condition the mixtures according to R 30, and compact the specimens to N_{design} gyrations in accordance with T 312. Record the specimen height to the nearest 0.1 mm after each revolution.

8.3. Determine the bulk specific gravity (G_{mb}) of each of the compacted specimens in accordance with T 166 or T 275 as appropriate.

Table 1—Superpave Gyratory Compaction Effort

Design ESALs[a] (million)	Compaction Parameters			Typical Roadway Application[b]
	$N_{initial}$	N_{design}	N_{max}	
< 0.3	6	50	75	Applications include roadways with very light traffic volumes, such as local roads, county roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to < 3	7	75	115	Applications include many collector roads or access streets. Medium-trafficked city streets and the majority of county roadways may be applicable to this level.
3 to < 30	8	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these are medium to highly trafficked city streets, many state routes, U.S. highways, and some rural Interstates.
≥ 30	9	125	205	Applications include the vast majority of the U.S. Interstate system, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

[a] The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

[b] As defined by *A Policy on Geometric Design of Highways and Streets*, 2004, AASHTO.

Note 9—When specified by the agency and the top of the design layer is ≥100 mm from the pavement surface and the estimated design traffic level is ≥0.3 million ESALs, decrease the estimated design traffic level by one, unless the mixture will be exposed to significant mainline construction traffic prior to being overlaid. If less than 25 percent of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for mixture design purposes.

Note 10—When the estimated design traffic level is between 3 and <10 million ESALs, the Agency may, at its discretion, specify $N_{initial}$ at 7, N_{design} at 75, and N_{max} at 115.

8.4. Determine the theoretical maximum specific gravity (G_{mm}) according to T 209 of separate samples representing each of these combinations that have been mixed and conditioned to the same extent as the compacted specimens.

Note 11—The maximum specific gravity for each trial mixture shall be based on the average of at least two tests.

9. EVALUATING COMPACTED TRIAL MIXTURES

9.1. Determine the volumetric requirements for the trial mixtures in accordance with M 323.

9.2. Calculate V_a and VMA at N_{design} for each trial mixture using Equations 2 and 3:

$$V_a = 100\left(1 - \left(\frac{G_{mb}}{G_{mm}}\right)\right) \quad (2)$$

$$\text{VMA} = 100\left(1 - \left(\frac{G_{mb}P_s}{G_{sb}}\right)\right) \quad (3)$$

where:

G_{mb} = bulk specific gravity of the extruded specimen;
G_{mm} = theoretical maximum specific gravity of the mixture;
P_s = percent of aggregate in the mix; and
G_{sb} = bulk specific gravity of the combined aggregate.

Note 12—Although the initial trial binder content was estimated for a design air void content of 4.0 percent, the actual air void content of the compacted specimen is unlikely to be exactly 4.0 percent. Therefore, the change in binder content needed to obtain a 4.0 percent air void content, and the change in VMA caused by this change in binder content, is estimated. These calculations permit the evaluation of VMA and VFA of each trial aggregate gradation at the same design air void content, 4.0 percent.

9.3. Estimate the volumetric properties at 4.0 percent air voids for each compacted specimen.

9.3.1. Determine the difference in average air void content at N_{design} (ΔV_a) of each aggregate trial blend from the design level of 4.0 percent using Equation 4:

$$\Delta V_a = 4.0 - V_a \quad (4)$$

where:

V_a = air void content of the aggregate trial blend at N_{design} gyrations.

9.3.2. Estimate the change in binder content (ΔP_b) needed to change the air void content to 4.0 percent using Equation 5:

$$\Delta P_b = -0.4\left(\Delta V_a\right) \quad (5)$$

9.3.3. Estimate the change in VMA (ΔVMA) caused by the change in the air void content (ΔVa) determined in Section 9.3.1 for each trial aggregate blend gradation, using Equation 6 or 7.

$$\Delta VMA = 0.2\left(\Delta V_a\right) \quad \text{if} \quad V_a > 4.0 \quad (6)$$

$$\Delta VMA = -0.1\left(\Delta V_a\right) \quad \text{if} \quad V_a < 4.0 \quad (7)$$

Note 13—A change in binder content affects the VMA through a change in the bulk specific gravity of the compacted specimen (G_{mb}).

9.3.4. Calculate the VMA for each aggregate trial blend at N_{design} gyrations and 4.0 percent air voids using Equation 8:

$$VMA_{design} = VMA_{trial} + \Delta VMA \quad (8)$$

where:

VMA_{design} = VMA estimated at a design air void content of 4.0 percent; and
VMA_{trial} = VMA determined at the initial trial binder content.

9.3.5. Using the values of ΔV_a determined in Section 9.3.1 and Equation 9, estimate the relative density of each specimen at $N_{initial}$ when the design air void content is adjusted to 4.0 percent at N_{design}:

$$\%G_{mm_{\text{initial}}} = 100\left(\frac{G_{mb}h_d}{G_{mm}h_i}\right) - \Delta V_a \qquad (9)$$

where:

$\%G_{mm_{\text{initial}}}$ = relative density at N_{initial} gyrations at the adjusted design binder content;
h_d = height of the specimen after N_{design} gyrations, from the Superpave gyratory compactor, mm; and
h_i = height of the specimen after N_{initial} gyrations, from the Superpave gyratory compactor, mm.

9.3.6. Calculate the effective specific gravity of the aggregate (G_{se}), the estimated percent of effective binder ($P_{be_{est}}$), and the estimated dust-to-binder ratio ($P_{0.075}/P_{be}$) for each trial blend using Equations 10, 11, and 12:

$$G_{se} = \frac{100 - P}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \qquad (10)$$

$$P_{be_{est}} = -\left(P_s \times G_b\right)\left(\frac{\left(G_{se} - G_{sb}\right)}{\left(G_{se} \times G_{sb}\right)}\right) + P_{b_{est}} \qquad (11)$$

where:

$P_{be_{est}}$ = estimated effective binder content;
P_s = aggregate content;
G_b = specific gravity of the binder;
G_{se} = effective specific gravity of the aggregate;
G_{sb} = bulk specific gravity of the combined aggregate; and
$P_{b_{est}}$ = estimated binder content.

$$P_{0.075}/P_{be} = \frac{P_{0.075}}{P_{be_{est}}} \qquad (12)$$

where:

$P_{0.075}$ = percent passing the 0.075-mm sieve.

9.3.7. Compare the estimated volumetric properties from each trial aggregate blend gradation at the adjusted design binder content with the criteria specified in M 323. Choose the trial aggregate blend gradation that best satisfies the volumetric criteria.

Note 14—Table 2 presents an example of the selection of a design aggregate structure from three trial aggregate blend gradations.

Note 15—Many trial aggregate blend gradations will fail the VMA criterion. Generally, the $\%G_{mm_{\text{initial}}}$ criterion will be met if the VMA criterion is satisfied. Section 12.1 gives a procedure for the adjustment of VMA.

Note 16—If the trial aggregate gradations have been chosen to cover the entire range of the gradation controls, then the only remaining solution is to make adjustments to the aggregate production or to introduce aggregates from a new source. The aggregates that fail to meet the required criteria will not produce a quality mix and should not be used. One or more of the aggregate stockpiles should be replaced with another material that produces a stronger

structure. For example, a quarry stone can replace a crushed gravel, or crushed fines can replace natural fines.

