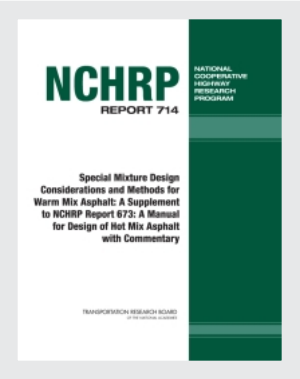

Special Mixture Design Considerations and Methods for Warm-Mix Asphalt: A Supplement to NCHRP Report 673: A Manual for Design of Hot-Mix Asphalt with Commentary

DETAILS

44 pages | | PAPERBACK

ISBN 978-0-309-21373-8 | DOI 10.17226/14615

AUTHORS

Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 714

Special Mixture Design Considerations and Methods for Warm Mix Asphalt: A Supplement to NCHRP Report 673: A Manual for Design of Hot Mix Asphalt with Commentary

Advanced Asphalt Technologies, LLC
Sterling, VA

Subscriber Categories
Highways • Materials

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2012
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 714

Project 9-43
ISSN 0077-5614
ISBN 978-0-309-21373-8
Library of Congress Control Number 2011943519

COPYRIGHT INFORMATION

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR NCHRP REPORT 714

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Edward T. Harrigan, *Senior Program Officer*
Melanie Adcock, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Hilary Freer, *Senior Editor*

NCHRP PROJECT 9-43 PANEL
Field of Materials and Construction—Area of Bituminous Materials

Dean A. Maurer, *Practical Asphalt Solutions Technology, Lewisberry, PA* (Chair)
David B. Powers, *Ohio DOT, Columbus, OH*
Cathrina Barros, *California DOT, Sacramento, CA*
Timothy R. Clyne, *Minnesota DOT, Maplewood, MN*
Gerald Huber, *Heritage Research Group, Indianapolis, IN*
Larry L. Michael, *Hagerstown, MD*
Jorge A. Prozzi, *University of Texas - Austin, Austin, TX*
Todd W. Whittington, *North Carolina DOT, Raleigh, NC*
Matthew Corrigan, *FHWA Liaison*
David E. Newcomb, *Texas Transportation Institute Liaison*
Frederick Hejl, *TRB Liaison*

FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report provides a mix design method tailored to the unique material properties of warm mix asphalt (WMA) technologies in the form of a supplement to *NCHRP Report 673: A Manual for Design of Hot Mix Asphalt*. The report will be of immediate interest to materials engineers in state highway agencies and industry.

WMA refers to asphalt mixtures produced at temperatures approximately 50°F (28°C) or cooler than typically used in the production of hot mix asphalt (HMA). The goal of WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA using substantially reduced production temperatures. Important environmental and health benefits associated with reduced production temperatures include lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also improve pavement performance by (1) reducing binder aging, (2) providing added time for mixture compaction, and (3) allowing improved compaction during cold weather paving.

For most WMA projects constructed in the United States to date, WMA has been substituted into a mixture designed as HMA with no change to the job mix formula. Provision of a formal mix design method for mixtures prepared with the wide variety of WMA technologies available now and in the future will further encourage their use.

The objective of NCHRP Project 9-43, "Mix Design Practices for Warm Mix Asphalt," was to develop a mix design method for WMA for use by engineers and technicians in the public and private sectors. *NCHRP Report 691: Mix Design Practices for Warm Mix Asphalt* fully documents the research leading to the key finding that a stand-alone WMA mix design method distinct from that for HMA is not warranted. Thus, the final product of the research was a proposed appendix to AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA),* titled *Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)*. This report provides that proposed appendix in the form of a supplement to *NCHRP Report 673: A Manual for Design of Hot Mix Asphalt,* produced in NCHRP Project 9-33.

CONTENTS

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

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

This report presents special mixture design considerations and methods used with warm mix asphalt (WMA) and is a supplement to *NCHRP Report 673: A Manual for Design of Hot Mix Asphalt*. In this report, all references to chapters refer to the corresponding chapters in *NCHRP Report 673*. Although the procedures described have been specifically selected for use in designing dense-graded mixtures, most can be applied to the design of other mix types with little or no modification. Before reading this report, engineers and technicians should make certain they have a thorough understanding of the dense-graded mix design process presented in Chapter 8 and the procedures for incorporating RAP into hot mix asphalt (HMA) discussed in Chapter 9 of *NCHRP Report 673*. *NCHRP Report 714* is based on research conducted in NCHRP Project 9-43, "Mix Design Practices for Warm Mix Asphalt," which concluded that only minor modifications of current mix design practice are needed to address WMA. These modifications are discussed in detail herein. Part II provides a commentary to support the proposed design considerations and methods.

What is WMA?

WMA refers to asphalt concrete mixtures 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 while 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 improve pavement performance by (1) reducing binder aging, (2) providing added time for mixture compaction, and (3) allowing improved compaction during cold weather paving. For these reasons, many WMA technologies may also be incorporated in the production of HMA at typical production temperatures during cold weather paving.

WMA technologies were first introduced in Europe in the late 1990s as one measure to reduce greenhouse gas emissions. Since then, many WMA processes have been developed in Europe and the United States. At the time this report was completed (2011), approximately 20 WMA processes were marketed in the United States. These processes included chemical, wax, and synthetic zeolite additives that can be blended with the binder or added to the mixture during production; plant foaming systems; and sequential mixing processes. The National Asphalt Pavement Association (NAPA) publication, *Quality Improvement Series 125,* "Warm-Mix Asphalt: Best Practices," presents more detailed information on many of these processes including the types of plant modifications needed with each.

Overview of WMA Design

The design of WMA is very similar to the design of HMA, following the 11 steps described in Chapter 8 for the design of dense-graded HMA. Table 1 summarizes the differences between WMA and HMA for each of the 11 steps.

Table 1. Steps in design of dense-graded HMA and WMA.

Step	Description	Major WMA Differences
1	Gather Information	1. WMA process, 2. Additive rates, 3. Planned production temperature, 4. Planned compaction temperature.
2	Select Asphalt Binder	1. Recommended limit on high-temperature stiffness of recycled binders. 2. May consider low-temperature grade improvement when using blending charts.
3	Determine Compaction Level	Same as HMA
4	Select Nominal Maximum Aggregate Size	Same as HMA
5	Determine Target VMA and Design Air Voids Value	Same as HMA
6	Calculate Target Binder Content	1. Lower asphalt absorption due to lower temperatures.
7	Calculate Aggregate Volume	Same as HMA
8	Proportion Aggregate Blends for Trial Mixtures	Same as HMA
9	Calculate Trial Mixture Proportions by Weight and Check Dust/Binder Ratio	Same as HMA
10	Evaluate and Refine Trial Mixtures	1. WMA process specific specimen fabrication procedures, 2. Lower short-term aging temperature, 3. Evaluate coating and compactability in lieu of viscosity-based mixing and compaction temperatures.
11	Compile Mix Design Report	Same as HMA

Specimen fabrication in Step 10, Evaluate and Refine Trial Mixtures, is the primary difference for the design of WMA compared with HMA. Procedures for specimen fabrication are process specific; therefore, information on the WMA process that will be used and the planned production and compaction temperatures must be collected in Step 1 at the beginning of the WMA mix design process. Given that binder absorption is lower in WMA mixtures, the lower absorption should be accounted for when estimating the target binder content in Step 6. Another important difference between WMA and HMA design occurs in the selection of binders in Step 2. The high-temperature grade of the recycled binders should be lower than the planned WMA compaction temperature to promote mixing of the new and recycled binders. When using blending charts, the low-temperature grade of the new binder may be improved due to the lower aging that occurs at WMA temperatures. The following sections provide step-by-step discussions of the similarities and differences between WMA and HMA. These are followed by an example WMA design.

Step 1. Gather Information

The design of WMA requires the same information about the design traffic level, the climate at the place of construction, available aggregates and binders, anticipated lift thickness, and pavement type (that is, surface, intermediate, or base course) as the design of HMA. In addition, WMA design requires information on the WMA process and the planned 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. Table 2 summarizes the information that should be collected for designing WMA mixtures and compares this information to that required for designing HMA mixtures.

Table 2. Information required for WMA and HMA design.

Type of Information	Detail	WMA	HMA
Site	Geographic Location	X	X
	Climate Relating to Binder Grade	X	X
	Design Traffic Level	X	X
	Design Life	X	X
	Unusual Performance Requirements	X	X
Construction	Lift Thickness	X	X
	Haul Time	X	X
	Construction Temperatures	X	X
	Unusual Specification Requirements	X	X
	Unusual Construction Requirements	X	X
Pavement	Mix Type	X	X
	Distance from Pavement Surface	X	X
Aggregate	Nominal Maximum Size	X	X
	Gradation	X	X
	Specific Gravity and Absorption	X	X
	Specification Properties	X	X
Binder	Performance Grade	X	X
	PG Plus Properties, if applicable	X	X
	Type of Modification, if applicable	X	X
	Continuous Performance Grade for Blending Chart Analysis	X	X
	Mixing and Compaction Temperatures	NA	X
RAP	Binder Content	X	X
	Continuous Performance Grade	X	X
	Nominal Maximum Size	X	X
	Gradation	X	X
	Specific Gravity and Absorption	X	X
	Specification Properties	X	X
Anti-Strip Additives	Type	X	X
	Dosage Rate	X	X
WMA	WMA Process	X	NA
	Additive Type	X	NA
	Additive Dosage Rate	X	NA
	Production Temperature	X	NA
	Compaction Temperature	X	NA

WMA process selection is best made by the producer in consultation with the specifying agency and WMA process suppliers considering (1) available performance data, (2) cost of the required warm mix additives, (3) planned production and compaction temperatures, (4) planned production rates, (5) existing plant capabilities, and (6) plant and laboratory modifications required to successfully use the WMA process.

For the purposes of mixture design, the various WMA processes can be grouped into four generic categories:

1. Additives blended into the binder,
2. Additives added to the mixture,
3. Wet aggregate mixtures, and
4. Foamed asphalt.

Specimen fabrication techniques are somewhat different for each of these categories. Given that viscosity-based mixing and compaction temperatures are not applicable to many WMA processes, the planned production and compaction temperatures are used in the WMA mixture design process to evaluate coating and the compactability/workability of the WMA. It should be emphasized that the optimal production and compaction temperatures are different for the various WMA processes and should be carefully considered when selecting production and compaction temperatures to be used in the WMA design process.

Step 2. Select Asphalt Binder

The grade of binder used in WMA mixtures with less than 15% recycled binder is the same as that for an HMA mixture designed for the same conditions. The change in the high- and low-temperature properties of the binder due to lower WMA temperatures is not sufficient to warrant a change in the grade of the binder used in the mixture. The binder grade used in WMA should be either (1) the grade required by the specifying agency for HMA or (2) selected as discussed in Chapter 8 considering

1. The climate at the project location,
2. High-temperature grade adjustment required for traffic level and speed, and
3. High-temperature grade adjustments for temporary construction.

When a recycled binder is used in WMA, it is recommended that the continuous high-temperature grade of the recycled binder be equal to or lower than the planned compaction temperature to ensure adequate mixing of the new and recycled materials. This recommendation will generally not affect the use of recycled asphalt pavement (RAP) in WMA. The high-temperature grade of RAP in the United States ranges from about 82°C in colder climates to about 100°C in hotter climates. Planned compaction temperatures for most warm mix processes are greater than 212°F (100°C). This recommendation will, however, limit the use of recycled asphalt shingles (RAS) in many WMA processes. Many RAS binders have high-temperature grades exceeding 124°C, indicating that these materials should not be used in WMA processes where the planned compaction temperature is less than about 255°F (124°C).

When adding more than 15% recycled binder to WMA, the blending chart analysis described in Chapter 9 for HMA should also be used. If permitted by the specifying agency, the low-temperature continuous grade of the new binder may be improved somewhat to account for the lower WMA process temperatures. The recommended improvement depends on the new binder grade and the production temperature. Table 3 presents recommended low-temperature binder grade improvements developed in NCHRP Project 9-43 for some common binder grades. For a WMA process having a production temperature of 250°F, the low-temperature grade improvement ranges from 0.3 to 0.7°C. For a typical blending chart analysis this translates to 5 to 10% additional RAP based on low-temperature binder grade considerations. As discussed in Chapter 9, binder grade is one of several considerations affecting the amount of RAP that can be added to a mixture.

