

## Mix Design Practices for Warm-Mix Asphalt

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**NCHRP REPORT 691**

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**Mix Design Practices  
for Warm Mix Asphalt**

**Ramon Bonaquist**

ADVANCED ASPHALT TECHNOLOGIES, LLC  
Sterling, VA

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# FOREWORD

By **Edward T. Harrigan**

Staff Officer

Transportation Research Board

This report presents a mix design method tailored to the unique material properties of warm mix asphalt (WMA) technologies. The report will be of immediate interest to materials engineers in state highway agencies and industry.

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Warm mix asphalt (WMA) refers to asphalt concrete mixtures that are produced at temperatures approximately 50°F (28°C) or more cooler than typically used in the production of hot mix asphalt (HMA). The goal of WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA using substantially reduced production temperatures. There are important environmental and health benefits associated with reduced production temperatures including lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also potentially improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving.

For most WMA projects constructed in the United States to date, WMA has been substituted into a mixture designed as HMA with no change to the job mix formula. An issue important to extending the implementation of WMA in the future is the lack of a formal mix design method for mixtures prepared with the wide variety of WMA technologies available now and in the future.

The objective of this project was to develop a mix design method for WMA in the form of a draft AASHTO recommended practice for use by engineers and technicians in the public and private sectors. This method was (1) to be based on Superpave mix design methodology, (2) to include a suite of performance tests to assess whether a WMA mix design will provide satisfactory field service, and (3) to be applicable to any WMA technology used to lower mixing and compaction temperatures.

The report fully documents the research leading to the key finding that a stand-alone WMA mix design method distinct from that for HMA is not warranted. Instead, the final product of the research is a draft recommended appendix to AASHTO R 35, Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA), titled Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA). This recommended appendix was developed and validated with the results of an extensive program of laboratory and field testing on a wide range of WMA technologies. In addition to this appendix, the contractor produced (1) a draft practice for measuring WMA properties for use in performance analyses with the Mechanistic-Empirical Pavement Design Guide, (2) a chapter on WMA mix design for inclusion in the mix design manual produced in NCHRP Project 09-33, "A Mix Design Manual for Hot Mix Asphalt," and (3) materials and media for a 1-day training course on WMA mix design.

The contractor's final report for NCHRP Project 09-43 includes the following appendices:

- Appendix A: Draft Appendix to AASHTO R 35: Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)
- Appendix B: Commentary to the Draft Appendix to AASHTO R 35
- Appendix C: Training Materials for the Draft Appendix to AASHTO R 35
- Appendix D: Proposed Standard Practice for Measuring Properties of Warm Mix Asphalt (WMA) for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide Software
- Appendix E: NCHRP Project 09-43 Experimental Plans, Results, and Analyses

Appendices A, B, and D are published herein. Appendices C and E are available on the TRB website at [www.trb.org/Main/Blurbs/165013.aspx](http://www.trb.org/Main/Blurbs/165013.aspx).

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## S U M M A R Y

# Mix Design Practices for Warm Mix Asphalt

Warm mix asphalt (WMA) refers to asphalt concrete mixtures that are produced at lower temperatures than the temperatures typically used in the production of hot mix asphalt (HMA) (50°F [28°C] lower or more). The goal with WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA using substantially reduced production temperatures. There are important environmental and health benefits associated with reduced production temperatures including lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also potentially improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving.

WMA technologies were first introduced in Europe in the late 1990s as a measure to reduce greenhouse gas emissions. Since then, a number of WMA processes have been developed in Europe and the United States. At the time that NCHRP Project 09-43 was completed, there were approximately 20 WMA processes being marketed in the United States. These processes include chemical, wax, and synthetic zeolite additives; plant foaming systems; and sequential mixing processes.

The objective of NCHRP Project 09-43 was to develop mixture design and analysis procedures that can be used with the wide range of WMA processes that are currently available or that are likely to become available in the future. The research conducted during NCHRP Project 9-43 included the following:

1. Development of a preliminary procedure based on a review of the literature and research in progress.
2. A first phase of testing and analysis to investigate critical aspects of the preliminary procedure including (1) effect of sample reheating, (2) binder grade selection, (3) mixture of recycled asphalt pavement (RAP) and new binders at WMA process temperatures, (4) appropriate short-term oven conditioning for WMA, and (5) evaluation of devices to measure workability.
3. Revisions to the preliminary procedure based on the findings of the first phase of testing and analysis.
4. A second phase of testing and analysis to evaluate the revised preliminary procedure. This phase included (1) a mix design study to test the engineering reasonableness, sensitivity, and practicality of the revised preliminary procedure; (2) a field validation study that used properties of laboratory- and field-produced WMA to validate the procedure; and (3) a fatigue study to investigate whether lower WMA temperatures improve mixture fatigue properties.
5. Final revision of the preliminary procedure based on the findings of the second phase of testing and analysis.

The primary products of NCHRP Project 09-43 are (1) a draft appendix to AASHTO R 35 titled Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA) (presented as Appendix A of this report) and (2) a draft standard practice titled Standard Practice for Measuring Properties of Warm Mix Asphalt (WMA) for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide Software (presented as Appendix D of this report). Training materials and a commentary for the draft appendix to AASHTO R 35 were developed to aid in implementing the research conducted under NCHRP Project 09-43. The following are the major conclusions drawn from the research completed in NCHRP Project 09-43:

1. **Volumetric Properties.** For HMA mixtures with 1.0 percent binder absorption or less, the volumetric properties of WMA designed with the procedures developed under NCHRP Project 09-43 were essentially the same as those obtained from an HMA design. This conclusion supports the current practice of substituting a WMA process into an approved HMA mixture design. However, the compactability, moisture sensitivity, and rutting resistance of the WMA may be significantly different than those of the HMA. Each of these (compactability, moisture sensitivity, and rutting resistance) is evaluated directly in the methods included in the draft appendix to AASHTO R 35.
2. **Binder Grade Selection.** The same grade of binder should be used in WMA and HMA mixtures designed for the same project location. Recovered binder test data from projects sampled and tested under NCHRP Project 09-43 indicated that only extremely low production temperatures resulted in a significant decrease in the stiffness of the recovered binder from the mixture. Additionally, WMA production temperatures resulted in a minor improvement in the low-temperature grade of the binder. The draft appendix to AASHTO R 35 (included herein as Appendix A), therefore, recommends that the same grade of binder be used in both WMA and HMA mixtures. High-temperature grade bumping may be necessary for WMA processes with extremely low production temperatures to meet the flow number rutting resistance requirements included in the draft appendix to AASHTO R 35.
3. **RAP in WMA.** RAP and new binders do mix at WMA process temperatures provided the mixture is held at elevated temperatures for a sufficient length of time. Because the mixing is time dependent, it appears that the new binder added to the mixture coats the virgin aggregate and RAP; then, during storage at elevated temperature, the two binders continue to mix. In the laboratory mixing studies that were conducted, 2 h of conditioning at the compaction temperature resulted in substantial mixing of RAP and new binders when the compaction temperature exceeded the high-temperature grade of the “as recovered” RAP binder. To ensure good mixing of RAP and new binders, the draft appendix to AASHTO R 35 recommends that the planned field compaction temperature for WMA exceed the high-temperature grade of the “as recovered” RAP binder.
4. **Short-Term Oven Conditioning.** Short-term oven conditioning is included in mixture design to simulate the absorption and aging of the binder that occurs during construction. For WMA, it is appropriate to use 2 h of oven conditioning at the compaction temperature—the same short-term conditioning that is used for design of HMA mixtures. The degree of binder aging that occurs, however, is less than that obtained using the AASHTO R 30 conditioning for performance testing—4 h at 275°F (135°C).
5. **Coating, Workability, and Compactability.** For the wide range of WMA processes available, viscosity-based mixing and compaction temperatures cannot be used to control coating, workability, and compactability. The draft appendix to AASHTO R 35 uses direct measures of coating and compactability on laboratory-prepared mixtures. The degree of coating obtained in the laboratory depends on the type of mixer that is used. The mixing

times included in the draft appendix to AASHTO R 35 were developed using a planetary mixer with a wire whip. If bucket mixers are used, appropriate WMA mixing times should be established by evaluating the coating of HMA mixtures prepared for various mixing times at the appropriate viscosity-based mixing temperature specified in Section 8.2.1 of AASHTO T 312.

Several workability devices were evaluated under NCHRP Project 09-43. These devices, which measure the torque or force required to move an auger or blade through the mixture, were able to measure differences between HMA and WMA mixtures, but only when temperatures dropped to the compaction range of WMA. At these temperatures, differences in air voids also were evident in gyratory compacted specimens. The draft appendix to AASHTO R 35 uses the change in the number of gyrations to 92-percent relative density when the compaction temperature is decreased 54°F (30°C) to characterize the compaction temperature sensitivity of the WMA processes. Increases that exceed 25 percent indicate that the WMA is more temperature sensitive than HMA. This measure of compactability was sensitive to the compaction temperature, the WMA process, and the presence of RAP in the mixture. The combination of RAP and low WMA process and compaction temperatures, may lead to WMA mixtures that are more sensitive to changes in temperature than similar HMA mixtures.

6. **Moisture Sensitivity.** Moisture sensitivity as measured by AASHTO T 283 will likely be different for WMA and HMA mixtures designed using the same aggregates and binder. WMA processes that included anti-strip additives improved the tensile strength ratio of some of the mixtures included in the NCHRP Project 09-43 testing and analysis. Of the nine WMA mixtures that used a WMA process that included an anti-strip additive, the tensile strength ratio remained the same or improved in 67 percent of the mixtures. For WMA mixtures produced using processes that did not include anti-strip additives, the tensile strength ratio never improved and decreased in 79 percent of the mixtures. The draft appendix to AASHTO R 35 includes evaluation of moisture sensitivity using AASHTO T 283.
7. **Rutting Resistance.** The draft appendix to AASHTO R 35 includes an evaluation of the rutting resistance of WMA using the flow number test. The test is conducted on specimens that have been short-term conditioned for 2 h at the compaction temperature to simulate the binder absorption and stiffening that occurs during construction. Because lower short-term conditioning temperatures are used for WMA mixtures as compared to HMA mixtures, binder aging in WMA mixtures is less, resulting in lower flow numbers for WMA mixtures produced with the same aggregates and binder as compared to HMA mixtures. Current criteria for the flow number and other rutting tests for HMA are based on 4 h of short-term conditioning at 275°F (135°C). The short-term conditioning study completed under NCHRP Project 09-43 shows that this level of conditioning represents the stiffening that occurs during construction as well as some time in service. Since it is inappropriate to condition WMA mixtures at temperatures exceeding their production temperature, the criteria for evaluating the rutting resistance of WMA mixtures were reduced compared to those currently recommended for HMA mixtures conditioned for 4 h at 275°F (135°C).
8. **Performance Evaluation.** The research completed under NCHRP Project 09-43 showed that for the same aggregates and binders, WMA mixtures designed in accordance with the draft appendix to AASHTO R 35 will have similar properties as HMA mixtures. Volumetric properties will essentially be the same, but the stiffness of the WMA mixture will probably be lower for as-constructed conditions. Since the differences between HMA and WMA are relatively small, an analysis of the performance of pavements constructed with WMA can be made using the Mechanistic-Empirical Pavement Design Guide (MEPDG) and appropriate material properties (1). A draft standard practice for fabricating WMA test

specimens and performing dynamic modulus master curves and low-temperature compliance and strength testing was developed to aid in the performance analysis of WMA using the MEPDG.

The research conducted under NCHRP 09-43 has shown that only minor changes to current mixture design practice are needed to design WMA mixtures. Although volumetric properties for HMA and WMA will be similar when binder absorption is 1.0 percent or less, the compactability, moisture sensitivity, and rutting resistance of WMA mixture will likely be different than the compactability, moisture sensitivity, and rutting resistance of an HMA mixture designed with the same aggregates and binders. Therefore, it is recommended that the procedures for WMA mixture design developed under NCHRP 09-43 be used when designing WMA mixtures.

The draft appendix to AASHTO R 35 should be used on a trial basis by agencies and producers to provide additional data to further refine the WMA mixture design methods and criteria before being considered for adoption. Elements that would benefit from additional evaluation and possible refinement include the process-specific specimen-fabrication procedures, and the criteria for coating, compactability, and rutting resistance.

At the time that NCHRP Project 09-43 was completed, two additional projects on WMA were initiated by NCHRP: NCHRP Project 09-47A, "Properties and Performance of Warm Mix Asphalt Technologies" and NCHRP 09-49, "Performance of WMA Technologies: Stage I—Moisture Susceptibility." NCHRP Project 09-47A will include an evaluation of the field performance of WMA mixtures, and NCHRP Project 09-49 will address the moisture susceptibility of WMA in detail. The findings of NCHRP Project 09-43 support the need for these studies addressing field performance and moisture sensitivity.

There are, however, two elements of the WMA mixture design process that require additional research that is not currently planned. First, the WMA specimen-fabrication procedures included in the draft appendix to AASHTO R 35 should be expanded to include bucket mixers, which are more readily available in most production mix design laboratories. Second, additional research is needed to develop a short-term conditioning procedure for specimens used for the evaluation of moisture sensitivity and rutting resistance that is equally applicable to both WMA and HMA. A two-step conditioning process should be considered. In the first step, the mixture would be conditioned for 2 h at the compaction temperature to simulate the binder absorption and stiffening that occurs during construction. In the second step, the mixture would be further conditioned for an extended time at a representative high in-service pavement temperature to simulate a short period of time in service. Based on an analysis of data collected under NCHRP Project 09-13, it appears that the second step will require less than 16 h of additional conditioning.

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## CHAPTER 1

# Introduction

### 1.1 Background

Warm mix asphalt (WMA) refers to asphalt concrete mixtures that are produced at temperatures approximately 50°F (28°C) lower (or more) than temperatures typically used in the production of hot mix asphalt (HMA). The goal with WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA using substantially reduced production temperatures. There are important environmental and health benefits associated with reduced production temperatures including lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also potentially improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving.

WMA technologies were first introduced in Europe in the late 1990s as a measure to reduce greenhouse gas emissions. Since then, a number of WMA processes have been developed in Europe and the United States. Brief descriptions of several of these processes are presented here. The National Asphalt Pavement Association (NAPA) publication, *Warm-Mix Asphalt: Best Practices* (2) presents more detailed information on many of these processes including the types of plant modifications that are needed with each. Table 1 summarizes the various WMA processes identified under NCHRP Project 09-43.

The earliest WMA processes developed in Europe were based on using either waxes or foamed asphalt. Waxes are added to the binder to reduce its viscosity and improve lubrication. These materials typically have melting points below normal HMA production temperatures. At temperatures above the melting point, these materials reduce the viscosity of the asphalt binder. Below the melting point, these materials tend to increase the stiffness of the binder. Recent research suggests that wax additives also improve the binder's lubrication capability resulting in improvement in mix workability

at lower temperatures (3). Lubrication rather than viscosity reduction may be the primary mechanism by which many WMA processes improve workability and compactability at lower temperatures.

Sasobit is the wax that has been used most extensively for WMA projects in the United States. Sasobit is a Fischer-Tropsch wax that is produced from coal gasification. It is supplied in pellet form and is typically added at the rate of 1.5 percent by weight of binder. The pellet can be added to the binder at the asphalt terminal or in the plant supply tank, or it can be added to the mixture by blowing it into the drum in a manner similar to the addition of fibers to stone matrix asphalt (SMA).

Several WMA processes use foaming to permit coating and provide workability at lower production temperatures. When small amounts of water are added to hot asphalt, the water vaporizes and the vapor is encapsulated in the binder. This produces a foaming action in the binder, temporarily increasing the volume of the binder and lowering its viscosity, which improves coating and workability. Foamed asphalt has been used for over 50 years to produce cold mixes (4). Early drum mix plants also took advantage of foaming that resulted from incomplete drying of aggregates to produce mixtures at lower temperatures (5).

A variety of methods are used to produce foamed asphalt. Aspha-min and Advera are synthetic zeolites. Zeolites are minerals that have approximately 20 weight percent water trapped in their porous structure. Upon heating to approximately 185°F (85°C), the water is released, and when this is done in the presence of asphalt binder, foamed asphalt is produced. Synthetic zeolite additives are typically added at the rate of 0.25 percent by weight of the asphalt mixture. A variety of methods can be used to add synthetic zeolites at the plant. To be effective, it is critical that the additive is quickly encapsulated in the asphalt binder and not lost in the exhaust air stream of the plant. Zeolites have been used on several projects in the United States.

**Table 1. Summary of WMA processes identified during NCHRP Project 09-43.**

Name	Process/Additive	Company	Website
Accu-Shear Dual Warm Mix Additive System	Foaming system	Stansteel	<a href="http://www.stansteel.com/sip.html">http://www.stansteel.com/sip.html</a>
Adesco/Madsen Static Inline Vortex Mixer	Foaming system	Adesco/Madsen	<a href="http://www.asphaltequipment.com/documents/Static%20Inline%20Vortex%20Mixer%20Brochure.pdf">http://www.asphaltequipment.com/documents/Static%20Inline%20Vortex%20Mixer%20Brochure.pdf</a>
Advera	Zeolite	PQ Corporation	<a href="http://www.pqcorp.com/products/AdveraWMA.asp">http://www.pqcorp.com/products/AdveraWMA.asp</a>
AQUABLACK	Foaming system	Maxam Equipment Company, Inc.	<a href="http://maxamequipment.com/AQUABlackWMA.htm">http://maxamequipment.com/AQUABlackWMA.htm</a>
AquaFoam	Foaming system	Reliable Asphalt Products	<a href="http://www.reliableasphalt.com/Default.asp">http://www.reliableasphalt.com/Default.asp</a>
Asphaltan –B	Montan wax	Romonta	<a href="http://www.romonta.de/ie4/english/romonta/i_wachse.htm">http://www.romonta.de/ie4/english/romonta/i_wachse.htm</a>
Aspha-min	Zeolite	Eurovia	<a href="http://www.eurovia.fr/en/produit/135.aspx?print=y">http://www.eurovia.fr/en/produit/135.aspx?print=y</a>
Cecabase RT	Unspecified additive	Ceca	<a href="http://www.cecachemicals.com/sites/ceca/en/business/bitumen_additives/warm_coated_material/warm_coated_material.page">http://www.cecachemicals.com/sites/ceca/en/business/bitumen_additives/warm_coated_material/warm_coated_material.page</a>
Double Barrel Green	Foaming system	Astec, Inc.	<a href="http://www.astecinc.com/index.php?option=com_content&amp;view=article&amp;id=117&amp;Itemid=188">http://www.astecinc.com/index.php?option=com_content&amp;view=article&amp;id=117&amp;Itemid=188</a>
Evotherm ET	Emulsion with unspecified additives	MeadWestvaco	<a href="http://www.meadwestvaco.com/Products/MWV002106">http://www.meadwestvaco.com/Products/MWV002106</a>
Evotherm DAT	Unspecified additive		
Evotherm 3G	Unspecified additive		
Licomont BS-100	Fatty acid derivative	Clariant	<a href="http://clariant.com/C12576850036A6E9/A0F44E23B922E21CC12576BF00484894/\$FILE/20100203_Clariant_LowEmissionModifierBoosts.pdf">http://clariant.com/C12576850036A6E9/A0F44E23B922E21CC12576BF00484894/\$FILE/20100203_Clariant_LowEmissionModifierBoosts.pdf</a>
Low Emission Asphalt	Sequential coating using wet fine aggregate and unspecified additive	McConnaughay Technologies	<a href="http://www.mcconnaughay.com/lowemissionasphalt_intro.php">http://www.mcconnaughay.com/lowemissionasphalt_intro.php</a>
Meeker Warm Mix Asphalt System	Foaming system	Meeker Equipment	<a href="http://www.meekerequipment.com/new_warmmixad1.html">http://www.meekerequipment.com/new_warmmixad1.html</a>
Rediset WMX	Unspecified additive	Akzo Nobel	<a href="http://www.surfactants.akzonobel.com/asphalt/pdf/Rediset%20Brochure_0907.PDF">http://www.surfactants.akzonobel.com/asphalt/pdf/Rediset%20Brochure_0907.PDF</a>
Sasobit	Fischer Tropsch wax	Sasobit	<a href="http://www.sasolwax.us.com/sasobit.html">http://www.sasolwax.us.com/sasobit.html</a>
Terex Warm Mix Asphalt	Foaming system	Terex Roadbuilding	<a href="http://www.terexrb.com/default.aspx?pgID=308">http://www.terexrb.com/default.aspx?pgID=308</a>
Thipoave	Sulfur plus compaction aid	Shell	<a href="http://www.shell.com/home/content/sulphur/your_needs/products/in_roads/">http://www.shell.com/home/content/sulphur/your_needs/products/in_roads/</a>
TLA-X	Trinidad Lake Asphalt plus modifiers	Lake Asphalt of Trinidad and Tobago	<a href="http://www.trinidadlakeasphalt.com/home/products/tla-x-warm-mix-technology.html">http://www.trinidadlakeasphalt.com/home/products/tla-x-warm-mix-technology.html</a>
Ultrafoam GX	Foaming system	Gencor Industries, Inc.	<a href="http://gencorgreenmachine.com">http://gencorgreenmachine.com</a>
WAM Foam	Soft binder followed by hard foamed binder	Kolo Veidekke, Shell Bitumen	<a href="http://www.shell.com/home/content/bitumen/products/shell_wam_foam/">http://www.shell.com/home/content/bitumen/products/shell_wam_foam/</a>

Asphalt foaming is also used in the low emission asphalt (LEA) process. In the LEA process, the coarse aggregate and a portion of the fine aggregate are heated to normal HMA temperatures and mixed with the binder. A coating and adhesion additive (approximately 0.5 percent by weight of binder) is added to the binder in the asphalt supply line to the plant. After the heated portion of the aggregate is coated, cold, wet, fine aggregate or a blend of fine aggregate and recycled asphalt pavement (RAP) are added. The wet portion of the mixture has a moisture content of 3 to 4 percent. When heated, this moisture is liberated as steam, which causes the asphalt coating to foam and encapsulate the uncoated fine aggregate. LEA is a complex thermodynamic process where the temperature of the mixture drops rapidly as the moisture in the wet portion of the aggregate turns to steam. The final discharge temperature is slightly less than 212°F (100°C), which allows some of the steam to condense into water that aids in the workability and compaction of the mixture. The LEA process has been used on several projects in New York and Pennsylvania.

Recently, major asphalt plant and equipment suppliers in the United States have introduced various foaming systems.

These systems produce foamed asphalt by directly injecting water into the hot asphalt binder at the mixing drum. Water is added at the rate of approximately 1 to 2 percent by weight of binder. The systems are designed to provide the appropriate ratio of water to asphalt binder, which governs the properties of the resulting foam. The primary reported benefits of these systems are the following: (1) there is no change in the mixing process, and (2) special additives are not required. Foaming systems have been used on numerous projects in the United States.

Foamed asphalt is also used in the two-stage WAM Foam process. This process adds a soft binder and a hard, foamed binder at different times during the mixing process. In the first stage, a soft binder is used to fully coat the coarse aggregate. The soft binder is typically 20 to 30 percent of the total binder content of the mixture. In the second stage, a hard binder is foamed onto the pre-coated aggregate. The grades of the two binders are selected to produce a blended binder that satisfies the performance grade requirement for the project location. The WAM Foam process has not been used to date in the United States.

A few processes that rely on chemical additives have been developed in the United States and Europe. The manufacturers do not disclose specific information on the chemicals used in these processes. The first chemical additive process used in the United States was the Evotherm process developed by MeadWestvaco and introduced in 2005. The active ingredients in Evotherm are chemical additives that reportedly improve coating, workability, and adhesion at lower temperatures. Initially, Evotherm was supplied as a high residue emulsion, currently referred to as Evotherm ET (Emulsion Technology). The emulsion contained approximately 70-percent asphalt binder by weight. The water in the emulsion vaporizes when mixed with hot aggregates leaving the residual asphalt and chemical additives. A number of projects were constructed in the United States using the Evotherm ET process. MeadWestvaco then introduced a process where the chemical additives are injected as a solution directly into the asphalt line at the plant. This process is referred to as Evotherm DAT (Dispersed Additive Technology). It has the advantage that much less water is added to the mixture compared to the emulsion process. MeadWestvaco has recently introduced a third-generation process referred as Evotherm 3G, which is a water-free warm mix technology developed jointly by Ergon Asphalt and Emulsions, Inc., and Mathy Construction Company. This process allows the additive to be mixed with the binder at a terminal and distributed to asphalt plants using the normal binder distribution process. Because of their improved convenience, Evotherm DAT and Evotherm 3G have largely replaced Evotherm ET.

Rediset WMX is a chemical process that was introduced in the United States in 2007. Rediset WMX is produced by Akzo Nobel and is marketed as a warm mix additive with adhesion-promoting properties. It is supplied as a pellet and added at

the rate of 1.5 to 2.5 percent by weight of the asphalt binder. The pellets can be added to the binder at the asphalt terminal or in the plant supply tank, or they can be added to the mixture by blowing them into the drum in a manner similar to the addition of fibers to SMA.

## **1.2 Problem Statement and Objective**

NAPA has been instrumental in bringing WMA technologies into practice in the United States. Numerous demonstration projects have been constructed since 2004. These projects have demonstrated the feasibility of using warm mix processes in the United States. Pavements have been successfully constructed using various warm mix processes with only minimal changes to equipment and quality control practices. These projects have served the important functions of introducing WMA to agency and contractor personnel; demonstrating the constructability of WMA; and providing initial data on energy usage, emissions, and pavement performance. The success of these demonstration projects has led some state highway agencies to allow WMA to be used routinely on paving projects.

One of the critical issues facing WMA is the lack of a formal mixture design procedure. For most WMA projects constructed in the United States, WMA has been substituted into a mixture designed as HMA with no change to the job mix formula. If warm mix is to replace hot mix in the future, a laboratory mixture design procedure for WMA must be established. The objective of NCHRP Project 09-43 was to develop mixture design and analysis procedures that can be used with the wide range of warm mix processes that are currently available or may likely become available in the future.

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## CHAPTER 2

# Research Approach

### 2.1 Overview

The general approach taken in NCHRP 09-43 to develop mix design and analysis procedures for WMA was to adapt as many of the current methods used with HMA as possible and to concentrate development efforts on areas where WMA and HMA differ substantially. Figure 1 presents a flow chart for the project. The project was divided into two phases. In Phase I, a preliminary mixture design and analysis procedure was developed based on a review of the literature and research in progress. The preliminary procedure was then revised based on the results of several laboratory studies directed at elements of the mixture design process that were expected to be different for WMA as compared to HMA. In Phase II, the revised preliminary procedure was evaluated through a laboratory sensitivity study designed to test the engineering reasonableness, sensitivity, and practicality of the mixture design procedure and a field validation study using mixtures from paving projects. Phase II also included a study to evaluate fatigue characteristics of WMA, the development of draft standards for WMA, and the development of workshop materials for the proposed WMA mixture design methods.

### 2.2 Differences Between the Design of WMA and HMA

HMA mixture design and analysis generally consists of five major steps: (1) materials selection, (2) design aggregate structure, (3) design binder content selection, (4) evaluate moisture sensitivity, and (5) performance analysis. Criteria for Steps 1 through 4 for HMA are contained in AASHTO M 323, Standard Specification for Superpave Volumetric Mix Design. AASHTO R 35, Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA), provides procedures for Steps 1 through 4. Although there is not a standard practice addressing performance testing of HMA, several performance tests have been developed and have received some level of

acceptance by industry. Performance tests are available for measuring mixture modulus, rutting resistance, and resistance to fatigue cracking and thermal cracking. The new mix design manual being developed under NCHRP Project 09-33 includes performance testing to ensure that mixtures subjected to traffic levels greater than 3 million equivalent single axle loads have adequate rutting resistance (6).

Several modifications to current HMA mix design procedures are needed to address the wide range of WMA processes currently available and likely to become available in the future. The first step in NCHRP Project 09-43 was to identify potential areas of the HMA mixture design process requiring modification for WMA. These are summarized in Table 2 and discussed below for the major steps in the mixture design and analysis process.

#### 2.2.1 Materials Selection

Some elements of materials selection may require modification for WMA. Aggregate requirements for warm mix will not be different than requirements for hot mix, but it may be necessary to select different binder grades for WMA. The lower temperatures used in WMA as compared to HMA probably result in less aging during plant mixing and construction; therefore, a stiffer high-temperature binder grade may be needed for satisfactory rutting performance. This effect, however, may be offset by the addition of warm mix additives and the effect that these additives and water have on binder aging. The lower production temperatures may also limit the types and quantity of recycled asphalt materials that can be used in WMA. Design of HMA assumes substantial mixing of new and recycled binders, which may not be possible at the lower production temperatures used in warm mix. Lower production temperatures may also limit the effectiveness of some anti-strip additives. Finally, WMA design will require the selection of an appropriate warm mix additive and dosage rate. Although dosage rates may be provided by warm mix additive



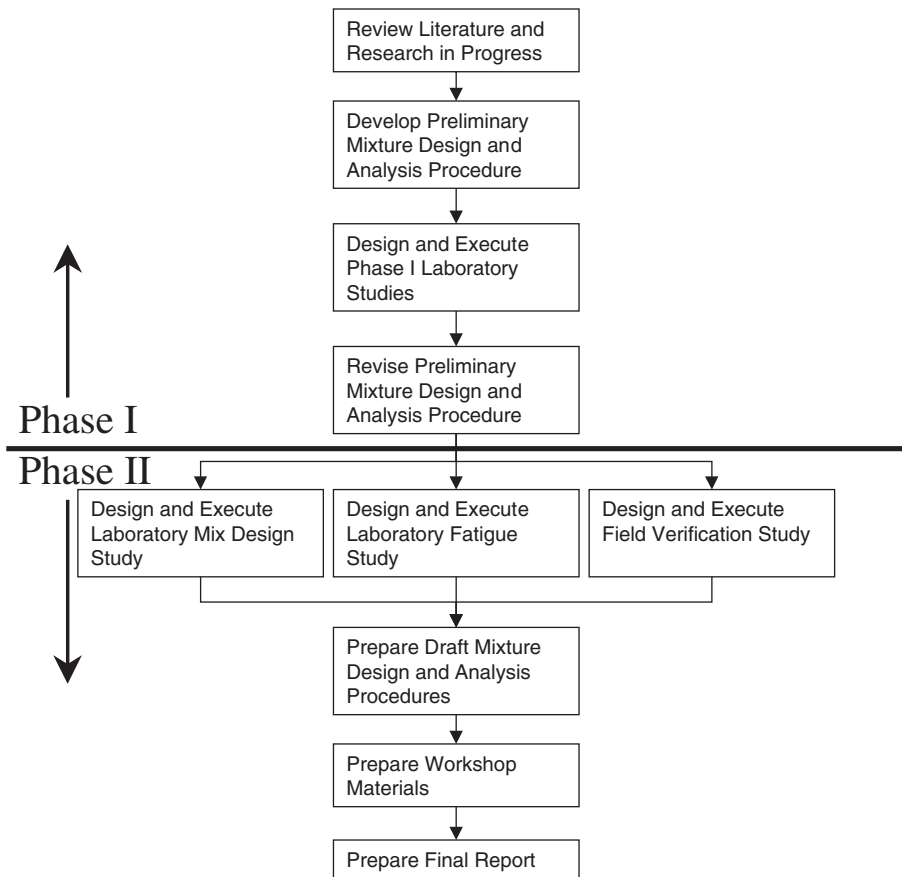


Figure 1. Flow chart for NCHRP Project 09-43.

Table 2. Areas of HMA mixture design and analysis potentially requiring modification for WMA.

Step	Item	Special Warm Mix Considerations
<b>Materials Selection</b>	Binder Selection	<ul style="list-style-type: none"> <li>Potentially less aging during mixing and construction due to lower production temperatures.</li> <li>Effect of any warm mix additives and warm mix processing on binder properties.</li> </ul>
	Aggregate Properties	<ul style="list-style-type: none"> <li>None</li> </ul>
	Recycled Asphalt Pavement	<ul style="list-style-type: none"> <li>Effect of production temperature on the degree of commingling of recycled and new binders.</li> <li>Effect of warm mix additives and warm mix processing on the degree of commingling of recycled and new binders.</li> </ul>
	Additives	<ul style="list-style-type: none"> <li>Warm-mix additive selection.</li> <li>Effect of lower production temperatures and warm mix additives on anti-strip additives.</li> </ul>
<b>Design Aggregate Structure</b>	Nominal Maximum Aggregate Size	<ul style="list-style-type: none"> <li>None</li> </ul>
	Trial Gradations	<ul style="list-style-type: none"> <li>None</li> </ul>
	Batching	<ul style="list-style-type: none"> <li>WMA process specific</li> </ul>
	Mixing	<ul style="list-style-type: none"> <li>WMA process specific</li> <li>Method to determine appropriate mixing temperatures for warm mix processes.</li> <li>Method to assess workability of WMA.</li> </ul>
	Conditioning	<ul style="list-style-type: none"> <li>Verify that short-term conditioning per AASHTO R 30 applies to WMA processes.</li> </ul>
	Compaction	<ul style="list-style-type: none"> <li>Method to determine appropriate compaction temperatures for warm mix processes.</li> <li>Verification of compaction levels.</li> </ul>
	Volumetric Analysis and Criteria	<ul style="list-style-type: none"> <li>None</li> </ul>
<b>Design Binder Content Selection</b>	Specimen Preparation	<ul style="list-style-type: none"> <li>See considerations above for laboratory batching, mixing, conditioning, and compaction.</li> </ul>
	Volumetric Analysis and Criteria	<ul style="list-style-type: none"> <li>None</li> </ul>
<b>Evaluate Moisture Sensitivity</b>	Specimen Preparation	<ul style="list-style-type: none"> <li>See considerations above for laboratory batching, mixing, conditioning, and compaction.</li> </ul>
	Testing and Analysis	<ul style="list-style-type: none"> <li>None</li> </ul>
<b>Performance Analysis</b>	Specimen Preparation	<ul style="list-style-type: none"> <li>See considerations above for laboratory batching, mixing, conditioning, and compaction.</li> </ul>
	Testing and Analysis	<ul style="list-style-type: none"> <li>None</li> </ul>

suppliers, agencies should have a procedure to ensure that the recommended dosage rate is appropriate.

## 2.2.2 Design Aggregate Structure

The design of the aggregate structure may also require some modifications for WMA. Since the goal of WMA is to produce mixtures with strength and performance characteristics similar to those of HMA, the volumetric criteria used in design should not differ from those used for HMA. However, the procedures used to fabricate and condition specimens may require some modification. Most WMA process developers have prepared laboratory procedures for specimen fabrication. Additionally, mixture coating, workability, and compactability must be evaluated directly instead of using viscosity-based mixing and compaction temperatures. In many WMA processes, it is impossible to directly measure the viscosity of the binder. Additionally, there is increasing evidence that the temperature reductions associated with many WMA processes are not related to the change in viscosity of the binder (3, 7).

## 2.2.3 Design Binder Content Selection

The selection of the design binder content should not require substantial modification other than specimen-fabrication as discussed above. In NCHRP Project 09-25, "Requirements for Voids in Mineral Aggregate for Superpave Mixtures" and NCHRP Project 09-31, "Air Void Requirements for Superpave Mix Design," relationships between mixture volumetric properties and pavement performance were developed (8). These relationships confirm the importance of many of the volumetric criteria included in the Superpave mixture design method. An important step in achieving WMA with performance characteristics comparable to HMA is to use the same volumetric criteria in the design of both mixtures.

## 2.2.4 Evaluate Moisture Sensitivity and Performance Analysis

Evaluation of the mixture for moisture sensitivity and performance also will not require substantial modification other than specimen fabrication. Although there is concern that some WMA may exhibit greater moisture sensitivity than HMA (9, 10, 11), AASHTO T 283, Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage, is a fairly reliable indicator of moisture-induced adhesive failure, which is the mechanism of greatest concern for WMA. The major consideration in the preparation of moisture sensitivity and performance specimens will be replicating the mechanical properties of field-mixed material in laboratory-prepared specimens. The same tests and criteria that are used for performance evaluation of HMA should be used with WMA.

## 2.3 Preliminary WMA Mixture Design and Analysis Procedure

### 2.3.1 Overview

Based on a review of available literature for the various WMA processes and discussions with WMA process developers, a preliminary mixture design and analysis procedure was developed. The preliminary procedure served two purposes. First, the preliminary procedure provided a starting point for the WMA mixture design and analysis procedure for review and comment by the project panel and WMA process developers. Second, the preliminary procedure focused the Phase I testing and analysis effort on the areas of mixture design and analysis that required additional development to properly address WMA. The preliminary procedure was revised based on the findings of the Phase I testing and analysis and the comments received on the preliminary procedure. The revised preliminary procedure was further modified based on the findings of the Phase II laboratory mix design study, field validation study, and fatigue study to produce the draft standards that were the primary products of NCHRP Project 09-43.

The preliminary WMA mixture design and analysis procedure was based on AASHTO R 35, Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA). The preliminary procedure referred to AASHTO M 323, Standard Specification for Superpave Volumetric Mix Design, and AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder, for criteria for materials selection, volumetric design, and moisture sensitivity evaluation. Table 3 summarizes the areas where the preliminary procedure differed from AASHTO R 35. The differences are discussed below.

### 2.3.2 WMA Process Selection

A section in the preliminary mixture design and analysis procedure for WMA addressed WMA process selection. It advised that WMA process selection should be done in consultation with the specifying agency and technical assistance personnel from WMA process suppliers. This section alerts users that when selecting a WMA process, consideration should be given to a number of factors including (1) available performance data, (2) the cost of any warm mix additives, (3) planned plant mixing and field compaction temperatures, (4) planned production rates, (5) plant capabilities, and (6) modifications required to successfully use the WMA process with available field and laboratory equipment.

