Appendix C
Training Materials for the Draft Appendix to AASHTO R 35

NCHRP
Project 9-43

Mix Design Practices for Warm Mix Asphalt

Instructor Guide

Appendix to AASHTO R35
Special Mixture Design Considerations and Methods for Warm Mix Asphalt

November 19, 2010

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Seminar Description:

Warm mix asphalt (WMA) is the term given 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 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. Because of these benefits, WMA is becoming increasingly popular with producers, paving contractors, and specifying agencies.

The design of WMA requires some changes to current HMA mix design practices. This seminar describes recommended procedures for designing dense-graded, asphalt concrete mixtures that will be produced using any one of several currently available WMA processes. These WMA mix design recommendations are based on research conducted in National Cooperative Highway Research Program (NCHRP) Project 9-43, *Mix Design Practices for Warm Mix Asphalt*, which concluded that only minor modification of current mix design practice is needed to address WMA. To implement the recommended modifications for WMA, an appendix to the current dense-graded HMA mix design procedure, AASHTO R35, *Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)*, was developed. This appendix titled *"Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)"* is the subject of this seminar.

Objective:

The objective of the WMA mixture design seminar is to present the modifications of the current Superpave volumetric design procedure, AASHTO R35, that are needed to design WMA. To accomplish this objective, this seminar will achieve the following training goals:

- Introduce WMA and the objective of WMA mixture design.
- Group the WMA processes into four generic WMA mixture design classifications.
- Describe the differences and similarities between WMA and HMA design.
- Present the mixture specific specimen fabrication procedures that are used with WMA.
- Present the mixture evaluations that are done for WMA.
- Compare volumetric and performance properties of properly designed WMA and HMA.

Target Audience:

There are two target audiences for the WMA mixture design seminar. The first is experienced HMA mixture design technicians and engineers who are interested in using WMA.

For this audience, which is already well trained in HMA mixture design, the seminar can be presented as stand-alone training addressing the special procedures that are to be used in the design of WMA. The second target audience is engineers and technicians who do not have formal training in HMA mixture design. For this audience, this seminar would be presented in conjunction with other training materials as part of an introductory asphalt concrete mixture design course.

Instructional Method and Lesson Plan:

The WMA mixture design seminar has been designed to be presented by a single instructor with experience in HMA and WMA mixture design. The seminar includes a lecture and discussion of several topics followed by a self-graded quiz to review the material that was covered and assess participant understanding. The duration of the seminar is approximately 2 hours. Instructional materials include: (1) Instructor Guide, (2) Visual Aids, and (3) Participant Workbook. All participants will receive a copy of the Participant Workbook which contains all of the material covered during the seminar, a copy of the proposed AASHTO R35 appendix, and a commentary on the AASHTO R35 appendix. These materials will serve as a resource for designing WMA mixtures. Table 1 presents the lesson plan for the seminar, identifying the major topics that are covered, the specific subject matter included in each major topic, and the time allotted to each major topic.

Table 1. WMA Mixture Design Seminar Lesson Plan.

Topic	Subject Matter	Time
1. Introduction	1.1 Objective 1.2 Outcomes 1.3 Lesson Plan 1.4 Materials	15 min
2. What is WMA?	2.1 WMA Definition 2.2 WMA Processes 2.3 WMA Mix Design Process Categories	10 min
3. Similarities and Differences Between WMA and HMA Design	3.1 Materials Selection 3.2 Volumetric Design 3.3 Evaluation	10 min
4. Appendix to AASHTO R35	4.1 Additional Equipment 4.2 WMA Process Selection	45 min

	4.3 Binder Grade Selection 4.4 RAP in WMA 4.5 Process Specific Specimen Fabrication Procedures 4.6 Evaluations 4.7 Adjusting WMA Mixtures to Meet Specification Requirements	
5. Comparison of WMA and HMA Properties	5.1 Volumetric Properties 5.2 Workability/Compactability 5.3 Resistance to Moisture Damage 5.4 Resistance to Rutting	15 min
6. Self Graded Quiz	Review of Topics 1 through 5	25 min

References:

In addition to the materials contained in this Instructor Guide, seminar instructors should read the following publication:

Prowell, B.E., and Hurley, G.C., "Warm Mix Asphalt: Best Practices," *Quality Improvement Series 125,"* National Asphalt Pavement Association, Lanham MD, 2007.

Introduction

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

Summary

Topic: Introduction

Time Allocation: 15 minutes

Learning Outcomes:
- Introduce instructor and participants.
- Identify the objective and training goals.
- Introduce lesson plan and materials.

Instructional Method Lecture/ Discussion:
- The instructor will begin the seminar by welcoming participants, introducing himself/herself, and providing the participants opportunity to introduce themselves and provide a short description of their background and interests in WMA.
- The Instructor will introduce the objective and training goals for the seminar.
- The instructor will review the lesson plan.
- The Instructor will distribute the Participant Workbook and explain its contents.

Evaluation Plan: None

Slide 1

🗝 **Key Message**: This seminar covers a recently developed appendix to AASHTO R35, *Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*, that addresses the design of warm mix asphalt (WMA). This appendix is the product of National Cooperative Highway Research Program (NCHRP) Project 9-43. It identifies the changes to the current mix design procedure for HMA that are needed to design WMA.

🗎 **Background Information**: NCHRP Project 9-43 was conducted to adapt existing HMA mixture design procedures to WMA. This research concluded that only minor modification of current mix design practice is needed to address WMA. To implement the recommended modifications for WMA, an appendix to the current dense-graded HMA mix design procedure, AASHTO R35, *Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*, was developed. This appendix titled *"Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)"* is the subject of this seminar.

🗣 **Presentation:** Welcome the participants to the seminar. Introduce yourself and provide a summary of your experience with the design of HMA and WMA.

Pass out the Participant Workbooks. Explain that all of the seminar materials are in the Participant Workbook. Direct the participants to Page 1-3 of the Participant Workbooks.

Introduce the seminar by explaining that the seminar covers a recently developed Appendix to AASHTO R35 that presents changes to current HMA mixture design that are necessary to design WMA.

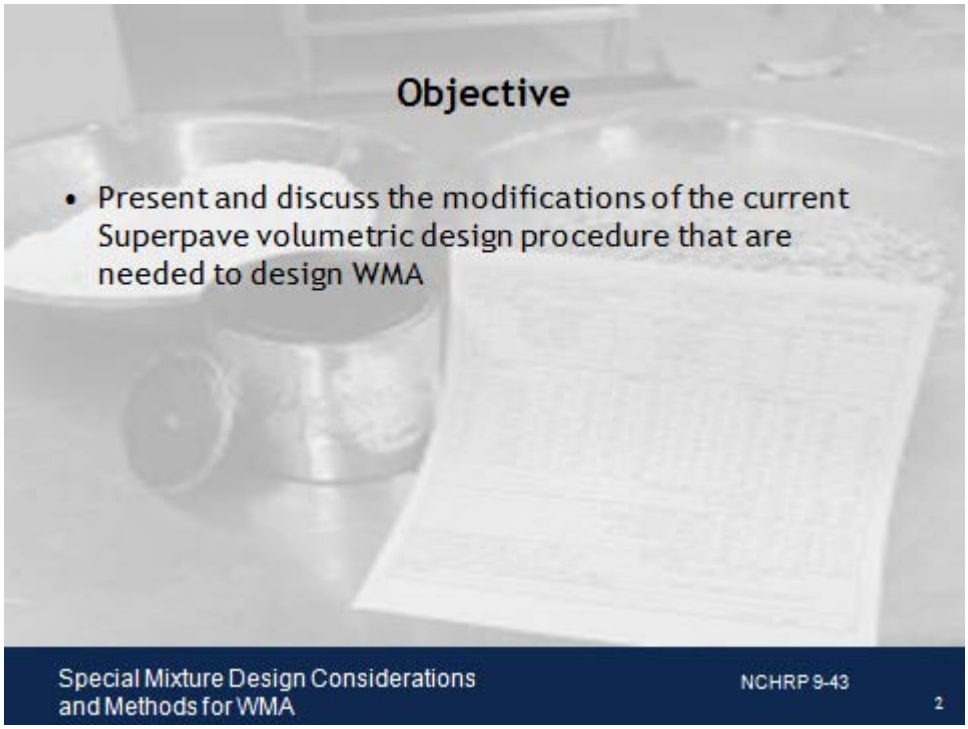
If appropriate, have each of the participants introduce themselves by providing:

- Name
- Affiliation

- Position
- Experience with WMA

Time: A total of 5 minutes

Slide 2



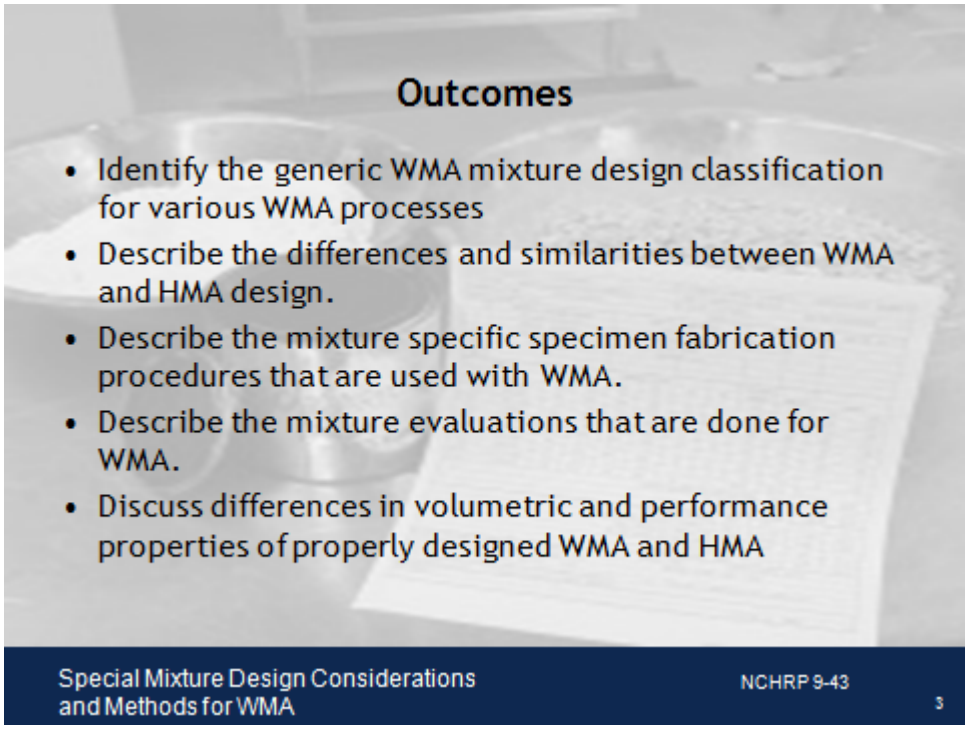
🗝 **Key Message**: The objective of the WMA seminar is to present and discuss the modifications of the current Superpave volumetric design procedure that are needed to design WMA.

🗎 **Background Information**:

🗣 **Presentation:** State the objective of the seminar.

🕒 **Time**: A total of 1 minute.

Slide 3



🗝 **Key Message**: After completing the WMA mix design seminar, the participants will understand how to design WMA mixtures. Specific outcomes are listed on the slide.

📰 **Background Information**:

🗣 **Presentation:** This slide is animated; the goals will appear upon each mouse click. Discuss each of the goals with the participants.

🕒 **Time**: A total of 2 minutes.

Slide 4

WMA Seminar Lesson Plan

Topic	Subject Matter	Time
1 Introduction	1.1 Objective 1.2 Outcomes 1.3 Lesson Plan 1.4 Materials	5 min
2 What is WMA?	2.1 WMA Definition 2.2 WMA Processes 2.3 WMA Mix Design Process Categories	10 min
3 Similarities & Differences Between HMA & WMA Design	3.1 Materials Selection 3.2 Volumetric Design 3.3 Evaluation	10 min

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Slide 5

WMA Seminar Lesson Plan (continued)

Topic	Subject Matter	Time
4 Appendix to AASHTO R35	4.1 Additional Equipment 4.2 WMA Process Selection 4.3 Binder Grade Selection 4.4 RAP in WMA 4.5 Process Specific Specimen Fabrication Procedures 4.6 Evaluations 4.7 Adjusting WMA Mixtures to Meet Specification Requirements	45 min
5 Comparison of WMA and HMA Properties	5.1 Volumetric Properties 5.2 Workability/Compactability 5.3 Resistance to Moisture Damage 5.4 Resistance to Rutting	15 min
6 Self Graded Exam		25 min

Special Mixture Design Considerations and Methods for WMA NCHRP 9-43 5

🗝 **Key Message**: These two slides summarize the topics and subject matter that will be covered in the seminar, and the time devoted to each topic.

🗎 **Background Information**:

Presentation: Go though each topic in the lesson plan.

1. Explain that we are nearly finished with Topic 1, Introduction.

2. During Topic 2, What is WMA?, we will define what WMA is, review the various WMA processes, and discuss how the various processes fit into four mix design categories.

3. Topic 3, Similarities and Differences Between WMA and HMA Design, highlights the areas where WMA and HMA design differ.

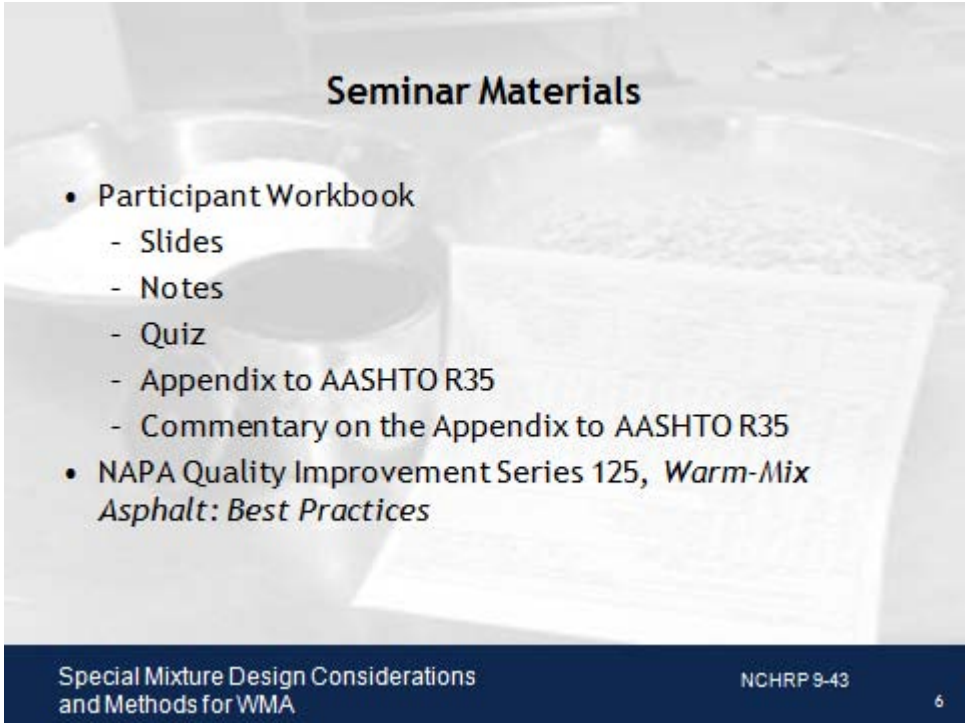
4. The majority of the time for the WMA seminar is spent in Topic 4, Appendix to AASHTO R35. During this part of the seminar each of the major parts of the WMA appendix will be discussed.

5. During Topic 5, Comparison of WMA and HMA Properties, volumetric and performance properties from mixtures made with the same materials but designed as WMA and HMA will be presented.

6. Topic 6 is a self-graded quiz. This quiz is designed to provide a review of the material covered in Topics 2 through 5 of the seminar.

Time: A total of 4 minutes.

Slide 6



🗝 **Key Message**: All of the materials from the WMA seminar are included in the Participant Workbook.

📰 **Background Information**:

🗣 **Presentation:** Explain that all of the materials for the WMA seminar are included in the Participant Workbook. This includes:

- Slides
- Lecture Notes
- Quiz
- Appendix to AASHTO R35 for designing WMA
- Commentary on the Appendix to AASHTO R35

Have the participants turn to the Appendix to AASHTO R35. Point out that they can use this as a reference when designing WMA mixtures.

Have the participants turn to the Commentary on the Appendix to AASHTO R35. Explain that the commentary provides background information on the research that led to each of the major recommendations in the Appendix to AASHTO R35.

In addition to the materials provided, recommend that the participants obtain a copy of NAPA Quality Improvement Series 125, *Warm-Mix Asphalt: Best Practices.* This publication provides additional information on many WMA processes including the equipment modifications that are needed.

Time: A total of 3 minutes.

What is WMA?

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

Summary

Topic: What is WMA?

Time Allocation: 10 minutes

Learning Outcomes:
- Define WMA.
- List the WMA Mixture Design Categories.

Instructional Method Lecture/ Discussion:
- The Instructor will define WMA and describe the benefits associated with WMA.
- The Instructor will show that there are numerous WMA processes being marketed in the United States.
- The Instructor will introduce the four WMA mixture design categories and explain how the various processes will fit into one of these four categories.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 7

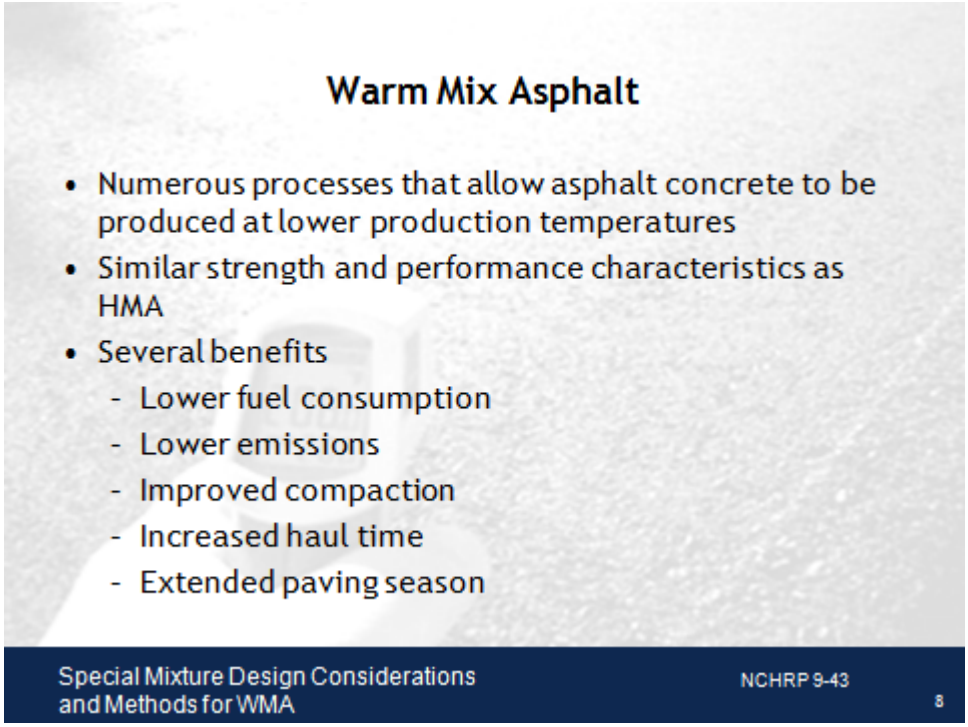
🗝 **Key Message**: Transition slide to introduce Topic 2

🗎 **Background Information**:

🗣 **Presentation:** Introduce this topic by explaining that this part of the seminar is a brief introduction to WMA and the various WMA processes.

🕒 **Time**: A total of 1 minute.

Slide 8



🗝 **Key Message**: WMA is a generic term for a number of processes that allow asphalt concrete to be produced at lower temperatures. WMA is expected to have similar strength, durability, and performance characteristics as HMA. It also has several environmental and engineering benefits.

📃 **Background Information**:

🗣 **Presentation:** Explain that WMA is a generic term used for a number of processes that allow asphalt concrete to be produced at lower temperatures. WMA has been successfully produced at temperatures that are 50 to 100 °F below the temperatures used to produce HMA.

Explain that WMA is expected to have similar strength and performance characteristics as HMA.

Explain that there are environmental and engineering benefits associated with WMA. The environmental benefits include: reduced fuel consumption, lower emissions. Some of the engineering benefits include: improved compaction, increased haul time, extended paving season.

🕒 **Time**: A total of 2 minutes.

Slide 9

🗝 **Key Message**: A number of WMA technologies are being marketed in the United States.

🗎 **Background Information**: There are over 20 WMA technologies being marketed in the United States. The list on this slide was taken on 10/21/2010 from the WMA Technologies page at the website www.warmmixasphalt.com.

🗣 **Presentation:** Use this slide as a lead to the next slide. Explain that there are over 20 WMA technologies being marketed in the United States and that an excellent reference for the technologies is the website www.warmmixasphalt.org. The list shown here was taken from that website on 10/21/2010. For each technology, there is a link to the technology provider's website where you can get additional information on the process.

Do not go over the individual processes, use this list to explain that for mixture design purposes, these technologies can be categorized into four processes.

🕓 **Time**: A total of 1 minutes.

Slide 10

🗝 **Key Message**: The WMA processes can be grouped into four categories for mixture design purposes: (1) additives added to the binder, (2) additives added to the mixture, (3) wet aggregate mixtures, and (4) foamed asphalt mixtures.

🗎 **Background Information**:

🗣 **Presentation:** This slide is animated. The categories and their photo will appear on each mouse click.

Start by explaining that the 20 technologies shown on the previous slide can be grouped into four categories for mixture design. Then reveal each category and ask the participants to provide an example of a process for each category. Remind the participants that there is space on Page 2-4 of the Participant Workbook to write in the processes.

Additives added to the binder?
1. Most chemical processes
2. Waxes
3. Advera

Additives added to the mixture?
1. Waxes
2. Aspha-min
3. Thiopave

Wet Aggregate?
1. Low Emission Asphalt

Foamed Asphalt?
1. Plant foaming systems

Explain that some processes may use more than one of these categories. For example in the Low Emission Asphalt process an additive is added to the binder and wet aggregate is used.

Time: A total of 6 minutes.

Similarities and Differences Between WMA and HMA Design

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

Summary

Topic: Similarities and Differences Between WMA and HMA Design

Time Allocation: 10 minutes

Learning Outcomes:

- Describe the similarities and differences between WMA and HMA design.

Instructional Method Lecture/ Discussion:

- The Instructor will summarize the differences and similarities between WMA and HMA design for the three major parts of the mixture design process:
    1. Materials Selection,
    2. Volumetric Design, and
    3. Mixture Evaluation.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 11

🗝 **Key Message**: Transition slide to introduce Topic 3.

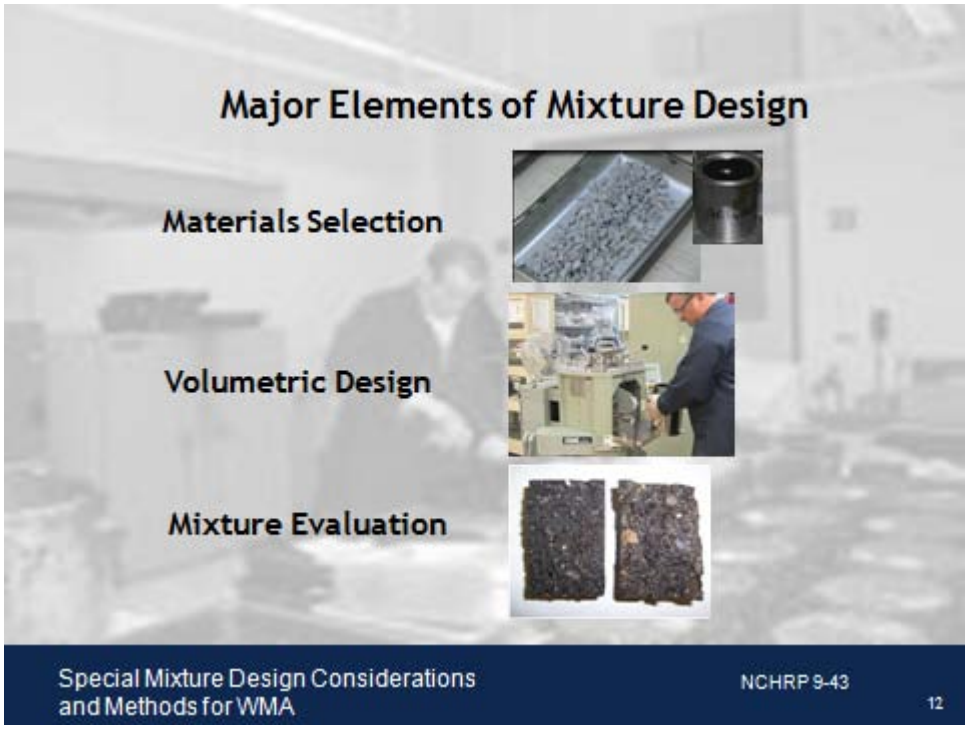
🗎 **Background Information**:

🗣 **Presentation:** Introduce this topic by explaining that this part of the seminar covers similarities and differences in the design of HMA and WMA mixtures.

The PC and Mac are both computers, but there are some differences that Apple has used to separate its products. The same is true for HMA and WMA.

🕒 **Time**: A total of 1 minute.

Slide 12



🗝 **Key Message**: There are three major parts to the mixture design process: (1) materials selection, (2) volumetric design, and (3) mixture evaluation.