Table 2—Selection of a Design Aggregate Structure (Example)

Volumetric Property	Trial Mixture (19.0-mm Nominal Maximum Aggregate) 20-Year Project Design ESALs = 5 million			Criteria
	1	2	3	
	At the Initial Trial Binder Content			
P_b (trial)	4.4	4.4	4.4	
$\%G_{mm_{initial}}$ (trial)	88.3	88.0	87.3	
$\%G_{mm_{design}}$ (trial)	95.6	94.9	94.5	
V_a at N_{design}	4.4	5.1	5.5	4.0
VMA_{trial}	13.0	13.6	14.1	
	Adjustments to Reach Design Binder Content (V_a = 4.0% at N_{design})			
ΔV_a	–0.4	–1.1	–1.5	
ΔP_b	0.2	0.4	0.6	
ΔVMA	–0.1	–0.2	–0.3	
	At the Estimated Design Binder Content (V_a = 4.0 % at N_{design})			
Estimated P_b (design)	4.6	4.8	5.0	
VMA (design)	12.9	13.4	13.8	≥ 13.0
$\%G_{mm_{initial}}$ (design)	88.7	89.1	88.5	≤ 89.0

Notes:
1. The top portion of this table presents measured densities and volumetric properties for specimens prepared for each aggregate trial blend at the initial trial binder content.
2. None of the specimens had an air void content of exactly 4.0 percent. Therefore, the procedures described in Section 9 must be applied to: (1) estimate the design binder content at which V_a = 4.0 percent, and (2) obtain adjusted VMA and relative density values at this estimated binder content.
3. The middle portion of this table presents the change in binder content (ΔP_b) and VMA (ΔVMA) that occurs when the air void content (V_a) is adjusted to 4.0 percent for each trial aggregate blend gradation.
4. A comparison of the VMA and densities at the estimated design binder content to the criteria in the last column shows that trial aggregate blend gradation No. 1 does not have sufficient VMA (12.9 percent versus a requirement of ≥13.0 percent). Trial blend No. 2 exceeds the criterion for relative density at $N_{initial}$ gyrations (89.1 percent versus a requirement of ≤89.0 percent). Trial blend No. 3 meets the requirement for relative density and VMA and, in this example, is selected as the design aggregate structure.

10. SELECTING THE DESIGN BINDER CONTENT

10.1. Prepare replicate mixtures (Note 8) containing the selected design aggregate structure at each of the following four binder contents: (1) the estimated design binder content, P_b (design); (2) 0.5 percent below P_b (design); (3) 0.5 percent above P_b (design); and (4) 1.0 percent above P_b (design).

10.1.1. Use the number of gyrations previously determined in Section 8.1.

10.2. Condition the mixtures according to R 30, and compact the specimens to N_{design} gyrations according to T 312. Record the specimen height to the nearest 0.1 mm after each revolution.

10.3. Determine the bulk specific gravity (G_{mb}) of each of the compacted specimens in accordance with T 166 or T 275 as appropriate.

10.4. Determine the theoretical maximum specific gravity (G_{mm}) according to T 209 of each of the four mixtures using companion samples that have been conditioned to the same extent as the compacted specimens (Note 11).

10.5. Determine the design binder content that produces a target air void content (V_a) of 4.0 percent at N_{design} gyrations using the following steps:

10.5.1. Calculate V_a, VMA, and VFA at N_{design} using Equations 2, 3, and 13:

$$VFA = 100\left(\frac{VMA - V_a}{VMA}\right) \quad (13)$$

10.5.2. Calculate the dust-to-binder ratio using Equation 14:

$$P_{0.075}/P_{be} = \frac{P_{0.075}}{P_{be}} \quad (14)$$

where:

P_{be} = effective binder content.

10.5.3. For each of the four mixtures, determine the average corrected specimen relative densities at $N_{initial}$ ($\%G_{mm_{initial}}$), using Equation 15:

$$\%G_{mm_{initial}} = 100\left(\frac{G_{mb}h_d}{G_{mm}h_i}\right) \quad (15)$$

10.5.4. Plot the average V_a, VMA, VFA, and relative density at N_{design} for replicate specimens versus binder content.

Note 17—All plots are generated automatically by the Superpave software. Figure 2 presents a sample data set and the associated plots.

10.5.5. By graphical or mathematical interpolation (Figure 2), determine the binder content to the nearest 0.1 percent at which the target V_a is equal to 4.0 percent. This is the design binder content (P_b) at N_{design}.

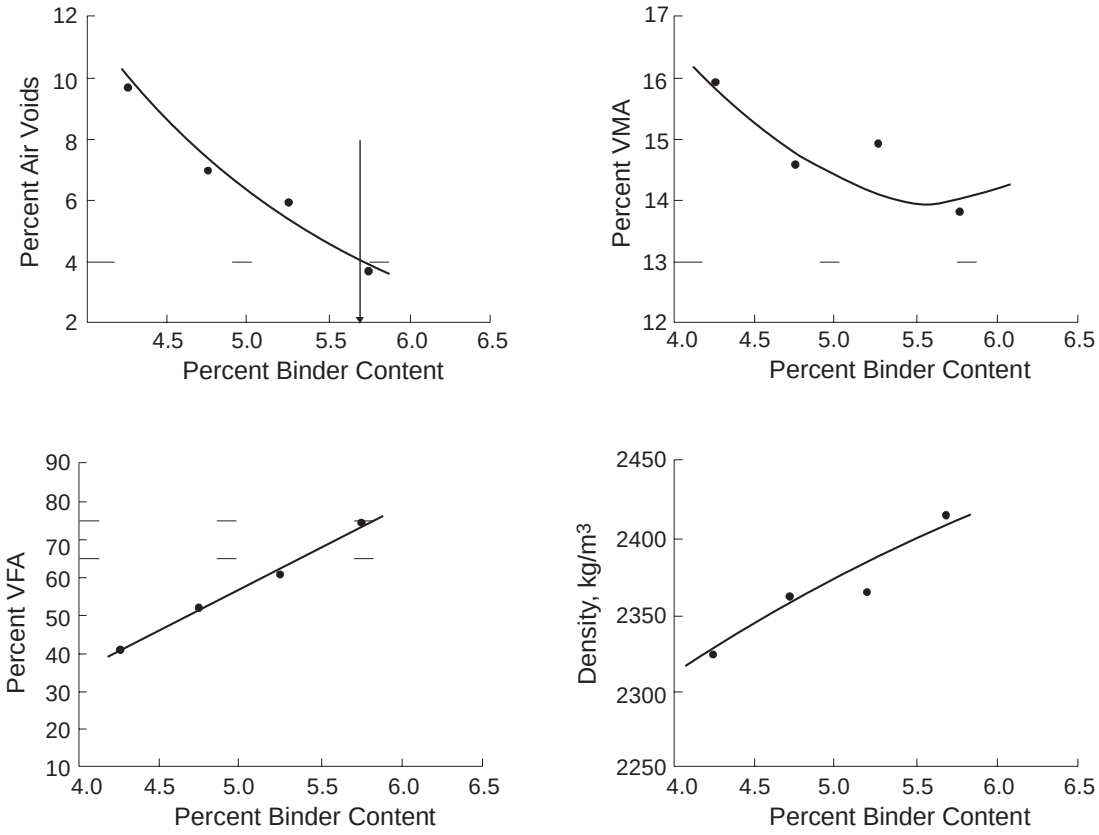
10.5.6. By interpolation (Figure 2), verify that the volumetric requirements specified in M 323 are met at the design binder content.