### 2.3.3 Binder Grade Selection and RAP

For the preliminary procedure, it was hypothesized that the WMA production temperature would be a consideration in the selection of the high-temperature binder grade and the allow-

**Table 3. Major new elements included in the preliminary WMA mixture design and analysis procedure.**

Key Element	Included in Preliminary Procedure
WMA Process Selection	Key considerations for WMA process selection.
Binder Grade Selection	Concept of high-temperature grade bumping based on WMA production temperature.
Recycled Asphalt Pavement Materials	Concept of limiting RAP content based on production temperature and compatibility of new and recycled binders.
Specimen-Fabrication Procedures	Process-specific fabrication procedures provided for major WMA processes.
Process Temperature	Direct evaluation of coating, workability, and compactability.
Required Performance Testing	Flow number in addition to moisture sensitivity testing in mixture design.
Optional Performance Testing	Recommended methods for measuring dynamic modulus, resistance to fatigue cracking, and resistance to thermal cracking included in mixture analysis.

able RAP content of the mixture. Because the lower production temperatures in WMA result in reduced binder aging, the preliminary procedure provided a conceptual table for bumping the high-temperature binder grade based on the planned production temperature. Similarly, since the degree of mixing of RAP and new binders in mixtures containing RAP is likely to be temperature dependent, the preliminary procedure provided a second conceptual table for limiting the RAP content of mixtures based on the production temperature and the compatibility of the RAP and new binder. An appendix was added to provide procedures for measuring the compatibility of two binders with ASTM D6703, Standard Test Method for Automated Heithaus Titrimetry. Experiments to flesh out the conceptual tables for binder grade bumping and RAP mixing were included in the Phase I testing and analysis.

In addition to the above, the preliminary procedure provided more detailed information on how to characterize RAP materials for mixture design. This information was provided in an appendix and was consistent with the recommendations for RAP analysis that were included in the mix design manual for HMA being developed under NCHRP Project 09-33 (6).

### 2.3.4 Specimen-Fabrication Procedures

The preliminary design procedure documented specimen-fabrication procedures for several WMA processes. These procedures identify the equipment and methods that are needed to prepare WMA specimens in the laboratory. These specimen-fabrication procedures were included in an appendix to the preliminary mixture design and analysis procedure for WMA. Short-term aging of WMA was tentatively set at 2 h at the planned field compaction temperature based on limited research performed by some WMA process developers.

### 2.3.5 Process Temperature

Since binder viscosity-temperature relationships cannot be developed for many WMA processes, mixing and compaction temperatures cannot be used to control coating, workability, and compactability of WMA. The preliminary procedure proposed evaluating coating, workability, and compactability directly during the evaluation of trial blends. This is accomplished by preparing trial blends using the planned production temperature and compacting the trial blends using the planned field compaction temperature. Coating is evaluated using AASHTO T 195, Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures. A standard procedure for evaluating workability is not available; therefore, as part of the Phase I testing and analysis several possible workability tests were evaluated. In the preliminary procedure for WMA, it was envisioned that the density at  $N_{\text{initial}}$  in the gyratory compactor would serve as a measure of compactability. The use of the density at  $N_{\text{initial}}$  as a measure of compactability was evaluated during the Phase I testing and analysis.

### 2.3.6 Required Performance Testing

Evaluation of the moisture sensitivity of the design mixture in the preliminary mixture design and analysis procedure for WMA is the same as that for HMA in AASHTO R 35. AASHTO T 283, Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage, is used except that the mixture conditioning procedure is the same as that used in the volumetric design, tentatively 2 h at the compaction temperature. The minimum tensile strength ratio is 0.80 as specified in AASHTO M 323 for HMA.

The preliminary procedure for WMA mixture design and analysis also included a mandatory evaluation of the design

**Table 4. Minimum flow number requirements.**

Traffic Level, Million ESALs	Minimum Flow Number
< 3	---
3 to < 10	53
10 to < 30	190
≥ 30	740

mixture for rutting resistance using the flow number test developed in NCHRP Project 09-19 (12). This test is conducted using the Asphalt Mixture Performance Tester (AMPT) on specimens that have been conditioned according to the volumetric design procedure, tentatively 2 h at the compaction temperature. The AMPT was formerly called the Simple Performance Test (SPT) system. The flow number test is conducted in accordance with AASHTO TP 79, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT). The test is conducted unconfined with a repeated deviatoric stress of 87 psi (600 kPa) and a contact deviatoric stress of 4.4 psi (30 kPa). The test temperature is the design high pavement temperature at 50-percent reliability as determined using *LTTPBind Version 3.1* (13). The temperature is computed at a depth of 0.79 in. (20 mm) for surface courses, and the top of the pavement layer for intermediate and base courses. Flow number criteria for various traffic levels are given in Table 4. These are the same criteria being recommended for HMA in the mix design manual being developed under NCHRP Project 09-33 (6).

### 2.3.7 Optional Mixture Analysis Tests

The preliminary mixture design and analysis procedure for WMA included optional performance tests to evaluate the dynamic modulus, resistance to fatigue cracking, and resistance to thermal cracking. Performance tests are not included in AASHTO R 35 for HMA. The optional performance tests can be used with the Mechanistic-Empirical Pavement Design Guide (MEPDG) to predict the performance of pavements incorporating WMA (1). The following performance tests and equipment were selected for the preliminary procedure:

- **Dynamic Modulus.** Dynamic modulus master curves for use in pavement structural design and performance analysis using the MEPDG (1) can be developed using the AMPT in accordance with AASHTO PP 61, Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester.
- **Fatigue Cracking.** Fatigue characteristics of WMA are evaluated using simplified continuum damage analysis of cyclic direct tension-compression tests. This procedure was developed in NCHRP Projects 09-25 and 09-31 to quickly char-

acterize the fatigue resistance of a mixture using a limited amount of testing (14). The same geometry specimen as used for the dynamic modulus and flow number can be used in the direct tension-compression fatigue testing. With appropriate tension grips, the test can be performed with the AMPT.

- **Thermal Cracking.** The recommended method for analysis of thermal cracking in flexible pavements requires measurement of compliance and strength properties of the mixture at low temperatures. These properties are then used in a thermo-viscoelastic stress analysis to estimate the thermal stresses induced in the pavement during cooling cycles. Mixture compliance and strength properties are obtained by testing specimens in the indirect tensile (IDT) mode in accordance with AASHTO T 322, Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Device. Two software programs are available to perform the thermo-viscoelastic stress analysis. The first is the MEPDG, which includes a model to predict the extent of thermal cracking in a flexible pavement considering environmental conditions at the project site and the thickness and properties of the asphalt concrete used in the pavement. This model has been calibrated using data from several in-service pavements (1). The second is an Excel Workbook called “LTSTRESS.xls,” which was developed at the Northeast Center for Excellence in Pavement Technology to reduce data from AASHTO T 322 and perform a simplified thermal cracking analysis (15). The output of this analysis is a critical cracking temperature, the temperature where the computed thermal stresses for a specified cooling rate exceed the tensile strength of the mixture. LTSTRESS.xls has not been calibrated to observed cracking and should be used for comparative evaluation of mixtures.

## 2.4 Phase I Laboratory Studies

In developing the preliminary mixture design and analysis procedure for WMA, several areas were identified where laboratory testing and analysis was needed to develop criteria for the procedure. This section describes the laboratory studies that were conducted and analyzed during Phase I of the project. Detailed results and analyses for each study are presented in Appendix E and summarized in Chapter 3. The preliminary procedure was then revised based on the results of these studies, and the revised preliminary procedure was used in the mix design, field validation, and fatigue studies. The resulting draft standards for WMA mixture design and analysis are discussed in Chapter 3.

### 2.4.1 Phase I Data Sources

Data for the Phase I studies were collected from four sources: the FHWA Mobile Asphalt Laboratory, FHWA Turner-

**Table 5. Phase I project mix design data.**

Property		I-70 Colorado Control HMA
Gradation (% passing)	Sieve Size	
	1/2 in	100.0
	3/8 in	95.0
	#4	73.0
	#8	54.0
	#16	40.0
	#30	29.0
	#50	18.0
	#100	11.0
#200	6.7	
Asphalt Content, %		6.2
$N_{design}$		75.0
Design Air Voids, %		3.9
Design VMA, %		16.9
Design VFA, %		77.0
Fines to Effective Asphalt Ratio		1.0
Fractured Faces (one face/two faces), %		100/99
Fine Aggregate Angularity (FAA)		48.6
Aggregate Water Absorption, %		0.8
Dry Tensile Strength, psi		64.0
Conditioned Tensile Strength, psi		58.0
Tensile Strength Ratio, %		91.0
Binder Grade		PG 58-28

Fairbank Highway Research Center, McConaughay Technologies, and a WMA project on I-70 in Colorado that was sampled by the research team. The FHWA Mobile Asphalt Laboratory and McConaughay Technologies provided mixture modulus data that were used to evaluate the effect of sample reheating on the mechanical properties of WMA. The FHWA Turner-Fairbank Highway Research Center provided data from an experiment that used the Rolling Thin Film Oven Test (RTFOT) to evaluate the effect of temperature on the short-term aging of asphalt binders. These data were used to develop preliminary recommendations for binder grade selection for WMA as a function of production temperature. Samples of loose mix and component materials from the Colorado I-70 WMA project were used to evaluate short-term oven conditioning and the mixing of RAP at WMA temperatures. The Colorado I-70 project included an HMA control mix and three WMA processes: Advera, Evotherm, and Sasobit. Table 5 presents the approved mixture design for the Colorado I-70 HMA. The three WMA processes used this same mix design without modification.

### 2.4.2 Sample Reheating Study

Since some of the planned experiments involved mechanical property tests on specimens prepared from loose mix, a study was conducted to determine if sample reheating significantly affected the mechanical properties of WMA. The response variable used in this study was the mixture dynamic modulus because it is very sensitive to changes in binder stiffness, and it was expected that sample reheating might result in

**Table 6. Summary of the sample reheating study.**

Mixture	Immediate	Delayed	Reheated
HMA Control	X	X	X
Aspha-min	X	X	X
Evotherm ET	X	X	X
LEA		X	X
Sasobit	X	X	X

additional stiffening of the binder in the mixture. The effect of sample reheating was evaluated for a control HMA and four WMA processes: Aspha-min, Evotherm ET, LEA, and Sasobit. The data for the control HMA, Aspha-min, Evotherm ET, and Sasobit mixtures were provided by the FHWA Mobile Asphalt Laboratory. The FHWA provided data for a WMA project constructed in St. Louis, Missouri, where modulus tests were performed for three conditions: (1) samples prepared at the time of construction and immediately tested, (2) samples prepared at the time of construction, but tested weeks later, and (3) reheated samples. McConaughay Technologies prepared dynamic modulus specimens for the LEA process during construction and the research team prepared an additional set of dynamic modulus specimens after reheating. Both sets of LEA specimens were tested by the research team. All of the dynamic modulus tests were conducted in accordance with AASHTO PP 61. Table 6 summarizes the sample reheating study. The data analysis consisted of comparing dynamic modulus master curves for the various sample preparation and testing conditions.

### 2.4.3 Binder Grade Study

The lower production temperatures used with WMA produce less aging of the binder during construction. This reduced aging may result in increased rutting of pavements produced using WMA processes and it may also result in improved resistance to fatigue and low-temperature cracking. NCHRP Project 09-43 included analysis of an experiment conducted by the FHWA where the effects of WMA production temperatures were simulated using the RTFOT (AASHTO T 240). In this experiment, binders were short-term aged in the RTFOT, at temperatures of 325°F, 266°F, and 230°F (163°C, 130°C, and 110°C). The high-temperature properties of the binders were then measured in accordance with AASHTO T 315 at multiple temperatures to determine the continuous RTFOT high-temperature grade of the binder. Low-temperature properties for several of the binders were measured during NCHRP Project 09-43 for RTFOT temperatures of 325°F and 230°F (163°C and 110°C). Low-temperature properties were measured in accordance with AASHTO T 313 at two temperatures to determine the continuous low-temperature grade of the binder. The RTFOT aged binders were further aged in the pressure aging vessel (PAV) in accordance with AASHTO R 28 at a temperature of 100°C prior to bending beam rheometer testing.

**Table 7. Binders used in FHWA RTFOT temperature experiment.**

Binder	Source	High Temperature	Low Temperature
B-6354	Missouri WMA PG 70-22	X	X
B-6348	Hawaii PG 70-16	X	X
B-6328	Venezuelan PG 64-22	X	X
AAM-1	SHRP MRL	X	X
AAM-2	SHRP MRL	X	X
AAG-1	SHRP MRL	X	Not Tested
AAD-1	SHRP MRL	X	X
B6272	ALF PG 70-22 Control	X	X
B6272+1.5% Sasobit	ALF PG 70-22 Control + Sasobit	X	Not Tested
B6272+3.0% Sasobit	ALF PG 70-22 Control + Sasobit	X	Not Tested

Table 7 summarizes the RTFOT temperature experiment. The continuous high-temperature grade data for these binders were used to develop preliminary production temperature limits below which consideration should be given to increasing the high-temperature grade of the binder. The continuous low-temperature grade data were used to develop preliminary recommendations for low-temperature binder grade selection based on production temperature.

#### 2.4.4 Short-Term Oven Conditioning Study

An important step in mixture design and analysis is short-term oven conditioning of laboratory-prepared loose mix prior to compaction. Short-term oven conditioning simulates the binder absorption and aging that occurs during construction. The short-term oven conditioning recommended for HMA at the end of the Strategic Highway Research Program (SHRP) was 4 h at 275°F (135°C) for both volumetric design and performance testing (16). This was included in AASHTO PP 2, Practice of Short and Long Term Aging of Hot Mix Asphalt (HMA), which later became AASHTO R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA). To expedite the mixture design process and reduce the number of ovens required for mixture design, the FHWA Mixtures and Aggregates Expert Task Group (ETG) reviewed data concerning the effect of conditioning time and temperature on the volumetric properties of asphalt mixtures. The ETG ultimately recommended that the short-term oven conditioning time for mixture design be changed to 2 h at the compaction temperature for aggregates with water absorption less than 4.0 percent. For aggregates with greater water absorption and for performance testing, the short-term oven conditioning time remained 4 h at 275°F (135°C). AASHTO R 30 was eventually modified to reflect the ETG's recommendation.

Short-term conditioning of 2 h at the compaction temperature has been recommended by some WMA process developers for mixture design. No recommendations have been made for short-term conditioning of WMA for performance testing. In Phase I of NCHRP Project 09-43, an experiment was undertaken to establish short-term oven conditioning times for both volumetric design and performance testing. The approach

that was used was to compare the maximum specific gravity, dynamic modulus, and tensile strength of laboratory-prepared mixtures with those from field mixtures. For convenience and to properly assess the effect of WMA process temperature, the short-term conditioning temperature was selected to be equal to the compaction temperature. Conditioning times of 2 h and 4 h were included in the experiment. The short-term oven conditioning experiment was completed for the Colorado I-70 mixtures, and a tentative short-term conditioning time was selected. This tentative conditioning time was then verified in the Phase II field validation study.

#### 2.4.5 RAP Study

The primary concern when using RAP in WMA is whether the RAP and new binders mix at the lower temperatures used in WMA. In the preliminary mixture design procedure, it was hypothesized that the allowable RAP content of WMA mixtures would decrease as the production temperature decreased. Two experiments were conducted in Phase I of NCHRP Project 09-43 in an attempt to determine production temperatures below which it may be necessary to limit the RAP content of WMA to some amount less than the amount allowed in HMA.

The first experiment included measurements of interfacial mixing to determine whether thin films of new binder on RAP binder actually mix and measurements of binder compatibility to determine the effect of mixing on the properties of the combined binder. The interfacial mixing measurements used atomic force microscope imaging of "film-on-film" interface contact lines. Asphalt binders including Advera and Sasobit WMA additives were used in the interfacial mixing measurements. Thin films of these WMA binders were cast onto a film of binder that was previously aged in the PAV to simulate an aged RAP binder. The specific procedures for the "film-on-film" imaging were developed by the Western Research Institute during Phase I of the project. The compatibility measurements were performed in accordance with ASTM D6703, Standard Test Method for Automated Heithaus Titrimetry. As the compatibility of an asphalt binder changes, the physical properties change. Less compatible binders tend to have more structure and more elastic properties. Compati-

**Table 8. Summary of compatibility testing.**

RAP Content (%)	AAB-1			AAG-1			Yellowstone National Park		
	Neat	1.5 % Sasobit	5 % Advera	Neat	1.5 % Sasobit	5 % Advera	Neat	1.5 % Sasobit	5 % Advera
0	X	X	X	X	X	X		X	X
5		X			X				
15		X			X				
25		X	X		X	X			X
50		X	X		X	X			X

Blank cells were not tested.

bility measurements were made for three neat asphalt binders, two WMA additives (Advera and Sasobit), one RAP binder, and four RAP percentages. Table 8 summarizes the compatibility testing.

The second experiment in the RAP study was a laboratory mixing experiment designed to assess the degree of mixing between RAP and new binders at WMA process temperatures. This experiment used an approach that was developed by Advanced Asphalt Technologies, LLC, for the Maryland State Highway Administration and the Pennsylvania Department of Transportation to evaluate the acceptability of plant mixing of mixtures containing RAP and recycled asphalt shingles (RAS) (17). The approach involves comparing dynamic moduli measured on mixture samples with dynamic moduli estimated using the properties of the binder recovered from the mixture samples. The dynamic modulus test is very sensitive to the stiffness of the binder in the mixture, and adding RAP will increase the dynamic modulus significantly when the RAP is properly mixed with the new materials. The dynamic modulus for the as-mixed condition was measured in accordance with AASHTO PP 61. The dynamic modulus for the fully blended condition was estimated using the Hirsch model (18) from the shear modulus of binder recovered from the dynamic modulus specimens.

Table 9 summarizes the experimental design for the laboratory mixing experiment. The experimental design included testing a control HMA and three WMA processes: Advera, Evotherm, and Sasobit. Each of the four mixtures was tested at two temperatures and three aging times. Each mixture was mixed at the mixing temperatures listed in Table 9, then short-

**Table 9. Experimental design for the laboratory RAP mixing experiment.**

Process	Mixing/Compaction Temperatures (°F)	Conditioning Time (h)		
		0.5	1.0	2.0
Control	280/255	X	X	X
	248/230	X	X	X
Advera	248/230	X	X	X
	230/212	X	X	X
Evotherm	248/230	X	X	X
	230/212	X	X	X
Sasobit	248/230	X	X	X
	230/212	X	X	X

term oven aged at the compaction temperature listed in Table 9 prior to compaction. Duplicate dynamic modulus specimens were prepared and tested for each mixture in accordance with AASHTO PP 61. The binder from one of the specimens was recovered in accordance with ASTM D5404. Dynamic shear rheometer (DSR) frequency sweep tests were performed on the recovered binders in accordance with AASHTO T 315 to determine binder modulus input values for the Hirsch model.

### 2.4.6 Workability Study

Phase I also included a screening study to select an appropriate workability device for use in WMA mixture design. To accommodate the wide range of WMA processes currently available and expected in the future, the preliminary procedure proposed evaluating coating, workability, and compactability directly during the evaluation of trial blends and during the optimum binder content selection. Six potential workability tests were identified by the research team. Table 10 presents a summary of key elements of these devices. After careful review of the workability devices in Table 10, the following devices were selected for the Phase I screening test:

- UMass Workability Device
- Nynäs Workability Device
- University of New Hampshire Workability Device
- Gyrotory Compactor with Shear Stress Measurement

The UMass, Nynäs, and University of New Hampshire workability devices are shown in Figures 2, 3, and 4, respectively. These devices measure either the torque (UMass and University of New Hampshire) or force (Nynäs) required to move a blade through the mixture. The University of New Hampshire device is very simple, consisting of a handheld drill with variable torque chuck clutch. The UMass and Nynäs devices are much more complex.

Some gyrotory compactors are equipped with devices that measure the force required to apply the gyrotory compaction angle. This measurement may be provided as a force or converted to stress based on the geometry of the equipment. The specific compactor used in the workability screening study was an Intensive Compaction Tester Model ICT-150R/RB manufactured by Invelop Oy of Finland and shown in Figure 5.

**Table 10. Key elements of potential workability devices for WMA.**

Device	Measurement	Modification of Procedure Needed for WMA	Advantages	Disadvantages
NCAT Prototype Workability Device	Torque to rotate paddle at constant speed.	None	<ul style="list-style-type: none"> <li>Measure workability during mixing.</li> <li>Previous research.</li> </ul>	Requires new mixer.
UMass Prototype Workability Device	Torque to rotate an auger at constant speed.	None	<ul style="list-style-type: none"> <li>Measure workability during mixing.</li> <li>Augur may better represent field movement.</li> </ul>	Requires new mixer.
Modified Nynäs Workability Device	Force to push a blade into a loose mix sample.	Temperature control at WMA placement and compaction temperatures.	<ul style="list-style-type: none"> <li>Simulates screed action.</li> <li>Relatively inexpensive.</li> </ul>	Requires new device.
ASTM D6704	Force to push a blade into a loose mix sample.	Temperature control at WMA placement and compaction temperatures.	<ul style="list-style-type: none"> <li>Simple and inexpensive.</li> <li>Uses existing equipment.</li> </ul>	May not represent field conditions.
Gyratory Shear Stress	Shear stress during gyratory compaction.	None for gyratory compactors with this capability.	<ul style="list-style-type: none"> <li>Measure workability during compaction.</li> </ul>	Requires gyratory compactor with shear stress measurement.
University of New Hampshire	Torque using blade attached to hand drill with adjustable torque settings.	None	<ul style="list-style-type: none"> <li>Simple and inexpensive.</li> <li>Can easily be performed after mixing or prior to compaction.</li> </ul>	Blade and drill torque settings need to be standardized.

The primary concern in the initial screening study was the effect of temperature and WMA additive on the workability of the mixture. The Phase I screening experiment is summarized in Table 11. It consisted of performing workability tests on a single mixture produced with three binders: PG 64-28 control, PG 64-28 with Sasobit, and PG 64-28 with Advera. Table 12 presents pertinent properties of the mixture used in the experiment. Sasobit and Advera were selected as the warm mix additives because these additives are easy to use in the laboratory. Duplicate workability tests were made with each device at three temperatures. Analysis of variance was used to evaluate the sensitivity of the test to changes in temperature and WMA additive. The sensitivity of the test along with ease of integration into the WMA design procedure were the factors considered in the final selection.



**Figure 2. UMass workability device.**



**Figure 3. Nynäs workability device.**





**Figure 4. University of New Hampshire workability device.**

### 2.5 Revised Preliminary Mixture Design Procedure

The preliminary mixture design procedure was modified based on the findings of the Phase I studies. These modifications generally involved substituting tentative criteria developed from the Phase I studies into the appropriate sections of the preliminary mixture design procedure. The criteria that were developed are discussed in Chapter 3. No modifications were made to the mixture analysis portion of the procedure.

**Table 11. Screening study for workability tests.**

Factor	Levels	Details
Mixtures	1	12.5 mm
Binders	3	PG 64-28 control PG 64-28 with Sasobit PG 64-28 with Advera
Workability Tests	5	UMass Prototype (auger) Modified Nynäs Gyratory Shear Stress University of New Hampshire
Temperatures	3	300°F 245°F 190°F
Replicates	2	—

Note. — = No qualifying details for replicates.



**Figure 5. Gyratory compactor with shear stress measurement.**

### 2.6 Phase II Studies

In Phase II of NCHRP Project 09-43, three studies were conducted to evaluate the revised preliminary procedure. The Phase II studies included (1) a laboratory mixture design study, (2) a field validation study, and (3) a WMA fatigue study. The sections that follow describe these studies.

**Table 12. Mixture used in the workability study.**

Property	Sieve Size	Value
Gradation (% Passing)	3/4 in	100.00
	1/2 in	99.00
	3/8 in	86.00
	#4	57.00
	#8	40.00
	#16	28.00
	#30	20.00
	#50	12.00
	#100	6.00
	#200	3.20
Asphalt Content, %		5.40
$N_{design}$		75.00
Design Air Voids, %		3.70
Design VMA, %		14.60
Design VFA, %		74.50
Fines to Effective Asphalt Ratio		0.69

### 2.6.1 Laboratory Mixture Design Study

The objective of the laboratory mixture design study was to test the engineering reasonableness, sensitivity, and practicality of the revised preliminary mixture design and analysis procedure for WMA. The study was designed to compare properties of WMA mixtures designed according to the revised preliminary procedure with those of corresponding HMA mixtures designed according to AASHTO R 35. As previously mentioned, the underlying principle for the mixture design procedure for WMA is to produce mixtures with strength and performance properties similar to those of HMA. The experimental design for the mix design study was a paired difference experiment. This design is commonly used to compare population means—in this case, the properties of properly designed WMA and HMA mixtures for the same traffic level, using the same aggregates with the same gradation. In this design, differences between the properties for WMA and HMA are computed for each mixture included in the experiment. If the two design procedures produce mixtures with the same properties, then the average of the differences will not be significantly different from zero. The difference for an individual mixture may be positive or negative, but the average difference over several mixtures should be zero. A *t*-test is used to assess the statistical significance of the average difference as summarized below.

Null hypothesis:  $\mu_{WMA} - \mu_{HMA} = 0$   
 Alternative hypothesis:  $\mu_{WMA} - \mu_{HMA} > 0$  or  $\mu_{WMA} - \mu_{HMA} < 0$   
 (as appropriate)  
 Test statistic:  $t = \frac{\bar{d}}{\left(\frac{s_d}{\sqrt{n}}\right)}$   
 Rejection region: Reject the null hypothesis and accept the alternative hypothesis if  $t > t_\alpha$  for  $n - 1$  degrees of freedom.

where

- $\mu_{WMA}$  = population mean for WMA mixtures,
- $\mu_{HMA}$  = population mean for HMA mixtures,
- $\bar{d}$  = average of the differences between WMA and HMA mixtures,
- $s_d$  = standard deviation of the differences, and
- $n$  = number of mixtures compared.

Table 13 presents the experimental design for the laboratory mix design study. In this study, various properties for WMA and corresponding HMA mixtures were evaluated using paired difference comparisons. Comparisons were made for Advera, Evotherm, and Sasobit. For the WMA processes, two mixing and compaction temperatures were used: one above the preliminary grade bumping temperature from the Phase I binder grade study and one below. The HMA mixtures and the WMA mixtures above the grade bumping temperature were made with PG 64-22 binder. Also, the WMA mixtures with RAP and Sasobit below the grade bumping temperature were made with PG 64-22 because both RAP and Sasobit increase the high-temperature grade of the binder. The Advera and Evotherm WMA mixtures below the grade bumping temperature were made with PG 70-22 binder. All mixtures were short-term conditioned for 2 h at the compaction temperature. The six mixtures were selected to provide a range of gyratory compaction levels and aggregate absorptions. One half of the mixtures included RAP at 25 percent. A total of 24 mixture designs were prepared using either AASHTO R 35 for HMA mixtures or the revised preliminary WMA mixture design procedure.

For the experimental design in Table 13, separate comparisons were made between the properties of HMA and each of the WMA processes. Comparisons were made for the following properties:

- Design air voids, vol %
- Design VMA, vol %
- Effective binder content (VBE), vol %

**Table 13. Mix design experiment.<sup>1</sup>**

No.	Mixture Identification			Process			
	<i>N</i> <sub>design</sub>	Aggregate Absorption	RAP <sup>2</sup>	HMA	Advera WMA	Evotherm G3 WMA	Sasobit WMA
1	50	High <sup>3</sup>	Yes	320/310 <sup>4</sup>	225/215	225/215	270/260
2	50	Low <sup>5</sup>	No	320/310	270/260	270/260	225/215
3	75	Low	Yes	320/310	270/260	225/215	270/260
4	75	High	No	320/310	225/215	270/260	225/215
5	100	High	Yes	320/310	270/260	270/260	225/215
6	100	Low	No	320/310	225/215	225/215	270/260

<sup>1</sup> Low-temperature Advera and Evotherm WMA use PG 70-22; all other mixtures use PG 64-22. All mixtures short-term conditioned 2 h at the compaction temperature.  
<sup>2</sup> RAP content 25 percent in all mixtures containing RAP.  
<sup>3</sup> High absorption > 2.0 percent.  
<sup>4</sup> XXX/XXX, e.g., 320/310, denotes mixing/compaction temperatures, °F.  
<sup>5</sup> Low absorption < 1.0 percent.

- Binder absorption, wt %
- Design binder content, wt %
- Effective binder content, wt %
- Coating
- Gyration to 8% air voids at the compaction temperature
- Gyration to 8% air voids at the compaction temperature minus 54°F (30°C)
- Density at  $N_{max}$
- Dry tensile strength
- Conditioned tensile strength
- Tensile strength ratio
- Flow number
- Rutting resistance

These properties are all obtained as part of the WMA mixture design process. The HMA mixtures required design in accordance with AASHTO R 35, flow number testing, and assessment of compactability at the lower temperature as proposed in the WMA mixture design procedure.

Table 14 presents the six mixtures that were included in the mix design study. The volumetric properties presented for these mixtures are those obtained from conducting an HMA mixture design in accordance with AASHTO R 35 and AASHTO M 323. The low-absorption mixtures were composed of limestone or diabase aggregate from Virginia. The high-absorption mixtures

were composed of gravel and limestone from Pennsylvania. The gravel material in these mixtures was selected for its historically high absorption, but the material supplied had lower absorption than expected, which resulted in lower water absorptions for the planned high-absorption mixtures. For the 50 and 75 gyration designs, the high-absorption mixtures have approximately twice the water absorption of the low-absorption mixtures. For the 100 gyration design, the planned low- and high-absorption mixtures have approximately the same water absorption. This difference was taken into account when performing statistical analysis of the experiment results. The same RAP was used in the three mixtures that incorporated RAP. Table 15 presents the gradation and binder content of the RAP material that was used. The RAP binder had a continuous performance grading of PG 95.9 (33.9) -13.1. The RAP was obtained from Loudoun County Asphalt in Leesburg, VA. All of the RAP mixtures used 25 percent RAP, which resulted in an RAP binder contribution of approximately 1.1 percent by weight. NuStar Asphalt Refining, LLC, provided the binders for this study from their Paulsboro, NJ, refinery. The dosage rate of the Sasobit was 1.5 percent by weight of the total binder (virgin plus RAP) in the mixture. The dosage rate of the Advera was 0.25 percent by total mix weight. Binders containing the Evotherm G3 were provided premixed by NuStar Asphalt Refining, LLC, and the Evotherm dosage rate was not adjusted

**Table 14. Mixtures used in the mix design experiment.**

Mix Number		1	2	3	4	5	6
Design Gyration		50	50	75	75	100	100
Aggregate Water Absorption, %		1.5	0.8	1.0	1.6	1.2	1.3
RAP		Yes	No	Yes	No	Yes	No
NMAS <sup>1</sup>		9.5 mm	9.5 mm	9.5 mm	9.5 mm	9.5 mm	9.5 mm
Aggregate Sources	Coarse	PA Gravel RAP	VA Limestone	VA Diabase RAP	PA Gravel	PA Gravel RAP	VA Diabase
	Fine	PA Limestone PA Gravel RAP	VA Limestone	VA Diabase Natural Sand RAP	PA Limestone PA Gravel	PA Limestone RAP	VA Diabase Natural Sand
	RAP	LCA, Leesburg, VA	None	LCA, Leesburg, VA	None	LCA, Leesburg, VA	None
Gradation	Sieve Size, mm						
	12.5	100	100	100	100	100	100
	9.5	97	94	94	98	97	98
	4.75	61	50	54	63	63	53
	2.36	43	32	38	44	41	40
	1.18	32	22	28	32	26	31
	0.6	25	14	21	22	17	22
	0.3	13	10	12	12	11	12
	0.15	6	7	8	5	7	7
0.075	3.8	5.4	5.2	3.0	4.6	4.8	
Aggregate Properties	FAA	44.1	45.8	46.1	43.5	45.4	48.3
	CAA <sup>2</sup>	98/95	100/100	100/99	98/95	98/95	100/100
	Flat & Elongated	4.5	1.6	2.7	7.4	4.4	7.6
	Sand Equivalent	93.2	75.0	59.4	80.2	91.9	76.7
Binder Content, wt %	6.4	6.8	5.5	6.3	6.0	5.7	
Effective Binder Content, wt %	5.6	6.1	4.8	5.3	5.4	4.7	
Air Voids, vol %	3.6	4.0	3.9	4.3	4.0	3.7	
Voids in Mineral Aggregate, vol %	16.4	18.0	15.9	16.3	16.4	15.1	
Effective Binder Content, vol %	12.8	14.0	12.0	12.0	12.4	11.4	
Voids Filled With Asphalt, %	78.0	77.8	75.5	73.6	75.6	75.5	
Dust to Effective Asphalt Ratio	0.7	0.9	1.1	0.6	0.9	1.0	

<sup>1</sup> NMAS = Nominal maximum aggregate size.

<sup>2</sup> CAA = Coarse aggregate angularity.

**Table 15. Properties of RAP used in the mixture design experiment.**

Property		Value
Gradation (% Passing)	Sieve Size (mm)	
	12.5	100
	9.5	92
	4.75	63
	2.36	44
	1.18	32
	0.6	24
	0.3	17
	0.15	11
	0.075	7.8
Asphalt Content, wt %		4.4
Continuous Performance Grade		PG 95.9 (33.9) -13.1
Aggregate Bulk Specific Gravity		2.877
Aggregate Water Absorption, %		1.01
Fine Aggregate Angularity, %		44.4
Crushed Aggregate Fractured Faces (1 Face), %		99.3
Crushed Aggregate Fractured Faces (2 Faces), %		94.3
Flat and Elongated Particles, %		0.5

for the RAP binder in the Evotherm RAP mixtures. The mixtures incorporating gravel required an anti-strip additive. Akzo-Nobel WETFIX 312 was used in the HMA, Sasobit, and Advera mixtures. The dosage rate for the anti-strip additive was 0.25 percent by weight of the total binder in the mixture. Representatives of Evotherm recommended that the anti-strip not be added when using the Evotherm G3 additive.

## 2.6.2 Field Validation Study

The objective of the field validation study was to use properties of laboratory- and field-produced WMA to validate selected parts of the revised preliminary WMA mixture design

and analysis procedure. The parts of the revised preliminary procedure addressed by the validation included the following:

- Binder grade selection
- RAP
- Short-term oven conditioning
- Specimen fabrication and compactability
- Moisture sensitivity
- Rutting resistance

Table 16 summarizes the mixtures that were included in the validation study. Materials from a total of 16 mixtures from six projects were sampled. The validation mixtures included a wide range of processes. Four mixtures were HMA control; three mixtures used the Advera WMA process; two mixtures used the Evotherm WMA process; two mixtures used the LEA process; two mixtures used plant foaming processes; and three mixtures used Sasobit. The WMA production temperatures ranged from 210°F to 275°F (99°C to 135°C), and the WMA compaction temperatures ranged from 195°F to 250°F (90°C to 121°C). Most of the WMA mixtures were produced around 250°F (121°C) and compacted around 230°F (121°C). The mixes included PG 58 and PG 64 binders. Only one mixture included RAP.

Table 17 summarizes the analyses that were completed in the validation study. Initial validation of the findings from the Phase I binder grade study was completed using recovered binder grading and estimates of rutting from the MEPDG rutting model using measured dynamic moduli from plant mixtures (1). Recovered binder grading data were collected on all of the 16 validation mixtures. Rutting estimates were made only for the mixtures included in the Colorado I-70, Yellowstone National Park, and New York Route 11 projects.

**Table 16. Field validation mixtures.**

Project	Process	Temperature (°F)		Mix Type
		Production	Compaction	
Colorado I-70	HMA Control	280	260	9.5 mm, PG 58-28, 75 gyrations
	Advera	250	230	
	Evotherm DAT	250	230	
	Sasobit	250	230	
Yellowstone National Park	HMA Control	325	315	19 mm, PG 58-34, Hveem
	Advera	275	250	
	Sasobit	275	245	
NY Route 11	LEA	210	205	9.5 mm, PG 64-22, 65 gyrations
PA SR2007	HMA Control	320	300	9.5 mm, PG 64-22, 50 gyrations
	Evotherm DAT	250	230	
PA SR2006 and PA SR2012	HMA	310	275	9.5 mm, PG 64-22, 75 gyrations
	Advera	250	230	
	Gencor Ultrafoam GX	250	230	
	LEA	210	195	
	Sasobit	250	230	
Monroe, North Carolina	Astec Double Barrel Green	275	260	9.5 mm, PG 64-22 with 30% RAP, 75 gyrations

**Table 17. Summary of validation study analyses.**

Component	Phase I Study	Validation Analyses
Binder Grade Selection	Binder Grade Selection	Recovered binder grading. Estimated rutting using MEPDG rutting model.
Mixing of RAP and New Binders	RAP Study	Mixing analysis of plant-produced WMA with RAP.
Short-Term Conditioning	Short-Term Conditioning Study	Compare maximum specific gravity and tensile strength of plant mixtures with laboratory mixtures.
Process-Specific Specimen-Fabrication Procedures	Literature Review and Research in Progress	Volumetric properties of WMA mixtures. WMA mixture design for plant foaming processes.
Compactability	Workability Study	Compare compactability of field mixtures to reported workability.
Moisture Sensitivity	Literature Review and Research in Progress	Compare moisture sensitivity results for HMA control and WMA mixtures.
Rutting Resistance	Literature Review and Research in Progress	Compare flow numbers for HMA control and WMA mixtures.

A binder mixing analysis using dynamic modulus and recovered binder testing on plant mix from the North Carolina project was used to validate that RAP and new binders mix at WMA process temperatures. The North Carolina project was the only project in the field validation study that included RAP.

The short-term oven conditioning process recommended in the Phase I short-term oven conditioning study was validated by comparing the maximum specific gravity of plant mixtures with laboratory-prepared mixtures and comparing the tensile strength of plant-mixed, laboratory-compacted samples with the tensile strength of laboratory-mixed, laboratory-compacted samples. Fifteen of the 16 validation mixtures were included in the analysis. The New York Route 11 LEA mixture was not included because the LEA additive used on the project was not available.

The process-specific specimen-fabrication procedures for WMA contained in the preliminary WMA mixture design procedure and the compactability criteria developed in the Phase I workability study were validated by preparing laboratory WMA mixtures replicating the field mixtures. Volumetric properties of the laboratory-prepared specimens were used to validate the process-specific specimen-fabrication procedures. Additionally, for the two projects that used plant foaming processes, a

WMA mixture design was completed using a Wirtgen WLB-10 laboratory foaming plant to assess the practicality of using this type of equipment for mixture design work. The compactability of the HMA and WMA mixtures from the field validation study was used to validate the tentative compactability criteria developed in the Phase I workability study.