📰 **Background Information**:

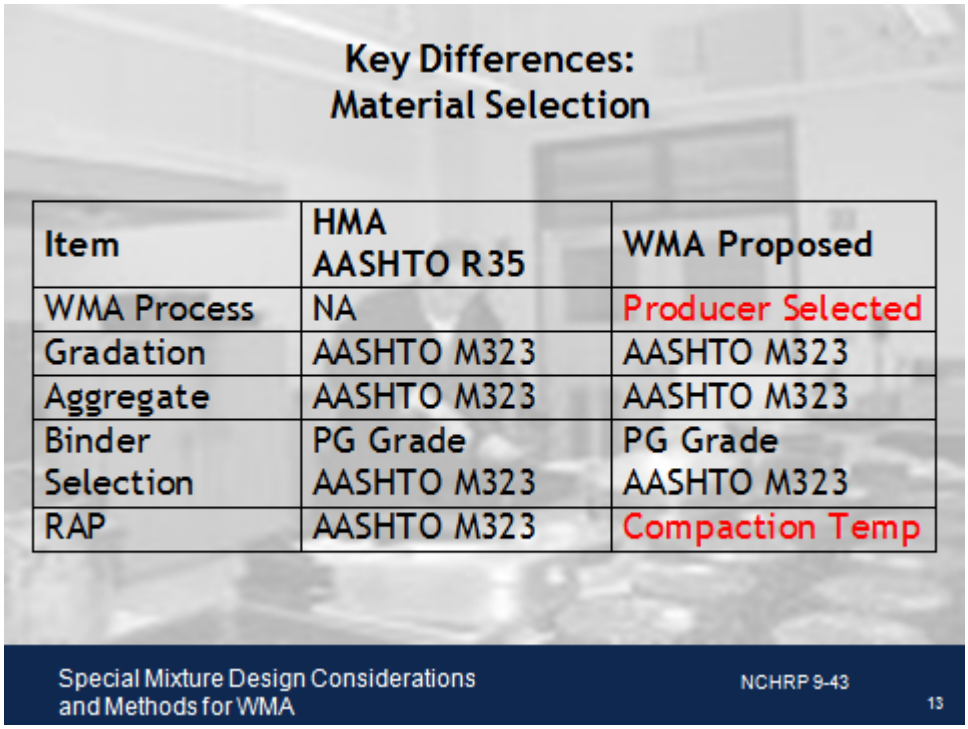
🗣 **Presentation:** This slide is animated. The major mix design elements and their photo will appear on each mouse click.

Use this slide to introduce the three main elements of asphalt concrete mixture design: (1) materials selection, (2) volumetric design, and (3) mixture evaluation.

Explain that the next three slides will compare WMA and HMA for each element

🕒 **Time**: A total of 2 minutes.

Slide 13



Item	HMA AASHTO R35	WMA Proposed
WMA Process	NA	Producer Selected
Gradation	AASHTO M323	AASHTO M323
Aggregate	AASHTO M323	AASHTO M323
Binder Selection	PG Grade AASHTO M323	PG Grade AASHTO M323
RAP	AASHTO M323	Compaction Temp

🗝 **Key Message**: There are several items to consider in materials selection. Mix gradation, and aggregate and binder selection are the same for WMA and HMA. For WMA the producer must select a WMA process and the planned field production and compaction temperatures. There are some limits on RAP stiffness based on the planned field compaction temperature.

🗎 **Background Information**:

🗣 **Presentation:** Explain that this chart presents a summary of the differences between HMA and WMA for the materials selection portion of the mixture design process. It shows the key item, how it is addressed in current HMA design, and the similarities and differences for WMA design. Go through each of the 5 items as follows:

1. **WMA Process.** For WMA design, the producer must select the WMA process and the planned field mixing and compaction temperatures because the fabrication of WMA specimens in the laboratory is process specific, simulating in an approximate manner, the production of the mixture in the field. WMA process selection is best made by the producer in consultation with the specifying agency and WMA process suppliers.

2. **Gradation.** Same as HMA.

3. **Aggregate.** Same as HMA.

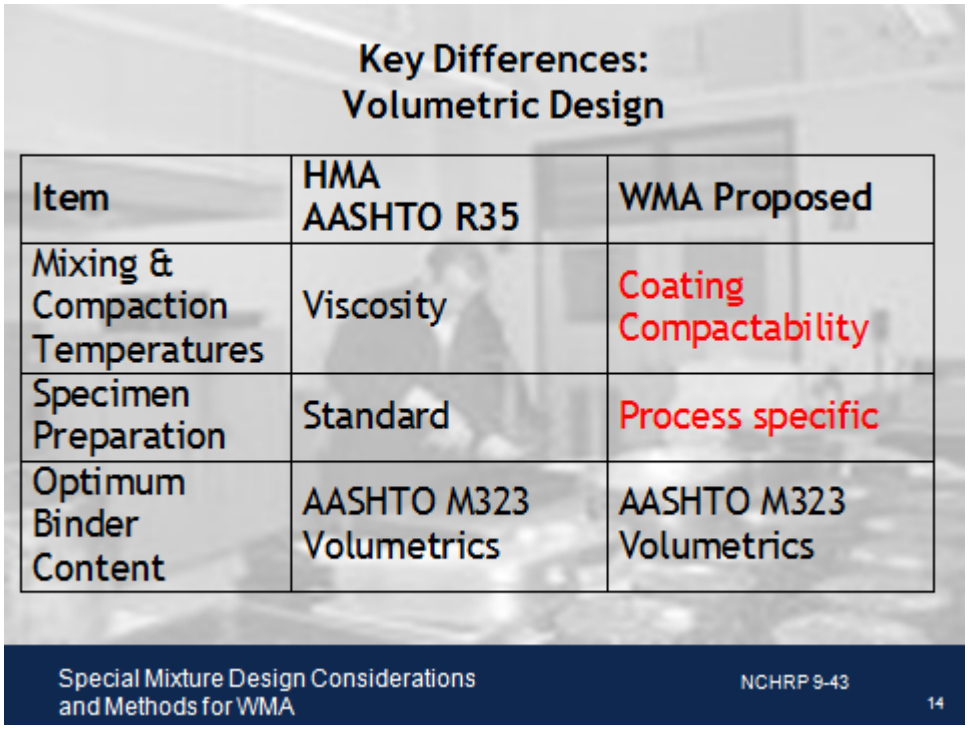
4. **Binder Grade.** Same as HMA.

5. **RAP.** When a recycled binder is used in WMA, there is a limit on the stiffness of the recycled binder to ensure adequate mixing of the new and recycled materials. This

limit will generally not affect RAP but will limit the use of recycled asphalt shingles (RAS) in many WMA mixtures.

Time: A total of 3 minutes.

Slide 14



Item	HMA AASHTO R35	WMA Proposed
Mixing & Compaction Temperatures	Viscosity	Coating Compactability
Specimen Preparation	Standard	Process specific
Optimum Binder Content	AASHTO M323 Volumetrics	AASHTO M323 Volumetrics

🗝 **Key Message**: The viscosity based mixing and compaction temperatures used in designing HMA cannot be used with the wide range of WMA processes that are available so coating and compactability are evaluated instead. Specimen preparation is process specific using one or more of the WMA categories previously discussed. The mixture volumetric criteria used in determining the design binder content are the same for WMA and HMA.

📃 **Background Information**:

🗣 **Presentation:** Explain that this chart presents a summary of the differences between HMA and WMA for the volumetric design portion of the mixture design process. It shows the key item, how it is addressed in current HMA design, and the similarities and differences for WMA design. Go through each of the 3 items as follows:

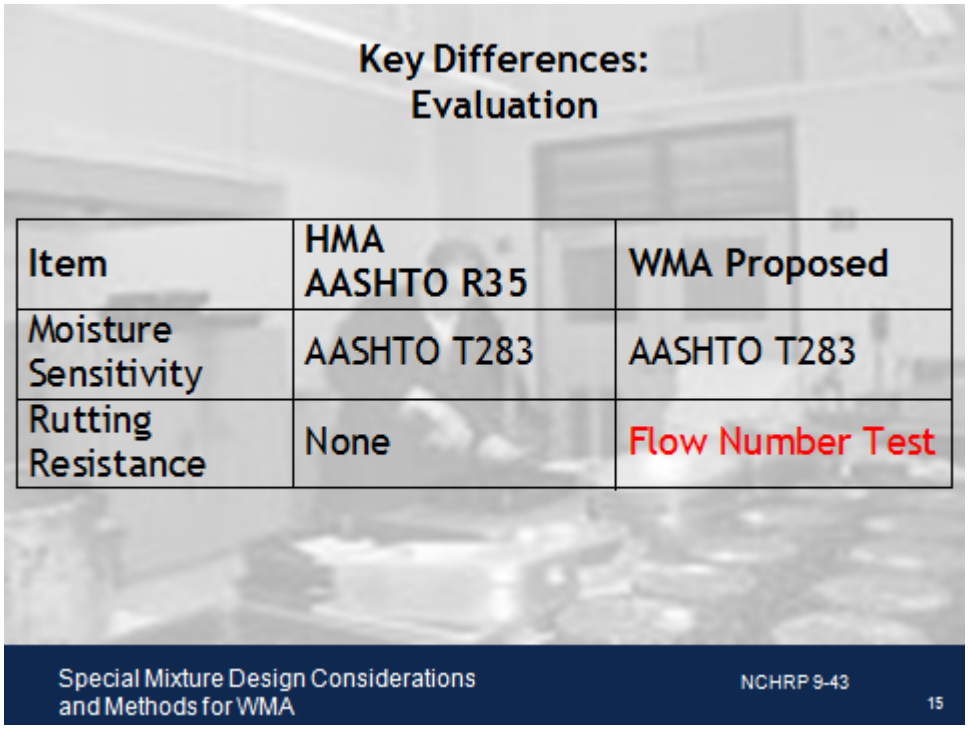
1. **Mixing and Compaction Temperature.** Viscosity based mixing and compaction temperatures cannot be used to control coating, workability, and compactability of WMA mixtures. For WMA coating and compactability are evaluated at the planned field production and compaction temperatures.

2. **Specimen Preparation.** Standard specimen fabrication procedures are used in HMA mixture design. For WMA the specimen fabrication procedures are process specific using one or more of the generic categories previously described: (1) additive added to the binder, (2) additive added to the mixture, (3) wet aggregate mixtures, or (4) foamed asphalt.

3. **Optimum Binder Content.** Same as HMA, using the same gyration level, same design air void content, same VMA criteria, and same limits on dust to effective asphalt ratio.

Time: A total of 2 minutes.

Slide 15



🗝 **Key Message**: Mixture evaluation includes an evaluation of the moisture sensitivity of the mixture and the rutting resistance. Moisture sensitivity evaluation is the same for WMA and HMA. Rutting resistance is evaluated using the flow number from the Asphalt Mixture Performance Tester (AMPT).

📃 **Background Information**:

🗣 **Presentation:** Explain that this chart presents a summary of the differences between HMA and WMA for the mixture evaluation portion of the mixture design process. It shows the key item, how it is addressed in current HMA design, and the similarities and differences for WMA design. Go through each of the 2 items as follows:

1. **Moisture Sensitivity.** The same evaluation, AASHTO T283, is recommended for WMA and HMA. The criteria for WMA are the same as HMA.

2. **Rutting Resistance.** Since the short-term aging of WMA mixtures will be less due to the lower temperatures, it is important to evaluate the rutting resistance of WMA mixtures. The Appendix to AASHTO R35 uses the flow number test for this evaluation. The flow number will likely be added in the future to HMA mixture design. States that currently use a wheel tracking device should also use that device for WMA mixtures.

🕒 **Time**: A total of 2 minutes.

Appendix to AASHTO R35

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

Summary

Topic: Appendix to AASHTO R35

Time Allocation: 45 minutes

Learning Outcomes:

- List the additional equipment needed to design WMA mixtures.
- Describe the major differences in the design of HMA and WMA mixtures.
- Explain why the specific WMA process and the planned field production and compaction temperatures are needed for WMA design.
- List the process specific specimen fabrication procedures used in WMA design.
- Describe why coating and compactability are evaluated during WMA design.
- List the steps in the procedure to evaluate coating.
- List the steps in the procedure to evaluate compactability.
- Describe how rutting resistance is evaluated in WMA design.

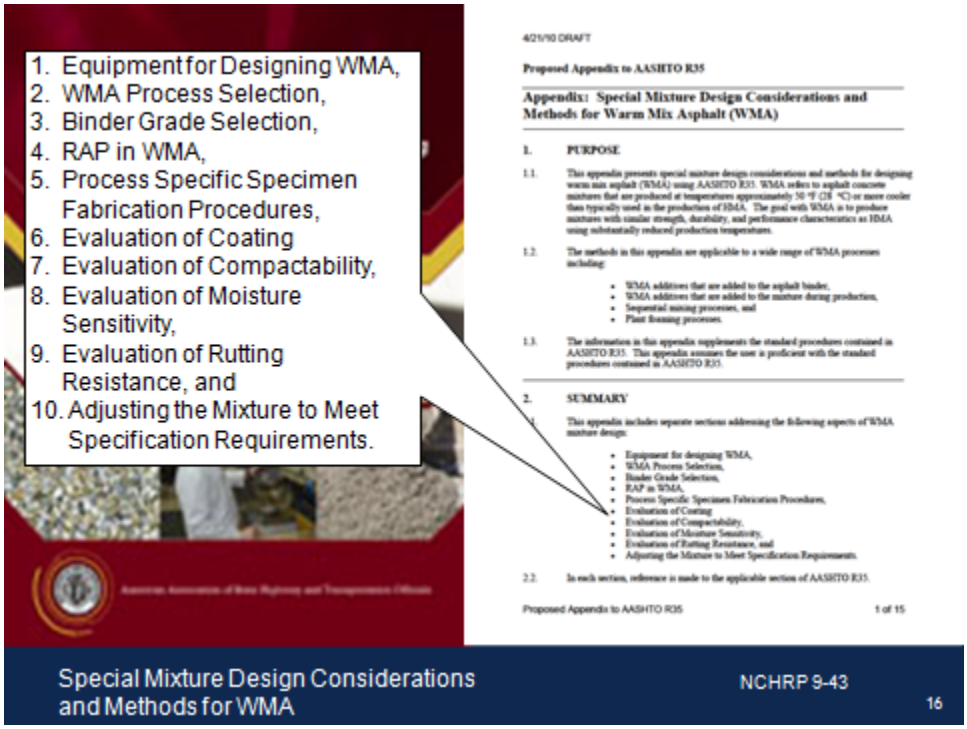
Instructional Method Lecture/ Discussion:

- The Instructor will summarize the important parts of the Appendix to AASHTO R35 including:

    1. Equipment for Designing WMA,
    2. WMA Process Selection,
    3. Binder Grade Selection,
    4. RAP in WMA,
    5. Process Specific Specimen Fabrication Procedures,
    6. Evaluation of Coating,
    7. Evaluation of Compactability,
    8. Evaluation of Moisture Sensitivity,
    9. Evaluation of Rutting Resistance, and
    10. Adjusting the Mixture to Meet Specification Requirements.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 16



🗝 **Key Message**: Transition slide to introduce Topic 4.

🗎 **Background Information**:

🗣 **Presentation:** This slide is animated. On the first mouse click the topics covered by the Appendix to AASHTO R35 and in this portion of the seminar are enlarged.

Introduce this topic by explaining that the major product of NCHRP Project 9-43 was an Appendix to AASHTO R35 titled, *Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA).* This appendix presents the modifications to the current Superpave mixture design procedure, AASHTO R35 that are necessary to design WMA mixtures.

Click the mouse to enlarge the topics in the Appendix to AASHTO R35 and explain that during this part of the seminar each of these topics will be covered.

Remind the participants that a copy of the Appendix to AASHTO R35 is at the back of their Participant Workbook. There is also a copy of the Commentary on the Appendix to AASHTO R35 that provides additional detail for each topic covered by the Appendix to AASHTO R35.

🕒 **Time**: A total of 1 minute.

Slide 17

🗝 **Key Message**: WMA design requires some additional equipment that is not needed for HMA design. This equipment includes (1) low shear mixer to mix some WMA additives into the binder, (2) mechanical mixer to mix the aggregate and binder at WMA temperatures, and (3) for plant foaming processes, laboratory scale asphalt foaming equipment.

🗎 **Background Information**: This section of the appendix 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.

The design of WMA mixtures includes an evaluation of coating using AASHTO T195. To standardize the mixing process, a mechanical mixer is required. During NCHRP Project 9-43, it was observed that planetary mixers and bucket mixers do not have the same mixing efficiency. The specimen fabrication procedures were developed in NCHRP Project 9-43 using a planetary mixer. If a bucket mixer is used, the user will have to develop appropriate mixing times.

NCHRP Project 9-43 demonstrated that it is feasible to perform foamed asphalt WMA mixture designs in the laboratory. In NCHRP project 9-43, 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 the replace the flow controller with a smaller, more precise flow controller to accommodate the water contents used in WMA mixtures. Since the completion of NCHRP 9-43, Pavement Technology, Inc. has introduced laboratory foaming equipment for simulating WMA plant foaming processes.

Presentation: This slide is animated. The additional equipment and its photo will appear on each mouse click.

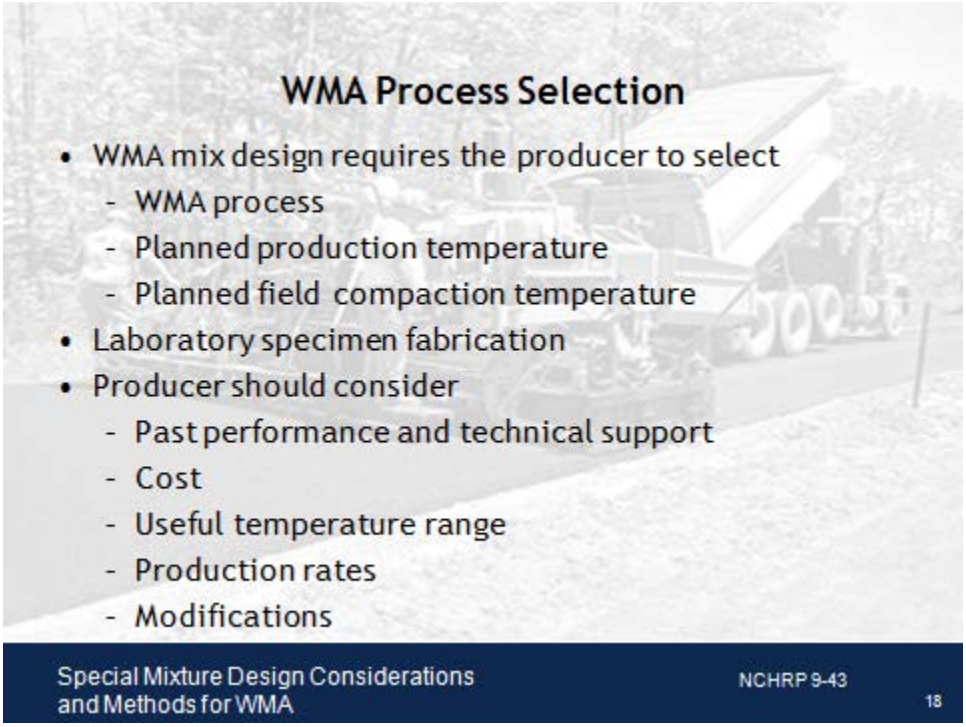
1. **Low Shear Mixer.** Explain that this mixer is needed when designing mixtures that require the WMA additive to be added to the binder. All that is needed is a variable speed drill motor mounted to a laboratory stand with an appropriate size impeller. A hot plate is used to maintain the temperature of the binder during mixing.

2. **Mechanical Mixer.** Explain that because coating is evaluated as part of the mix design process, it is necessary to standardize WMA mixing. Two types of mixers are available: planetary and bucket. The mixing times included in the Appendix to AASHTO R35 are based on planetary mixers and until additional research is done with bucket mixers, designers using bucket mixers will have to develop appropriate mixing times.

3. **Laboratory Foaming Equipment.** For plant foaming processes, laboratory foaming equipment is needed to simulate the plant foaming. Explain that there are only two manufacturers of this equipment. The one on the left by Writgen was designed for in-place base course stabilization and needs to be modified to operate at the lower water contents used in WMA production. The one on the right by Pavement Technology, Inc. was designed to simulate WMA processes.

Time: A total of 5 minutes.

Slide 18



🗝 **Key Message**: WMA mix design requires that the WMA process and the planned field production and compaction temperatures be known at the start of the design so that proper procedures for specimen fabrication will be used. The WMA process and the temperatures are selected by the producer considering several items.

📃 **Background Information**:

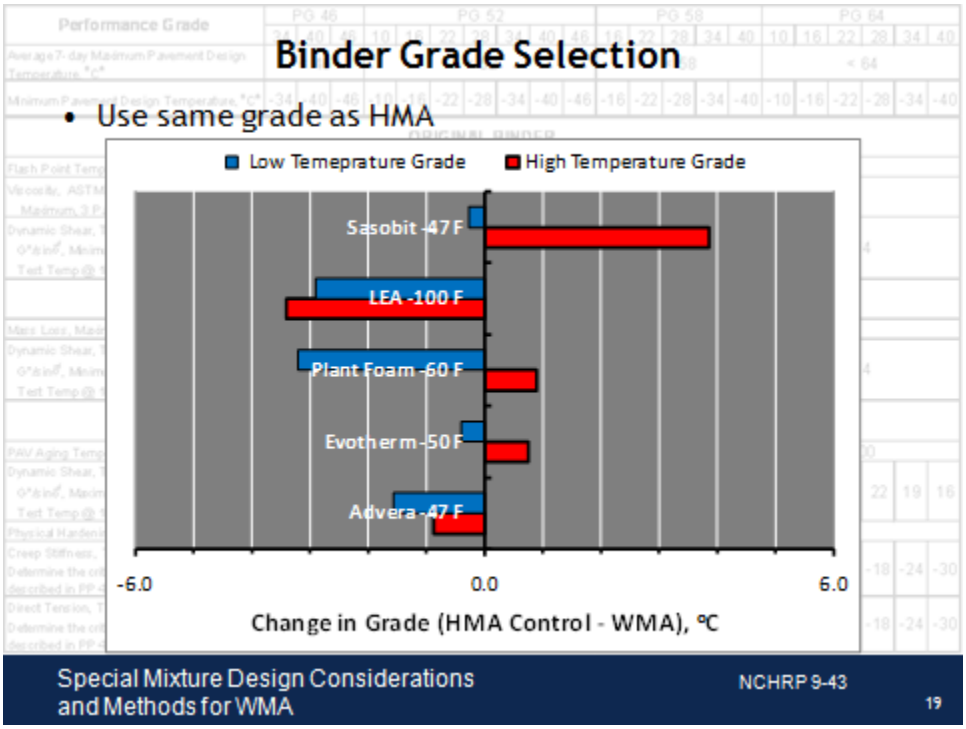
🗣 **Presentation:** Explain that the WMA mix design process uses process specific specimen fabrication procedures. Also coating and compactability are evaluated at the planned field production and compaction temperatures in lieu of viscosity based mixing and compaction temperatures.

Producers should select the WMA process and the planned field production and compaction temperatures considering several factors including:

1. Past performance and technical support
2. Cost
3. Useful temperature range
4. Production rates
5. Plant modifications

🕒 **Time**: A total of 2 minutes.

Slide 19



🗝 **Key Message**: The same binder grade should be used for HMA and WMA mixtures designed for the same traffic and environmental conditions. This recommendation is based on recovered binder data from several mixtures tested during NCHRP 9-43.

🗎 **Background Information**: Performance grading data for binders recovered from several WMA projects sampled during NCHRP Project 9-43 show only small differences in the grade of the binder for WMA and HMA sections. The average differences in the continuous high and low temperature grade between HMA and WMA are shown in the graph. Excluding Sasobit, which increases the high temperature grade of the binder, an approximately 50 °F (28 °C) reduction in production temperature resulted in only a small change in the high temperature grade of the recovered binder. 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 1.5 °C, while an approximately 100 °F (56 °C) reduction in production temperature resulted in 2.9 °C improvement for one LEA project.

🗣 **Presentation:** This slide is animated. The graph showing the recovered binder grade results will appear on the first mouse click.

First explain that the same binder grade should be used for HMA and WMA mixtures designed for the same traffic and environmental conditions.

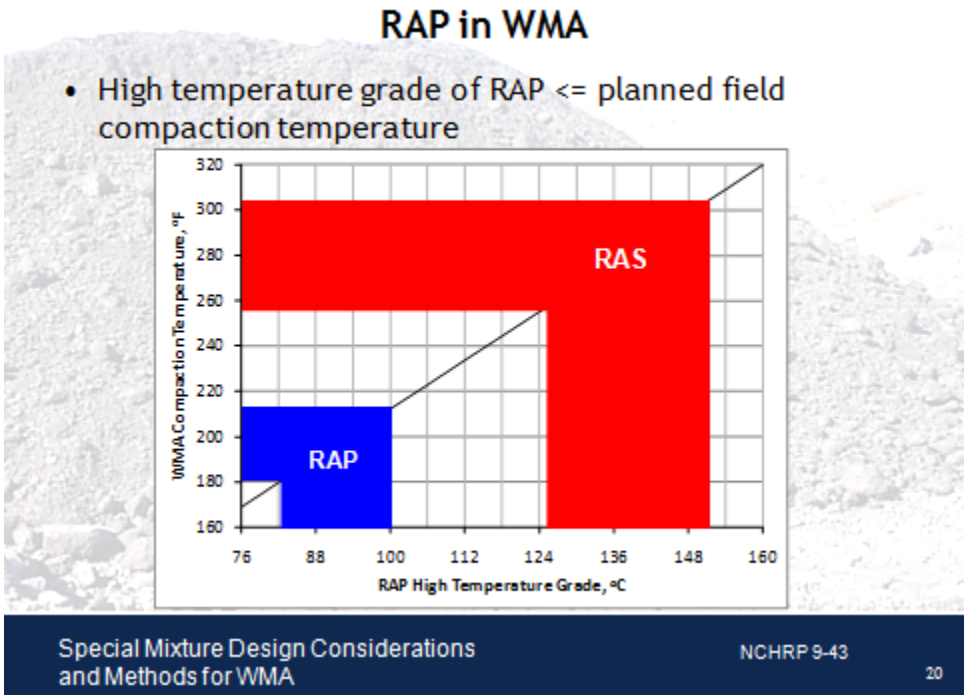
Show the graph and explain that this recommendation is based on recovered binder data from several mixtures tested during NCHRP 9-43 that are summarized in the graph. Explain that the graph shows the difference between the performance grading properties for WMA and HMA control sections on the same project.

Point out how the high temperature grade changes little for Advera, Evotherm, and plant foaming for approximately -50 ^{o}F reduction in production temperature. The LEA process which has a greater reduction in temperature of about 100 ^{o}F, results in about one-half grade reduction in the high temperature grade. Sasobit results in about a one-half grade increase in high temperature grade.

Point out that there is an improvement in the low temperature grade for all processes. This improvement ranges from about 0.5 to 3 ^{o}C.

Time: A total of 5 minutes.

Slide 20



🗝 **Key Message**: To ensure good mixing of the new and recycled binders, the high temperature grade of the binder in RAP used in WMA should be lower than the planned compaction temperature.