10.6. Compare the calculated percent of maximum relative density with the design criteria at $N_{initial}$ by interpolation, if necessary. This interpolation can be accomplished by the following procedure.

10.6.1. Prepare a densification curve for each mixture by plotting the measured relative density at X gyrations, $\%G_{mm_x}$, versus the logarithm of the number of gyrations (see Figure 3).

10.6.2. Examine a plot of air void content versus binder content. Determine the difference in air voids between 4.0 percent and the air void content at the nearest, lower binder content. Determine the air void content at the nearest, lower binder content at its data point, not on the line of best fit. Designate the difference in air void content as ΔV_a.

10.6.3. Using Equation 15, determine the average corrected specimen relative densities at $N_{initial}$ ($\%G_{mm_{initial}}$). Confirm that $\%G_{mm_{initial}}$ satisfies the design requirements in M 323 at the design binder content.



Average V_a, VMA, VFA, and Relative Density at N_{design}

P_b (%)	V_a (%)	VMA (%)	VFA (%)	Density at N_{design} (kg/m^3)
4.3	9.5	15.9	40.3	2320
4.8	7.0	14.7	52.4	2366
5.3	6.0	14.9	59.5	2372
5.8	3.7	13.9	73.5	2412

Notes:
1. In this example, the estimated design binder content is 4.8 percent; the minimum VMA requirement for the design aggregate structure (19.0-mm nominal maximum size) is 13.0 percent, and the VFA requirement is 65 to 75 percent.
2. Entering the plot of percent air voids versus percent binder content at 4.0 percent air voids, the design binder content is determined as 5.7 percent.
3. Entering the plots of percent VMA versus percent binder content and percent VFA versus percent binder content at 5.7 percent binder content, the mix meets the VMA and VFA requirements.

Figure 2—Sample Volumetric Design Data at N_{design}

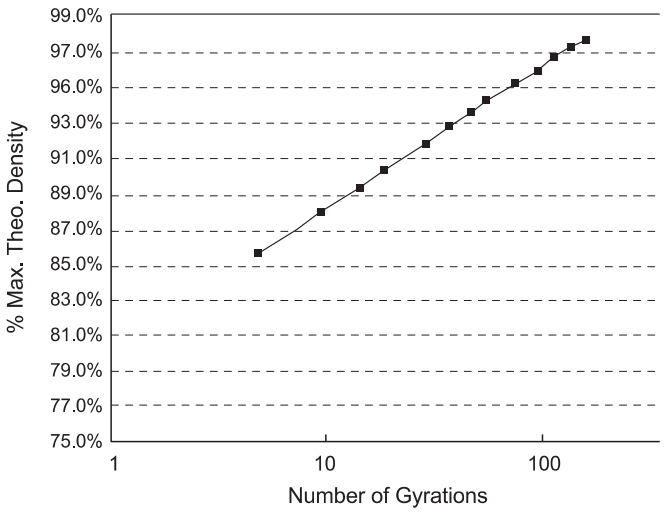


Figure 3—Sample Densification Curve

10.7. Prepare replicate (Note 8) specimens composed of the design aggregate structure at the design binder content to confirm that $\%G_{mm_{max}}$ satisfies the design requirements in M 323.

10.7.1. Condition the mixtures according to R 30, and compact the specimens according to T 312 to the maximum number of gyrations, N_{max}, from Table 1.

10.7.2. Determine the average specimen relative density at N_{max}, $\%G_{mm_{max}}$, by using Equation 16, and confirm that $\%G_{mm_{max}}$ satisfies the volumetric requirement in M 323.

$$\%G_{mm_{max}} = 100\left(\frac{G_{mb}}{G_{mm}}\right) \qquad (16)$$

where:

$\%G_{mm_{max}}$ = relative density at N_{max} gyrations at the design binder content.

11. EVALUATING MOISTURE SUSCEPTIBILITY

11.1. Prepare six mixture specimens (nine are needed if freeze-thaw testing is required) composed of the design aggregate structure at the design binder content. Condition the mixtures in accordance with R 30, and compact the specimens to 7.0 ± 0.5 percent air voids in accordance with T 312.

11.2. Test the specimens and calculate the tensile strength ratio in accordance with T 283.

11.3. If the tensile strength ratio is less than 0.80, as required in M 323, remedial action such as the use of anti-strip agents is required to improve the moisture susceptibility of the mix. When remedial agents are used to modify the binder, retest the mix to assure compliance with the 0.80 minimum requirement.

12. ADJUSTING THE MIXTURE TO MEET PROPERTIES

12.1. *Adjusting VMA*—If a change in the design aggregate skeleton is required to meet the specified VMA, there are three likely options: (1) change the gradation (Note 18); (2) reduce the minus

0.075-mm fraction (Note 19); or (3) change the surface texture and/or shape of one or more of the aggregate fractions (Note 20).

Note 18—Changing gradation may not be an option if the trial aggregate blend gradation analysis includes the full spectrum of the gradation control area.

Note 19—Reducing the percent passing the 0.075-mm sieve of the mix will typically increase the VMA. If the percent passing the 0.075-mm sieve is already low, this is not a viable option.

Note 20—This option will require further processing of existing materials or a change in aggregate sources.

12.2. *Adjusting VFA*—The lower limit of the VFA range should always be met at 4.0 percent air voids if the VMA meets the requirements. If the upper limit of the VFA is exceeded, then the VMA is substantially above the minimum required. If so, redesign the mixture to reduce the VMA. Actions to consider for redesign include (1) changing to a gradation that is closer to the maximum density line; (2) increasing the minus 0.075-mm fraction, if room is available within the specification control points; or (3) changing the surface texture and shape of the aggregates by incorporating material with better packing characteristics, e.g., less thin, elongated aggregate particles.

12.3. *Adjusting the Tensile Strength Ratio*—The tensile strength ratio can be increased by (1) adding chemical anti-strip agents to the binder to promote adhesion in the presence of water or (2) adding hydrated lime to the mix.

13. REPORT

13.1. The report shall include the identification of the project number, traffic level, and mix design number.

13.2. The report shall include information on the design aggregate structure, including the source of aggregate, kind of aggregate, required quality characteristics, and gradation.

13.3. The report shall contain information about the design binder, including the source of binder and the performance grade.

13.4. The report shall contain information about the HMA, including the percent of binder in the mix; the relative density; the number of initial, design, and maximum gyrations; and the VMA, VFA, V_{be}, V_{ba}, V_a, and dust-to-binder ratio.