Finally, specimens of WMA and HMA prepared from laboratory mixtures were subjected to moisture sensitivity and flow number testing as required by the preliminary WMA mixture design procedure. A comparison was made between the results of the HMA control and the results of the WMA mixture for each project.

### 2.6.3 Fatigue Study

One of the potential benefits of WMA mixtures is improved fatigue characteristics compared to HMA mixtures due to the reduced aging that occurs during plant mixing at the lower WMA process temperatures. Phase II included a brief study to evaluate the fatigue resistance of WMA compared to HMA. The experimental design for this study is presented in Table 18. Two of the mixtures from the mix design experiment were used in this study. Continuum damage fatigue tests were

**Table 18. Experimental design for the WMA fatigue study.<sup>1</sup>**

No.	Mixture Identification			Process			
	$N_{design}$	Aggregate Absorption	RAP	HMA	WMA Organic	WMA Foam	WMA Chemical
4	75	High	No	320/310 <sup>2</sup>	250/240	250/240	250/240
6	100	Low	No	320/310	250/240	250/240	250/240

<sup>1</sup> Mixtures from Table 14. All mixtures use PG 64-22 binder. All mixtures short-term conditioned 2 h at the compaction temperature. All mixtures long-term conditioned 120 h at 185°F.

<sup>2</sup> XXX/XXX, e.g., 320/310, denotes mixing/compaction temperatures, °F.

performed on the HMA control and WMA mixtures produced using Advera, Evotherm, and Sasobit. All mixtures used PG 64-22 binder. The HMA mixture was prepared at the recommended viscosity-based mixing and compaction temperatures. The WMA mixtures were prepared at the midpoint of the temperatures used in the mix design experiment. After compaction, all specimens were long-term oven aged in accordance with AASHTO R 30 to simulate the effects of long-term aging. The data from the study were evaluated to determine whether the fatigue characteristics of WMA mixtures are significantly improved over HMA mixtures.

## **2.7 Draft Standards for WMA**

The mixture design portion of the revised preliminary procedure was further modified based on the findings of

the Phase II studies. The final modifications are discussed in detail in Chapter 3. The mixture design portion of the revised preliminary procedure was reformatted to be in the form of an appendix to AASHTO R 35 highlighting special mixture design considerations and procedures for addressing WMA during mixture design. This document is included in Appendix A of this report. Appendix B is a commentary that provides supporting information for use in adoption and future revision of the mix design considerations and methods for WMA. Training materials for introducing the recommended WMA methods are included in Appendix C. The mixture analysis portion of the procedure was reformatted to be a standard practice for measuring properties of WMA for performance analysis using the MEPDG (1). This proposed standard practice is included in Appendix D.

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## CHAPTER 3

# Findings and Applications

This chapter presents the major findings from the various studies conducted in NCHRP Project 09-43 and discusses how these findings shaped the draft appendix to AASHTO R 35, Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA), which is contained in Appendix A herein. Detailed results and supporting analyses for these findings are included in Appendix E. Conclusions and recommendations drawn from these findings are presented in Chapter 4.

### 3.1 Phase I Findings

#### 3.1.1 Sample Reheating Study

The sample reheating study was conducted to determine whether sample reheating significantly affects the mechanical properties of WMA mixtures. HMA samples are often reheated for a variety of acceptance and performance tests. When the WMA process includes an irreversible component, such as foamed asphalt or some of the chemical additives, it may not be possible to use reheated samples for volumetric acceptance. However, reheated samples can be used to evaluate the mechanical properties of WMA mixtures for pavement analysis provided the effect of reheating on WMA samples is similar to the effect of reheating on HMA.

The sample reheating study found that reheating has a similar effect on the mechanical properties of WMA and HMA. Details of this analysis are presented in Section E2 of Appendix E. Figures 6 through 10 show the effect of sample reheating on the dynamic modulus master curve for a control HMA and four WMA processes: Aspha-min, Evotherm ET, Sasobit, and LEA. The error bars in these figures represent 95 percent confidence intervals for the mean based on a typical coefficient of variation for the dynamic modulus test of 14 percent and the number of samples that were tested. When the confidence intervals do not overlap, there is a significant difference in the dynamic modulus for the various conditions. Reheating has an effect on the stiffness of WMA that is similar to the effect it has

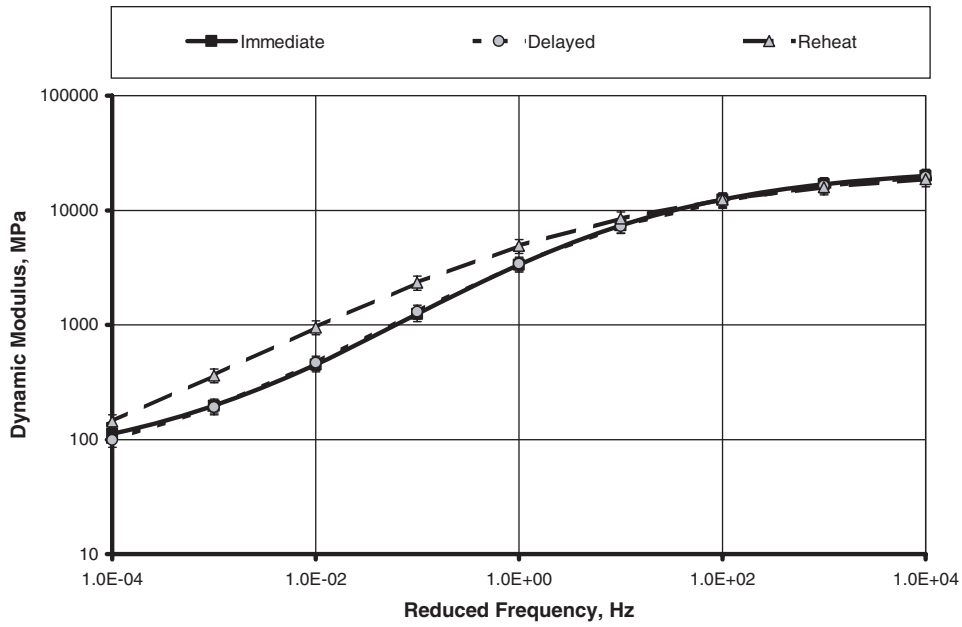
on the stiffness of HMA. There is a stiffening of the middle portion of the dynamic modulus master curve, which is most sensitive to changes in binder stiffness.

Table 19 quantifies the stiffening caused by reheating. This table presents the ratio of the reheated modulus to the immediate modulus and the delayed modulus for tests at 68°F (20°C), 0.1 Hz loading, which corresponds to a reduced frequency of 0.1 Hz in Figures 6 through 10, and is near the maximum difference between the master curves. The modulus after reheating is 60 to 150 percent higher than the immediate modulus and 30 to 80 percent higher than the delayed modulus. When the immediate modulus is used as the basis, the Aspha-min mixture was more sensitive to reheating effects than the HMA control and the Evotherm and Sasobit mixtures. When the delayed modulus is used as the basis, the WMA mixtures and the HMA control have similar sensitivity to reheating. The reheating effect is probably the result of the additional aging that occurs when field samples are reheated to temperatures high enough to allow proper compaction. As with HMA, reheating times and temperatures for WMA should be limited to minimize this effect.

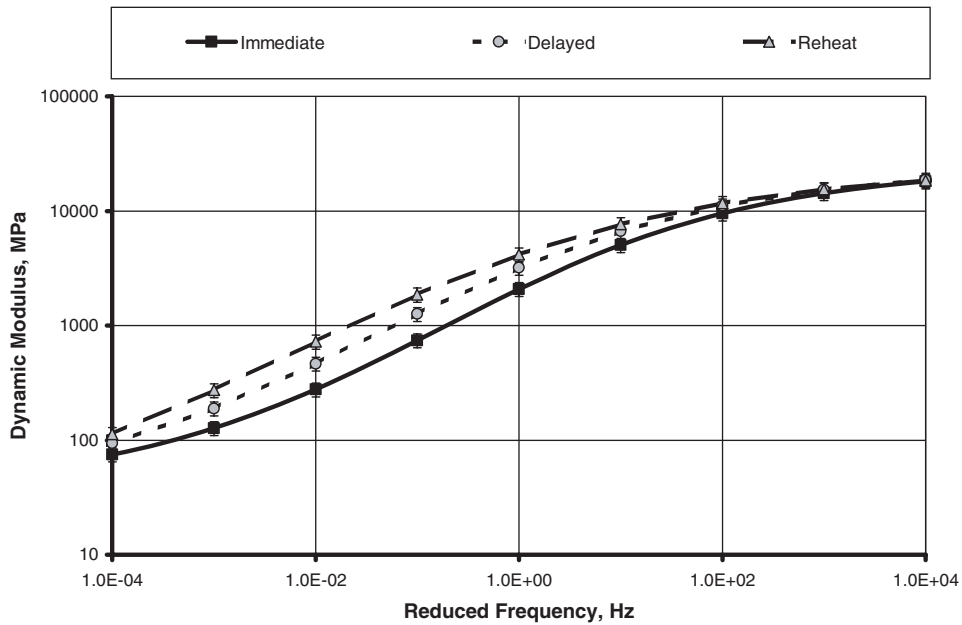
#### 3.1.2 Binder Grade Study

The lower production temperatures used with WMA produce less aging of the binder during construction. This reduced aging may result in increased rutting of pavements produced using WMA processes, and it may also result in improved resistance to fatigue and low-temperature cracking. NCHRP Project 09-43 included analysis of an experiment conducted by the FHWA where the effects of WMA production temperatures were simulated using the RTFOT—AASHTO T 240. This section presents key findings from this analysis. The detailed analysis is presented in Section E3 of Appendix E.

Analysis of the data from the RTFOT study showed that the high-temperature grade of the binder is affected more by changes in the RTFOT temperature than the low-temperature

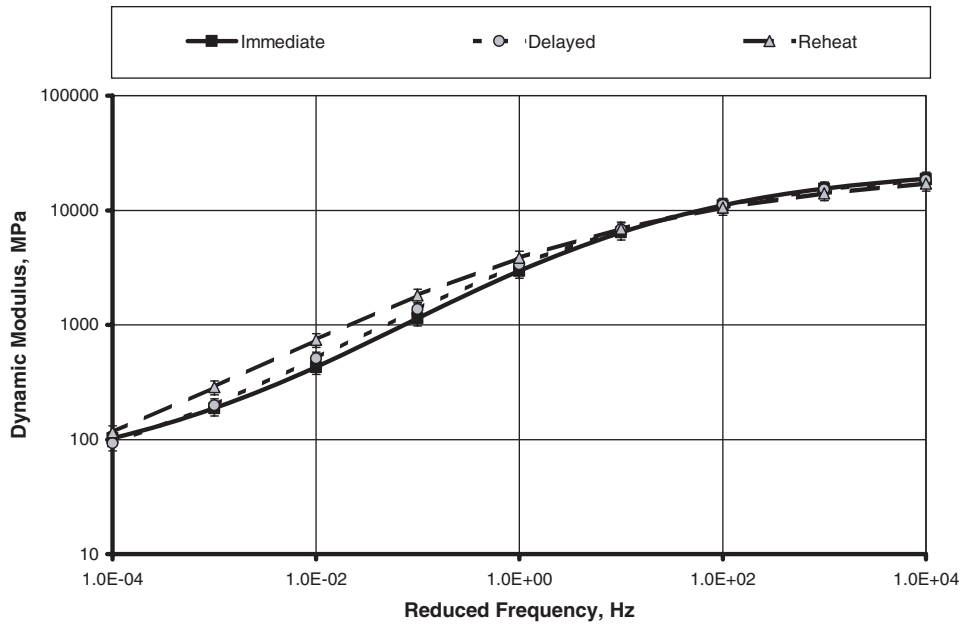


**Figure 6. Effect of sample reheating on the dynamic modulus of the St. Louis HMA control mixture.**

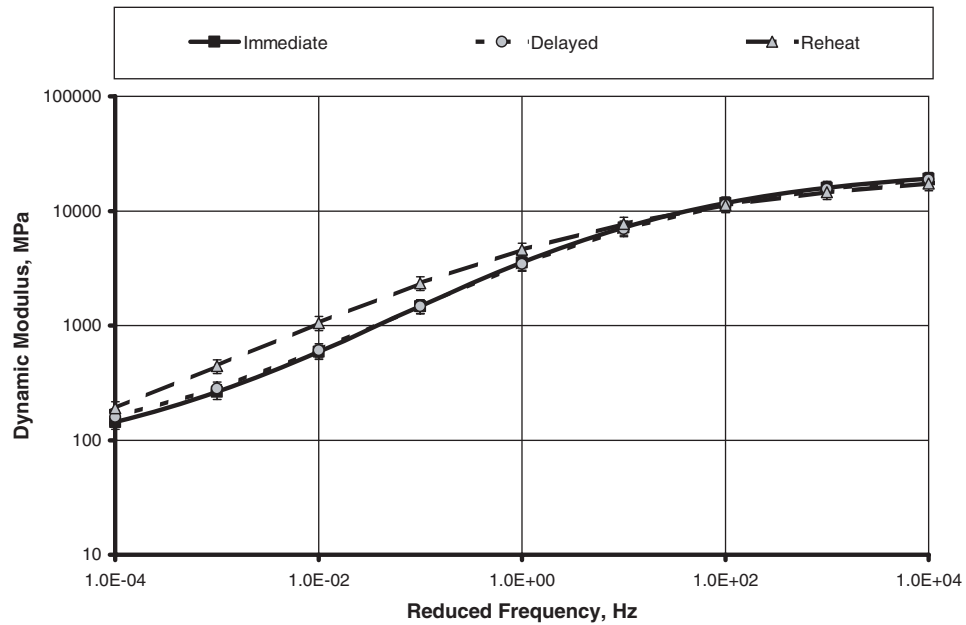


**Figure 7. Effect of sample reheating on the dynamic modulus of the St. Louis Aspha-min mixture.**

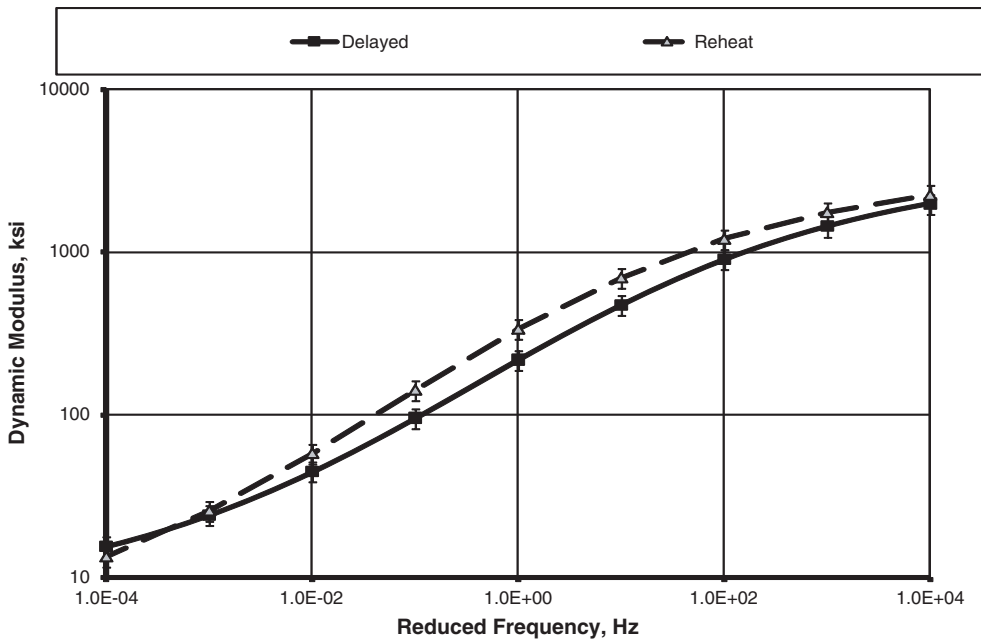




**Figure 8.** Effect of sample reheating on the dynamic modulus of the St. Louis Evotherm mixture.



**Figure 9.** Effect of sample reheating on the dynamic modulus of the St. Louis Sasobit mixture.



**Figure 10. Effect of sample reheating on the dynamic modulus of the New York LEA mixture.**

grade. The high-temperature continuous grade of the binder decreased approximately one grade (6°C) when the RTFOT aging temperature was reduced from 325°F to 230°F (163°C to 110°C). For the same change in aging temperature, the low-temperature grade improved only about one third of a grade level (2.0°C). The additional aging from the PAV that is included in the characterization of the low-temperature properties of binders is the likely cause of this difference. Apparently, improvements in low-temperature binder properties resulting from lower short-term aging temperatures are offset by the simulated long-term aging from the PAV, resulting in little change in the low-temperature grade of the binder.

The high-temperature grade change was sufficient to consider high-temperature grade bumping when WMA produc-

tion temperatures are low enough to result in a half grade (3°C) change in the high-temperature grade. The high-temperature grade bumping limits were developed by relating the change in the high-temperature grade of the binder to the aging index of the binder as shown in Figure 11. The aging index of the binder is defined by Equation 1 and can be obtained from normal binder testing. It is a measure of the aging susceptibility of the binder. Binders with higher aging indices stiffen more in the RTFOT test, and, as shown in Figure 11, are affected more by changes in the RTFOT aging temperature.

$$AI = \frac{(G^*/\sin \delta)_{RTFOT}}{(G^*/\sin \delta)_{TANK}} \tag{1}$$

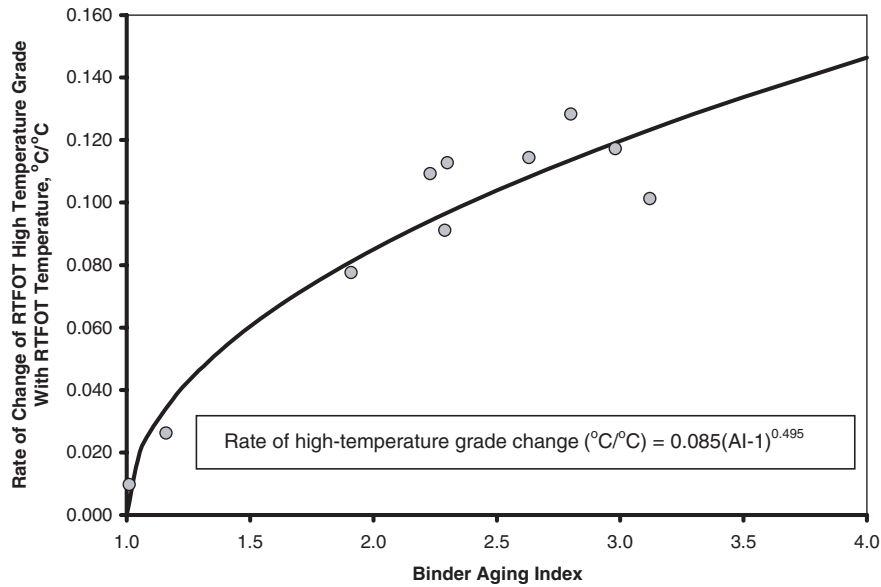
where

- $AI$  = aging index,
- $(G^*/\sin \delta)_{RTFOT}$  = RTFOT high-temperature stiffness at grade temperature, and
- $(G^*/\sin \delta)_{TANK}$  = Tank high-temperature stiffness at grade temperature.

The relationship shown in Figure 11 was used to estimate the effect of WMA production temperature on the high-temperature properties of the binder. To limit the change in high-temperature grade to one-half of one grade level, divide 3°C by the slope obtained from the binder aging index and the relationship shown in Figure 11. Equation 2 presents the allowable temperature changes to limit the high-temperature grade change to less than one-half of one grade level. For a typical

**Table 19. Comparison of reheated to immediate and delayed dynamic moduli for 68°F (20°C), 0.1 Hz Loading.**

Mixture	Dynamic Modulus Ratio 68°F (20°C) 0.1 Hz	
	Reheat to Immediate	Reheat to Delayed
Control	1.89	1.80
Aspha-min	2.52	1.48
Evotherm	1.59	1.32
LEA	NT	1.49
Sasobit	1.59	1.60



**Figure 11. Effect of short-term aging susceptibility on the rate of change of RTFOT high-temperature grade with RTFOT temperature.**

binder with an aging index of 2.4, the maximum allowable temperature change is  $-54^{\circ}\text{F}$  ( $-30^{\circ}\text{C}$ ).

$$\Delta T_{1/2 \text{ grade}} = \frac{-35.3}{(AI - 1)^{0.495}} \quad (2)$$

where

$\Delta T_{1/2 \text{ grade}}$  = maximum temperature change for a  $\frac{1}{2}$  grade change,  $^{\circ}\text{C}$ ; and

AI = binder aging index at the performance grade temperature.

Plant mixing temperatures below which consideration should be given to increasing the binder grade were obtained using Equation 2 and typical HMA production temperatures. Table 20 summarizes typical plant mixing temperatures recommended by the Asphalt Paving Environmental Council (19) based on the high-temperature performance grade of the binder. WMA production temperatures below which consider-

ation should be given to increasing the performance grade were obtained by combining the temperature change from Equation 2 with the typical mixing temperatures from Table 20. The results rounded to the nearest  $5.0^{\circ}\text{F}$  ( $2.8^{\circ}\text{C}$ ) are presented in Table 21 for various binder grades and levels of the aging index of the binder. If the planned plant mixing temperatures are lower than those listed in Table 21, consideration should be given to increasing the high-temperature performance grade of the binder one grade level above that normally used for HMA.

The relatively small effect of RTFOT temperature on the low-temperature binder grade did not warrant recommended changes in low-temperature binder grade selection for WMA. The low-temperature grade improvement, however, can be significant when considering mixtures incorporating RAP. When RAP blending charts are used, the low-temperature continuous grade of the binder changes approximately  $0.6^{\circ}\text{C}$  for every 10 percent of the total binder in the mixture replaced with RAP binder (20). Thus, improving the low temperature properties of the virgin binder in the mixture  $0.6^{\circ}\text{C}$  by lowering the production temperature will allow 10 percent additional RAP binder to be added to the mixture. The data collected in the RTFOT study indicated that the low-temperature grade improvement was approximately  $0.035^{\circ}\text{C}$  per  $^{\circ}\text{C}$  reduction in RTFOT temperature for PG XX-28 binders;  $0.025^{\circ}\text{C}$  per  $^{\circ}\text{C}$  reduction in RTFOT temperature for PG XX-22 binders; and  $0.022^{\circ}\text{C}$  per  $^{\circ}\text{C}$  reduction in RTFOT temperature for PG XX-16 binders. Using these values and typical HMA production temperatures for various binder grades given in Table 20, low-temperature grade improvements for RAP blending chart analyses were developed for some common grades

**Table 20. Typical HMA mixing temperatures (19).**

PG High-Temperature Grade	Recommended Mid-Point HMA Mixing Temperature ( $^{\circ}\text{F}$ )
52	270
58	285
64	292
67	300
70	302
76	308
82	315

**Table 21. Minimum WMA production temperatures not requiring a high-temperature PG grade increase based on the RTFOT experiment.**

PG High-Temperature Grade	Aging Index											
	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6
	Minimum WMA Mixing Temperature Not Requiring PG Grade Increase (°F)											
52	170	190	200	205	210	215	220	220	225	225	230	230
58	185	205	215	220	225	230	235	235	240	240	245	245
64	190	210	220	230	235	235	240	245	245	250	250	250
67	200	220	230	235	240	245	250	255	255	255	260	260
70	200	220	230	240	245	245	250	255	255	260	260	260
76	210	225	235	245	250	255	260	260	265	265	265	270
82	215	235	245	250	255	260	265	265	270	270	275	275

of binder. These improvements are summarized in Table 22. For a mixture using PG 64-22 virgin binder and a WMA production temperature of 250°F, the virgin binder low-temperature continuous grade would be improved 0.6°C to account for the lower WMA production temperature.

### 3.1.3 Short-Term Oven Conditioning Study

An important step in mixture design and analysis is short-term oven conditioning of laboratory-prepared loose mix

prior to compaction. Short-term oven conditioning simulates the binder absorption and aging that occurs during construction. Comparisons of properties of plant- and laboratory-prepared mixtures for the Colorado I-70 WMA project were used to select an appropriate short-term conditioning. For convenience, the short-term conditioning temperature was selected to be the compaction temperature. Conditioning times of 2 h and 4 h were investigated. This section presents the findings from the short-term oven conditioning study. The detailed analysis is presented in Section E4 of Appendix E.

**Table 22. Anticipated 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 °C Reduction in Plant Temperature	0.035	0.025	0.025	0.012	0.025
WMA Production Temperature, °F	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
205	1.6	1.1	1.2	0.6	1.3
200	1.7	1.2	1.3	0.6	1.4

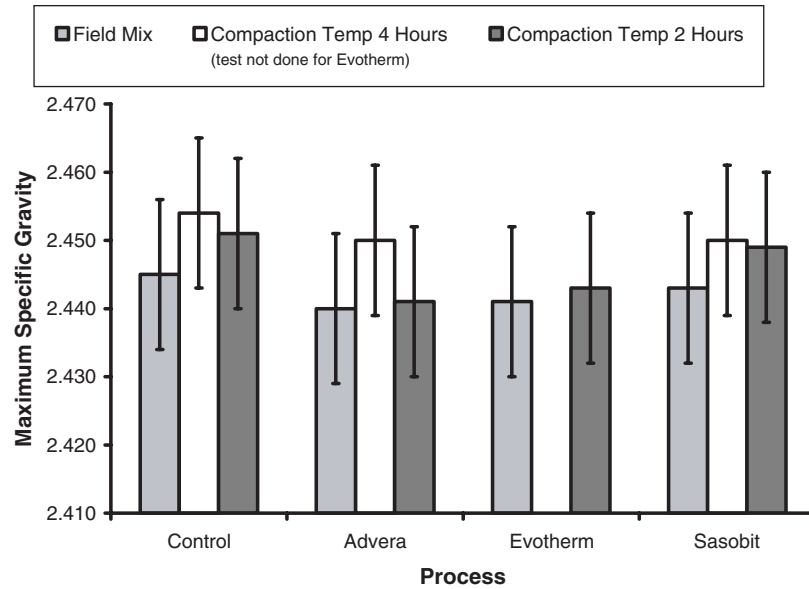


Figure 12. Maximum specific gravity for Colorado I-70 mixtures.

The short-term oven conditioning study confirmed the practice suggested by some WMA process developers of using 2 h of oven aging at the WMA compaction temperature. Figure 12 compares maximum specific gravity measurements for the mixtures used in the Colorado I-70 WMA project. The error bars shown in Figure 12 are the acceptable range of maximum specific gravity measurements based on the single operator precision statement given in AASHTO T 209. Figure 12 shows that for the aggregate used in the Colorado I-70 mixtures, the maximum specific gravity is essentially the same for all processes and all short-term aging conditions. The reported

water absorption for the Colorado I-70 job mix formula was 0.8 percent.

Figure 13 compares the indirect tensile data for plant-mixed, laboratory-compacted specimens and laboratory-mixed, laboratory-compacted specimens. The error bars in Figure 13 are 95-percent confidence intervals for the average indirect tensile strength. The graphical analysis shown in Figure 13 suggests that 2 h of conditioning at the compaction temperature provides tensile strengths for laboratory-prepared specimens that are approximately equal to those for field mixtures. Supporting statistical analyses for this finding are presented in

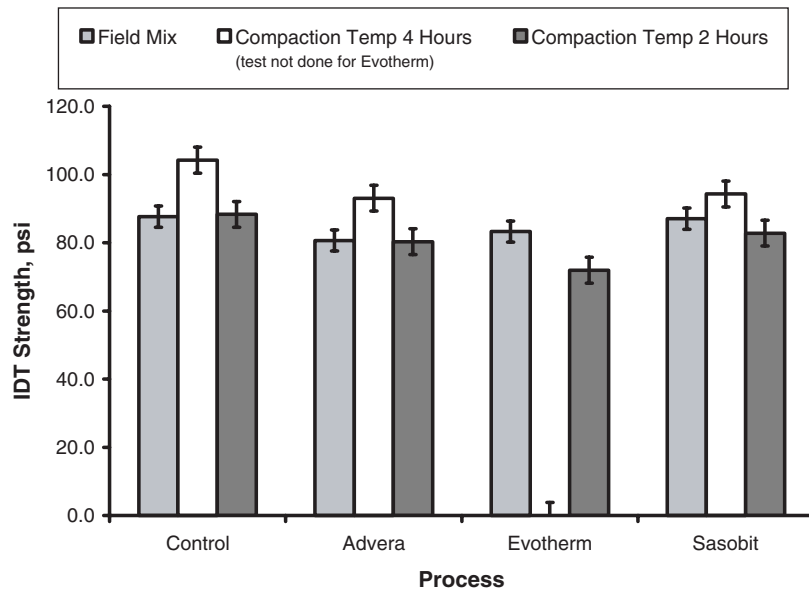


Figure 13. Comparison of tensile strengths for Colorado I-70 mixtures.

Section E4 of Appendix E. Section E4 of Appendix E also includes graphical and statistical analysis of dynamic moduli that also supports the use of 2 h at the compaction temperature for short-term conditioning of WMA mixtures.

### 3.1.4 RAP Study

The primary concern when using RAP in WMA is whether the RAP and new binders mix at the lower temperatures used in WMA. The RAP study included two experiments designed to assess the mixing of RAP and new binders at WMA process temperatures. This section presents the findings from the RAP study. Detailed analysis of the data from the RAP study is presented in Section E5 of Appendix E.

The first experiment was an interfacial mixing study that used atomic force microscope (AFM) imaging of “film-on-film” interface contact lines. A thin film of WMA binder was cast onto a film of binder that was previously aged in the PAV to simulate an aged RAP binder. These samples were imaged via AFM in the center of the new binder film, at the contact line

between the two films, and toward the edge of the RAP binder film where the new binder had not coated this film. All sample films were imaged after casting, then periodically imaged after being thermally conditioned in a 266°F (130°C) oven. The interfacial mixing study found that the binder films mixed under thermal cycling. This is shown in the AFM images presented in Figure 14. The lower left image is the surface of the RAP binder. The surface of the WMA binder, in this case Sasobit modified, is shown in the upper right image. Finally, the upper left image is that of the thermally mixed interfacial contact line. It depicts a transition in structuring between the RAP binder surface and the new binder surface, indicating that the two binders are mixing during thermal conditioning at 266°F (130°C).

This finding was confirmed through a laboratory mixing experiment. In the laboratory mixing experiment, HMA and WMA mixtures incorporating RAP were prepared at different temperatures and short-term conditioned for periods ranging from 0.5 h to 2.0 h. The mixing of the new and recycled binders was quantified by comparing dynamic moduli measured on

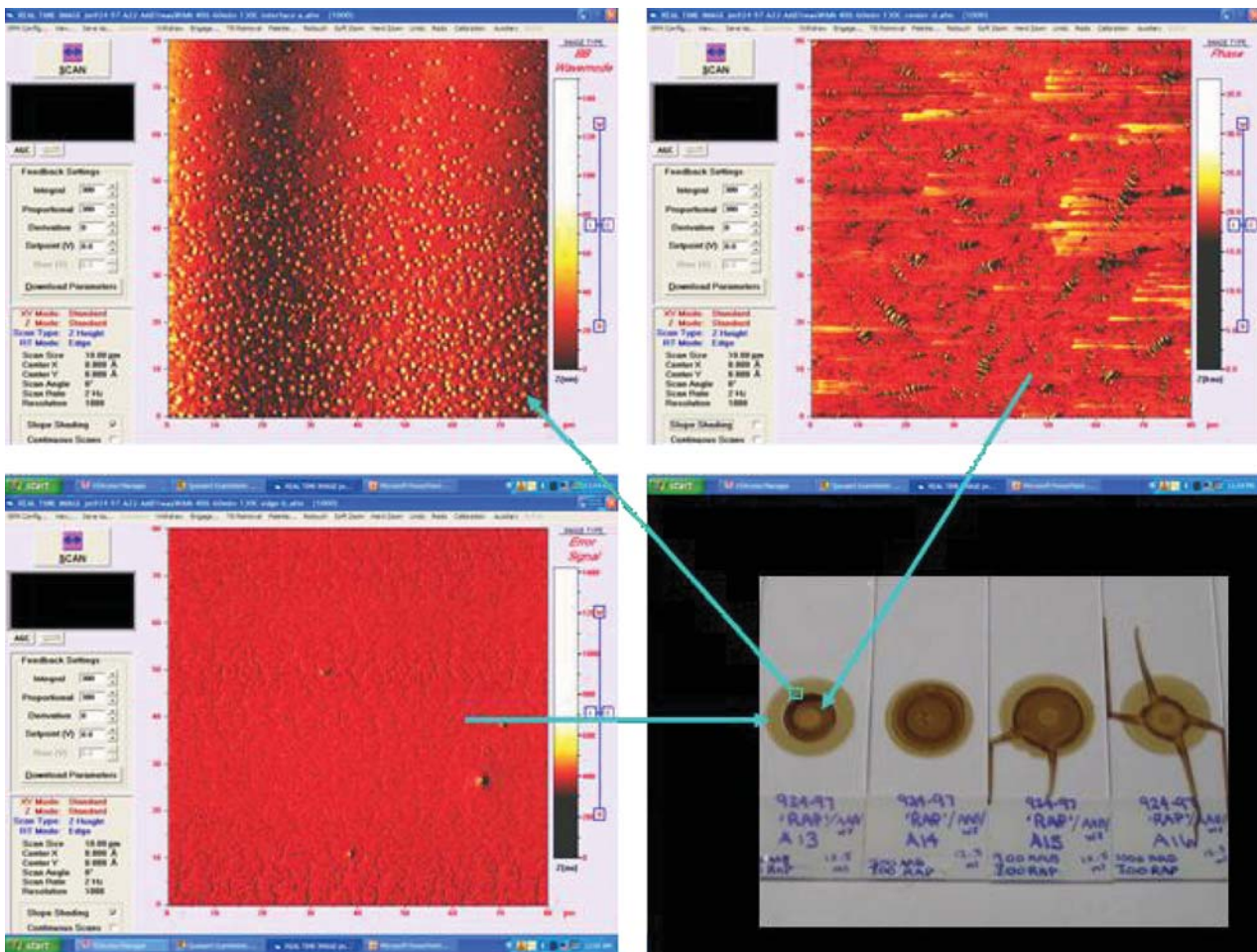


Figure 14. AFM Scans at the interfacial contact line (upper left), at the new binder surface (upper right), and at the RAP binder surface (lower left) after annealing.

samples of the mixtures with dynamic moduli estimated using binder recovered from the mixtures. The measured dynamic moduli represented the “as mixed” condition; the estimated moduli represented the “fully blended” condition. A measured-to-estimated dynamic modulus ratio approaching one indicated a high degree of mixing of the RAP and new binders.

The findings of the laboratory mixing experiment are shown in Figure 15. At conditioning times of 0.5 h and 1.0 h, there is little blending of the new and recycled binders. For all processes and temperatures, the ratio of the measured-to-estimated fully blended moduli range from about 0.35 to 0.55. At the 2 h conditioning time, the ratio of the measured-to-estimated fully blended moduli reach values approaching 1.0 for the Control, Advera, and Sasobit. The effect of temperature is also evident for these processes, with the higher conditioning temperature resulting in somewhat higher ratios. The ratio of the measured-to-estimated fully blended moduli for the Evotherm WMA remained low even at the 2 h conditioning time. This suggests that either the particular form of Evotherm used in this study retards the mixing of the new and recycled binders or that the extraction and recovery process stiffens the Evotherm modified binder. Other findings from the mixture design study show that RAP and new binders do mix well for the Evotherm G3 process for 2 h of conditioning time. Mixtures with 25-percent RAP designed using Evotherm G3 had the same optimum binder content as 25-percent RAP mixtures designed as HMA.

The findings from the two experiments in the RAP study show that RAP and new binders mix at WMA process temperatures in a manner that is similar to the way that they mix in HMA at higher temperatures. Clearly the mixing is time

dependent, indicating that the new binder coats the virgin aggregate and RAP, and then, during storage at elevated temperature, the two binders continue to mix. The RAP used in this study was very stiff, having a continuous performance grade of PG 105.8–2.3, and likely represents a worst-case scenario. Since the binders continued to mix during oven conditioning at the compaction temperature, the compaction temperature was probably the critical temperature in the mixing study. It is likely that the minimum temperature that can be used is related to the viscosity of the RAP binder at that temperature. The RAP binder used in this study had a viscosity of approximately 22,000 P (220 Pa•s) at the average compaction temperature of 221°F (105°C) used in this study, suggesting that a reasonable tentative requirement for RAP in WMA is that the RAP have a viscosity less than 22,000 P (220 Pa•s) at the planned field compaction temperature. This is approximately equivalent to requiring the planned field compaction temperature to be greater than the temperature where the as-recovered RAP binder meets the AASHTO M 320 requirement of  $G^*/\sin\delta = 2.20$  kPa.