📰 **Background Information**: Research completed in NCHRP Project 9-43 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 9-43, 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 100 resulting in corresponding minimum field compaction temperatures ranging from 180 to 212 °F (82 to 100 °C), so this criteria will have little effect on the use or RAP in WMA. It will, however, limit the use of recycled asphalt shingle (RAS) in WMA. RAS binders have high temperature grades exceeding 125 °C, limit the use of these binder in WMA to the highest temperature WMA processes.

🗣 **Presentation:** This slide is animated. The graph will appear on the first mouse click.

First explain that NCHRP Project 9-43 found that RAP binders mix at WMA process temperatures and continue to mix while the mixture is stored at elevated temperatures. To

ensure that adequate mixing of the 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.

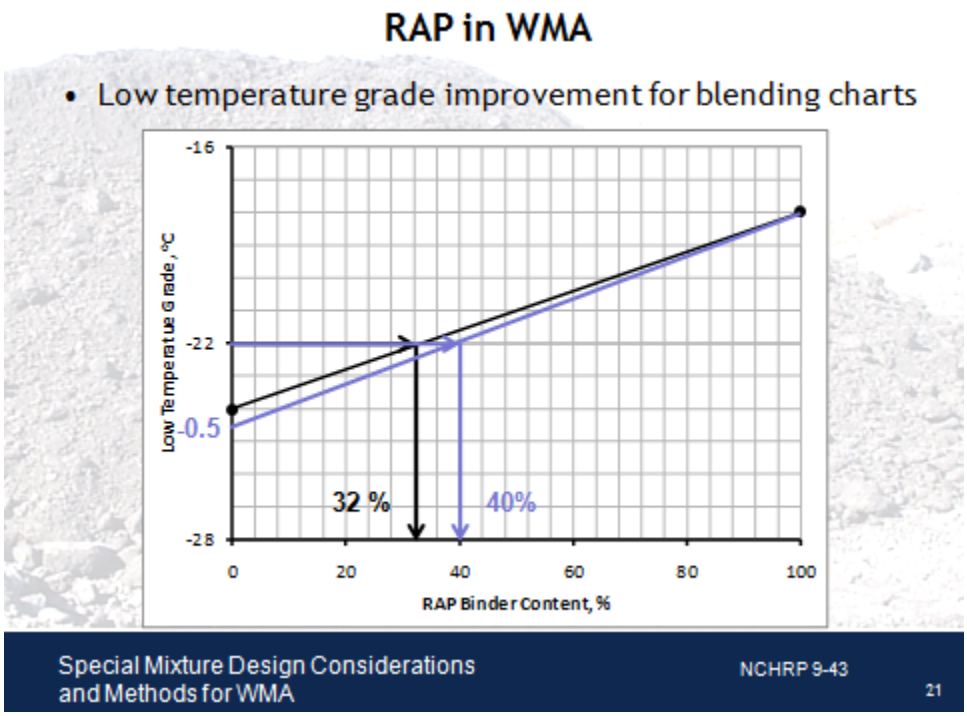
Show the graph and explain that the criterion is the planned field compaction temperature should be equal to or less than the high temperature grade of the recycled binder.

Use the animation on the graph to show how the criterion should not have a major effect for RAP. For the range of RAP found in the US, the criterion requires the planned field compaction temperature to be greater than 180 to 212 ^{o}F. Explain that most WMA is compacted above this temperature.

Use the animation on the graph to show how the criteria will limit the WMA processes that can be used with RAS. RAS typically has high temperature grade exceed 125 ^{o}C, requiring planned field compaction temperatures exceeding 255 ^{o}F.

Time: A total of 5 minutes.

Slide 21



🗝 **Key Message**: The lower production temperature for WMA results in an improvement in the low temperature grade of the binder. Accounting for this improvement when performing blending chart analysis will allow a greater amount of RAP to be used in WMA.

🗎 **Background Information**: 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. 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.

🗣 **Presentation:** This slide is animated. The graph will appear on the first mouse click.

? Ask how many participants are familiar with blending charts?

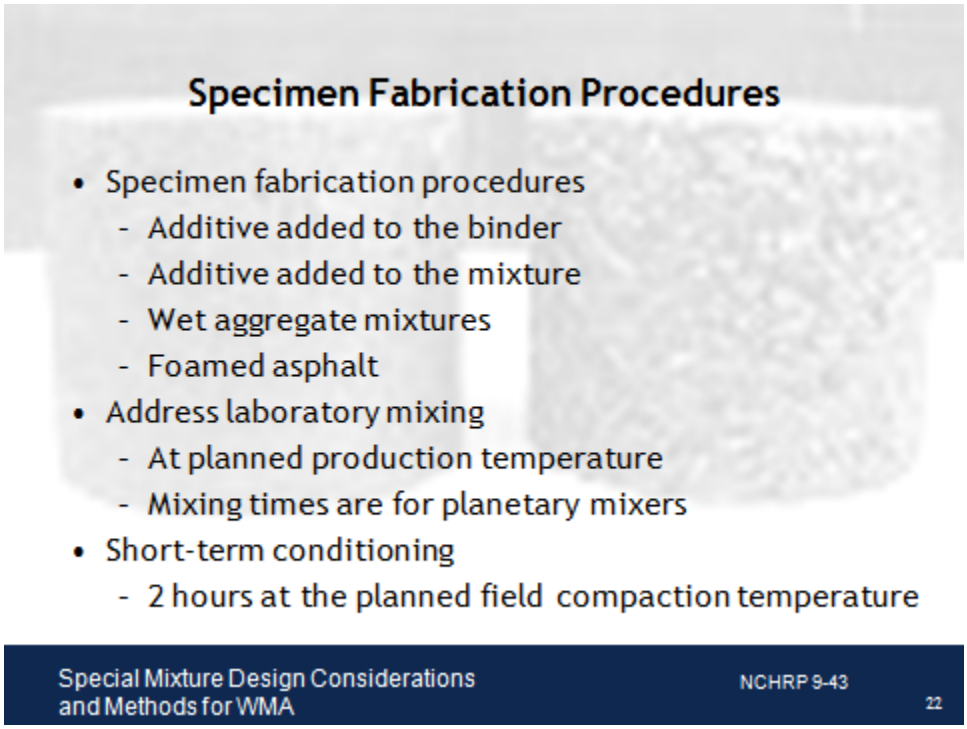
Explain that the graph shows a blending chart for the low temperature grade. The point at 0 percent RAP is the low temperature grade of the virgin binder. The point at 100 percent RAP is the low temperature grade of the RAP binder. The blending chart is the line between these points.

Next explain how for a minimum low temperature grade of -22 °C, this blending chart will allow up to 32 percent of the binder in the mixture to be replaced with RAP binder.

Next explain that a conservative low temperature grade improvement for WMA is 0.5 °C. Then show how the allowable binder replacement for this example increases to 40 percent.

Time: A total of 5 minutes.

Slide 22



🗝 **Key Message**: The specimen fabrication procedures for WMA are process specific, roughly simulating the field mixture production process.

🗎 **Background Information**: The specimen fabrication procedures were designed to reasonably reproduce the WMA process. Procedures are provided in the Appendix to AASHTO R35 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 9-43.

In these procedures, mixtures are mixed at the planned production temperature. Short-term conditioning is 2 hours at the planned field compaction temperature. Specimens are compacted in the normal manner with a Superpave gyratory compactor at the planned field compaction temperature.

🗣 **Presentation:** Briefly review the key points shown on the slide. Then refer the participants to Page A-6 and briefly describe the four mixing procedures as follows:

1. **Additives added to the binder.** Explain that the procedure describes how to mix additives with binder for the case where the WMA process supplier does not provide specific directions. If the process supplier provides directions, follow the directions

provided. Once the additive is blended with the binder the mixing of binder and aggregate proceeds in the normal manner.

2. **Additives added to the mixture.** Refer the participants to Page A-7 of the Appendix to AASHTO R35. Explain that the procedure is very similar to that for HMA. After the binder is added to the mixture, the additive is added and then mixed in the normal manner.

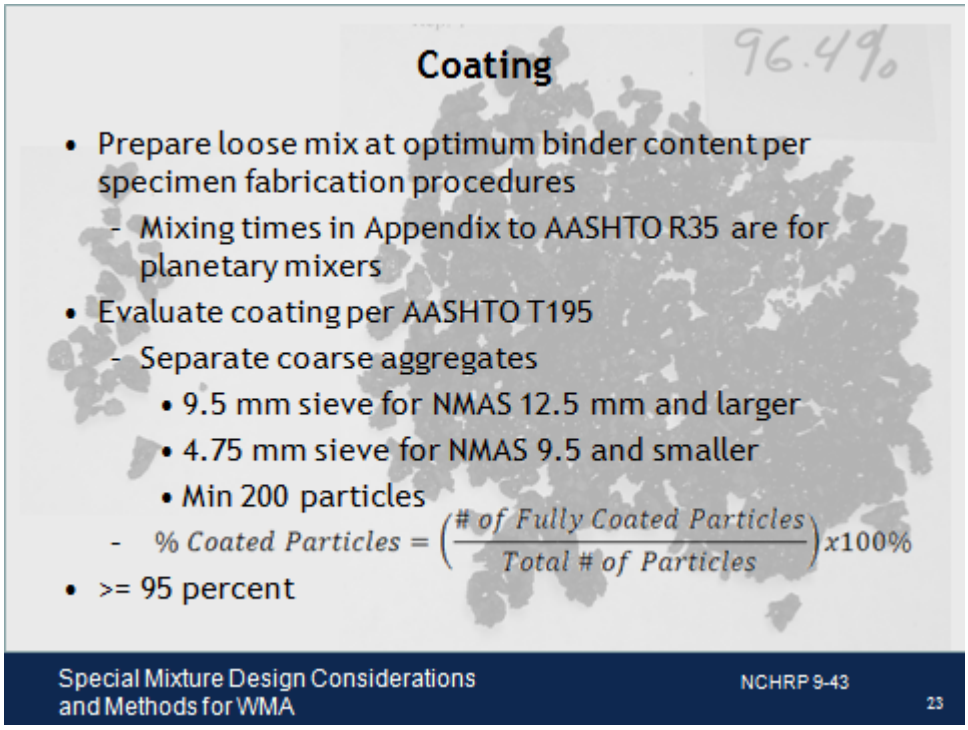
3. **Wet aggregate mixtures.** Refer the participants to Page A-8 of the Appendix to AASHTO R35. Explain that for this process some of the fine aggregate is added cold and wet to the mixture. The amount of wet aggregate, its moisture content, and the temperatures are determined by the WMA process supplier. First, the coarse aggregate and the warm portion of the fine aggregate are mixed with the binder at the initial temperature specified by the process supplier. Then the wet aggregate is added cold. As the wet aggregate is heated by the hot aggregate, the binder begins to foam and coat the fine aggregate. The final temperature of the mix should be less than 100 ^{o}C.

4. **Foamed Asphalt Mixtures.** Refer the participants to Page A-10 of the Appendix to AASHTO R35. Explain that a laboratory foaming plant is needed to produce mix designs for plant foaming processes. The water content used in the laboratory device should be the same as that used in field production. For foamed asphalt mixtures, the foamed asphalt is added to the heated aggregate. The laboratory foaming equipment uses a timer to control the amount of foamed 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 maximum specific gravity specimen then splitting the individual samples.

Short term-conditioning is 2 hours at the planned compaction temperature. Compaction is as usual using a Superpave gyratory compactor.

Time: A total of 5 minutes.

Slide 23



🗝 **Key Message**: Viscosity based mixing and compaction temperatures cannot be used with the wide range of WMA processes that are currently available. Coating is evaluated at the planned production temperature.

📰 **Background Information**: 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 T195, which measures the percentage of fully coated coarse aggregate particles.

Coating is one way to evaluate planned WMA production temperatures that is relevant to all WMA processes. In NCHRP Project 9-43, coating was evaluated on a number of HMA and WMA mixtures using AASHTO T195. 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 criterion of 95 percent was based on the planetary mixer data.

🗣 **Presentation:** Explain that coating is evaluated at the planned production temperature in lieu of the viscosity based mixing temperature used in the design of HMA. Coating is used because it can be applied to a wide range of processes.

Explain that the coating evaluation is done at the optimum binder content and requires an additional loose mixture to be prepared at the optimum binder content. This additional loose mixture is prepared following the applicable specimen fabrication procedure for the WMA process, **without short-term oven conditioning.** Then the coating is evaluated using AASHTO T195.

Briefly explain how AASHTO T195 is conducted. First split out the coarse aggregate particles. The sieve that the splitting is done on depends on the nominal maximum size of the mixture.

Then separate out the fully coated particles from the partially coated particles. The percent coating is the ratio of the number of fully coated particles to the total number of particles.

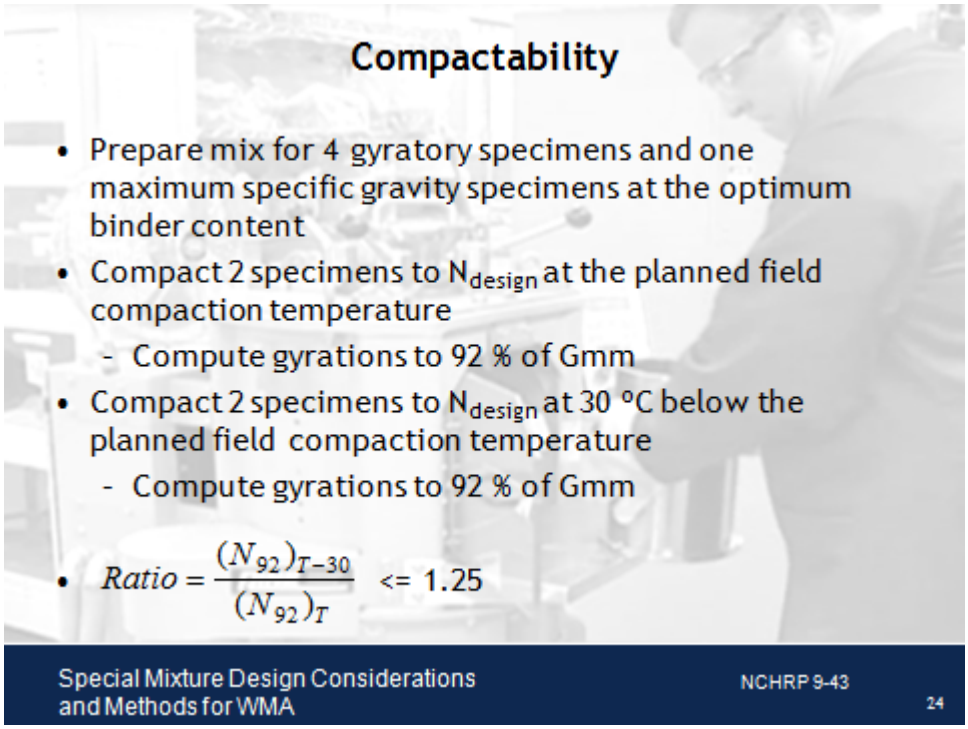
Emphasize that this is a very strict criterion because it is 95 percent of the coarse aggregate **fully** coated. The mixing times that are included in the Appendix to AASHTO R35 are based on tests on WMA and HMA mixtures that were mixed in the laboratory with a planetary mixer. When a bucket mixer was used with a smaller number of mixes and the same mixing times the coating was much lower. Until additional research is done with bucket mixers, designers using bucket mixers will have to develop appropriate mixing times for their materials.

> ? Ask the participants how they might develop appropriate mixing times for bucket mixers?
>
> Answer: Mix several mixtures at the mixing temperature for HMA from the viscosity based mixing temperature and determine the time required to reach essentially full coating.

Remind the participants to fill in the approach discussed in the space provided on Page 4-9 of their Participant Workbook

Time: A total of 4 minutes.

Slide 24



🗝 **Key Message**: Viscosity based mixing and compaction temperatures cannot be used with the wide range of WMA processes that are currently available. One of the major benefits of WMA is it expands the useable compaction temperature for asphalt concrete. Compactability is evaluated at the planned field compaction temperature and 30 °C below the planned field compaction temperature.

🗎 **Background Information**: The compactability evaluation is used in lieu of the viscosity based compaction temperature used in the design of 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 compaction 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.

The methodology for the compactability evaluation resulted from a workability study conducted in NCHRP Project 9-43. 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 temperatures. 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 compactability. 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 9 WMA field projects sampled in NCHRP 9-43. The increase in gryations for the WMA processes ranged from 0 to 20 percent. Workability and compactability was not reported to be a problem on any of the projects.

🗣 **Presentation:** Explain that compactability is evaluated at the planned field compaction temperature in lieu of the viscosity based compaction temperature used in the design of HMA. Like coating, compactability is used because it can be applied to a wide range of processes.

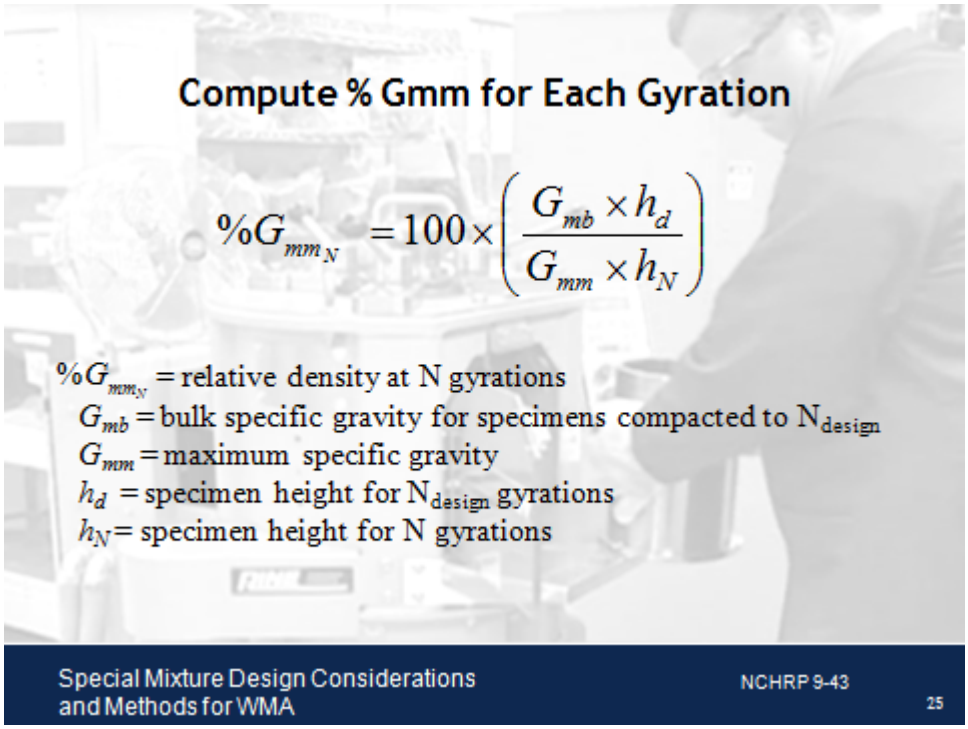
Explain that the compactability evaluation is done at the optimum binder content and requires four additional gyratory specimens and a maximum specific gravity specimen to be prepared at the optimum binder content. Mixtures for these additional specimens are prepared following the applicable specimen fabrication procedure for the WMA process.

Briefly explain how the compactability evaluation is conducted. First 2 gyratory specimens are prepared at the planned field compaction temperature. The specimens are compacted to N_{design} gyrations, then the number of gyrations to a density of 92 percent of Gmm is calculated from the measured density at N_{design} gyrations and the recorded specimen height data. Next 2 gyratory specimens are prepared at 30 ºC below the planned field compaction temperature. The loose mix for these specimens should be short-term conditioned at the planned field compaction temperature then the temperature is lowered by stirring the mixture at room temperature. The number of gyrations to a density of 92 percent of Gmm is calculated from the measured density at N_{design} gyrations and the recorded specimen height data.

Explain that the compactability criterion is that the ratio of the gyrations to 92 percent of Gmm at 30 ºC below the planned field compaction temperature to that at the planned field compaction temperature. The tentative limit is a maximum of 1.25.

🕒 **Time**: A total of 3 minutes.

Slide 25



🗝 **Key Message**: In the compactability evaluation, the measured density at N_{design}, the maximum specific gravity, and the height data from the gyratory compactor are used to estimate the density for each gyration.

📰 **Background Information**: In the compactability evaluation, the density, expressed as a percent of Gmm is computed for each gyration level using the following equation:

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

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

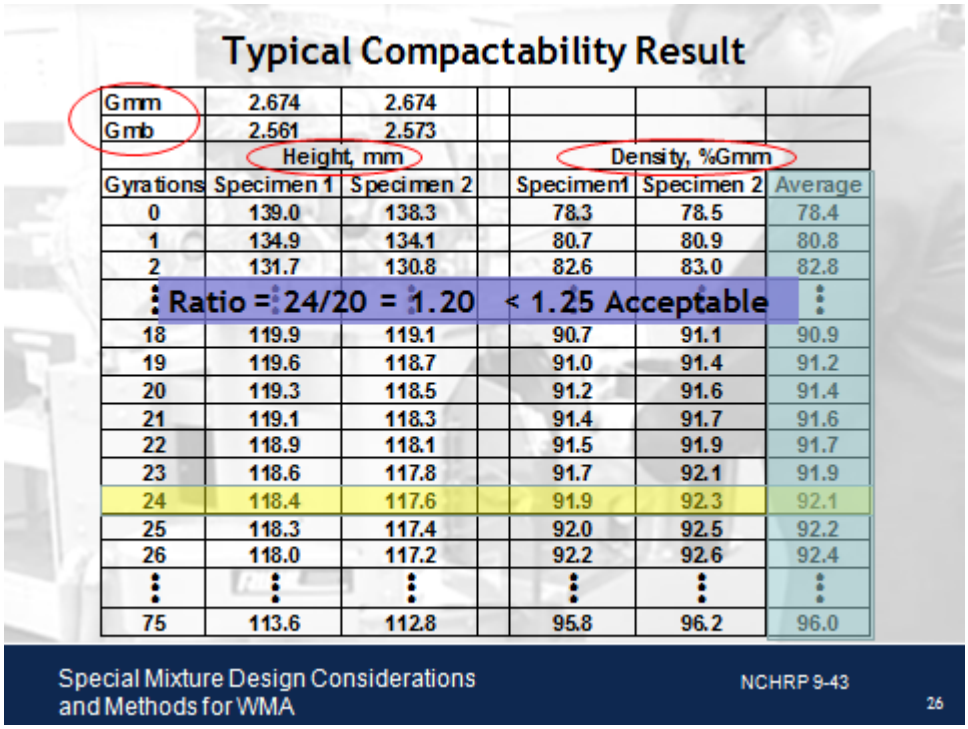
This is the same approach that was used early in the implementation of the Superpave gyratory compactor.

🗣 **Presentation:** Briefly explain that the compactability evaluation requires the computation of the density for each gyration to determine the number of gyrations to reach 92 percent of Gmm. The equation on the slide presents the computation. This is the same approach that was used early in the implementation of the Superpave gyratory compactor.

The computation is done for each specimen at the two temperatures, then averaged to determine the gyrations at that temperature to reach 92 percent of Gmm.

Time: A total of 2 minutes.

Slide 26



Typical Compactability Result

Gmm	2.674	2.674			
Gmb	2.561	2.573			
	Height, mm		Density, %Gmm		
Gyrations	Specimen 1	Specimen 2	Specimen1	Specimen 2	Average
0	139.0	138.3	78.3	78.5	78.4
1	134.9	134.1	80.7	80.9	80.8
2	131.7	130.8	82.6	83.0	82.8
⋮	Ratio = 24/20 = 1.20		< 1.25 Acceptable		⋮
18	119.9	119.1	90.7	91.1	90.9
19	119.6	118.7	91.0	91.4	91.2
20	119.3	118.5	91.2	91.6	91.4
21	119.1	118.3	91.4	91.7	91.6
22	118.9	118.1	91.5	91.9	91.7
23	118.6	117.8	91.7	92.1	91.9
24	118.4	117.6	91.9	92.3	92.1
25	118.3	117.4	92.0	92.5	92.2
26	118.0	117.2	92.2	92.6	92.4
⋮	⋮	⋮	⋮	⋮	⋮
75	113.6	112.8	95.8	96.2	96.0

Special Mixture Design Considerations and Methods for WMA NCHRP 9-43 26

🗝 **Key Message**: Example of the compactability evaluation.

🗎 **Background Information**:

🗣 **Presentation:** This slide is animated. The following will occur on successive mouse clicks:

1. Ovals showing inputs and outputs of the density as a function of gyration calculations.
2. Ovals disappear and average density column is highlighted.
3. Row for to the density of 92.0 percent of Gmm is highlighted.
4. Textbox with gyration ratio calculation.
5. Textbox with the criteria

Explain that this slide shows part of the compactability evaluation for a WMA mixture with planned field compaction temperature of 250 ºF. A set of specimen was compacted at 250 ºF and the number of gyrations to 92 percent of Gmm was found to be 20 gyrations. The data shown are for specimens compacted at 196 ºF.

Click the mouse and highlight the inputs and outputs of the density as a function of gyration level calculation. Explain that the calculation was made using the bulk specific gravity of each specimen, the maximum specific gravity for the mixture, and the height data for each specimen using the equation on the previous slide.

Click the mouse and highlight the Average Density column. Explain that the next step is to search this column looking for the point where the average density is equal to or exceeds 92.0.

Click the mouse to highlight the 24 gyration row. Explain that in this example the density is equal to or exceeds 92 percent at 24 gyrations.

Click the mouse to show the computation of the gyration ratio. Explain that the gyration ratio is the gyrations at the lower temperature divided by the gyrations at the high temperature. For this mixture the gyration ratio is 1.20.

? Ask if the compactability for this mixture is acceptable?
Answer: Yes

Click the mouse to show that it is acceptable. Remind the participants to record this answer on Page 4-11 of their Participants Workbook.

Time: A total of 2 minutes.

Slide 27

Moisture Sensitivity and Rutting Resistance

- AASHTO T283
  - Tensile strength ratio >= 0.80 with no visual stripping
- Rutting resistance
  - Flow number, AASHTO T79

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

Special Mixture Design Considerations and Methods for WMA NCHRP 9-43 27

🗝 **Key Message**: Moisture sensitivity and rutting resistance are evaluated as part of the WMA mix design process. The methods that are used are the same as used for HMA.