In summary, the grade of binder used in most WMA mixtures will be the same as that used in a comparable HMA mixture. When the WMA mixture incorporates a recycled binder, it is recommended that the high-temperature grade of the recycled binder be equal to or lower than the planned compaction temperature to ensure adequate mixing of the new and recycled materials. If permitted by the specifying agency, it is reasonable to improve the low-temperature grade of the new binder somewhat when performing blending chart analyses for higher RAP content mixtures. Although small, this improvement may permit 5 to 10% additional RAP to be added, based on low-temperature binder grade considerations.

Step 3. Determine Compaction Level

Although it is well documented that WMA mixtures are generally easier to compact than HMA, the same design compaction level should be used with WMA and HMA. In NCHRP Project 9-43, several mixtures with less than 1% binder absorption designed as WMA and HMA following the procedures given in this manual had optimum binder contents and volumetric properties that were essentially the same. The recommended design compaction levels for both WMA and HMA

Table 3. 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
205	1.6	1.1	1.2	0.6	1.3
200	1.7	1.2	1.3	0.6	1.4

are summarized in Table 4. As discussed in Chapter 8, these compaction levels are under review and could be modified soon.

Step 4. Select Nominal Maximum Aggregate Size

The same nominal maximum aggregate size mixture should be used when designing the mixture as WMA or HMA. Usually, the nominal maximum size is given by the specifying agency. When it is not, the recommendations in Chapter 8 on the ratio of lift thickness to nominal maximum aggregate size should be followed. These recommendations are reproduced in Table 5. As with HMA, smaller aggregate sizes should be used for wearing course mixtures and where extra durability is desired; this will help provide a mix that compacts easily, has low permeability, and resists fatigue cracking.

Table 4. Recommended design compaction levels for dense-graded HMA mixtures.

Design Traffic (Million ESALs)	N_{design}
< 0.3	50
0.3 to < 3	75
3 to < 10	100
10 to < 30	100
≥ 30	125

Step 5. Determine Target VMA and Design Air Voids Values

In the design procedure presented herein, the target VMA and design air void content are used to initially calculate the design binder content for the mixture using an assumed value for binder absorption. Trial mixtures are then prepared using the design binder content to determine an aggregate gradation that provides the design air void content. Minor adjustments to the

Table 5. Recommended nominal maximum aggregate sizes for dense-graded HMA mixtures.

Application	Recommended NMAS, mm	Minimum Lift Thickness, mm	
		Fine-Graded Mixtures	Coarse-Graded Mixtures
Leveling course mixtures	4.75	15 to 25	20 to 25
	9.5	30 to 50	40 to 50
Wearing course mixtures	4.75	15 to 25	20 to 25
	9.5	30 to 50	40 to 50
	12.5	40 to 65	50 to 65
Intermediate course mixtures	19.0	60 to 100	75 to 100
	25.0	75 to 125	100 to 125
Base course mixtures	19.0	60 to 100	75 to 100
	25.0	75 to 125	100 to 125
	37.5	115 to 150	150
Rich base course mixtures	9.5	30 to 50	40 to 50
	12.5	40 to 65	50 to 65

Table 6. VMA requirements for dense-graded mixtures.

Aggregate NMAS (mm)	Minimum VMA[A] (%)	Maximum VMA[A] (%)	Target VMA (%)
4.75	16.0	18.0	17.0
9.5	15.0	17.0	16.0
12.5	14.0	16.0	15.0
19.0	13.0	15.0	14.0
25.0	12.0	14.0	13.0
37.5	11.0	13.0	12.0

[A]The specifying agency may increase the minimum and maximum values for VMA by up to 1.0% to obtain mixtures with increased asphalt binder content, which can improve field compaction, fatigue resistance, and general durability. Care should be taken to ensure that the resulting HMA mixtures maintain adequate rut resistance for their intended application.

design binder content may also be necessary to account for differences between the initially assumed binder absorption and the actual absorption in the trial mixtures.

For the design of WMA mixtures, the same minimum, maximum, and target VMA values discussed in Chapter 8 for HMA should be used. These values are reproduced in Table 6. Higher design VMA will increase the binder content of the mixture, thereby improving compactability, durability, and resistance to fatigue damage, but decreasing the resistance to rutting. Decreasing the design VMA will have the opposite effect on compactability, durability, resistance to fatigue damage, and resistance to rutting. The target air void content for WMA mixtures should be 4.0% with an acceptable range of 3.5 to 4.5%. Lower design air voids will increase the design binder content of the mixture, thereby improving compactability, durability, and resistance to fatigue damage, but decreasing the resistance to rutting. Higher design air voids will have the opposite effect on compactability, durability, resistance to fatigue damage, and resistance to rutting.

Step 6. Calculate Target Binder Content

The target binder content by volume for WMA is calculated in the same manner as described in Chapter 8 for HMA: target VMA minus design air voids plus volume of binder absorbed. The lower temperatures for WMA mixtures result in less binder absorption compared with HMA. In NCHRP Project 9-43, the binder absorption for WMA mixtures was about 90% of that for HMA

mixtures designed using the same binder and aggregates. A reasonable estimate of the volume of binder absorbed in WMA mixtures is 45% of the volume of water absorbed by the aggregates used in the mixture. This estimate is given in Equation 1 and is used in the software program HMA Tools (available for download at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=967) to estimate the binder content by volume for WMA mixtures.

$$V_b = VMA - VA + \left(1 - \frac{VMA}{100}\right)\left(\frac{G_{sb} P_{wa}}{2.2}\right) \quad (1)$$

where

V_b = total asphalt content by volume %
VMA = target voids in the mineral aggregate, vol. %
VA = design air voids, vol. %
G_{sb} = aggregate bulk specific gravity
P_{wa} = water absorption of the aggregate, weight %

As with HMA mixture design, the binder content by volume computed at this point is an estimate that will be refined during Step 10, Evaluate and Refine Trial Mixtures, of the design process. For batching, the binder content by volume must be converted to binder content by weight using the specific gravity of the binder and the aggregates in the mixture. These calculations were presented in Chapter 8 and are performed by HMA Tools.

Step 7. Calculate Aggregate Content by Volume

The total aggregate content by volume is calculated in the same manner as described in Chapter 8 for HMA: 100% minus target VMA. Determination of the total aggregate content by weight will depend on the aggregate specific gravity values, and the specific blend of aggregates used in each mixture. These calculations were presented in Chapter 8 and are performed by HMA Tools.

Step 8. Proportion Aggregates for Trial Mixtures

Proportioning aggregates for trial WMA mixtures is the same as described in Chapter 8 for design of HMA mixtures. The mix design procedure presented in this manual sets the binder content at a value that will provide the proper VMA once the design air void content is met. Therefore, proportioning aggregates can be thought of as determining the blend of aggregates that will provide the proper air void content for the mixture. Note that the control points given in Chapter 8 are considered guidelines and not specification requirements.

Chapter 8 presented a graphical procedure for aggregate blending that uses the continuous maximum density (CMD) plot. This plot quantifies how much various aggregate gradations deviate from the maximum density gradation and is effective at identifying those changes that potentially affect the VMA of the mixture. This procedure should be followed when designing new WMA mixtures.

Most WMA mixture design work will be able to adapt a specific WMA process to an existing HMA design. For this type of design, there is no need to change the aggregate proportions from those used in the HMA design; unless the binder absorption is very high, the volumetric properties of the WMA and HMA mixtures will be very similar. When performing a WMA design of an existing HMA mixture in HMA Tools, enter the aggregate and RAP data (if used) in worksheets "Aggregates," and "RAP_Aggregates." Then, the aggregate blend for the existing mix is entered

Table 7. Coarse aggregate fractured faces (CAFF) requirements.

Design ESALs (million)	Percentage of Particles with at Least One/Two Fractured Faces, for Depth of Pavement Layer[A], mm	
	0 to 100	Below 100
< 0.30	55 / ---	--- / ---
0.3 to < 3	75 / ---	50 / ---
3 to < 10	85 / 80	60 / ---
10 to < 30	95 / 90	80 / 75
30 or more	98 / 98[B]	98 / 98[B]

[A]Depth of pavement layer is measured from pavement surface to surface of pavement layer.
[B]The CAFF requirement for design traffic levels of 30 million ESALs or more may be reduced to 95/95 if experience with local conditions and materials indicate that this would provide HMA mixtures with adequate rut resistance under very heavy traffic.

in worksheet "Trial_Blends." The design then proceeds as described in Chapter 8 for HMA, determining the air void content and VMA for trial batches, and then making further refinements in the aggregate gradation as needed, until the desired mix properties are met.

The aggregates used in WMA should meet the aggregate specification properties given in Chapter 8 for HMA. There are four aggregate specification properties: (1) coarse aggregate fractured faces (CAFF); (2) flat and elongated particles in the coarse aggregate; (3) fine aggregate angularity (FAA); and (4) clay content of the fine aggregate (sand equivalent). These requirements are presented in Tables 7 to 10. Note that the aggregate specification requirements apply to the blended aggregates and should be measured on the final design blend of aggregates. For trial batches, they can be

Table 8. Criteria for flat and elongated particles.

Design ESALs (million)	Maximum Percentage of Flat and Elongated Particles at 5:1
< 0.30	---
0.3 to < 3	10
3 to < 10	10
10 to < 30	10
30 or more	10

Criteria are presented as percent flat and elongated particles by mass.

Table 9. Fine aggregate angularity (FAAAQ15) requirements.

Design ESALs (million)	Depth of Pavement Layer from Surface, mm	
	0 to 100[a]	Below 100[a]
< 0.30	---[b]	---
0.3 to < 3	40	---
3 to < 10	45[c]	40
10 to < 30	45[c]	45[c]
30 or more	45[c]	45[c]

Criteria are presented as percent air voids in loosely compacted fine aggregate.

[a] If Less than 25 percent of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for mixture design purposes.
[b] Although there is no FAA requirement for design traffic levels below 0.30 million ESALS, consideration should be given to requiring a minimum uncompacted void content of 40 percent for 4.75 mm nominal maximum aggregate size mixes.
[c] The FAA requirement of 45 may be reduced to 43 if experience with local conditions and materials indicate that this would produce HMA mixtures with adequate rut resistance under the given design traffic level.

Table 10. Maximum clay content requirements.

Design ESALs (million)	Minimum Sand Equivalency Value
< 0.30	40
0.3 to < 3	40
3 to < 10	45
10 to < 30	45
30 or more	50

Criteria are presented as sand equivalent value.

estimated from the specification property values for the individual aggregates using HMA Tools. These estimates should then be verified by measurements on the final design blend.

Step 9. Calculate Trial Mix Proportions By Weight and Check Dust-to-Binder Ratio

This step in the design of WMA mixtures is identical to that described in Chapter 8 for HMA mixtures. This step involves calculating the following for each trial blend of aggregates:

1. Bulk specific gravity of the aggregate blend,
2. Weight percentage of binder in the mixture,
3. Weight percentage of total aggregate in the mixture,
4. Effective binder content by weight,
5. Weight percentage of each aggregate in the mixture,
6. Weight percentage of mineral dust in the mixture, and
7. Dust to effective binder ratio.

These calculations are performed automatically by HMA Tools and when RAP is included in the mixture, binder from the RAP is properly accounted for in the calculations. WMA mixtures should meet the requirements for the ratio of dust to effective binder content given in Chapter 8 for HMA. These requirements are reproduced in Table 11.

Step 10. Evaluate and Refine Trial Mixtures

This step involves the preparation and evaluation of laboratory specimens of WMA. The procedure follows that described in Chapter 8 for HMA with slight modification. Table 12 summarizes the steps for WMA and HMA design. The modifications required for WMA design are

1. For some processes, the WMA additive must be calculated.
2. Viscosity-based mixing temperatures are not used with WMA. Laboratory mixing is done at the planned production temperature.

Table 11. Requirements for dust/binder ratio.

Mix Aggregate NMAS, mm	Allowable Range for Dust/Binder Ratio, by Weight
> 4.75	0.8 to 1.6[A]
4.75	0.9 to 2.0

[A]The specifying agency may lower the allowable range for dust/binder ratio to 0.6 to 1.2 if warranted by local conditions and materials. The dust/binder ratio should however not be lowered if VMA requirements are increased above the standard values as listed in Table 13-6.

Table 12. Comparison of trial specimen fabrication procedures for WMA and HMA design.