### 3.1.5 Workability Study

The workability study was conducted to identify a workability test to be used in place of viscosity-based mixing and compaction temperatures to directly evaluate workability and compactability of WMA mixtures. Three devices that measure either the torque or the force required to move a blade through the loose mixture were evaluated as potential workability devices: (1) UMass Workability Device, (2) Nynäs Workability Device, and (3) University of New Hampshire Workability

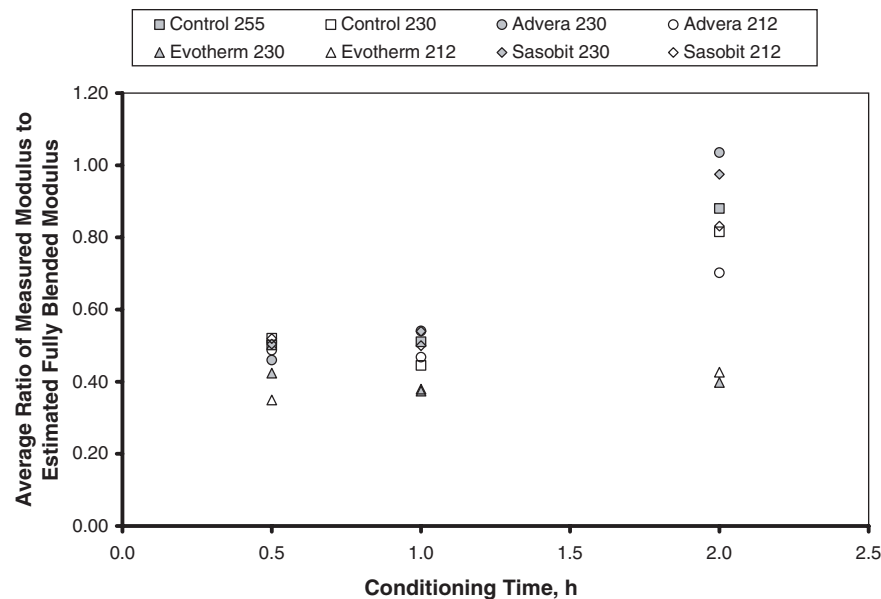
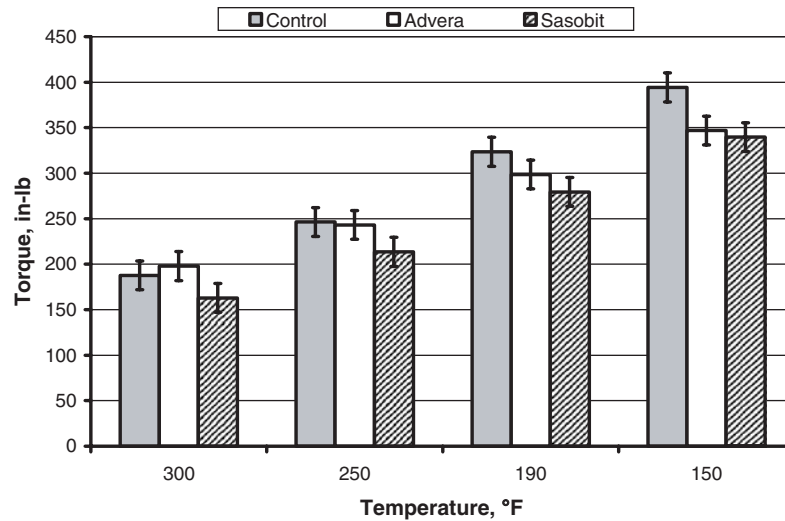


Figure 15. Comparison of the ratio of measured to fully blended dynamic moduli.



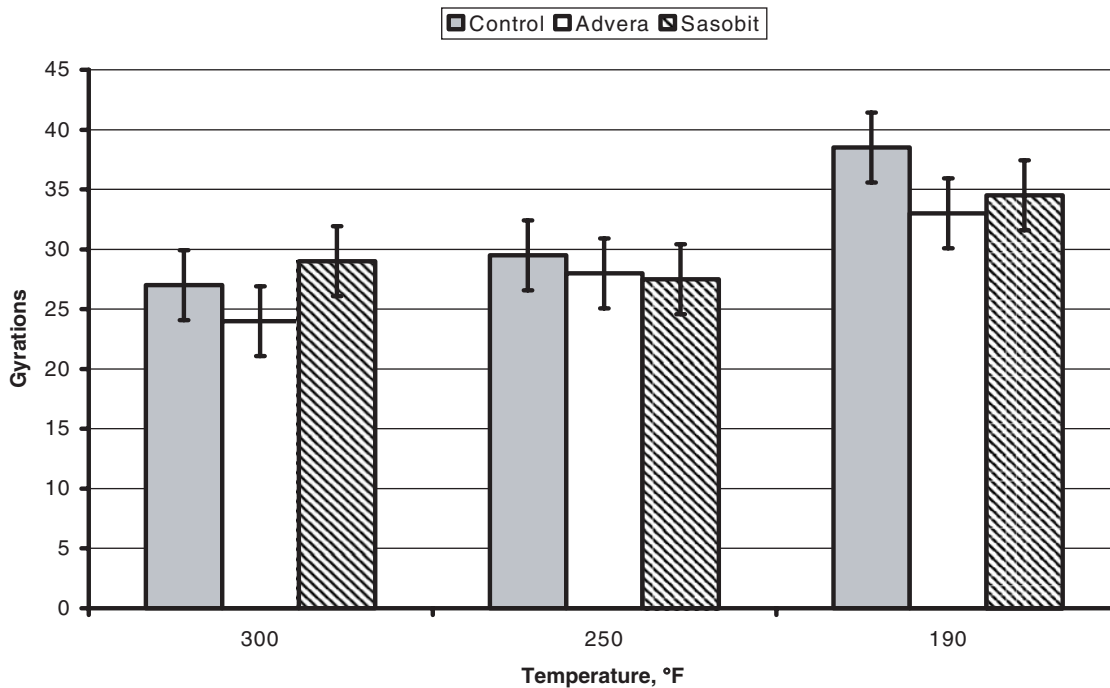
**Figure 16. Effect of temperature and WMA additive on torque measured in the UMass workability device.**

Device. Additionally, various parameters that could be obtained during gyratory compaction, including the gyratory shear stress, were evaluated as measures of compactability. This section, presents the findings from the workability study. Detailed analysis of the data from the workability study is presented in Section E6 of Appendix E.

The primary finding from the workability study for the three workability devices was that these devices could only discriminate between HMA and WMA at temperatures that are much lower than the temperatures normally associated with the pro-

duction of WMA. This is illustrated in Figure 16, which presents torque measurements at different temperatures for the UMass Workability Device. The workability study further found that the number of gyrations to reach 92-percent relative density in the gyratory compactor, shown in Figure 17, had similar sensitivity to temperature and WMA additives.

The workability study demonstrated that it is possible to measure differences in the workability and compactability of WMA as compared to HMA. The differences, however, are only significant at temperatures that are below typical WMA



**Figure 17. Effect of temperature and WMA additive on gyrations to 92-percent relative density.**



discharge temperatures. This suggests that it is not necessary to evaluate workability at the planned production temperature. The evaluation of coating at the planned production temperature should suffice. It appears that workability and compactability can be evaluated by using the gyratory compactor to determine the gyrations to 8-percent air voids at the planned field compaction temperature and a second temperature that is approximately 55°F (30°C) lower than the planned field compaction temperature. This will permit an assessment of the temperature sensitivity of the workability and compactability of the mixture.

### 3.2 Preliminary Mixture Design Procedure Revisions

The preliminary mixture design procedure was modified based on the findings of the Phase I studies. Table 23 summarizes how the findings from each of the Phase I studies were used to revise the preliminary mixture design procedure.

The key finding from the sample reheating study was that reheating has a similar stiffening effect on WMA and HMA. This finding was not directly incorporated into the revised preliminary mixture design procedure. It was used in analysis of data from the other Phase I studies, particularly the selection of a short-term conditioning time for WMA.

The binder grade study yielded three key findings. First, the high-temperature grade of the binder was significantly affected by changes in the RTFOT aging temperature. A relationship among the short-term aging temperature, the aging index of the binder, and the change in high-temperature grade of the binder was developed and used to provide preliminary guidance on production temperatures below which the high-temperature binder grade should be increased one grade level. This guidance was included in the revised preliminary procedure. The second key finding from the binder grade study was that the changes in the low-temperature grade of the binder that resulted from changes in the RTFOT aging temperature were small and did not warrant recommended changes in low-temperature binder grade selection for WMA. The third key finding was that small improvements in the low-temperature properties could result in increased RAP usage when a blending chart analysis is conducted.

The key finding from the short-term conditioning study was that 2 h of conditioning at the compaction temperature reasonably reproduced the absorption and binder aging that occurred during construction. The revised preliminary procedure specified 2 h of conditioning at the compaction temperature for volumetric design and performance testing.

The RAP study found that RAP and new binders do mix at WMA production and compaction temperatures in a manner

**Table 23. Summary of preliminary design procedure revisions.**

Phase I Study	Key Findings	Preliminary Design Procedure Revisions
Sample Reheating	1. Reheating has similar stiffening effect for WMA and HMA	1. Not directly incorporated. Used in selection of tentative short-term conditioning time.
Binder Grade	1. The high-temperature binder grade is significantly affected by the RTFOT temperature. The temperature effect was greater for binders with greater short-term aging susceptibility. 2. The effect of RTFOT temperature on the low-temperature binder grade was small. 3. The effect of RTFOT temperature on the low-temperature grade could affect RAP contents when blending charts are used.	1. Preliminary recommendations were included in the binder grade selection to increase the high-temperature performance grade based on the planned production temperature and Table 21. 2. No change required. 3. Preliminary recommendations for improving the low-temperature grade of the virgin binder for blending chart analyses were added based on Table 22.
Short-Term Conditioning	1. 2 h of oven conditioning at the compaction temperature reasonably reproduced the binder absorption and binder stiffening that occurs during construction.	1. 2 h at the compaction temperature was specified for volumetric design and performance testing.
RAP	1. RAP and new binders mix at WMA production and compaction temperatures in a manner similar to HMA. The mixing depends on the time at elevated temperature and probably the stiffness of the RAP binder.	1. Note added that the “as recovered” high-temperature grade of the RAP binder should be less than the planned field compaction temperature. Also, if the mix time at elevated temperature was expected to be less than 2 h, plant mixing studies should be conducted to verify the degree of mixing of the RAP and new binders.
Workability	1. Differences in workability and compactability of WMA could only be measured at temperatures that are below WMA production temperatures.	1. A workability test was not included in the revised preliminary procedure. Coating is evaluated at the planned production temperature. Limits on the gyrations to 92-percent relative density at the planned field compaction temperature and 54°F below the planned field compaction temperature were added to control compactability.

that is similar to the way RAP and binders mix in HMA production and compaction at higher temperatures. The mixing depends on the time at elevated temperature and probably the stiffness of the RAP binder. In the preliminary mixture design and analysis procedure for WMA, it was envisioned that the amount of RAP that could be added to WMA would be limited by the planned WMA production temperature and the compatibility of the new and RAP binders. Since the Phase I RAP study showed that substantial mixing of the RAP and new binders does occur at WMA process temperatures, the limitations on RAP usage included in the preliminary procedure were removed. The appendix describing compatibility testing for blended binders was also removed because the compatibility tests completed during Phase I showed blends of RAP and new binders had compatibility values within the range of typical unmodified binders. A requirement that the planned field compaction temperature for WMA incorporating RAP should exceed the temperature where the recovered RAP binder has a  $G^*/\sin\delta$  value of 2.2 kPa was added. A note indicating that the effectiveness of the RAP in a mixture will depend on the total time that the mixture is exposed to elevated temperatures was added. This note also recommends that dynamic modulus tests should be conducted on samples of plant mix if the mix will be exposed to temperatures above the compaction temperature used in design for less than 2 h.

The workability study found that it was possible to measure differences in the workability and compactability of WMA as compared to HMA. The differences, however, were only significant at temperatures that are below typical WMA production temperatures. This indicated that it is not necessary to evaluate workability at the planned production temperature. The evaluation of coating at the planned production temperature is sufficient. Workability and compactability can be evaluated by using the gyratory compactor to determine the gyrations to 92-percent relative density at the planned field compaction temperature and a second temperature that is approximately 54°F (30°C) lower than the planned field compaction temperature. This will permit an assessment of the effect of temperature on the workability and compactability of the mixture. The preliminary mixture design and analysis procedure for WMA was modified accordingly. Evaluation of workability and compactability at the planned production temperature was eliminated from the “design aggregate structure” and “design binder content” sections of the procedure. The measure of gyrations to 92-percent relative density was used to assess the compactability of the mixture. This is evaluated in the “design binder content” section of the procedure. A tentative limit of 35 percent of the design gyrations was included based on research reported by NCAT (21). To evaluate workability and compactability, two additional specimens at the optimum binder content are compacted at 54°F (30°C) below the planned field compaction temperature and the number of

gyrations to 92-percent relative density is determined. A tentative limit of 125 percent of the value at the planned field compaction temperature was included based on the limited testing performed during the Phase I workability study.

### 3.3 Phase II Findings

Phase II of NCHRP Project 09-43 was directed at evaluating and validating the revised preliminary WMA mixture design procedure. Phase II included three studies: (1) a laboratory mixture design study, (2) a field validation study, and (3) a fatigue study. Findings from each of these studies are presented in the following sections. Detailed analysis of the Phase II studies is included in Appendix E.

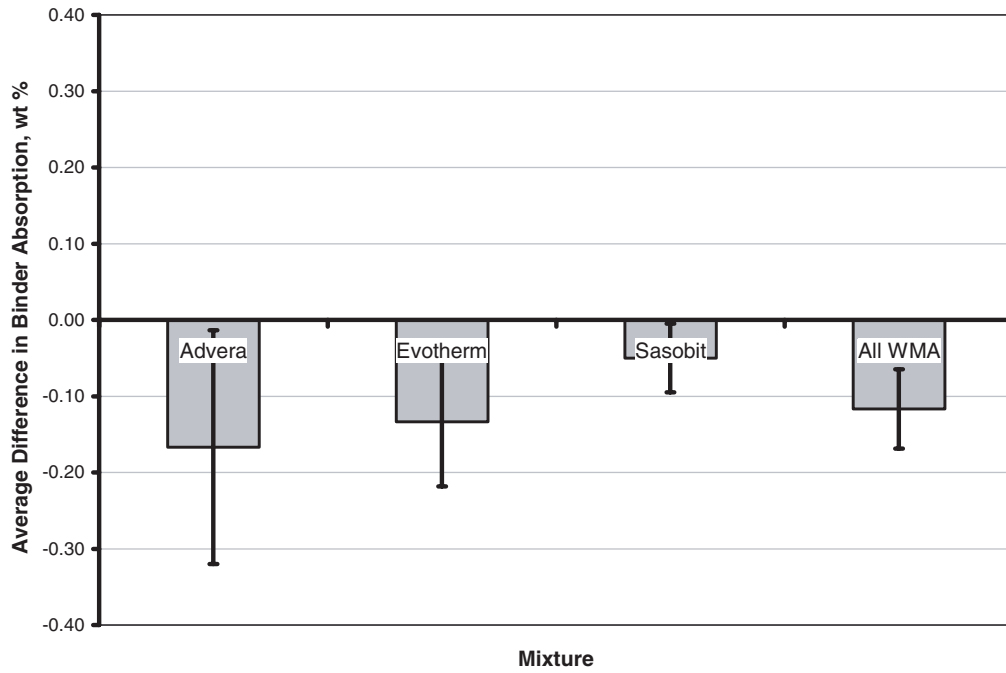
#### 3.3.1 Laboratory Mixture Design Study

In the laboratory mixture design study, the revised preliminary WMA mixture design procedure was successfully applied to several WMA mixtures. For the mixtures tested, the volumetric properties were not sensitive to the WMA process type or the WMA process temperature. Mixture compactability, moisture sensitivity, and rutting resistance were sensitive to the WMA process type and the WMA process temperature. Specific findings are presented and discussed below. Details of the analysis leading to these findings are presented in Section E7 of Appendix E.

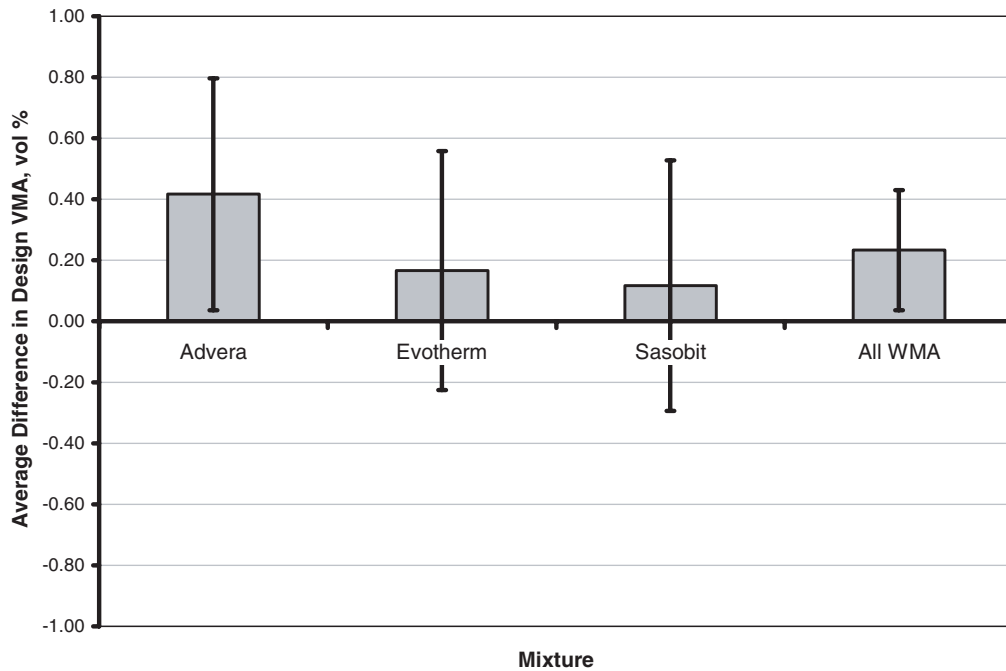
##### 3.3.1.1 Volumetric Properties

For a specific combination of aggregates and binder, the paired difference statistical analysis presented in Section E7 of Appendix E found little difference in the volumetric properties of properly designed WMA and HMA when the binder absorption for the HMA was 1.0 percent or less. These findings are shown graphically in Figures 18 through 21.

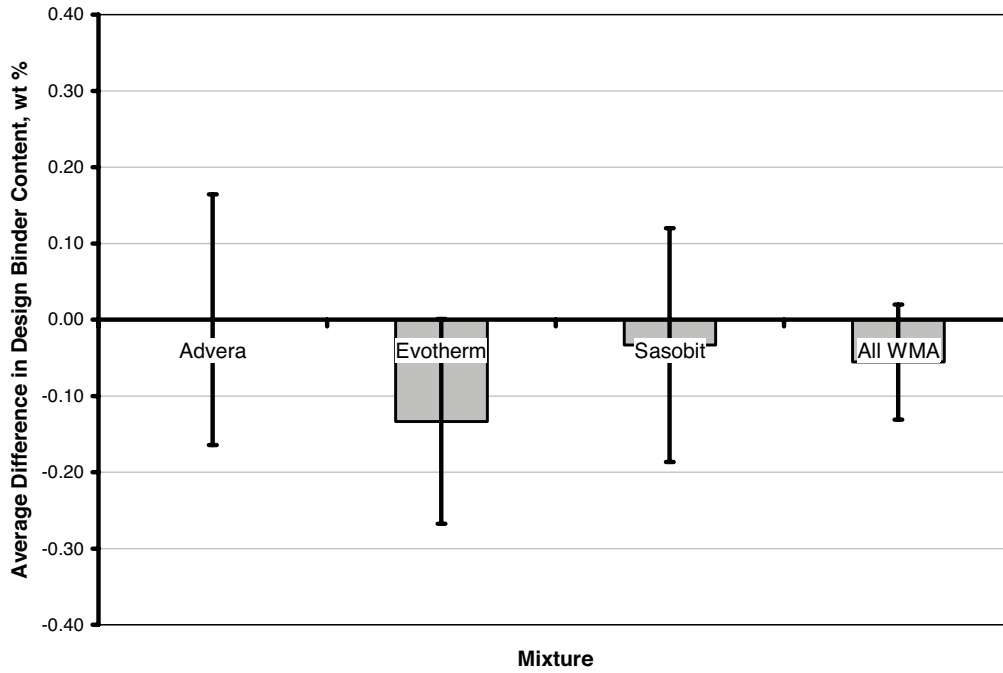
Figure 18 shows the difference in binder absorption for WMA compared to HMA for the mixtures included in the mixture design study. The absorption in the WMA mixtures was on average 0.1 percent less than the absorption in the HMA mixtures. This difference in binder absorption was statistically significant. It resulted in an average increase in the design VMA for the WMA of approximately 0.2 percent as shown in Figure 19, which was also statistically significant. However, it had little effect on the design binder content and the effective volume of binder (VBE) for the mixtures as shown in Figures 20 and 21. The average design binder content for the WMA was less than 0.1 percent lower than the average design binder content for the HMA while the average design VBE was 0.1 percent higher for WMA as compared to HMA. Neither of these was statistically significant. The design VBE for the Advera mixtures was significantly higher than the design VBE for the HMA.



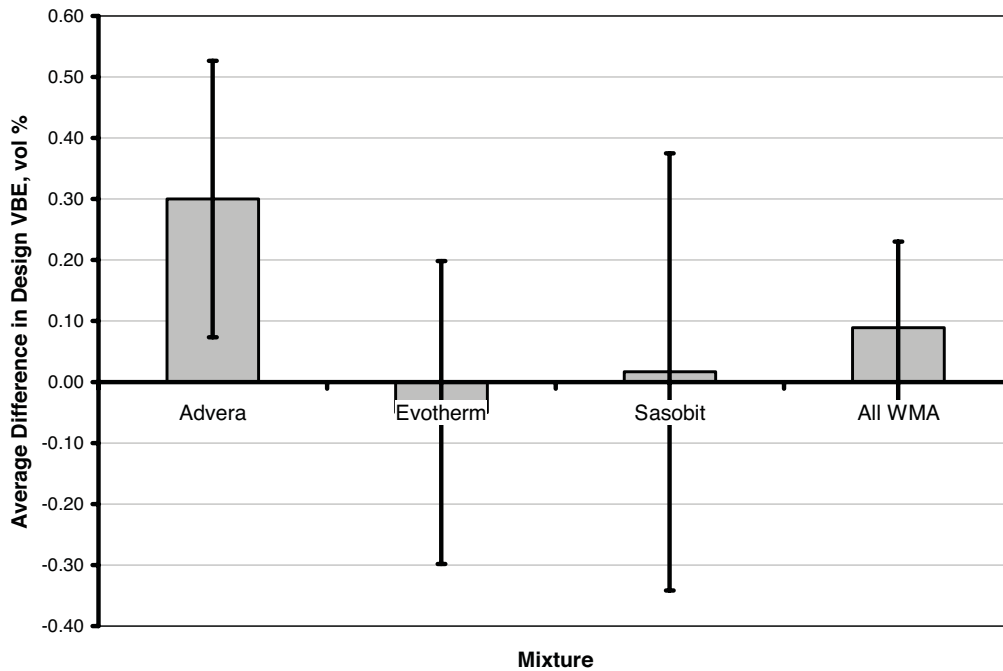
**Figure 18.** Average difference in binder absorption (WMA-HMA) from the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).



**Figure 19.** Average difference in design VMA (WMA-HMA) from the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).



**Figure 20.** Average difference in design binder content (WMA-HMA) from the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).



**Figure 21.** Average difference in design VBE (WMA-HMA) for the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).

### 3.3.1.2 Compactability

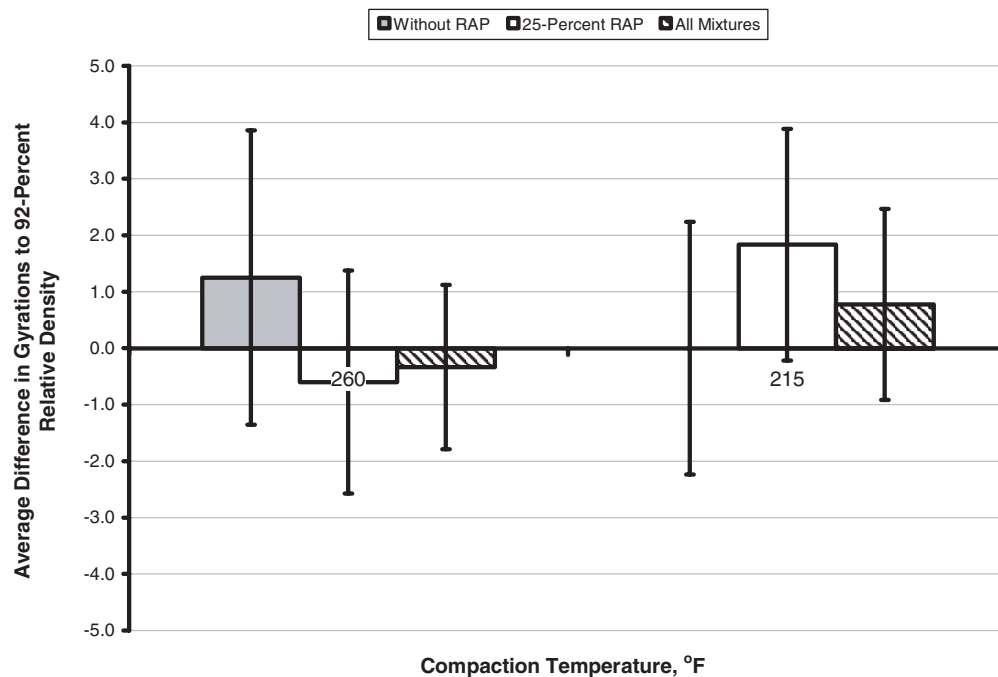
The revised preliminary procedure uses the gyratory compactor to evaluate the compactability of the mixture by measuring the number of gyrations required to reach 92-percent relative density at the planned field compaction temperature and again at 54°F (30°C) below the planned field compaction temperature. The paired difference statistical analysis presented in Section E7 of Appendix E found that the compactability of WMA mixtures (as measured by the increase in the gyrations to 92-percent relative density when the compaction temperature is decreased 54°F [30°C]) was sensitive to the process temperature, presence of RAP in the mixture, and the WMA process. Figure 22 shows the effects of temperature and RAP on the number of gyrations to reach 92-percent relative density at the planned field compaction temperature. Figure 22 shows that the compactability of the WMA at 260°F and 215°F (126°C and 102°C) was no different than that for HMA at 310°F (154°C) indicating that the WMA processes are effective even with 25-percent RAP added.

Figures 23 and 24 show the effects of temperature, WMA process, and RAP on the increase in the gyrations to reach 92-percent relative density when the compaction temperature is decreased 54°F (30°C). Figure 23 shows that the combination of low process temperature and RAP significantly decreases the compactability of WMA. The proposed limit in the revised preliminary mixture design procedure was 25 percent, and this was exceeded by the RAP mixtures at the lower compaction

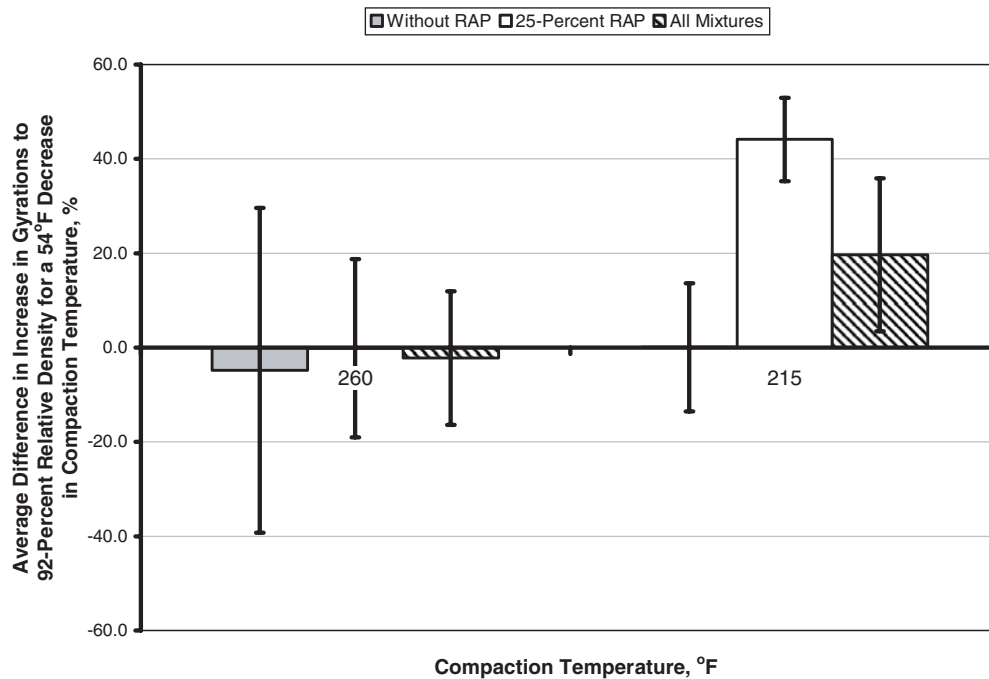
temperature of 215°F (102°C). Figure 24 shows that different WMA processes have different effects on compactability when the compaction temperature decreases. The Evotherm WMA with RAP was more sensitive to reductions in the compaction temperature compared to the other processes. It should be noted that because the Evotherm was blended in the binder at the terminal, the Evotherm concentration as a percentage of the total binder in the mixture was reduced for the RAP mixtures, and this may have affected the compactability of the Evotherm WMA with RAP mixtures.

### 3.3.1.3 Moisture Sensitivity

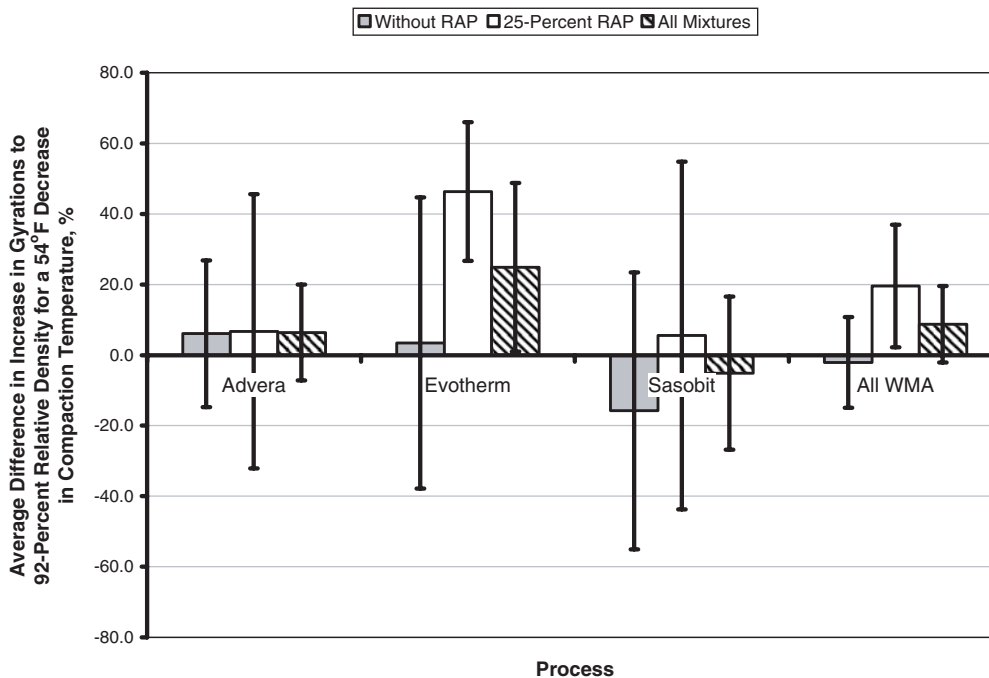
Moisture sensitivity is evaluated in both the revised preliminary WMA mixture design procedure and AASHTO R 35, Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA), using AASHTO T 283, Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage. The test is performed on samples that have been short-term conditioned for 2 h at the compaction temperature. The paired difference statistical analysis presented in Section E7 of Appendix E found the dry tensile strength, conditioned tensile strength, and tensile strength ratio to be significantly lower for WMA as compared to HMA. The analysis also found that the WMA process affected the tensile strength ratio. Figure 25 shows the effect of the WMA process on dry tensile strength. The dry tensile strengths of the WMA mixtures averaged 25 psi (172 kPa) less than the strength of the HMA



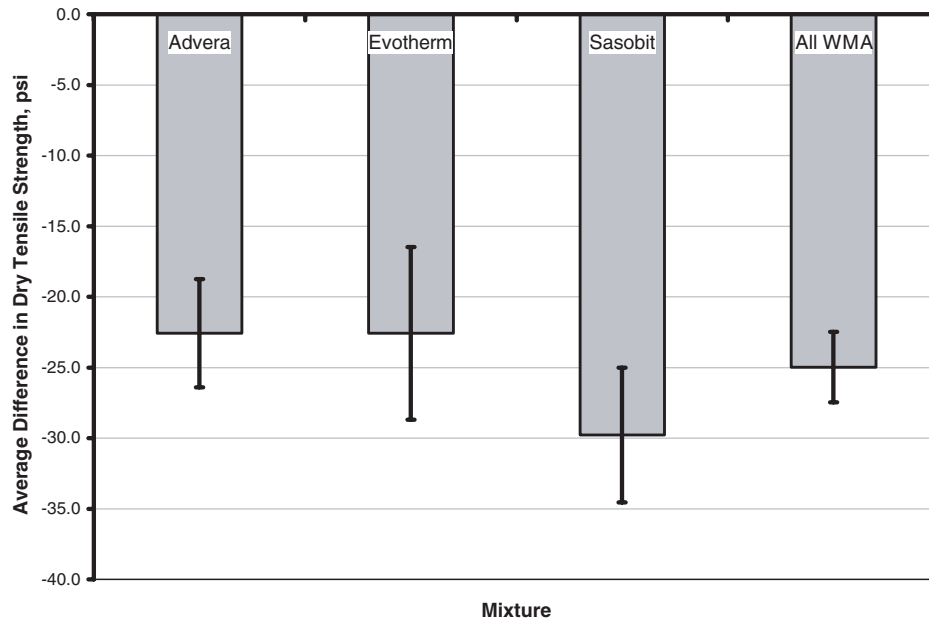
**Figure 22. Average difference in gyrations to 92-percent relative density at the compaction temperature (WMA-HMA) for the mix design study (error bars are ± 95-percent one-sided confidence intervals).**



**Figure 23.** Effect of temperature on the average difference in increase in gyrations to 92-percent relative density for a 54°F decrease in compaction temperature (WMA-HMA) for the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).



**Figure 24.** Effect of WMA process on the average difference in increase in gyrations to 92-percent relative density for a 54°F decrease in compaction temperature (WMA-HMA) for the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).



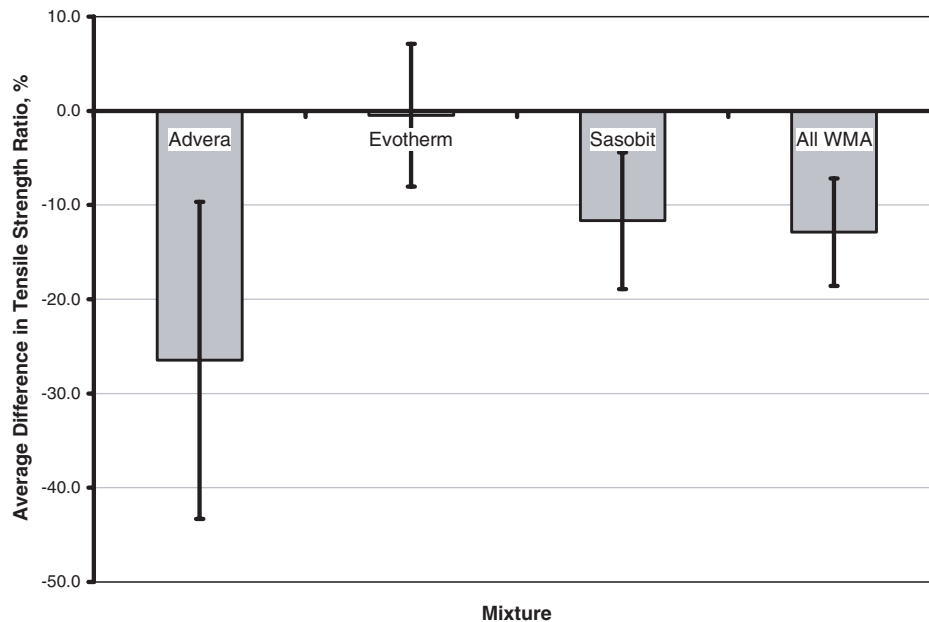
**Figure 25.** Effect of WMA process on the average difference in dry tensile strength at 25°C (WMA-HMA) for the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).

mixtures. This reduction was consistent for all WMA processes and similar for the 260°F and 215°F (127°C and 102°C) compaction temperatures.

Figure 26 shows the effect of the WMA process on the tensile strength ratio. There was no reduction in the tensile strength ratio for the Evotherm process, which uses an anti-strip addi-

tive, even though the tensile strength was reduced significantly due to the reduced aging of the WMA mixture.

Table 24 summarizes the tensile strength ratios for all of the mixtures included in the study. Most of the WMA mixtures had tensile strength ratios below the AASHTO M 323 minimum of 80 percent. Only mixtures produced with Evotherm



**Figure 26.** Effect of WMA process on the average difference in tensile strength ratio (WMA-HMA) for the mix design study (error bars are  $\pm$  95-percent one-sided confidence intervals).

**Table 24. Summary of tensile strength ratios.**

Mixture	Gyrations Level	Design Traffic MESAL	RAP	HMA		Advera		Evotherm		Sasobit	
				TSR, %	Compaction Temp., °F	TSR, %	Compaction Temp., °F	TSR, %	Compaction Temp., °F	TSR, %	Compaction Temp., °F
1	50	< 0.3	Yes	88.3	310	74.5	215	83.0	215	81.7	260
2	50	< 0.3	No	92.3	310	95.2	260	93.9	260	94.9	215
3	75	< 3	Yes	81.4	310	34.5	260	89.8	260	68.4	260
4	75	< 3	No	91.8	310	66.7	215	83.6	260	71.5	215
5	100	< 10	Yes	94.7	310	70.6	260	83.7	260	74.0	215
6	100	< 10	No	69.8	310	17.9	215	81.5	215	57.8	260

consistently had tensile strength ratios exceeding 80 percent. Mixture 2, made with Virginia limestone and having a very high binder content, was highly resistant to moisture damage with tensile strength ratios exceeding 92 percent for HMA and all WMA processes.