🗎 **Background Information**: Moisture sensitivity is evaluated using AASHTO T283. Tests conducted during NCHRP Project 9-43 showed 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 9-43 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.

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 9-33. The test is conducted on specimens that have been short-term conditioned for 2 hours 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 in less, resulting in lower flow numbers for WMA mixtures produced with the same aggregates and binder.

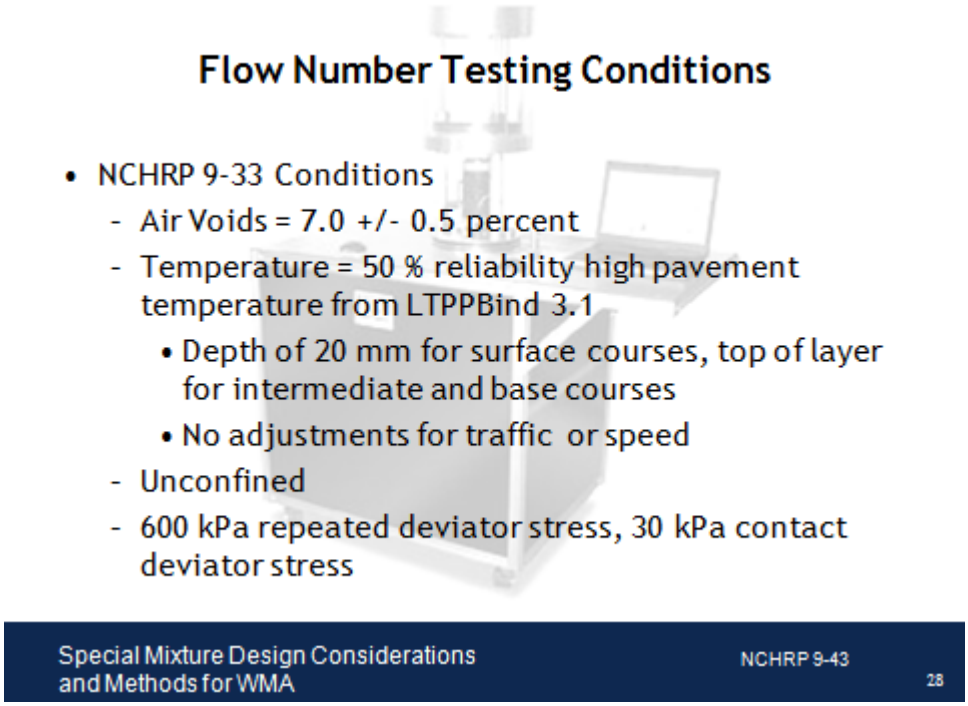
🗣 **Presentation:** Explain that moisture sensitivity and rutting resistance are evaluated for WMA mixtures and the methods that are used are the same as those used in testing HMA.

AASHTO T283 is used to evaluate moisture sensitivity. The same criteria for tensile strength ratio and visual stripping are used with WMA and HMA.

Rutting resistance is evaluated for mixtures designed for traffic levels of 3 million ESALs and greater. The flow number from AASHTO TP 79 is used. Flow number criteria as a function of traffic level are given in the table. The measured flow must exceed the value in the table for the mix to be acceptable for the design traffic level. The flow number criteria for WMA are lower than HMA due to the reduced short-term conditioning used with WMA. For WMA, flow number specimens are short-term conditioned for 2 hours at the compaction temperature. This represents the aging that occurs during construction. For HMA, the conditioning is 4 hours at 275 ºF (135 ºC) which appears to represent construction aging plus some time in service.

Time: A total of 2 minutes.

Slide 28



🗝 **Key Message**: The correct testing conditions must be used in the flow number testing. The criteria in the Appendix to AASHTO R35 are based on the testing conditions recommended in NCHRP Project 9-33 for HMA.

🗎 **Background Information**: Several methods for conducting the flow number test have been recommended in various research and development projects. These differ in the temperature and stress levels used to test the specimen. The testing conditions have a major influence on the measured flow number; therefore, the testing conditions must be matched with the criteria. The testing conditions that should be used to evaluate the rutting resistance of WMA are those recommended in NCHRP 9-33 for HMA:

- Air Voids of 7.0 +/- 0.5 percent
- The test temperature should be the 50 % reliability high pavement temperature from LTPPBind 3.1 at a depth of 20 mm for surface courses or the top of the layer for intermediate and base courses. No temperature adjustments for traffic or speed should be made.
- Unconfined
- 600 kPa repeated deviator stress, 30 kPa contact deviator stress

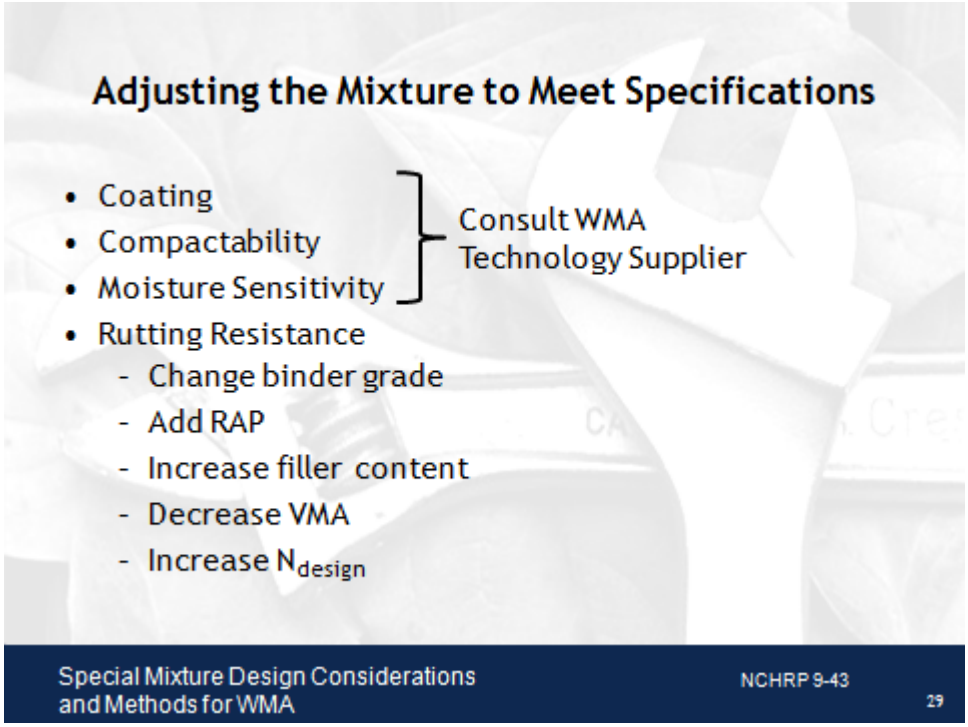
🗣 **Presentation:** Explain that the measured flow number is highly dependent on the testing conditions that are used. The criteria in the Appendix to AASHTO R35 for evaluating the rutting resistance of WMA are based on the test being conducted using the testing conditions recommended in NCHRP 9-33 for HMA. These conditions are:

- Air Voids of 7.0 +/- 0.5 percent

- The test temperature should be the 50 % reliability high pavement temperature from LTPPBind 3.1 at a depth of 20 mm for surface courses or the top of the layer for intermediate and base courses. No temperature adjustments for traffic or speed should be made.
- Unconfined
- 600 kPa repeated deviator stress, 30 kPa contact deviator stress

Time: A total of 2 minutes.

Slide 29



🗝 **Key Message**: The Appendix to AASHTO R35 includes a section on adjusting the mixture to meet specification requirements. This section addresses coating, compactability, moisture sensitivity, and rutting resistance.

🗎 **Background Information**: This section provides information that can be used to adjust WMA mixtures to meet the evaluation criteria contained in the Appendix to AASHTO R35. For coating, compactability, and moisture sensitivity, the user is directed to consult the WMA process supplier. The effect of changing binder grade, volumetric properties, and compaction level on rutting resistance are provided.

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*

🗣 **Presentation:** This slide is animated. The four WMA evaluations will appear on the first four mouse clicks. Reveal these and explain that this section of the Appendix to AASHTO R35 addresses these properties.

On the next mouse click the bracket and the recommendation to consult the WMA technology supplier will appear. Explain that because the various WMA technologies are so much different, general recommendations for improving coating, compactability and resistance to moisture damage cannot be provided. Rutting resistance can be improved by:

- Changing the binder grade,

- Adding RAP,
- Increasing filler content,
- Decreasing VMA, and
- Increasing N_{design}

Explain that the Appendix to AASHTO R35 includes information on the effect of each of these based on recommendations included in NCHRP Report 567, *Volumetric Requirements for Superpave Mix Design*

Time: A total of 2 minutes.

Comparison of WMA and HMA Properties

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

Summary

Topic: Comparison of WMA and HMA Properties

Time Allocation: 15 minutes

Learning Outcomes:

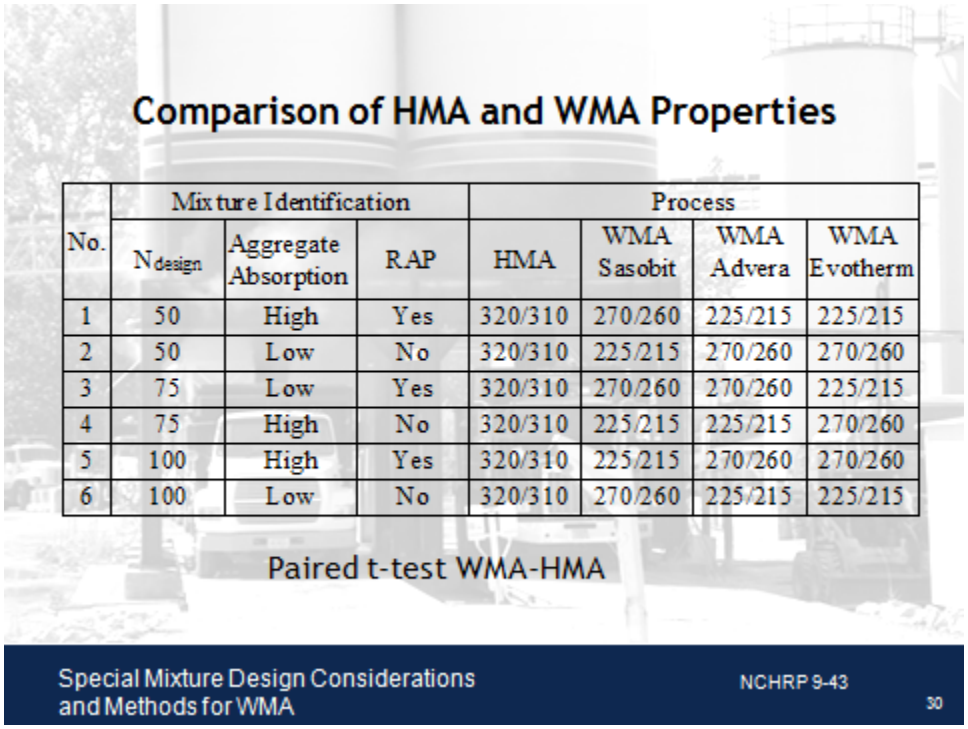
- Describe differences in volumetric properties of mixtures designed as WMA and HMA.
- Describe differences in compactability of mixtures designed as WMA and HMA.
- Describe differences in moisture sensitivity of mixtures designed as WMA and HMA.
- Describe differences in rutting resistance of mixtures designed as WMA and HMA

Instructional Method Lecture/ Discussion:

- The Instructor will present and discuss results from a major mixture design experiment completed in NCHRP 9-43 where mixtures composed of the same aggregates and binder and designed for the same conditions were designed as WMA and HMA.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 30



No.	Mixture Identification			Process			
	N_{design}	Aggregate Absorption	RAP	HMA	WMA Sasobit	WMA Advera	WMA Evotherm
1	50	High	Yes	320/310	270/260	225/215	225/215
2	50	Low	No	320/310	225/215	270/260	270/260
3	75	Low	Yes	320/310	270/260	270/260	225/215
4	75	High	No	320/310	225/215	225/215	270/260
5	100	High	Yes	320/310	225/215	270/260	270/260
6	100	Low	No	320/310	270/260	225/215	225/215

🗝 **Key Message**: Transition slide to introduce Topic 5. The comparisons for WMA and HMA that will be shown are from a major mixture design experiment conducted in NCHRP 9-43 that included the design of 24 mixtures; 18 WMA and 6 HMA.

🗎 **Background Information**: NCHRP Project 9-43 included a major mixture design study that was designed to compare properties of WMA mixtures designed according the Appendix to AASHTO R35 with those of corresponding HMA mixtures designed according to AASHTO R35. Recall, the underlying principal for WMA is to produce mixtures with similar strength, durability, and performance properties as 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 were 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.

One way to present the results is to develop 95 percent confidence intervals for the mean difference in the properties for WMA compared to HMA. If the 95 percent confidence intervals capture zero, the properties are statistically the same for WMA and HMA. This approach is used in the next several slides to illustrate the results of the experiment.
🗣 **Presentation:** This slide is animated. On the first mouse click the table shown the design of the NCHRP Project 9-43 mixture design experiment will appear.

Introduce this topic by stating that most WMA mixture designs will be to convert existing HMA designs to WMA. The next slides will show what should be expected when converting HMA designs to WMA.

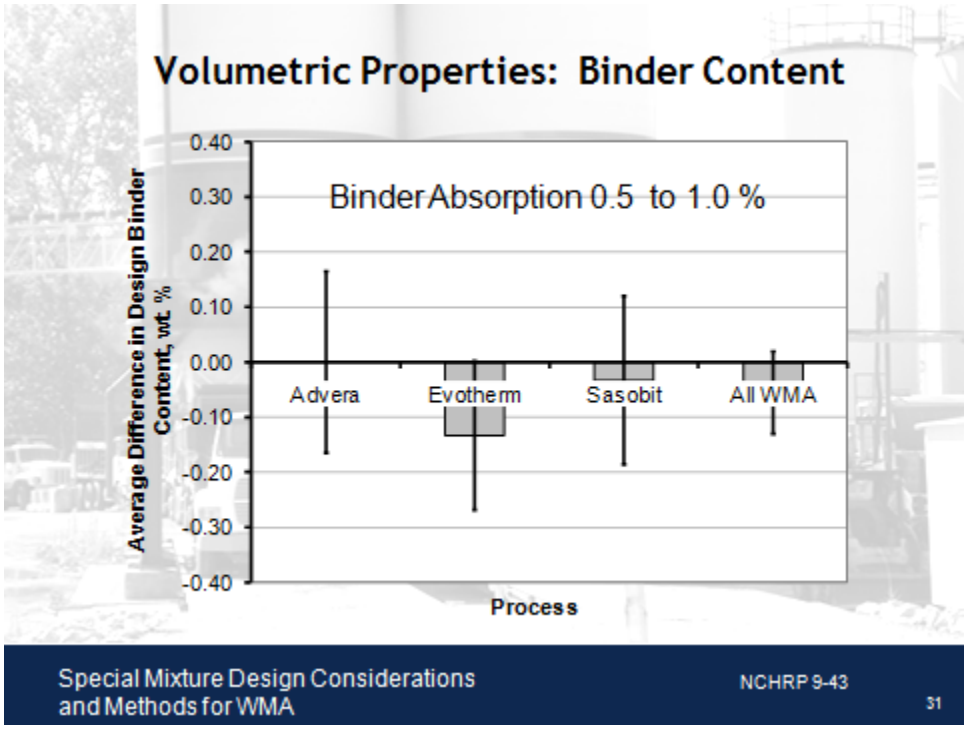
Show the table and explain that the comparisons that will be shown are from a major mixture design experiment that was conducted in NCHRP 9-43. In this experiment six different mixtures were designed as HMA and WMA using three different processes. The mixtures used the same asphalt binder and aggregates. Various properties were compared using a paired difference analysis. In this analysis the difference between WMA and HMA are computed for each of the mixtures. If WMA and HMA 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.

In the slides that follow, the results of the paired difference analysis will be presented for the following:

- Volumetric properties
- Compactability
- Moisture sensitivity
- Rutting resistance

Time: A total of 3 minutes.

Slide 31



🗝 **Key Message**: The volumetric properties of HMA and WMA mixtures designed with the same asphalt binder and aggregate are very similar.

📃 **Background Information**:

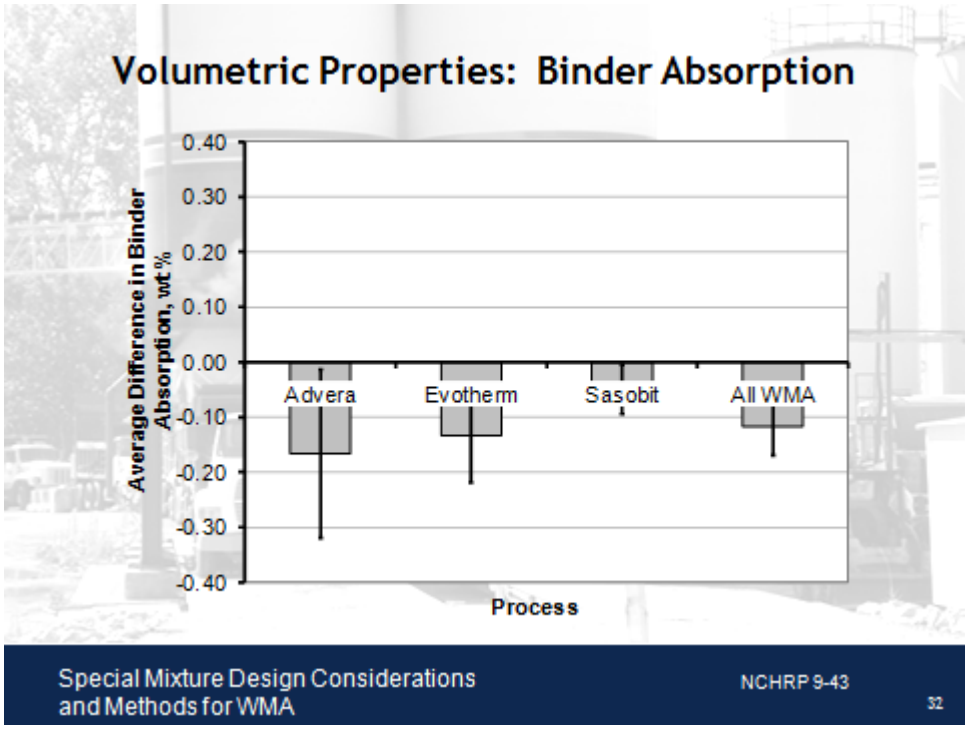
🗣 **Presentation:** This slide is animated. The text box about binder absorption will appear on the first mouse click.

Explain that this chart summarizes the findings of the NCHRP 9-43 mixture design study for the difference in the design binder content between WMA and HMA. Explain that the error bars in the chart are 95 percent confidence intervals for the difference in the design binder content; WMA design binder content minus HMA design binder content. If the confidence interval captures zero, then there is not a statistically significant difference in the design binder content. The design binder content considering all of the WMA mixtures is about 0.05 percent lower than that for HMA. As shown this difference is not statistically significant. Other volumetric properties were also very similar.

Click the mouse to show the text box about binder absorption. Explain that the mixtures used in the NCHRP 9-43 mixture design study had binder absorption between 0.5 and 1.0 percent. The conclusion may be different for mixtures with greater binder absorption.

🕒 **Time**: A total of 2 minutes.

Slide 32



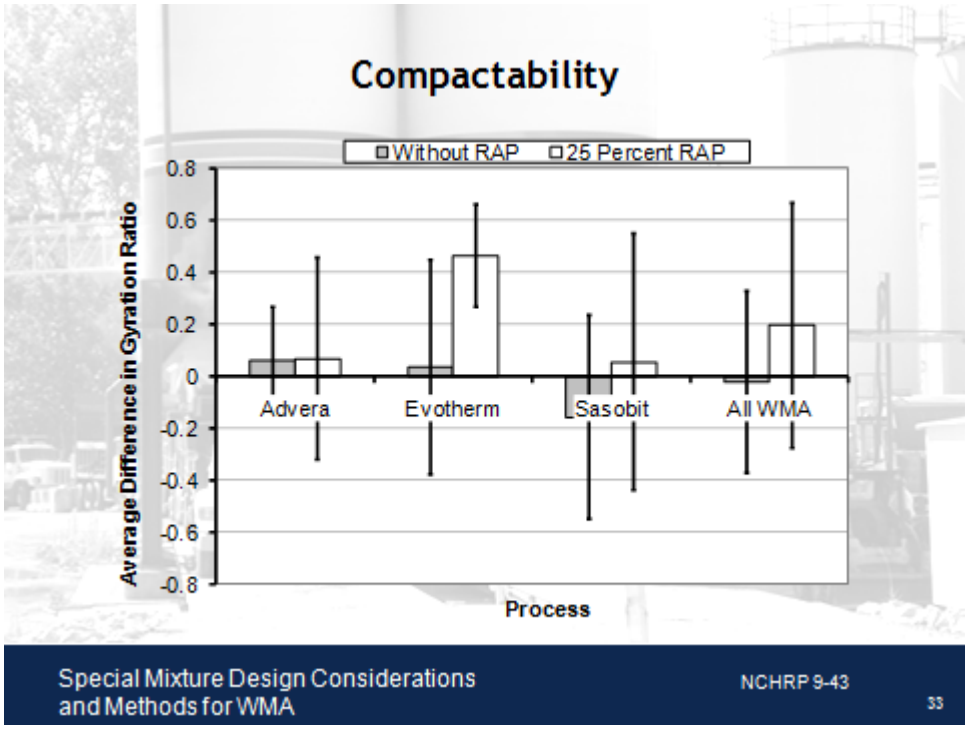
🗝 **Key Message**: Binder absorption is somewhat lower for WMA compared to HMA.

🗎 **Background Information**:

🗣 **Presentation:** Explain that this slide shows the difference in binder absorption from the NCHRP 9-43 mixture design experiment. Binder absorption is lower for WMA compared to HMA. Remember the mixtures in this experiment had binder absorption that was less than 1 percent. The difference in binder absorption will probably be higher for mixtures with higher binder absorption. This will likely result in a greater difference in the volumetric properties between WMA and HMA for mixtures with higher binder absorption.

🕒 **Time**: A total of 2 minutes.

Slide 33



🗝 **Key Message**: Compactability may be different for WMA compared to HMA.

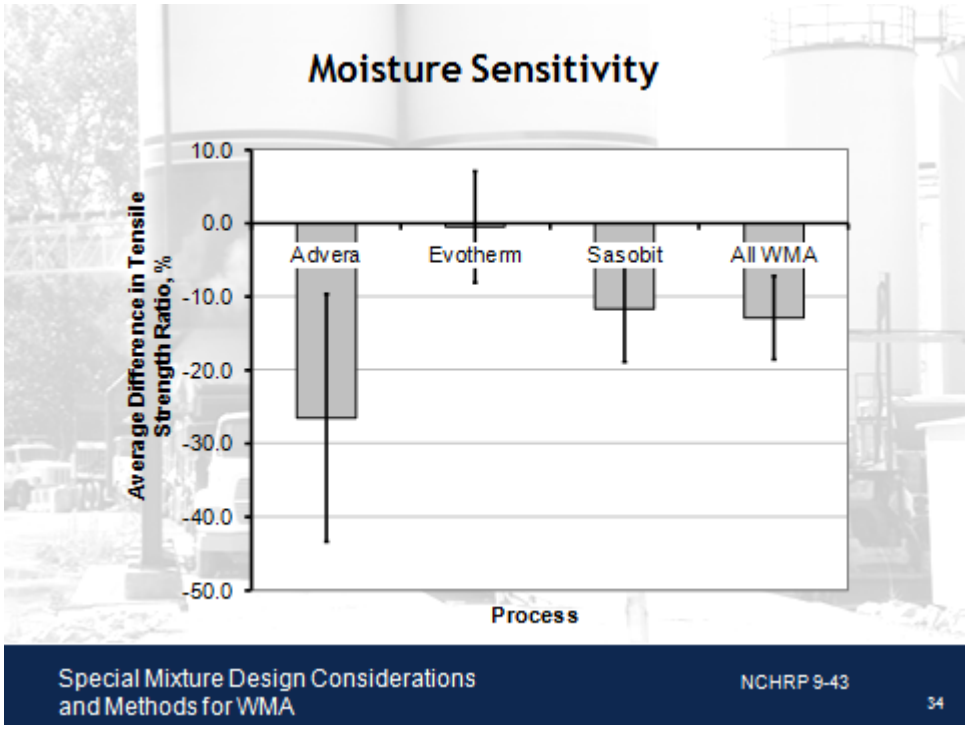
🗎 **Background Information**:

🗣 **Presentation:** Explain that this slide shows the difference in compactability from the NCHRP 9-43 mixture design experiment. The chart shows the difference in the gyration ratio for WMA compared to HMA. A positive difference means WMA was less compactable. Remember the compactability evaluation for the HMA was at a higher temperature compared to that for the WMA.

This chart shows that for most mixtures, the compactability of the WMA mixture at its lower temperature was similar to the corresponding HMA mixture. The exception was the Evotherm process for mixtures with RAP. The Evotherm that was used in this experiment was blended into the binder at the terminal. The Evotherm concentration was not adjusted to account for the RAP binder in the mixture. Approximately 25 percent of the binder in the RAP mixtures came from the RAP binder. The other additives were added at the recommended dosage rate based on the total binder content of the mixture.

🕒 **Time**: A total of 2 minutes.