Step	Description	HMA	WMA	Comment
1	Calculate batch weights	X	X	Must calculate WMA additive content for some processes
2	Batch aggregates	X	X	Must batch WMA additive for some processes
3	Heat aggregates and asphalt binder	X	X	Use planned production temperature for WMA
4	Mix aggregates and binder	X	X	Procedure is WMA process specific
5	Mixture conditioning procedures	X	X	WMA uses lower temperature
6	Compact laboratory specimens	X	X	WMA uses lower temperature
7	Calculate volumetric composition of laboratory specimens	X	X	
8	Adjust aggregate proportions to meet volumetric requirements	X	X	
9	Evaluate coating and compactability	NA	X	Used in WMA design in place of viscosity-based mixing and compaction temperatures
10	Conduct performance testing	X	X	Moisture sensitivity for all mixtures, rutting resistance for design traffic levels of 3 m ESALs or greater

3. The short-term conditioning temperature for WMA is the planned compaction temperature.
4. Viscosity-based compaction temperatures are not used with WMA. Laboratory compaction is done at the planned compaction temperature.
5. WMA design includes an evaluation of coating and compactability using the planned production and compaction temperatures.

These modifications are discussed in the sections that follow.

Calculate Batch Weights

Some WMA processes require an additive to be added either to the binder or to the mixture. The amount of additive needed may be specified by the WMA process supplier as percent by weight of binder or total mixture. The "Additive" sheet in HMA Tools allows the user to specify the dosage rate for up to three additives and whether the dosage rate is based on binder or total mixture weight.

Batch Aggregates

For most WMA processes, aggregate batching is identical to that for HMA. HMA Tools provides a convenient tool for calculating batch weights for various specimens and degrees of aggregate processing. In one WMA process, water is added to a portion of the fine aggregate, then this wet, fine aggregate is added cold to the mixture during the mixing process. For this process, treat the wet portion of the fine aggregate as a separate fine aggregate in HMA Tools. Compute the dry aggregate batch weight for this aggregate, then add the required weight of water to the dry aggregate, mix, cover, and let stand 2 hours before using it in the mixing process.

Heat Aggregates and Asphalt Binder

The most notable differences between the design of WMA and HMA occur in the specimen fabrication process, which begins with this step and continues through the next three steps. Viscosity-based mixing and compaction criteria cannot be used with the wide range of WMA

processes available. In fact, research in progress suggests that enhanced lubrication, not viscosity reduction, is the primary mechanism governing the success of WMA processes.

The design of WMA mixtures is done using the planned field production and compaction temperatures. The aggregates and binder that will be used are heated in an oven to approximately 27°F (15°C) above the planned production temperature. Aggregates may be heated overnight. The asphalt binder and RAP, if used, should be heated the minimum time necessary to reach this target temperature.

Mix Aggregates and Binder

For mixture design purposes, the various WMA processes can be grouped into the following generic categories:

1. Additives blended into the binder,
2. Additives added to the mixture,
3. Wet aggregate mixtures, and
4. Foamed asphalt.

This section describes laboratory procedures for preparing each of these types of WMA mixtures. Some WMA processes may include elements from two or more of these processes.

The laboratory equipment needed to produce the mixtures is generally the same as that required for HMA. A mechanical mixer capable of mixing 10 to 45 lb (5 to 20 kg) batches is needed for all WMA processes. The mixing times presented later are based on a planetary mixer with a wire whip. Bucket mixers are less efficient than planetary mixers; therefore, the mixing times may need to be increased. For WMA processes requiring the additive to be blended in the binder, a low-shear mechanical stirrer with appropriate size impeller is needed to homogeneously blend the additive in the binder. Finally, for foamed asphalt mixtures, a laboratory-scale foamed asphalt plant capable of producing consistent foamed asphalt at the water content used in field production is needed. An example of such a device is shown in Figure 1. The device should be capable of producing foamed asphalt for laboratory batches ranging in size from approximately 20 to 45 lb (10 to 20 kg). Note that laboratory foaming plants designed for cold mix applications will require a more precise flow controller to allow foamed asphalt production

Figure 1. A foaming device for preparing WMA in the laboratory.

at the lower water contents used in WMA. Also, because these machines are designed to produce large quantities of foamed asphalt, it will be necessary to produce larger batches of WMA and then split the material needed for the various tests required.

Additives Blended in the Binder

For WMA processes that require the WMA additive to be blended in the binder, the additive must be blended into the binder before the WMA mixture can be produced. The required dosage rate will be provided by the WMA process supplier who usually will also provide instructions for blending the additive in the binder. HMA Tools will compute the mass of additive to add for a given batch size. If instructions for blending the additive are not provided, use the following procedure:

1. Follow the manufacturer's instruction for storage of the additive (e.g., temperature and humidity) particularly after opening the manufacturer's packaging.
2. Weigh the required amount of the additive into a small container. 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.
3. 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.
4. Add the required amount of additive to the binder and stir with a mechanical stirrer until the additive is totally dispersed in the binder.
5. Store the binder with WMA additive at room temperature in a covered container until needed for use in the mixture design.

Some binders are being supplied with the WMA additive pre-blended into the binder. For these binders, it is not necessary to blend the additive, and the preparation of the WMA mixture proceeds as outlined below.

Once the WMA additive has been added to the binder, the preparation of the WMA mixture proceeds in a similar manner as that for HMA. The following steps summarize the mixture preparation process:

1. Heat the aggregate, RAP, binder, and mixing tools to approximately 27°F (15°C) above the planned production temperature. Aggregates may be heated overnight. The asphalt binder and RAP should be heated the minimum time necessary to reach this target temperature.
2. If a liquid antistrip is required, add it to the binder per the manufacturer's instructions.
3. Place the hot mixing bowl on a scale and zero the scale.
4. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
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. 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:
   a. Record the oven dry weight of the aggregates and RAP, w_i
   b. 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 a
$P_{b_{new}}$ = % by weight of total mix of new binder in the mixture

   c. Add new binder to the bowl to reach w_t

6. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.
7. Transfer the mixture to a flat shallow pan at an even thickness of 1 to 2 in (25 to 50 mm) for short-term conditioning.

Additives Added to the Mixture

Some WMA processes specify that the additive be added to the mixture during plant mixing. The additive dosage rate may be given as a percent of the total mixture mass or a percentage of the binder in the mixture. If the mixture contains RAP and the dosage rate is as a percentage of the binder, remember to include the RAP binder contribution when computing the amount of additive. HMA Tools will compute the mass of additive to add for a given batch size. For these processes, the following mixing procedure should be followed:

1. Follow the manufacturer's instruction for storage of the additive (e.g., temperature and humidity) particularly after opening the manufacturer's packaging.
2. Weigh the required amount of the additive into a small container.
3. Heat the aggregate, RAP, binder, and mixing tools to approximately 27°F (15°C) above the planned production temperature. Aggregates may be heated overnight. The asphalt binder and RAP should be heated the minimum time necessary to reach this target temperature.
4. If a liquid antistrip is required, add it to the binder per the manufacturer's instructions.
5. Place the hot mixing bowl on a scale and zero the scale.
6. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
7. Form a crater in the blended aggregate and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight. 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:
   a. Record the oven dry weight of the aggregates and RAP, w_i
   b. 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 a
   $P_{b_{new}}$ = % by weight of total mix of new binder in the mixture

   c. Add new binder to the bowl to reach w_t
8. Pour the WMA additive into the pool of new asphalt binder.
9. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.
10. Transfer the mixture to a flat shallow pan at an even thickness of 1 to 2 in (25 to 50 mm) for short-term conditioning.

Figure 2 shows a WMA additive being added to a mixture in the laboratory.

Wet Aggregate Mixtures

One WMA process uses cold, wet fine aggregate to produce asphalt concrete at significantly lower discharge temperatures. In this process, a portion of the total aggregate is added wet. The coarse aggregate and dry portion of the fine aggregate are mixed with the binder at normal HMA production temperatures. The percentage of the fine aggregate that will be added wet, the moisture content of that portion of the fine aggregate, and the initial mixing temperature are recommended by the WMA process supplier. An additive is also added to the binder following the steps described above for Additives Blended in the Binder. In HMA Tools, treat the portion of the fine

Figure 2. Adding a WMA additive to a mixture in the laboratory.

aggregate that will be added wet as a separate aggregate. Compute the dry aggregate batch weight for this aggregate, then the weight of water to add (based on the recommended moisture content), and then proceed as follows:

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.
2. Heat the aggregate, RAP, binder, and mixing tools to approximately 27°F (15°C) above the initial mixing temperature. Aggregates may be heated overnight. The asphalt binder and RAP should be heated the minimum time necessary to reach this target temperature.
3. Place the hot mixing bowl on a scale and zero the scale.
4. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
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. 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:
   a. Record the oven dry weight of the heated aggregates and RAP, w_i
   b. 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 a
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

   c. 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

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

6. Remove the mixing bowl from the scale and mix with a mechanical mixer for 30 sec.
7. Stop the mixer and immediately add the wet fraction.
8. Restart the mixer and continue to mix for 60 sec.
9. Transfer the mixture to a flat shallow pan at an even thickness of 1 to 2 in (25 to 50 mm) for short-term conditioning.
10. Check the temperature of the mixture in the pan. It should be between 90 and 100°C.

Foamed Asphalt

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. The procedure for preparing foamed asphalt mixtures is as follows:

1. Prepare the asphalt binder foaming equipment and load it with binder per the manufacturer's instructions.
2. If a liquid antistrip is required, add it to the binder in the foaming equipment per the manufacturer's instructions.
3. Heat the aggregate, RAP, and mixing tools to approximately 27°F (15°C) above the planned production temperature. Aggregates may be heated overnight. The asphalt binder and RAP should be heated the minimum time necessary to reach this target temperature.
4. Prepare the foamed asphalt binder per the instructions for the foaming equipment.
5. Place the hot mixing bowl on a scale and zero the scale.
6. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
7. Form a crater in the blended aggregate and add the required amount of foamed asphalt into the mixture to achieve the desired batch weight. 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 foamed binder based on the oven dry weight of the aggregates and RAP as follows:
   a. Record the oven dry weight of the aggregates and RAP, w_i
   b. 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 a
$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

   c. Add foamed binder to the bowl to reach w_t

   The laboratory foaming equipment uses a timer to control the amount of foamed binder provided. Make sure the batch size is large enough that the required amount of foamed binder 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 at a given asphalt content and then splitting the individual samples.
8. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

9. Transfer the mixture to a flat shallow pan at an even thickness of 1 to 2 in (25 to 50 mm) for short-term conditioning.

Mixture Conditioning Procedures

AASHTO R 30 describes three different procedures for mixture conditioning in a forced draft oven: (1) mixture conditioning for volumetric mix design; (2) short-term conditioning for mixture mechanical property testing; and (3) long-term conditioning for mixture mechanical property testing. The last procedure, long-term conditioning for mixture mechanical property testing, is generally not used in the design and testing of WMA mixtures and is not addressed here. WMA mixtures for both volumetric mixture design and mechanical property testing (performance evaluation) should be conditioned for 2 hours at the planned compaction temperature. The conditioning should follow AASHTO R 30, using a preheated forced-draft oven, a mixture thickness of 1 to 2 in (25 to 50 mm), and stirring of the mixture after 1 hour. The conditioning procedure for volumetric mix design is essentially identical for WMA and HMA, the only difference being in the definition of compaction temperature for the two types of mixes. Short-term conditioning for performance testing differs in that only 2 hours is required for WMA mixtures, while 4 hours is required when conditioning HMA. Also, WMA mixtures for performance testing are conditioned at the planned compaction temperature, whereas AASHTO R 30 specifies a conditioning temperature of 135°C for HMA mixtures for mechanical testing.

Compact Laboratory Specimens

WMA specimens are compacted in the same manner as described in Chapter 8 for HMA using a properly calibrated and maintained Superpave gyratory compactor (see Figure 3). Compact duplicate specimens in accordance with AASHTO T 312.

Calculate Volumetric Composition of Laboratory Specimens

Volumetric analysis of compacted WMA specimens is the same as described in Chapter 8 for HMA. Recall that the procedure used in this manual sets the binder content at a value that

Figure 3. Compacting a WMA specimen in a Superpave gyratory compactor.

will provide the proper VMA once the design air void content is met, and the gradation was selected to provide an acceptable ratio of dust to effective binder content by mass. Thus the air void content is the primary volumetric factor used to determine the acceptability of the trial mixture. Given that the binder content was initially set using an assumed binder absorption, the effective binder content and VMA of the trial mixture should also be analyzed. The following equations (which were derived in Chapter 5) are used to perform the volumetric analysis.