**3.3.1.4 Rutting Resistance**

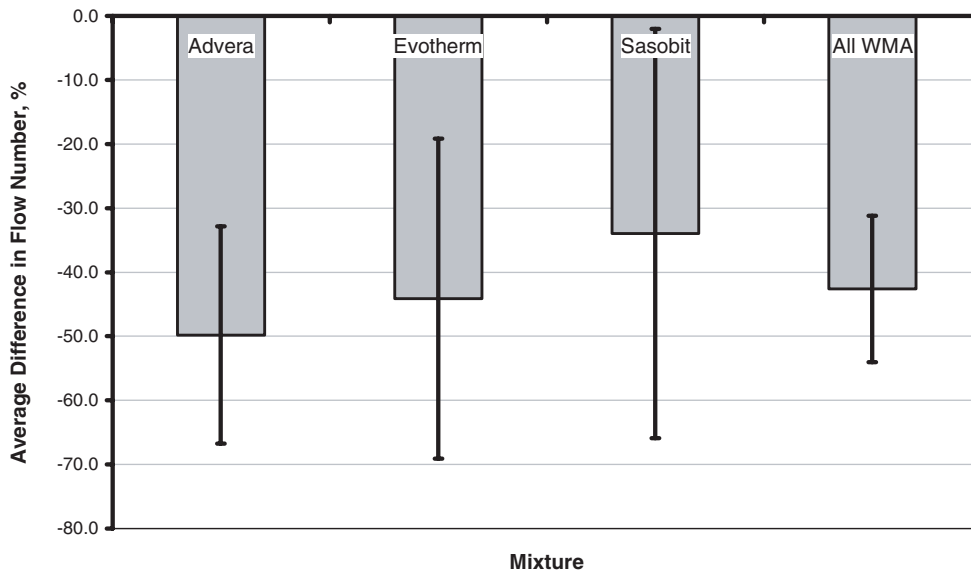
Rutting resistance in the revised preliminary mixture design procedure is evaluated using the flow number, AASHTO TP 79, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT). The flow number has also been proposed for evaluating the rutting resistance of HMA in NCHRP Project 09-33 (6). Because the flow number is significantly different for different gyrations levels, the paired difference statistical analysis used normalized differences defined by Equation 3. Normalized differences were used so that the mixtures with the higher flow numbers would not dominate the analysis.

$$ND = \left( \frac{Nf_{WMA} - Nf_{HMA}}{Nf_{HMA}} \right) * 100 \tag{3}$$

where

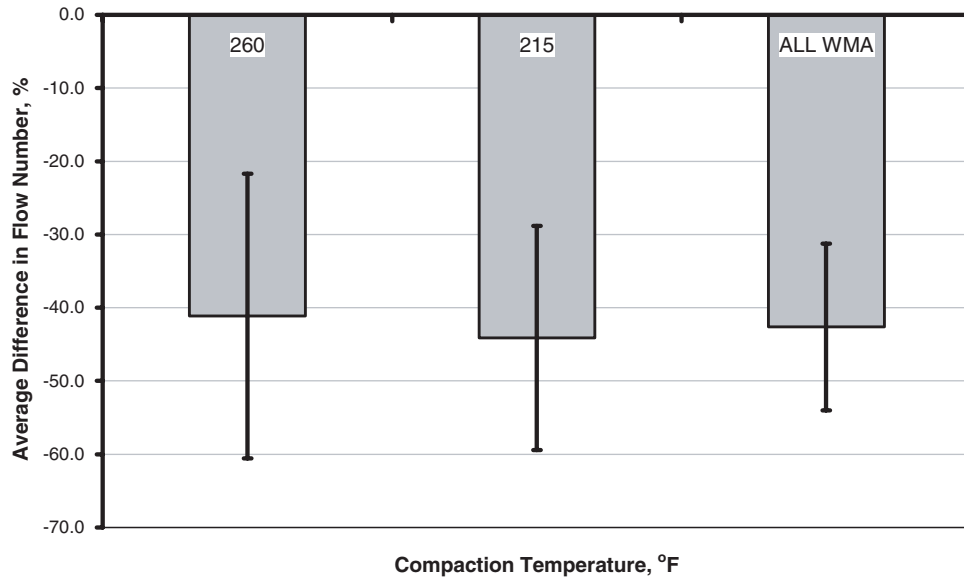
- ND* = normalized difference,
- Nf<sub>WMA</sub>* = flow number for the WMA mixture, and
- Nf<sub>HMA</sub>* = flow number for the HMA mixture.

The paired difference statistical analysis presented in Section E7 of Appendix E for the flow number showed the flow numbers to be significantly lower for the WMA in comparison to the HMA. Figure 27 shows the effect of WMA process on the flow number. The average difference was approximately 40 percent and it was similar for all WMA processes. It was also similar at both compaction temperatures, as shown in Figure 28. The rutting resistance was similar for all WMA processes and both temperatures because the high-temperature binder grade for the non-RAP Advera and Evotherm mixtures was increased one grade level for the 215°F (102°C) compaction temperature based on the findings from the Phase I



**Figure 27. Average normalized difference in flow number (WMA-HMA)/HMA for the mix design study (error bars are ± 95-percent one-sided confidence intervals).**





**Figure 28. Effect of compaction temperature on the average normalized difference in flow number (WMA-HMA)/HMA for the mix design study (error bars are ± 95-percent one-sided confidence intervals).**

binder grade study. Increasing the binder stiffness for these conditions increased the measured flow numbers, making the measured flow number difference smaller.

In NCHRP Project 09-33, the following relationship between the flow number and the allowable traffic to a rut depth of 0.5 in. (12.5 mm) was developed (6):

$$MESAL = \frac{F_n^{0.873}}{6.222} \tag{4}$$

where

MESAL = estimated traffic to 12 mm rutting, million equivalent single axle loads (MESAL); and

$F_n$  = flow number per NCHRP 09-33 test conditions, cycles.

Table 25 summarizes the allowable traffic from Equation 4 for all of the mixtures included in the study. Based on the HMA data, the rutting resistance of the two 50 gyration mixtures is significantly higher than required because both of these mixtures

used aggregates that far exceeded the angularity requirements in AASHTO M 323 for this traffic level. The rutting resistance of the HMA design for Mixture 4 is slightly less than the design traffic level, while the rutting resistance for Mixture 6 is only one-half of the design traffic level. The rutting resistance of the mixtures with RAP is significantly higher than the rutting resistance of the mixtures without RAP. Analysis of the data in Table 25 suggests that it will be difficult for WMA mixtures designed for 10 MESAL or greater to meet the flow number rutting resistance criteria developed in NCHRP Project 09-33.

### 3.3.2 Field Validation Study

The field validation study addressed several parts of the revised preliminary mixture design procedure including (1) binder grade selection, (2) RAP, (3) short-term oven conditioning, (4) specimen fabrication, (5) coating and compactability, (6) moisture sensitivity, and (7) rutting resistance. Specific findings for each of these parts are presented and

**Table 25. Summary of NCHRP 09-33 rutting resistance from flow number testing.**

Mixture	Gyration Level	Design Traffic MESAL	RAP	HMA		Advera		Evotherm		Sasobit	
				MESAL	Compaction Temp., °F	MESAL	Compaction Temp., °F	MESAL	Compaction Temp., °F	MESAL	Compaction Temp., °F
1	50	< 0.3	Yes	6.1	310	2.4	215	2.0	215	3.5	260
2	50	< 0.3	No	2.2	310	1.0	260	1.8	260	1.6	215
3	75	< 3	Yes	13.5	310	4.7	260	5.9	260	9.5	260
4	75	< 3	No	2.8	310	2.6	215	2.2	260	1.6	215
5	100	< 10	Yes	12.3	310	3.5	260	5.0	260	4.1	215
6	100	< 10	No	4.9	310	3.9	215	3.9	215	5.9	260

**Table 26. Summary of continuous grading of recovered binders.**

Project	Process	Production Temperature (°F)	Continuous Grade Temperature (°C)		
			High	Intermediate	Low
Colorado I-70	Specified	NA	58.0	19.0	-28.0
	Control	280	59.3	14.2	-30.6
	Advera	250	60.0	13.7	-31.6
	Evotherm	250	61.3	14.1	-31.1
	Sasobit	250	63.9	15.1	-29.9
Yellowstone National Park	Specified	NA	58.0	16.0	-34.0
	Control	325	60.0	11.1	-34.1
	Advera	275	56.3	8.9	-36.2
	Sasobit	275	60.7	10.1	-35.6
New York Route 11	Specified	NA	64.0	22.0	-28.0
	LEA	210	60.5	14.0	-31.1
Pennsylvania SR2007	Specified	NA	64.0	25.0	-22.0
	Control	320	67.7	22.0	-24.6
	Evotherm	250	67.2	22.0	-24.9
Pennsylvania SR2006	Specified	NA	64.0	25.0	-22.0
	Control	310	66.6	24.1	-22.5
	Advera	250	67.0	22.9	-24.1
	Gencor	250	67.5	21.7	-25.7
	LEA	210	63.2	21.6	-25.4
	Sasobit	250	72.9	23.3	-22.5
Monroe, North Carolina	Specified	NA	70.0	28.0	-22.0
	Astec	275	71.5	23.7	-23.9

discussed below. Details of the analysis leading to these findings are presented in Section E8 of Appendix E.

**3.3.2.1 Binder Grade Selection**

Recovered binder grading and estimates of rutting using dynamic modulus test data from plant mixtures and the MEPDG rutting model were used to validate the high-temperature grade bumping table developed from the RTFOT experiment (1). Table 26 summarizes the continuous grades for the recovered binders from each of the validation mixtures. Table 26 includes the specified binder grade as well as the recovered grade. In all cases, the low and intermediate temperature properties for the WMA processes comply with the binder grade specified for the project. There are three cases where the high-temperature grade was lower than specified:

Advera for the Yellowstone National Park project was 1.7°C lower, LEA for the NY Route 11 project was 3.5°C lower, and LEA for the Pennsylvania SR2006 project was 0.8°C lower.

Table 27 summarizes the average difference in continuous grade temperatures for WMA as compared to HMA. The high-temperature grade changes are significantly less than estimated from the RTFOT experiment. From the RTFOT experiment, the estimated reduction in high-temperature grade for 50°F and 100°F (28°C and 56°C) reductions in production temperature for a typical asphalt binder having an aging index of 2.4 are 2.8°C and 5.6°C, respectively. For the field data—excluding Sasobit, which increases the high-temperature grade of the binder—an approximately 50°F (28°C) reduction in production temperature resulted in less than a 1°C decrease in high-temperature grade, while an approximately 100°F (56°C) reduction in production temperature resulted in approximately

**Table 27. Summary of average difference in continuous grade temperatures for WMA compared to HMA.**

Process	Number	Average Difference in Production Temperature (°F)	Average Difference in Continuous Grade Temperature (°C)		
			High	Intermediate	Low
Advera	3	-46.7	-0.9	-1.3	-1.6
Evotherm	2	-50.0	0.8	0.0	-0.4
LEA	1	-100.0	-3.4	-2.5	-2.9
Plant Foaming	1	-60.0	0.9	-2.4	-3.2
Sasobit	3	-46.7	3.9	-0.3	-0.3

a one-half grade decrease in the high-temperature grade for one LEA project. The low-temperature grade changes, on the other hand, are greater than estimated from the RTFOT experiment. From the RTFOT experiment, the estimated improvement in the low-temperature grade for 50°F and 100°F (28°C and 56°C) reductions in production temperature are 0.5°C and 1.0°C, respectively. For the field data—excluding Sasobit, which increases the low-temperature grade of the binder—an approximately 50°F (28°C) reduction in production temperature resulted in an average improvement in the low-temperature grade of the binder of 1.5°C, while an approximately 100°F (56°C) reduction in production temperature resulted in a 2.9°C improvement in the low-temperature grade for one LEA project. Based on the recovered binder testing, it does not appear that the binder grade should be changed when using WMA as long as the production temperature is not decreased by more than 100°F (56°C).

Rutting for the Colorado I-70, Yellowstone National Park, and New York Route 11 projects was predicted using the Excel spreadsheet, *E\*Rutting.xls*, developed by Arizona State University for the dynamic modulus simple performance test (22). This spreadsheet rapidly performs asphalt layer rutting predictions using the calibrated rutting model contained in the MEPDG (1). The mixture dynamic modulus master curve is the required material property for this analysis. Master curves were developed for plant mixtures in accordance with AASHTO PP 61. The rutting estimates for these three projects are shown in Figures 29, 30, and 31. These figures show the following:

1. The predicted rut depths for the control mixtures are reasonable for the design traffic levels. The design traffic level of the Colorado project was 10 million equivalent single axle loads (MESAL), and the estimated rut depth is 0.11 in. (2.8 mm). The design traffic level of the Yellowstone National Park and New York projects was 3 MESAL, and the estimated rut depth was 0.09 in. (2.3 mm) in both cases.
2. For the Colorado I-70 project, the predicted rutting for the Advera and Evotherm mixtures was slightly greater than the control while the predicted rutting for the Sasobit mixture was slightly less than the control. The predicted rutting for the Advera and Evotherm mixtures was only 0.13 in. (3.3 mm).
3. For the Yellowstone National Park project, the predicted rutting of the Sasobit and Advera mixtures was essentially the same as the control at the design traffic level.
4. For the New York project, the predicted rutting for the PG 64-28 LEA mixture was 0.11 in (2.8 mm), while the predicted rutting for the PG 70-22 LEA mixture is 0.05 in. (1.3 mm).

The differences in estimated rutting resistance from field-mixed WMA do not support the binder grade bumping recommendations developed from the RTFOT experiment. For production temperature decreases as large as 100°F (56°C), the estimated rutting for a mixture produced as WMA is only approximately 25 percent greater than that for the same mixture produced as HMA.

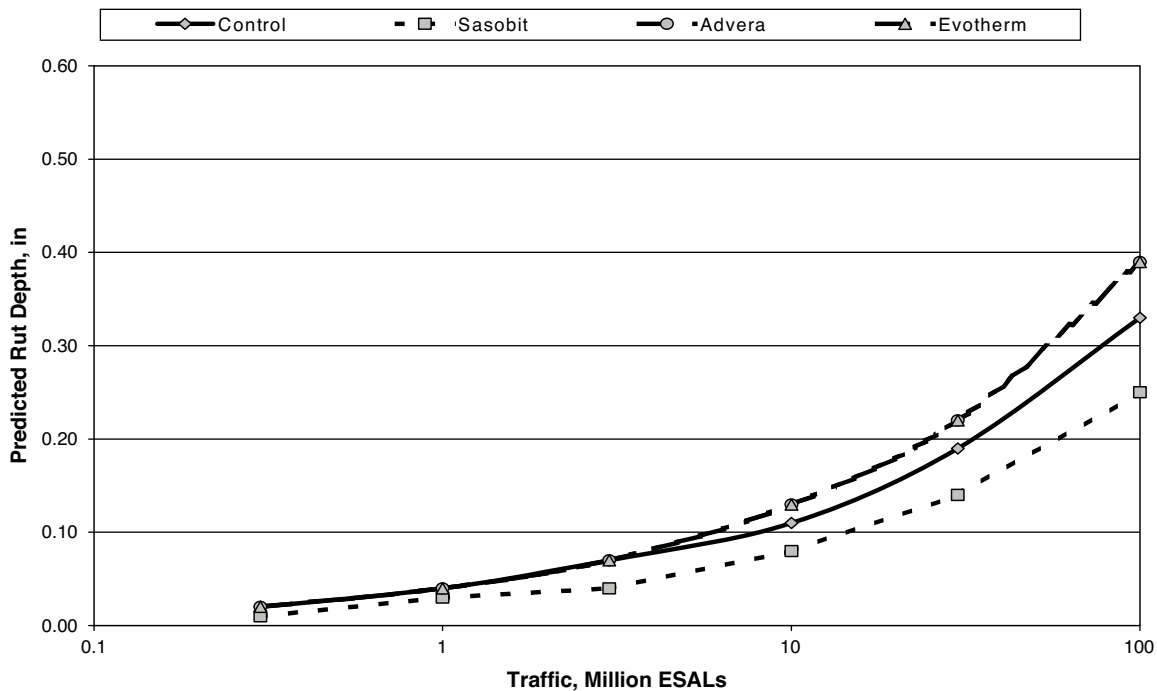


Figure 29. Predicted rutting for the Colorado I-70 project.

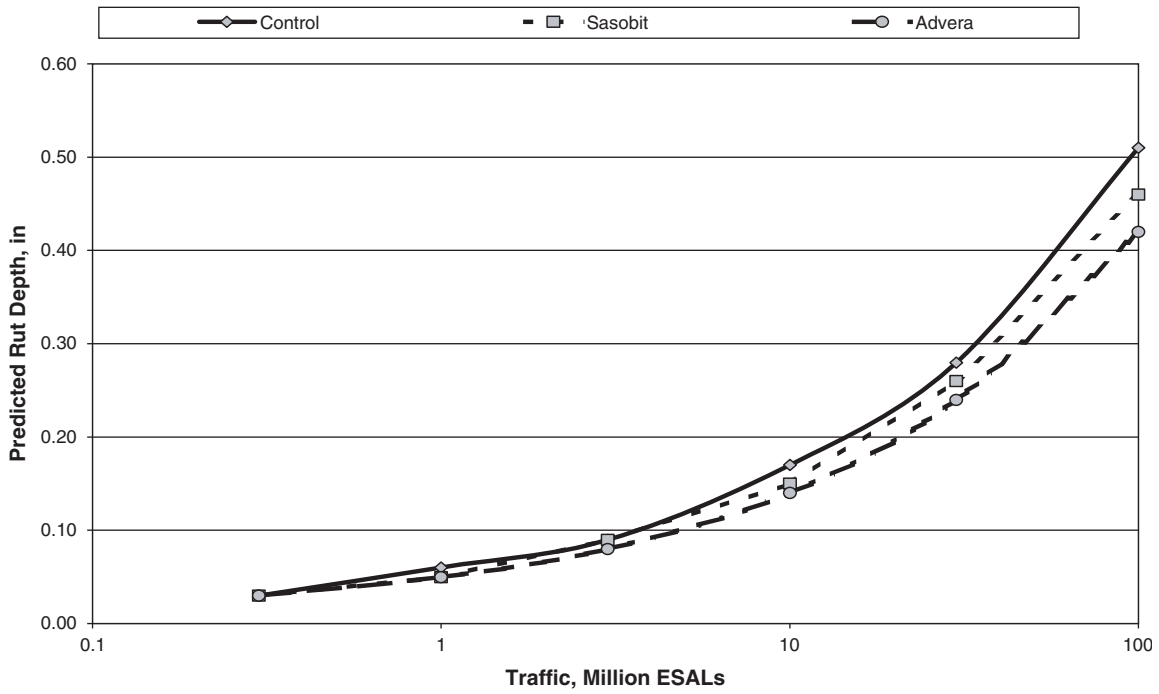


Figure 30. Predicted rutting for the Yellowstone National Park project.

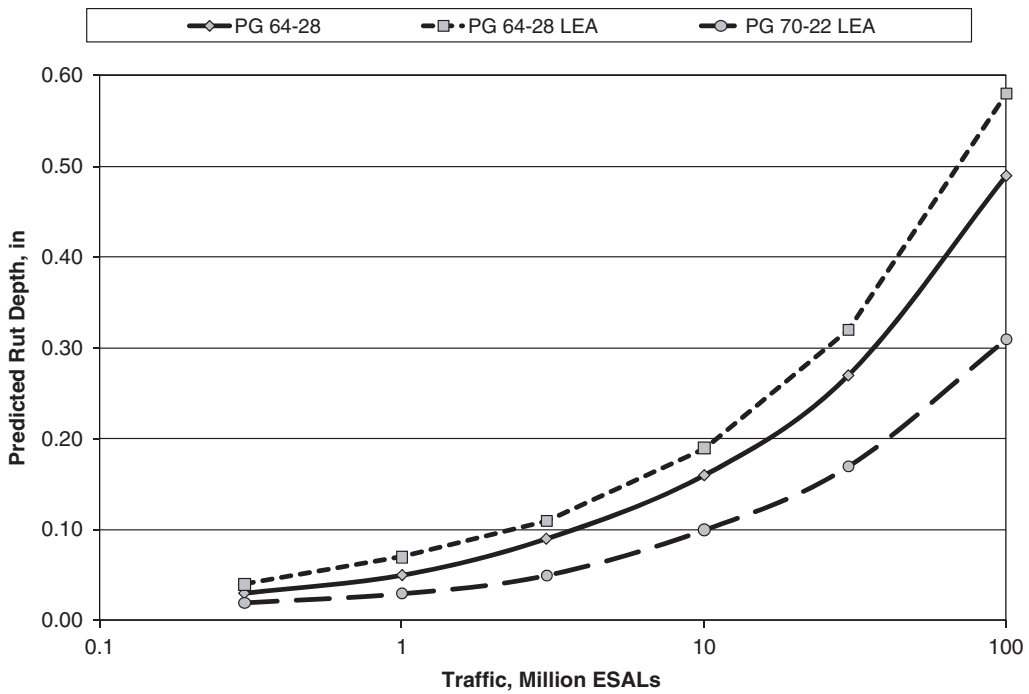


Figure 31. Predicted rutting for the New York project.

**Table 28. Measured and estimated fully blended dynamic modulus for the Monroe, North Carolina, mixture produced with the Astec Double Barrel Green process and 30-percent RAP.**

Temperature (°F)	Frequency (Hz)	Recovered Binder G* (psi)	Hirsch Estimated E* (ksi)	Measured E* (ksi)	Ratio of Measured to Estimated
39.2	10.0	15,681	2,145	2,344	1.09
39.2	1.0	7,339	1,755	1,785	1.02
39.2	0.1	2,839	1,281	1,216	0.95
68.0	10.0	2,014	1,123	1,083	0.96
68.0	1.0	596	663	626	0.94
68.0	0.1	145	328	316	0.96
104.0	10.0	100	270	201	0.74
104.0	1.0	19	114	80	0.70
104.0	0.1	3	51	38	0.74

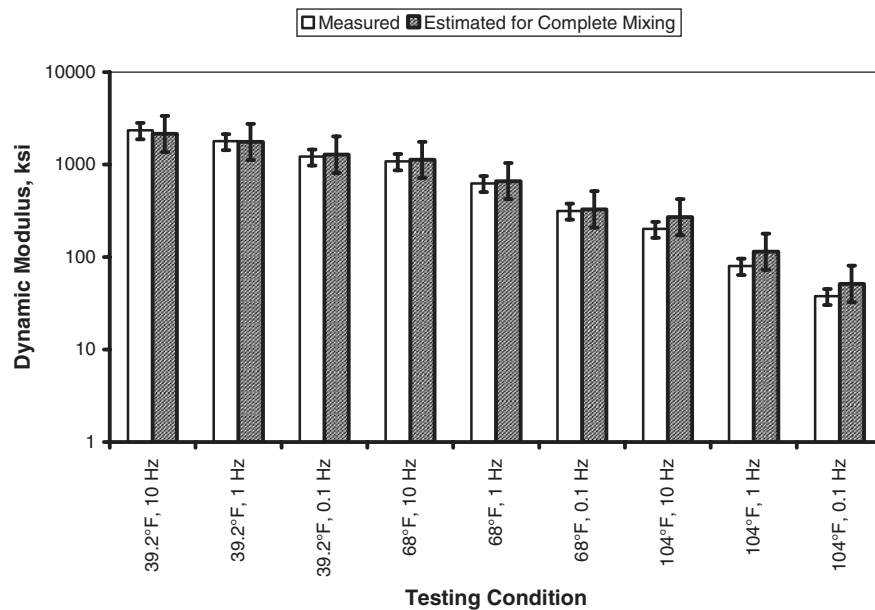
### 3.3.2.2 RAP

Only one of the validation mixtures—the Monroe, North Carolina, mixture—included RAP. This mixture used PG 64-22 binder with 30-percent RAP to produce a mixture meeting the requirements for PG 70-22 binder. The mixture was produced at 275°F using the Astec Double Barrel Green process. For this mixture, the mixing analysis—based on dynamic modulus testing of the plant mixture described earlier in the laboratory RAP study (see Section 3.1.4)—was conducted to validate that RAP and new binder mix in field-produced WMA. The results of this analysis are summarized in Table 28 and shown in Figure 32. The error bars in Figure 32 are 95-percent confidence intervals for the measured data and 95-percent prediction intervals for the Hirsch model predictions. Since

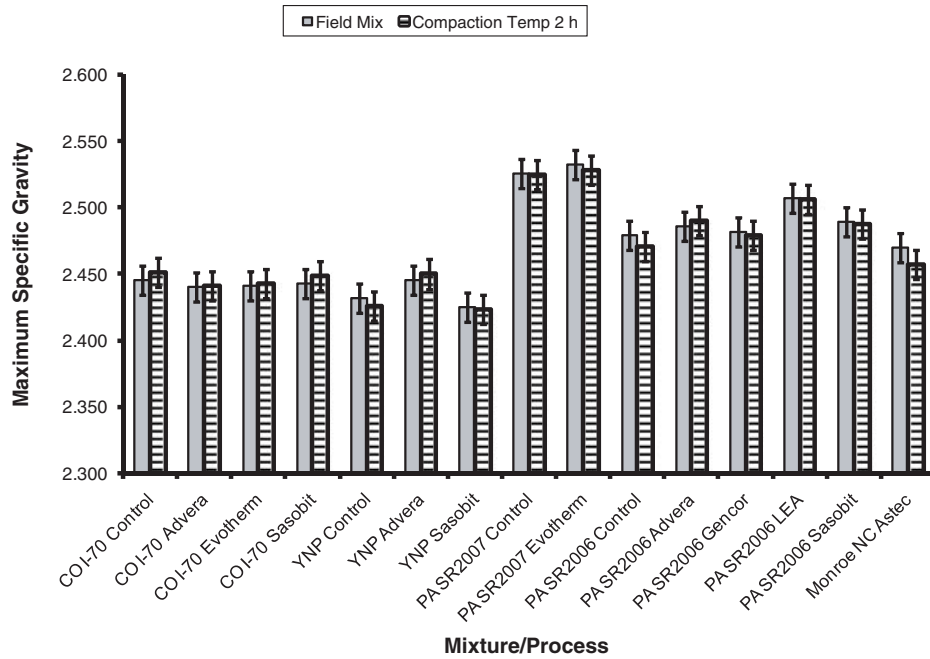
the averages of the measured data fall within the prediction intervals for the Hirsch model, the plant-mixed modulus is not significantly different from the fully blended modulus, indicating that the mixing of the RAP and new binders is acceptable.

### 3.3.2.3 Short-Term Oven Conditioning

For WMA and HMA, short-term oven conditioning of 2 h at the compaction temperature was determined by comparing properties of field-mixed, laboratory-compacted specimens with properties of laboratory-mixed, laboratory-compacted specimens for the mixtures from the Colorado I-70 project. The properties that were compared were maximum specific



**Figure 32. Comparison of measured and estimated fully blended dynamic modulus for the Monroe, North Carolina, mixture produced with the Astec Double Barrel Green process and 30-percent RAP.**



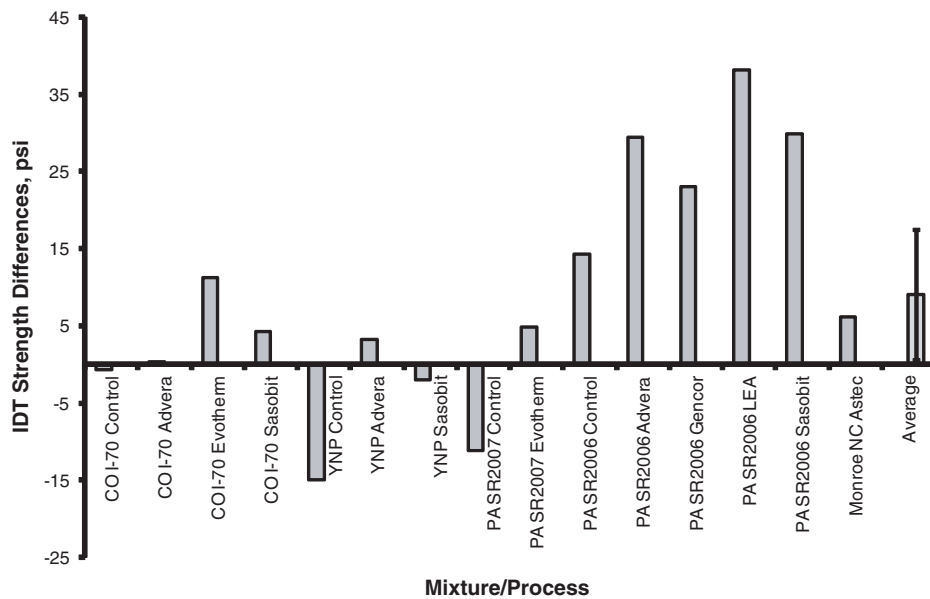
**Figure 33. Comparison of maximum specific gravity for all validation mixtures.**

gravity, indirect tensile strength, and dynamic modulus. To validate this short-term conditioning, maximum specific gravity and indirect tensile strength measurements were made on all of the validation sections.

Figures 33 and 34 compare the maximum specific gravity and tensile strength data for all of the validation mixtures. The error bars shown in Figure 33 are the single operator d2s precision from AASHTO T 209. These data show that the maxi-

imum specific gravity of the laboratory and field mixtures is the same, indicating that the binder absorption is the same for the laboratory and field mixtures. The aggregate water absorption ranged from 0.5 percent for the Pennsylvania SR2007 mixtures to 2.5 percent for the Yellowstone National Park mixtures.

Figure 34 shows differences in indirect tensile strength for the field mixtures minus the laboratory mixtures. The error bars for the average difference in this figure are 95-percent con-



**Figure 34. Differences in indirect tensile strength between field mixes and laboratory mixes short-term conditioned for 2 h at the compaction temperature.**

fidence intervals for a paired *t*-test comparison. Since the error bars for the average difference do not capture zero, the tensile strength of the field-mixed specimens is statistically higher than the tensile strength of the laboratory-mixed specimens. This indicates that short-term conditioning of 2 h at the compaction temperature provides less aging on average than the field mixtures. The findings from this analysis appear to have been biased by the data from the Pennsylvania SR2006 project. This project provided one-third of the data for the analysis, and the field mixtures for this project had consistently higher tensile strength than the laboratory-prepared mixtures. The average difference for all projects was 9 psi (48 kPa); not considering the Pennsylvania SR2006 project, the average difference was only 1.4 psi (9.8 kPa). Considering the bias from this project, the recommended short-term oven conditioning in the final WMA mixture design procedure was kept at 2 h at the compaction temperature.

### 3.3.2.4 Specimen Fabrication

In the validation study, the WMA specimen-fabrication procedures were used to fabricate specimens for several WMA processes including Advera, Astec Double Barrel Green, Evotherm DAT, Gencor Ultrafoam, LEA, and Sasobit. Figure 35 shows the difference in air voids at  $N_{design}$  between the WMA mixture and either the HMA job mix formula or the corresponding HMA control mixture. The average difference over all projects is less than 0.03 percent. The error bars shown for the average are 95-percent confidence levels. Since the error

bars capture zero, this indicates that the WMA mixtures are very similar to the HMA that they were based on. These findings confirm the findings of the mixture design study that the volumetric properties of properly designed WMA and HMA mixtures are very similar.

The WMA mixture design procedure uses process-specific, specimen-fabrication procedures to simulate the WMA process. For plant foaming systems this requires the production of foamed asphalt in the laboratory. At the time NCHRP Project 09-43 was completed, the Wirtgen WLB-10 laboratory foaming machine was the only commercially available laboratory foaming equipment. An evaluation of the feasibility and practicality of designing foamed asphalt WMA mixtures in the laboratory using the Wirtgen WLB-10 was conducted at the University of Wisconsin-Madison. The evaluation was conducted for the Gencor WMA process from the Pennsylvania SR2006 project and for the Astec WMA process from the Monroe, North Carolina, project. The following describes the process used to fabricate foamed asphalt using this equipment.

Operation of the Wirtgen WLB-10 foaming machine requires asphalt binder temperatures above 320°F (160°C), thus the mixing temperature of the foamed asphalt mixture is controlled by the temperature of the aggregates. It is assumed that the asphalt binder will quickly revert to the mixing temperature when it comes in contact with the aggregate. The mass of foamed asphalt that is required is calculated based on the weight of the aggregates. The aggregate and mixing bucket are placed under the foaming head, and the foamed asphalt is shot into the bucket as shown in Figure 36. The flow of foamed

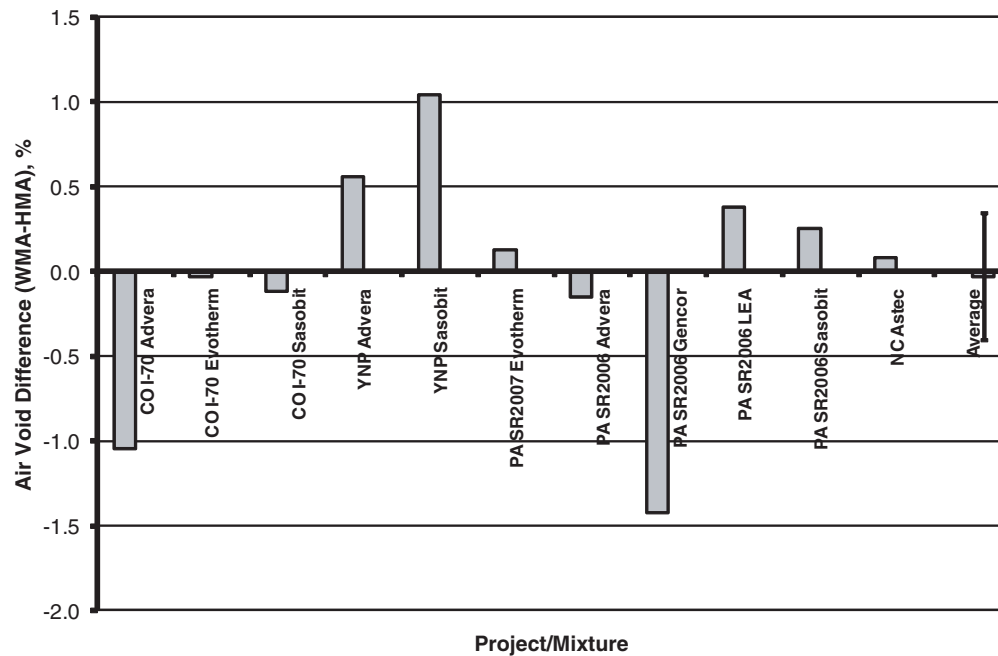


Figure 35. Differences in air voids at  $N_{design}$  between WMA and corresponding HMA mixtures.



**Figure 36.** Introducing foamed asphalt to mixing bucket.

asphalt into the mixing bucket is metered using a flow controller. Based on a known flow rate, the user prescribes the time required to obtain the appropriate quantity of asphalt binder.

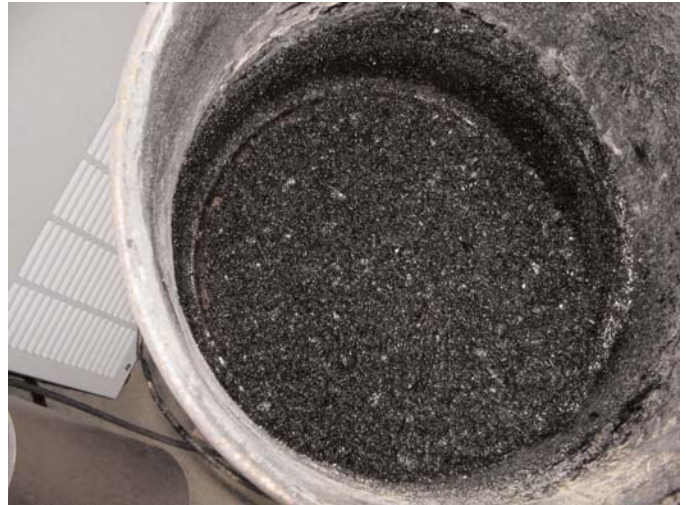
The mixing bucket, with the foamed asphalt sitting on top of the aggregate, is immediately transferred to the laboratory mixer, mixed for 90 s, and transferred to a shallow pan. Illustrations of the foamed asphalt mixture before and after the 90 s mixing time are provided in Figures 37 and 38, respectively. After mixing, the foamed mix is short-term aged at the compaction temperature for 2 h and compacted.

The operation of the foaming machine presents some practical concerns for WMA laboratory mixture design.

- The machine is intended for preparation of samples of foam-stabilized asphalt base course and cold in-place recycling. These applications require foamed asphalt with water contents above 10 percent by weight of the asphalt binder. In contrast, the water content for WMA applications ranges



**Figure 37.** Foamed asphalt before mixing.



**Figure 38.** Foamed asphalt mixture after 90 s mixing time.

from 1.0 to 3.0 percent. To accommodate this difference, the existing flow controller was replaced with one that was smaller and more precise. Operation of the machine for WMA applications was possible; however, due to the low percentage of water required for WMA, the operation of the flow controller was approaching its minimum control tolerance. The more precise flow controller was selected with the intent of delivering a more consistent foam at the water content used in the WMA field production.

- The machine is designed to produce large quantities of material. This was an issue especially in trying to prepare samples for evaluation of the maximum specific gravity. The sample size to conduct the maximum specific gravity test for 9.5-mm mixtures is 1,000 g. A timer is used to control the amount of foamed asphalt shot into the bucket. Because of the flow rate of the foaming head, the machine provides the required 50 to 60 g of foamed asphalt in a fraction of a second. This amount of time is insufficient for the machine to produce a consistent asphalt foam, introducing potential reproducibility issues into the results. Use of this machine for small batches of aggregate is not recommended; instead, large batch sizes should be produced and then split for the various tests required.
- At times the air line in the machine becomes clogged, so instead of foamed asphalt, an asphalt/water mix is produced. This problem has been encountered with both the neat PG 64-22 binders from the Pennsylvania and North Carolina projects and Styrene-Butadiene-Styrene (SBS) modified PG 76-22 binder used in another project. The valve that controls the flow of the air at the foaming head becomes clogged regularly, requiring disassembly and cleaning of the head. This issue occurred on three separate occasions while preparing samples for this project, each time resulting in a



delay of 2 to 3 h. The regularity with which this problem occurs suggests that redesign of the foaming head of the machine may be needed for continuous use as a mix design tool. The problem was more severe with the SBS modified binder. After production of approximately 20 samples, the machine clogged and had to be taken apart and fully cleaned before further use.