Slide 34



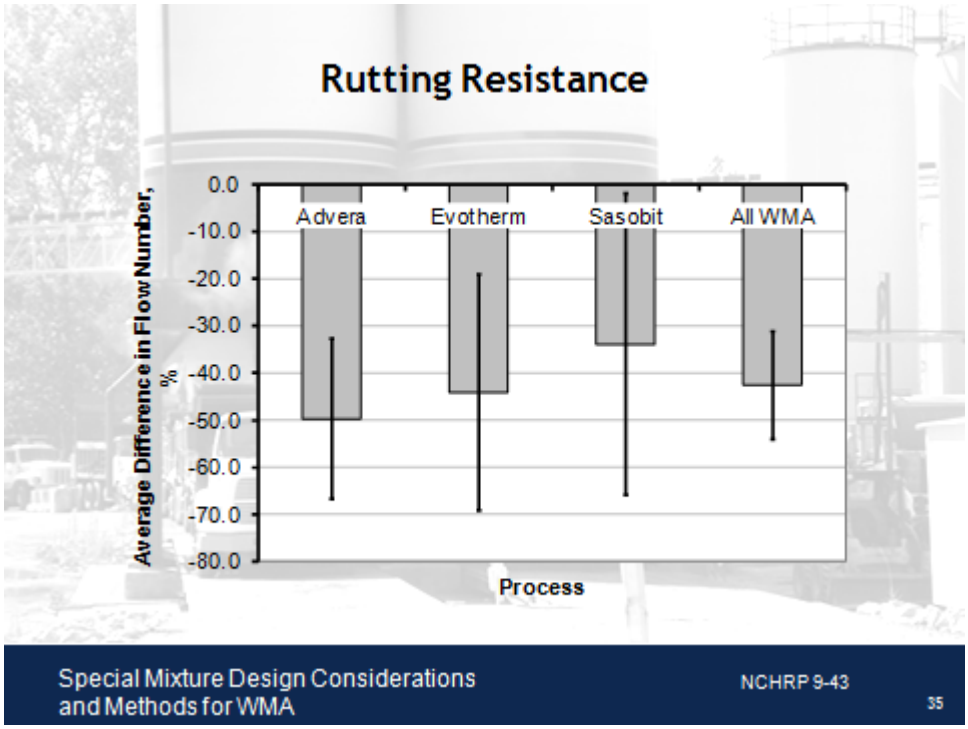
🗝 **Key Message**: Moisture sensitivity may be different for WMA compared to HMA.

🗎 **Background Information**:

🗣 **Presentation:** Explain that this slide shows the difference in tensile strength ratio from the NCHRP 9-43 mixture design experiment. Many engineers are concerned that WMA mixtures will have poorer resistance to moisture damage than HMA mixtures because of the lower temperature and the presence of water in some of the WMA processes. This slide shows that the resistance to moisture damage is process specific. The Evotherm used in the NCHRP 9-43 mixture design experiment contained an anti-strip and there was little difference in the tensile ratio for the Evotherm WMA mixtures compared to the HMA. The other WMA processes had a significant drop in the tensile strength ratio.

🕒 **Time**: A total of 2 minutes.

Slide 35



🗝 **Key Message**: Rutting resistance is lower for WMA compared to HMA.

🗎 **Background Information**:

🗣 **Presentation:** Explain that this slide shows the difference in the flow number from the NCHRP 9-43 mixture design experiment. All mixtures were short-term conditioned for 2 hours at the compaction temperature. The lower flow numbers for the WMA processes are due to the reduced aging of the binder due to the lower temperatures.

Although WMA mixtures have lower flow numbers compared to HMA, there have been no reported problems with rutting in field mixtures. The flow number criteria included in the Appendix to AASHTO R35 account for the reduced aging of WMA mixtures.

🕒 **Time**: A total of 2 minutes.

Self Graded Quiz

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

Summary

Topic: Self Graded Quiz

Time Allocation: 25 minutes

Learning Outcomes:

- Review content contained in Topics 2 through 5.

Instructional Method:

- Self Graded Quiz

Evaluation Plan: Content None

Slide 36

🗝 **Key Message**: The self graded quiz provides a review of the information presented during the WMA seminar.

🗎 **Background Information**:

🗣 **Presentation:** Have the participants turn to Page 6-3 of the Participant Workbook and complete the quiz. Give the participants about 15 minutes to complete the quiz, then provide the answer sheet and review the answer and answer any questions.

🕒 **Time**: A total of 25 minutes.

Quiz

1. Give a short definition for warm mix asphalt.

2. Warm mix asphalt is designed to have inferior strength, durability and performance characteristics compared to hot mix asphalt.
   a. True
   b. False

3. List the four generic WMA mixture design categories.

   a.

   b.

   c.

   d.

4. Why is a mechanical mixer needed for laboratory design of WMA
   a. WMA is much more difficult to mix than HMA.
   b. The mixing must be standardized to evaluate coating.
   c. WMA specimens are larger than HMA specimens.
   d. To speed up the WMA mix design process.

5. Which of the following information about the field production is needed to perform a laboratory WMA mixture design?
   a. WMA process that will be used.
   b. WMA additive dosage rate.
   c. Planned field production temperature.
   d. Planned field compaction temperature
   e. All of the above

6. The high temperature grade of the binder in a WMA mixture should be one grade level higher than that used in an HMA mixture for the same design conditions.
   a. True
   b. False

7. RAP should not be used in WMA.
    a. True
    b. False

8. Which generic WMA mix design process would you use to simulate a plant foaming process?
    a. Additive added to the binder
    b. Additive added to the mixture
    c. Wet aggregate mixture
    d. Foamed asphalt

9. The results of a compactability evaluation for a WMA mixture made with ACME Additive A are summarized below. Is the compactability of the mixture acceptable?
    a. Yes
    b. No

Temperature, ºF	**Average Gyrations to 92 % of Gmm**
260	26
206	28

Gyration Ratio = 1.08

10. WMA mixture design includes evaluation of which of the following?
    a. Coating
    b. Compactability
    c. Moisture sensitivity
    d. Rutting resistance
    e. All of the above

11. List three things to consider to improve the rutting resistance of WMA mixtures.

    a.

    b.

    c.

12. An existing HMA design having binder absorption of 0.75 percent is being converted to a WMA design for a plant foaming process. The optimum binder content of the HMA design is 5.6 percent. The optimum binder content of the WMA mixtures will be _____ the HMA mixture.
    a. much higher than
    b. much lower than
    c. about the same as

13. WMA mixtures always have improved compactability compared to HMA mixtures.
    a. True
    b. False

14. WMA mixtures always have poorer resistance to moisture damage than HMA mixtures made with the same aggregates and binders.
    a. True
    b. False

15. WMA mixtures will generally have lower flow numbers compared to HMA mixtures made with the same aggregates and binder.
    a. True
    b. False

Quiz Solution

1. (Slide 8) A number of processes that allow asphalt concrete to be produced at lower temperatures than used for hot mix asphalt.

2. (Slide 8)
   b. False, WMA is designed to have similar strength, durability and performance characteristics as HMA

3. (Slide 10)
   a. WMA additives added to the binder
   b. WMA additives added to the mixture,
   c, wet aggregate mixtures,
   d. foamed asphalt

4. (Slide 17 and Slide 23)
   b. The mixing must be standardized to evaluate coating.

5. (Slide 18)
   e. All of the above

6. (Slide 19)
   b. False. The same binder grade should be used for HMA and WMA designed for the same conditions.

7. (Slide 20)
   b. False. The limit on the stiffness of RAP in WMA will have little effect on the use of RAP in WMA in most cases.

8. (Slide 22)
   d. foamed asphalt

9. (Slide 24)
   a. Yes. Gyration ratio of 1.08 is less than 1.25

10. (Slide 23, Slide 24, and Slide 27)
    e. All of the above

11. (Slide 29)
    a. Increase high temperature binder grade
    b. Add RAP
    c. Increase filler content
    d. Decrease VMA
    e. Increase N_{design}

12. (Slide 31)
    c. about the same as. Binder absorption may be a little lower, but that will probably no affect the optimum binder content.

13. (Slide 33)
    b. False. The compactability will depend on the process, temperature, and materials used in the mixture. It may be better, poorer, or the same as a similar designed HMA mixture.

14. (Slide 34)
    b. False. Moisture sensitivity depends on the process, temperature, and materials used in the mixture. WMA processes that include an anti-strip additive will probably have similar or improved resistance to moisture damage compared to HMA.

15. (Slide 35)
    a. True. The lower short-term conditioning temperature for WMA mixtures result in less aging and lower flow number. The reduced aging is considered in the criteria for rutting resistance for WMA mixtures.

Proposed Appendix to AASHTO R35

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

1. PURPOSE

1.1. This appendix presents special mixture design considerations and methods for designing warm mix asphalt (WMA) using AASHTO R35. 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 R35. This appendix assumes the user is proficient with the standard procedures contained in AASHTO R35.

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 R35.

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 T312.

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 M323 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.

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 M323.

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, ^{o}F	285	285	292	292	300
Rate of Improvement of Virgin Binder Low Temperature Grade per ^{o}C Reduction in Plant Temperature	0.035	0.025	0.025	0.012	0.025
WMA Production Temperature, ^{o}F	Recommended Improvement in Virgin Binder Low Temperature Continuous Grade for RAP Blending Chart Analysis, ^{o}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 T283 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 T283	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:

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

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.

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8. WMA MIXTURE EVALUATIONS

8.1. At the optimum binder content determined in accordance with Section 10 of AASHTO R35, 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 T195 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 T195.

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 T312. Record the specimen height for each gyration.

8.3.4. Determine the bulk specific gravity of each specimen in accordance with AASHTO T166.

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 T312. Record the specimen height for each gyration

8.3.6. Determine the bulk specific gravity of each specimen in accordance with AASHTO T166.

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.

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

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 ± 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 TP79

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 PP60 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 ± 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
≥ 30	415

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 R35.

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 percent will improve rutting resistance by a factor of 1.2.
- Increasing N_{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 R35.

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. Gyrations 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.

B1. Introduction

One of the products of National Cooperative Highway Research Program (NCHRP) Project 9-43 was a draft appendix to AASHTO R35 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
- Additional Reporting Requirements for WMA.

This commentary to the draft appendix provides supporting information taken from the NCHRP Project 9-43 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 9-43 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 T195. To standardize the mixing process, a mechanical mixer is required. During NCHRP Project 9-43, 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 9-43 using a planetary mixer. Mixing times for bucket mixers will likely be longer.

NCHRP Project 9-43 demonstrated that it is feasible to perform foamed asphalt WMA mixture designs in the laboratory. In NCHRP project 9-43, 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 the 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 9-43 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 9-43 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 9-43. 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 1.5 °C, while an approximately 100 °F (56 °C) reduction in production temperature resulted in 2.9 °C improvement for one LEA project.

Table 2. 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 3. 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

Need for Further Research

Additional recovered binder grade data should be collected and analyze to verify the conclusion from NCHRP Project 9-43 that binder grade changes are not necessary for WMA.

B7. Section 6. RAP in WMA

General Comments

Research completed in NCHRP Project 9-43 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 9-43, 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 to 200 °F (82 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 9-43 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 hours, 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 hour 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 hour 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 design study completed in NCHRP Project 9-43. 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 process 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.

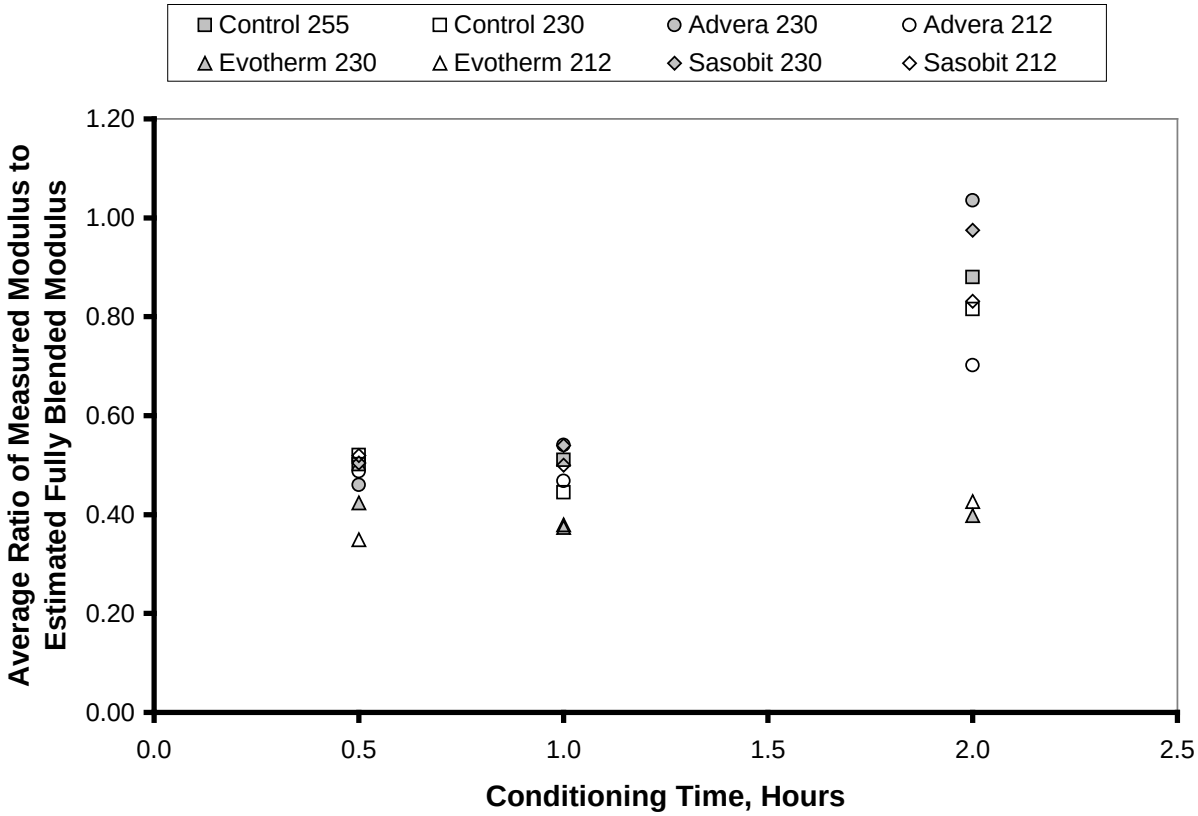


Figure 1. Comparison of the Ratio of Measured to Fully Blended Dynamic Moduli.

Table 4. Optimum Binder Contents for RAP Mixtures from the NCHRP 9-43 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

NCHRP Project 9-43 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 to 2 °C which is only 1/6th to 1/3rd of a grade level.

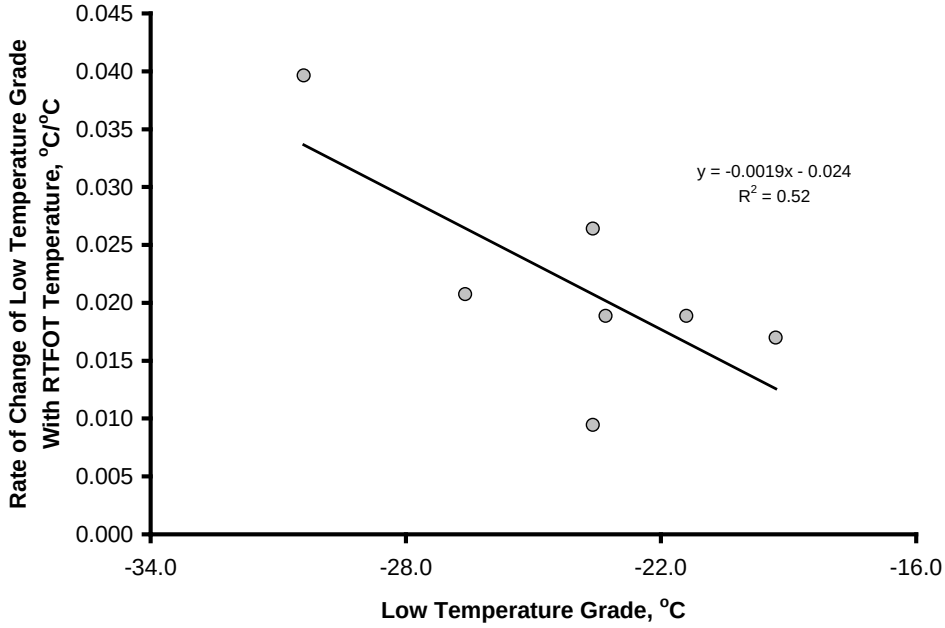


Figure 2. Effect of Low Temperature Binder Grade on the Rate of Change of Low Temperature Grade With RTFOT Temperature.

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 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.

Table 5. 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

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 9-43 included one field project that used 30 percent RAP, the Astec Double Barrel Green WMA process, and field mixing and compaction temperatures of 275 and 260 °F (135 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 9-33.

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 R35.

B9. Section 8. WMA Mixture Evaluations

General Comments

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

- Coating
- Compactability
- Moisture sensitivity
- 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 T195, 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 T283, the same as HMA. The criteria for AASHTO T283 are the same as that for HMA.

Finally, rutting resistance is evaluated using the flow number test in AASHTO TP79. 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 9-43, coating was evaluated on a number of HMA and WMA mixtures using AASHTO T195. 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 was based on the planetary mixer data.

The methodology for the compactability evaluation resulted from a workability study conducted in NCHRP Project 9-43. 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 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 compactability. 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 9 WMA field mixtures projects sampled in NCHRP 9-43. The increase in gryations for the WMA processes ranged from 0 to 20 percent. Workability and compactability was not reported to be a problem on any of the projects.

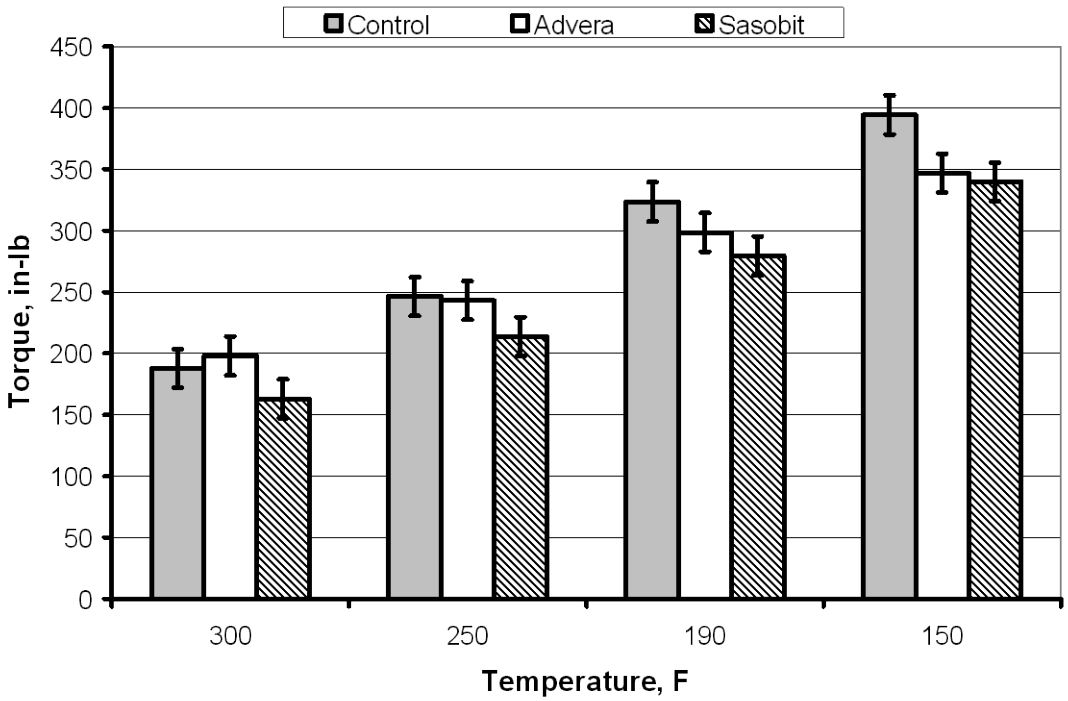


Figure 3. Effect of Temperature and WMA Additive on Torque Measured in the UMass Workability Device.

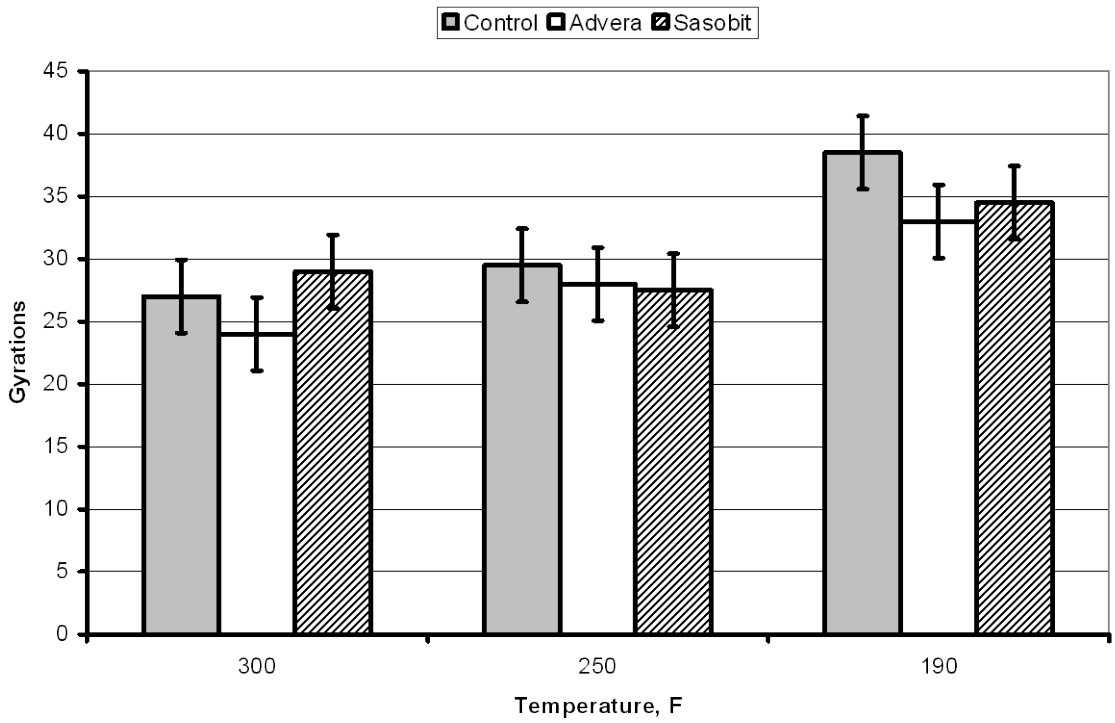


Figure 4. Effect of Temperature and WMA Additive on Gyrations to 92 Percent Relative Density.

Moisture sensitivity is evaluated using AASHTO T283. Tests conducted during NCHRP Project 9-43 showed 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 9-43 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 9-33. The test is conducted on specimens that have been short-term conditioned for 2 hours 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 in 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 processes increases the rutting resistance because it increases the high temperature grade of the binder.

Table 6. 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

Current criteria for the flow number and other rutting tests for HMA are based on 4 hours of short-term conditioning at 275 °F (135 °C). The short-term conditioning study completed in NCHRP Project 9-43 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 hours 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 9-49, *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 9-43 concluded that 2 hours 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 hours 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 T283 for moisture sensitivity testing was 16 hours at 140 °F (60 °C). Additionally, most rutting criteria are based on 4 hours of conditioning at 275 °F (135 °C). In NCHRP Project 9-13, mixtures were conditioned for 2 hours at 275 °F (135 °C), 4 hours at 275 °F (135 °C), and 16 hours at 140 °F (60 °C). Analysis of this data in NCHRP Project 9-43 concluded that 16 hours at 140 °F (60 °C) resulted in somewhat more aging than 4 hours at 275 °F (135 °C). The difference in aging between 2 and 4 hours 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 hours 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. 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 hours 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 T35. For coating, compactability, and moisture sensitivity, the user is directed to consult the WMA process supplier. The effect 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 moistures 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.

NCHRP
Project 9-43

Mix Design Practices for Warm Mix Asphalt

Participant Workbook

Appendix to AASHTO R35
Special Mixture Design Considerations and Methods for Warm Mix Asphalt

November 19, 2010

Table of Contents

Seminar Description:

Warm mix asphalt (WMA) is the term given 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 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. Because of these benefits, WMA is becoming increasingly popular with producers, paving contractors, and specifying agencies.

The design of WMA requires some changes to current HMA mix design practices. This seminar describes recommended procedures for designing dense-graded, asphalt concrete mixtures that will be produced using any one of several currently available WMA processes. These WMA mix design recommendations are based on research conducted in National Cooperative Highway Research Program (NCHRP) Project 9-43, *Mix Design Practices for Warm Mix Asphalt*, which concluded that only minor modification of current mix design practice is needed to address WMA. To implement the recommended modifications for WMA, an appendix to the current dense-graded HMA mix design procedure, AASHTO R35, *Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)*, was developed. This appendix titled *"Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)"* is the subject of this seminar.

Objective:

The objective of the WMA mixture design seminar is to present the modifications of the current Superpave volumetric design procedure, AASHTO R35, that are needed to design WMA. To accomplish this objective, this seminar will achieve the following training goals:

- Introduce WMA and the objective of WMA mixture design.
- Group the WMA processes into four generic WMA mixture design classifications.
- Describe the differences and similarities between WMA and HMA design.
- Present the mixture specific specimen fabrication procedures that are used with WMA.
- Present the mixture evaluations that are done for WMA.

- Compare volumetric and performance properties of properly designed WMA and HMA.

Target Audience:

There are two target audiences for the WMA mixture design seminar. The first is experienced HMA mixture design technicians and engineers who are interested in using WMA. For this audience, which is already well trained in HMA mixture design, the seminar can be presented as stand-alone training addressing the special procedures that are to be used in the design of WMA. The second target audience is engineers and technicians who do not have formal training in HMA mixture design. For this audience, this seminar would be presented in conjunction with other training materials as part of an introductory asphalt concrete mixture design course.

Instructional Method and Lesson Plan:

The WMA mixture design seminar has been designed to be presented by a single instructor with experience in HMA and WMA mixture design. The seminar includes a lecture and discussion of several topics followed by a self-graded quiz to review the material that was covered and assess participant understanding. The duration of the seminar is approximately 2 hours. Instructional materials include: (1) Instructor Guide, (2) Visual Aids, and (3) Participant Workbook. All participants will receive a copy of the Participant Workbook which contains all of the material covered during the seminar, a copy of the proposed AASHTO R35 appendix, and a copy of the commentary on the AASHTO R35 appendix. These materials will serve as a resource for designing WMA mixtures. Table 1 presents the lesson plan for the seminar, identifying the major topics that are covered, the specific subject matter included in each major topic, and the time allotted to each major topic.

Table 7. WMA Mixture Design Seminar Lesson Plan.