14. KEYWORDS

14.1. HMA mix design; Superpave; volumetric mix design.

APPENDIXES

(Nonmandatory Information)

X1. CALCULATING AN INITIAL TRIAL BINDER CONTENT FOR EACH AGGREGATE TRIAL BLEND

X1.1. Calculate the bulk and apparent specific gravities of the combined aggregate in each trial blend using the specific gravity data for the aggregate fractions obtained in Section 6.6 and Equations X1.1 and X1.2:

$$G_{sb} = \frac{P_1 + P_2 + \mathrm{K} + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \mathrm{K} + \frac{P_n}{G_n}} \qquad (X1.1)$$

$$G_{sa} = \frac{P_1 + P_2 + \mathrm{K} + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \mathrm{K} + \frac{P_n}{G_n}} \qquad (X1.2)$$

where:

G_{sb} = bulk specific gravity for the combined aggregate;
$P_1, P_2, \ldots P_n$ = percentages by mass of aggregates 1, 2, . . . *n*;
$G_1, G_2, \ldots G_n$ = bulk specific gravities (Equation X1.1) or apparent specific gravities (Equation X1.2) of aggregates 1, 2, *n*; and
G_{sa} = apparent specific gravity for the combined aggregate.

X1.2. Estimate the effective specific gravity of the combined aggregate in the aggregate trial blend using Equation X1.3:

$$G_{se} = G_{sb} + 0.8(G_{sa} - G_{sb}) \qquad (X1.3)$$

where:

G_{se} = effective specific gravity of the combined aggregate;
G_{sb} = bulk specific gravity of the combined aggregate; and
G_{sa} = apparent specific gravity of the combined aggregate.

Note X1—The multiplier, 0.8, can be changed at the discretion of the designer. Absorptive aggregates may require values closer to 0.6 or 0.5.

Note X2—The Superpave mix design system includes a mixture-conditioning step before the compaction of all specimens; this conditioning generally permits binder absorption to proceed to completion. Therefore, the effective specific gravity of Superpave mixtures will tend to be close to the apparent specific gravity in contrast to other design methods where the effective specific gravity generally will lie near the midpoint between the bulk and apparent specific gravities.

X1.3. Estimate the volume of binder absorbed into the aggregate, V_{ba}, using Equations X1.4 and X1.5:

$$V_{ba} = W_s\left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right) \quad (X1.4)$$

where:

W_s, the mass of aggregate in 1 cm^3 of mix, g, is calculated as:

$$W_s = \frac{P_s\left(1 - V_a\right)}{\frac{P_b}{G_b} + \frac{P_s}{G_{se}}} \quad (X1.5)$$

and where:

P_s = mass percent of aggregate, in decimal equivalent, assumed to be 0.95;
V_a = volume of air voids, assumed to be 0.04 cm^3 in 1 cm^3 of mix;
P_b = mass percent of binder, in decimal equivalent, assumed to be 0.05; and
G_b = specific gravity of the binder.

Note X3—This estimate calculates the volume of binder absorbed into the aggregate, V_{ba}, and subsequently the initial, trial binder content at a target air void content of 4.0 percent.

X1.4. Estimate the volume of effective binder using Equation X1.6:

$$V_{be} = 0.176 - \left[0.0675\log\left(S_n\right)\right] \quad (X1.6)$$

where:

V_{be} = volume of effective binder, cm^3; and
S_n = nominal maximum sieve size of the largest aggregate in the aggregate trial blend, mm.

Note X4—This regression equation is derived from an empirical relationship (1) VMA and V_{be} when the air void content, V_a, is equal to 4.0 percent: V_{be} = VMA – V_a = VMA – 4.0; and (2) the relationship between VMA and the nominal maximum sieve size of the aggregate in M 323.

X1.5. Calculate the estimated initial trial binder (P_{bi}) content for the aggregate trial blend gradation using Equation X1.7:

$$P_{bi} = 100\left(\frac{G_b\left(V_{be} + V_{ba}\right)}{\left(G_b\left(V_{be} + V_{ba}\right)\right) + W_s}\right) \quad (X1.7)$$

where:

P_{bi} = estimated initial trial binder content, percent by weight of total mix.

X2. SPECIAL MIXTURE DESIGN CONSIDERATIONS AND PRACTICES FOR WARM MIX ASPHALT (WMA)

X2.1. *Purpose:*

X2.1.1. This appendix presents special mixture design considerations and methods for designing warm mix asphalt (WMA) using R 35. WMA refers to asphalt mixtures that are produced at temperatures approximately 50°F (28°C) or more than typically used in the production of HMA. The goal of WMA is to produce mixtures with equivalent strength, durability, and performance characteristics as HMA using substantially reduced production temperatures.

These special mixture design considerations and practices are applicable anytime a WMA technology is being used. The WMA technologies may be used as coating and compaction aids without lowering the production temperature by 50°F (28°C).

X2.1.2. The practices in this appendix are applicable to a wide range of WMA technologies including:

- WMA additives that are added to the asphalt binder,
- WMA additives that are added to the mixture during production,
- Wet aggregate mixtures, and
- Plant foaming processes.

X2.1.3. The information in this appendix supplements the procedures in R 35. This appendix assumes the user is proficient with the standard procedures in R 35.

X2.2. *Summary:*

X2.2.1. This appendix includes separate sections addressing the following aspects of WMA mixture design:

- Equipment for Designing WMA,
- WMA Technology Selection,
- Binder Grade Selection,
- RAP in WMA,
- Technology-Specific Specimen Fabrication Procedures,
- Evaluation of Coating,
- Evaluation of Compactability,
- Evaluation of Moisture Sensitivity,
- Evaluation of Rutting Resistance, and
- Adjusting the Mixture to Meet Specification Requirements.

X2.2.2. In each section, reference is made to the applicable section of R 35.

X2.3. *Additional Laboratory Equipment:*

X2.3.1. **All WMA Processes**:

X2.3.1.1. *Mechanical Mixer*—A planetary mixer with a wire whip having a capacity of 20 qt or a 5-gal bucket mixer.

Note X5—The mixing times in this appendix were developed using a planetary mixer with a wire whip, Blakeslee Model B-20 or equivalent. Appropriate mixing times for bucket mixers should be established by evaluating the coating of HMA mixtures prepared at the viscosity-based mixing temperatures specified in T 312.

X2.3.2. **Binder Additive WMA Processes**:

X2.3.2.1. *Low-Shear Mechanical Stirrer*—A low-shear mechanical stirrer with appropriate impeller to homogeneously blend the additive in the binder.

X2.3.3. **Plant Foaming Processes**:

Laboratory Foamed Asphalt Plant—A laboratory-scale foamed asphalt plant capable of producing consistent foamed asphalt at the water content used in field production. The device should be capable of producing foamed asphalt for laboratory batches ranging from approximately 10 to 20 kg.

X2.4. *WMA Technology Selection:*

X2.4.1. More than 20 WMA technologies are being marketed in the United States. Select the WMA technology that will be used in consultation with the specifying agency and technical representatives from the WMA technology providers. Consideration should be given to a number of factors including (1) available performance data, (2) the cost of the WMA additives, (3) planned production and compaction temperatures, (4) planned production rates, (5) plant capabilities, and (6) modifications required to successfully use the WMA technology with available field and laboratory equipment.

X2.4.2. Determine the planned production and field compaction temperatures.

X2.5. *Binder Grade Selection:*

X2.5.1. Use the same grade of binder normally used with HMA. Select the performance grade of the binder in accordance with M 323, considering the environment and traffic at the project site.