- Finally, the preparation of the foamed mixes requires a significant amount of technician time and expertise. Each mix design evaluated for this project required three separate days for foamed mix production.

### 3.3.2.5 Coating and Compactability

As required by the revised preliminary WMA mixture design procedure, coating and compactability were measured on all of the WMA mixtures in the field validation study. Coating was evaluated using AASHTO T 194, which counts the number of fully coated coarse aggregate particles in the mixture. Compactability was evaluated on the basis of the number of gyrations necessary to achieve 92-percent relative density at the planned field compaction temperature and again at 54°F (30°C) below the planned field compaction temperature. Table 29 summarizes the results of the evaluation of coating and compactability.

Coating was 100 percent for all of the mixtures that were mixed using a planetary mixer with a wire whip. The percentage of coating was lower for the two mixtures mixed with a bucket mixer and particularly low for the North Carolina mixture, which had about 16 percent of its total binder content contributed by the RAP. All of the mixtures were prepared using 90 s of mixing. Apparently, the bucket mixer is less efficient and requires longer mixing times for equivalent coating. There were no reported coating issues for any of the field mixtures.

The compactability data in Table 29 indicate that the Colorado I-70, Pennsylvania SR2007, and Monroe, North Carolina, mixtures were easy to compact. National Center for Asphalt Technology (NCAT) reported average gyrations to 92-percent relative density of 35 and 20 percent of  $N_{design}$  for dense graded HMA mixtures with coarse and fine gradations (21). At the compaction temperature, the gyrations to 92-percent relative density for these three projects ranged from 20 to 40 percent of  $N_{design}$ . For the other two projects, Yellowstone National Park and Pennsylvania SR2006, the mixtures were less compactable. The Yellowstone National Park mixtures were designed using the Hveem method and therefore had much lower binder content than they would have if they had been designed using AASHTO R 35 or the revised preliminary WMA mixture design procedure. The air void content at 75 gyrations for the HMA control mixture for this project was 6.8 percent. The Pennsylvania SR2006 control HMA mixture could not be verified by the research team. At the optimum binder content from the approved mix design, the air void content at 75 gyrations was 6.2 percent, well above the design value of 4.0 percent.

The effect of temperature on the compactability of the mixtures is quantified by the percent increase in the number of gyrations to 92-percent relative density. The revised preliminary WMA mixture design procedure limits this increase to 25 percent. All of the WMA mixtures included in the field validation study met this criterion. There were no reported workability issues for any of the field mixtures.

### 3.3.2.6 Moisture Sensitivity

Moisture sensitivity was evaluated for all of the validation mixtures using AASHTO T 283. Specimens were compacted to a target air void content of 7.0 percent ± 0.5 percent using

**Table 29. Coating and compactability of field validation mixtures.**

Project	Process	Temperature, °F		Coating	Gyrations to 92% of $G_{mm}$		
		Mix	Compact		At Compact Temp	At Compact Temp -54°F	Gyrations Increase, %
Colorado I-70	Advera	250	230	100 <sup>1</sup>	15	18	20
	Evotherm DAT	250	230	100 <sup>1</sup>	20	23	15
	Sasobit	250	230	100 <sup>1</sup>	19	22	16
Yellowstone National Park	Advera	275	250	100 <sup>1</sup>	69	—	—
	Sasobit	275	245	100 <sup>1</sup>	> 75	—	—
PA SR2007	Evotherm DAT	250	230	100 <sup>1</sup>	20	24	20
PA SR2006 and PA SR2012	Advera	250	230	100 <sup>1</sup>	47	48	2
	Gencor Ultrafoam GX	250	230	81 <sup>2</sup>	35	38	9
	LEA	210	195	100 <sup>1</sup>	50	52	4
	Sasobit	250	230	100 <sup>1</sup>	51	59	16
Monroe, North Carolina	Astec Double Barrel Green	275	260	65 <sup>2</sup>	16	16	0

<sup>1</sup> Mixed with Blakeslee planetary mixer with wire whip.

<sup>2</sup> Mixed with bucket mixer.

**Table 30. Summary of AASHTO T 283 results.**

Project	Process	Production Temperature (°F)	Compaction Temperature (°F)	Dry Tensile Strength (psi)	Conditioned Tensile Strength (psi)	Tensile Strength Ratio (%)
Colorado I-70	Control	280	260	88.3	80.4	91
	Advera	250	230	80.3	0.0	0
	Evotherm	250	230	71.9	32.4	45
	Sasobit	250	230	82.8	58.8	71
Yellowstone National Park	Control	325	315	110.2	87.1	79
	Advera	275	250	86.4	65.7	76
	Sasobit	275	245	95.4	72.5	76
Pennsylvania SR2007	Control	320	300	102.3	92.1	90
	Evotherm	250	230	86.0	79.1	92
Pennsylvania SR2006	Control	310	275	104.6	65.6	63
	Advera	250	230	98.3	34.8	35
	Gencor	250	230	97.3	42.1	43
	LEA	210	195	103.7	86.1	83
	Sasobit	250	230	97.1	51.8	53
Monroe, North Carolina	Astec	275	260	164.0	127.7	78

the binder content from the job mix formula or the binder content determined from the mix design verification. Per the preliminary WMA mixture design procedure the mixture was conditioned 2 h at the compaction temperature. Table 30 summarizes the results.

Nine of the 11 WMA mixtures and 2 of the 4 HMA control mixtures have tensile strength ratios less than 80 percent. The effect of the WMA process on moisture sensitivity is mixture and process specific. For the Colorado I-70 project, the tensile strength ratio was reduced by all of the WMA processes. For this project, the Advera specimens failed during the conditioning processes. The WMA processes had no effect on the tensile strength ratio for the Yellowstone National Park and Pennsylvania SR2007 projects. For the Pennsylvania SR2006 project, the Advera, Gencor, and Sasobit WMA processes reduced the tensile strength ratio, while the LEA process increased it. The LEA process includes an anti-strip that is added to the binder at the plant. For the plant foaming processes, the AASHTO T 283 results may have been adversely affected by the poorer coating obtained with the bucket mixer when simulating these processes.

### 3.3.2.7 Rutting Resistance

Rutting resistance was evaluated for all of the field validation mixtures using the flow number test, AASHTO TP 79. Specimens were compacted to a target air void content of 7.0 percent  $\pm$  0.5 percent using the job mix formula binder content or the binder content determined from the mix design verification. All of the specimens were within this tolerance except for the Gencor mixture for the Pennsylvania SR2006 project, which was compacted to 4.5 percent. Per the preliminary WMA mixture design procedure, the mixture was conditioned

2 h at the compaction temperature. The flow number test was conducted at the 50-percent reliability high pavement temperature from LTPPBind 3.1 for the project location. As recommended in NCHRP 09-33, the flow number testing used unconfined specimens with repeated deviator stress of 87 psi (600 kPa) and contact deviator stress of 4.4 psi (30 kPa). Table 31 summarizes the results.

The allowable traffic in Table 31 was calculated using the relationship between flow number and allowable traffic to an estimated rut depth of 0.5 in. (12.5 mm) developed in NCHRP Project 09-33 (see Equation 4) and discussed earlier in the mixture design study (see Section 3.3.1.4). Three of the mixtures do not meet the rutting resistance criteria: the Advera and LEA mixtures for the Pennsylvania SR2006 project and the Monroe, North Carolina, mixture. The North Carolina mixture has a very high design VMA of 17.6 percent, indicating that the rutting resistance of this mixture could be improved by decreasing the design VMA. In NCHRP Project 09-33, a maximum VMA of 17 percent has been recommended for 9.5-mm mixtures to limit the effective binder content of the mixture and provide adequate rutting resistance. The rutting resistance of the Hveem designed mixtures from the Yellowstone project is very high. Also, the rutting resistance of the 50-gyraton mixtures from the Pennsylvania SR2007 project is high considering the design traffic level. These mixtures were produced with highly angular manufactured sand and crushed stone.

Table 32 compares the rutting resistance of the WMA mixtures to that of the HMA control mixtures. The Gencor mixture from the Pennsylvania SR2006 project was not included in this analysis because the air void content of the specimens for this mixture was much lower than the air void content of all of the others. The rutting resistance for all WMA processes except Sasobit is less than the HMA control due to the lower

**Table 31. Summary of flow number and rutting resistance results.**

Project	Design Traffic Level (MESAL)	Process	Production Temperature (°F)	Compaction Temperature (°F)	Test Temperature (°F)	Flow Number	NCHRP 09-33 Allowable Traffic (MESAL)
Colorado I-70	< 10	Control	280	260	101	321	24.8
		Advera	250	230		165	13.9
		Evotherm	250	230		154	13.0
		Sasobit	250	230		409	30.7
Yellowstone National Park	< 3 (estimated)	Control	325	315	106	687	48.2
		Advera	275	250		459	33.9
		Sasobit	275	245		1089	72.2
Pennsylvania SR2007	< 0.3	Control	320	300	126	124	10.8
		Evotherm	250	230		93	8.4
Pennsylvania SR2006	< 3	Control	310	275	121	42	4.2
		Advera	250	230		27	2.8
		Gencor	250	230		104 <sup>1</sup>	9.3 <sup>1</sup>
		LEA	210	195		21	2.3
		Sasobit	250	230		54	5.2
Monroe, North Carolina	< 10	Astec	275	260	136	38	3.9

<sup>1</sup> Specimens compacted to 4.5-percent air voids instead of 7.0 percent.

short-term conditioning temperatures. The rutting resistance decreases approximately 6 percent for every 10°F (5.5°C) reduction in compaction temperature. Sasobit increases the high-temperature stiffness of the binder, resulting in improved rutting resistance.

### 3.3.3 Feasibility of Using a Two-Step Aging Process for Performance Testing

Criteria for evaluating rutting resistance using the flow number and other tests are generally based on mixtures that have been laboratory conditioned for 4 h at 275°F (135°C) in accordance with AASHTO R 30. Although it is generally accepted that this conditioning represents the binder stiffening that occurs during construction, it appears from the short-term conditioning study that this level of conditioning is more representative of the stiffness of the binder after some short period in service. The findings from the mix design study and the field validation study show that the rutting resistance of WMA mixtures that are conditioned 2 h at the compaction

temperature, which represents the stiffness of WMA mixtures at the time of construction, generally fail criteria that are based on 4 h of conditioning at 275°F (135°C). To extend existing performance criteria to WMA, a two-step loose mix conditioning procedure should be considered. This two-step procedure would include 2 h of conditioning at the compaction temperature to simulate the absorption and binder stiffening that occurs during construction, followed by aging at a representative high in-service pavement temperature to simulate early stiffening during the service life of the pavement. The representative in-service pavement temperature should be in the range of 120°F to 150°F (50°C to 65°C) depending on the project location and based on the 50-percent reliability high pavement temperature from LTPPBind 3.1. The conditioning time should be selected such that typical HMA mixtures reach approximately the same stiffness after the two-step conditioning procedure as they reach after 4 h of conditioning at 275°F (135°C). This additional study was beyond the scope of NCHRP Project 09-43, but an analysis of the feasibility was performed using loose mix aging data collected under NCHRP Project 09-13 (23).

NCHRP Project 09-13 included data that could be analyzed to investigate the effect of aging at in-service pavement temperatures compared to HMA mixing and compaction temperatures. With the database reported for NCHRP Project 09-13, dry tensile strengths were collected on Superpave gyratory-compacted samples for five mixtures prepared for four loose mix aging conditions:

- Unaged,
- 2 h at 275°F (135°C),
- 4 h at 275°F (135°C), and
- 16 h at 140°F (60°C).

**Table 32. Summary of average difference in allowable traffic WMA compared to HMA.**

Process	Number	Average Difference in Compaction Temperature (°F)	Average Difference in Allowable Traffic (%)
Advera	3	-46.7	-35
Evotherm	2	-50.0	-35
LEA	1	-80.0	-45
Sasobit	3	-48.3	+32

Dry tensile strengths were measured after two compacted sample conditioning periods: 0 h and 96 h at room temperature. The database extracted from this study is presented in Section E9 of Appendix E.

In analyzing this data, the data for the two compacted mix aging conditions were combined. Figure 39 shows plots of the ratio of the average strength of the conditioned specimens to the unaged specimens. From Figure 39, it appears that there is an error in the unaged data for the Maryland mixture because the ratios of the conditioned to unaged tensile strengths are always less than one, indicating that the mixture softens upon loose mix conditioning, which is not rational. Individual specimen air voids were not reported, but the text stated that the air void tolerance for specimen fabrication was  $7.0 \pm 1.0$  percent.

Because of the questionable unaged data for the Maryland mixture, the unaged data were eliminated from the analysis. Figure 40 shows the average tensile strength for the remaining three loose mix aging conditions: 2 h at 275°F (135°C), 4 h at 275°F (135°C), and 16 h at 140°F (60°C). The error bars in Figure 40 are 95-percent confidence intervals based on the measured data for each mixture. Figure 40 shows that the tensile strengths for 16 h at 140°F (60°C) are somewhat higher than the other aging conditions, indicating that this aging condition stiffens the mixture somewhat more than the shorter aging times at the higher temperatures. This was confirmed by a two-way analysis of variance that is presented in Section E9 of Appendix E.

This analysis shows that it is possible to reach the level of binder stiffening caused by 4 h of loose mix oven condition-

ing at 275°F (135°C) through loose mix oven conditioning at representative in-service temperatures. Since the suggested two-step procedure would include 2 h of conditioning at the compaction temperature to simulate the absorption and binder stiffening that occurs during construction, the in-service aging step will require less than 16 h of loose mix aging at the representative in-service temperature.

### 3.3.4 Fatigue Study

One of the potential benefits of WMA mixtures is improved fatigue characteristics in comparison to HMA mixtures due to the reduced aging that occurs during plant mixing at the lower WMA process temperatures. The fatigue study was designed to evaluate the fatigue resistance of WMA in comparison to HMA. The study was conducted on the two mixtures summarized in Table 33.

For each mixture, specimens were prepared as HMA and WMA using three processes: Advera, Evotherm G3, and Sasobit. The fatigue resistance of the eight mixtures was then characterized using continuum damage theory. Continuum damage theory is a new, powerful tool for characterizing the fatigue behavior of asphalt concrete in a thorough and rational way with relatively limited amounts of testing. Continuum damage theory has recently been applied to the fatigue response of asphalt concrete mixtures by several researchers (24, 25). Recently a practical approach for using continuum damage theory to quickly and accurately characterize the fatigue resistance of asphalt concrete mixtures was developed (26). In this

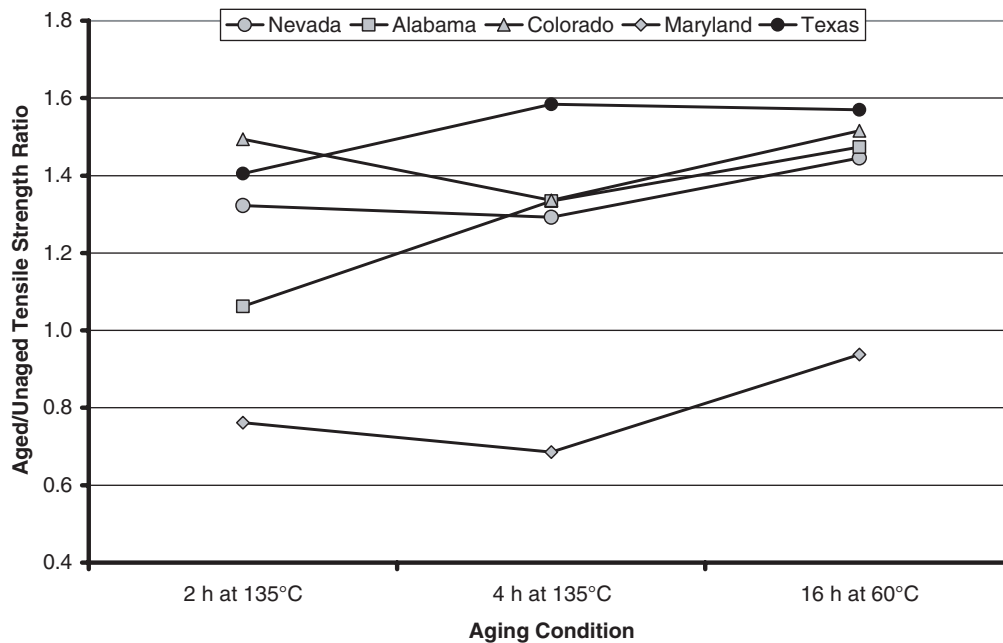


Figure 39. Effect of loose mix aging on tensile strength (23).

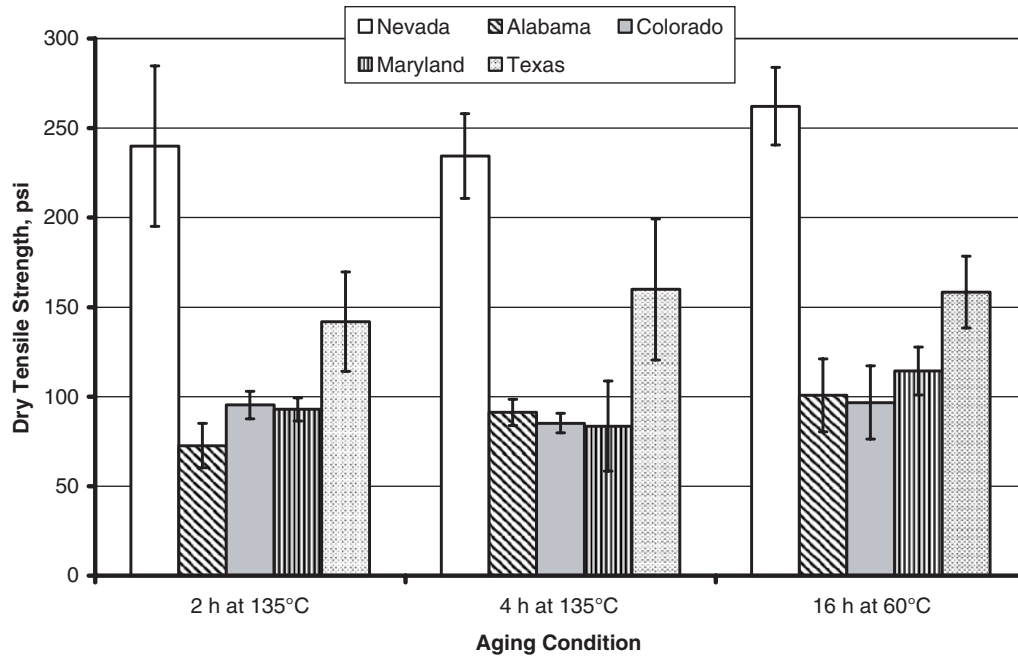


Figure 40. Comparison of tensile strengths for loose mix aging conditions (23).

Table 33. Design properties for fatigue study mixtures.

<b>Mix Number</b>		4	6
<b>Design Gyration</b>		75	100
<b>Aggregate Water Absorption, %</b>		1.6	1.3
<b>RAP</b>		No	No
<b>NMAS</b>		9.5 mm	9.5 mm
<b>Aggregate Sources</b>	Coarse	PA Gravel	VA Diabase
	Fine	PA Limestone PA Gravel	VA Diabase Natural Sand
	RAP	None	None
<b>Gradation</b>	Sieve Size, mm		
	12.5	100	100
	9.5	98	98
	4.75	63	53
	2.36	44	40
	1.18	32	31
	0.6	22	22
	0.3	12	12
	0.15	5	7
0.075	3.0	4.8	
<b>Aggregate Properties</b>	FAA	43.5	48.3
	CAA	98/95	100/100
	Flat & Elongated	7.4	7.6
	Sand Equivalent	80.2	76.7
<b>Binder Content, wt %</b>		6.3	5.7
<b>Effective Binder Content, wt %</b>		5.3	4.7
<b>Air Voids, vol %</b>		4.3	3.7
<b>Voids in Mineral Aggregate, vol %</b>		16.3	15.1
<b>Effective Binder Content, vol %</b>		12.0	11.4
<b>Voids Filled With Asphalt, %</b>		73.6	75.5
<b>Dust to Effective Asphalt Ratio</b>		0.6	1.0

approach, cyclic direct tension fatigue tests are performed at two strain levels and temperatures. For this study, the cyclic fatigue tests were performed at 39.2°F and 68°F (4°C and 20°C) using a low strain level of approximately 150  $\mu$ strain, and a high strain level of approximately 250  $\mu$ strain (peak-to-peak). The resulting data were analyzed using the concept of reduced cycles (26). In this approach, the damage ratio,  $C$  (damaged modulus divided by the linear viscoelastic modulus), for each specimen tested is plotted as a function of reduced cycles,  $N_R$ , at the reference temperature of 39.2°F (4°C) and the reference strain of 200  $\mu$ strain using Equation 5.

$$N_R = N_{R\text{-ini}} + N \left( \frac{f_0}{f} \right) \left( \frac{|E^*|_{\text{LVE}}}{|E^*|_{\text{LVE}/0}} \right)^{2\alpha} \left( \frac{\epsilon}{\epsilon_0} \right)^{2\alpha} \left[ \frac{1}{a(T/T_0)} \right] \quad (5)$$

where

$N_R$  = reduced cycles;

$N_{R\text{-ini}}$  = initial value of reduced cycles, prior to the selected loading period;

$N$  = actual loading cycles;

$f_0$  = reference frequency;

$f$  = actual test frequency;

$|E^*|_{\text{LVE}}$  = initial (linear viscoelastic or LVE) dynamic modulus under given conditions;

$|E^*|_{\text{LVE}/0}$  = reference initial (LVE) dynamic modulus (the LVE modulus at 4°C was used);

$\alpha$  = continuum damage material constant;

$\epsilon$  = applied strain level;

$\epsilon_0$  = reference effective strain level (0.0002 suggested); and

$a(T/T_0)$  = shift factor at test temperature  $T$  relative to reference temperature  $T_0$ .

The values of the continuum damage material constant,  $\alpha$ , and the shift factor,  $a(T/T_0)$ , are then varied until the  $C$  versus  $N_R$  plots for the tests at different temperatures and strain levels converge into a single continuous function. Experience has shown that the damage ratio,  $C$ , follows the following function of  $N_R$ :

$$C = \frac{1}{1 + (N_R/K_1)^{K_2}} \quad (6)$$

where

$C$  = damage ratio,

$K_1$  = cycles to 50% damage at the reference effective strain, and

$K_2$  = a model constant.

The values of  $\alpha$ ,  $a(T/T_0)$ ,  $K_1$ , and  $K_2$  are best determined using numerical optimization. Figure 41 presents typical results of the analysis. This figure shows the shifted fatigue test data, the reduced cycles damage relationship, and comparisons of the measured and predicted damage ratio. The reference temperature for the analysis was 39°F (4°C), and the reference strain was 200  $\mu$ strain. The detailed analysis is included Section E10 of Appendix E.

Table 34 summarizes the parameters from the reduced cycles continuum damage analysis for all of the mixtures. The parameter  $K_1$  is the number of cycles at the reference temperature and strain level to reach a 50-percent reduction in the modulus of the mixture, the fatigue half-life. The WMA mixture fatigue half-lives range from approximately 70 percent to 170 percent of the fatigue half-life of the control HMA for the 100-gyratation mixture and 70 percent to 92 percent for the 75-gyratation mixture. This indicates that the fatigue resistance of WMA and HMA mixtures produced from the same aggregates and binders are essentially the same. Figures 42 and 43 provide further evidence of the similarity of the WMA and HMA fatigue resistance. These figures compare the fitted reduced cycles damage curves for the 100- and 75-gyratation mixtures, respectively. The reduced cycles damage curves are very similar for the WMA processes and the HMA controls, providing further evidence that the fatigue performance of WMA and HMA mixtures produced from the same aggregates and binders will essentially be the same.

### 3.4 Draft AASHTO Standards

Table 35 summarizes the major findings of the studies conducted during NCHRP Project 09-43 and the final disposition of each finding in the draft AASHTO standards that are the primary products of NCHRP Project 09-43. Perhaps the most important finding from the laboratory studies was that the volumetric design of WMA mixtures does not differ substantially from that of HMA. Therefore, a separate mixture design procedure for WMA is not needed. The mixture design portion of the revised preliminary procedure was reformatted to be in the form of an appendix to AASHTO R 35 highlighting special mixture design considerations and procedures for addressing WMA during mixture design. This document is included as Appendix A of this report. Appendix B is a commentary that provides supporting information for use in adoption and future revision of the mix design considerations and methods for WMA. Training materials for introducing the recommended WMA methods are included in Appendix C. The mixture analysis portion of the procedure was reformatted to be a standard practice for measuring properties of WMA for performance analysis using the MEPDG (1). This document is

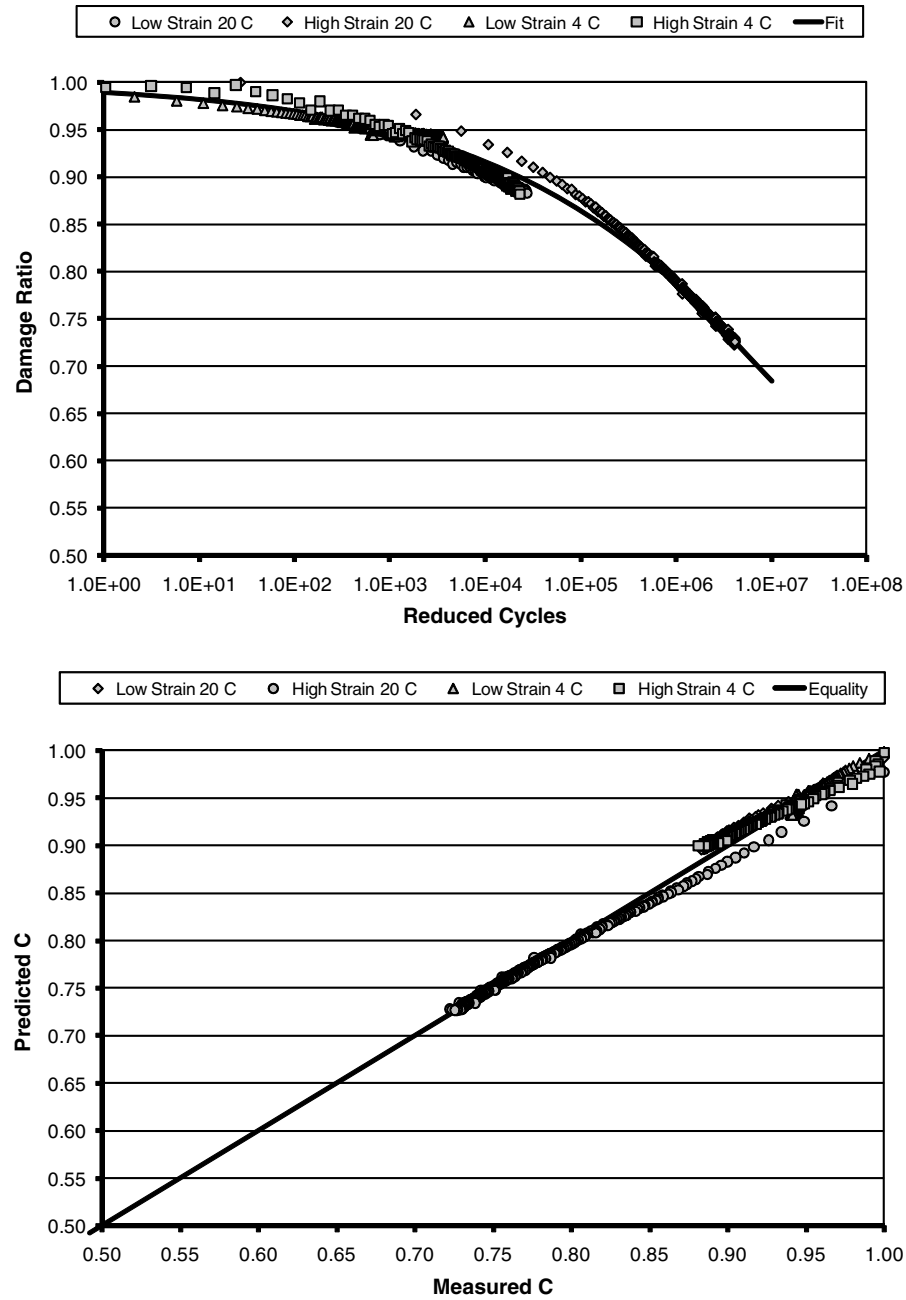


Figure 41. Continuum damage analysis for 100-gyraton Advera WMA.

Table 34. Summary of continuum damage fatigue parameters.

Process	Mixture Gyration Level	Reference Temperature	Reference Modulus (ksi)	$\alpha$	Continuum Damage Shift Factor	Fatigue Half-Life $K_1$ ( $10^7$ )	$K_2$
Control	100	39	2,155	3.5	2,098	6.07E+07	0.23
Advera	100	39	2,000	2.5	3,137	1.03E+08	0.25
Evotharm	100	39	1,941	3.1	4,370	5.95E+07	0.25
Sasobit	100	39	2,135	3.6	3,731	4.41E+07	0.25
Control	75	39	774	2.8	2,183	3.06E+08	0.21
Advera	75	39	773	2.0	5,000	2.75E+08	0.23
Evotharm	75	39	1,697	3.6	5,183	2.21E+08	0.21
Sasobit	75	39	1,667	3.8	3,573	2.83E+08	0.21

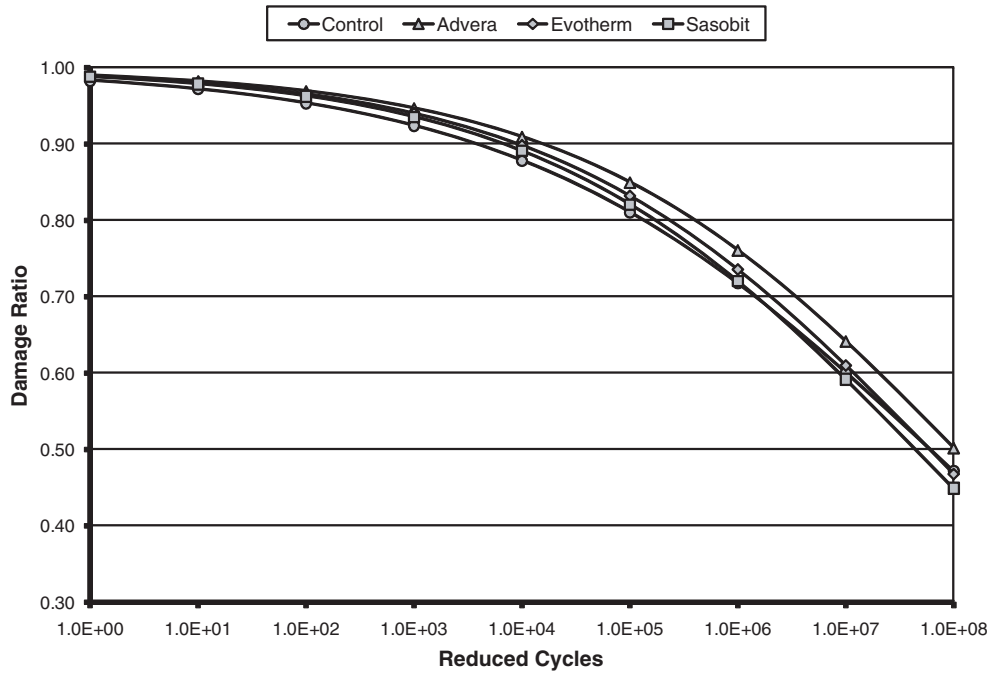


Figure 42. Comparison of continuum damage fatigue curves for the 100-gradation mix.

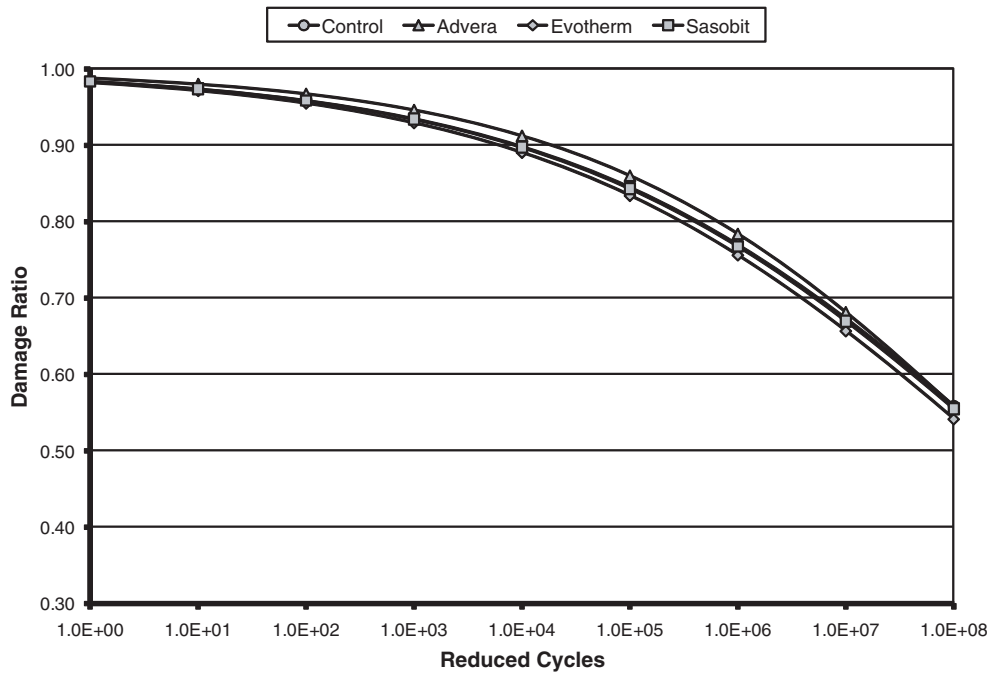


Figure 43. Comparison of continuum damage fatigue curves for the 75-gradation mix.



**Table 35. Major findings of NCHRP Project 09-43 studies.**

<b>Topic</b>	<b>Major Finding</b>	<b>Disposition</b>
<b>Sample Reheating</b>	Sample reheating has a similar effect on WMA and HMA. It further stiffens the binder of the mixture.	Not included directly in the products of NCHRP 09-43. Considered during analysis of comparisons of field and laboratory data.
<b>High-Temperature Binder Grade Selection</b>	The RTFOT study showed a major effect of temperature on high-temperature binder grade. This finding was not confirmed by the recovered binder testing from the field validation mixtures except for the LEA process where the mixture temperature is approximately 100°F (56°C) lower than typical HMA production temperatures.	Draft Appendix to AASHTO R 35 does not include a recommendation for high-temperature binder grade bumping. A note is included that high-temperature grade bumping may be needed if the mixture rutting resistance is inadequate and cannot be improved through reductions in VMA or increase in the filler content of the mixture.
<b>Low-Temperature Binder Grade Selection</b>	Both the RTFOT study and the recovered binder testing from the field validation mixtures showed a minor improvement in low-temperature grade for WMA compared to HMA.	Draft Appendix to AASHTO R 35 does not include recommendations for changes in low-temperature binder grade selection. Low- and intermediate-temperature binder grade improvements may be considered for RAP blending chart analysis. A table of recommended improvements as a function of production temperature was included.
<b>Short-Term Conditioning</b>	Short-term conditioning of 2 h at the planned field compaction temperature reasonably reproduces the binder absorption and stiffening that occurs during WMA production.	The Draft Appendix to AASHTO R 35 recommends 2 h of conditioning at the planned field compaction temperature for volumetric design, moisture sensitivity testing, and flow number testing. The draft standard practice for measuring properties of WMA for performance analysis using the MEPDG recommends 2 h of conditioning at the planned field compaction temperature for dynamic modulus testing for structural design.
<b>RAP</b>	RAP and new binders do mix at WMA process temperatures when conditioned 2 h at the compaction temperature.	The Draft Appendix to AASHTO R 35 recommends limiting the high-temperature grade of the recovered RAP binder to the planned field compaction temperature of the WMA to ensure adequate mixing of the RAP and new binders. The optimum binder content of WMA mixtures incorporating RAP should be determined using the proposed RAP source, and the total binder content of the mixture is the sum of the binder content of the RAP and new binder added.
<b>Specimen-Fabrication Procedures</b>	All of the WMA process, including plant foaming processes, could be reasonably reproduced in the laboratory for mixture design and performance evaluation.	The Draft Appendix to AASHTO R 35 includes process-specific specimen-fabrication procedures for the major categories of WMA processes.
<b>Coating</b>	The type of mixer used to prepare laboratory mixtures of WMA significantly affects the coating of coarse aggregate particles.	The Draft Appendix to AASHTO R 35 includes a note that the mixing times included in the appendix were developed using a mechanical planetary mixer with a wire whip. Mixing time for bucket mixers should be determined by preparing HMA mixtures using the viscosity-based mixing temperature from AASHTO T 312, and evaluating coating.
<b>Workability</b>	Devices that measure the torque during mixing or the force to move a blade through loose mix could not detect differences between HMA and WMA mixtures at normal WMA production temperatures. Differences could be detected at lower temperatures associated with compaction.	The Draft Appendix to AASHTO R 35 does not include an evaluation of workability.
<b>Compactability</b>	A primary benefit of WMA is improved compactability at lower temperatures. The change in the gyrations to reach 92-percent relative density when the compaction temperature was reduced 54°F (30°C) provides a simple procedure to evaluate the compactability of WMA.	The Draft Appendix to AASHTO R 35 includes evaluating the compactability of WMA mixtures by determining the number of gyrations to 92-percent relative density at the planned field compaction temperature and 54°F (30°C) below the planned field compaction temperature. A maximum increase in gyrations of 25 percent when the compaction temperature is reduced is recommended.