Topic	Subject Matter	Time
1. Introduction	1.1 Objective 1.2 Outcomes 1.3 Lesson Plan 1.4 Materials	15 min
2. What is WMA?	2.1 WMA Definition 2.2 WMA Processes 2.3 WMA Mix Design Process Categories	10 min
3. Similarities and Differences Between WMA and HMA Design	3.1 Materials Selection 3.2 Volumetric Design 3.3 Evaluation	10 min
4. Appendix to AASHTO R35	4.1 Additional Equipment 4.2 WMA Process Selection 4.3 Binder Grade Selection 4.4 RAP in WMA 4.5 Process Specific Specimen Fabrication Procedures 4.6 Evaluations 4.7 Adjusting WMA Mixtures to Meet Specification Requirements	45 min
5. Comparison of WMA and HMA Properties	5.1 Volumetric Properties 5.2 Workability/Compactability 5.3 Resistance to Moisture Damage 5.4 Resistance to Rutting	15 min
6. Self Graded Quiz	Review of Topics 1 through 5	25 min

References:

In addition to the materials contained in this Participant Workbook, participants should obtain a copy of the following publication:

Prowell, B.E., and Hurley, G.C., "Warm Mix Asphalt: Best Practices," *Quality Improvement Series 125,"* National Asphalt Pavement Association, Lanham MD, 2007.

Introduction

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

Summary

Topic: Introduction

Time Allocation: 15 minutes

Learning Outcomes:
- Introduce instructor and participants.
- Identify the objective and training goals.
- Introduce lesson plan and materials.

Instructional Method Lecture/ Discussion:
- The instructor will begin the seminar by welcoming participants, introducing himself/herself, and providing the participants opportunity to introduce themselves and provide a short description of their background and interests in WMA.
- The Instructor will introduce the objective and training goals for the seminar.
- The instructor will review the lesson plan.
- The Instructor will distribute the Participant Workbook and explain its contents.

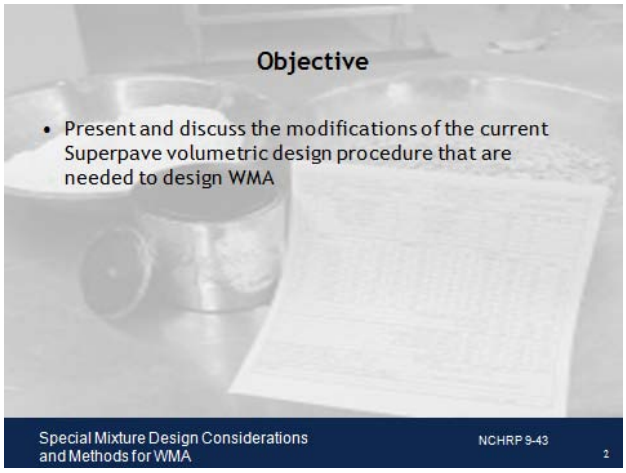
Evaluation Plan: None

Slide 1

This seminar covers a recently developed appendix to AASHTO R35, *Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)*, that addresses the design of warm mix asphalt (WMA). This appendix is the product of National Cooperative Highway Research Program (NCHRP) Project 9-43. It identifies the changes to the current mix design procedure for HMA that are needed to design WMA.

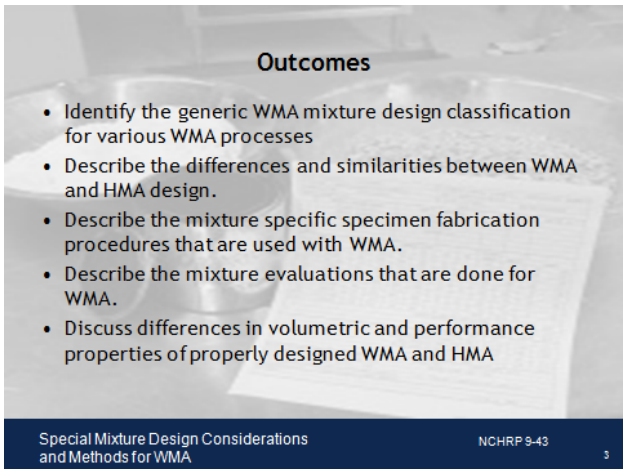
NCHRP Project 9-43 was conducted to adapt existing HMA mixture design procedures to WMA. This research concluded that only minor modification of current mix design practice is needed to address WMA. To implement the recommended modifications for WMA, an appendix to the current dense-graded HMA mix design procedure, AASHTO R35 was developed. This appendix titled *"Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)"* is the subject of this seminar.

Slide 2



The objective of the WMA seminar is to present and discuss the modifications of the current Superpave volumetric design procedure that are needed to design WMA.

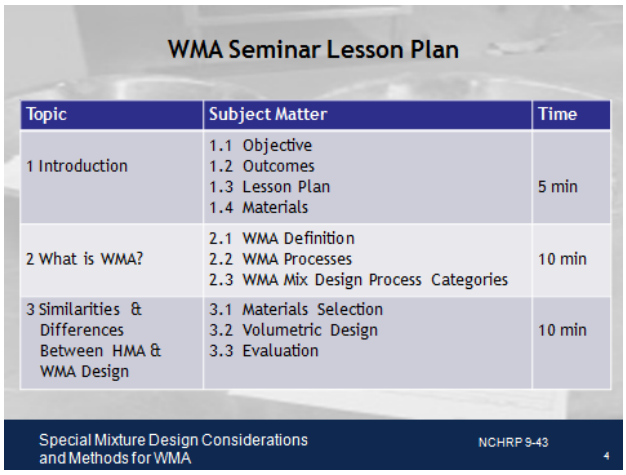
Slide 3



After completing the WMA mix design seminar, the participants will understand how to design WMA mixtures. Specific outcomes include:

- Identify the generic WMA mixture design classification for various WMA processes
- Describe the differences and similarities between WMA and HMA design.
- Describe the mixture specific specimen fabrication procedures that are used with WMA.
- Describe the mixture evaluations that are done for WMA.
- Discuss differences in volumetric and performance properties of properly designed WMA and HMA

Slide 4



WMA Seminar Lesson Plan

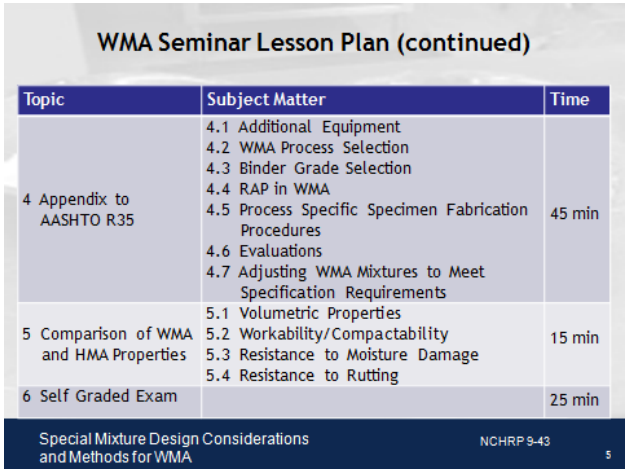
Topic	Subject Matter	Time
1 Introduction	1.1 Objective 1.2 Outcomes 1.3 Lesson Plan 1.4 Materials	5 min
2 What is WMA?	2.1 WMA Definition 2.2 WMA Processes 2.3 WMA Mix Design Process Categories	10 min
3 Similarities & Differences Between HMA & WMA Design	3.1 Materials Selection 3.2 Volumetric Design 3.3 Evaluation	10 min

Special Mixture Design Considerations and Methods for WMA NCHRP 9-43 4

These two slides summarize the topics and subject matter that will be covered in the seminar, and the time devoted to each topic. Content summary is listed below:

7. Introduction. Introduction of seminar and participants.
8. Topic 2. Define WMA, review the various WMA processes, and discuss how the various processes fit into four mix design categories.
9. Topic 3. Discuss similarities and differences between WMA and HMA design. Highlight the areas where WMA and HMA design differ.
10. Topic 4. The majority of the time for the WMA seminar is spent in Topic 4, Appendix to AASHTO R35. During this part of the seminar each of the major parts of the WMA appendix will be discussed.
11. Topic 5. Comparison of WMA and HMA properties, both volumetric and performance, from mixtures made with the same materials but designed as HMA and WMA will be presented.
12. Topic 6. Self-graded quiz. The quiz is designed to provide a review of the material covered in Topics 2 through 5 of the seminar.

Slide 5

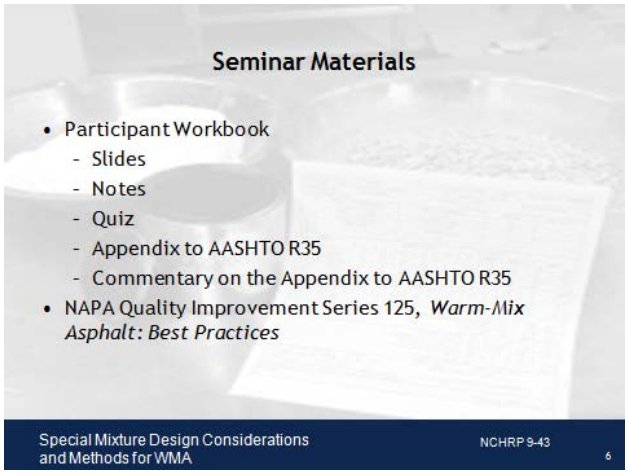


WMA Seminar Lesson Plan (continued)

Topic	Subject Matter	Time
4 Appendix to AASHTO R35	4.1 Additional Equipment 4.2 WMA Process Selection 4.3 Binder Grade Selection 4.4 RAP in WMA 4.5 Process Specific Specimen Fabrication Procedures 4.6 Evaluations 4.7 Adjusting WMA Mixtures to Meet Specification Requirements	45 min
5 Comparison of WMA and HMA Properties	5.1 Volumetric Properties 5.2 Workability/Compactability 5.3 Resistance to Moisture Damage 5.4 Resistance to Rutting	15 min
6 Self Graded Exam		25 min

Special Mixture Design Considerations and Methods for WMA NCHRP 9-43 5

Slide 6



The Participant Workbook includes the materials needed for the WMA Seminar:

- Slides
- Lecture Notes
- Quiz
- Appendix to AASHTO R35 for designing WMA
- Commentary on the Appendix to AASHTO R35

Participants should also obtain a copy of NAPA Quality Improvement Series 125, *Warm-Mix Asphalt: Best Practices.* This publication provides additional information on many WMA processes including the equipment modifications that are needed.

What is WMA?

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

Summary

Topic: What is WMA?

Time Allocation: 10 minutes

Learning Outcomes:
- Define WMA.
- List WMA Mixture Design Categories.

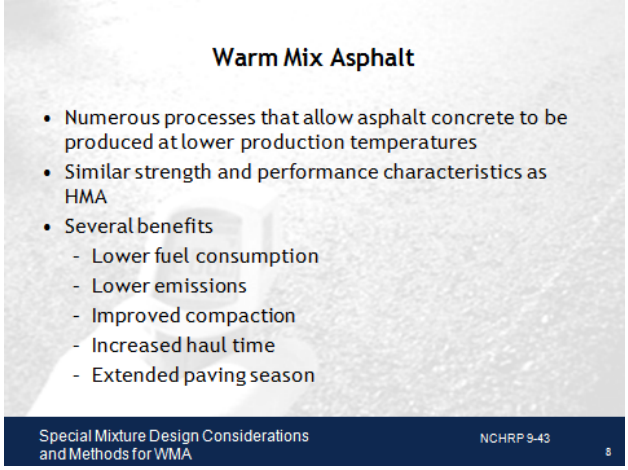
Instructional Method Lecture/ Discussion:
- The Instructor will define WMA and describe the benefits associated with WMA.
- The Instructor will show that there are numerous WMA processes being marketed in the United States.
- The Instructor will introduce the four WMA mixture design categories and explain how the various processes will fit into one of these four categories.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 7

This is the start of Topic 2, What is WMA? This topic includes a brief introduction to WMA and the various processes.

Slide 8



WMA is a generic term for a number of processes that allow asphalt concrete to be produced at lower temperatures. WMA has been successfully produced at temperatures that are 50 to 100 °F below the temperatures used to produce HMA. WMA is expected to have similar strength, durability, and performance characteristics as HMA. It also has several environmental and engineering benefits. The environmental benefits include: reduced fuel consumption and lower emissions. Some of the engineering benefits include: improved compaction, increased haul time, extended paving season.

Slide 9

There are over 20 WMA technologies being marketed in the United States. The list on this slide was taken on 10/21/2010 from the WMA Technologies page at the website www.warmmixasphalt.com.

Slide 10

The WMA processes can be grouped into four categories for mixture design purposes: (1) additives added to the binder, (2) additives added to the mixture, (3) wet aggregate mixtures, and (4) foamed asphalt mixtures.

Example of additives added to the binder?

1. _____.

Example of additives added to the mixture?

1. _____.

Example of wet aggregate process?

1. _____.

Example of foamed asphalt?

1. _____.

Similarities and Differences Between WMA and HMA Design

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

Summary

Topic: Similarities and Differences Between WMA and HMA Design

Time Allocation: 10 minutes

Learning Outcomes:

- Describe the similarities and differences between WMA and HMA design.

Instructional Method Lecture/ Discussion:

- The Instructor will summarize the differences and similarities between WMA and HMA design for the three major parts of the mixture design process:
    4. Materials Selection,
    5. Volumetric Design, and
    6. Mixture Evaluation.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

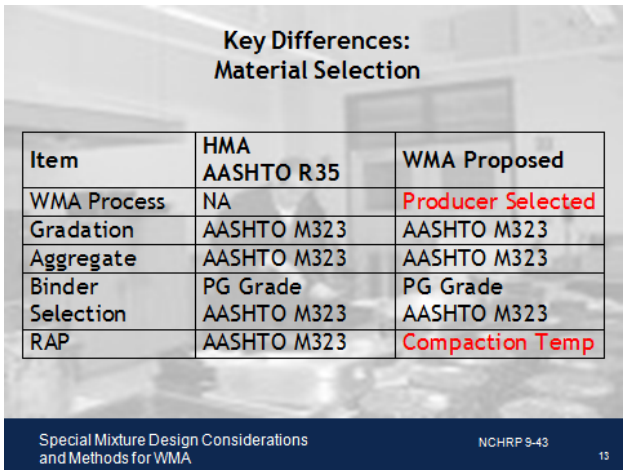
Slide 11

Topic 3 presents is a summary of the similarities and differences in the design of HMA and WMA mixtures.

Slide 12

There are three major parts to the mixture design process: (1) materials selection, (2) volumetric design, and (3) mixture evaluation.

Slide 13



Item	HMA AASHTO R35	WMA Proposed
WMA Process	NA	Producer Selected
Gradation	AASHTO M323	AASHTO M323
Aggregate	AASHTO M323	AASHTO M323
Binder Selection	PG Grade AASHTO M323	PG Grade AASHTO M323
RAP	AASHTO M323	Compaction Temp

There are several items to consider in materials selection.

5. **WMA Process.** For WMA design, the producer must select the WMA process and the planned field mixing and compaction temperatures because the fabrication of WMA specimens in the laboratory is process specific, simulating in an approximate manner, the production of the mixture in the field. WMA process selection is best made by the producer in consultation with the specifying agency and WMA process suppliers.

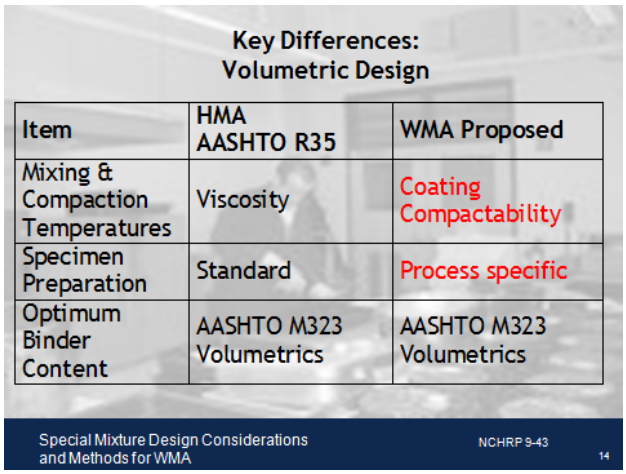
6. **Gradation.** Same as HMA.

7. **Aggregate.** Same as HMA.

8. **Binder Grade.** Same as HMA.

6. **RAP.** When a recycled binder is used in WMA, there is a limit on the stiffness of the recycled binder to ensure adequate mixing of the new and recycled materials. This limit will generally not affect RAP but will limit the use of recycled asphalt shingles (RAS) in many WMA mixtures.

Slide 14



This chart presents a summary of the similarities and differences between HMA and WMA for the volumetric design portion of the mixture design process.

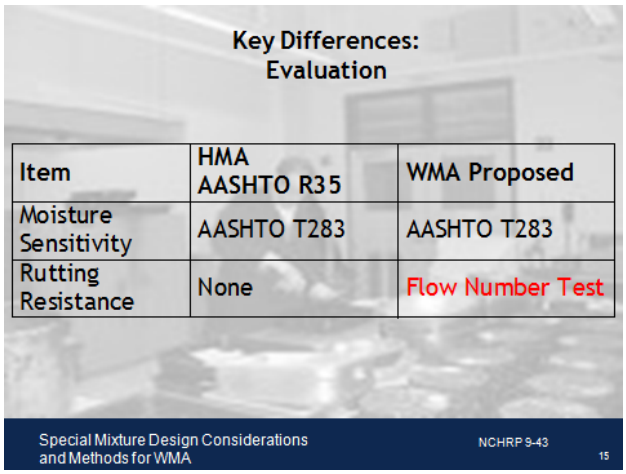
3. **Mixing and Compaction Temperature.** Viscosity based mixing and compaction temperatures cannot be used to control coating, workability, and compactability of WMA mixtures. For WMA coating and compactability are evaluated at the planned field production and compaction temperatures.

4. **Specimen Preparation.** Standard specimen fabrication procedures are used in HMA mixture design. For WMA, the specimen fabrication procedures are process specific using one or more of the generic categories previously described: (1) additive added to the binder, (2) additive added to the mixture, (3) wet aggregate mixtures, (4) foamed asphalt.

4. **Optimum Binder Content.** Same as HMA, using the same gyration level, same design air void content, same

VMA criteria, and same limits on dust to effective asphalt ratio.

Slide 15



Mixture evaluation includes an evaluation of the moisture sensitivity of the mixture and the rutting resistance as follows:

2. **Moisture Sensitivity.** The same evaluation, AASHTO T283, is recommended for WMA and HMA. The criteria for WMA are the same as HMA.

3. **Rutting Resistance.** Since the short-term aging of WMA mixtures will be less due to the lower temperatures, it is important to evaluate the rutting resistance of WMA mixtures. The Appendix to AASHTO R35 uses the flow number test for this evaluation. The flow number will likely be added in the future to HMA mixture design. States that currently use a wheel tracking device should also use that device for WMA mixtures.

Appendix to AASHTO R35

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

Summary

Topic: Appendix to AASHTO R35

Time Allocation: 45 minutes

Learning Outcomes:

- List the additional equipment needed to design WMA mixtures.
- Describe the major differences in the design of HMA and WMA mixtures.
- Explain why the specific WMA process and the planned field production and compaction temperatures are needed for WMA design.
- List the process specific specimen fabrication procedures used in WMA design.
- Describe why coating and compactability are evaluated during WMA design.
- List the steps in the procedure to evaluate coating.
- List the steps in the procedure to evaluate compactability.
- Describe how rutting resistance is evaluated in WMA design.

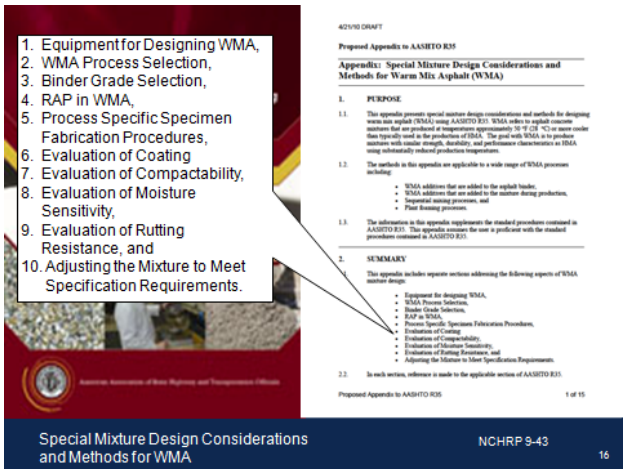
Instructional Method Lecture/ Discussion:

- The Instructor will summarize the important parts of the Appendix to AASHTO R35 including:

    11. Equipment for Designing WMA,
    12. WMA Process Selection,
    13. Binder Grade Selection,
    14. RAP in WMA,
    15. Process Specific Specimen Fabrication Procedures,
    16. Evaluation of Coating
    17. Evaluation of Compactability,
    18. Evaluation of Moisture Sensitivity,
    19. Evaluation of Rutting Resistance, and
    20. Adjusting the Mixture to Meet Specification Requirements.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 16



Topic 4 covers the major product of NCHRP Project 9-43; an Appendix to AASHTO R35 titled, *Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA).* This appendix presents the modifications to the current Superpave mixture design procedure, AASHTO R35, that are necessary to design WMA mixtures. It includes sections addressing:

1. Equipment for Designing WMA,
2. WMA Process Selection,
3. Binder Grade Selection,
4. RAP in WMA,
5. Process Specific Specimen Fabrication Procedures,
6. Evaluation of Coating
7. Evaluation of Compactability,
8. Evaluation of Moisture Sensitivity,
9. Evaluation of Rutting Resistance, and
10. Adjusting the Mixture to Meet Specification Requirements.

Slide 17

WMA design requires some additional equipment that is not needed for HMA design. This equipment includes:

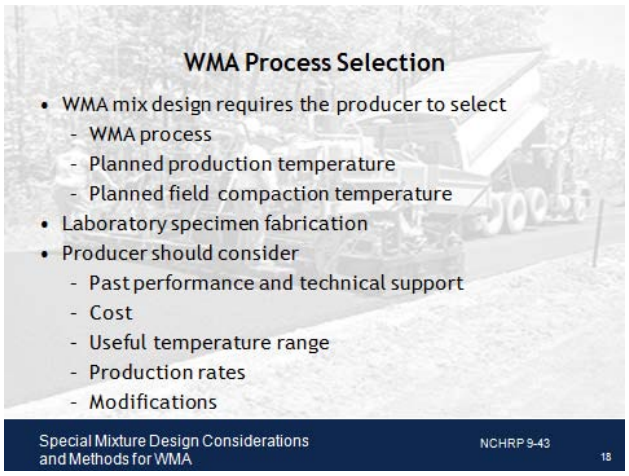
4. **Low Shear Mixer.** This mixer is needed when designing mixtures that require the WMA additive to be added to the binder. All that is needed is a variable speed drill motor mounted to a laboratory stand with an appropriate size impeller. A hot plate is used to maintain the temperature of the binder during mixing.

5. **Mechanical Mixer.** Because coating is evaluated as part of the mix design process, it is necessary to standardize WMA mixing. Two types of mixers are available: planetary and bucket. These two mixers mix differently. The mixing times included in the Appendix to AASHTO R35 are based on

planetary mixers and until additional research is done with bucket mixers, designers using bucket mixers will have to develop appropriate mixing times.

6. **Laboratory Foaming Equipment.** For plant foaming processes, laboratory foaming equipment is needed to simulate the plant foaming. There are only two manufacturers of this equipment. The one on the left by Wirtgen was designed for in-place base course stabilization and needs to be modified to operate at the lower water contents used in WMA production. The one of the right by Pavement Technology, Inc. was designed to simulate WMA processes.

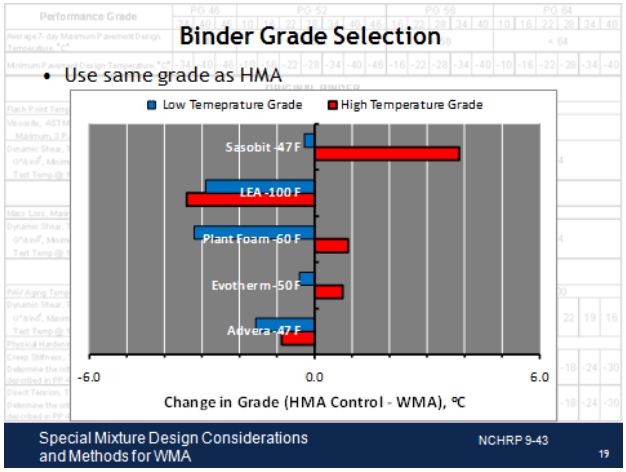
Slide 18



WMA mix design requires that the WMA process and the planned field production and compaction temperatures be known at the start of the design so that proper procedures for specimen fabrication will be used. The WMA process and the temperatures are selected by the producer considering several items including:

6. Past performance and technical support,
7. Cost,
8. Useful temperature range,
9. Production rates, and
10. Plant modifications.

Slide 19

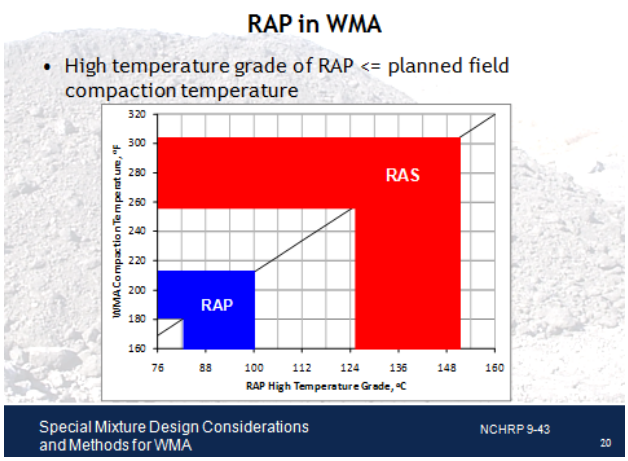


The same binder grade should be used for HMA and WMA mixtures designed for the same traffic and environmental conditions. This recommendation is based on recovered binder data from several mixtures tested during NCHRP 9-43.

Performance grading data for binders recovered from several WMA projects sampled during NCHRP Project 9-43 show only small differences in the grade of the binder for WMA and HMA sections. The average differences in the continuous high and low temperature grade between HMA

and WMA are shown in the graph. Excluding Sasobit, which increases the high temperature grade of the binder, an approximately 50 °F (28 °C) reduction in production temperature resulted in only a small change in the high temperature grade of the recovered binder. 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 1.5 °C, while an approximately 100 °F (56 °C) reduction in production temperature resulted in 2.9 °C improvement for one LEA project.