Note X6—For WMA technologies having production temperatures that are 100°F (56°C) or more lower than HMA production temperatures, it may be necessary to increase the high-temperature performance grade of the binder one grade level to meet the rutting resistance requirements included in this appendix.

X2.6. *RAP in WMA:*

X2.6.1. For WMA mixtures incorporating RAP, the planned field compaction temperature shall be greater than the as-recovered high-temperature grade of the RAP binder.

Note X7—This requirement is included to ensure mixing of the new and reclaimed binders. Laboratory studies showed that new and reclaimed binders do mix at WMA process temperatures provided this requirement is satisfied and the mixture remains at or above the planned compaction temperature for at least 2 h. Plant mixing should be verified through an evaluation of volumetric or stiffness properties of plant-produced mixtures.

X2.6.2. Select RAP materials in accordance with M 323.

X2.6.3. For blending chart analyses, the intermediate and low-temperature properties of the virgin binder may be improved using Table X2.1.

Note X8—The intermediate and low-temperature grade improvements given in Table X2.1 will allow additional RAP to be used in WMA mixtures when blending chart analyses are used. An approximate 0.6°C improvement in the low-temperature properties will allow approximately 10 percent additional RAP binder to be added to the mixture based on blended binder grade requirements.

Table X2.1—Recommended Improvement in Virgin Binder Low-Temperature Continuous Grade for RAP Blending Chart Analysis for WMA Production Temperatures

Virgin Binder PG Grade	58-28	58-22	64-22	64-16	67-22
Average HMA Production Temperature, °F	285	285	292	292	300
Rate of Improvement of Virgin Binder Low-Temperature Grade per 1°C Reduction in Plant Temperature	0.035	0.025	0.025	0.012	0.025
WMA Production Temperature, °F	Recommended Improvement in Virgin Binder Low-Temperature Continuous Grade for RAP Blending Chart Analysis, °C				
300	NA	NA	NA	NA	0.0
295	NA	NA	NA	NA	0.1
290	NA	NA	0.0	0.0	0.1
285	0.0	0.0	0.1	0.0	0.2
280	0.1	0.1	0.2	0.1	0.3
275	0.2	0.1	0.2	0.1	0.3
270	0.3	0.2	0.3	0.1	0.4
265	0.4	0.3	0.4	0.2	0.5
260	0.5	0.3	0.4	0.2	0.6
255	0.6	0.4	0.5	0.2	0.6
250	0.7	0.5	0.6	0.3	0.7
245	0.8	0.6	0.7	0.3	0.8
240	0.9	0.6	0.7	0.3	0.8
235	1.0	0.7	0.8	0.4	0.9
230	1.1	0.8	0.9	0.4	1.0
225	1.2	0.8	0.9	0.4	1.0
220	1.3	0.9	1.0	0.5	1.1
215	1.4	1.0	1.1	0.5	1.2
210	1.5	1.0	1.1	0.5	1.3

X2.6.4. **Blending Chart Example**:

X2.6.4.1. *Problem Statement*—A producer will be producing WMA using a virgin PG 64-22 binder at a temperature of 250°F. In the mixture, 35 percent of the total binder will be replaced with RAP binder, so according to M 323, a blending chart analysis is needed. The continuous grade of the recovered RAP binder is PG 93.0 (29.4) – 18.1. The continuous grade of the virgin PG 64-22 binder is PG 66.2 (21.1) – 23.9. The specified grade for the blended binder in the mixture is PG 64-22. Use the M 323 blending chart analysis to determine if the proposed RAP and virgin binder provide an acceptable blended binder.

X2.6.4.2. *Solution as WMA*—Because the mixture will be produced as WMA at 250°F, determine the virgin binder grade improvement for the blending chart analysis by entering Table X2.1 in the PG 64-22 column and reading the intermediate- and low-temperature improvement from the row for 250°F. The intermediate- and low-temperature grade improvement is 0.6°C. For WMA at 250°F, perform the M 323 blending chart analysis using PG 66.2 (20.5) –24.5 for the virgin binder and PG 93.0 (29.4) –18.1 for the RAP binder. Because a PG 64-XX virgin binder is being used and a PG 64-XX is specified, it is not necessary to check the high-temperature grade. Use Equation X1.12 from M 323 to determine the maximum allowable RAP content based on the intermediate and low temperature. For PG 64-22, 25°C is the maximum allowable blended binder intermediate-temperature grade and –22°C the maximum allowable blended binder low-temperature grade.

$$\%RAP = \frac{\left(T_{\text{blend}} - T_{\text{virgin}}\right)}{\left(T_{RAP} - T_{\text{virgin}}\right)} \times 100 \quad \text{(Eq. X1.12 from M 323)}$$

where:

T_{blend} = continuous grade temperature of the blended binder (high, intermediate, low);
T_{virgin} = continuous grade temperature of the virgin binder (high, intermediate, low); and
T_{RAP} = continuous grade temperature of the RAP binder (high, intermediate, low).

Maximum RAP Binder Based on Intermediate-Temperature Grade:

$$\%RAP = \frac{(25 - 20.5)}{(29.4 - 20.5)} \times 100 = \frac{4.5}{8.9} \times 100 = 50.5\%$$

Maximum RAP Binder Based on Low-Temperature Grade:

$$\%RAP = \frac{(-22 - (-24.5))}{(-18.1 - (-24.5))} \times 100 = \frac{2.5}{6.4} \times 100 = 39.0\%$$

The critical property is the low-temperature grade, which allows 39.0 percent of the binder to be RAP binder. The proposed mixture contains only 35 percent RAP binder; therefore, it is acceptable.

X2.6.4.3. *Solution as HMA*—If the mixture were produced as HMA, the blending chart analysis would be completed using PG 66.2 (21.1) –23.9 for the virgin binder and PG 93.0 (29.4) – 18.1 for the RAP binder.

Maximum RAP Binder Based on Intermediate-Temperature Grade:

$$\%RAP = \frac{(25 - 21.1)}{(29.4 - 21.1)} \times 100 = \frac{3.9}{8.3} \times 100 = 47.0\%$$

Maximum RAP Binder Based on Low-Temperature Grade:

$$\%RAP = \frac{(-22 - (-23.9))}{(-18.1 - (-23.9))} \times 100 = \frac{1.9}{5.8} \times 100 = 32.7\%$$

Again the critical property is the low-temperature grade, but this time the proposed RAP binder content of 35 percent exceeds the maximum allowable of 32.7 percent; therefore, the HMA mixture is not acceptable.

X2.7. *Technology-Specific Specimen Fabrication Procedures:*

X2.7.1. **Batching**:

X2.7.1.1. Determine the number and size of specimens required. Table X2.2 summarizes approximate specimen sizes for WMA mixture design.

Note X9—The mass of mixture required for the various specimens depends on the specific gravity of the aggregate and the air void content of the specimen. Trial specimens may be required to determine appropriate batch weights for T 283 and flow number testing.