Air Void Content

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

where

VA = Air void content, volume %
G_{mb} = Bulk specific gravity of compacted mixture
G_{mm} = Maximum theoretical specific gravity of loose mixture

Total Binder Content by Volume

$$VB = \frac{P_b G_{mb}}{G_b} \quad (3)$$

where

VB = Total asphalt binder content, % by total mix volume
P_b = Total asphalt binder content, % by mix mass
G_{mb} = Bulk specific gravity of the mixture
G_b = Specific gravity of the asphalt binder

Absorbed Binder by Volume

$$VBA = G_{mb}\left[\left(\frac{P_b}{G_b}\right) + \left(\frac{P_s}{G_{sb}}\right) - \left(\frac{100}{G_{mm}}\right)\right] \quad (4)$$

where

VBA = Absorbed asphalt content, % by total mixture volume
G_{mb} = Bulk specific gravity of the mixture
P_b = Total asphalt binder content, % by mix mass
G_b = Specific gravity of the asphalt binder
P_s = Total aggregate content, % by mix mass, equal to $100 - P_b$
G_{sb} = Average bulk specific gravity for the aggregate blend
G_{mm} = Maximum specific gravity of the mixture

Effective Binder Content by Volume

$$VBE = VB - VBA \quad (5)$$

where

VBE = Effective asphalt content, % by total mixture volume
VB = Asphalt binder content, % by mix volume
VBA = Absorbed asphalt content, % by total mixture volume

Effective Binder Content by Mass

$$P_{be} = P_b\left(\frac{VBE}{VB}\right) \quad (6)$$

where

P_{be} = Effective asphalt binder content, % by total mass
P_b = Asphalt binder content, % by total mass
VBE = Effective asphalt binder content, % by total mixture volume
VB = Asphalt binder content, % by mix volume

Voids in Mineral Aggregate

$$VMA = VA + VBE \quad (7)$$

where

VMA = Voids in the mineral aggregate, % by total mixture volume
VA = Air void content, % by total mix volume
VBE = Effective binder content, % by total mixture volume

Dust Proportion

$$D/B = \frac{P_{0.075}}{P_{be}} \quad (8)$$

where

D/B = dust/binder ratio, calculated using effective binder content
$P_{0.075}$ = mineral dust content, % by total mix weight
P_{be} = effective binder content, % by total mix weight

HMA Tools performs the volumetric analysis using data on the bulk and maximum specific gravity of the trial mixture. The design procedure in this manual provides acceptable ranges for three volumetric factors: (1) air void content, (2) VMA, and (3) dust proportion. The acceptable ranges are summarized in Table 13. These are the same ranges used for the design of HMA.

Adjust Aggregate Proportions to Meet Volumetric Requirements

Adjusting WMA mixtures to meet volumetric requirements is the same as discussed in Chapter 8 for HMA. The procedure presented in this manual is designed to provide accept-

Table 13. Acceptable range for volumetric factors.

Aggregate NMAS (mm)	VMA[A] Minimum (%)	VMA[A] Maximum (%)	Air Voids Minimum (%)	Air Voids Maximum (%)	Dust Proportion[B] Minimum	Dust Proportion[B] Maximum
4.75	16.0	18.0	3.5	4.5	0.9	2.0
9.5	15.0	17.0	3.5	4.5	0.8	1.6
12.5	14.0	16.0	3.5	4.5	0.8	1.6
19.0	13.0	15.0	3.5	4.5	0.8	1.6
25.0	12.0	14.0	3.5	4.5	0.8	1.6
37.5	11.0	13.0	3.5	4.5	0.8	1.6

[A]The specifying agency may increase the minimum and maximum values for VMA by up to 1.0% to obtain mixtures with increased asphalt binder content, which can improve field compaction, fatigue resistance, and general durability. Care should be taken to ensure that the resulting HMA mixtures maintain adequate rut resistance for their intended application.
[B]The specifying agency may lower the allowable range for dust/binder ratio to 0.6 to 1.2 for NMAS mixtures of 9.5 mm and greater if warranted by local conditions and materials. The dust/binder ratio should, however, not be lowered if VMA requirements are increased using Note A above.

able volumetric properties when specimens of the trial mixture meet the design air void content. After preparing trial specimens, it may be necessary to make minor adjustments to the binder content to account for differences between the assumed and actual binder absorption. If the air voids of the trial specimens are more than a few tenths of a percent outside the design range, then the aggregate gradation should be adjusted to change the VMA of the mixture. The general rule for adjusting aggregate blends to meet VMA requirements is that the closer an aggregate gradation is to a maximum density gradation, the lower will be its VMA.

Evaluate Coating and Compactability

The viscosity-based mixing and compaction temperatures used in the design of HMA cannot be used with the wide range of WMA processes currently available. For WMA, the design procedure, therefore, includes an evaluation of coating at the planned production temperature and an evaluation of compactability at the planned compaction temperature. The sections that follow describe these evaluations.

Coating

Coating is evaluated at the planned production temperature by preparing loose mix of the design mixture following the specimen fabrication procedures presented earlier and evaluating the coating of the coarse aggregate particles using AASHTO T 195, Standard Method of Test for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures. This test method consists of separating out the coarse aggregates of the mixture and determining the percentage of the coarse aggregate particles that are fully coated. The recommended criterion is 95% of the coarse aggregates fully coated. It should be noted that this criterion and the mixing times given earlier were developed using a planetary mixer with a wire whip. Bucket mixers are not as efficient as planetary mixers; therefore, laboratory mixing times may need to be increased if a bucket mixer is used.

Compactability

Compactability is evaluated by compacting two specimens at the planned compaction temperature and two specimens at 30°C below the planned compaction temperature. The number of gyrations required to reach 8% air voids is determined for both sets of specimens. It is recommended that the increase in gyrations to 8% air voids between the planned compaction temperature and 30°C below the planned compaction temperature should be less than 25% of the number of gyrations at the planned compaction temperature. The procedure is described in detail below:

1. Prepare a sufficient quantity of the design mixture for four gyratory specimens and one maximum specific gravity measurement using the appropriate WMA fabrication procedure.
2. Determine the theoretical maximum specific gravity (G_{mm}) according to AASHTO T 209.
3. Compact duplicate specimens at the planned compaction temperature to N_{design} gyrations in accordance with AASHTO T 312. Record the specimen height for each gyration.
4. Determine the bulk specific gravity of each specimen in accordance with AASHTO T 166.
5. Allow the mixture to cool to 30°C below the compaction temperature. Compact duplicate specimens to N_{design} gyrations in accordance with AASHTO T 312. Record the specimen height for each gyration
6. Determine the bulk specific gravity of each specimen in accordance with AASHTO T 166.
7. For each specimen determine the height at a relative density of 92.0% using Equation 9.

$$h_{92} = h_d\left(\frac{\%G_{mmd}}{92}\right) \tag{9}$$

where

h_{92} = height at a relative density of 92%
h_d = height at N_{design}, as measured by the gyratory compactor
$\%G_{mmd}$ = relative density at N_{design}

8. For each specimen, determine the number of gyrations to reach 92% relative density. This can be done by looking at the output from the gyratory compactor giving specimen height as a function of gyrations—simply find the number of gyrations at a height where the relative density is 92%, h_{92} as determined in Step 7 above.
9. Determine the gyration ratio using Equation 10.

$$Ratio = \frac{(N_{92})_{T-30}}{(N_{92})_T} \tag{10}$$

where

$Ratio$ = gyration ratio
$(N_{92})_{T\text{-}30}$ = gyrations to 92% relative density at 30°C below the planned compaction temperature.
$(N_{92})_T$ = gyrations to 92% relative density at the planned compaction temperature

10. The compactability is acceptable if the gyration ratio is less than 1.25.

Conduct Performance Testing

Like HMA, the final stage of laboratory work in a WMA design is evaluating the performance of the mixture. Performance evaluation for WMA is the same as HMA and includes evaluation of the resistance to moisture damage for all mixtures and evaluation of rutting resistance for mixtures designed for traffic levels of 3 million ESALs and higher. As discussed above, the primary difference between WMA and HMA is in mixture conditioning—HMA mixtures are conditioned for 4 hours at 135°C, whereas WMA mixtures for performance testing are conditioned at the planned compaction temperature for 2 hours. Otherwise, the procedure for short-term conditioning for mixture mechanical testing as described in AASHTO R 30 should be followed when preparing WMA specimens for performance testing.

The resistance to moisture damage is evaluated using AASHTO T 283, Resistance of Compacted Asphalt Mixture to Moisture-Induced Damage. Like HMA, WMA mixtures have acceptable resistance to moisture damage if the tensile strength ratio is equal to or greater than 80% and there is no visual evidence of stripping in the conditioned test specimens. When redesigning an existing HMA mixture using a WMA process that does not include an antistrip additive, it is not uncommon to find that the WMA mixture is less resistant to moisture damage. For these mixtures, the use of hydrated lime or an antistrip additive will usually provide acceptable results. Many WMA processes include an antistrip additive. For these processes, consult the process supplier for recommendations to improve resistance to moisture damage if unacceptable results are obtained at normal WMA additive dosage rates.

The rutting resistance of WMA is evaluated for mixtures designed for 3 million ESALs and higher using the flow number test, AASHTO TP 79, Determining the Dynamic Modulus and Flow Number of Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT). The same testing conditions used for HMA are used with WMA.

Table 14. Flow number criteria for WMA mixtures.

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

1. Specimens compacted to 7.0 ± 0.5% air voids,
2. Test temperature equal to the 50% reliability, 7-day maximum pavement temperature as determined using LTPPBind version 3.1. For surface courses, compute the test temperature at a depth of 20 mm. For intermediate and base courses, compute the test temperature at the top of the layer.
3. Unconfined testing with a repeated deviator stress of 87 psi (600 kPa) and a contact deviator stress of 4.4 psi (30 kPa).

Lower criteria are used for WMA compared with HMA because of the reduced short-term conditioning. Recall that HMA used in making specimens for performance testing is conditioned for 4 hours at 275°F (135°C) while WMA used for making specimens for performance testing is conditioned for only 2 hours at the planned compaction temperature, which is usually lower than 275°F (135°C). The shorter conditioning time and lower condition temperature result in less aging for the binder in the WMA specimens. The WMA flow number criteria are listed in Table 14.

The rutting resistance of WMA mixtures can be improved using the same adjustments described in Chapter 8 for HMA. These include

- Increasing the binder high-temperature grade
- Adding RAP to the mixture
- If the binder is not modified, considering using a polymer-modified binder of the same grade or one high-temperature grade lower
- If the binder is polymer-modified, trying a different type of modified binder
- Increasing the amount of mineral filler in the mix and adjusting the aggregate gradation if necessary to maintain adequate VMA
- Decreasing the design VMA value, if possible, by adjusting the aggregate gradation
- Replacing part or all of the aggregate (fine or coarse or both) with a material or materials having improved angularity

If a different asphalt binder is used in the mix, the volumetric composition should not change. However, if other aspects of the mix design are changed, the volumetric composition might change significantly which will require further refinement of the mix prior to further rut resistance testing.

Step 11. Compile Mix Design Report

The mix design report is compiled in the same manner as described for HMA. In many states, standard forms must be filled out by producers and submitted to the appropriate state agency or office for approval. In some cases, engineers or technicians may wish to develop their own mix design reports, for internal purposes or for use on private jobs. In such cases, the following information should be included in the report:

- The organization that performed the mix design
- The name of the technician or engineer responsible for developing the mix design

- The date the mix design was completed
- The name of the client for which the mix design was developed
- The name of the project for which the mix design was developed (if applicable)
- General mix design information, including the type of mix (surface course, intermediate course, base course), the nominal maximum aggregate size, the design traffic level, the N_{design} value, and any special requirements
- Complete aggregate information, including for each aggregate the producer, the size designation of the aggregate, gradation, specific gravity, and all applicable specification properties
- Binder information, including the binder PG grade and the name of the supplier
- Composition of the mixture, including the design air void content, the design VMA, the design VBE, the mineral filler content, the target dust/binder ratio and the estimated unit weight for the mix
- The planned production and compaction temperatures
- The results of the evaluation of coating
- The results of the compactability analysis
- The results of moisture resistance testing
- The results of rut resistance testing, if applicable (generally for mixtures designed for traffic levels of 3 million ESALs and over)

HMA Tools includes a comprehensive mix design report that contains all of this information and additional information on the results of trial mixtures evaluated during the mix design process. This HMA Tools report might be useful to some engineers and technicians for internal purposes and might also serve as a template for those wishing to develop their own customized mix design reports.