Slide 20

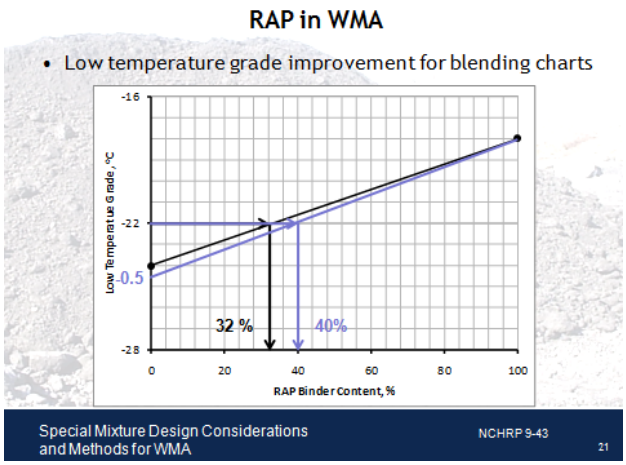


To ensure good mixing of the new and recycled binders, the high temperature grade of the binder in RAP used in WMA should be lower than the planned field compaction temperature.

Research completed in NCHRP Project 9-43 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 9-43, 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 100

resulting in corresponding minimum planned field compaction temperatures ranging from 180 to 212 °F (82 to 100 °C), so this criteria will have little effect on the use or RAP in WMA. It will, however, limit the use of recycled asphalt shingle (RAS) in WMA. RAS binders have high temperature grades exceeding 125 °C, limiting the use of these binders in WMA to the highest temperature WMA processes.

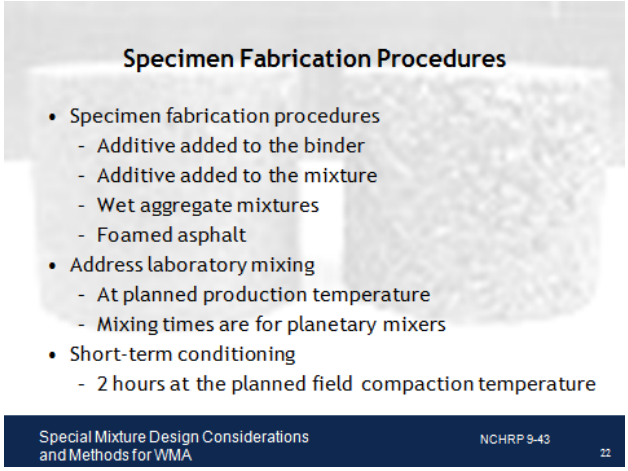
Slide 21



The lower production temperature for WMA results in an improvement in the low temperature grade of the binder. Accounting for this improvement when performing blending chart analysis will allow a greater amount of RAP to be used in WMA.

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. 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 0.5 °C by lowering the production temperature will allow 8 percent additional RAP binder to be added to the mixture.

Slide 22



The WMA specimen fabrication procedures were designed to reasonably reproduce the WMA process. Procedures are provided in the Appendix to AASHTO R35 for:

2. **Additives added to the binder.** This procedure describes how to mix additives with binder for the case where the WMA process supplier does not provide specific directions. If the process supplier provides directions, follow the directions provided. Once the additive is blended with the binder the mixing of binder and aggregate proceeds in the normal manner.

5. **Additives added to the mixture.** This procedure is very similar to that for HMA. After the binder is added to the mixture, the additive is added and then mixed in the normal manner.

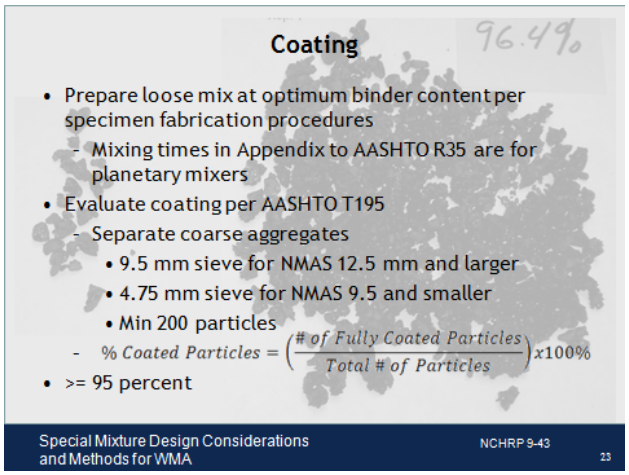
6. **Wet aggregate mixtures.** In this process, some of the fine aggregate is added cold and wet to the mixture. The amount of wet aggregate, its moisture content, and the temperatures are determined by the WMA process supplier. First, the coarse aggregate and the warm portion of the fine aggregate are mixed with the binder at the initial temperature specified by the WMA process supplier. Then the wet aggregate is added cold. As the wet aggregate is heated by the hot aggregate, the binder begins to foam and coat the fine aggregate. The final temperature of the mix should be less than 100 ^{o}C.

7. **Foamed Asphalt Mixtures.** A laboratory foaming plant is needed to produce mix designs for plant foaming processes. The water content used in the laboratory device should be the same as that used in field production. For foamed asphalt

mixtures, the foamed asphalt is added to the heated aggregate. 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 maximum specific gravity specimen then splitting the individual samples.

The procedures in the Appendix to AASHTO R35 were developed from guidance provided by WMA process developers and verified through laboratory testing in NCHRP Project 9-43. In these procedures, mixtures are mixed at the planned production temperature. Short-term conditioning is 2 hours at the planned field compaction temperature. Specimens are compacted in the normal manner at the planned field compaction temperature using a Superpave gyratory compactor.

Slide 23



Viscosity based mixing and compaction temperatures cannot be used with the wide range of WMA processes that are currently available. Coating is evaluated at the planned field production temperature in lieu of the viscosity based mixing temperature used in the design of HMA. Coating is used because it can be applied to a wide range of processes.

The coating evaluation is done at the optimum binder content and requires an additional loose mixture to be prepared at the optimum binder content. This additional loose mixture is prepared following the applicable specimen fabrication procedure for the WMA process, **without short-term oven conditioning.** Then the coating is evaluated using AASHTO T195.

In AASHTO T195, the coarse aggregate particles are split out. The sieve that the

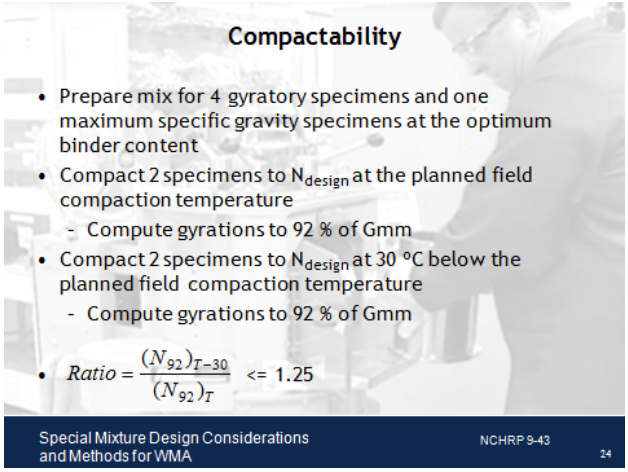
splitting is done on depends on the nominal maximum size of the mixture. Then the fully coated particles are separated from the partially coated particles. The percent coating is the ratio of the number of fully coated particles to the total number of particles.

This is a very strict criterion because it is 95 percent of the coarse aggregate **fully** coated. The mixing times that are included in the Appendix to AASHTO R35 are based on tests on WMA and HMA mixtures that were mixed in the laboratory with a planetary mixer. When a bucket mixer was used with a smaller number of mixes and the same mixing times the coating was much lower. Until additional research is done with bucket mixers, designers using bucket mixers will have to develop appropriate mixing times for their materials.

How would you develop appropriate mixing times for bucket mixers?

Answer:

Slide24



Compactability is evaluated at the planned field compaction temperature in lieu of the viscosity based compaction temperature used in the design of HMA. Like coating, compactability is used because it can be applied to a wide range of processes.

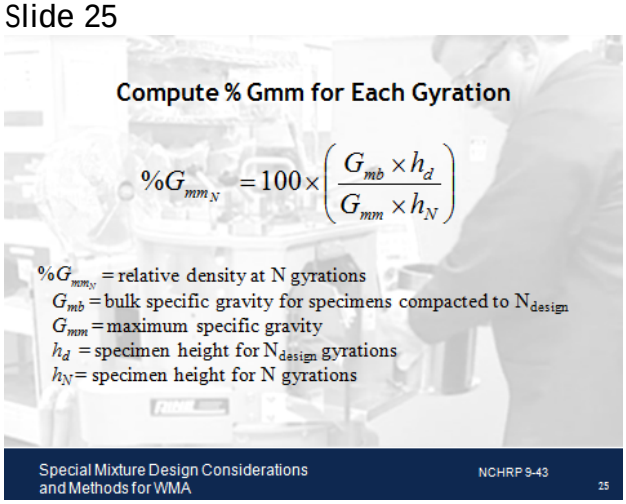
The compactability evaluation is done at the optimum binder content and requires four additional gyratory specimens and a maximum specific gravity specimen to be prepared at the optimum binder content. Mixtures for these additional specimens are

prepared following the applicable specimen fabrication procedure for the WMA process.

The compactability evaluation is conducted as follows. First 2 gyratory specimens are prepared at the planned field compaction temperature. The specimens are compacted to N_{design} gyrations, then the number of gyrations to a density of 92 percent of Gmm is calculated from the measured density at N_{design} gyrations and the recorded specimen height data. Next 2 gyratory specimens are prepared at 30 ºC below the planned field compaction temperature. The loose mix for these specimens should be short-term conditioned at the planned field compaction temperature then the temperature lowered by stirring the mixture at room temperature. The number of gyrations to a density of 92 percent of Gmm is calculated from the measured density at N_{design} gyrations and the recorded specimen height data.

The compactability criterion is the ratio of the gyrations to 92 percent of Gmm at 30 ºC below the planned field compaction temperature to that at the planned compaction temperature. The tentative limit is a maximum of 1.25.

Slide 25



In the compactability evaluation, the density, expressed as a percent of Gmm, is computed for each gyration level using the following equation:

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

where:

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

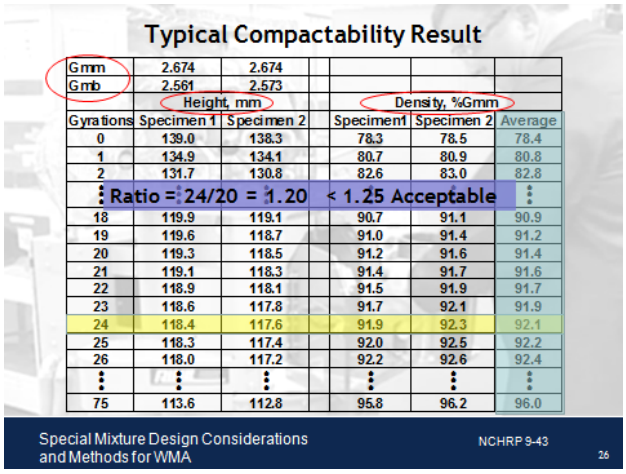
G_{mb} = bulk specific gravity of specimen compacted to N_{design} gyrations;

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

This is the same approach that was used early in the implementation of the Superpave gyratory compactor.

Slide 26



Gmm	2.674	2.674			
Gmb	2.561	2.573			
	Height, mm		Density, %Gmm		
Gyrations	Specimen 1	Specimen 2	Specimen1	Specimen 2	Average
0	139.0	138.3	78.3	78.5	78.4
1	134.9	134.1	80.7	80.9	80.8
2	131.7	130.8	82.6	83.0	82.8
⋮					⋮
18	119.9	119.1	90.7	91.1	90.9
19	119.6	118.7	91.0	91.4	91.2
20	119.3	118.5	91.2	91.6	91.4
21	119.1	118.3	91.4	91.7	91.6
22	118.9	118.1	91.5	91.9	91.7
23	118.6	117.8	91.7	92.1	91.9
24	118.4	117.6	91.9	92.3	92.1
25	118.3	117.4	92.0	92.5	92.2
26	118.0	117.2	92.2	92.6	92.4
⋮	⋮	⋮	⋮	⋮	⋮
75	113.6	112.8	95.8	96.2	96.0

This slide shows part of the compactability evaluation for a WMA mixture with planned field compaction temperature of 250 ºF. A set of specimen was compacted at 250 ºF and the number of gyrations to 92 percent of Gmm was found to be 20 gyrations. The data shown are for specimens compacted at 196 ºF.

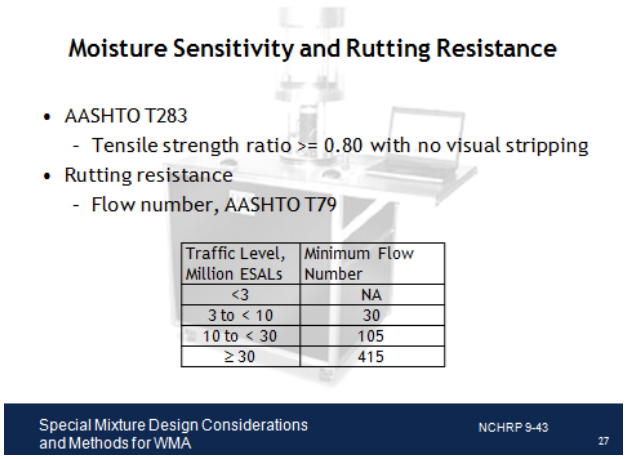
The density as a function of gyration level calculation was made using the bulk specific gravity of each specimen, the maximum specific gravity for the mixture, and the height data for each specimen using the equation on the previous slide.

Once these calculations are made, search the "Average Density" column looking for the point where the average density is equal to or exceeds 92.0. In this example the density is equal to or exceeds 92 percent at 24 gyrations.

The gyration ratio is the gyrations at the lower temperature divided by the gyrations at the higher temperature. For this mixture the gyration ratio is 1.20.

? Is the compactability of this mixture acceptable?
Answer:

Slide 27



Moisture sensitivity and rutting resistance are evaluated as part of the WMA mix design process. The methods that are used are the same as used for HMA.

Moisture sensitivity is evaluated using AASHTO T283. The same criteria for tensile strength ratio and visual stripping are used with WMA and HMA.

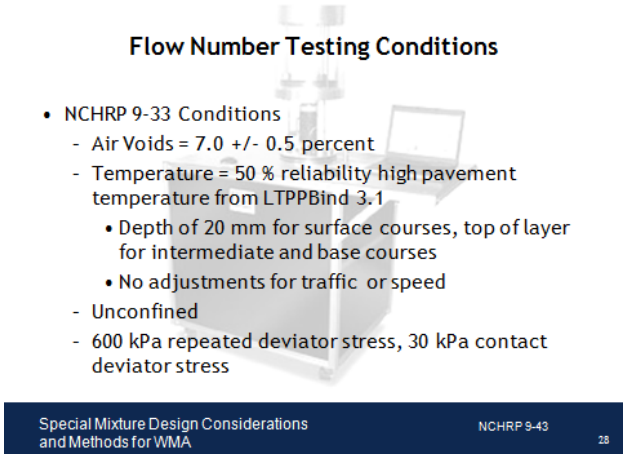
Rutting resistance is evaluated for mixtures designed for traffic levels of 3 million ESALs and greater. The flow number in AASHTO TP 79 is used. Flow number criteria as a function of traffic level are given in the table below:

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

The measured flow number must exceed the value in the table for the mix to be acceptable for the design traffic level.

The flow number criteria for WMA are lower than HMA due to the reduced short-term conditioning used with WMA. For WMA, flow number specimens are short-term conditioned for 2 hours at the compaction temperature. This represents the aging that occurs during construction. For HMA, the conditioning is 4 hours at 275 ºF (135 ºC) which appears to represent construction aging plus some time in service.

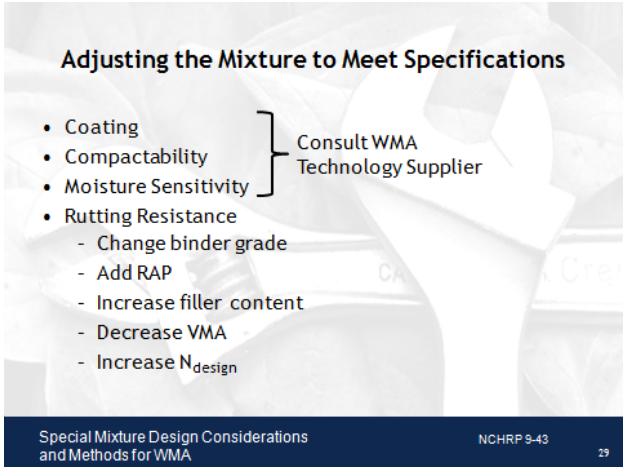
Slide 28



The correct testing conditions must be used in the flow number testing. The criteria in the Appendix to AASHTO R35 are based on the testing conditions recommended in NCHRP Project 9-33 for HMA:

- Air Voids of 7.0 +/- 0.5 percent
- The test temperature should be the 50 % reliability high pavement temperature from LTPPBind 3.1 at a depth of 20 mm for surface courses or the top of the layer for intermediate and base courses. No temperature adjustments for traffic or speed should be made.
- Unconfined
- 600 kPa repeated deviator stress, 30 kPa contact deviator stress

Slide 29



The Appendix to AASHTO R35 includes a section on adjusting the mixture to meet specification requirements. This section addresses coating, compactability, moisture sensitivity, and rutting resistance.

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 user is referred to the specific WMA technology supplier.

Rutting resistance can be improved by:

- Changing the binder grade,
- Adding RAP,
- Increasing filler content,
- Decreasing VMA, and
- Increasing N_{design}

The Appendix to AASHTO R35 includes information on the effect of each of these based on recommendations included in NCHRP Report 567, *Volumetric Requirements for Superpave Mix Design.*

Comparison of WMA and HMA Properties

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

Summary

Topic: Comparison of WMA and HMA Properties

Time Allocation: 15 minutes

Learning Outcomes:

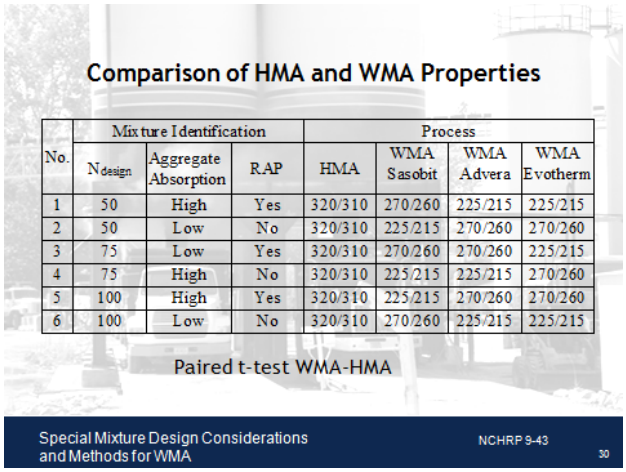
- Describe differences in volumetric properties of mixtures designed as WMA and HMA.
- Describe differences in compactability of mixtures designed as WMA and HMA.
- Describe differences in moisture sensitivity of mixtures designed as WMA and HMA.
- Describe differences in rutting resistance of mixtures designed as WMA and HMA

Instructional Method Lecture/ Discussion:

- The Instructor will present and discuss results from a major mixture design experiment completed in NCHRP 9-43 where mixtures composed of the same aggregates and binder and designed for the same conditions were designed as WMA and HMA.

Evaluation Plan: Content from this topic is included on the end of seminar quiz.

Slide 30



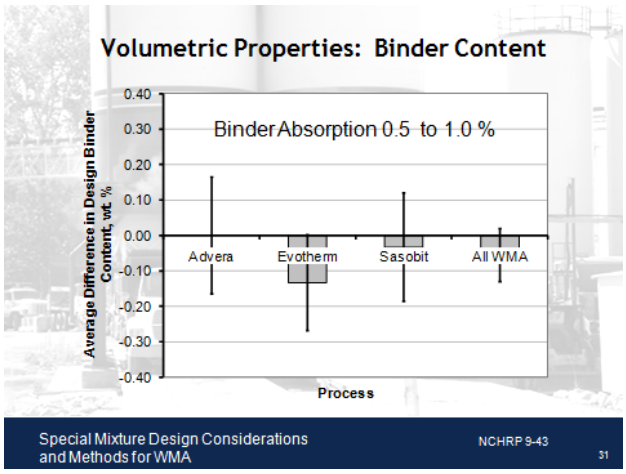
No.	Mixture Identification			Process			
	N_{design}	Aggregate Absorption	RAP	HMA	WMA Sasobit	WMA Advera	WMA Evotherm
1	50	High	Yes	320/310	270/260	225/215	225/215
2	50	Low	No	320/310	225/215	270/260	270/260
3	75	Low	Yes	320/310	270/260	270/260	225/215
4	75	High	No	320/310	225/215	225/215	270/260
5	100	High	Yes	320/310	225/215	270/260	270/260
6	100	Low	No	320/310	270/260	225/215	225/215

The comparisons for WMA and HMA that will be shown in the next several slides are from a major mixture design experiment conducted in NCHRP 9-43 that included the design of 24 mixtures; 18 WMA and 6 HMA.

NCHRP Project 9-43 included a major mixture design study that was designed to compare properties of WMA mixtures designed according the Appendix to AASHTO R35 with those of corresponding HMA mixtures designed according to AASHTO R35. Recall, the underlying principal for WMA is to produce mixtures with similar strength, durability, and performance properties as 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 were 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.

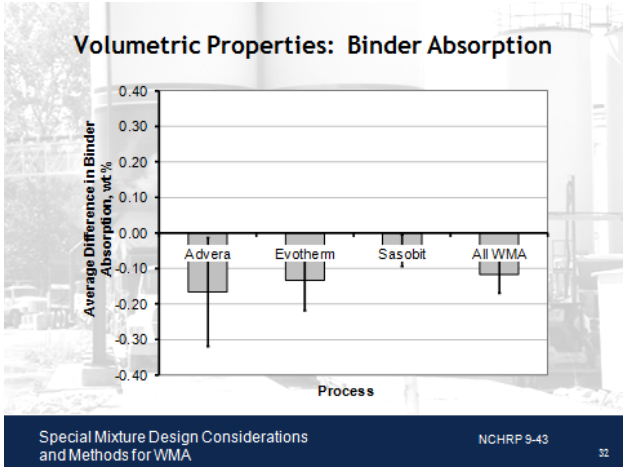
One way to present the results is to develop 95 percent confidence intervals for the mean difference in the properties for WMA compared to HMA. If the 95 percent confidence intervals capture zero, the properties are statistically the same for WMA and HMA. This approach is used in the next several slides to illustrate the results of the experiment.

Slide 31



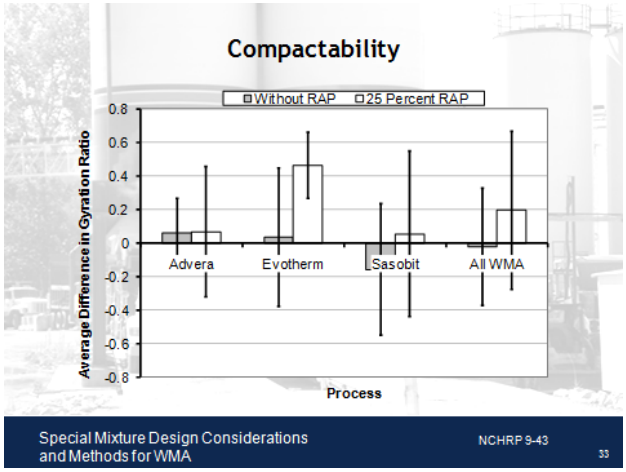
This chart summarizes the findings of the NCHRP 9-43 mixture design study for the difference in the design binder content between WMA and HMA. The error bars in the chart are 95 percent confidence intervals for the difference in the design binder content; WMA design binder content minus HMA design binder content. If the confidence interval captures zero, then there is not a statistically significant difference in the design binder content. The design binder content considering all of the WMA mixtures is about 0.05 percent lower than that for HMA. As shown this difference is not statistically significant. The mixtures used in the NCHRP 9-43 mixture design study had binder absorption between 0.5 and 1.0 percent. The conclusion may be different for mixtures with greater binder absorption.

Slide 32



This slide shows the difference in binder absorption from the NCHRP 9-43 mixture design experiment. Binder absorption is lower for WMA compared to HMA. Remember the mixtures in this experiment had binder absorption that was less than 1 percent. The difference in binder absorption will probably be higher for mixtures with higher binder absorption. This will likely result in a greater difference in the volumetric properties between WMA and HMA for mixtures with higher binder absorption.

Slide 33

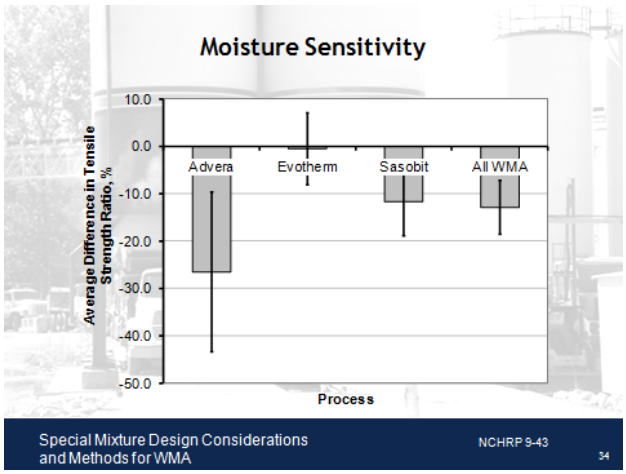


This slide shows the difference in compactability from the NCHRP 9-43 mixture design experiment. The chart shows the difference in the gyration ratio for WMA compared to HMA. A positive difference means WMA was less compactable. Remember the compactability evaluation for the HMA was at a higher temperature compared to that for the WMA.