Table X2.2—Specimen Requirements

Specimen Type	Gyratory Specimen Size	Approximate Specimen Mass	Number Required
Maximum Specific Gravity	NA	500 to 6,000 g depending on maximum aggregate size	2 per trial blend, plus 8 to determine design binder content, plus 1 at the design binder content for compactability evaluation
Volumetric Design	150-mm diameter by 115 mm high	4,700 g	2 per trial blend, plus 8 to determine design binder content
Coating	NA	500 to 6,000 g depending on maximum aggregate size	1 at the design binder content
Compactability	150-mm diameter by 115 mm high	4,700 g	4 at the design binder content
T 283	150-mm diameter by 95 mm high	3,800 g	6 at the design binder content
Flow Number	150-mm diameter by 175 mm high	7,000 g	4 at the design binder content

X2.7.1.2. Prepare a batch sheet showing the batch weight of each aggregate fraction, RAP, and the asphalt binder.

X2.7.1.3. Weigh into a pan the weight of each aggregate fraction.

Note X10—For WMA processes that use wet aggregate, weigh the portion of the aggregate that will be heated into one pan and weigh the portion of the aggregate that will be wetted into a second pan.

X2.7.1.4. Weigh into a separate pan, the weight of RAP.

X2.7.2. **Heating**:

X2.7.2.1. Place the aggregate in an oven set at approximately 15°C higher than the planned production temperature.

Note X11—The aggregate will require 2 to 4 h to reach the temperature of the oven. Aggregates may be placed in the oven overnight.

X2.7.2.2. Heat the RAP in the oven with the aggregates, but limit the heating time for the RAP to 2 h.

X2.7.2.3. Heat the binder to the planned production temperature.

X2.7.2.4. Heat mixing bowls and other tools to the planned production temperature.

X2.7.2.5. Preheat a forced draft oven and pans to the planned field compaction temperature for use in short-term conditioning the mixture.

X2.7.3. **Preparation of WMA Mixtures with WMA Additive Added to the Binder**:

Note X12—If specific mixing and storage instructions are provided by the WMA additive supplier, follow the supplier's instructions.

X2.7.3.1. *Adding WMA Additive to Binder*:

X2.7.3.1.1. Weigh the required amount of the additive into a small container.

Note X13—The additive is typically specified as a percent by weight of binder. For mixtures containing RAP, determine the weight of additive based on the total binder content of the mixture.

X2.7.3.1.2. Heat the asphalt binder in a covered container in an oven set at 135°C until the binder is sufficiently fluid to pour. During heating, occasionally stir the binder manually to ensure homogeneity.

X2.7.3.1.3. Add the required amount of additive to the binder, and stir it with a mechanical stirrer until the additive is totally dispersed in the binder.

X2.7.3.1.4. Store the binder with WMA additive at room temperature in a covered container until needed for use in the mixture design.

X2.7.3.2. *Preparing WMA Specimens*:

X2.7.3.2.1. Heat the mixing tools, aggregate, RAP, and binder in accordance with Section X2.7.2.

X2.7.3.2.2. If a liquid anti-stripping additive is required, add it to the binder per the manufacturer's instructions.

X2.7.3.2.3. Place the hot mixing bowl on a scale, and tare the scale.

X2.7.3.2.4. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.

X2.7.3.2.5. Form a crater in the blended aggregate, and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note X14—If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

1. Record the oven-dry weight of the aggregates and RAP, w_i.
2. Determine the target total weight of the mixture as follows:

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{new}}}{100}\right)} \qquad (X2.1)$$

where:

w_t = target total weight, g;

w_i = oven-dry weight from Step 1, g; and

$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture.

3. Add new binder to the bowl to reach w_t.

X2.7.3.2.6. Remove the mixing bowl from the scale, and mix the material with a mechanical mixer for 90 s.

X2.7.3.2.7. Place the mixture in a flat, shallow pan at an even thickness of 25 to 50 mm, and place the pan in the forced-draft oven at 116 °C ~~the planned field compaction temperature~~ for 2 h. Stir the mixture once after 1 h. If preparing field-mixed, laboratory-compacted specimens, no loose-mix conditioning is performed. Instead, reheat the mixture in a forced-draft oven until it reaches 116°C.

X2.7.4. **Preparation of WMA Mixtures with WMA Additive Added to the Mixture**:

Note X15—If specific mixing and storage instructions are provided by the WMA additive supplier, follow the supplier's instructions.

X2.7.4.1. Weigh the required amount of the additive into a small container.

Note X16—The quantity of additive may be specified as a percent by weight of binder or a percent by weight of total mixture.

X2.7.4.2. If a liquid anti-stripping additive is required, add it to the binder per the manufacturer's instructions.

X2.7.4.3. Heat the mixing tools, aggregate, RAP, and binder in accordance with Section X2.7.2.

X2.7.4.4. Place the hot mixing bowl on a scale, and tare the scale.

X2.7.4.5. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.

X2.7.4.6. Form a crater in the blended aggregate, and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note X17—If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

1. Record the oven dry weight of the aggregates, and RAP, w_i.
2. Determine the target total weight of the mixture as follows:

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{new}}}{100}\right)} \qquad (X2.2)$$

where:

w_t = target total weight, g;
w_i = oven-dry weight from Step 1, g; and
$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture.

3. Add new binder to the bowl to reach w_t.

X2.7.4.7. Pour the WMA additive into the pool of new asphalt binder.

X2.7.4.8. Remove the mixing bowl from the scale, and mix material with a mechanical mixer for 90 s.

X2.7.4.9. Place the mixture in a flat, shallow pan at an even thickness of 25 to 50 mm, and place the pan in the forced-draft oven at 116°C ~~the planned field compaction temperature~~ for 2 h. Stir the mixture once after 1 h. If preparing field-mixed, laboratory-compacted specimens, no loose-mix conditioning is performed. Instead, reheat the mixture in a forced-draft oven until it reaches 116°C.

X2.7.5. **Preparation of WMA Mixtures with a Wet Fraction of Aggregate**

Note X18—Consult the WMA process supplier for appropriate additive dosage rates, mixing temperatures, percentage of wet aggregate, and wet aggregate moisture content.

X2.7.5.1. *Adding WMA Additive to Binder*:

X2.7.5.1.1. Weigh the required amount of the additive into a small container.

Note X19—The additive is typically specified as a percent by weight of binder. For mixtures containing RAP, determine the weight of additive based on the total binder content of the mixture.

X2.7.5.1.2. Heat the asphalt binder in a covered container in an oven set at 135°C until the binder is sufficiently fluid to pour. During heating, occasionally stir the binder manually to ensure homogeneity.

X2.7.5.1.3. Add the required amount of additive to the binder, and stir it with a mechanical stirrer until the additive is totally dispersed in the binder.

X2.7.5.2. *Preparing WMA Specimens*:

X2.7.5.2.1. Add the required amount of moisture to the wet fraction of the aggregate. Mix it thoroughly, then cover and let stand for at least 2 h before mixing it with the heated fraction.

X2.7.5.2.2. Heat the mixing tools, dry aggregate portion, and dry RAP portion to the initial mixing temperature in accordance with Section X2.7.2.

X2.7.5.2.3. Place the hot mixing bowl on a scale, and tare the scale.

X2.7.5.2.4. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.

X2.7.5.2.5. Form a crater in the blended aggregate, and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note X20—If the aggregates and RAP have been stored for an extended period of time in a humid environment, it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

1. Record the oven-dry weight of the aggregates and RAP, w_i.
2. Determine the target total weight of the mixture as follows:

$$w_t = \frac{\left(w_i + w_{dwf}\right)}{\left(1 - \frac{P_{b_{new}}}{100}\right)} \qquad (X2.3)$$

where:

w_t = target total weight, g;
w_i = oven-dry weight from Step 1, g;
w_{dwf} = oven-dry weight of the wet fraction from the batch sheet, g; and
$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture.