*(continued on next page)*

**Table 35. (Continued).**

Topic	Major Finding	Disposition
<b>Volumetric Properties</b>	For mixtures with 1.0-percent binder absorption or less, the volumetric properties of properly designed WMA and HMA mixtures using the same aggregates and binders are very similar.	The Draft Appendix to AASHTO R 35 states that volumetric properties of WMA for mixtures with 1.0 percent or less binder absorption will be the same as those for HMA. Evaluation of compactability, moisture sensitivity, and rutting resistance at the optimum binder content should be conducted using the WMA procedures.
<b>Moisture Sensitivity</b>	Moisture sensitivity, as measured by AASHTO T 283, will likely be different for WMA compared to HMA. Some WMA processes improve the resistance to moisture damage because they include anti-strip additives. Anti-strip dosage rates may be different for WMA compared to HMA.	The Draft Appendix to AASHTO R 35 recommends that moisture sensitivity be evaluated and that appropriate anti-strip additives be used if needed.
<b>Rutting Resistance</b>	The rutting resistance of all WMA processes except Sasobit, as measured by the flow number test on mixtures conditioned for 2 h at the planned field compaction temperature, is lower compared to HMA. Current criteria for the flow number test are based on mixtures that have been short-term conditioned for 4 h at 275°F (135°C). This conditioning represents the aging that occurs during construction as well as some time in service. A two-step conditioning process that includes 2 h at the compaction temperature followed by further loose mix aging at a representative service temperature appears feasible.	The Draft Appendix to AASHTO R 35 recommends performing flow number tests on laboratory-prepared mixtures that have been conditioned 2 h at the planned field compaction temperature to simulate the effect of construction. The flow number criteria included in the Draft Appendix to AASHTO R 35 were adjusted to be 56 percent of the values recommended in NCHRP Project 09-33. This adjustment was made to account for the fact that the standard aging of 4 h at 275°F (135°C) used with HMA accounts for the stiffening that occurs during construction as well as some time in service.
<b>Fatigue Resistance</b>	The fatigue resistance of WMA and HMA are similar for mixtures made from the same asphalt binders and aggregates and having the same volumetric properties.	The draft standard practice for measuring properties of WMA for performance analysis using the MEPDG does not include a fatigue test since the calibrated fatigue relationship in the MEPDG should also apply to WMA mixtures.

included as Appendix D of this report. The sections that follow describe the two draft AASHTO standards.

**3.4.1 Draft Appendix to AASHTO R 35: Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)**

One of the major findings of the mixture design study conducted in Phase II of NCHRP Project 09-43 was that the volumetric properties of HMA and WMA mixtures having 1 percent or less binder absorption were very similar. It is, therefore, not necessary to have a separate design procedure for WMA because the major differences in the way WMA and HMA mixtures are designed are the specimen-fabrication procedures and the evaluation of coating and compactability. These differences can easily be included in AASHTO R 35 by adding an appendix addressing special

considerations and procedures for design of WMA mixtures. The draft appendix titled, *Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)*, addresses the following:

1. **WMA Process Selection.** The draft appendix includes a limited discussion of items to be considered when selecting one of the 20 or so WMA processes currently available. It advises that WMA process selection be done in consultation with the specifying agency and technical assistance personnel from WMA process suppliers. This section alerts users that when selecting a WMA process, consideration should be given to a number of factors, including (1) available performance data, (2) the cost of any warm mix additives, (3) planned mixing and compaction temperatures, (4) planned production rates, (5) plant capabilities, and (6) modifications required to successfully use the WMA process with available field and laboratory equipment.

2. **Binder Grade Selection.** The draft appendix explains to users that it is not necessary to change the grade of the binder in WMA from that normally used in HMA. If a mixture does not have adequate rutting resistance and volumetric properties and gradation cannot be altered, then the high-temperature grade of the binder may be increased to provide acceptable rutting performance.
3. **RAP in WMA.** The draft appendix explains that designing WMA mixtures with RAP is essentially the same as designing HMA mixtures with RAP. The only additional requirement for WMA is that the high temperature of the “as recovered” RAP binder should be less than the planned field compaction temperature of the WMA mixture in order to ensure adequate mixing of the RAP and new binders. A table for low-temperature grade improvement of the virgin binder for RAP blending chart analysis is provided.
4. **Process-Specific Specimen-Fabrication Procedures.** The draft appendix includes process-specific specimen-fabrication procedures for several common WMA processes that were used in NCHRP Project 09-43, including (1) WMA additives added to the binder, (2) WMA additives added to the mixture during production, (3) WMA produced using wet aggregate, and (4) plant foaming.
5. **Evaluation of Coating and Compactability.** The draft appendix describes the procedures for evaluating coating and compactability of WMA mixtures. Both of these evaluations are made on the mixture at the design binder content. Coating is evaluated at the planned production temperature using AASHTO T 195. Compactability is evaluated using the gyrations to 92-percent relative density at the planned field compaction temperature and 54°F (30°C) below the planned field compaction temperature.
6. **Evaluation of Rutting Resistance.** The draft appendix explains how to use the flow number test, AASHTO TP 79, to evaluate the rutting resistance of WMA. Recommended criteria as a function of traffic level are provided. These criteria are 56 percent of the values recommended in NCHRP Project 09-33 for HMA. This adjustment was made to account for the fact that the standard conditioning of 4 h at 275°F (135°C) used with HMA accounts for the binder stiffening that occurs during construction as well as some time in service while the standard conditioning of 2 h at the planned field compaction temperature for WMA only addresses the stiffening that occurs during construction.
7. **Adjusting the Mixture to Meet Specification Requirements.** The draft appendix expands this section of AASHTO R 35 to address the following: (1) coating, (2) compactability, (3) moisture sensitivity, and (4) rutting resistance.

### 3.4.2 Proposed Standard Practice for Measuring Properties of WMA for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide Software

The evaluation of the performance characteristics of WMA should not differ from the evaluation of the performance characteristics of HMA. NCHRP Project 09-33 included an evaluation of various performance tests and concluded that only moisture sensitivity and rutting resistance need to be evaluated as part of the mixture design process; fatigue and thermal cracking can be effectively controlled by controlling the effective binder content of the mixture and the low-temperature binder grade, respectively (6). The WMA mixture design process discussed above includes testing to evaluate moisture sensitivity and rutting resistance.

Predicted rutting and cracking from the MEPDG can be used to evaluate the performance of HMA and WMA mixtures in specific pavement structures (1). In addition to in-place volumetric properties for the mixtures, the following engineering properties are needed for a Level 1 analysis using the MEPDG (1):

- Dynamic modulus master curve,
- Low-temperature creep compliance, and
- Low-temperature strength.

The dynamic modulus master curve is used in the stress-strain calculations as well as the rutting and fatigue-cracking models. The low-temperature creep compliance and strength properties are used in the thermal-cracking model. These models were field calibrated as part of the MEPDG development (1). The permanent deformation and fatigue tests on WMA conducted during NCHRP Project 09-43 indicate that permanent deformation and fatigue characteristics of WMA mixtures are similar to HMA mixtures; therefore, the calibrated MEPDG models should provide a reasonable estimate of the expected performance of pavements constructed with WMA mixtures.

The mixture analysis portion of the revised preliminary mixture design and analysis procedure was reformatted to be a standard practice for measuring properties of WMA for performance analysis using the MEPDG (1). The draft standard practice describes how to prepare WMA performance test specimens and conduct dynamic modulus and low-temperature creep compliance and strength tests to obtain material properties for analysis using the MEPDG. This proposed standard practice is presented in Appendix D of this report.

## CHAPTER 4

# Conclusions and Recommendations

### 4.1 Conclusions

The objective of NCHRP Project 09-43 was to develop mixture design and analysis procedures that can be used with the wide range of WMA processes that are currently available or are likely to become available in the future. The research conducted under NCHRP Project 09-43 included the following:

1. Development of a preliminary procedure based on a review of the literature and research in progress.
2. A first phase of testing and analysis to investigate critical aspects of the preliminary procedure, including (1) the effect of sample reheating, (2) binder grade selection, (3) mixing of RAP and new binders at WMA process temperatures, (4) appropriate short-term oven conditioning for WMA, and (5) evaluation of devices to measure workability.
3. Revisions to the preliminary procedure based on the findings of the first phase of testing and analysis.
4. A second phase of testing and analysis to evaluate the revised preliminary procedure. This phase included (1) a mix design study to test the engineering reasonableness, sensitivity, and practicality of the revised preliminary procedure; (2) a field validation study that used properties of laboratory- and field-produced WMA to validate the procedure; and (3) a fatigue study to investigate whether lower WMA temperatures improve mixture fatigue properties.
5. Final revision of the preliminary procedure based on the findings of the second phase of testing and analysis.

The primary products of NCHRP Project 09-43 are (1) a draft appendix to AASHTO R 35 titled Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA) and (2) a draft standard practice titled Standard Practice for Measuring Properties of Warm Mix Asphalt (WMA) for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide Software. Training materials and a commentary for the draft appendix to AASHTO R 35 were developed

to aid in implementing the research conducted in NCHRP Project 09-43.

The draft appendix to AASHTO R 35 addresses the most widely used WMA processes, including (1) additives that are added to the binder, (2) additives that are added to the mixture during production, (3) wet aggregate mixtures, and (4) plant foaming systems. The following unique aspects of WMA mixture design are addressed by the draft appendix to AASHTO R 35:

- Process-specific specimen-fabrication procedures,
- An evaluation of coating at the planned production temperature,
- An evaluation of compactability at the planned field compaction temperature and lower using the Superpave gyratory compactor, and
- A check on rutting resistance using the flow number test.

The standard practice for measuring performance properties for WMA describes how to prepare WMA performance test specimens and conduct dynamic modulus and low-temperature creep compliance and strength tests to obtain material properties for analysis using the MEPDG (1). The sections that follow describe specific conclusions from the research completed in NCHRP Project 09-43.

#### 4.1.1 Volumetric Properties

A major conclusion drawn from the research conducted under NCHRP Project 09-43 was that the volumetric properties of properly designed WMA and HMA mixtures are very similar. For HMA mixtures with 1.0-percent binder absorption or less, the volumetric properties of WMA designed with the procedures developed in NCHRP Project 09-43 were essentially the same as those obtained from an HMA design. This conclusion supports the current practice of substituting a WMA process into an approved HMA mixture design.

However, the compactability, moisture sensitivity, and rutting resistance of the WMA may be significantly different than those of the HMA. Each of these is evaluated directly in the recommended WMA mixture design method.

#### 4.1.2 Binder Grade Selection

The same grade of binder should be used in WMA and HMA mixtures designed for the same project location. Although the RTFOT experiment that was conducted in Phase I of NCHRP Project 09-43 showed a significant effect of temperature on the high-temperature grade of the binder, recovered binder test data from projects sampled and tested in Phase II of the project indicated that only extremely low production temperatures resulted in a significant decrease in the stiffness of the recovered binder from the mixture. WMA production temperature showed a minor improvement in the low-temperature grade of binders in both the RTFOT experiment and the recovered binder testing. The draft appendix to AASHTO R 35, therefore, recommends that the same grade of binder be used in both WMA and HMA mixtures. High-temperature grade bumping may be necessary for WMA processes with extremely low production temperatures to meet the flow number rutting resistance requirements included in the draft appendix.

#### 4.1.3 RAP in WMA

RAP and new binders do mix at WMA process temperatures provided the mixture is held at elevated temperatures for a sufficient length of time. Because the mixing is time dependent, it appears that the new binder added to the mixture coats the virgin aggregate and RAP; then, during storage at elevated temperature, the two binders continue to mix. In the laboratory mixing studies that were conducted, 2 h of conditioning at the compaction temperature resulted in substantial mixing of RAP and new binders when the compaction temperature exceeded the high-temperature grade of the “as recovered” RAP binder. To ensure good mixing of RAP and new binders, the draft appendix to AASHTO R 35 recommends that the planned field compaction temperature for WMA exceed the high-temperature grade of the “as recovered” RAP binder.

#### 4.1.4 Short-Term Oven Conditioning

Short-term oven conditioning is included in mixture design to simulate the absorption and aging of the binder that occurs during construction. For WMA, it is appropriate to use 2 h of oven conditioning at the planned field compaction temperature, the same short-term conditioning that is used for design of HMA mixtures. The degree of binder aging that occurs,

however, is less than that obtained using the AASHTO R 30 conditioning for performance testing—4 h at 275°F (135°C).

#### 4.1.5 Coating, Workability, and Compactability

For the wide range of WMA processes available, viscosity-based mixing and compaction temperatures cannot be used to control coating, workability, and compactability. The draft appendix to AASHTO R 35 uses direct measures of coating and compactability on laboratory-prepared mixtures. The degree of coating obtained in the laboratory depends on the type of mixer that is used. The mixing times included in the draft appendix to AASHTO R 35 were developed using a planetary mixer with a wire whip. If bucket mixers are used, appropriate WMA mixing times should be established by evaluating the coating of HMA mixtures prepared for various mixing times at the appropriate viscosity-based mixing temperature specified in Section 8.2.1 of AASHTO T 312.

Several workability devices were evaluated under NCHRP Project 09-43. These devices, which measure the torque or force required to move an auger or blade through the mixture, were able to measure differences between HMA and WMA mixtures, but only when temperatures dropped to the compaction range of WMA. At these temperatures, differences in air voids also were evident in gyratory-compacted specimens. The draft appendix to AASHTO R 35 uses the change in the number of gyrations to 92-percent relative density when the compaction temperature is decreased 54°F (30°C) to characterize the compaction temperature sensitivity of the WMA processes. Increases that exceed 25 percent indicate that the WMA is more temperature sensitive than HMA. This measure of compactability is sensitive to the compaction temperature, the WMA process, and the presence of RAP in the mixture. The combination of RAP and low WMA production and compaction temperatures may lead to WMA mixtures that are more sensitive to changes in temperature than similar HMA mixtures.

#### 4.1.6 Moisture Sensitivity

Moisture sensitivity as measured by AASHTO T 283 will likely be different for WMA and HMA mixtures designed using the same aggregates and binder. WMA processes that included anti-strip additives improved the tensile strength ratio of some of the mixtures included in the NCHRP Project 09-43 testing and analysis. Of the nine WMA mixtures that used a WMA process that included an anti-strip additive, the tensile strength ratio remained the same or improved in 67 percent of the mixtures. For WMA mixtures produced using processes that did not include anti-strip additives, the tensile strength ratio never improved and decreased in 79 percent of

the mixtures. The draft appendix to AASHTO R 35 includes evaluation of moisture sensitivity using AASHTO T 283.

#### 4.1.7 Rutting Resistance

The draft appendix to AASHTO R 35 includes an evaluation of the rutting resistance of WMA using the flow number test. The test is conducted on specimens that have been short-term conditioned for 2 h at the planned field compaction temperature to simulate the binder absorption and stiffening that occurs during construction. Because lower short-term conditioning temperatures are used for WMA mixtures than are used for HMA mixtures, binder aging in WMA mixtures is less, resulting in lower flow numbers for WMA mixtures produced with the same aggregates and binder. Current criteria for the flow number and other rutting tests for HMA are based on 4 h of short-term conditioning at 275°F (135°C). The short-term conditioning study completed in NCHRP Project 09-43 shows that this level of conditioning represents the stiffening that occurs during construction as well as some time in service. Since it is inappropriate to condition WMA mixtures at temperatures exceeding their production temperature, the criteria for evaluating the rutting resistance of WMA mixtures were changed from those currently recommended for WMA (conditioned for 4 h at 275°F [135°C]). Based on an analysis of data from NCHRP Project 09-13, it appears feasible that WMA can reach approximately the same level of binder stiffening that occurs in 4 h at 275°F (135°C) by using a two-step aging process: (1) 2 h of conditioning at the compaction temperature to simulate construction effects and (2) extended loose mix conditioning at a representative high in-service pavement temperature to represent early in-service aging. The duration of the extended conditioning will likely be less than 16 h.

#### 4.1.8 Performance Evaluation

The research completed under NCHRP Project 09-43 has shown that for the same aggregates and binders, WMA mixtures designed in accordance with the draft appendix to AASHTO R 35 will have similar properties to HMA mixtures. Volumetric properties will essentially be the same, but the stiffness of the WMA mixture will probably be lower for as-constructed conditions. Since the differences between HMA and WMA are relatively small, an analysis of the performance of pavements constructed with WMA can be made using the MEPDG and appropriate material properties (1). A draft standard practice for fabricating WMA test specimens and performing dynamic modulus master curves and low-temperature creep compliance and strength testing was developed to aid in the performance analysis of WMA using the MEPDG.

## 4.2 Recommendations

The research conducted under NCHRP Project 09-43 has shown that only minor changes to current mixture design practice are needed to design WMA mixtures. Although volumetric properties for HMA and WMA will be similar when binder absorption is 1.0 percent or less, the compactability, moisture sensitivity, and rutting resistance of WMA mixtures will likely be different than HMA mixtures designed with the same aggregates and binders. Therefore, it is recommended that the procedures for WMA mixture design developed under NCHRP Project 09-43 be used when designing WMA mixtures. For the mixtures studied under NCHRP Project 09-43, compactability was sensitive to the WMA process and temperature, particularly for mixtures incorporating RAP. The combination of low WMA temperatures and RAP yielded mixtures with compactability that was more temperature sensitive than HMA mixtures. Moisture sensitivity as measured by AASHTO T 283 will likely be lower for WMA mixtures than HMA mixtures unless the WMA process includes an anti-strip additive. Finally, very low WMA temperatures may lead to mixtures with inadequate rutting resistance. All of these issues can be evaluated using the methods included in the draft appendix to AASHTO R 35.

To aid in the implementation of this recommendation, a draft appendix to AASHTO R 35 titled *Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)*, was developed to address differences between the design of WMA and HMA. This appendix covers the following:

- WMA Process Selection,
- Binder Grade Selection,
- RAP in WMA,
- Process-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.

The draft appendix should be used on a trial basis by agencies and producers to provide additional data to further refine the WMA mixture design methods and criteria before being considered for adoption. Elements that would benefit from additional evaluation and possible refinement include the process-specific specimen-fabrication procedures and the criteria for coating, compactability, and rutting resistance. Additionally, agencies and producers should encourage the manufacturers of plant foaming equipment to develop laboratory foaming equipment that can be used to design foamed asphalt WMA mixtures in the laboratory. The laboratory foaming equipment that was used in NCHRP Project 09-43

was designed for preparing laboratory samples of foamed stabilized bases, not WMA. Although it is feasible to design WMA mixtures for plant foaming processes using this equipment, devices specifically designed to replicate the WMA foaming process and produce the smaller quantities of foamed asphalt used in mix design batches without extensive cleaning are needed to make the design process efficient.

At the time that NCHRP Project 09-43 was completed, three additional projects on WMA were initiated by NCHRP: (1) NCHRP 09-47A, "Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies," (2) NCHRP 09-49, "Performance of WMA Technologies: Stage I—Moisture Susceptibility," and (3) NCHRP Project 09-49A, "Performance of WMA Technologies: Stage II—Long-Term Field Performance." NCHRP Projects 09-47A and 09-49A will include an evaluation of the field performance of WMA mixtures, and NCHRP Project 09-49 will address the moisture susceptibility of WMA in detail. The findings of NCHRP Project 09-43 support the need for these studies addressing field performance and moisture sensitivity.

There are, however, two elements of the WMA mixture design process that require additional research that is not currently planned. First, mixing procedures for laboratory mixtures have not been standardized. For design of HMA, mixing can be done manually or with a mechanical mixer. Two types of mechanical mixers are available: planetary mixers and bucket mixers. To use coating of laboratory mixtures as a design criterion, a mechanical mixer must be used, and the mixing process must be standardized. Coating evaluations performed during NCHRP Project 09-43 indicate that there is a significant difference in the efficiency of planetary and bucket mixers. The mixing times included in the draft appendix to AASHTO R 35 are based on a planetary mixer with a wire whip. Since bucket mixers are probably more readily available in most production mix design laboratories, additional mixing studies should be conducted to establish mixing times for WMA specimen fabrication for bucket mixers. The draft appendix to AASHTO R 35 should then be modified to include mixing times for bucket mixers.

The second element of WMA mix design that requires additional research is the development of a short-term con-

ditioning procedure that is applicable to both WMA and HMA for the specimens used to evaluate moisture sensitivity and rutting resistance. Research completed under NCHRP Project 09-43 concluded that 2 h of oven conditioning at the field compaction temperature reasonably reproduces the binder absorption and stiffening that occurs during construction for both WMA and HMA mixtures. WMA mixtures that are conditioned 2 h at the field compaction temperature have binder that is less stiff than similarly conditioned HMA mixtures because of the lower conditioning temperature. Current criteria for evaluating moisture sensitivity and rutting resistance are based on mixtures that have been aged to a greater degree. The conditioning originally specified in AASHTO T 283 for moisture sensitivity testing was 16 h at 140°F (60°C). Additionally, most rutting criteria are based on 4 h of conditioning at 275°F (135°C). Under NCHRP Project 09-13, mixtures were conditioned for 2 h at 275°F (135°C), 4 h at 275°F (135°C), and 16 h at 140°F (60°C). From analysis of this data, the NCHRP Project 09-43 research team concluded that 16 h at 140°F (60°C) resulted in somewhat more aging than 4 h at 275°F (135°C). The difference in aging between 2 h and 4 h at 275°F (135°C) was not statistically significant. To simulate both WMA and HMA, a two-step conditioning process should be considered for specimens used to evaluate moisture sensitivity and rutting resistance. In the first step, the mixture would be conditioned for 2 h at the field compaction temperature to simulate the binder absorption and stiffening that occurs during construction. In the second step, the mixture would be further conditioned for an extended time at a representative high in-service pavement temperature to simulate a short period of time in service. Only specimens used to evaluate moisture sensitivity and rutting resistance would receive the second conditioning step. Volumetric design would be based only on the first step. The temperature and duration of the extended conditioning would be selected based on temperatures from LTPPBind and typical laboratory working hours. Most likely, the second step would require conditioning specimens overnight. The extended conditioning temperature and time would be selected so that HMA conditioned using the two-step process would have a similar stiffness to HMA conditioned for 4 h at 275°F (135°C).

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## APPENDIX A

# Draft Appendix to AASHTO R 35: Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)

## Draft Appendix to AASHTO R 35

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# Appendix: Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)

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## 1. PURPOSE

- 1.1. This appendix presents special mixture design considerations and methods for designing warm mix asphalt (WMA) using AASHTO R 35. WMA refers to asphalt concrete mixtures that are produced at temperatures approximately 50 °F (28 °C) or more cooler than typically used in the production of HMA. The goal with WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA using substantially reduced production temperatures.
- 1.2. The methods in this appendix are applicable to a wide range of WMA processes 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.
- 1.3. The information in this appendix supplements the standard procedures contained in AASHTO R 35. This appendix assumes the user is proficient with the standard procedures contained in AASHTO R 35.

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## 2. SUMMARY

- 2.1. This appendix includes separate sections addressing the following aspects of WMA mixture design:
- Equipment for Designing WMA,
  - WMA Process Selection,
  - Binder Grade Selection,
  - RAP in WMA,
  - Process 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.

- 2.2. In each section, reference is made to the applicable section of AASHTO R 35.
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### 3. ADDITIONAL LABORATORY EQUIPMENT

- 3.1. All WMA Processes:

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

**Note 1** – The mixing times in this appendix were developed using a planetary mixer with wire whip, Blakeslee Model B-20 or equivalent. Appropriate mixing times for bucket mixers should be established by evaluating coating of HMA mixtures prepared at the viscosity based mixing temperatures specified in Section 8.2.1 of AASHTO T 312.

- 3.2. Binder Additive WMA Processes:

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

- 3.3. Plant Foaming Processes:

- 3.3.1. **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.
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### 4. WMA PROCESS SELECTION

- 4.1. There are over 20 WMA processes being marketed in the United States. Select the WMA process that will be used in consultation with the specifying agency and technical assistance personnel from the WMA technology providers. Consideration should be given to a number of factors including: (1) available performance data, (2) the cost of the warm mix additives, (3) planned production and compaction temperatures, (4) planned production rates, (5) plant capabilities, and (6) modifications required to successfully use the WMA process with available field and laboratory equipment.
- 4.2. Determine the planned production and planned field compaction temperatures.
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### 5. BINDER GRADE SELECTION

- 5.1. Use the same grade of binder normally used with HMA. Select the performance grade of the binder in accordance with Section 5 of AASHTO M 323 considering the environment and traffic at the project site.

**Note 2** – For WMA processes 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.

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## 6. RAP IN WMA

- 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 3** – This requirement is included to ensure that there is mixing of the new and recycled binders. Laboratory studies showed that new and recycled binders do mix at WMA process temperatures provided this requirement is met and the mixture remains at or above the planned compaction temperature for at least 2 hours. Plant mixing should be verified through an evaluation of volumetric or stiffness properties of plant produced mixtures.

- 6.2. Select RAP materials in accordance with Section 6 of AASHTO M 323.

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

**Note 4** – The intermediate and low temperature grade improvements given in Table 1 will allow additional RAP to be used in WMA mixtures when blending chart analyses are used. An approximately 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 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 °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

## 7. PROCESS SPECIFIC SPECIMEN FABRICATION PROCEDURES

### 7.1. Batching

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

**Note 5** – 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 the AASHTO T 283 and flow number testing.

**Table 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 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
AASHTO 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

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

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

**Note 6** – 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.

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

## 7.2. Heating

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

**Note 7** – The aggregate will require 2 to 4 hours to reach the temperature of the oven. Aggregates may be placed in the oven overnight.

- 7.2.2. Heat the RAP in the oven with the aggregates, but limit the heating time for the RAP to 2 hours.
- 7.2.3. Heat the binder to the planned production temperature.
- 7.2.4. Heat mixing bowls and other tools to the planned production temperature.
- 7.2.5. Preheat a forced draft oven and necessary pans to the planned field compaction temperature for use in short-term conditioning the mixture.

### 7.3. Preparation of WMA Mixtures With WMA Additives Added to the Binder

**Note 8** – If specific mixing and storage instructions are provided by the WMA additive supplier, follow the supplier’s instructions.

#### 7.3.1. Adding WMA Additive to Binder

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

**Note 9** – 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.

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

#### 7.3.2. Preparing WMA Specimens

- 7.3.2.1. Heat the mixing tools, aggregate, RAP, and binder in accordance with Section 7.2.
- 7.3.2.2. If a liquid anti-strip is required, add it to the binder per the manufacturer’s instructions.
- 7.3.2.3. Place the hot mixing bowl on a scale and zero the scale.
- 7.3.2.4. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.



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 10** – 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

$$w_t = \frac{w_i}{\left(1 - \frac{p_{b_{new}}}{100}\right)}$$

where:

$w_t$  = target total weight

$w_i$  = oven dry weight from step 1

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

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

7.3.2.6. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

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 the planned field compaction temperature for 2 hours. Stir the mixture once after the first hour.

#### 7.4. Preparation of WMA Mixtures With WMA Additive Added to the Mixture

**Note 11** – If specific mixing and storage instructions are provided by the WMA additive supplier follow the supplier's instructions.

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

**Note 12** – The quantity of additive may be specified as a percent by weight of binder or a percent by weight of total mixture.

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

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

7.4.4. Place the hot mixing bowl on a scale and zero the scale.

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

- 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 13** – 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

$$w_t = \frac{w_i}{\left(1 - \frac{p_{b_{new}}}{100}\right)}$$

where:

$w_t$  = target total weight

$w_i$  = oven dry weight from step 1

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

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

- 7.4.7. Pour the WMA additive into the pool of new asphalt binder.
- 7.4.8. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.
- 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 the planned field compaction temperature for 2 hours. Stir the mixture once after the first hour.

## 7.5. Preparation of WMA Mixtures With A Wet Fraction of Aggregate

**Note 14** – Consult the WMA process supplier for appropriate additive dosage rates, mixing temperatures, percentage of wet aggregate and wet aggregate moisture content.

### 7.5.1. Adding WMA Additive to Binder

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

**Note 15** – 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.

- 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.

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

### 7.5.2. Preparing WMA Specimens

7.5.2.1. Add the required moisture to the wet fraction of the aggregate, mix thoroughly, then cover and let stand for at least 2 hours before mixing with the heated fraction.

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

7.5.2.3. Place the hot mixing bowl on a scale and zero the scale.

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

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 16** – 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 heated aggregates and RAP,  $w_i$
2. Determine the target total weight of the mixture:

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

where:

$w_t$  = target total weight

$w_i$  = oven dry weight from step 1

$w_{dwf}$  = oven dry weight of the wet fraction from the batch sheet

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

3. Determine the target weight of the heated mixture:

$$w_{thm} = w_t - w_{dwf}$$

where:

$w_{thm}$  = target weight of the heated mixture

$w_t$  = target total weight

$w_{dwf}$  = oven dry weight of the wet fraction from the batch sheet

4. Add new binder to the bowl to reach  $w_{thm}$
- 7.5.2.6. Add the additive to the binder immediately before mixing with the heated fraction of the aggregate per Section 7.5.1.
- 7.5.2.7. Remove the mixing bowl from the scale and mix with a mechanical mixer for 30 sec.
- 7.5.2.8. Stop the mixer and immediately add the wet fraction.
- 7.5.2.9. Restart the mixer and continue to mix for 60 sec.
- 7.5.2.10. Place the mixture in a flat shallow pan at an even thickness of 25 to 50 mm.
- 7.5.2.11. Check the temperature of the mixture in the pan. It shall be between 90 and 100 °C.
- 7.5.2.12. Place the pan in the forced draft oven at the planned field compaction temperature for 2 hours. Stir the mixture once after the first hour.

## 7.6. Preparation of Foamed Asphalt Mixtures

- 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.
- 7.6.2. Prepare the asphalt binder foaming equipment and load it with binder per the manufacturer's instructions.
- 7.6.3. If a liquid anti-strip is required, add it to the binder in the foaming equipment per the manufacturer's instructions.
- 7.6.4. Heat the mixing tools, aggregate, and RAP in accordance with Section 7.2.
- 7.6.5. Prepare the foamed asphalt binder per the instructions for the foaming equipment.
- 7.6.6. Place the hot mixing bowl on a scale and zero the scale.
- 7.6.7. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
- 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 17** – The laboratory foaming equipment uses a timer to control the amount of foamed asphalt provided. Make sure the batch size is large enough that the required amount of foamed asphalt is within the calibrated range of the foaming device. This may require producing one batch for the two gyratory specimens and the two maximum specific gravity specimens at each asphalt content then splitting the larger batch into individual samples.

**Note 18** – 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

$$w_t = \frac{w_i}{\left(1 - \frac{p_{b_{new}}}{100}\right)}$$

where:

$w_t$  = target total weight

$w_i$  = oven dry weight from step 1

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

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

7.6.9. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

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 the planned field compaction temperature for 2 hours. Stir the mixture once after the first hour.

## 8. WMA MIXTURE EVALUATIONS

- 8.1. At the optimum binder content determined in accordance with Section 10 of AASHTO R 35, prepare WMA mixtures in accordance with the appropriate procedure from Section 7 of this appendix for the following evaluations:
  - Coating
  - Compactability
  - Moisture sensitivity
  - Rutting resistance

## 8.2. Coating

- 8.2.1. Prepare sufficient mixture at the design binder content to perform AASHTO T 195 using the appropriate WMA fabrication procedure from Section 7 of this appendix. Do not short-term condition the mixture.
- 8.2.2. Evaluate the coating in accordance with AASHTO T 195.
- 8.2.3. The recommended coating criterion is at least 95 percent of the coarse aggregate particles fully coated.

## 8.3. Compactability

- 8.3.1. Prepare sufficient mixture at the design binder content for 4 gyratory specimens and one maximum specific gravity measurement using the appropriate WMA fabrication procedure from Section 7 of this Appendix including short-term conditioning for 2 hours at the planned compaction temperature.
- 8.3.2. Determine the theoretical maximum specific gravity ( $G_{mm}$ ) according to AASHTO T 209.
- 8.3.3. Compact duplicate specimens at the planned field compaction temperature to  $N_{design}$  gyrations in accordance with AASHTO T 312. Record the specimen height for each gyration.
- 8.3.4. Determine the bulk specific gravity of each specimen in accordance with AASHTO T 166.
- 8.3.5. Allow the mixture to cool to 30 °C below the planned field compaction temperature. Compact duplicate specimens to  $N_{design}$  gyrations in accordance with AASHTO T 312. Record the specimen height for each gyration.
- 8.3.6. Determine the bulk specific gravity of each specimen in accordance with AASHTO T 166.
- 8.3.7. For each specimen determine the corrected specimen relative densities for each gyration using Equation 1.

$$\%G_{mm_N} = 100 \times \left( \frac{G_{mb} \times h_d}{G_{mm} \times h_N} \right) \quad (1)$$

where:

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

$G_{mb}$  = bulk specific gravity of 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

- 8.3.8. For each specimen, determine the number of gyrations to reach 92 percent relative density.
- 8.3.9. Determine the average number of gyrations to reach 92 percent relative density at the planned field compaction temperature.
- 8.3.10. Determine the average number of gyrations to reach 92 percent relative density at 30 °C below the planned field compaction temperature.
- 8.3.11. Determine the gyration ratio using Equation 2.

$$Ratio = \frac{(N_{92})_{T-30}}{(N_{92})_T} \quad (2)$$

where:

$Ratio$  = gyration ratio

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

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

- 8.3.12. The recommended compactability criterion is the gyration ratio should be less than or equal to 1.25.

**Note 18** – 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.

#### 8.4. Evaluating Moisture Sensitivity

- 8.4.1. Prepare sufficient mixture at the design binder content for 6 gyratory specimens using the appropriate WMA fabrication procedure from Section 7 of this appendix including short-term conditioning.
- 8.4.2. Compact test specimens to  $7.0 \pm 0.5$  percent air voids in accordance with AASHTO T 312.
- 8.4.3. Group, condition and test the specimens in accordance with AASHTO T 283.
- 8.4.4. The recommended moisture sensitivity criteria are the tensile strength ratio should be greater than 0.80 and there should not be any visual evidence of stripping.

## 8.5. Evaluating Rutting Resistance

- 8.5.1. Evaluate rutting using the flow number test in AASHTO TP 79.
- 8.5.2. Prepare sufficient mixture at the design binder content for four flow number test specimens using the appropriate WMA fabrication procedure from Section 7 of this appendix including short-term conditioning.
- 8.5.3. The test is conducted on 100 mm diameter by 150 mm high test specimens that are sawed and cored from larger gyratory specimens that are 150 mm diameter by at least 175 mm high. Refer to AASHTO PP 60 for detailed procedures for test specimen fabrication procedures. The short-term conditioning for WMA specimens is 2 hours at the compaction temperature.
- 8.5.4. Prepare the flow number test specimens to  $7.0 \pm 1.0$  percent air voids.
- 8.5.5. Perform the flow number test at the design temperature at 50 % 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.
- 8.5.6. Perform the flow number test unconfined using repeated deviatoric stress of 600 kPa with a contact deviatoric stress of 30 kPa.
- 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 3.

Table 3. Minimum Flow Number Requirements

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

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## 9. ADJUSTING THE MIXTURE TO MEET SPECIFICATION PROPERTIES

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



- 9.2. **Improving Coating-** Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve coating.
- 9.3. **Improving Compactability-** Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve compactability.
- 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.
- 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 to improve rutting resistance.
- Increasing the high temperature performance grade one grade level improves rutting resistance by a factor of 2.
  - Adding 25 to 30 percent RAP will increase the high temperature performance grade approximately one grade level.
  - Increasing the fineness modulus (sum of the percent passing the .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  $N_{\text{design}}$  by one level will improve rutting resistance by factor of 1.2.

## 10. ADDITIONAL REPORTING REQUIREMENTS FOR WMA

- 10.1. For WMA mixtures, report the following information in addition to that required in Section 13 of AASHTO R 35.
- 10.1.1. WMA process description.
- 10.1.2. Planned production temperature.
- 10.1.3. Planned field compaction temperature.
- 10.1.4. High temperature grade of the binder in the RAP for mixtures incorporating RAP.
- 10.1.5. Coating at the design binder content.
- 10.1.6. Gyration to 92 percent relative density for the design binder content at the planned field compaction temperature and 30 °C below the planned field compaction temperature
- 10.1.7. Gyration ratio.

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

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

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## APPENDIX B

# Commentary to the Draft Appendix to AASHTO R 35

## B1. Introduction

One of the products of National Cooperative Highway Research Program (NCHRP) Project 09-43 was a draft appendix to AASHTO R 35 titled, *Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)*. The draft appendix addresses the following aspects of WMA mixture design:

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

This commentary to the draft appendix provides supporting information taken from the NCHRP Project 09-43 Final Report for each of the major sections of the draft appendix. It is intended for those who are responsible for the adoption and future revision of the draft appendix. Each section of the commentary has the following structure:

### General Comments

Description of general contents of the section and the underlying philosophy.

### Basis for Critical Content

Provides engineering justification for the critical content contained in the section. It includes a summary of the analyses and findings from NCHRP Project 09-43 that support the critical content.

### Need for Further Research

Describes additional research that is needed to improve the section.

## B2. Section 1. Purpose

### General Comments

This section describes the purpose of the Appendix.

### Basis for Critical Content

There is no critical content in this section.

### Need for Further Research

There is no need for additional research.

## B3. Section 2. Summary

### General Comments

This section lists the major topic covered by the appendix.

### Basis for Critical Content

There is no critical content in this section.

### Need for Further Research

There is no need for additional research.

## B4. Section 3. Additional Laboratory Equipment

### General Comments

This section describes the additional equipment needed for designing WMA mixtures in the laboratory. Since coating is used in lieu of viscosity-based mixing temperatures, a mechanical mixer is required. For WMA processes where the additive is blended in the binder, a mechanical stirrer is needed. For designing mixtures for plant foaming processes, a laboratory foamed asphalt plant that can produce foamed asphalt at the moisture content used by the field equipment is also needed.

### Basis for Critical Content

The design of WMA mixtures includes an evaluation of coating using AASHTO T 195. To standardize the mixing process, a mechanical mixer is required. During NCHRP Project 09-43, it was observed that planetary mixers and bucket mixers do not have the same mixing efficiency. The mixing times in the specimen fabrication procedures in Section 7 of the draft appendix were developed in NCHRP Project 09-43 using a planetary mixer. Mixing times for bucket mixers will likely be longer.

NCHRP Project 09-43 demonstrated that it is feasible to perform foamed asphalt WMA mixture designs in the laboratory. In NCHRP Project 09-43, a modified Wirtgen WLB-10 laboratory foaming plant was used to simulate the Gencor Ultrafoam GX process using 1.25 percent water by weight of binder and the Astec Double Barrel Green process using 2.0 percent water by weight of binder. The modification that was required was to replace the flow controller with a smaller, more precise flow controller to accommodate the water contents used in WMA mixtures.