This chart shows that for most mixtures, the compactability of the WMA mixture at its lower temperature was similar to the corresponding HMA mixture. The exception

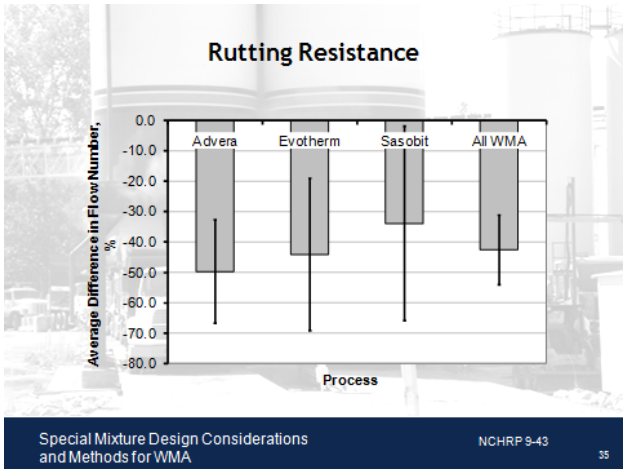
was the Evotherm process for mixtures with RAP. The Evotherm that was used in this experiment was blended into the binder at the terminal. The Evotherm concentration was not adjusted to account for the RAP binder in the mixture. Approximately 25 percent of the binder in the RAP mixtures came from the RAP binder. The other additives were added at the recommended dosage rate based on the total binder content of the mixture.

Slide 34



This slide shows the difference in tensile strength ratio from the NCHRP 9-43 mixture design experiment. Many engineers are concerned that WMA mixtures will have poorer resistance to moisture damage than HMA mixtures because of the lower temperature and the presence of water in some of the WMA processes. This slide shows that the resistance to moisture damage is process specific. The Evotherm used in the NCHRP 9-43 mixture design experiment contained an anti-strip and there was little difference in the tensile ratio for the Evotherm WMA mixtures compared to the HMA. The other WMA processes had a significant drop in the tensile strength ratio. In the NCHRP 9-43 experiment anti-strip additives were not added to any of the mixtures to improve the resistance to moisture sensitivity.

Slide 35



This slide shows the difference in the flow number from the NCHRP 9-43 mixture design experiment. All mixtures were short-term conditioned for 2 hours at the compaction temperature. The lower flow numbers for the WMA processes are due to the reduced aging of the binder due to the lower temperatures.

Although WMA mixtures have lower flow numbers compared to HMA, there have been no reported problems with rutting in field mixtures. The flow number criteria included in the Appendix to AASHTO R35 account for the reduced aging of WMA mixtures.

Self Graded Quiz

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

Summary

Topic: Self Graded Quiz

Time Allocation: 25 minutes

Learning Outcomes:
- Review content contained in Topics 2 through 5.

Instructional Method Lecture/ Discussion:
- Self Graded Quiz

Evaluation Plan: None

Quiz

16. Give a short definition for warm mix asphalt.

17. Warm mix asphalt is designed to have inferior strength, durability and performance characteristics compared to hot mix asphalt.
    a. True
    b. False

18. List the four generic WMA mixture design categories.

    a.

    b.

    c.

    d.

19. Why is a mechanical mixer needed for laboratory design of WMA
    a. WMA is much more difficult to mix than HMA.
    b. The mixing must be standardized to evaluate coating.
    c. WMA specimens are larger than HMA specimens.
    d. To speed up the WMA mix design process.

20. Which of the following information about the field production is needed to perform a laboratory WMA mixture design?
    a. WMA process that will be used.
    b. WMA additive dosage rate.
    c. Planned field production temperature.
    d. Planned field compaction temperature
    e. All of the above

21. The high temperature grade of the binder in a WMA mixture should be one grade level higher than that used in an HMA mixture for the same design conditions.
    a. True
    b. False

22. RAP should not be used in WMA.
    a. True
    b. False

23. Which generic WMA mix design process would you use to simulate a plant foaming process?
    a. Additive added to the binder
    b. Additive added to the mixture
    c. Wet aggregate mixture
    d. Foamed asphalt

24. The results of a compactability evaluation for a WMA mixture made with ACME Additive A are summarized below. Is the compactability of the mixture acceptable?
    a. Yes
    b. No

Temperature, ºF	**Average Gyrations to 92 % of Gmm**
260	26
206	28

Gyration Ratio = 1.08

25. WMA mixture design includes evaluation of which of the following?
    a. Coating
    b. Compactability
    c. Moisture sensitivity
    d. Rutting resistance
    e. All of the above

26. List three things to consider to improve the rutting resistance of WMA mixtures.

    a.

    b.

    c.

27. An existing HMA design having binder absorption of 0.75 percent is being converted to a WMA design for a plant foaming process. The optimum binder content of the HMA design is 5.6 percent. The optimum binder content of the WMA mixtures will be _____ the HMA mixture.
    a. much higher than
    b. much lower than
    c. about the same as

28. WMA mixtures always have improved compactability compared to HMA mixtures.
    a. True
    b. False

29. WMA mixtures always have poorer resistance to moisture damage than HMA mixtures made with the same aggregates and binders.
    a. True
    b. False

30. WMA mixtures will generally have lower flow numbers compared to HMA mixtures made with the same aggregates and binder.
    a. True
    b. False

Quiz Solution

4. (Slide 8) A number of processes that allow asphalt concrete to be produced at lower temperatures than used for hot mix asphalt.

5. (Slide 8)
   b. False, WMA is designed to have similar strength, durability and performance characteristics as HMA

6. (Slide 10)
   a. WMA additives added to the binder
   b. WMA additives added to the mixture,
   c, wet aggregate mixtures,
   d. foamed asphalt

16. (Slide 17 and Slide 23)
    b. The mixing must be standardized to evaluate coating.

17. (Slide 18)
    e. All of the above

18. (Slide 19)
    b. False. The same binder grade should be used for HMA and WMA designed for the same conditions.

19. (Slide 20)
    b. False. The limit on the stiffness of RAP in WMA will have little effect on the use of RAP in WMA in most cases.

20. (Slide 22)
    d. foamed asphalt

21. (Slide 24)
    a. Yes. Gyration ratio of 1.08 is less than 1.25

22. (Slide 23, Slide 24, and Slide 27)
    e. All of the above

23. (Slide 29)
    f. Increase high temperature binder grade
    g. Add RAP
    h. Increase filler content
    i. Decrease VMA
    j. Increase N_{design}

24. (Slide 31)
    c. about the same as. Binder absorption may be a little lower, but that will probably no affect the optimum binder content.

25. (Slide 33)
    b. False. The compactability will depend on the process, temperature, and materials used in the mixture. It may be better, poorer, or the same as a similar designed HMA mixture.

26. (Slide 34)
    b. False. Moisture sensitivity depends on the process, temperature, and materials used in the mixture. WMA processes that include an anti-strip additive will probably have similar or improved resistance to moisture damage compared to HMA.

27. (Slide 35)
    a. True. The lower short-term conditioning temperature for WMA mixtures result in less aging and lower flow number. The reduced aging is considered in the criteria for rutting resistance for WMA mixtures.

Proposed Appendix to AASHTO R35

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

3. PURPOSE

3.1. This appendix presents special mixture design considerations and methods for designing warm mix asphalt (WMA) using AASHTO R35. 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.

3.2. 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.

3.3. The information in this appendix supplements the standard procedures contained in AASHTO R35. This appendix assumes the user is proficient with the standard procedures contained in AASHTO R35.

4. SUMMARY

4.1. 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.

4.2. In each section, reference is made to the applicable section of AASHTO R35.

11. ADDITIONAL LABORATORY EQUIPMENT

11.1. All WMA Processes:

11.1.1. **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 T312.

11.2. Binder Additive WMA Processes

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

11.3. Plant Foaming Processes:

11.3.1. **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.

12. WMA PROCESS SELECTION

12.1. 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.

12.2. Determine the planned production and planned field compaction temperatures.

13. BINDER GRADE SELECTION

13.1. Use the same grade of binder normally used with HMA. Select the performance grade of the binder in accordance with Section 5 of AASHTO M323 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.

14.RAP IN WMA

14.1. 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.

14.2. Select RAP materials in accordance with Section 6 of AASHTO M323.

14.3. 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

15.PROCESS SPECIFIC SPECIMEN FABRICATION PROCEDURES

15.1. Batching

15.1.1. 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 T283 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 T283	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

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

15.1.3. 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.

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

15.2. **Heating**

15.2.1. 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.

15.2.2. Heat the RAP in the oven with the aggregates, but limit the heating time for the RAP to 2 hours.

15.2.3. Heat the binder to the planned production temperature.

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

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

15.3. 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.

15.3.1. Adding WMA Additive to Binder

15.3.1.1. 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.

15.3.1.2. 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.

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

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

15.3.2. Preparing WMA Specimens

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

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

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

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

15.3.2.5. 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:

4. Record the oven dry weight of the aggregates and RAP, w_i
5. 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

6. Add new binder to the bowl to reach w_t

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

15.3.2.7. 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.

15.4. 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.

15.4.1. 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.

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

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

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

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

15.4.6. 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:

4. Record the oven dry weight of the aggregates and RAP, w_i
5. 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

6. Add new binder to the bowl to reach w_t

15.4.7. Pour the WMA additive into the pool of new asphalt binder.

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

15.4.9. 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.

15.5. 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.

15.5.1. Adding WMA Additive to Binder

15.5.1.1. 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.

15.5.1.2. 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.

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

15.5.2. Preparing WMA Specimens

15.5.2.1. 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.

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

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

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

15.5.2.5. 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:

5. Record the oven dry weight of the heated aggregates and RAP, w_i
6. Determine the target total weight of the mixture:

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

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

7. 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

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

15.5.2.6. Add the additive to the binder immediately before mixing with the heated fraction of the aggregate per Section 7.5.1.

15.5.2.7. Remove the mixing bowl from the scale and mix with a mechanical mixer for 30 sec.

15.5.2.8. Stop the mixer and immediately add the wet fraction.

15.5.2.9. Restart the mixer and continue to mix for 60 sec.

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

15.5.2.11. Check the temperature of the mixture in the pan. It shall be between 90 and 100 °C.

15.5.2.12. 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.

15.6. Preparation of Foamed Asphalt Mixtures

15.6.1. 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.

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

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

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

15.6.5. Prepare the foamed asphalt binder per the instructions for the foaming equipment.

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

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

15.6.8. 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:

4. Record the oven dry weight of the aggregates and RAP, w_i
5. 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

6. Add foamed binder to the bowl to reach w_t

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

15.6.10. 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.

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16. WMA MIXTURE EVALUATIONS

16.1. At the optimum binder content determined in accordance with Section 10 of AASHTO R35, 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

16.2. Coating

16.2.1. Prepare sufficient mixture at the design binder content to perform AASHTO T195 using the appropriate WMA fabrication procedure from Section 7 of this appendix. Do not short-term condition the mixture.

16.2.2. Evaluate the coating in accordance with AASHTO T195.

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

16.3. Compactability

16.3.1. 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.

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

16.3.3. Compact duplicate specimens at the planned field compaction temperature to N_{design} gyrations in accordance with AASHTO T312. Record the specimen height for each gyration.

16.3.4. Determine the bulk specific gravity of each specimen in accordance with AASHTO T166.

16.3.5. 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 T312. Record the specimen height for each gyration

16.3.6. Determine the bulk specific gravity of each specimen in accordance with AASHTO T166.

16.3.7. 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

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

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

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

16.3.11. Determine the gyration ratio using Equation 2.

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

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

16.3.12. 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.

16.4. Evaluating Moisture Sensitivity

16.4.1. 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.

16.4.2. Compact test specimens to 7.0 ± 0.5 percent air voids in accordance with AASHTO T 312.

16.4.3. Group, condition and test the specimens in accordance with AASHTO T 283.

16.4.4. 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.

16.5. **Evaluating Rutting Resistance**

16.5.1. Evaluate rutting using the flow number test in AASHTO TP79

16.5.2. 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.

16.5.3. 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 PP60 for detailed procedures for test specimen fabrication procedures. The short-term conditioning for WMA specimens is 2 hours at the compaction temperature.

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

16.5.5. 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.

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

16.5.7. 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
≥ 30	415

17. ADJUSTING THE MIXTURE TO MEET SPECIFICATION PROPERTIES

17.1. 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 R35.

17.2. **Improving Coating**- Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve coating.

17.3. **Improving Compactability**- Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve compactability.

17.4. **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.

17.5. **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 percent will improve rutting resistance by a factor of 1.2.
- Increasing N_{design} by one level will improve rutting resistance by factor of 1.2.

18.ADDITIONAL REPORTING REQUIREMENTS FOR WMA

18.1. For WMA mixtures, report the following information in addition to that required in Section 13 of AASHTO R35.

18.1.1. WMA process description.

18.1.2. Planned production temperature.

18.1.3. Planned field compaction temperature.

18.1.4. High temperature grade of the binder in the RAP for mixtures incorporating RAP.

18.1.5. Coating at the design binder content.

18.1.6. Gyrations 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

18.1.7. Gyration ratio.

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

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

B1. Introduction

One of the products of National Cooperative Highway Research Program (NCHRP) Project 9-43 was a draft appendix to AASHTO R35 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
- Additional Reporting Requirements for WMA.

This commentary to the draft appendix provides supporting information taken from the NCHRP Project 9-43 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 9-43 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 T195. To standardize the mixing process, a mechanical mixer is required. During NCHRP Project 9-43, 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 9-43 using a planetary mixer. Mixing times for bucket mixers will likely be longer.

NCHRP Project 9-43 demonstrated that it is feasible to perform foamed asphalt WMA mixture designs in the laboratory. In NCHRP project 9-43, 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 the 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 9-43 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 9-43 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 9-43. 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 1.5 °C, while an approximately 100 °F (56 °C) reduction in production temperature resulted in 2.9 °C improvement for one LEA project.

Table 8. 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 9. 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

Need for Further Research

Additional recovered binder grade data should be collected and analyze to verify the conclusion from NCHRP Project 9-43 that binder grade changes are not necessary for WMA.

B7. Section 6. RAP in WMA

General Comments

Research completed in NCHRP Project 9-43 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 9-43, 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 to 200 °F (82 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 9-43 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 hours, 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 hour 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 hour 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 design study completed in NCHRP Project 9-43. 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 process 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.

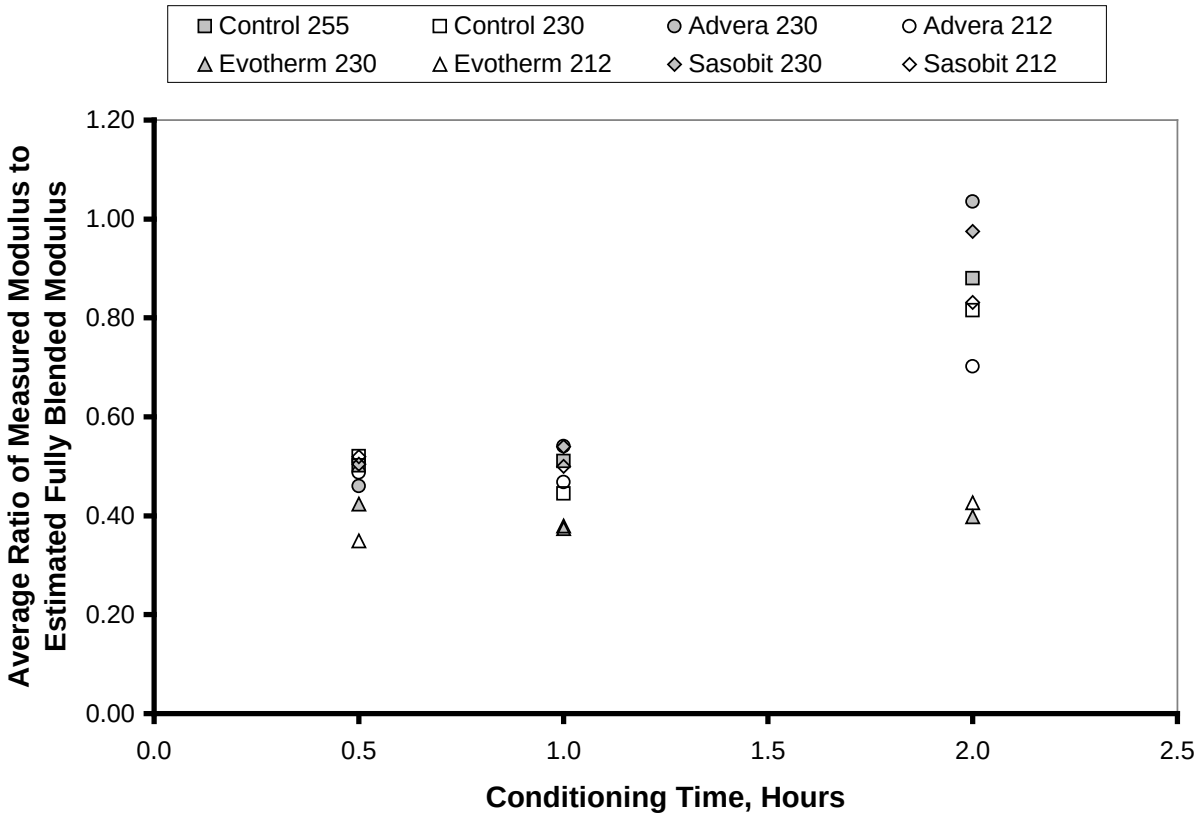

Figure 5. Comparison of the Ratio of Measured to Fully Blended Dynamic Moduli.

Table 10. Optimum Binder Contents for RAP Mixtures from the NCHRP 9-43 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

NCHRP Project 9-43 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 to 2 °C which is only 1/6th to 1/3rd of a grade level.

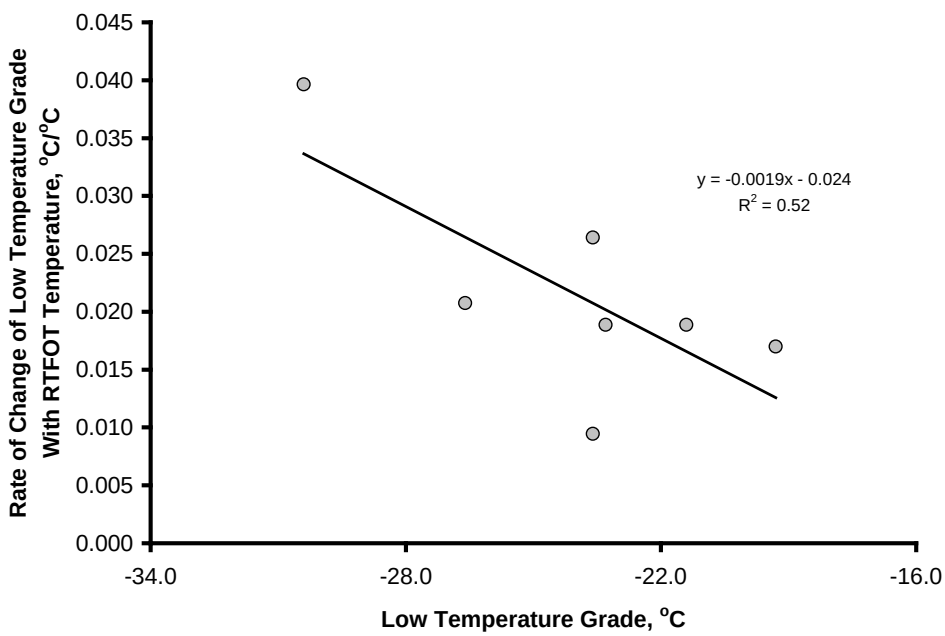

Figure 6. Effect of Low Temperature Binder Grade on the Rate of Change of Low Temperature Grade With RTFOT Temperature.

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 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.

Table 11. 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

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 9-43 included one field project that used 30 percent RAP, the Astec Double Barrel Green WMA process, and field mixing and compaction temperatures of 275 and

260 °F (135 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 9-33.

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 R35.

B9. Section 8. WMA Mixture Evaluations

General Comments

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

- Coating
- Compactability
- Moisture sensitivity
- 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 T195, 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 T283, the same as HMA. The criteria for AASHTO T283 are the same as that for HMA.

Finally, rutting resistance is evaluated using the flow number test in AASHTO TP79. 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 9-43, coating was evaluated on a number of HMA and WMA mixtures using AASHTO T195. 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 was based on the planetary mixer data.

The methodology for the compactability evaluation resulted from a workability study conducted in NCHRP Project 9-43. 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 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 compactability. 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 9 WMA field mixtures projects sampled in NCHRP 9-43. The increase in gryations for the WMA processes ranged from 0 to 20 percent. Workability and compactability was not reported to be a problem on any of the projects.

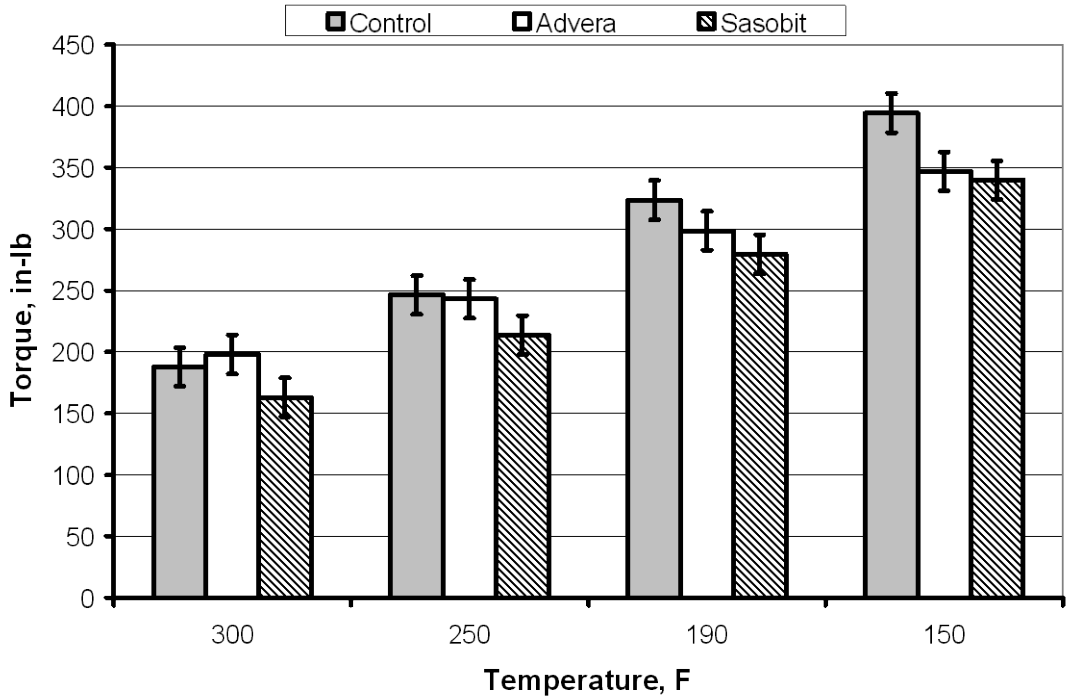

Figure 7. Effect of Temperature and WMA Additive on Torque Measured in the UMass Workability Device.

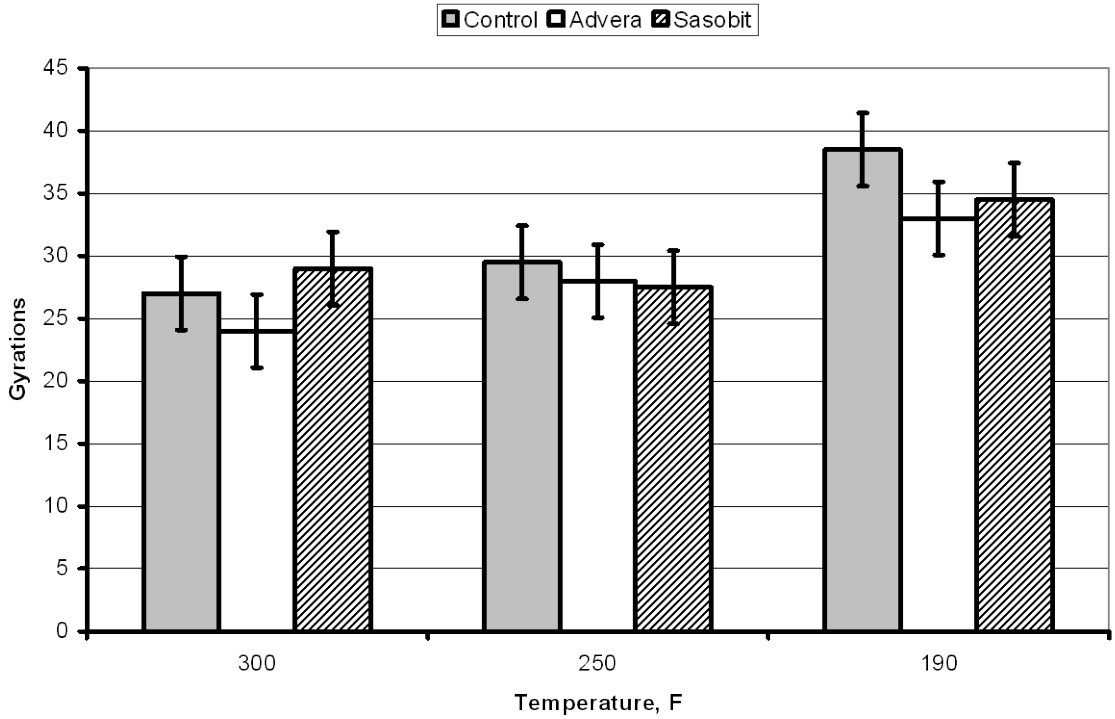

Figure 8. Effect of Temperature and WMA Additive on Gyrations to 92 Percent Relative Density.

Moisture sensitivity is evaluated using AASHTO T283. Tests conducted during NCHRP Project 9-43 showed 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 9-43 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 9-33. The test is conducted on specimens that have been short-term conditioned for 2 hours 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 in 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 processes increases the rutting resistance because it increases the high temperature grade of the binder.

Table 12. 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

Current criteria for the flow number and other rutting tests for HMA are based on 4 hours of short-term conditioning at 275 °F (135 °C). The short-term conditioning study completed in NCHRP Project 9-43 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 hours 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 9-49, *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 9-43 concluded that 2 hours 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 hours 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 T283 for moisture sensitivity testing was 16 hours at 140 °F (60 °C). Additionally, most rutting criteria are based on 4 hours of conditioning at 275 °F (135 °C). In NCHRP Project 9-13, mixtures were conditioned for 2 hours at 275 °F (135 °C), 4 hours at 275 °F (135 °C), and 16 hours at 140 °F (60 °C). Analysis of this data in NCHRP Project 9-43 concluded that 16 hours at 140 °F (60 °C) resulted in somewhat more aging than 4 hours at 275 °F (135 °C). The difference in aging between 2 and 4 hours 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 hours 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. 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 hours 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 T35. For coating, compactability, and moisture sensitivity, the user is directed to consult the WMA process supplier. The effect 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 moistures 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.