3. Determine the target weight of the heated mixture:

$$w_{thm} = w_t - w_{dwf} \qquad (X2.4)$$

where:

w_{thm} = target weight of the heated mixture, g;
w_t = target total weight, g; and
w_{dwf} = oven-dry weight of the wet fraction from the batch sheet.

X2.7.5.2.6. Add new binder to the bowl to reach w_{thm}.

X2.7.5.2.7. Add the additive to the binder immediately before mixing it with the heated fraction of the aggregate according to Section X2.7.5.1.

X2.7.5.2.8. Remove the mixing bowl from the scale, and mix the material with a mechanical mixer for 30 s.

X2.7.5.2.9. Stop the mixer, and immediately add the wet fraction aggregate.

X2.7.5.2.10. Restart the mixer, and continue to mix for 60 s.

X2.7.5.2.11. Place the mixture in a flat, shallow pan at an even thickness of 25 to 50 mm.

X2.7.5.2.12. Check the temperature of the mixture in the pan to ensure it is between 90 and 100°C.

X2.7.5.2.13. Place the pan in the forced-draft oven at 116°C ~~the planned field compaction temperature~~ for 2 h. Stir the mixture once after 1 h. If preparing field-mixed, laboratory-compacted specimens, no loose-mix conditioning is performed. Instead, reheat the mixture in a forced-draft oven until it reaches 116°C.

X2.7.6. **Preparation of Foamed Asphalt Mixtures**:

X2.7.6.1. The preparation of foamed asphalt mixtures requires special asphalt binder foaming equipment that can produce foamed asphalt using the amount of moisture that will be used in field production.

X2.7.6.2. Prepare the asphalt binder foaming equipment, and load it with binder per the manufacturer's instructions.

X2.7.6.3. If a liquid anti-stripping additive is required, add it to the binder in the foaming equipment according to the manufacturer's instructions.

X2.7.6.4. Heat the mixing tools, aggregate, and RAP in accordance with Section X2.7.2.

X2.7.6.5. Prepare the foamed asphalt binder according to the instructions for the foaming equipment.

X2.7.6.6. Place the hot mixing bowl on a scale, and tare the scale.

X2.7.6.7. Charge the mixing bowl with the heated aggregates and RAP, and dry-mix thoroughly.

X2.7.6.8. Form a crater in the blended aggregate, and add the required amount of foamed asphalt into the mixture to achieve the desired batch weight.

Note X21—The laboratory foaming equipment uses a timer to control the amount of foamed asphalt produced. Ensure the batch size is large enough that the required amount of foamed asphalt is within the calibrated range of the foaming device. This operation may require producing one batch for the two gyratory specimens and the two maximum specific gravity specimens at each asphalt content and then splitting the larger batch into individual samples.

Note X22—If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven-dry weight of the aggregates and RAP as follows:

1. Record the oven-dry weight of the aggregates and RAP, w_i.
2. Determine the target total weight of the mixture as follows:

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{new}}}{100}\right)} \qquad (X2.5)$$

where:

w_t = target total weight, g;

w_i = oven-dry weight from Step 1, g; and

$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture.

3. Add foamed binder to the bowl to reach w_t.

X2.7.6.9. Remove the mixing bowl from the scale, and mix the materials with a mechanical mixer for 90 s.

X2.7.6.10. Place the mixture in a flat, shallow pan at an even thickness of 25 to 50 mm, and place the pan in the forced-draft oven at 116°C ~~the planned field compaction temperature~~ for 2 h. Stir the mixture once after 1 h. If preparing field-mixed, laboratory-compacted specimens, no loose-mix conditioning is performed. Instead, reheat the mixture in a forced-draft oven until it reaches 135°C.

X2.8. *WMA Mixture Evaluations:*

X2.8.1. At the optimum binder content determined in accordance with R 35, prepare WMA mixtures in accordance with the appropriate procedure from Section X2.7 for the following evaluations:

- Coating
- Compactability
- Moisture sensitivity
- Rutting resistance

X2.8.2. **Coating**:

X2.8.2.1. Prepare a sufficient amount of mixture at the design binder content to perform the coating evaluation procedure in T 195 using the appropriate WMA fabrication procedure from Section X2.7. Do not short-term condition the mixture.

X2.8.2.2. Evaluate the coating in accordance with T 195.

X2.8.2.3. The recommended coating criterion is at least 95 percent of the coarse aggregate particles being fully coated.

X2.8.3. **Compactability**:

X2.8.3.1. Prepare a sufficient amount of mixture at the design binder content for four gyratory specimens and one maximum specific gravity measurement using the appropriate WMA fabrication procedure from Section X2.7, including short-term conditioning for 2 h at the planned compaction temperature.

X2.8.3.2. Determine the theoretical maximum specific gravity (G_{mm}) according to T 209.

X2.8.3.3. Compact duplicate specimens at the planned field compaction temperature to N_{design} gyrations according to T 312. Record the specimen height for each gyration.

X2.8.3.4. Determine the bulk specific gravity (G_{mb}) of each specimen according to T 166.

X2.8.3.5. Allow the mixture to cool to 30°C below the planned field compaction temperature. Compact duplicate specimens to N_{design} gyrations according to T 312. Record the specimen height for each gyration.

X2.8.3.6. Determine the bulk specific gravity (G_{mb}) of each specimen according to T 166.

X2.8.3.7. For each specimen, determine the corrected specimen relative densities for each gyration using Equation X2.6:

$$\%G_{mm_N} = 100\left(\frac{G_{mb}h_d}{G_{mm}h_N}\right) \quad (X2.6)$$

where:

$\%G_{mm_N}$ = relative density at N gyrations;

G_{mb} = bulk specific gravity of the specimen compacted to N_{design} gyrations;

h_d = height of the specimen after N_{design} gyrations, from the Superpave gyratory compactor, mm; and

h_N = height of the specimen after N gyrations, from the Superpave gyratory compactor, mm.

X2.8.3.8. For each specimen, determine the number of gyrations needed to reach 92 percent relative density.

X2.8.3.9. Determine the average number of gyrations needed to reach 92 percent relative density at the planned field compaction temperature.

X2.8.3.10. Determine the average number of gyrations needed to reach 92 percent relative density at 30°C below the planned field compaction temperature.

X2.8.3.11. Determine the gyration ratio using Equation X2.7:

$$Ratio = \frac{(N_{92})_{T-30}}{(N_{92})_T} \quad (X2.7)$$

where:

Ratio = gyration ratio;

$(N_{92})_{T-30}$ = gyrations needed to reach 92 percent relative density at 30°C below the planned field compaction temperature; and

$(N_{92})_T$ = gyrations needed to reach 92 percent relative density at the planned field compaction temperature.

X2.8.3.12. The recommended compactability criterion is a gyration ratio less than or equal to 1.25.

Note X23—The compactability criterion limits the temperature sensitivity of WMA to that for a typical HMA mixture. The criterion is based on limited research conducted in NCHRP 9-43. The criterion should be considered tentative and subject to change as additional data on WMA mixtures are collected.