### Need for Further Research

Bucket mixers are significantly less expensive and likely more readily available in mix design laboratories than planetary mixers. Additional research should be conducted to develop appropriate mixing times for bucket mixers.

Manufacturers of plant foaming equipment should be encouraged to develop laboratory foaming equipment that can be used to design foamed asphalt WMA mixtures in the laboratory. The laboratory foaming equipment that was used in NCHRP Project 09-43 was designed for preparing laboratory samples of foamed stabilized bases, not WMA. Although it is feasible to design WMA mixtures for plant foaming processes using this equipment, devices specifically designed to replicate the WMA foaming process and produce the smaller quantities of foamed asphalt used in mix design batches without extensive cleaning are needed to make the design process efficient.

### B5. Section 4. WMA Process Selection

#### General Comments

This section lists factors to be considered when selecting a WMA process.

#### Basis for Critical Content

There is no critical content in this section.

#### Need for Further Research

There is no need for additional research.

### B6. Section 5. Binder Grade Selection

#### General Comments

The same grade of binder should be used with WMA and HMA. For WMA processes with very low production temperatures it may be necessary to increase the high-temperature performance grade of the binder to meet rutting resistance requirements.

#### Basis for Critical Content

Performance grading data for binders recovered from several WMA projects sampled during NCHRP Project 09-43 showed only small differences in the grade of the binder for WMA and HMA sections. Table 1 summarizes the recovered binder data from NCHRP Project 09-43. Table 2 presents average differences in the continuous grade between HMA and WMA. Excluding Sasobit, which increases the high-temperature grade of the binder, an approximately 50°F (28°C) reduction in production temperature resulted in less than a 1°C decrease in the high-temperature grade, while an approximately 100°F (56°C) reduction in production temperature resulted in approximately a one-half grade decrease for one low energy asphalt (LEA) project. For the low-temperature grade, again excluding Sasobit, an approximately 50°F (28°C) reduction in production temperature resulted in an average improvement in the low-temperature grade of binder of

**Table 1. Summary of continuous grading of recovered binders.**

Project	Process	Production Temperature (°F)	Continuous Grade Temperature (°C)		
			High	Intermediate	Low
Colorado I-70	Specified	NA	58.0	19.0	-28.0
	Control	280	59.3	14.2	-30.6
	Advera	250	60.0	13.7	-31.6
	Evotherm	250	61.3	14.1	-31.1
	Sasobit	250	63.9	15.1	-29.9
Yellowstone National Park	Specified	NA	58.0	16.0	-34.0
	Control	325	60.0	11.1	-34.1
	Advera	275	56.3	8.9	-36.2
	Sasobit	275	60.7	10.1	-35.6
New York Route 11	Specified	NA	64.0	22.0	-28.0
	LEA	210	60.5	14.0	-31.1
Pennsylvania SR2007	Specified	NA	64.0	25.0	-22.0
	Control	320	67.7	22.0	-24.6
	Evotherm	250	67.2	22.0	-24.9
Pennsylvania SR2006	Specified	NA	64.0	25.0	-22.0
	Control	310	66.6	24.1	-22.5
	Advera	250	67.0	22.9	-24.1
	Gencor	250	67.5	21.7	-25.7
	LEA	210	63.2	21.6	-25.4
	Sasobit	250	72.9	23.3	-22.5
Monroe, North Carolina	Specified	NA	70.0	28.0	-22.0
	Astec	275	71.5	23.7	-23.9

**Table 2. Summary of average difference in continuous grade temperatures for WMA compared to HMA.**

Process	Number	Average Difference in Production Temperature (°F)	Average Difference in Continuous Grade Temperature (°C)		
			High	Intermediate	Low
Advera	3	-46.7	-0.9	-1.3	-1.6
Evotherm	2	-50.0	0.8	0.0	-0.4
LEA	1	-100.0	-3.4	-2.5	-2.9
Plant Foaming	1	-60.0	0.9	-2.4	-3.2
Sasobit	3	-46.7	3.9	-0.3	-0.3

1.5°C, while an approximately 100°F (56°C) reduction in production temperature resulted in 2.9°C improvement for one LEA project.

### Need for Further Research

Additional recovered binder grade data should be collected and analyzed to verify the conclusion from NCHRP Project 09-43 that binder grade changes are not necessary for WMA.

## B7. Section 6. RAP in WMA

### General Comments

Research completed in NCHRP Project 09-43 found that recycled asphalt pavement (RAP) binders and new binders do mix at WMA process temperatures. Therefore, it is appropriate to design WMA mixtures containing RAP in the same manner as HMA, accounting for the contribution of the RAP binder to the total binder content of the mixture. From the research completed in NCHRP Project 09-43, the RAP and new binders continue to mix while the mix is held at elevated temperature. To ensure that adequate mixing of RAP and new binders does occur, a limit is placed on the maximum stiffness of RAP binders for WMA. That limit is based on the planned field compaction temperature of the mixture since this temperature will govern the temperature of the mix during storage and transport. The limit is the RAP binder should have a high-temperature grade that is less than the planned field compaction temperature for the WMA. RAP binders typically range from PG 82 to PG 94 resulting in corresponding minimum field compaction temperatures ranging from 180°F to 200°F (82°C to 94°C).

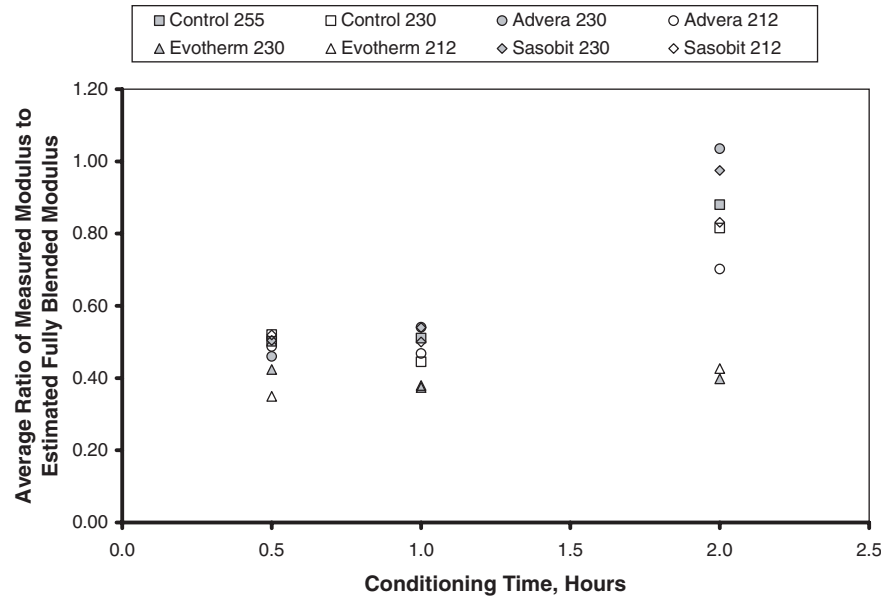
Binders from WMA mixtures have improved low-temperature properties due to the lower amount of aging that occurs during production. Although the improvement in low-temperature properties is not large enough to warrant changing the low-temperature grade, it is large enough to affect the amount of RAP that can be added to a mixture when blending chart analyses are used.

### Basis for Critical Content

NCHRP Project 09-43 included a laboratory mixing study where the WMA and HMA mixtures incorporating RAP were prepared in the laboratory and stored for various lengths of time at the compaction temperature. The degree of mixing of the RAP and new binders was evaluated by comparing dynamic moduli measured on mixture samples with the dynamic moduli estimated using the properties of the binder recovered from the mixture samples. The dynamic modulus test is very sensitive to the stiffness of the binder in the mixture, and adding RAP will increase the dynamic modulus significantly when the RAP is properly mixed with the new materials. The measured dynamic modulus values represent the as-mixed condition. The dynamic modulus for the fully blended condition was estimated using the Hirsch model from the shear modulus of binder recovered from the dynamic modulus specimens. If the measured and estimated dynamic moduli are the same, there is good mixing of the RAP and new binders.

The findings of the laboratory mixing experiment are shown in Figure 1. At conditioning times of 0.5 and 1.0 h, there is little blending of the new and recycled binders. For all processes and temperatures, the ratio of the measured to estimated fully blended moduli range from about 0.35 to 0.55. At the 2-h conditioning time, the ratio of the measured to estimated fully blended moduli reach values approaching 1.0 for the Control HMA, Advera WMA, and Sasobit WMA. The effect of temperature is also evident for these processes, with the higher conditioning temperature resulting in somewhat improved blending. The ratio of the measured to estimated fully blended moduli for the Evotherm WMA remained low even at the 2-h conditioning time. This suggests that either the particular form of Evotherm used in this study retards the mixing of the new and recycled binders or that the extraction and recovery process stiffens the Evotherm modified binder.

Further evidence of the mixing of new and RAP binders at WMA process temperatures was obtained from a mixture



**Figure 1. Comparison of the ratio of measured to fully blended dynamic moduli.**

design study completed in NCHRP Project 09-43. In this study, six mixtures were designed as HMA and as WMA and various volumetric and engineering properties were compared. Three of the mixtures included RAP. Table 3 summarizes the optimum binder content for the three mixtures containing RAP. As shown, the optimum binder content is the same or lower for the WMA compared to the HMA, further supporting the conclusion that RAP and new binders do mix at WMA process temperatures. In this study, the Evotherm mixtures do not have higher optimum binder contents than the HMA and the other processes suggesting that the Evotherm does mix and that the differences shown in Figure 1 for this process are due to the extraction and recovery process used in the mixing study.

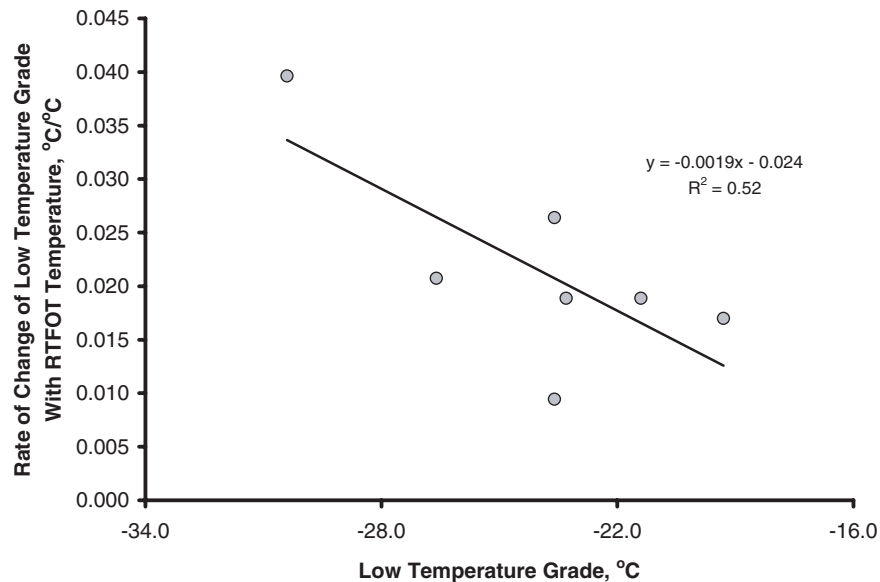
NCHRP Project 09-43 included a binder grade study where the Rolling Thin Film Oven Test (RTFOT) was used to simulate the effect on binder properties of changes in production temperatures. Figure 2 shows that there appears to be a weak relationship between the rate of change in low-temperature grade with RTFOT temperature and the low-temperature grade of the binder. Binders with better low-temperature properties tend to show more improvement in low-temperature

properties when the RTFOT temperature is decreased. The relatively small effect of RTFOT temperature on the low-temperature binder grade does not warrant recommended changes in low-temperature binder grade selection for WMA. For the binders tested, decreasing the production temperature by 95°F (53°C) only improved the low-temperature grade of the binder by 1°C to 2°C which is only 1/3 to 1/2 of a grade level.

The low-temperature grade improvement, however, can be significant when considering mixtures incorporating recycled asphalt pavement (RAP). When RAP blending charts are used, the low-temperature continuous grade of the binder changes approximately 0.6°C for every 10 percent of the total binder in the mixture replaced with RAP binder. Thus, improving the low-temperature properties of the virgin binder in the mixture 0.6°C by lowering the production temperature will allow 10 percent additional RAP binder to be added to the mixture. Using the relationship shown in Figure 2, for the middle of the low-temperature binder grade temperature range, recommended improvements in virgin binder low-temperature continuous grade for RAP blending chart analysis can be made as a function of WMA production temperature for mixtures

**Table 3. Optimum binder contents for RAP mixtures from the NCHRP 09-43 mixture design study.**

Mixture	HMA	Advera WMA	Evotherm WMA	Sasobit WMA
50 gyrations, 25 % RAP	6.4	6.5	6.1	6.3
75 gyrations, 25% RAP	5.5	5.3	5.2	5.3
100 gyrations, 25 % RAP	6.0	6.1	5.8	6.2



**Figure 2.** Effect of low-temperature binder grade on the rate of change of low-temperature grade with RTFOT temperature.

incorporating PG XX-16, PG XX-22, and PG XX-28. These recommended improvements are summarized in Table 4 for some common binder grades. For a mixture using PG 64-22 virgin binder and a WMA production temperature of 250°F, the virgin binder low-temperature continuous grade would be improved 0.6°C to account for the lower WMA production temperature.

### Need for Further Research

Plant mixing studies similar to the laboratory mixing study are needed to confirm that RAP and new binders mix at WMA process temperatures for field conditions. NCHRP Project 09-43 included one field project that used 30-percent RAP, the Astec Double Barrel Green WMA process, and field mixing and compaction temperatures of 275°F and 260°F (135°C and 127°C). For this project, the mixing analysis showed good mixing of the RAP and new binders. Additional studies of this type are needed.

Recovered binder tests on WMA with RAP should be conducted to verify the suggested improvements in low-temperature properties for blending chart analyses.

## B8. Section 7. Process-Specific Specimen Fabrication Procedures

### General Comments

This section describes specimen fabrication procedures for several common types of WMA processes.

### Basis for Critical Content

The specimen fabrication procedures were designed to reasonably reproduce the WMA process. Procedures are provided for:

- WMA additives that are added to the binder.
- WMA additives that are added to the mixture.
- WMA processes incorporating wet fine aggregate and sequential mixing.
- Plant foaming processes.

These procedures were developed from guidance provided by WMA process developers and verified through laboratory testing in NCHRP Project 09-33.

### Need for Further Research

Developers of new WMA processes should be encouraged to prepare specimen fabrication procedures in a similar format so that they can be added in the future to the appendix to AASHTO R 35.

## B9. Section 8. WMA Mixture Evaluations

### General Comments

This section described four evaluations of the WMA mixture at the design binder content:

- Coating,
- Compactability,



**Table 4. 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 °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

- Moisture sensitivity, and
- Rutting resistance.

The coating evaluation is used in lieu of the viscosity-based mixing temperature used for HMA. Coating is evaluated at the design binder content using AASHTO T 195, which measures the percentage of fully coated coarse aggregate particles.

The compactability evaluation is used in lieu of the viscosity-based compaction temperature used for HMA. Compactability is evaluated by compacting specimens to  $N_{design}$  at the planned field compaction temperature and again at 54°F (30°C) below the planned field temperature. The number of gyrations to reach 92-percent relative density is then calculated from the height data. The ratio of the gyrations to 92-percent relative density at the lower temperature to the higher temperature should be less than 1.25.

Moisture sensitivity is evaluated using AASHTO T 283, the same as HMA. The criteria for AASHTO T 283 are the same as that for HMA.

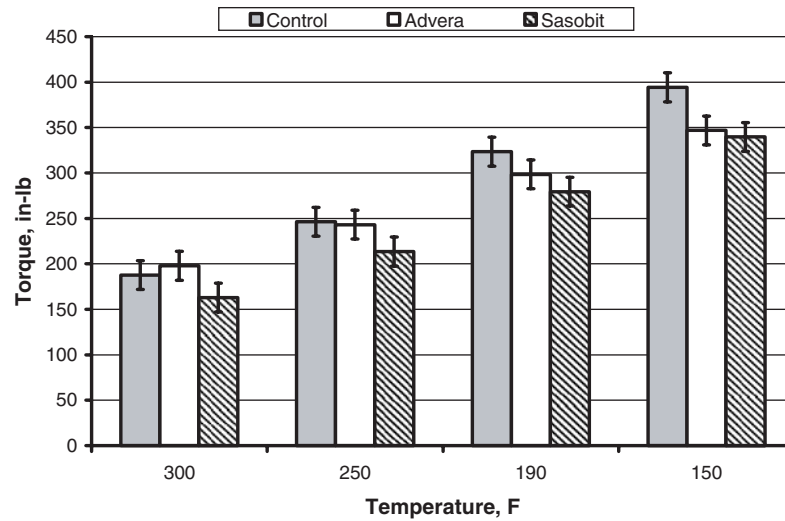
Finally, rutting resistance is evaluated using the flow number test in AASHTO TP 79. The test is conducted at the 50-percent reliability high pavement temperature from LTPPBind 3.1 for the project location. An unconfined flow number test with a repeated deviatoric stress of 87 psi (600 kPa) and a contact

deviatoric stress of 4.4 psi (30 kPa) is used. Minimum flow numbers as a function of traffic level are provided.

### Basis for Critical Content

Coating is one way to evaluate planned WMA production temperatures that is relevant to all WMA processes. In NCHRP Project 09-43, coating was evaluated on a number of HMA and WMA mixtures using AASHTO T 195. When a planetary mixer was used, coating was always found to be nearly 100 percent for both WMA and HMA. When a bucket mixer was used with a smaller number of WMA mixes, the coating was much lower. The mixing times and the recommended criterion of 95 percent were based on the planetary mixer data.

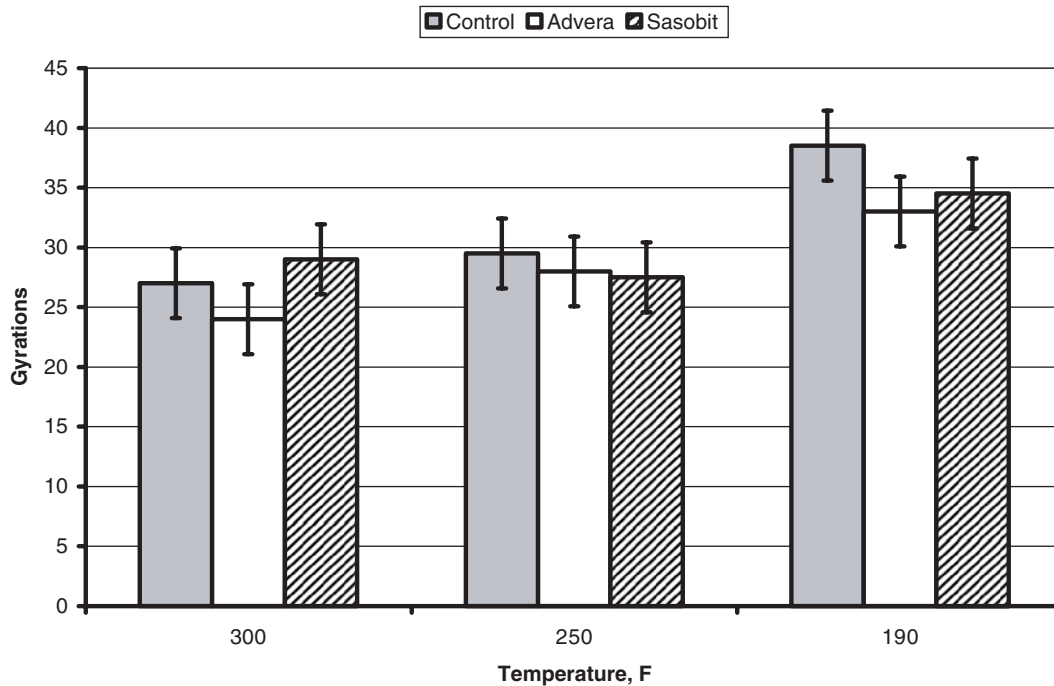
The methodology for the compactability evaluation resulted from a workability study conducted in NCHRP Project 09-43. The workability study evaluated the feasibility of using various workability devices and the gyratory compactor to measure WMA workability during the mixture design process. The workability study demonstrated that it is possible to measure differences in the workability and compactability of WMA compared to HMA. The differences, however, were only significant at temperatures that are below typical WMA discharge



**Figure 3. Effect of temperature and WMA additive on torque measured in the UMass workability device.**

temperatures. Figures 3 and 4 show the effect of WMA process and temperature on workability and compactability. Since the workability devices were not able to discriminate more precisely than compaction data obtained from a standard Superpave gyratory compactor, the method for evaluating the temperature sensitivity of the compactability of WMA was developed for assessing WMA workability and com-

pactability. It involves determining the number of gyrations to 8-percent air voids at the planned field compaction temperature and a second temperature that is approximately 54°F (30°C) lower than the planned field compaction temperature. A tentative limit allowing a 25-percent increase in the number of gyrations when the temperature is decreased was developed. This limit was investigated using data from nine WMA field



**Figure 4. Effect of temperature and WMA additive on gyrations to 92-percent relative density.**

mixture projects sampled in NCHRP 09-43. The increase in gyrations for the WMA processes ranged from 0 to 20 percent. Workability and compactability were not reported to be a problem on any of the projects.

Moisture sensitivity is evaluated using AASHTO T 283. Tests conducted during NCHRP Project 09-43 showed that the moisture sensitivity will likely be different for WMA and HMA mixtures designed using the same aggregates and binder. WMA processes that included anti-strip additives improved the tensile strength ratio of some of the mixtures included in the NCHRP Project 09-43 testing and analysis. Of the nine WMA mixtures that used a WMA process that included an anti-strip additive, the tensile strength ratio remained the same or improved in 67 percent of the mixtures. For WMA mixtures produced using processes that do not include anti-strip additives, the tensile strength ratio never improved and decreased in 79 percent of the mixtures.

Rutting resistance is evaluated using the flow number test. This test has also been recommended to evaluate rutting resistance for HMA mixtures in NCHRP Project 09-33. The test is conducted on specimens that have been short-term conditioned for 2 h at the compaction temperature to simulate the binder absorption and stiffening that occurs during construction. Because lower short-term conditioning temperatures are used for WMA compared to HMA mixtures, binder aging in WMA mixtures is less, resulting in lower flow numbers for WMA mixtures produced with the same aggregates and binder. Table 5 summarizes the difference in flow numbers obtained for the field validation mixtures. The Sasobit process increases the rutting resistance because it increases the high-temperature grade of the binder.

Current criteria for the flow number and other rutting tests for HMA are based on 4 h of short-term conditioning at 275°F (135°C). The short-term conditioning study completed in NCHRP Project 09-43 shows that this level of conditioning represents the stiffening that occurs during construction as well as some time in service. Since it is inappropriate to condition WMA mixtures at temperatures exceeding their production temperature, the criteria for evaluating the rutting resistance of WMA mixtures were reduced compared to those

currently recommended for HMA conditioned for 4 h at 275°F (135°C).

### Need for Further Research

Bucket mixers are significantly less expensive and likely more readily available in mix design laboratories. Additional research should be conducted to develop appropriate mixing times for bucket mixers.

As the draft appendix to AASHTO R 35 is used on a trial basis, data on coating and compactability should be compiled to aid in future revision of the criteria for these two evaluations.

Additional research concerning the moisture sensitivity of WMA is needed and has been initiated by NCHRP in NCHRP Project 09-49, “Performance of WMA Technologies: Stage I—Moisture Susceptibility.”

Additional research is needed on the development of a short-term conditioning procedure for specimens used for the evaluation of moisture sensitivity and rutting resistance that is equally applicable to both WMA and HMA. Research completed in NCHRP Project 09-43 concluded that 2 h of oven conditioning at the compaction temperature reasonably reproduces the binder absorption and stiffening that occurs during construction for both WMA and HMA mixtures. WMA mixtures that are conditioned 2 h at the compaction temperature have binder that is less stiff than similarly conditioned HMA mixtures because of the lower conditioning temperature. Current criteria for evaluating moisture sensitivity and rutting resistance are based on mixtures that have been aged to a greater degree. The conditioning originally specified in AASHTO T 283 for moisture sensitivity testing was 16 h at 140°F (60°C). Additionally, most rutting criteria are based on 4 h of conditioning at 275°F (135°C). In NCHRP Project 09-13, mixtures were conditioned for 2 h at 275°F (135°C), 4 h at 275°F (135°C), and 16 h at 140°F (60°C). Analysis of this data in NCHRP Project 09-43 concluded that 16 h at 140°F (60°C) resulted in somewhat more aging than 4 h at 275°F (135°C). The difference in aging between 2 and 4 h at 275°F (135°C) was not statistically significant. To simulate both WMA and HMA, a two-step conditioning process should be considered for specimens used for evaluation of moisture sensitivity and rutting resistance. In the first step, the mixture would be conditioned for 2 h at the compaction temperature to simulate the binder absorption and stiffening that occurs during construction. In the second step, the mixture would be further conditioned for an extended time at a representative high in-service pavement temperature to simulate a short period of time in service. Only specimens used to evaluate moisture sensitivity and rutting resistance would receive the second conditioning step. Volumetric design would be based on only the first step. The temperature and duration of the extended conditioning would be selected based on temperatures from LTPPBind and typical laboratory working hours.

**Table 5. Summary of average difference in flow number of WMA compared to HMA.**

Process	Number	Average Difference in Compaction Temperature (°F)	Average Difference in Flow Number (%)
Advera	3	-46.7	-39
Evotherm	2	-50.0	-38
LEA	1	-80.0	-50
Sasobit	3	-48.3	+38

Most likely, the second step would require conditioning specimens overnight. The extended conditioning temperature and time would be selected such that HMA mixtures conditioned using the two-step process would have similar stiffness as mixtures conditioned for 4 h at 275°F (135°C).

## **B10. Section 9. Adjusting the Mixture to Meet Specification Properties**

### **General Comments**

This section provides information that can be used to adjust WMA mixtures to meet the evaluation criteria contained in the draft appendix to AASHTO R 35. For coating, compactability, and moisture sensitivity, the user is directed to consult the WMA process supplier. The effects of changing binder grade, volumetric properties, and compaction level on rutting resistance are provided.

### **Basis for Critical Content**

Because WMA processes differ greatly, it was not possible to develop recommendations for adjusting the mixture to meet coating, compactability, and moisture sensitivity requirements. The recommendations for rutting resistance are based on the

effects published in NCHRP Report 567: *Volumetric Requirements for Superpave Mix Design*.

### **Need for Further Research**

Additional research is needed to provide insight on how to change WMA mixtures to improve coating, compactability, and moisture sensitivity. The changes will most likely be process specific.

## **B11. Section 10. Additional Reporting Requirements for WMA**

### **General Comments**

This section describes additional data that should be reported for WMA mixtures.

### **Basis for Critical Content**

There is no critical content in this section.

### **Need for Further Research**

There is no need for additional research.

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## APPENDIX D

# Proposed Standard Practice for Measuring Properties of Warm Mix Asphalt (WMA) for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide Software

Proposed Standard Practice for

# Measuring Properties of Warm Mix Asphalt (WMA) for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide (MEPDG)

AASHTO Designation: PP XX-XX

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## 1. SCOPE

- 1.1. This standard presents procedures measuring engineering properties of warm mix asphalt (WMA) for performance analysis using the Mechanistic-Empirical Pavement Design Guide (MEPDG). The Level 1 inputs to the MEPDG that can be measured with this standard are: (1) dynamic modulus master curve, and (2) low temperature creep compliance and (3) low temperature tensile strength. Specimen fabrication procedures that replicate various WMA processes are also included.
- 1.2. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.*
- 

## 2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards:*

- R 35, Superpave Volumetric Mixture Design
- T 166, Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens
- T 209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
- T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures
- T 312, Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyrotory Compactor
- T 322, Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device
- TP 60, Preparing Cylindrical Performance Test Specimens Using the Superpave Gyrotory Compactor (SGC)

- TP 61, Developing Dynamic Modulus Master Curves for Hot Mix Asphalt Using the Asphalt Mixture Performance Tester (AMPT)
- TP 79, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).

## 2.2. *Other Documents:*

- ASTM D 3549, Thickness of Height of Compacted Bituminous Paving Mixture Specimens
- Equipment Specification for the Simple Performance Test System, Version 3.0, Prepared for National Cooperative Highway Research Program (NCHRP), October 16, 2007
- Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice, AASHTO, Washington DC, 2008

## 3. TERMINOLOGY

- 3.1. *Warm Mix Asphalt (WMA)* – Warm mix asphalt refers to asphalt concrete mixtures that are produced at temperatures approximately 50 °F (28 °C) or more cooler than typically used in the production of hot mix asphalt. The goal with warm mix asphalt is to produce mixtures with similar strength, durability, and performance characteristics as hot mix asphalt using substantially reduced production temperatures.
- 3.2. *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.
- 3.3. *Creep* – The time-dependent part of strain resulting from stress.
- 3.4. *Creep compliance* – The time-dependent strain divided by the applied stress.
- 3.5. *Dynamic Modulus* –  $|E^*|$ , the absolute value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.
- 3.6. *Dynamic Modulus Master Curve* – A composite curve constructed at a reference temperature by shifting dynamic modulus data from various temperatures along the log frequency axis.
- 3.7. *Tensile strength* – The strength shown by a specimen subjected to tension.
- 3.8. *Voids in the mineral aggregate (VMA)* – The volume of the intergranular void space between the aggregate particles of a compacted paving mixture that include the air voids and the effective binder content, expressed as a percent of the total volume of the specimen.

- 3.9. *Voids filled with asphalt (VFA)* – The percentage of the VMA filled with binder (the effective binder volume divided by the VMA).
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## **4. SUMMARY OF THE PRACTICE**

- 4.1. This practice describes methods for preparing WMA test specimens and testing methods to measure the dynamic modulus, low temperature creep compliance, and low temperature strength of WMA mixtures.
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## **5. SIGNIFICANCE AND USE**

- 5.1. The engineering properties of WMA measured using this practice are Level 1 inputs for WMA layers for pavement performance analysis using the MEPDG.
- 5.2. With the measured engineering properties and the MEPDG, project specific estimates of the performance of pavements incorporating WMA layers can be made.
- 5.3. The dynamic modulus is used in the MEPDG stress-strain analysis, rutting model, and fatigue cracking model.
- 5.4. The low temperature creep compliance and strength are used in the MEPDG thermal cracking model.
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## **6. APPARATUS**

- 6.1. *Specimen Fabrication Equipment* – Equipment for fabricating dynamic modulus test specimens as described in AASHTO TP 60.
- 6.2. *Dynamic Modulus Test System* – A dynamic test system meeting the requirements of Equipment Specification for the Simple Performance Test System, Version 3.0.
- 6.3. *Indirect Tensile Test System* – A low temperature indirect tensile test system meeting the requirements of AASHTO T 322.
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## **7. DYNAMIC MODULUS**

### **7.1. Specimen Preparation**

- 7.1.1. Prepare two 100 mm diameter by 150 mm high test specimen.



- 7.1.2. Prepare test specimens in accordance with AASHTO TP 60, except mixture preparation shall be as specified in the WMA Appendix to AASHTO R 35, and short-term oven aging shall be 2 hours at the proposed compaction temperature.
- 7.1.3. The target air void content for the dynamic modulus specimens should be representative of the in-place air void content required by the agency specifications.

## 7.2. **Dynamic Modulus Testing**

- 7.2.1. Test each dynamic modulus specimen at the temperatures and frequencies specified in AASHTO TP 61.
- 7.2.2. Conduct dynamic modulus tests in accordance with AASHTO TP 79.

## 7.3. **Data Analysis**

- 7.3.1. Analyze the resulting data and prepare a dynamic modulus master curve in accordance with AASHTO TP 61.

**Note 1** –A Microsoft Excel™ workbook “MASTERSOLVER2.1.xls” was developed in NCHRP Project 09-29 to perform this analysis.

- 7.3.2. From the fitted dynamic modulus master curve, compute the dynamic modulus at the following temperatures and frequencies for use in the MEPDG software. A total of 30 dynamic modulus values should be calculated.

Temperatures	Frequencies
-10, 4.4, 21.1, 37.8, and 54.4 °C (14, 40, 70, 100, 130, °F)	25, 10, 5, 1, 0.5, and 0.1 Hz

## 7.4. **Report the following:**

- 7.4.1. Mixture identification.
- 7.4.2. Target air voids and the actual air voids for the specimens tested.
- 7.4.3. VMA and VFA of each specimen tested.
- 7.4.4. Average VMA and VFA for the specimens tested.
- 7.4.5. Measured dynamic modulus and phase angle data for each specimen at each temperature/frequency combination.
- 7.4.6. Average measured dynamic modulus and phase angle at each temperature/frequency combination.

- 7.4.7. Coefficient of variation of the measured dynamic modulus data at each temperature/frequency combination.
  - 7.4.8. Standard deviation of the measured phase angle data at each temperature/frequency combination.
  - 7.4.9. Reference temperature.
  - 7.4.10. Parameters of the fitted master curve ( $Max$ ,  $\delta$ ,  $\beta$ ,  $\gamma$  and  $\Delta E_a$ ).
  - 7.4.11. Goodness of fit statistics for the fitted master curve ( $Se$ ,  $Sy$ ,  $Se/Sy$ ,  $R^2$ ).
  - 7.4.12. Plot of the fitted dynamic modulus master curve as a function of reduced frequency showing average measured dynamic modulus data.
  - 7.4.13. Plot of shift factors as a function of temperature.
  - 7.4.14. Plot of average phase angle as a function of reduced frequency.
  - 7.4.15. Tabulated temperature, frequency, and dynamic modulus for input into MEPDG.
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## **8. LOW TEMPERATURE COMPLIANCE AND STRENGTH**

### **8.1. Specimen Preparation**

- 8.1.1. Compact three 150 mm diameter by 115 mm high gyratory specimens in accordance with AASHTO T 312 to a void content that is 1 percent higher than the target test specimen air void content. The target test specimen air void content should be representative of the in-place air void content required by the agency specifications.
- 8.1.2. Prepare a companion sample of loose mix meeting the sample size requirements of AASHTO T 209.
- 8.1.3. Mixture preparation shall be as specified in the WMA Appendix to AASHTO R 35, and short-term oven aging shall be 2 hours at the proposed compaction temperature.
- 8.1.4. To simulate long-term aging, condition the gyratory specimens and the companion loose mix sample in accordance with Sections 7.3.4 through 7.3.6 of AASHTO R 30.
- 8.1.5. Saw one 50 mm thick IDT specimen from the middle of each gyratory specimen.
- 8.1.6. Determine the maximum specific gravity of the companion long-term oven aged loose mix sample in accordance with AASHTO T 209. Record the maximum specific gravity of the mixture.

- 8.1.7. For dense- and gap-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with AASHTO T 166. Record the bulk specific gravity of the test specimen.

**Note 2** – When wet sawing methods are used, measure the immersed mass followed by the surface dry mass followed by the dry mass to minimize drying time and expedite the specimen fabrication process.

- 8.1.8. For open-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with Section 6.2 of AASHTO T 269. Record the bulk specific gravity of the test specimen.
- 8.1.9. Compute the air void content of the test specimen in accordance with AASHTO T 269. Record the air void content of the test specimen.
- 8.1.10. Using calipers, measure the diameter of each test specimen along axes that are 90 ° apart. Record the average diameter to the nearest 1 mm.
- 8.1.11. Measure the height of each test specimen in accordance with Section 6.1.2 of ASTM D 3549. Record the average height to the nearest 1 mm.

## 8.2. Creep and Strength Testing

- 8.2.1. Instrument each test specimen and perform creep tests on each test specimen at temperatures of –20, –10, and 0 °C in accordance with AASHTO T 322. A total of 9 creep tests will be performed.
- 8.2.2. Record the load, horizontal deformation on each face, and vertical deformation on each face at 0.1 sec intervals for the first 10 sec, then at 1 sec intervals from 10 to 100 sec.
- 8.2.3. Remove the specimen mounted instrumentation and perform a strength test at –10 °C in accordance with AASHTO T 322. A total of 3 strength tests will be performed.
- 8.2.4. Determine the corrected tensile strength of each specimen using the following relationship:

$$S_{corrected} = 0.78 \times S_{uncorrected} + 38$$

where:

$S_{corrected}$  = corrected tensile strength for thermal cracking analysis, psi

$$S_{uncorrected} = \frac{2P_{max}}{\pi \times h \times d}$$

$P_{max}$  = peak load during the strength test, lb

$h$  = thickness of the test specimen, in

$d$  = diameter of the test specimen, in

**Note 3** – The corrected strength provides a good estimate of the AASHTO T 322 first failure tensile strength of the specimen without the risk of damage to the specimen mounted instrumentation.

8.2.5. Reduce the creep test data for each temperature in accordance with Section 13 of AASHTO T 322 and compute the average creep compliance as a function of loading time.

8.3. **Report the following:**

8.3.1. Mixture identification.

8.3.2. Target air voids and the actual air voids for the specimens tested.

8.3.3. VMA and VFA of each specimen tested.

8.3.4. Average VMA and VFA for the specimens tested.

8.3.5. Tabulated values of the average compliance versus time for  $-20$ ,  $-10$ , and  $0$  °C.

8.3.6. Corrected tensile strength at  $-10$  °C.

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**9. KEYWORDS**

9.1. Warm Mix Asphalt (WMA), MEPDG, Dynamic modulus, creep compliance, tensile strength

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## UNPUBLISHED MATERIAL

# Appendices C and E

Appendices C and E to the contractor's final report for NCHRP Project 09-43 are not published herein but are available on the TRB website at [www.trb.org/Main/Blurbs/165013.aspx](http://www.trb.org/Main/Blurbs/165013.aspx).

The appendix titles are the following:

- Appendix C: Training Materials for the Draft Appendix to AASHTO R 35
- Appendix E: NCHRP Project 09-43 Experimental Plans, Results, and Analysis

*Abbreviations and acronyms used without definitions in TRB publications:*

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	Air Transport Association
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
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