Example WMA Mix Design

A 12.5-mm WMA mix is to be designed, using a foaming process. The gradation of the aggregates to be used is listed in Table 15; the table includes the gradation of the RAP to be included in the mix design. Other test properties for the four aggregates are listed in Table 16. The RAP was separated into fine and coarse fractions for testing, and the results are also included in Table 16. The specified binder grade is PG 64-22, while the grade of the binder extracted from the RAP is PG 76-16. Binder test data are given in Table 17. The binder content of the RAP is 5.2% by total weight. The design traffic level is 6 million ESALs.

Referring to Table 1, the steps in a WMA mix design are as follows:

1. Gather information
2. Select asphalt binder

Table 15. Aggregate gradations for WMA example.

Sieve Size (mm)	% Passing by Weight				
	No. 67 Stone	1B Stone	Screenings	Sand	RAP
19.000	100.0	100.0	100.0	100.0	100.0
12.500	72.0	91.0	100.0	100.0	100.0
9.500	48.0	48.0	100.0	100.0	95.0
4.750	8.0	10.0	81.0	100.0	76.0
2.360	6.0	5.0	45.0	91.0	56.0
1.180	4.0	3.0	30.0	48.0	42.0
0.600	4.0	3.0	20.0	36.0	28.0
0.300	3.0	3.0	16.0	21.0	19.0
0.150	3.0	2.8	8.0	12.0	14.0
0.075	2.6	2.2	5.8	7.1	11.4

Table 16. Aggregate test properties for WMA example.

Property	No. 67 Stone	1B stone	Screenings	Sand	RAP, Fine	RAP, Coarse
Bulk Specific Gravity	2.635	2.639	2.771	2.630	2.631	2.605
Apparent Specific Gravity	2.699	2.702	2.856	2.760	2.682	2.694
Water Absorption	0.90	0.88	1.07	1.79	0.72	1.27
CAFF, One Fractured Face, %	96.0	96.0	N/A	N/A	N/A	100.0
CAFF, Two Fractured Faces, %	91.0	93.0	N/A	N/A	N/A	95.0
Flat & Elongated, %	0.8	0.0	N/A	N/A	N/A	1.5
FAA, Uncompacted Voids	N/A	N/A	48.0	43.0	44.2	N/A
Sand Equivalent	N/A	N/A	58.0	89.0	N/A	N/A

Table 17. Binder properties for WMA example.

Property	PG 64-22 Binder	RAP Binder
Specific Gravity	1.030	1.030
Continuous high-temperature grade, °C	59.0	81.4
Continuous intermediate-temperature grade, °C	13.0	27.4
Continuous low-temperature grade, °C	-30.1	-19.7

3. Determine compaction level
4. Select nominal maximum aggregate size
5. Determine target VMA and air voids values
6. Calculate target binder content
7. Calculate aggregate content
8. Proportion aggregate blends for trial mixtures
9. Calculate trial mix proportions by weight and check dust/binder ratio
10. Evaluate and refine trial mixtures
11. Compile mix design report

In this example, much of Steps 1, 2, and 4 have been completed and the pertinent information listed above. The purpose of this example is to illustrate those parts of the mix design process that differ from normal HMA mix design as outlined in Chapter 8 of this manual. Therefore, those steps in the mix design that do not differ from standard HMA mix design practice are not discussed in detail in this example; readers uncertain of these steps should review Chapter 8.

One of the important differences in the WMA mix design process is the limits on production and compaction temperatures. In this case, these limits have been established by the producer: 132°C for production and 124°C for compaction. In order to ensure proper compaction, the high-temperature grade of the RAP binder (81.4°C) must be less than the specified WMA compaction temperature—124°C in this case, so the RAP binder is acceptable. The mix design in this example requires the use of two liquid additives in the mix design: an antistrip additive and a recycling agent. The antistrip additive has a specific gravity of 1.030 and is to be added at 0.50% by binder weight. The recycling additive has a specific gravity of 1.020 and is to be added at 1.00% by total mix weight.

After entering the binder grading data in HMA Tools, the blended binder grade is given as a PG 64-22, with an intermediate grading temperature of 25°C. This meets the specified requirement. Note that HMA Tools includes the low-temperature grade adjustment as described in

Table 18. Aggregate proportions of WMA example.

Aggregate	Wt. % in Aggregate Blend
No. 67 Stone	20
1B Stone	25
Screenings	10
Manufactured Sand	15
RAP (aggregate only)	30

Table 3. Details on the calculations used to estimate blended binder grades for HMA and WMA containing RAP are given in AASHTO M 323.

At a traffic level of 6 million ESALs, N_{design} is 100 gyrations (Table 8-2). Given the NMAS of 12.5 mm, the minimum VMA is 15.0% and the maximum 17.0%; therefore, a target VMA of 16.0% is selected. A target air void content of 4.0% is also selected for the mix design. For this example, an aggregate gradation somewhat below maximum density is selected, with aggregate proportions as shown in Table 18. Calculation of the volumetric composition for the trial blend is complicated by the use of liquid additives. The suggested procedure involves working through the known composition by volume, and then working back and forth between weight and volume calculations until the total binder volume and weight can be calculated. Then, the weights of the additives can be calculated. The various steps are shown in Table 19.

The volume compositions in Table 19 are given in percents, which are equivalent to cm^3 per 100 cm^3 total volume. The weights are then calculated simply by multiplying this volume by the appropriate specific gravity. (Note that the component weights are not percentages but are in units

Table 19. Calculation of volume percentages and weights for WMA example.

Step	Calculation	Formula	Result
1.	VMA	Given	16.00
2.	Volume % of air voids (VA)	Given	4.00
3.	Binder effective volume % (VBE)	VBE=VMA–VA	12.00
4.	Volume % of aggregate (VS)	VS=100–VMA	84.00
5.	Weight of aggregate (P_s), g/100 cm^3	$P_s = VS \times G_{sb}$	222.06
6.	Weight of RAP aggregate (P_{sr}), g/100 cm^3	$P_{sr} = P_s \times$ % RAP in Aggregate Blend	66.62
7.	Weight of RAP binder (P_{br}), g/100 cm^3	$P_{br} = P_{sr} \times$ RAP binder content	3.46
8.	Volume % RAP binder (VBR)	VBR=P_{br}/RAP binder specific gravity	3.36
9.	Volume % of effective new binder and liquid additives (VBEN)	VBEN=VBE–VBR	8.64
10.	Approximate weight of effective new binder and liquid additives (P_{ben}), g/100 cm^3	P_{ben}=VBA/specific gravity of new binder	8.86
11.	Weight of absorbed binder (P_{ba}), g/100 cm^3	$P_{ba}=P_s \times$ water absorption of aggregate × 0.45	1.09
12.	Weight of new binder, RAP binder and liquid additives (P_b), g/100 cm^3	$P_b=P_{br}+P_{ben}+P_{ba}$	13.42
13.	Total weight of mix (P_{tot}), g/100 cm^3	Sum all weights	235.47
14.	Weight of antistrip additive, g/100 cm^3	$= (0.50/100)\times P_b$	0.066
15.	Weight of recycling additive, g/100 cm^3	$= (1.0/100)\times P_{tot}$	2.309
16.	Weight % of various components	=Wt. in g/100 cm^3 / P_{tot} × 100 %	Varies

of g/100 cm^3 volume.) In the final step (Step 16), these weights are converted to percentages by dividing by the total mix weight and multiplying by 100%. In order to simplify calculations, the volume and weight of new binder and liquid additives are lumped together and assumed to have the same specific gravity—that of the new binder. Because the amount of liquid additives should be very small and their specific gravity values close to that of the binder, the error in this assumption is quite small. Note that in the calculation of absorbed asphalt (Step 11), the water absorption is multiplied by 0.45 to estimate the asphalt binder absorption; in HMA designs, water absorption is multiplied by 0.50 rather than 0.45. The last step in this procedure is calculation of composition in weight percent, which is done by dividing the weight of the various components by the total mix weight. The final volumetric composition of the trial mixture is summarized in Table 20. Although this procedure appears complicated, it can be performed using HMA Tools (or other similar spreadsheet programs), simplifying the calculations and reducing the chance for errors.

In preparing laboratory specimens, parts of the procedure are similar to those for HMA practice. Batch weights are calculated in the same way. Because this is a foamed asphalt, a laboratory foaming unit is used to foam the binder (with antistrip additive) prior to mixing it with the hot aggregate and RAP. In this case, the recycling additive is added to the hot aggregate and RAP and mixed for a few seconds prior to the addition of the foamed asphalt binder. The mixed WMA is short-term oven conditioned for 2 hours at the planned compaction temperature, 124°C. It is then compacted in the Superpave gyratory compactor for 100 gyrations.

Provided the volumetrics of the trial mix are acceptable, the WMA, just as for HMA, must be evaluated for moisture resistance according to AASHTO T 283. However, the WMA must also be evaluated for coating and compactability. For the particle coating test (ASTM T 195), some of the freshly mixed WMA is set aside and spread out on a metal pan to cool. The coarse aggregate particles are then separated out and the degree of coating determined. The number of completely coated, partially coated, and uncoated particles is counted. In this case, there are 145 completely coated particles, 6 particles that are partially coated, and none that are completely uncoated. The percentage of coated particles is then $145/(145+6) \times 100\% = 96\%$. Since this is greater than 95%, this WMA passes the coating test.

Calculations for the compactability test are shown in Table 21. As explained previously, four specimens are compacted—two at the planned compaction temperature of 124°C and two at a temperature 30°C below this, 94°C. Then, the relative density and height and N_{design} are

Table 20. WMA mix composition by weight percentage from volume percentage and specific gravity values.

Mix Component	Percent by Total Mix Volume	Bulk Specific Gravity	Percent by Aggregate Weight	Percent by Total Mix Weight
Air	4.00	---	---	---
New Asphalt Binder	7.34	1.026	---	3.19
RAP Asphalt Binder	3.37	1.030	---	1.47
Liquid Antistrip Additive	0.066	1.020	---	0.028
Recycling Additive	2.31	1.030	---	1.00
No. 67 Stone	16.67	2.635	20	18.86
1B Stone	20.81	2.639	25	23.58
Screenings	7.90	2.771	10	9.43
Manufactured Sand	12.36	2.630	15	14.15
RAP Aggregate	25.13	2.619	30	28.29

Note: Calculations may not agree exactly because of rounding.

Table 21. Calculation of gyration ratio for compactability test.

Property	124°C		94°C	
	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Density @ N_{design}	96.0	95.9	96.1	96.0
Height @ N_{design}, mm	116.7	115.3	114.1	113.0
Height @ Relative Density = 92%	121.8	120.2	119.2	117.9
Gyrations at 92% Relative Density	33	38	42	39
Gyration Ratio	1.14 < 1.25 Pass			

determined for each specimen. Then, Equation 9 is used to calculate the height at a relative density of 92%. The gyratory output files are then examined to determine the number of gyrations required to reach a relative density of 92%, N_{92}. The gyration ratio is then calculated as the ratio of N_{92} at T_C-30/T_C:

$$Gyration\ Ratio = \frac{(42+39)/2}{(33+38)/2} = 1.14 \quad (11)$$

In this example, the gyration ratio is 1.14, which is below the maximum allowable value of 1.25 so the mix passes this test.

Because the design traffic level in this case—6 million ESALs—is greater than or equal to 3 million ESALs, performance testing using the AMPT is required as a final step in the mix design. After short-term oven conditioning for 2 hours at 116°C, two gyratory specimens are prepared and tested for flow number. In this example, the 7-day maximum pavement temperature at a depth of 20 mm and at 50% reliability is determined to be 58.5°C. The two specimens are tested at this temperature and produce flow number values of 27 and 29, giving an average value of 28. Unfortunately, this is below the minimum required value of 30 (Table 14). The mix must be adjusted to provide better rut resistance. A second trial mix design is made, increasing the RAP content from 30% to 40%; given that the asphalt binder in RAP is relatively stiff, this should increase the rut resistance of the mix. The resulting mix meets all requirements for volumetric composition, moisture resistance, coating, and compactability. Performance testing results in an average flow number of 33, meeting the minimum requirements. The laboratory mix design is completed and a report prepared.

A Note on Using HMA Tools to Perform WMA Mix Designs

HMA Tools has several features designed specifically for use in designing WMA. In worksheet "General," there is a section for entering information generally required for WMA, such as production and compaction temperature, and whether or not to allow adjustment in the low-temperature grade of the virgin binder. If allowed, HMA Tools will make this adjustment automatically. There is also a worksheet for recording data from the two mixture tests required for WMA—the coating and compactability tests. The worksheet on liquid additives, although not exclusively for use in designing WMA, allows for rigorous inclusion of such materials in the volumetric analyses performed in HMA Tools.

References

AASHTO Standards

M 320, Standard Specification for Performance-Graded Asphalt Binder
R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
T 166, Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens
T 209, Theoretical Maximum Specification Gravity and Density of Bituminous Paving Mixtures
T 283, Resistance of Compacted Asphalt Mixture to Moisture-Induced Damage
T 312, Preparing and Determining the Density of Hot-Mix Asphalt Specimens by Means of the Superpave Gyratory Compactor
TP79, Determining the Dynamic Modulus and Flow Number of Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)

Other Publications

Bonaquist, R., "Mix Design Practices for Warm Mix Asphalt," *NCHRP Report 691*, National Cooperative Highway Research Program, Washington, D.C., 2011.
Christensen, D. W., "A Manual for the Design of Hot Mix Asphalt with Commentary," *NCHRP Report 673*, National Cooperative Highway Research Program, Washington, D.C., 2010.
Prowell, B. D., and Hurley, G. C., "Warm-Mix Asphalt: Best Practices," *Quality Improvement Series 125*, National Asphalt Pavement Association, Lanham, MD, 2007.

II. Commentary on Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)

Part I of this report 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. Although the procedures described have been specifically selected for use in designing dense-graded mixtures, most can be applied to the design of other mix types with little or no modification.

The following sections of this Part II of the report are a commentary that presents supporting information from the NCHRP 9-43 research report for the recommendations included in Part I. Many of these sections also include recommended additional research, because NCHRP Project 9-43 was the first major study addressing WMA mixture design, and some of the findings require further validation through additional research. Both Parts I and II are organized around the eleven steps described in Chapter 8 of *NCHRP Report 673: A Manual for the Design of Hot Mix Asphalt with Commentary* for the design of dense-graded HMA. Table 1 summarizes the differences between WMA and HMA design for each of the eleven steps.

Step 1. Gather Information

For the design of WMA, additional information must be collected on the WMA process that will be used, additive rates, and planned production and compaction temperatures. The reason that this information is needed is the design of WMA uses process-specific specimen fabrication procedures. These specimen fabrication procedures were designed to simulate, in an approximate manner, the WMA process in the field. For the purposes of mixture design, the various WMA processes can be grouped into four generic categories:

1. Additives blended into the binder,
2. Additives added to the mixture,
3. Wet aggregate mixtures, and
4. Foamed asphalt.

Specimen fabrication techniques are somewhat different for each of these categories. Given that viscosity-based mixing and compaction temperatures are not applicable to many WMA processes, the planned production and compaction temperatures are used in the WMA mixture design process to evaluate coating and the compactability/workability of the WMA. It should be emphasized that the optimal production and compaction temperatures are different for the various WMA processes and should be carefully considered when selecting production and compaction temperatures to be used in the WMA design process.

Table 1. Steps in design of dense-graded HMA and WMA.

Step	Description	Major WMA Differences
1	Gather Information	1. WMA process, 2. Additive rates, 3. Planned production temperature, 4. Planned compaction temperature.
2	Select Asphalt Binder	1. Recommended limit on high-temperature stiffness of recycled binders. 2. May consider low-temperature grade improvement when using blending charts.
3	Determine Compaction Level	Same as HMA
4	Select Nominal Maximum Aggregate Size	Same as HMA
5	Determine Target VMA and Design Air Voids Value	Same as HMA
6	Calculate Target Binder Content	1. Lower asphalt absorption due to lower temperatures.
7	Calculate Aggregate Volume	Same as HMA
8	Proportion Aggregate Blends for Trial Mixtures	Same as HMA
9	Calculate Trial Mixture Proportions by Weight and Check Dust/Binder Ratio	Same as HMA
10	Evaluate and Refine Trial Mixtures	1. WMA process-specific specimen fabrication procedures, 2. Lower short-term aging temperature. 3. Evaluate coating and compactability in lieu of viscosity-based mixing and compaction temperatures.
11	Compile Mix Design Report	Same as HMA

Step 2. Select Asphalt Binder

Performance Grade

The same grade of binder should be used with WMA and HMA designed for the same environmental and traffic conditions. This recommendation is based on recovered binder grading data collected during NCHRP Project 9-43. These data showed only small differences in the grade of the binder for WMA and HMA sections. Table 2 summarizes the recovered binder data from NCHRP Project 9-43. Table 3 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 a small average decrease in the high-temperature grade of –0.2°C, 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 the 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.

The differences in the high- and low-temperature binder properties between WMA and HMA are not large enough to warrant changing the grade of the binder when WMA is used. 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. Additional recovered binder grade data should be collected and analyzed to verify the conclusion from NCHRP Project 9-43 that binder grade changes are not necessary for WMA.

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

Maximum RAP Stiffness

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 occurs, a limit is placed on the maximum stiffness of RAP binders for WMA. That limit is based on the compaction temperature of the mixture given that this temperature will govern the temperature of the mix during storage and transport. The RAP binder should have a high-temperature grade that is less than the compaction temperature for the WMA.

This limit will have little effect on the use of RAP in WMA. RAP binders typically range from PG 82 to PG 100, resulting in corresponding minimum WMA compaction temperatures ranging

Table 3. Summary of average differences 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

from 180 to 212°F (82 to 100°C). The limit will, however, restrict the use of recycled asphalt shingles (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.

NCHRP Project 9-43 included a laboratory mixing study where 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 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 increases 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 ratios of the measured to estimated fully blended moduli ranges from about 0.35 to 0.55. At the 2-hour conditioning time, the ratios 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 ratios 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 stiffened 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 4 summarizes the optimum binder

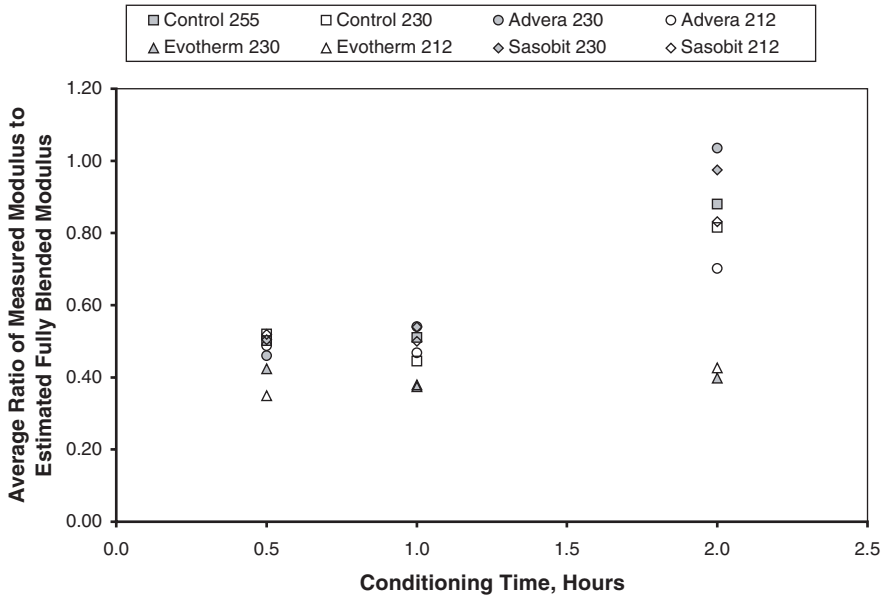

Figure 1. Comparison of the ratios of measured to fully blended dynamic moduli.

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

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 or the other WMA processes, suggesting that the RAP and new binder do mix in Evotherm mixtures and that the differences shown in Figure 15 for this process are due to the extraction and recovery process used in the mixing study.

Plant mixing studies similar to the NCHRP 9-43 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% RAP, the Astec Double Barrel Green WMA process, and mixing and compaction temperatures 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.

Blending Chart Analysis

The NCHRP Project 9-43 recovered binder data (shown in Table 29) confirmed that binders from WMA mixtures have improved low-temperature properties, probably due to the lesser 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, the improvement is large enough to affect the amount of RAP that can be added to a mixture when blending chart analyses are used.

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. 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. As discussed earlier this change is not sufficient to warrant changing the low-temperature grade for WMA mixtures; however, this low-temperature grade improvement 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% 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% additional RAP binder to be added to the mixture.

Using the relationship shown in Figure 16, for the middle of the low-temperature binder grade temperature range, recommended improvements in virgin binder low-temperature continuous grades for RAP blending chart analysis were developed 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 5 for some common binder grades. For a mixture

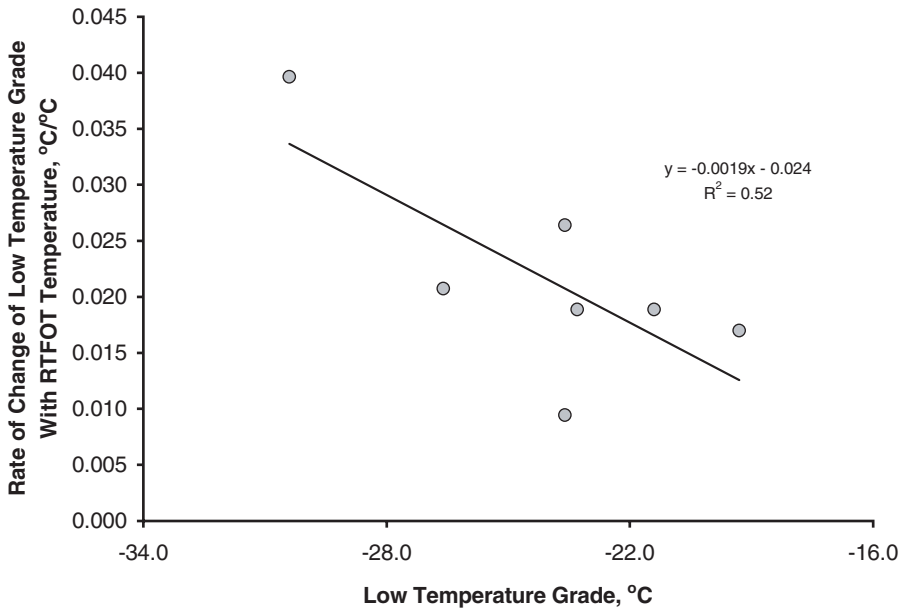

Figure 2. Effect of low-temperature binder grade on the rate of change of low-temperature grade with RTFOT temperature.

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
205	1.6	1.1	1.2	0.6	1.3
200	1.7	1.2	1.3	0.6	1.4

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. This would allow approximately 10% additional RAP binder to be added to the mixture through the blending chart analysis. The ability to use 10% additional RAP binder without changing the grade of the virgin binder may be significant in some areas of the United States.

These recommended binder grade improvements are reasonable, based on the recovered binder grading data presented earlier in Tables 29 and 30. Recovered binder tests on WMA with RAP should be conducted to verify the suggested improvements in low-temperature properties for blending chart analyses.

Step 3. Determine Compaction Level

The same compaction levels are recommended for designing WMA and HMA mixtures.

Step 4. Select Nominal Maximum Aggregate Size

The same aggregate requirements are recommended for designing WMA and HMA mixtures.

Step 5. Determine Target VMA and Air Voids Values

The same target VMA and air voids values are recommended for designing WMA and HMA mixtures.

Step 6. Calculate Target Binder Content

Asphalt absorption is somewhat lower in WMA compared to HMA. NCHRP Project 9-43 included a mixture design study designed to assess the difference in volumetric and engineering properties between WMA and HMA mixtures. Six combinations of binder and aggregate were designed as HMA and then again as WMA using three different processes. The HMA and WMA mixtures prepared at mixing/compaction temperatures of 270/260°F were made using a PG 64-22 binder, while the WMA mixtures prepared at mixing/compaction temperatures of 225/215°F were made using a PG 70-22 binder. The RAP content was 25% for mixtures made with RAP. All mixtures were prepared using short-term conditioning for 2 hours at the compaction temperature. Table 6 summarizes the design of this experiment.

The experimental design for the NCHRP mix design study was a paired difference experiment. This design is commonly used to compare population means, in this case the properties of properly designed WMA and HMA mixtures for the same traffic level, using the same aggregates with the same gradation. In this design, differences between the properties for WMA and HMA are computed for each mixture included in the experiment. If the two design procedures produce mixtures with the same properties, then the average of the differences will not be significantly different from zero. The difference for an individual mixture may be positive or negative, but the average difference over several mixtures should be zero. A t-test is used to assess the statistical significance of the average difference as summarized below:

Null hypothesis: $\mu_{WMA} - \mu_{HMA} = 0$

Alternative hypothesis: $\mu_{WMA} - \mu_{HMA} > 0$ or $\mu_{WMA} - \mu_{HMA} < 0$ (as appropriate)

Table 6. Mix design experiment.

No.	Mixture Identification			Mixing/Compaction Temperature, °F, for Process:			
	N_{design}	Aggregate Water Absorption, %	RAP	HMA	Advera WMA	Evotherm 3G WMA	Sasobit WMA
1	50	1.5	Yes	320/310	225/215	225/215	270/260
2	50	0.8	No	320/310	270/260	270/260	225/215
3	75	1.0	Yes	320/310	270/260	225/215	270/260
4	75	1.6	No	320/310	225/215	270/260	225/215
5	100	1.2	Yes	320/310	270/260	270/260	225/215
6	100	1.3	No	320/310	225/215	225/215	270/260

Test statistic: $$t = \frac{\bar{d}}{\left(\frac{s_d}{\sqrt{n}}\right)}$$

Rejection region: Reject the null hypothesis and accept the alternative hypothesis if $t > t_\alpha$ for n-1 degrees of freedom.

where

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

One way to present the results is to develop 95% confidence intervals for the mean difference in the properties for WMA compared to HMA. If the 95% confidence intervals capture zero, the properties are statistically the same for WMA and HMA. The paired difference comparisons for design binder content and binder absorption are shown in Figures 3 and 4, respectively.

Figure 3 shows that the average design binder content for the WMA mixtures was 0.05% lower than that for HMA mixtures made with the same aggregates and binder. This difference, however, was not statistically significant. Figure 4 shows that the binder absorption was significantly less for the WMA mixtures. The average difference was 0.1%. The average absorption for the mixtures tested was approximately 1.0%. Thus, absorption for WMA was about 90% of that for HMA. Based on these data it was recommended to use 45% of the water absorption as the initial estimate binder absorption in WMA compared to 50% of the water absorption for HMA.

Step 7. Calculate Aggregate Content by Volume

These calculations are identical to those for HMA.

Step 8. Proportion Aggregates for Trial Mixtures

These calculations are identical to those for HMA.

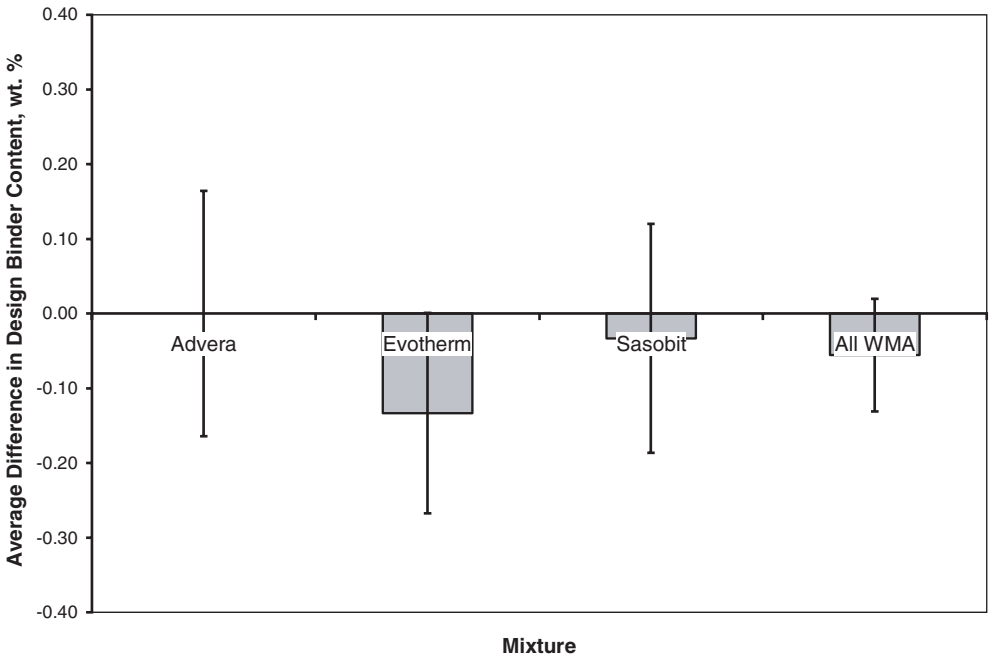

Figure 3. Average difference in design binder content (WMA-HMA) from the NCHRP 9-43 mix design study (error bars are ± 95% one-sided confidence intervals).

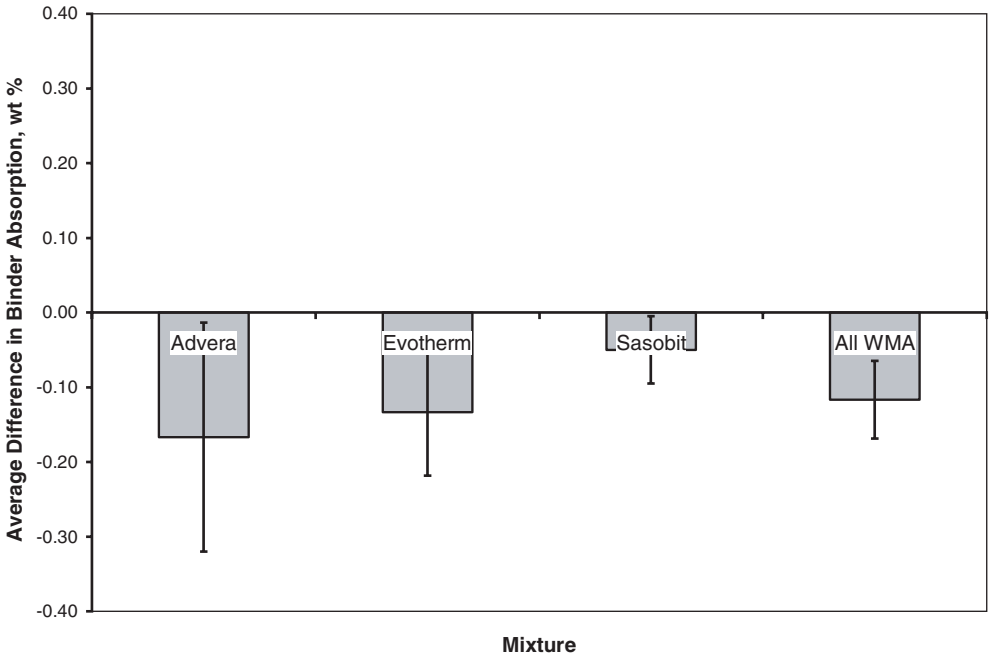

Figure 4. Average difference in binder absorption (WMA-HMA) from the NCHRP 9-43 mix design study (error bars are ± 95% one-sided confidence intervals).

Step 9. Calculate Trial Mixture Proportions by Weight and Check Dust-to-Binder Ratio

These calculations are identical to those for HMA.

Step 10. Evaluate and Refine Trial Mixtures

This step involves the preparation and evaluation of laboratory specimens of WMA. The procedure follows that for HMA with slight modification. Table 7 summarizes the steps for WMA and HMA design. The modifications required for WMA design are

1. For some processes, the WMA additive must be calculated.
2. Viscosity-based mixing temperatures are not used with WMA. Laboratory mixing is done at the planned production temperature.
3. Process-specific specimen fabrication procedures are used to prepare laboratory mixtures.
4. The short-term conditioning temperature for WMA is the planned compaction temperature.
5. Viscosity-based compaction temperatures are not used with WMA. Laboratory compaction is done at the planned compaction temperature.
6. WMA design includes an evaluation of coating and compactability using the planned production and compaction temperatures.

Supporting data from NCHRP Project 9-43 for these modifications are discussed in the sections that follow.

Additive Dosage

The computation of WMA additive dosage rates is straightforward. The amount of additive needed may be specified by the WMA process supplier as percent by weight of binder or total

Table 7. Comparison of trial specimen fabrication procedures for WMA and HMA design.

Step	Description	HMA	WMA	Comment
1	Calculate batch weights	X	X	Must calculate WMA additive content for some processes
2	Batch aggregates	X	X	Must batch WMA additive for some processes
3	Heat aggregates and asphalt binder	X	X	Use planned production temperature for WMA
4	Mix aggregates and binder	X	X	Procedure is WMA process specific
5	Short-term oven conditioning	X	X	WMA uses lower temperature.
6	Compact laboratory specimens	X	X	WMA uses lower temperature
7	Calculate volumetric composition of laboratory specimens	X	X	
8	Adjust aggregate proportions to meet volumetric requirements	X	X	
9	Evaluate coating and compactability	NA	X	Used in WMA design in place of viscosity-based mixing and compaction temperatures
10	Conduct performance testing	X	X	Moisture sensitivity for all mixtures, rutting resistance for design traffic levels of 3 m ESALs or greater

mixture. For wet aggregate processes, water is added to a portion of the fine aggregate, and then this wet, fine aggregate is added cold to the mixture during the mixing process. The proportion of the aggregate that is added wet and the moisture content are provided by the WMA technology provider.

Mixing Temperatures

Viscosity-based mixing temperatures cannot be used with the wide range of WMA processes currently available. Laboratory specimens are mixed at the planned production temperature, and coating is evaluated to determine the acceptability of the WMA process.

Process-Specific Specimen Fabrication Procedures

For mixture design, the various WMA processes were grouped into four generic categories:

1. Additives blended into the binder,
2. Additives added to the mixture,
3. Wet aggregate mixtures, and
4. Foamed asphalt.

The procedures in the report address laboratory mixing. These were developed based on recommendations from various WMA technology providers and verified during the mix design experiment completed in NCHRP Project 9-43. Once mixing is complete, specimen fabrication for all processes continues with short-term conditioning and specimen compaction. These steps are the same for all processes and the same as done with HMA.

WMA mixture designs will require additional equipment. Since coating is used in lieu of viscosity-based mixing and compaction temperatures, 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. Planetary mixers are more efficient. The specimen fabrication procedures were developed in NCHRP Project 9-43 using a planetary mixer. 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. 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 Gencore Ultrafoam GX process using 1.25% water by weight of binder and the Astec Double Barrel Green process using 2.0% 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.

Short-Term Conditioning

Short-term conditioning for WMA was set at 2 hours at the planned compaction temperature to represent the absorption and binder stiffening that occurs during construction. This level of conditioning is used for the volumetric design and for the moisture sensitivity and rutting evaluation. These conditions were selected based on comparisons of properties of laboratory-mixed, laboratory-compacted specimens with those from field-mixed, laboratory-compacted specimens.

Figures 5 and 6 summarize the results of comparisons of maximum specific gravity and indirect tensile strength for the field sections tested in NCHRP Project 9-43. The error bars shown in Figure 5 are the single operator D2s precision from AASHTO T 209. These data show that the maximum specific gravity of the lab and field mixtures are the same, indicating that the binder absorption is the same for the lab and field mixtures. The aggregate water absorption ranged from 0.5% for the Pennsylvania SR2007 mixtures to 2.5% of the Yellowstone National Park mixtures.

Figure 6 shows average differences in indirect tensile strength for the field mixtures minus the laboratory mixtures. The error bars in this figure are 95% confidence intervals for a paired t-test comparison. If the error bars do not capture zero, then the difference in the tensile strength of the field- and laboratory-mixed specimens is different from zero. Figure 6 shows that several mixtures have significantly different tensile strengths. The differences are not consistently in one direction except for the Pennsylvania SR2006 project, where the field-mixed specimens always have significantly higher tensile strengths compared to the laboratory-mixed specimens. Given that one-third of the mixtures were from this project, this difference biased the results. The average difference for all projects was 7 psi (48 kPa); not considering the Pennsylvania SR2006 project, the average difference was essentially zero.

Short-term conditioning for performance evaluations, moisture sensitivity, and rutting was one of the areas where additional research was recommended in NCHRP Project 9-43. This additional research was recommended because it appears that the current HMA short-term conditioning procedure for performance evaluation, 4 hours at 275°F (135°C), represents the stiffening that occurs during construction and some short time in service.

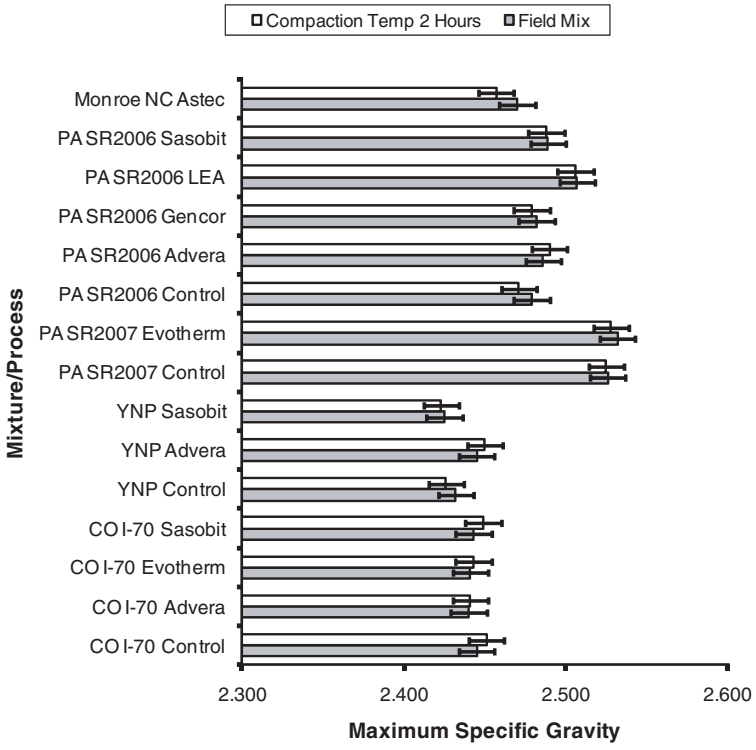

Figure 5. Comparison of maximum specific gravity between field mixes and laboratory mixes short-term conditioned 2 hours at the compaction temperature.

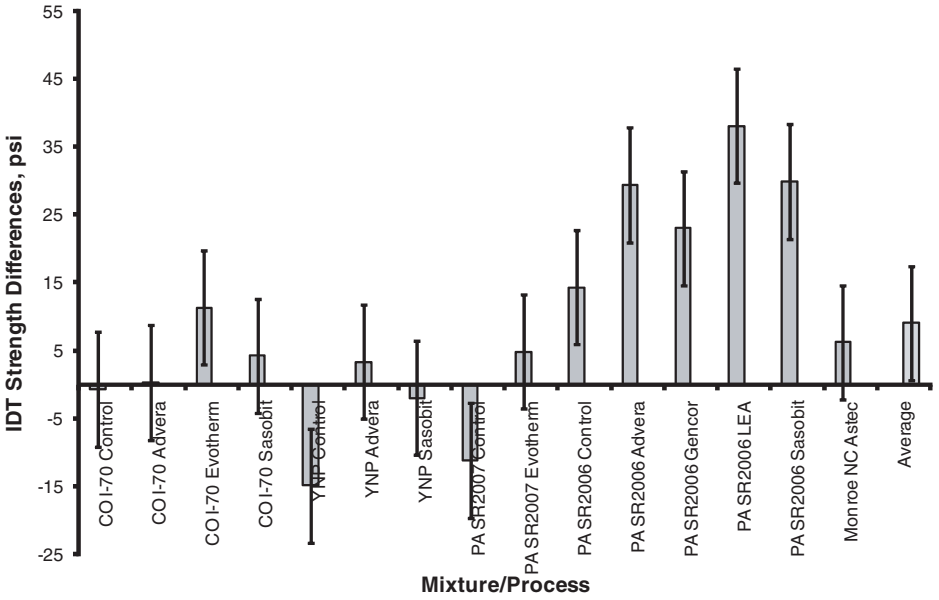

Figure 6. Differences in indirect tensile strength between field mixes and laboratory mixes short-term conditioned 2 hours at the compaction temperature.

Compaction Temperatures

Viscosity-based compaction temperatures cannot be used with the wide range of WMA processes currently available. Laboratory specimens are compacted at the planned compaction temperature. Additionally a compactability evaluation is conducted to ensure that the mixture is compactable at the planned compaction temperature.

WMA Evaluations

Four evaluations are conducted on WMA mixtures at the design binder content: (1) coating, (2) compactability, (3) moisture sensitivity, and (4) rutting resistance. The sections below describe the supporting information from NCHRP Project 9-43 for these evaluations.

Coating

Coating is one way to evaluate proposed 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 T 195. AASHTO T 195 counts the percentage of the coarse aggregates in the mixture that are **fully** coated. This is a strict criterion. 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. This indicates that the bucket mixer is less efficient than the planetary mixer. The criterion of 95% was based on the planetary mixer data. Though bucket mixers are less efficient than planetary mixers, they are significantly less expensive and likely more readily available in mix design laboratories. Until additional research is conducted to develop appropriate mixing times for bucket mixers, technicians and engineers will have to develop mixing times for their WMA mixtures based on coating evaluations for HMA mixtures produced using the traditional viscosity-based mixing temperatures.

Compactability

The compactability evaluation is used in lieu of the viscosity-based mixing 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 compaction temperature. The number of gyrations to reach 92% relative density is then calculated from the height data. The ratio of the gyrations to 92% 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. Figures 7 and 8 show the effect of WMA process and temperature on workability and compactability.

Given that 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. The method involves determining the number of gyrations to 8% air voids at the proposed compaction temperature and a second temperature that is approximately 54°F (30°C) lower than the proposed compaction temperature. A tentative limit allowing a 25% increase in the number of gyrations when the temperature is decreased was developed. This limit was investigated using data from nine WMA field mixture projects sampled in NCHRP 9-43. The increase in gyrations for the WMA processes ranged from 0 to 20%. Workability and compactability was not reported to be a problem on any of the projects.

Moisture Sensitivity

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

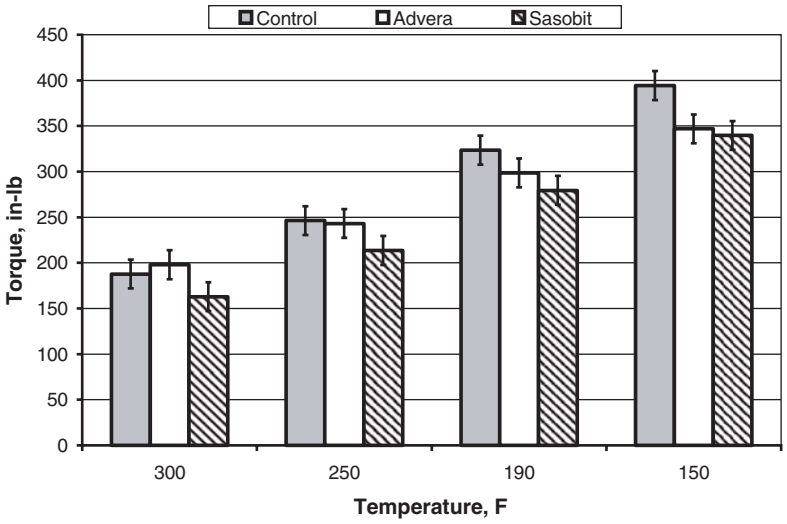

Figure 7. Effect of temperature and WMA additive on torque measured in the UMass workability device.

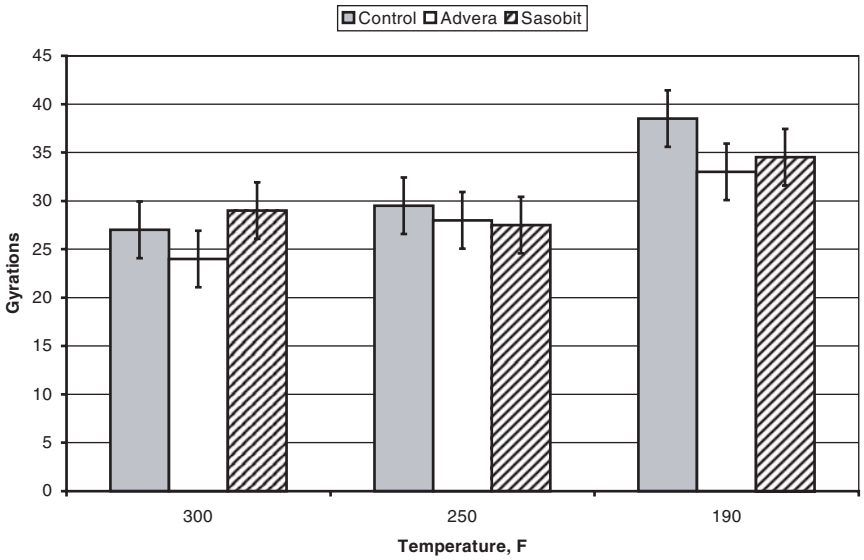

Figure 8. Effect of temperature and WMA additive on gyrations to 92% relative density.

Tests conducted during NCHRP Project 9-43 showed that the moisture sensitivity will likely be different for WMA and HMA mixtures designed using the same aggregates and binder. WMA processes that included antistrip 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 antistrip additive, the tensile strength ratio remained the same or improved in 67% of the mixtures. For WMA mixtures produced using processes that do not include antistrip additives, the tensile strength ratio never improved and decreased in 79% of the mixtures.

Rutting Resistance

Rutting resistance is evaluated using the flow number test, AASHTO TP 79. The same testing conditions that are used for HMA flow number testing are used with WMA:

- Air voids of 7.0 ± 0.5%
- 50% reliability high pavement temperature from LTPPBind 3.1 for the project location, 20 mm below the pavement surface, or 20 mm below the top of the sub-surface pavement layer of interest
- Unconfined
- Repeated deviator stress of 87 psi (600 kPa), contact deviator stress of 4.4 psi (30 kPa),

Minimum flow numbers as a function of traffic level are provided and these are lower than those for HMA. Table 8 compares the recommended flow numbers for WMA and HMA. The

Table 8. Flow number criteria for WMA and HMA mixtures.

Traffic Level, Million ESALs	Minimum Flow Number	
	WMA	HMA
< 3	NA	NA
3 to < 10	30	50
10 to < 30	105	190
≥ 30	415	740

Table 9. Summary of average difference in flow number of WMA compared to HMA for the NCHRP 9-43 field validation sections.

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

recommended WMA flow numbers are approximately 55% of those recommended for HMA. The different criteria are needed because of the different short-term conditioning used for WMA compared to HMA. WMA flow number specimens are conditioned 2 hours at the planned field compaction temperature while HMA flow number specimens are conditioned 4 hours at 275°F (135°C). NCHRP Project 9-43 included comparisons of flow number data for 10 pairs of WMA and HMA sections. Table 9 summarizes the difference in flow numbers obtained for field validation mixtures. The Sasobit process increases the rutting resistance because it increases the high-temperature grade of the binder.

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. Current criteria for evaluating moisture sensitivity and rutting resistance are based on mixtures that have been aged to a greater degree. The conditioning originally specified in AASHTO T 283 for moisture sensitivity testing was 16 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 these 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.

Step 11. Compile Mix Design Report

This step is the same as that for HMA with some additional information provided. The additional information for WMA is that needed in Step 1 of the mix design process:

- WMA process,
- WMA additive rate,
- Planned production temperature, and
- Planned compaction temperature.

References

Bonaquist, R., "Mix Design Practices for Warm Mix Asphalt," *NCHRP Report 691*, National Cooperative Highway Research Program, Washington, D.C., 2011.

Christensen, D. W., "A Manual for the Design of Hot Mix Asphalt with Commentary," *NCHRP Report 673*, National Cooperative Highway Research Program, Washington, D.C., 2010.

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

Abbreviations and acronyms used without definitions in TRB publications:

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