X2.8.4. **Evaluating Moisture Sensitivity**:

X2.8.4.1. Evaluation by T 283:

X2.8.4.1.1. Prepare a sufficient amount of mixture at the design binder content for six gyratory specimens using the appropriate WMA fabrication procedure from Section X2.7, including short-term conditioning. If evaluating aged specimens, prepare long-term aged-compacted specimens according to R 30.

X2.8.4.1.2. Compact test specimens to 7.0 ± 0.5 percent air voids according to T 312.

X2.8.4.1.3. Group, condition, and test the specimens according to T 283.

X2.8.4.1.4. The recommended moisture sensitivity criteria for unaged specimens are a wet IDT strength of 65 psi and a tensile strength ratio greater than 0.70 ~~0.80~~ and no visual evidence of stripping. If preparing field-mixed, laboratory-compacted specimens, a wet IDT strength of 100 psi is required. The recommended moisture sensitivity criterion for aged specimens is a wet IDT strength of 115 psi. If only the aged criteria are met, spring construction is recommended.

X2.8.4.2. Evaluation by M_R:

X2.8.4.2.1. Prepare a sufficient amount of mixture at the design binder content for six gyratory specimens using the appropriate WMA fabrication procedure from Section X2.7, including short-term conditioning. If evaluating aged specimens, prepare long-term aged-compacted specimens according to R 30.

X2.8.4.2.2. Compact test specimens to 7.0 ± 0.5 percent air voids according to T 312.

X2.8.4.2.3. Group, condition, and test the specimens according to ASTM D7369 with horizontal deformation measured across the diameter.

X2.8.4.2.4. The recommended moisture sensitivity criteria for unaged specimens are a wet M_R of 200 ksi and a tensile strength ratio greater than 0.70 ~~0.80~~ and no visual evidence of stripping. If preparing field-mixed, laboratory-compacted specimens, a wet M_R of 300 ksi is required. The recommended moisture sensitivity criterion for aged specimens is a wet M_R of 450 ksi. If only the aged criteria are met, spring construction is recommended.

X2.8.4.3. Evaluation by T 324:

X2.8.4.3.1. Prepare a sufficient amount of mixture at the design binder content for four gyratory specimens using the appropriate WMA fabrication procedure from Section X2.7, including short-term conditioning. If evaluating aged specimens, prepare long-term aged-compacted specimens according to R 30.

X2.8.4.3.2. Compact test specimens to 7.0 ± 0.5 percent air voids according to T 312.

X2.8.4.3.3. Group and test the specimens according to T 324 at 50°C.

X2.8.4.3.4. The recommended moisture sensitivity criteria for unaged specimens are a SIP of 3,500 cycles and a stripping slope of 5.3 μm/cycle. If preparing field-mixed, laboratory-compacted specimens, a SIP of 6,000 cycles and a stripping slope of 2.0 μm/cycle is required. The recommended moisture sensitivity criteria for aged specimens is a SIP of 12,000 cycles and a stripping slope of 1.4 μm/cycle. If only the aged criteria are met, spring construction is recommended.

X2.8.5. **Evaluating Rutting Resistance**:

X2.8.5.1. Evaluate rutting using the flow number test in TP 79.

Note X24—WMA additives and processes may affect the rutting resistance of the mixture and rutting resistance should be evaluated. Agencies with established criteria for other test methods, such as T 320 (SST), T 324 (Hamburg), and T 340 (APA), may specify those methods in lieu of TP 79.

X2.8.5.2. Prepare a sufficient amount of mixture at the design binder content for four flow number test specimens using the appropriate WMA fabrication procedure from Section X2.7, including short-term conditioning.

X2.8.5.3. The test is conducted on 100-mm-diameter by 150-mm-high test specimens sawed and cored from larger gyratory specimens that are 150-mm diameter by at least 175-mm high. Refer to PP 60 for detailed test specimen fabrication procedures. The short-term conditioning for WMA specimens is 2 h at the compaction temperature.

X2.8.5.4. Prepare the flow number test specimens to 7.0 ± 1.0 percent air voids.

X2.8.5.5. Perform the flow number test at the design temperature at 50-percent reliability as determined using LTPP Bind Version 3.1. The temperature is computed at 20 mm for surface courses, and the top of the pavement layer for intermediate and base courses.

X2.8.5.6. Perform the flow number test unconfined using a repeated deviatoric stress of 600 kPa with a contact deviatoric stress of 30 kPa.

X2.8.5.7. Determine the flow number for each specimen; then average the results. Compare the average flow number with the criteria given in Table X2.3.

Table X2.3—Minimum Flow Number Requirements

Traffic Level, Million ESALs	Minimum Flow Number
<3	NA
3 to <10	30
10 to <30	105
≥30	415

X2.9. *Adjusting the Mixture to Meet Specification Properties:*

X2.9.1. This section provides guidance for adjusting the mixture to meet the evaluation criteria contained in Section X2.8. For WMA mixtures, this section augments Section 12 in R 35.

X2.9.2. *Improving Coating*—Most WMA processes involve complex chemical reactions, thermodynamic processes, or both. Consult the WMA additive supplier for methods to improve coating.

X2.9.3. *Improving Compactability*—Most WMA processes involve complex chemical reactions, thermodynamic processes, or both. Consult the WMA additive supplier for methods to improve compactability.

X2.9.4. *Improving the Tensile Strength Ratio*—Some WMA processes include adhesion promoters to improve resistance to moisture damage. Consult the WMA additive supplier for methods to improve the tensile strength ratio.

X2.9.5. *Improving Rutting Resistance*—The rutting resistance of WMA can be improved through changes in binder grade and volumetric properties. The following rules of thumb can be used to identify mixture adjustments that improve rutting resistance.

- Increasing the high-temperature performance grade by one grade level improves rutting resistance by a factor of 2.
- Adding 25 to 30 percent RAP will increase the high-temperature performance grade by approximately one grade level.
- Increasing the fineness modulus (sum of the percent passing the 0.075-, 0.150-, and 0.300-mm sieves) by 50 improves rutting resistance by a factor of 2.
- Decreasing the design VMA by 1 percent will improve rutting resistance by a factor of 1.2.
- Increasing N_{design} by one level will improve rutting resistance by a factor of 1.2.

Note X25—These rules for mixture adjustment are documented in *NCHRP Report 567: Volumetric Requirements for Superpave Mix Design.*

X2.10. *Additional Reporting Requirements for WMA:*

X2.10.1. For WMA mixtures, report the following information in addition to that required in R 35.

X2.10.1.1. WMA process description.

X2.10.1.2. Planned production temperature.

X2.10.1.3. Planned field compaction temperature.

X2.10.1.4. High-temperature grade of the recovered binder in the RAP for mixtures incorporating RAP.

X2.10.1.5. Coating at the design binder content.

X2.10.1.6. Gyrations needed to reach 92 percent relative density for the design binder content at the planned field compaction temperature and 30°C below the planned field compaction temperature.

X2.10.1.7. Gyration ratio.

X2.10.1.8. Dry tensile strength, tensile strength ratio, and observed stripping at the design binder content.

X2.10.1.9. Flow number test temperature and the flow number at the design binder content.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation