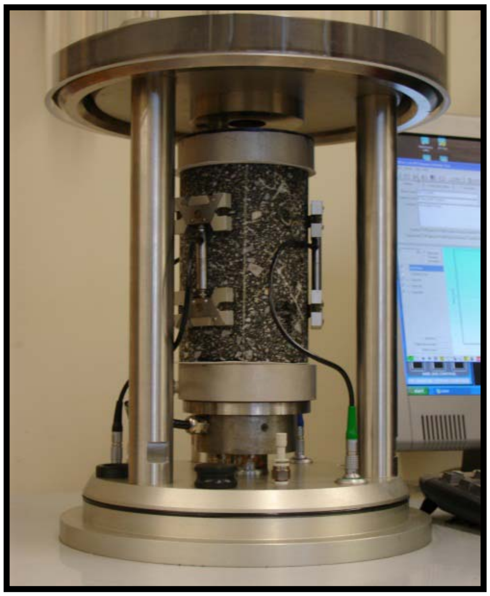
February
2016

Evaluation of Specialized Hot Mix Asphalt Mixes for Massachusetts



Charles D. Baker, *Governor*
Karyn E. Polito, *Lieutenant Governor*
Stephanie Pollack, *MassDOT Secretary & CEO*

U.S. Department of Transportation
Federal Highway Administration

massDOT
Massachusetts Department of Transportation

Technical Report Document Page

1. Report No. SPR-001-S-645-000	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle Evaluation of Specialized Hot Mix Asphalt Mixes for Massachusetts		5. Report Date December 2015
		6. Performing Organization Code N/A
7. Author(s) Dr. Walaa S. Mogawer, P.E., F.ASCE Mr. Alexander J. Austerman, P.E.		8. Performing Organization Report No. UMTC 12.04
9. Performing Organization Name and Address University of Massachusetts Dartmouth Highway Sustainability Research Center (HSRC) 151 Martine Street - Room 131, Fall River, MA 02723		10. Work Unit No. (TRAIS) N/A
		11. Contract or Grant No. ISA #0053492
12. Sponsoring Agency Name and Address Massachusetts Department of Transportation Office of Transportation Planning 10 Park Plaza, Suite 4150 Boston, MA 02116		13. Type of Report and Period Covered Final December 2007 to December 2012
		14. Sponsoring Agency Code N/A

15. Supplementary Notes
N/A

16. Abstract

Many state transportation agencies have begun exploring and implementing the use of specialized types of Hot Mix Asphalt (HMA) paving mixtures for their potential economic, performance and/or environmental benefits. The specialized asphalt mixture needs for Massachusetts were identified as expanded and increased use of technologies (Warm Mix Asphalt (WMA)); increased use of recycled materials, such as Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and Ground Tire Rubber (GTR); increased use of technologies and recycled materials in combination; and thin lifts for pavement preservation. Previous research has suggested that WMA may increase mixture moisture susceptibility. Additionally, high amounts of recycled materials may adversely impact mixture stiffness and reduce mixture workability. In this study, these types of mixtures were developed and evaluated in terms of stiffness, cracking resistance, moisture susceptibility, and rutting.

Testing of 9.5 mm WMA mixtures suggested that aging time and temperature had a significant effect on moisture susceptibility performance. Development and evaluation of a 12.5 mm gap graded mixture (incorporating up to 40% RAP, GTR and WMA) and 9.5 mm pavement preservation thin lift mixtures (incorporating up to 40% RAP, 5% RAS and WMA) indicated acceptable mixture performance in terms of moisture susceptibility and rutting, but decreased cracking performance and reflective cracking.

17. Key Word Warm Mix Asphalt, Reclaimed Asphalt Pavement, Recycled Asphalt Shingles, Ground Tire Rubber, Pavement Preservation, Thin Lift, Sustainable	18. Distribution Statement No restrictions. This document is available to the public through the sponsoring agent.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 89	22. Price N/A

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

This page left intentionally blank.

Evaluation of Specialized Hot Mix Asphalt Mixes for Massachusetts

Final Report

Prepared By:

Principal Investigator:
Dr. Walaa S. Mogawer, P.E., F.ASCE

Contributing Author:
Alexander J. Austerman, P.E.

University of Massachusetts Dartmouth
Highway Sustainability Research Center
151 Martine Street – Room 131
Fall River, MA 02723

Prepared For:

Massachusetts Department of Transportation
Office of Transportation Planning
10 Park Plaza, Suite 4150
Boston, MA 02116

December 2015

This page left intentionally blank.

Acknowledgements

Prepared in cooperation with the Massachusetts Department of Transportation, Office of Transportation Planning, and the United States Department of Transportation, Federal Highway Administration.

The Project Team would like to acknowledge the efforts of Gregory Doyle, Construction Quality Engineer for FHWA, Massachusetts Division and Ed Naras, Pavement Engineer for MassDOT. The Project Team would also like to acknowledge research assistants Michael Roussel, Anthony Reppucci, and Brenton Mederios who were involved with the laboratory testing for this project.

Disclaimer

The contents of this report reflect the views of the author(s), who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

This page left intentionally blank.

Executive Summary

This study of the Evaluation of Specialized Hot Mix Asphalt (HMA) Mixes for Massachusetts was undertaken as part of the Massachusetts Department of Transportation Research Program. This program is funded with Federal Highway Administration (FHWA) Statewide Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Many state transportation agencies have begun exploring and implementing the use of specialized types of HMA paving mixtures for their potential economic, performance and/or environmental benefits. The specialized asphalt mixture needs for Massachusetts were identified as expanded and increased use of technologies (Warm Mix Asphalt (WMA)); increased use of recycled materials, such as Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and Ground Tire Rubber (GTR); increased use of technologies and recycled materials in combination; and thin lifts for pavement preservation.

The use of RAP and RAS may lead to material cost savings, GTR has been proven to improve the performance of asphalt mixtures, and WMA will allow for the production of mixtures at lower temperatures leading to environmental benefits. Even with all of the potential benefits, there are concerns associated with the use of these types of mixtures. Higher amounts of RAP and RAS in mixtures will increase the stiffness of the overall binder and reduce mixture workability. Additionally, WMA may negatively affect the mixture moisture susceptibility.

The research presented here focuses on the development and evaluation of WMA mixtures; thin lift mixtures incorporating high amounts of RAP; thin lift mixtures incorporating high amounts of RAP and RAS; thin lifts mixtures incorporating high amounts of RAP, RAS and WMA technology; mixtures incorporating high amounts of RAP and GTR; and mixtures incorporating high amounts of RAP, GTR, and WMA technology.

The performance of the WMA specialized mixtures were evaluated for moisture susceptibility using the Hamburg Wheel Tracking Device (HWTD) and dynamic modulus |E*| ratio (ESR). For gap graded mixtures incorporating RAP, GTR and WMA, the mixture performance was evaluated in terms of stiffness using the Asphalt Mixture Performance Tester (AMPT), moisture susceptibility/rutting using the HWTD, cracking using the Texas Overlay Tester (OT), fatigue cracking using the beam fatigue test, and workability using the Asphalt Workability Device (AWD). For thin lift pavement preservation mixtures incorporating RAP, RAS and WMA, the mixture performance was evaluated in terms of stiffness using the AMPT, moisture susceptibility/rutting using the HWTD, cracking using the Texas OT, and thermal cracking using the Asphalt Concrete Cracking Device (ACCD).

The performance evaluation of WMA mixtures indicated that the mixture aging time and temperature had a significant effect on the moisture susceptibility performance. Generally, moisture susceptibility performance improved as the aging time and temperature increased.

Additionally, WMA mixture moisture susceptibility performance may be improved with the addition of anti-strip additives.

For the gap graded mixtures incorporating up to 40% RAP, GTR and WMA, the data indicated that the addition of RAP increased the mixture stiffness. This increase in stiffness could be mitigated through the use of the WMA technology and corresponding reduced aging temperatures. Fatigue tests indicated that the resistance of the mixtures to fatigue cracking decreased with the incorporation of higher amounts of RAP, regardless of whether WMA technology was included. A similar trend held true for the reflective cracking susceptibility of these mixtures. As the amount of RAP incorporated into the mixture increased, there was a corresponding decrease in mixture workability. The addition of WMA greatly improved the workability of the mixtures with RAP to a level similar to that of the control mixture. The addition of RAP and/or WMA did not negatively impact the moisture susceptibility or rutting of the mixture.

For the thin lift mixtures incorporating up to 40% RAP, 5% RAS and WMA, the data indicated that the addition of RAP or RAS increased the mixture stiffness. The stiffness increase was significant for the 40% RAP and 35% RAP + 5% RAS mixtures with and without WMA technology. Generally, mixtures incorporating the WMA technology showed lower dynamic modulus values than the mixtures without the technology. This was likely due to reduced mixing and compaction (aging) temperatures. Reflective cracking results indicated that mixtures incorporating the RAP and/or RAS had reduced reflective cracking resistance as compared to the control. The addition of the WMA technology increased the reflective cracking resistance of the mixtures, but not to the same level as the control mixture with the WMA technology. Low temperature cracking resistance test results indicated that the addition of RAP, RAS and/or WMA technology did not have a negative impact on the low temperature performance. The addition of RAP and/or RAS to the mixture showed improved moisture susceptibility relative to the control mixtures.

Overall, the study data indicated that the use of sustainable material and new technologies in specialized mixtures is viable. However, further study is needed to address the reduction in the cracking resistance of the mixtures that incorporate higher amounts of the sustainable materials.

Finally, based on the data and analysis, a testing protocol was developed to evaluate WMA mixtures in Massachusetts. Additionally, a pilot performance-based specification was developed for a sustainable thin lift asphalt mixture that incorporates RAP, RAS, and WMA. This mixture can be used as a pavement preservation/minor rehabilitation strategy in the state of Massachusetts.

Table of Contents

List of Tables

This page left intentionally blank.

List of Figures

This page left intentionally blank.

List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ACCD	Asphalt Concrete Cracking Device
ADOT	Arizona Department of Transportation
AMPT	Asphalt Mixture Performance Tester
AR	Asphalt Rubber
ARGG	Asphalt Rubber Gap Graded
ASTM	American Society for Testing and Materials
AWD	Asphalt Workability Device
DOT	Department of Transportation
EOT	Executive Office of Transportation
ESALs	Equivalent Single Axle Loads
ESR	Dynamic Modulus |E*| Stiffness Ratio
FHWA	Federal Highway Administration
GSHPThinOL	Green Sustainable High Performance Thin Overlay
GTR	Ground Tire Rubber
HMA	Hot Mix Asphalt
HSRC	Highway Sustainability Research Center
HWTD	Hamburg Wheel Tracking Device
LVDT	Linear Variable Differential Transducer
MassDOT	Massachusetts Department of Transportation
NMAS	Nominal Maximum Aggregate Size
OGFC	Open Graded Friction Course
OT	Overlay Tester
PG	Performance Grade
PMA	Polymer Modified Asphalt
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingle
RCRL	Reflective Crack Relief Interlayers
SGC	Superpave Gyratory Compactor
SIP	Stripping Inflection Point
SMA	Stone Matrix Asphalt
SPR	Statewide Planning and Research
TSR	Tensile Strength Ratio
TxDOT	Texas Department of Transportation
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
WMA	Warm Mix Asphalt

This page left intentionally blank.

1.0 Introduction

This study of the Evaluation of Specialized Hot Mix Asphalt (HMA) Mixes for Massachusetts was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) Statewide Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Throughout the United States many state Department of Transportation (DOT) agencies have begun exploring and implementing the use of specialized types of Hot Mix Asphalt (HMA) paving mixtures, including: Warm Mix Asphalt (WMA) mixtures, high percentage Reclaimed Asphalt Pavement (RAP) mixtures, mixtures incorporating Recycled Asphalt Shingles (RAS), Asphalt Rubber Gap Graded (ARGG) mixtures incorporating Ground Tire Rubber (GTR) from waste tires, Stone Matrix Asphalt (SMA), Open Graded Friction Course (OGFC), Polymer Modified Asphalt (PMA) mixtures, Superpave, and Reflective Crack Relief Interlayers (RCRL) (*1,2,3,4,5,6*). Each of these specialized mixtures has unique design and testing considerations that must be taken into account in order for the mixture to perform acceptably in the field.

Prior to this study, Massachusetts had limited experience with the use of specialized mixtures. MassDOT has previously placed SMA and OGFC mixtures, and has placed mixtures with PMA on trial projects, with mix designs based on specifications developed by Rhode Island. Since 2000, MassDOT has had numerous projects involving the design and placement of Superpave mixes. MassDOT has an RCRL mixture placed on an experimental basis for use on Interstate 495 (I-495), Southbound. In 2005, MassDOT placed the first WMA mixture in the state on I-95 between Danvers and Rowley, Massachusetts. Generally, the experience with developing and placing these specialized mixtures indicated that issues will arise during mixture design development and construction. Hence, it became critical to design these mixes according to the latest standards and to use the experience of other states that have placed similar mixtures. Many of the mixtures used on trial projects in Massachusetts were developed under older specifications that have since been revised based on industry experience throughout the country.

Successful mixture design development of certain types of specialized mixes have the potential to provide benefits for Massachusetts, including: extension of the construction season, reduction in field paving visible emissions, increased use of waste materials (RAP, RAS, and rubber), increased cost savings through recycling, and increased mixture field performance.

Therefore, the goals of this research included the following: 1) to identify the paving mixture performance needs of Massachusetts (better cracking resistance, fatigue resistance, reflective crack mitigation, etc.), 2) to identify and select the specialized mixtures that have applications relevant to the performance needs of Massachusetts, 3) to develop gradation and mixture designs for each specialized mix according to the most recent available specifications, and 4) to evaluate the performance of the specialized mixtures in the laboratory, in terms of moisture susceptibility, rutting, reflective cracking, fatigue cracking, thermal cracking, and workability.

2.0 Specialized Mixture Types Identified for Evaluation

The specialized mixture needs of Massachusetts were evaluated with regard to preventing or mitigating certain distresses and/or for exploration of new technologies. Representatives of agencies related to pavement and roadways falling under the jurisdiction of MassDOT were contacted for their input on the specialized mixture needs of Massachusetts. Based on these discussions, the specialized asphalt mixture needs for Massachusetts were identified as expanded and increased use of technologies (WMA); increased use of recycled materials, such as RAP, RAS and GTR; increased use of technologies and recycled materials in combination; and thin lifts for pavement preservation. Accordingly, the research presented here focuses on the development and evaluation of WMA mixtures; thin lift mixtures incorporating high amounts of RAP; thin lift mixtures incorporating high amounts of RAP and RAS; thin lift mixtures incorporating high amounts of RAP, RAS and WMA technology; mixtures incorporating high amounts of RAP and rubber; and mixtures incorporating high amounts of RAP, rubber, and WMA technology.

2.1 Warm Mix Asphalt

The term WMA generally refers to asphalt mixtures produced and paved at lower temperatures than conventional HMA. WMA mixtures can be produced by means of various technologies including several proprietary products and processes. These technologies include foaming (moisture-based) agents, wax-based additives, emulsion-based products and surfactants.

WMA mixtures have reduced production and paving temperatures; therefore, they have significant benefits, such as reduced emissions and odors, decreased energy consumption for production and improved environmental working conditions at plants and paving sites. Lower production temperatures also yield a mixture with less oxidative hardening, which can reduce its cracking susceptibility. Additionally, the use of WMA technologies may improve the workability and compatibility of polymer modified asphalt mixtures (*7, 8*). The current methodology to improve the workability and compactibility of these types of mixtures is to increase the mixing and compaction temperatures. This action can lead to increased aging of the binder (which may reduce the cracking resistance of the mixture) and increased emissions at the plant and in the field. Therefore, the addition of a WMA technology allows for improved workability and compactibility without increasing mixture temperatures (*8*).

Because of limited long-term field performance data with WMA mixtures in the United States, concerns associated with the use of WMA technologies have been identified and will require further investigation. Currently, the main concern is the effect of WMA technologies on the moisture susceptibility of asphalt mixtures. This concern is primarily based on the fact that WMA mixtures are produced at lower temperatures, which could lead to the possibility of inadequate drying of aggregates. Furthermore, some WMA technologies introduce water into the mixture to increase its workability. Aggregates that are not sufficiently dried and/or the introduction of water into the mixture can adversely impact the adhesion between the aggregates and the asphalt binder. Poor adhesion at the aggregate to binder interface can lead to moisture damage.

For field projects placed in the United States, there is no reported evidence of moisture-related distresses due to the use of WMA technologies. However, some WMA mixtures have failed in the laboratory using standardized tests, such as the American Association of State Highway and Transportation Officials (AASHTO) T283 “Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage” and AASHTO T324 “Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)” (*9*,*10*,*11*). One of the reasons for the discrepancy between laboratory and field results could be related to the methods used in the laboratory to age WMA mixtures. Because these mixtures are produced at lower temperatures and therefore exhibit less stiffness than conventional HMA mixtures, it is plausible that WMA mixtures may need to be aged longer to attain the in-situ stiffness that is reached in the field.

The focus in this study was to measure the effect of aging time and temperature on the moisture susceptibility of different WMA mixtures using the Hamburg Wheel Tracking Device (HWTD) and dynamic modulus |E*| stiffness ratio (ESR). The HWTD testing was included in this study because it is one of the tests that some states utilize as a mixture acceptance criterion in their specification. The HWTD is conducted on specimens submerged under water and it is believed to assess the mechanical effects of water (i.e., pore pressure, water flow) on asphalt mixtures. The ESR was used to evaluate the effect of moisture on reduction in stiffness, which could occur due to reduction of binder cohesive strength and loss of some of the adhesive bonds in the mixture due to moisture conditioning.

2.2 Mixtures Incorporating Asphalt Rubber, High RAP, and/or WMA Technology [Asphalt Rubber Gap Graded Mixtures]

The HMA industry is constantly seeking technological improvements to produce sustainable, cost effective, and environmentally friendly mixes. A logical approach to achieve such mixtures is to use readily available recycled materials like RAP and GTR (*12*). Also, to advance environmental stewardship, the industry has been using WMA technologies that allow for the production of asphalt mixtures at temperatures in the range of 17° to 54°C (30° to 100°F) lower than typical HMA.

RAP is comprised of aggregates and asphalt binder from HMA mixtures that have been removed and reclaimed from an existing pavement. The aggregates in the RAP are coated with aged (oxidized) asphalt binder. RAP has been used successfully in surface HMA mixtures since the 1970’s at around 20%. A concern associated with the use of higher RAP content is that the resultant mixture might become too stiff and consequently might be prone to failures in the field (*13, 14, 15*). The increased stiffness is due to the aged binder in the

RAP. In mixtures with higher amounts of RAP, blending of the RAP and virgin binders will result in a binder that is stiffer than the virgin binder used for production. Softer asphalt binders or rejuvenating additives can be used to counteract the stiffness of the RAP binder, thus enabling the use of higher percentages of RAP in HMA. It has been documented that rejuvenating agents can be carried by GTR, because of its absorptive properties, to revitalize the properties of the RAP binder (*12*).

GTR is recycled tire rubber, which has been ground into very small particles and used as an asphalt modifier. GTR is introduced into HMA mixtures through a wet or a dry process. A wet process refers to blending the GTR with the liquid asphalt at elevated temperatures. A dry process refers to mixing GTR rubber into the mixture as a small part of the aggregate or filler rather than blending the rubber with the liquid asphalt. The results of modifying asphalt binders with GTR using a wet process is rubberized asphalt or asphalt rubber (AR). Rubberized asphalt is a term applied to rubber-modified asphalt with less than 15% by total weight of the liquid asphalt. AR is defined by the American Society for Testing and Materials (ASTM) Specification D 6114-97 as “a blend of paving grade asphalt cements, GTR and other additives, as needed, for use as binder in pavement construction.” The rubber shall be blended and interacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles prior to use. It has been found that at least 15% GTR by weight of the total blend is usually necessary to provide acceptable properties of asphalt rubber (*16*). Asphalt rubber is typically used when designing a gap-graded HMA and requires a higher amount of asphalt binder than a dense graded mix. Because of the high binder content, asphalt rubber gap-graded mixtures have several positive qualities, such as improved fatigue cracking resistance, improved ability to retard reflective cracking, resistance to aging and oxidization resistance, resistance to surface-initiated cracking and resistance to rutting due to a higher viscosity and softening point (*17, 18*).

The term WMA refers to mixtures that are produced and placed at significantly lower temperatures than conventional HMA mixtures. WMA mixtures can be produced by means of various technologies such as foaming, emulsion-based products, moisture-based agents, wax-based additives and surfactants (*19*). The lower production and placement temperatures provide several benefits, such as reduced emissions and odors, decreased energy consumption for production and improved environmental working conditions at plants and paving sites (*19*). Additionally, WMA has been reported to improve the workability of high RAP content asphalt mixtures.

Designing a gap-graded asphalt rubber surface mixture with high RAP content (greater than 20%) and WMA would meet the goal of producing a sustainable, cost effective and environmentally friendly mixture. However, because the high amount of RAP will introduce a high amount of aged RAP binder into the mixture, the performance qualities of such mixtures should be evaluated to confirm that RAP binder did not negatively impact the performance of the mixture.

The research study presented herein focused on developing and evaluating the performance of asphalt rubber surface mixtures with RAP content up to 40%, with and without the use of a WMA technology. The effect of higher RAP content and WMA on the performance of the mixture, in terms of stiffness, cracking, rutting and moisture susceptibility, were measured. Because the high RAP content utilized may lead to a mixture with increased stiffness and a corresponding reduction in compactibility, the workability and potential workability improvements resulting from the use of a WMA technology were also evaluated.

2.3 Mixtures Incorporating High RAP, RAS and/or WMA Technology [Thin Lift Mixtures for Pavement Preservation]

Thin lift HMA overlays are quickly becoming an integral component of the ‘pavement preservation toolbox’ as noted by the FHWA, Foundation for Pavement Preservation and other groups (*20*). These overlays are typically placed at a thickness of 1 to 1.5 inches. They seal the pavement, reduce the rate of pavement deterioration, correct surface deficiencies, reduce permeability, correct rutting and improve ride quality (*21*). Because other pavement preservation strategies (surface treatments) do not improve ride quality (*20*), thin lift overlays are becoming an appealing pavement preservation strategy alternative.

Even though they are becoming more appealing, thin lift overlays are reported to have a higher initial cost than other pavement preservation strategies. The higher initial cost can be offset by using larger amounts of recycled materials, including RAP and RAS. These materials are incorporated into HMA because they contain asphalt binder and aggregates, which can substitute for a portion of the virgin materials needed to produce new HMA mixtures. Because of their lower associated costs as compared to virgin asphalt binder and aggregates, the use of recycled materials can decrease the cost for new HMA mixtures, as is the case for mixtures incorporating higher RAP content (*22*). These cost reductions have the potential to make thin lift overlays a more economically appealing pavement preservation strategy alternative.

For many years, RAP has been utilized in HMA mixtures at percentages generally less than 20%, while RAS content has tended to be less than 5%. The addition of these materials at higher percentages can significantly affect the performance of the HMA mixture. RAP and RAS contain a significant portion of aged asphalt binder, which is much stiffer than a virgin binder. Therefore, a large amount of the aged binder will be introduced into the HMA mixture. As previous research has suggested, the aged and virgin binders will mix (blend) to some extent, changing the properties of the mixture (*7, 13, 22, 23, 24, 25*). Mixtures incorporating higher amounts of RAP and/or RAS will have higher mixture and binder stiffness due to the mixing of the aged and virgin binders. This increased stiffness can be a benefit and detriment to the mixture at the same time. Increased mixture stiffness tends to lead to a more rut resistant mixture at higher temperatures. However, the same mixture at intermediate and low temperatures may be more susceptible to cracking. Additionally, increased mixture stiffness may lead to less workable mixtures. Therefore, difficulties in handling, placement and compaction may arise. In all, the effects on the mixture performance may be less pronounced when smaller amounts of RAP and/or RAS are utilized.

Recently, technologies have been introduced that may help improve performance of mixtures incorporating larger amounts of recycled materials and concurrently make them more environmentally friendly. These technologies, known as WMA technologies, permit production and placement of HMA mixtures at lower temperatures than conventional mixtures. These temperature reductions allow for the fabrication of more environmentally friendly mixtures, as plant and field emissions are reduced. The lower production temperatures may also decrease the amount of mixture aging, thereby decreasing the mixture stiffness. This may lead to a mixture less prone to cracking. The use of WMA technologies has been proven to improve the workability of HMA mixtures (*26, 27*). More recently, WMA manufacturers claim that WMA technologies allow for more RAP to be utilized in the mixture.

The research presented herein focused on designing a HMA mixture for use as a thin lift overlay pavement preservation strategy. A Superpave 9.5 mm mixture was designed using solely virgin materials and designated as the control mixture. The control mixture was then duplicated with a high RAP content, RAS and WMA technology on an individual and collective basis. The effect of RAP, RAS and WMA technology on the performance of the control mixture was then evaluated. The low temperature cracking, reflective cracking potential and mixture stiffness characteristics of each mixture were measured, as the addition of RAP and/or RAS may increase mixture stiffness and cracking susceptibly. Because the stiffness of the HMA mixtures is influenced heavily by the stiffness of the asphalt binder, the asphalt binder of each mixture was extracted and its Performance Grade (PG) was measured. Additionally, because stiffer binders are harder to peel from the aggregate, the adhesion properties (moisture susceptibility) of the mixture may be improved with the addition of RAP and/or RAS. The adhesion properties of the mixtures were evaluated by measuring moisture susceptibility.

2.3.1 Reclaimed Asphalt Pavement (RAP) in HMA

RAP is a commonly recycled material that is incorporated in the production of new HMA. It can be generated from full-depth removal or milling of an existing HMA layer, utilizing both hot and cold processes, and also from plant waste HMA materials. Currently, around 75% of all state standard specifications allow for at least 10% RAP in the surface course mixtures and greater than or equal to 10% in lower pavement lifts. With lower percentages of RAP (less than 20%), mixtures have been found to perform similarly to virgin mixtures. With higher percentages of RAP (greater than 20%), mixtures have exhibited an increased resistance to rutting, but decreased resistance to cracking (thermal and reflective cracking). This is due to the stiffening effect imparted by the aged RAP binder to the blended binder in the mixture. Therefore, when using higher RAP content, it is necessary to measure the stiffness of the mixture as well as the mixture's resistance to reflective cracking and low temperature cracking. RAP has also been used as a recycled aggregate base layer, which has greater strength in comparison to conventional aggregate base (*28*).

2.3.2 Recycled Asphalt Shingles (RAS) in HMA

Several state agencies allow up to 5% RAS in HMA mixtures, while other states extend the range to 10% (*29, 30*). AASHTO PP35 provides suggestions to limit the addition of RAS based on performance measurements of the new HMA (*30*). Most state agencies allow the RAS to be comprised of manufacturer's scrap, with the exception of tear-off shingles. Depending on the source of the RAS, the asphalt content may range from 18% to 40%. These percentages of asphalt are much larger than those found in RAP, demonstrating that the use of RAS may significantly reduce the amount of virgin asphalt binder needed in new HMA mixtures. The permitted amount of RAS (5%) is low in comparison to the amounts permitted for RAP, which is due in part to the fact that the asphalt binder in the shingles is substantially stiffer than a typical asphalt binder used in producing HMA mixtures. This high stiffness binder has made agencies cautious of using RAS, as it may significantly impact the properties of the mixture binder (stiffness and cracking susceptibility). Consequently, the performance of the asphalt mixture might also be impacted.

2.3.3 Benefits of High RAP Content, RAS, and WMA in Thin Lift Overlay Mixture

The use of higher RAP content and RAS leads to a reduction in the amount of virgin asphalt binder required for HMA mixtures, resulting in reduced mixture costs. The use of RAS in HMA will decrease the volume of asphalt shingles being disposed of in landfill sites, which benefits the environment (*29*). The use of WMA technologies will lead to more environmentally friendly mixtures, as plant and field emissions are reduced. Due to the lower production temperatures associated with WMA, less fuel is consumed in order to heat the raw materials for the HMA, resulting in financial savings. Finally, WMA technologies may allow for the incorporation of increasing amounts of RAP into the HMA mixture, aiding in improving the mixture workability (*7*).

3.0 Experimental Methodology

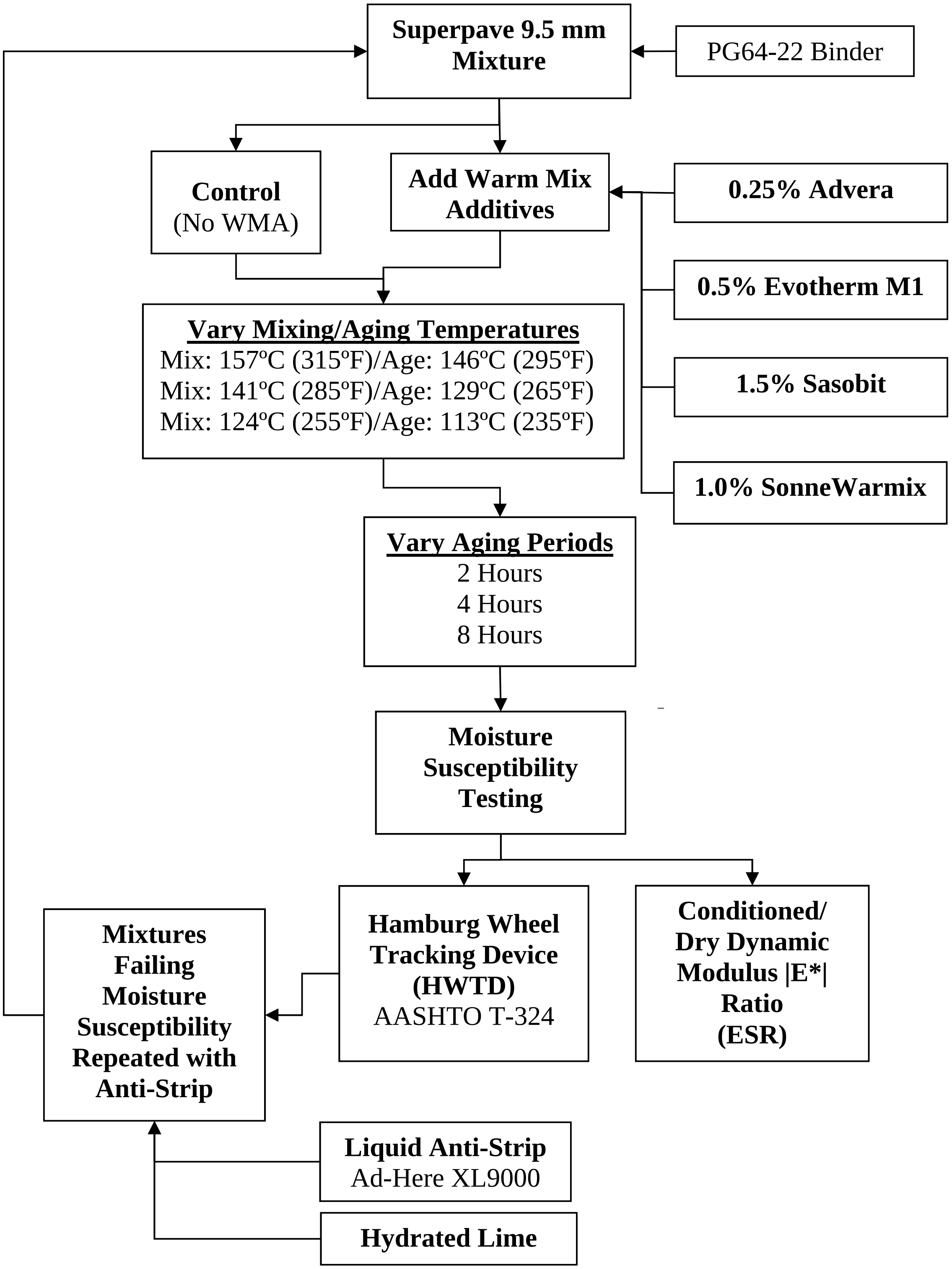
3.1 Effect of Temperature & Time on the Moisture Susceptibility of WMA Mixtures

In order to achieve the objectives of the study, an experimental plan was developed as shown in Figure 1. Four WMA technologies were used, including a moisture-based process (Advera), two wax-based technologies (Sasobit and SonneWarmix) and a chemical additive technology (Evotherm). The dosage rate of the Advera was 0.25% by weight of the mixture. The remaining technologies were dosed by the weight of binder in the mixture.

The Sasobit dose was 1.5%, the SonneWarmix dose was 1% and the Evotherm dose was 0.5%. To introduce the WMA technologies into the mixtures, a crater was formed in the heated blended aggregate and the required amount of heated binder was then added. Immediately following the addition of the binder, the required amount of the WMA technology was added to the binder and stirred until well blended. Finally, the binder and aggregates were mixed by hand and then subsequently mixed using a mechanical mixer.

To measure the effect of aging temperature and aging time on the moisture characteristics of these WMA mixtures, loose mixtures were aged at three aging temperatures and three aging periods prior to compaction. Based on the binder viscosity for the control mixture, the aging temperature was 146ºC (295ºF). For the mixtures in this study, aging temperatures of 146ºC (295ºF), 129ºC (265ºF) and 113ºC (235ºF) were used. The lower aging temperatures represented a 17ºC (30ºF) and 33ºC (60ºF) temperature reduction from the viscosity-based control aging temperature. At each temperature, the mixtures were aged for three different periods: two, four and eight hours. The parameters measured to evaluate the moisture characteristics of the mixtures included Stripping Inflection Point (SIP) in the HWTD and E* stiffness ratio (ESR). Mixtures that failed the HWTD were modified with a liquid anti-stripping additive and hydrated lime, and were then retested in the HWTD. The results from the HWTD were used as a guide to select which mixtures should be tested further. The tests conducted in this study were selected to represent various methods that have been used in the past to assess various mechanisms and manifestations associated with moisture damage. These mechanisms include an increase in permanent deformation due to the mechanical effects of water flow on the mixture, reduction in mixture stiffness, loss of cohesive and adhesive bonds in the mixture, an increase in dissipated energy and reduction in resistance to fracture.

Figure 1: Experimental Plan to Determine the Effect of Temperature and Time on the Moisture Susceptibility of WMA Mixtures

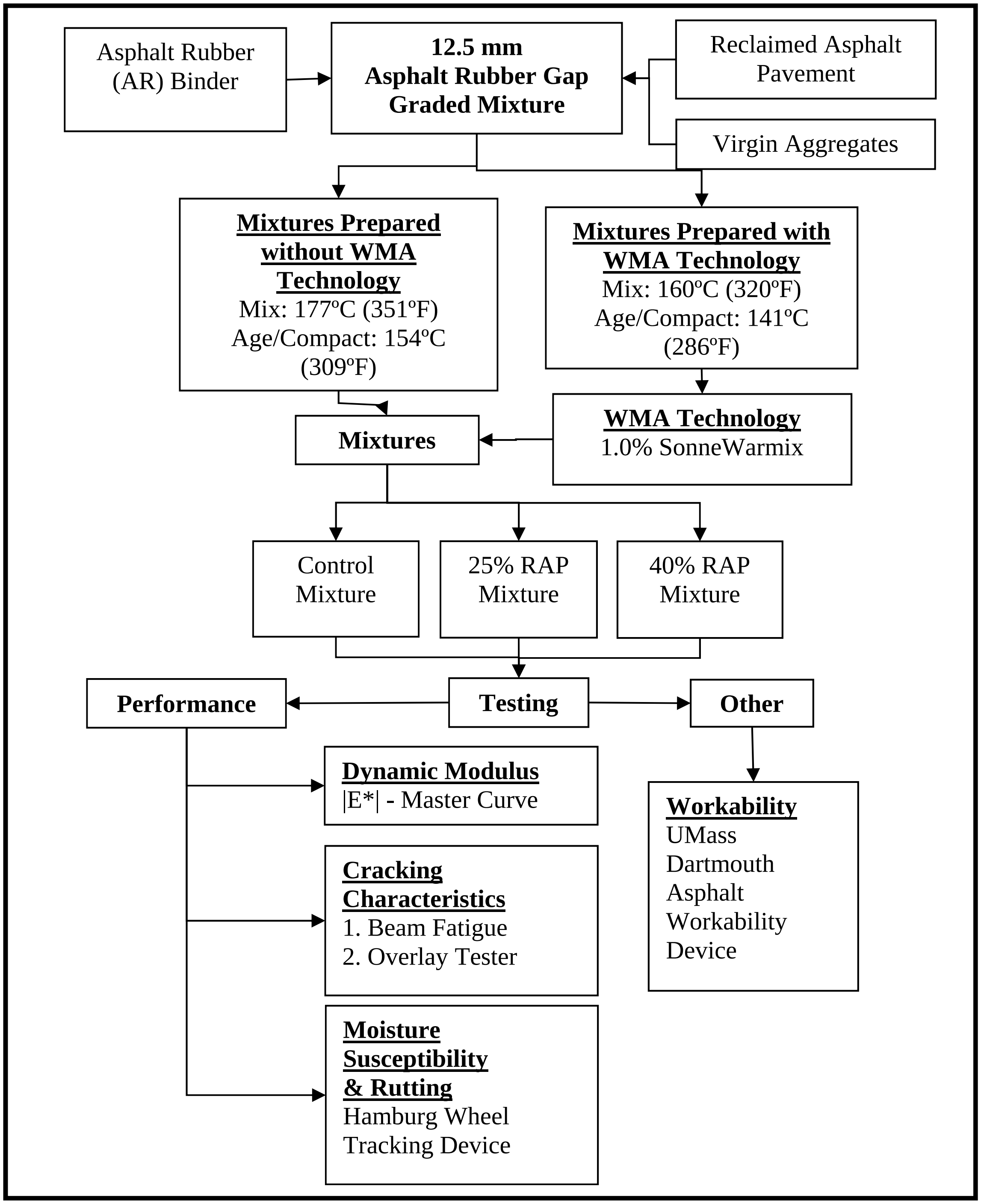


3.2 Performance Characteristics of Asphalt Rubber Gap Graded Mixtures with RAP and/or WMA

In order to achieve the objectives of this study, an experimental plan was developed as shown in Figure 2. The plan consisted of designing a 12.5 mm Nominal Maximum Aggregate Size (NMAS) ARGG control mixture in accordance with Arizona Department of Transportation (ADOT) materials specification Section 413 “Asphaltic Concrete (Asphalt-Rubber)” (*31*). This specification was followed, as it is one of few specifications for ARGG that is being used by multiple state agencies. An ARGG mixture was designed without RAP, in conformance with this specification, and was referred to as the control mixture. The control mixture was then re-designed with 25% RAP and 40% RAP. The aggregate gradations requirements and target volumetric for the control and RAP mixtures were the same. All mixtures were then subsequently verified with the inclusion of a WMA technology.

Overall, a total of six mixtures were evaluated in this study. The effect of RAP and WMA on the performance of the mixtures was measured in terms of stiffness, fatigue cracking, reflective cracking, rutting and moisture damage. Emphasis was placed on the fatigue cracking analysis, as the mixture durability may have been negatively impacted due to poor blending of the RAP and virgin binders, thus yielding mixtures with hardened aged asphalt binder. Also, mixtures with asphalt rubber and high RAP content may be less workable and more difficult to compact due to the aged binder in the RAP. It has been reported that the workability of such mixtures can be improved by the incorporation of a WMA technology to the mixture (*32*). Accordingly, the effect of WMA on the workability of the ARGG with RAP mixtures used in this study was evaluated.

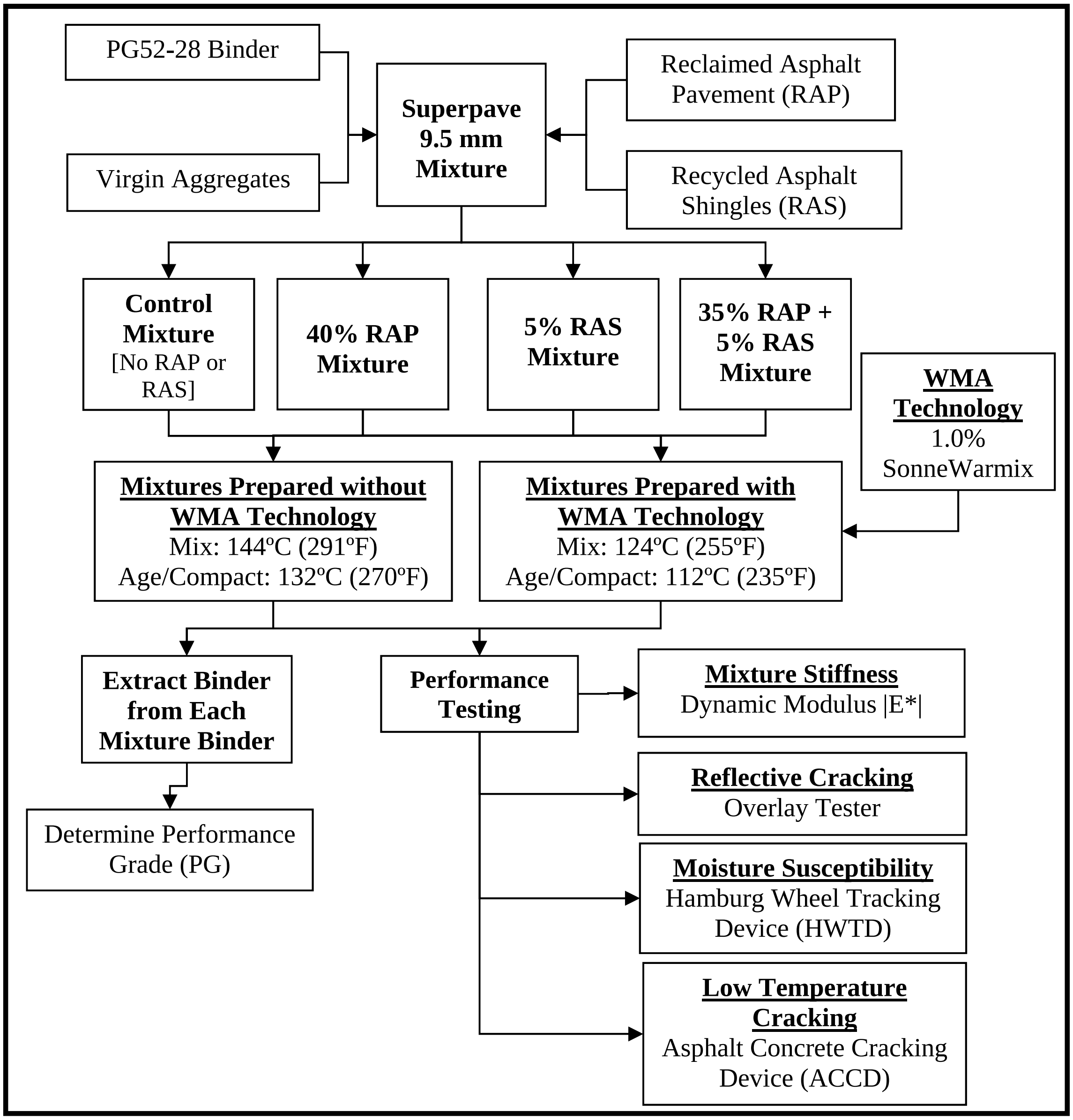
Figure 2: Experimental Plan to Determine the Performance Characteristics of Asphalt Rubber Gap Graded Mixtures with RAP and/or WMA



3.3 Thin Lift Mixtures with High RAP, RAS, and/or WMA for Pavement Preservation

In order to achieve the objectives of this study, an experimental plan was developed as shown in Figure 3. The plan consisted of designing a Superpave 9.5 mm control mixture, which was redesigned by incorporating RAP, RAS and a WMA technology both individually and collectively. The stiffness, low temperature cracking, reflective cracking and moisture susceptibility of the mixtures were measured to evaluate the effect of RAP, RAS and WMA on the mixture performance as compared to the control mixture.

Figure 3: Experimental Plan for Evaluating Thin Lift Mixtures with High RAP, RAS, and/or WMA for Pavement Preservation



4.0 Materials & Mixture Design

4.1 Effect of Temperature & Time on the Moisture Susceptibility of WMA Mixtures

4.1.1 Binder

For this study, a PG64-22 asphalt binder from a regional supplier was utilized for all mixture and binder testing. This grade of binder is recommended for the temperatures in southern Massachusetts as determined by the LTPPBind software. The PG of the PG64-22 was determined in accordance with AASHTO R29 "Grading or Verifying the Performance Grade of an Asphalt Binder" and AASHTO M320 "Performance-Graded Asphalt Binder" (*9*). Similarly, the appropriate amount of each WMA technology was blended with the PG64-22 and the resultant binder was subsequently graded to determine the impact of each technology on the PG grade.

4.1.2 Aggregate

The aggregates utilized for this study were from a crushed stone source in Wrentham, Massachusetts (Aggregate Industries). Three different aggregate stockpiles were obtained from the source, including 9.5 mm crushed stone, stone dust and washed sand. Each stockpile was tested to determine the aggregate properties in accordance with AASHTO and ASTM specifications (*9, 16*). These aggregates were then utilized to complete the mixture designs for this study. The results of the aggregate testing are shown in Table 1.

Table 1: WMA Average Aggregate Stockpile Properties

Sieve Size	9.5 mm Stone	Stone Dust	Washed Sand
19.0 mm	100	100	100
12.5 mm	100	100	100
9.5 mm	97.1	100	100
4.75 mm	39.0	99.4	98.6
2.36 mm	6.0	81.6	81.7
1.18 mm	3.1	56.1	56.5
0.600 mm	2.7	38.4	38.1
0.300 mm	2.5	25.3	23.5
0.150 mm	2.3	16.1	12.7
0.075 mm	2.0	11.2	6.6
Specific Gravity, G_{sb}(AASHTO T84/T85)	2.640	2.600	2.631
Absorption, %	0.54	0.77	0.51
Coarse Aggregate Angularity, % (ASTM D4791)	97.0	n/a	n/a
Flat and Elongated Particles, % (ASTM D5821)	3.0	n/a	n/a
Fine Aggregate Angularity, % (AASHTO T304)	n/a	47.2	47.9
Sand Equivalent, % (AASHTO T176)	n/a	73.0	90.0

4.1.3 Anti-Stripping Additives

For selected tests conducted during this study, two anti-stripping additives were utilized. The first additive was hydrated lime, which was added at a dose of 1.0% by weight of the aggregate, as recommended by the contractor that supplied the lime. The second additive was ArrMaz Custom Chemicals XL9000 chemical liquid anti-strip, which was added at a dose of 0.5% by weight of asphalt binder.

4.1.4 Mixture Design

A mixture was developed in accordance with AASHTO M323 “Superpave Volumetric Mix Design” and AASHTO R35 “Superpave Volumetric Design for Hot Mix Asphalt” (*9*). The mixture was designed as a coarse-graded 9.5 mm nominal maximum aggregate size Superpave mixture. The mixture gradation and combined aggregate properties are shown in Table 2.

Table 2: WMA Mixture Gradation and Combined Aggregate Properties

Sieve Size	**9.5 mm Mixture Gradation**	**9.5 mm Superpave Specification Range**
12.5 mm	100	100 min.
9.5 mm	98.6	90-100
4.75 mm	69.1	90 max.
2.36 mm	44.0	32-67
1.18 mm	29.8	-
0.600 mm	20.5	-
0.300 mm	13.5	-
0.150 mm	8.4	-
0.075 mm	5.5	2-10
Coarse Aggregate Angularity, % (ASTM D4791)	97.0	95/90
Flat and Elongated Particles, % (ASTM D5821)	3.0	10 max.
Fine Aggregate Angularity, % (AASHTO T304)	47.6	45 min.
Sand Equivalent, % (AASHTO T176)	81.5	45 min.
Combined Specific Gravity, G_{sb}	2.628	-

The design Equivalent Single Axle Loads (ESALs) for this study was selected as 3 to <30 million. This ESALs level was consistent with high traffic surface course mixtures in New England. The design Superpave gyratory compactive effort for this ESALs level was Ndesign = 100 gyrations.

Volumetric specimens were batched, mixed and short-term aged at the compaction temperature for two hours in accordance with AASHTO R30 “Mixture Conditioning of Hot Mix Asphalt (HMA)” (*9*). After aging, specimens (150 mm diameter) were compacted in the Superpave Gyratory Compactor (SGC) to Ndesign. The mixture was designed to meet the Superpave volumetric requirements for air voids, Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA) and Dust to Binder Ratio. The mixture was designed as close to the VFA range as possible without negatively impacting the other volumetric properties.

Finally, some mixtures incorporating 1.0% hydrated lime were fabricated to be tested in the HWTD. Because the hydrated lime was added by weight of the aggregate, a new mixture design was completed for mixtures containing lime. This resulted in a mixture design with an optimum binder content of 6.0% to achieve the desired volumetric properties. The volumetric properties of the mix design specimens are shown in Table 3.

Table 3: WMA 9.5 mm Superpave Mixture Properties at Ndesign

Properties	Control	Superpave Specification
Binder Content, %	6.2	-
Air Voids, %	3.8	4.0
VMA, %	16.8	15 min.
VFA, %	77.0	73 – 76
Dust to Binder Ratio	0.7	0.6 -1.2

VMA = Voids in Mineral Aggregate
VFA = Voids Filled with Asphalt

4.2 Performance Characteristics of Asphalt Rubber Gap Graded Mixtures with RAP and/or WMA

4.2.1 Asphalt Rubber Binder

An AR binder obtained from a regional asphalt supplier was utilized for all mixture designs. This AR binder was fabricated using a PG58-28 base binder incorporating 17% rubber through a wet process. The AR binder conformed to the requirements of ASTM D 6114 Type II specifications (*16*). Based on the recommendation of the AR binder supplier, the mixing temperature was 177ºC (351ºF) and the compaction temperature was 154ºC (309ºF).

4.2.2 Warm Mix Asphalt Technology

To determine if asphalt rubber mixtures incorporating RAP and WMA technology can be produced and compacted at lower temperatures while maintaining the performance characteristics and workability of the control mixture, a waxed-based WMA technology known as SonneWarmix was used.

SonneWarmix was chosen because it had been previously utilized in numerous field projects in Massachusetts and other New England states. This technology was added at the manufacturer’s recommended dosage rate of 1.0% by weight of total binder (Virgin binder + RAP binder). Mixtures incorporating the WMA were fabricated at lower mixing and compaction temperatures (160ºC [320ºF] and 141ºC [286ºF] respectively) than the control mixture (177ºC [351ºF] and 154ºC [309ºF] respectively) without the technology. These temperatures correspond to the same temperatures that the asphalt rubber supplier has been using when producing similar mixtures with the same WMA technology.

4.2.3 Aggregates and Reclaimed Asphalt Pavement

The virgin aggregates were from a crushed stone source in Wrentham, Massachusetts. Four different aggregate stockpiles were obtained, including 12.5 mm crushed stone, 9.5 mm crushed stone, stone sand and stone dust. Each stockpile was tested to determine the aggregate properties in accordance with AASHTO specifications (*9*). The aggregate properties of each stockpile are shown in Table 4.

The RAP was obtained from the same contractor that supplied the virgin aggregates. The binder content of the RAP was determined by the ignition method in accordance with AASHTO T308 (*9*). The aggregates remaining after ignition were then tested in accordance with AASHTO aggregate test specifications (T11, T27, T84 and T85) in order to determine the gradation and specific gravity of the RAP aggregates. The properties of the RAP are shown in Table 4.

Table 4: ARGG Average Virgin Aggregate and RAP Stockpile Properties

Sieve Size	**12.5 mm**	**9.5 mm**	**Stone Sand**	**Stone Dust**	**RAP**
19.0 mm	100	100	100	100	100
12.5 mm	82.8	99.4	100	100	97.7
9.5 mm	23.9	93.8	100	100	86.3
4.75 mm	1.2	29.7	99.8	99.7	64.3
2.36 mm	1.1	5.2	83.7	83.7	49.4
1.18 mm	1.1	2.8	54.3	57.1	38.3
0.600 mm	1.1	2.3	33.8	38.6	28.6
0.300 mm	1.1	2.1	19.0	24.9	18.6
0.150 mm	0.9	1.8	9.4	15.9	11.4
0.075 mm	0.8	1.5	4.3	10.9	7.7
Bulk Specific Gravity, G_{sb} (AASHTO T84/T85)	2.641	2.642	2.644	2.629	2.638
Absorption, %	0.39	0.43	0.53	0.60	0.76
Binder Content of RAP, % (AASHTO T308) =			4.80		

For this study a 12.5 mm ARGG control mixture was developed in accordance with ADOT materials specification as previously outlined (*31*). The same mixture was redesigned with the incorporation of 25% RAP and 40% RAP. The design mixture gradation and combined aggregate properties for each design are shown in Table 5. Based on the aggregate stockpile used and the amount of fine material in the RAP, it was not possible to design a mixture meeting the gradation requirements for the No. 200 sieve. The mixture gradations were slightly above the 2.5% upper limit for the sieve but were within the specification limitations once the production tolerance was considered (1%). Mixtures specimens were compacted using the SGC with a compactive effort of 75 gyrations. The gyration level corresponded to a design ESALs of 0.3 to <3 million using the Superpave design methodology. Volumetric specimens were batched, mixed and short-term aged at the compaction temperature for two hours in accordance with AASHTO R30 (*9*). After aging, specimens were compacted in the SGC. The volumetric properties for each mixture are shown in Table 6.

Table 5: ARGG Mixture Gradations and Combined Aggregate Properties

Sieve Size	Control	25% RAP	40% RAP	ADOT Specification Section 413 Asphaltic Concrete	ADOT Specification Production Tolerance
19.0 mm	100	100	100	100	±4
12.5 mm	92.6	92.3	92.6	80-100	±4
9.5 mm	65.4	66.2	65.4	65-80	±4
4.75 mm	33.9	33.1	33.9	28-42	±4
2.36 mm	20.3	19.5	20.3	14-22	±3
1.18 mm	13.5	14.2	15.8	-	-
0.600 mm	9.3	10.4	11.5	-	-
0.300 mm	6.2	6.9	7.5	-	-
0.150 mm	4.1	4.3	4.6	-	-
0.075 mm	2.9	3.0	3.1	0-2.5	±1

Table 6: ARGG Mixture Properties

Properties	**Control**	**25% RAP**	**40% RAP**	**Spec.**
Total Binder Content, %	8.00	8.00	7.70	-
Binder from RAP, %	0.00	1.26	1.86	-
Virgin Binder Added, %	8.00	6.74	5.84	-
Air Voids, %	5.80	2.60	3.90	5.5±1.0
Voids in Mineral Aggregate, %	21.90	19.00	18.90	19 min
Voids Filled with Asphalt, %	73.70	86.50	79.70	-
Binder Absorbed, %	0.73	0.86	1.20	0 -1.0
Dust to Binder Ratio	0.40	0.42	0.50	-
Properties	**Control + WMA**	**25% RAP + WMA**	**40% RAP + WMA**	**Spec.**
Total Binder Content, %	8.00	8.00	7.70	-
Binder from RAP, %	0.00	1.26	1.86	-
Virgin Binder Added, %	8.00	6.74	5.84	-
Air Voids, %	5.90	4.70	4.80	5.5±1.0
Voids in Mineral Aggregate, %	22.00	20.90	20.10	19 min.
Voids Filled with Asphalt, %	73.30	78.00	76.30	-
Binder Absorbed, %	0.73	0.77	0.90	0 -1.0
Dust to Binder Ratio	0.40	0.41	0.45	-

The 25% RAP mixture without the WMA technology was the first RAP mixture designed for the study. This mixture exhibited air voids of 2.6%, which was outside of the specification range of 5.5±1.0%. For these mixtures, the dried RAP was placed on the heated virgin aggregate for two hours at the mixing temperature prior to commencement of mixing. The cause of the low air voids was probably the RAP heating time, where two hours was not enough for proper heating of the RAP prior to mixing. Thus, the RAP heating time was increased to four hours for all subsequent RAP mixtures for this study. The increase in the heating time helped to achieve a percent air voids closer to the target of 5.5±1.0%. There was insufficient material to re-fabricate the 25% RAP mixture with the four hours of RAP heating prior to mixing. However, the performance specimen volumetric properties for the 25% RAP mixture with the four-hour heating were consistently within the appropriate air void tolerance.

4.3 Thin Lift Mixtures with High RAP, RAS, and/or WMA for Pavement Preservation

4.3.1 Asphalt Binder

A PG52-28 binder obtained from a local asphalt supplier was utilized for all mixture designs. It was the softest grade available that met the low temperature requirement of a PGXX-28 binder that is typically specified in the Northeast. It was used in an attempt to offset the potential mixture stiffening due to the use of high percentage of RAP and/or RAS in the mixtures. Based on the viscosity of the binder, the mixture mixing temperature was 144ºC (291ºF) and the compaction temperature was 132ºC (270ºF).

4.3.2 Warm Mix Asphalt Technology

A waxed-based WMA technology, SonneWarmix, was utilized in this study. SonneWarmix was chosen because it had been previously utilized in numerous field projects in Massachusetts and other New England states. This technology was added to the selected mixtures at the manufacturer’s recommended dosage rate of 1.0% by weight of total binder (Virgin binder + RAP binder + RAS binder). Mixtures incorporating this technology were fabricated at lower mixing and compaction temperatures (124ºC [255ºF] and 112ºC [235ºF] respectively) than the conventional mixtures without the technology. This was done to determine if the WMA technology could help in producing mixtures with RAP and RAS that are environmentally friendly while retaining or improving the performance of the mixtures.

4.3.3 Aggregates, RAP and RAS

The aggregates utilized were from a crushed stone source in Wrentham, Massachusetts. Four aggregate stockpiles were obtained; including 9.5 mm crushed stone, natural sand, stone sand and stone dust. RAP was obtained from the same contractor. Each aggregate stockpile and the RAP were tested to determine their properties, which are shown in Table 7. An asphalt shingle recycling facility located in Fitchburg, Massachusetts, supplied the RAS. The RAS was pre-consumer (i.e., manufacturer’s waste) and not post-consumer (i.e., tear offs). The properties of the RAS were determined in the same manner as the RAP. The properties of the RAS are shown in Table 7.

Table 7: Thin Lift Average Virgin Aggregate, RAP and RAS Stockpile Properties

Sieve Size	9.5 mm	Natural Sand	Stone Sand	Stone Dust	RAP	RAS
19.0 mm	100	100	100	100	100	100
12.5 mm	99.4	100	100	100	100	100
9.5 mm	93.8	100	100	100	100	100
4.75 mm	29.7	99.7	99.8	99.7	74.1	100
2.36 mm	5.2	98.3	83.7	83.7	57.8	99.1
1.18 mm	2.8	93.3	54.3	57.1	45.5	84.6
0.600 mm	2.3	73.3	33.8	38.6	34.4	65.9
0.300 mm	2.1	29.7	19.0	24.9	22.4	58.7
0.150 mm	1.8	4.8	9.4	15.9	13.5	43.8
0.075 mm	1.5	0.9	4.3	10.9	9.1	26.4
Specific Gravity, G_{sb} (AASHTO T84/T85)	2.642	2.624	2.644	2.629	2.638	2.629
Absorption, %	0.43	0.45	0.53	0.60	0.76	0.60
Binder Content (AASHTO T308) =					5.95%	17.7%

4.3.4 Thin Lift Mixture Design

A control mixture, a 40% RAP mixture, a 5% RAS mixture and a 35% RAP + 5% RAS mixture were designed. These percentages were chosen based on discussions with producers in the state of Massachusetts. Each mixture design was repeated at a lower mixing and compaction temperature using the addition of the WMA technology. All mixtures had the same aggregate gradation. For the 5% RAS mixture, the RAS content was limited to 5%, as this is generally considered the acceptable limit of RAS due to the high stiffness of the RAS binder. Each mixture was developed to meet the requirements for a 9.5 mm Superpave mixture in accordance with AASHTO M323 "Superpave Volumetric Mix Design" and AASHTO R35 "Superpave Volumetric Design for Hot Mix Asphalt" *(9)*. The design gradations for each mixture are shown in Table 8.

Table 8: Thin Lift Mixture Gradations

Sieve Size	Control	40% RAP	5% RAS	35% RAP + 5% RAS	9.5 mm Superpave Specification
19.0 mm	100	100	100	100	-
12.5 mm	99.7	99.8	100	100	100 min.
9.5 mm	97.1	97.8	97.4	98.1	90-100
4.75 mm	66.8	64.5	66.2	66.5	90 max.
2.36 mm	47.8	45.3	45.8	46.6	32-67
1.18 mm	33.5	32.6	33.2	33.9	-
0.600 mm	23.0	22.9	23.4	23.9	-
0.300 mm	13.3	13.6	13.9	14.4	-
0.150 mm	7.1	7.1	7.6	7.5	-
0.075 mm	4.4	4.7	4.6	5.1	2-10

The design ESALs for this project was selected as 0.3 to <3 million, which is consistent with surface course mixtures in New England. The design Superpave gyratory compactive effort for this ESALs level was Ndesign = 75 gyrations. Due to moisture in the RAP, it was air dried until a constant mass was achieved. The RAP was added to heated aggregate two hours prior to adding the binder during the mixing process. Similarly, the RAS was air dried, but only added to heated aggregates five minutes prior to adding the binder. This helped reduce the agglomeration of RAS in the mixture. Also, the binder content for each mixture was verified using the ignition method in accordance with AASHTO T308 "Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method" (9). The volumetric properties for each mixture are shown in Table 9.

Table 9: Thin Lift Mixtures Volumetric Properties

Properties	**Control**	**40% RAP**	**5% RAS**	**35% RAP + 5% RAS**	**9.5 mm Superpave Specification**
Total Binder Content, %	6.0	6.0	6.0	6.0	-
Virgin Binder Added, %	6.0	3.6	5.1	3.0	-
Air Voids, %	3.9	4.2	3.7	4.2	4.0%
VMA, %	16.2	16.1	16.0	15.9	15% min.
VFA, %	76.3	73.8	76.8	73.8	65-78
Dust to Binder Ratio	0.82	0.89	0.86	1.01	0.6-1.2
Properties	**Control + 1% WMA**	**40% RAP + 1% WMA**	**5% RAS + 1% WMA**	**35% RAP + 5% RAS + 1% WMA**	**9.5 mm Superpave Specification**
Binder Content, %	6.0	6.0	6.0	6.0	-
Virgin Binder Added, %	6.0	3.6	5.1	3.0	-
Air Voids, %	3.9	3.8	4.4	4.7	4.0%
VMA, %	16.7	15.7	16.8	16.4	15% min.
VFA, %	76.9	75.7	74.2	71.6	65-78
Dust to Binder Ratio	0.78	0.90	0.84	1.00	0.6-1.2

- Not Applicable
VMA = Voids in Mineral Aggregate
VFA = Voids Filled with Asphalt
WMA = Warm Mix Asphalt Technology (1.0% SonneWarmix by total weight of binder)

4.3.5 Thin Lift Mixture Percent Binder Replacement

Previous research (*15, 33*) has suggested that the amount of RAP allowed in a mixture should be limited by the percent of binder that the RAP binder would replace in the mixture. The percent binder replaced calculation provides a means to estimate how much aged RAP binder can potentially be imparted to the mixture. Under current specifications utilizing RAP content by percent weight of mixture, less or more aged RAP binder is actually being added to the mixture than the target by weight content. This is a result of RAP stockpiles having different binder contents. A mixture developed using the same RAP content by percentage of mixture, but different RAP sources, will not necessarily have the same total RAP binder contribution. A mixture developed with a lower binder content RAP will have less RAP binder in the resultant mixture and vice versa. The percent binder replacement calculation normalizes the RAP content in the mixture with respect to the asphalt content in the RAP and the asphalt content in the mixture. This method assumes 100% blending of the RAP and virgin binder. The means to calculate percent binder replaced is shown in Equation 1.

Equation 1:
$$\text{Binder Replacment}, \% = \frac{(\text{Percent Binder in the RAP}) \times (\text{Percent RAP in Mixture})}{\text{Total Percent Binder in Mixture}}$$

Equation 1 was also used to calculate the percent binder replaced by RAS. For mixtures combining RAP and RAS, the percent binder replaced was determined through summation of the binder replaced for the RAP and RAS. The amount of virgin binder replaced for each mixture is shown in Table 10. Table 10 illustrates that the binder from the high RAP content and RAS will replace a significant amount of the design binder content if 100% blending of the aged and virgin binders occurs.

Table 10: Thin Lift Mixtures Percent Binder Replacement for Each Mixture

	40% RAP	**35% RAP + 5% RAS**	**5% RAS**
Target Mixture Binder Content, %	6.0	6.0	6.0
Average Mixture Binder Content, % (By Ignition)	5.97	5.96	6.06
Binder in RAP, %	5.95	5.95	5.95
RAP in Mixture by Weight, %	40	35	0
Binder in RAS, %	17.7	17.7	17.7
RAS in Mixture by Weight, %	0	5	5
RAP Binder in Mixture, %	2.38	2.08	0
RAS Binder in Mixture, %	0	0.89	0.89
Total Recycled Binder in Mixture, %	2.38	2.97	0.89
Virgin Binder Replaced with Recycled Binder	39.9%	49.8%	14.7%
	40% RAP + 1% WMA	**35% RAP + 5% RAS + 1% WMA**	**5% RAS + 1% WMA**
Target Mixture Binder Content, %	6.0	6.00	6.0
Average Mixture Binder Content, % (By Ignition)	6.16	6.23	6.14
Binder in RAP, %	5.95	5.95	5.95
RAP in Mixture by Weight, %	40	35	0
Binder in RAS, %	17.7	17.7	17.7
RAS in Mixture by Weight, %	0	5	5
RAP Binder in Mixture, %	2.38	2.08	0
RAS Binder in Mixture, %	0	0.89	0.89
Total Recycled Binder in Mixture, %	2.38	2.97	0.89
Virgin Binder Replaced with Recycled Binder	38.6%	47.7%	14.5%

This page left intentionally blank.

5.0 Evaluation of Mixture Performance

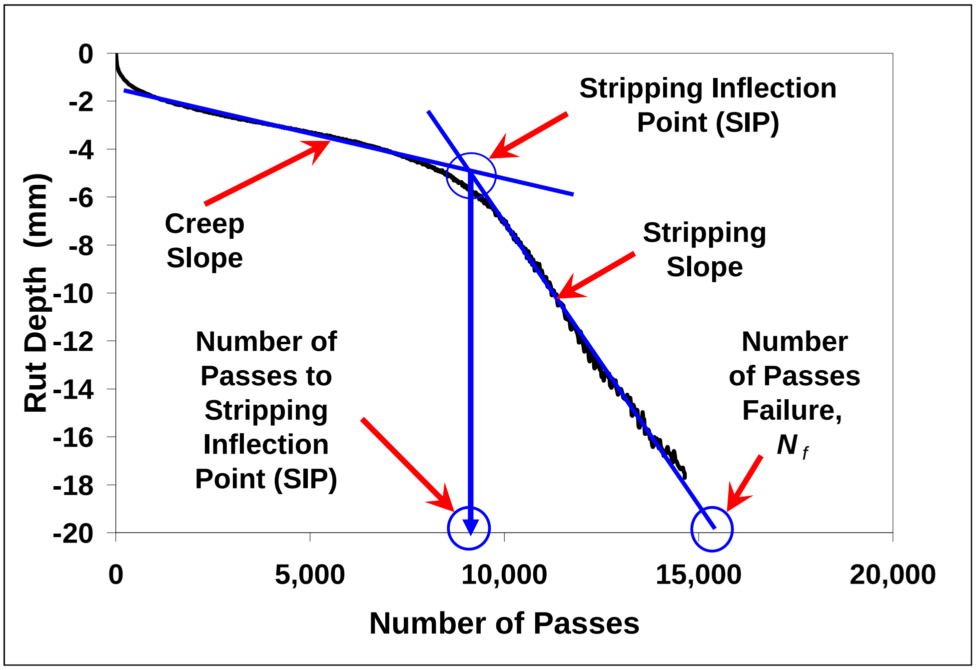
5.1 Effect of Temperature & Time on the Moisture Susceptibility of WMA Mixtures

5.1.1 Moisture Susceptibility - Hamburg Wheel Tracking Device (HWTD)

To evaluate the moisture susceptibility of each mixture, testing was conducted in accordance with AASHTO T324 "Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)" (*9*). In this test a mixture is submerged in water heated to 50°C (122°F) and subjected to repeated loading from a 705N (158 lb) solid steel wheel with a diameter of 204 mm (8 in) and a width of 47 mm (1.9 in). The test specimens may be in the form of a rectangular slab or two gyratory compactor specimens that have had the end thickness trimmed on one side of each specimen so that the two specimens may be butted together at the trimmed faces. This process yields one larger continuous specimen. During the test, as the steel wheel loads the specimen, the corresponding rut depths at specific points along the specimen are automatically and continuously measured with a 0.01 mm accurate linear variable differential transducer (LVDT) and recorded.

A standard test length is approximately 20,000 passes of the loaded wheel. The data collected during the test is customarily reported as rut depth versus number of wheel passes. Figure 4 provides an illustration of the typical output produced from the test, including the test parameters. Generally, the data analysis for this test includes the creep slope, SIP and stripping slope. The SIP is the number of passes at the intersection of the creep slope and stripping slope, which is where the stripping starts to dominate performance. The stripping slope is a measure of the accumulation of rutting primarily from moisture damage, and is the number of passes required to create a 1 mm rut depth after the SIP (*34*). For each mixture in this the study, the SIP was determined.

Figure 4: Output of HWTD Testing



The HWTD results are presented in Tables 11 through 13. The HWTD results showed that aging temperature and time had a dramatic effect on the moisture susceptibility of the control and WMA mixtures. Higher temperature coupled with a longer aging period led to a higher number of cycles to reach a SIP. At 146ºC (295ºF) and eight hours aging, the control and the WMA mixtures had no SIP. At 129ºC (265ºF) and eight hours aging, the Evotherm, Sasobit and Sonnewarmix had no SIP, while the control required either the chemical anti-strip agent or the lime to reach the same performance. Advera was able to meet the same performance with only the addition of lime.

Table 11: WMA HWTD Stripping Inflection Points - 2 Hour Aging

	Aging Temperature		
	146ºC (295ºF)	129ºC (265ºF)	113ºC (235ºF)
Mix Type	**No Anti-Strip or Lime**		
Control	12,600	5,800	4,300
Advera	9,700	3,100	2,300
Evotherm	14,200	7,900	4,500
Sasobit	13,700	6,800	3,700
SonneWarmix	10,300	4,900	2,300
Mix Type	**With Liquid Anti-Strip**		
Control	NT	9,500	5,900
Advera	NT	7,900	3,000
Evotherm	NT	8,200	4,500
Sasobit	NT	13,000	3,700
SonneWarmix	NT	5,100	6,500

NT: These mixtures were not tested.

Table 12: WMA HWTD Stripping Inflection Points - 4 Hour Aging

	Aging Temperature		
	146ºC (295ºF)	**129ºC (265ºF)**	**113ºC (235ºF)**
Mix Type	**No Anti-Strip or Lime**		
Control	16,500	9,000	7,500
Advera	17,500	5,500	3,400
Evotherm	20,000	16,900	8,900
Sasobit	20,000	16,800	7,200
SonneWarmix	16,200	13,400	4,300
Mix Type	**With Liquid Anti-Strip**		
Control	NT	13,700	6,500
Advera	NT	9,400	4,200
Evotherm	NT	12,300	8,800
Sasobit	NT	17,200	6,500
SonneWarmix	NT	15,900	9,800
Mix Type	**With Hydrated Lime**		
Control	NT	15,600	10,500
Advera	NT	11,200	6,900
Evotherm	NT	15,400	5,700
Sasobit	NT	17,000	9,800
SonneWarmix	NT	16,600	7,400

Table 13: WMA HWTD Stripping Inflection Points - 8 Hour Aging

	Aging Temperature		
	146ºC (295ºF)	**129ºC (265ºF)**	**113ºC (235ºF)**
Mix Type	**No Anti-Strip or Lime**		
Control	20,000	16,400	8,800
Advera	20,000	10,600	4,600
Evotherm	20,000	20,000	13,100
Sasobit	20,000	20,000	9,100
SonneWarmix	20,000	20,000	9,100
Mix Type	**With Liquid Anti-Strip**		
Control	NT	20,000	16,000
Advera	NT	13,100	7,200
Evotherm	NT	NT	10,800
Sasobit	NT	NT	11,200
SonneWarmix	NT	NT	8,600
Mix Type	**With Hydrated Lime**		
Control	NT	20,000	13,100
Advera	NT	20,000	8,500
Evotherm	NT	NT	9,500
Sasobit	NT	NT	15,500
SonneWarmix	NT	NT	10,500

All the mixtures reached 20,000 cycles with no SIP at the highest temperature 146ºC (295ºF) and the longest aging time (eight hours). This was expected because greater aging occurs at the higher temperatures. However, WMA mixtures are typically placed at lower temperatures around 113ºC (235ºF). The HWTD data indicated that none of the mixtures tested (without anti-strip) passed the tests at any aging times associated with the 113ºC (235ºF) aging temperature.

5.1.2 Dynamic Modulus |E*| Ratio

Dynamic modulus (|E*|) of conditioned and dry specimens were determined in accordance with AASHTO TP79-09 "Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) using the Asphalt Mixture Performance Tester (AMPT)." Based on previous studies, the ESR of conditioned to dry dynamic modulus was utilized to evaluate the moisture susceptibility of HMA mixtures and showed good correlation with field data (*35*). Furthermore, a research study (*36*) was conducted to assess if the E* test can be used to evaluate the moisture susceptibility of HMA mixtures, as a replacement test property to the indirect tensile strength ratio in AASHTO T283. AASHTO T283 is considered the most widely used test to evaluate the stripping potential of HMA mixtures. Tensile strength ratio (TSR) of conditioned to dry specimens is measured; generally a ratio of 0.7 to 0.8 would be considered acceptable. Because the E* test is a nondestructive test, unlike the indirect tensile strength test, the advantage would be that the same specimens could be tested before and after conditioning. The study found that there was no statistically significant difference between the TSR and ESR, and concluded that the ESR can potentially replace the TSR to assess moisture susceptibility of HMA mixtures (*36*).

Two specimens were prepared for each mixture. These specimens were first tested dry to determine the dynamic modulus at loading frequencies of 10 Hz, 1 Hz and 0.1 Hz at 20ºC (68ºF). Next, the same specimens were conditioned by being subjected to vacuum saturation, an initial soak cycle, a freeze cycle, a heating cycle and a second ambient soak cycle prior to being tested again for their dynamic modulus. The ratio of the dynamic modulus values of the conditioned to the dry specimens was then calculated and used to indicate the moisture susceptibility of the mixtures. A summary of specimen preparation, conditioning process and the ESR test and calculations are described below.

After mixing the binder and aggregate, the loose mix was oven-aged in a forced draft oven at the different aging periods and aging temperatures. After aging, the mixtures were compacted using the SGC. The compacted specimens were allowed to cool to room temperature prior to cutting and coring the final dynamic modulus test specimen. The target air voids for the cored specimens were 7 ± 1%.

A modified AASHTO T283 conditioning process was utilized. This procedure was developed under previous research (*37*) to reduce the conditioning time required by AASHTO T283. The major differences between the two procedures were the vacuum saturation time, length of freezing time at -17.7ºC (0ºF) and length of time in the heated water bath.

AASHTO T283 requires iterative manipulation of the vacuum saturation procedure until a degree of saturation of 70-80% is obtained. Specimens exhibiting over 80% saturation must be discarded. Next, the specimens are sealed in plastic and placed inside of a plastic bag along with 10 mL of water at 25°C (77°F) and frozen at -18°C (0°F) for 16 hours. The specimens are removed from the freeze cycle and placed in a water bath at 60°C (140°F) for 24 hours. Finally, the specimens are placed into a water bath at 25°C (77°F) for a two-hour ambient soak prior to further testing or additional freeze-thaw cycles.

The conditioning process utilized in the modified procedure involves vacuum saturating the specimens under 25.4 cm (10 in) of mercury for 30 minutes, in water with an initial temperature of 25°C (77°F) without determination of the saturation level. After thirty minutes of saturation, the vacuum is removed and the specimens are allowed to soak for an additional ten minutes. The specimens are then sealed in plastic and placed inside of a plastic bag along with 10 mL of water at 25°C (77°F). The specimens are frozen in an environmental chamber set at -18°C (0°F) for four hours (the freeze period begins once the specimens reach -18°C). After the freeze cycle the specimens are removed from the plastic bag and seal and placed directly into a water bath at 60°C (140°F) for 16 hours. This cycle begins with the end of a typical workday and concludes with the start of the following morning. The specimens are then placed into a water bath at 25°C (77°F) for a two-hour ambient soak. The specimens are then tested to determine their conditioned dynamic modulus. It should be noted that initial test specimens conditioned in the 60°C (140°F) water bath were too soft to handle. The specimens were placed on their side to fit into the water bath, which may have contributed to the damage that appeared. Thus, the heat cycle conditioning temperature was changed to 40ºC (104ºF), which coincided with the highest dynamic modulus test temperature recommended for mixtures fabricated with PG64-XX binders. The previously damaged specimens were discarded and replicates were fabricated and conditioned at 40ºC (104ºF).

For the E* testing, the mixtures were aged at four and eight hours and the aging temperatures were 129ºC (265°F) and113ºC (235°F). The two-hour aging period and the 146.1ºC (295ºF) aging temperature were eliminated.

Tables 14 and 15 show the E* dry (unconditioned) and wet (condition) and also the ESR of conditioned to dry specimens. At 146.1ºC (295ºF) aging temperature and aging periods of four and eight hours, only the mixture with Advera at 0.1 Hz and 1 Hz had a marginally lower ratio than 70%. At 113ºC (235ºF) aging temperature and aging periods of four and eight hours, all mixtures had an ESR ratio greater than 80%, except for the control mixture after eight hours aging. The control mixture had a ratio marginally lower than 80% at the 10 Hz frequency and between 72% and 74% at 0.1 Hz and 1 Hz respectively. Generally, the WMA mixtures had an ESR ratio higher at the 113ºC (235ºF) at both aging periods relative to the 129ºC (265ºF). It should also be noted that the mixtures with Advera and Evotherm had a substantial increase in their ESR at 113ºC (235ºF) in comparison to 129ºC (265ºF). The reason for that increase is unknown and will require further investigation. Also, it is interesting to note that at a temperature of 113ºC (235ºF) and an aging period of 8 hours, all of the WMA mixtures performed better than the control.

A three way analysis of variance (ANOVA) was performed using the statistical package SPSS to determine the effect of aging temperatures, aging periods, WMA type and the interaction among those variables on ESR. Based on the output, the aging temperatures, aging periods, type of WMA and the interaction among aging temperatures and aging periods did have a significant effect on the ESR.

Table 14: WMA Dynamic Modulus Data for 129ºC (265ºF) Aging

Mixture	Aging Temp.	Aging Time (hrs.)	Loading Freq.	Average E* (ksi) DRY	Average E* (ksi) COND	ESR Ratio
Control	129ºC	4	10 Hz	600.2	599.7	99.9
			1 Hz	303.1	305.7	100.8
			0.1 Hz	141.6	143.1	101.0
Advera	129ºC	4	10 Hz	731.4	538.8	73.7
			1 Hz	372.7	253.3	68.0
			0.1 Hz	161.6	104.6	64.8
Evotherm	129ºC	4	10 Hz	603.4	456.7	75.7
			1 Hz	288.8	204.9	70.9
			0.1 Hz	118.6	83.0	70.0
Sasobit	129ºC	4	10 Hz	774.0	655.8	84.7
			1 Hz	411.2	335.4	81.6
			0.1 Hz	193.6	156.1	80.6
SonneWarmix	129ºC	4	10 Hz	645.9	550.1	85.2
			1 Hz	326.9	260.8	79.8
			0.1 Hz	142.4	110.7	77.7
Control	129ºC	8	10 Hz	670.9	653.8	97.4
			1 Hz	371.7	352.3	94.8
			0.1 Hz	187.0	174.9	93.6
Advera	129ºC	8	10 Hz	761.7	549.4	72.1
			1 Hz	400.6	259.9	64.9
			0.1 Hz	182.5	112.3	61.5
Evotherm	129ºC	8	10 Hz	645.1	510.4	79.1
			1 Hz	340.8	252.1	74.0
			0.1 Hz	160.1	114.4	71.4
Sasobit	129ºC	8	10 Hz	746.5	706.8	94.7
			1 Hz	422.7	388.3	91.9
			0.1 Hz	220.0	197.8	89.9
SonneWarmix	129ºC	8	10 Hz	755.9	657.7	87.0
			1 Hz	404.4	340.0	84.1
			0.1 Hz	193.3	158.8	82.2

Table 15: WMA Dynamic Modulus Data for 113ºC (235ºF) Aging

Mixture	Aging Temp.	Aging Time (hrs.)	Loading Freq.	Average E* (ksi) DRY	Average E* (ksi) COND	ESR Ratio
Control	113ºC	4	10 Hz	562.5	502.9	89.4
			1 Hz	254.3	226.9	89.2
			0.1 Hz	98.5	88.5	89.8
Advera	113ºC	4	10 Hz	569.8	575.4	101.0
			1 Hz	259.2	264.1	101.9
			0.1 Hz	103.3	105.3	102.0
Evotherm	113ºC	4	10 Hz	528.2	558.5	105.8
			1 Hz	235.8	248.6	105.4
			0.1 Hz	90.9	97.4	107.1
Sasobit	113ºC	4	10 Hz	675.8	614.3	90.9
			1 Hz	335.7	299.2	89.1
			0.1 Hz	142.9	126.9	88.8
SonneWarmix	113ºC	4	10 Hz	647.2	601.5	92.9
			1 Hz	294.0	276.6	94.1
			0.1 Hz	116.7	110.0	94.2
Control	113ºC	8	10 Hz	622.7	491.4	78.9
			1 Hz	301.5	221.1	73.3
			0.1 Hz	123.7	88.6	71.7
Advera	113ºC	8	10 Hz	613.9	588.6	95.9
			1 Hz	295.4	276.9	93.7
			0.1 Hz	120.9	113.3	93.7
Evotherm	113ºC	8	10 Hz	560.0	509.4	91.0
			1 Hz	259.5	227.7	87.7
			0.1 Hz	103.9	90.9	87.5
Sasobit	113ºC	8	10 Hz	623.2	562.4	90.2
			1 Hz	316.5	278.3	87.9
			0.1 Hz	141.9	123.4	87.0
SonneWarmix	113ºC	8	10 Hz	596.5	535.0	89.7
			1 Hz	284.2	250.6	88.2
			0.1 Hz	119.0	105.5	88.7

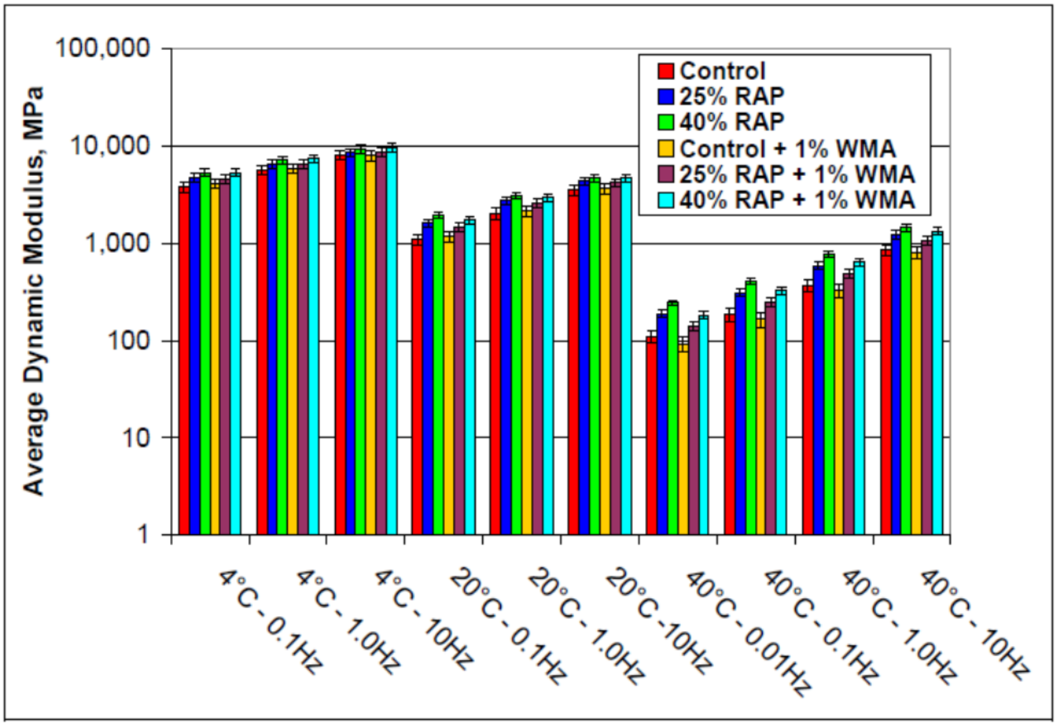
5.2 Performance Characteristics of Asphalt Rubber Gap Graded Mixtures with RAP and/or WMA

5.2.1 Stiffness - Dynamic Modulus

Complex dynamic modulus |E*| testing was conducted to determine changes in mixture stiffness due to the incorporation of RAP and/or the WMA technology. In order to determine the dynamic modulus, test specimens were placed in the Asphalt Mixture Performance Tester (AMPT) device and subjected to a sinusoidal (haversine) axial compressive stress at the different temperatures and frequencies. The resultant recoverable axial strain (peak-to-peak) was measured. From this data the dynamic modulus was calculated.

Replicate dynamic modulus specimens were fabricated in the SGC for each mixture. Specimens incorporating WMA technology were produced at the lower mixing and compaction temperatures noted previously. All specimens were aged for four hours at the compaction temperature in a loose state prior to compaction. Each specimen was subsequently prepared for dynamic modulus testing in accordance with AASHTO PP60 “Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor” (*30*). The final test specimens had an air void content of 7.0 ± 1.0%. Dynamic modulus testing was conducted in accordance with TP62 “Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)” (*30*). Each specimen was tested at temperatures of 4ºC, 20ºC, and 40ºC (39°F, 68°F and 104°F) and loading frequencies of 10 Hz, 1 Hz, 0.1 Hz and 0.01 Hz (40°C only). Figure 5 shows the results of the dynamic modulus testing for all the mixtures. The error bars shown on Figure 5 indicate the 95% confidence interval. Thus, error bars that overlap indicate that the modulus values are not significantly different.

Figure 5: ARGG Dynamic Modulus Comparison - All Mixtures (20ºC reference temperature)



The mixture master curves for each mixture were then developed from the dynamic modulus data in accordance with AASHTO PP61 and AASHTO PP62 "Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA)" (*30*) at a reference temperature of 20ºC (68ºF). Figures 6 and 7 show the mixture master curves created from the dynamic modulus testing data.

Examination of the dynamic modulus and master curves data showed similar results. First, the moduli of the mixtures were not statistically significantly different at the low test temperature of 4ºC at all frequencies tested. This is represented in the master curves by the curves overlapping on the right side of the graph. Second, the master curves indicated that the addition of the 25% or 40% RAP to the control mixture increased the mixture stiffness at the intermediate and high test temperatures. Figure 5 showed that there was a significant increase in the stiffness at 20°C and 40°C (68ºF and 104ºF), however, not at all frequencies.

Figure 6: ARGG Mixture Master Curve Comparison - WMA Technology Mixtures (20°C Reference Temperature)

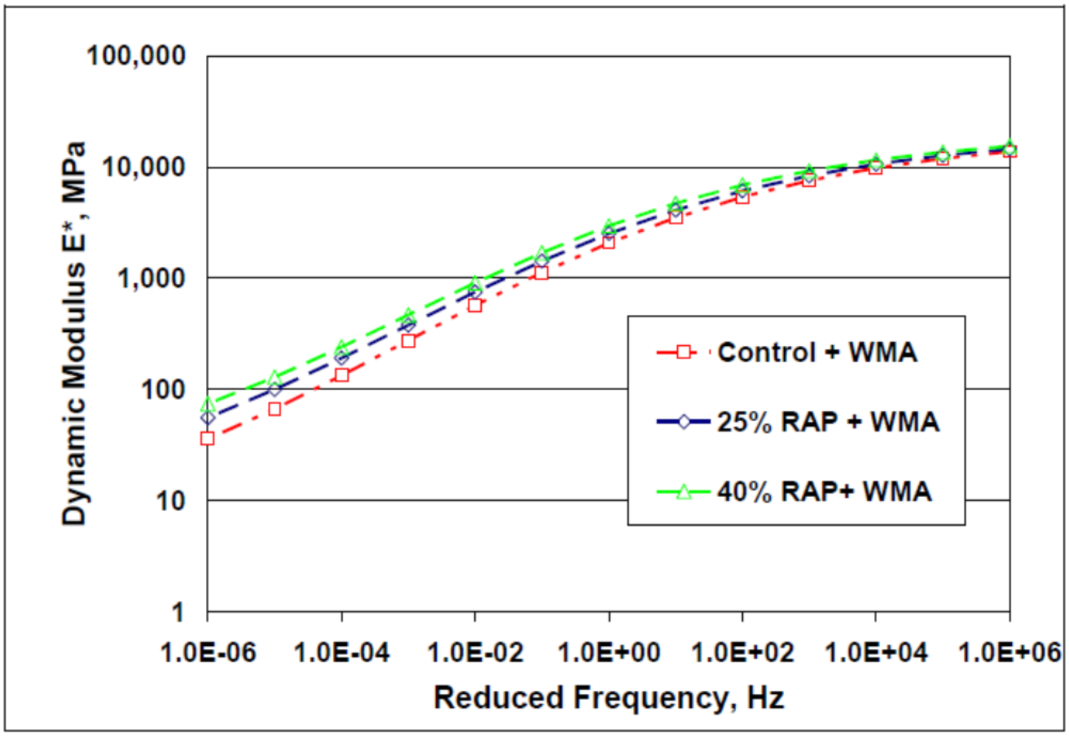
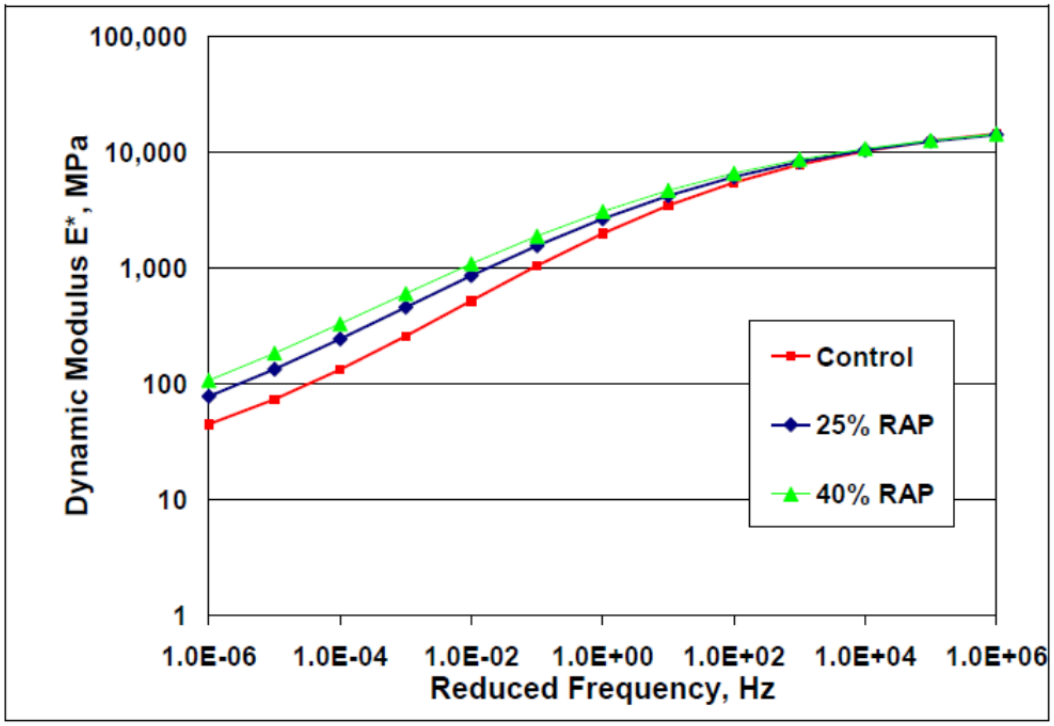


Figure 7: ARGG Mixture Master Curve Comparison – Mixtures without WMA Technology (20°C Reference Temperature)



The same observation held true when comparing the control mixture incorporating the WMA technology to the same mixture incorporating both levels of RAP. Comparison of the dynamic modulus and master curve data for the same mixtures with and without the WMA technology suggests that the control mixture and control mixture with the WMA technology exhibited similar stiffness. For the remaining mixtures, in general, there was a decrease in the measure of mixture stiffness for the mixtures incorporating the WMA technology, although this difference was not always significant. This occurrence may be a result of less aging due to reduced mixing and compaction (aging) temperatures associated with the mixtures incorporating the WMA technology.

Overall, the $|E^*|$ data indicated that addition of RAP to the control mixture resulted in an increase in mixture stiffness. Generally, the stiffness increase in the mixtures containing RAP was mitigated through the use of a WMA technology and corresponding reduced aging temperatures. The addition of the WMA technology to the control mixture had little to no effect on the stiffness of the mixture.

5.2.2 Fatigue Cracking – Four Point Flexural Beam Fatigue Tests

One of the most common and historically used laboratory test procedures to evaluate the fatigue cracking resistance of asphalt mixtures is the four point flexural beam fatigue test. This flexural fatigue test is the only standard test method for fatigue testing of HMA. The typical test protocols for conducting this test are AASHTO T321 “Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending” (*9*) and ASTM D7460 “Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending” (*16*). In order to investigate the relative fatigue performance of the mixtures, the four point bending beam fatigue tests were conducted on the mixtures.

Slabs with dimensions of 150 mm x 180 mm x 450 mm were fabricated for each mixture using the IPC Global Pressbox slab compactor. From each slab, beams with dimensions of 63 mm wide, 50 mm tall and 380 mm long were cut such that the sides had smooth faces. The air voids of the final cut specimens were 7 ± 1%. Beam specimens were conditioned at the test temperature of 15ºC (59°F) for at least two hours prior to testing. The 15ºC (59°F) temperature was selected, as it represents the intermediate temperature for the Northeast.

Each beam fatigue test was conducted in strain control mode at a loading frequency of 10 Hz, applied using a sinusoidal waveform. Specimens were tested at strain levels of 300 microstrain ($\mu\varepsilon$), 500$\mu\varepsilon$, 700$\mu\varepsilon$ and 900$\mu\varepsilon$. The number of cycles to failure was determined by fitting an exponential function to the flexural stiffness versus number of cycles and then evaluating the number of cycles that it took to decrease the initial stiffness by 50%. The results of the testing are shown in Table 16.

Table 16: ARGG Four Point Bending Beam Fatigue Test Results

Number of Cycles to 50% Initial Stiffness, Nf			
Strain Level, με	**Control**	**Control + 25% RAP**	**Control + 40% RAP**
300	> 4,000,000	3,724,655	2,390,822
500	572,541	957,959	289,898
700	544,687	197,625	46,895
900	25,567	24,984	16,255
Number of Cycles to 50% Initial Stiffness, Nf			
Strain Level, με	**Control + WMA**	**Control + 25% RAP + WMA**	**Control + 40% RAP + WMA**
300	2,946,065	1,759,123	1,526,473
500	1,366,510	761,263	234,645
700	196,372	99,901	51,134
900	21,616	27,026	4,697

Generally, the beam fatigue results (in strain control mode) indicated that the resistance to fatigue cracking of the mixtures decreased with the incorporation of higher amounts of RAP. The same trend was also apparent with the incorporation of the WMA technology. Furthermore, at each strain level, the number of cycles to failure for the mixtures dropped when WMA was incorporated. For the 300, 500 and 700με, the drop in the number of cycles to failure when WMA was used was up to 50%. For the mixtures incorporating WMA, the mixing and compaction temperatures were dropped 17°C (63°F) and 13°C (55°F) respectively. This drop in the temperature might have caused the RAP and AR binders not to comingle sufficiently, leading to mixtures with hardened aged asphalt binders. Accordingly, it is recommended to further investigate and develop a procedure to determine the proper allowable drop in temperature for asphalt rubber mixtures that incorporate and/or WMA. Also, the type and dose of the WMA technology may have impacted the cracking resistance of these ARGG mixtures. The dose utilized may not have been enough to realize the full benefit of the WMA technology for the mixtures tested. Further investigations into the optimal type and proper dose of the WMA technology are needed.

5.2.3 Reflective Crack Testing - Overlay Test

In order to evaluate the resistance of the mixtures to reflective cracking, the mixtures were tested in the Texas Overlay Tester (OT). This test is a displacement control test, in which a trimmed gyratory compacted specimen is glued with epoxy onto two plates as shown in Figure 8. The joint between the plates is located at the midpoint of the specimen length. The glued test specimen is placed into the OT device. During testing, one of the plates remains stationary while the other is displaced. The moving plate is pulled, thereby opening the joint between the plates, to a known displacement. The plate is then pushed back to the original location, thereby retuning the joint between the plates to its original position. The opening and closing (displacement) of the joint between the plates occurs in 10 seconds (5 seconds to open the joint and 5 seconds to close the joint). Each opening and closing motion is one cycle. During each cycle the load required to move the plates to the specified displacement is recorded. The device is set to terminate the test when either the load is reduced by a certain percentage from the load recorded for the first cycle, or when the sample reaches a specific number of cycles without reaching the required load reduction.

Figure 8: Specimen Setup in Overlay Test (OT) Device

For this study, the Texas Department of Transportation (TxDOT) specification (Tex-248-F) for testing bituminous mixtures with the OT (*38*) was followed. Specimens were then fabricated in the SGC and then trimmed. The air void level of the trimmed specimens was 7.0±1.0%.

All mixtures for this study were tested with a joint opening (displacement) of 0.06 cm (0.025 in), a test temperature of 15ºC (59ºF) and a failure criteria of 93% reduction in the load measured during the first cycle or 1,200 cycles (whichever occurs first). The average results of the testing are shown in Table 17. Generally, mixtures exhibiting more cycles to failure exhibit more cracking resistance.

Table 17: ARGG Overlay Test Results

Mixture	Average OT Cycles to Failure
Control	351
25% RAP	43
40% RAP	54
Control + 1% WMA	275
25% RAP + 1% WMA	64
40% RAP + 1% WMA	21

Generally, the results from the OT test indicated that the reflective cracking resistance of the mixture decreased with the incorporation of higher amounts of RAP (except for the 40% RAP mixture which performed slightly better than the 25% RAP mixture). The same trend was apparent regardless of whether or not the mixture incorporated WMA technology. This trend was similar to the beam fatigue tests; however, it was opposite to the trend observed in push-pull fatigue tests. The reason for the push-pull tests showing a different trend than the overlay tester and the beam fatigue is unknown.

Comparing the results for the mixtures with and without the WMA technology, a slight improvement in the reflective cracking resistance was noted for the 25% RAP mixture with the WMA technology. Conversely, a slight reduction in the reflective cracking resistance was noted for the control and 40% RAP mixtures. These data agree with the results of the beam fatigue and SCB testing which showed a reduced cracking resistance for the mixture incorporating WMA. Overall, the results indicated that mixtures incorporating RAP were more susceptible to reflective cracking as compared to the control mixtures.

5.2.4 Moisture Susceptibility & Rutting - Hamburg Wheel Tracking Device (HWTD)

The mixtures in this study were evaluated for their rutting and moisture susceptibility to determine if high RAP content and/or the WMA technology had any effect on their performance. It is not known how the use of asphalt rubber, RAP and WMA technology affects mixture moisture susceptibility. Previous research (*27, 39*) has suggested that the addition of a WMA technology may increase the moisture susceptibility of conventional mixtures. Therefore, in order to understand the performance of these mixtures, they were subjected to moisture susceptibility testing in a HWTD.

Testing was conducted in accordance with AASHTO T324 "Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)" (*9*). The test is utilized to determine the failure susceptibility of the mixture due to weakness in the aggregate structure, inadequate binder stiffness or moisture damage (*9*). In this test, the mixture is submerged in heated water (typically 40-50ºC) and subjected to repeated loading from a 705N steel wheel. As the steel wheel loads the specimen, the corresponding rut depth of the specimen is recorded. The rut depth versus numbers of passes of the wheel is plotted to determine the SIP as shown previously in Figure 4. The SIP gives an indication of when the test specimen begins to exhibit stripping (moisture damage). Gyratory specimens were fabricated using the SGC to an air void level of 7.0 ± 2.0% as required by AASHTO T324. Testing was conducted at a test temperature of 50ºC (122ºF). The specimens were tested at a rate of 52 passes per minute after a soak time of 30 minutes at the test temperature. Testing terminated at 20,000 wheel passes or when visible stripping was noted. Table 18 shows the results of the moisture susceptibility testing. All mixtures passed the moisture susceptibility testing in the HWTD and had an average total rut depth at the end of each test less than 1.10 mm (0.043 in).

Table 18: ARGG Moisture Susceptibility and Rutting HWTD Test Results

Mixture	Stripping Inflection Point	Average Rut Depth at 10,000 Cycles (mm)	Average Rut Depth at 20,000 Cycles (mm)
Control	NONE	0.88	1.09
25% RAP	NONE	0.41	0.51
40% RAP	NONE	0.23	0.28
Control + 1% WMA	NONE	0.45	0.65
25% RAP + 1% WMA	NONE	0.14	0.23
40% RAP + 1% WMA	NONE	0.85	0.96

NONE = Mixture passed 20,000 cycle test with no SIP.

5.2.5 Mixture Workability – Asphalt Workability Device (AWD)

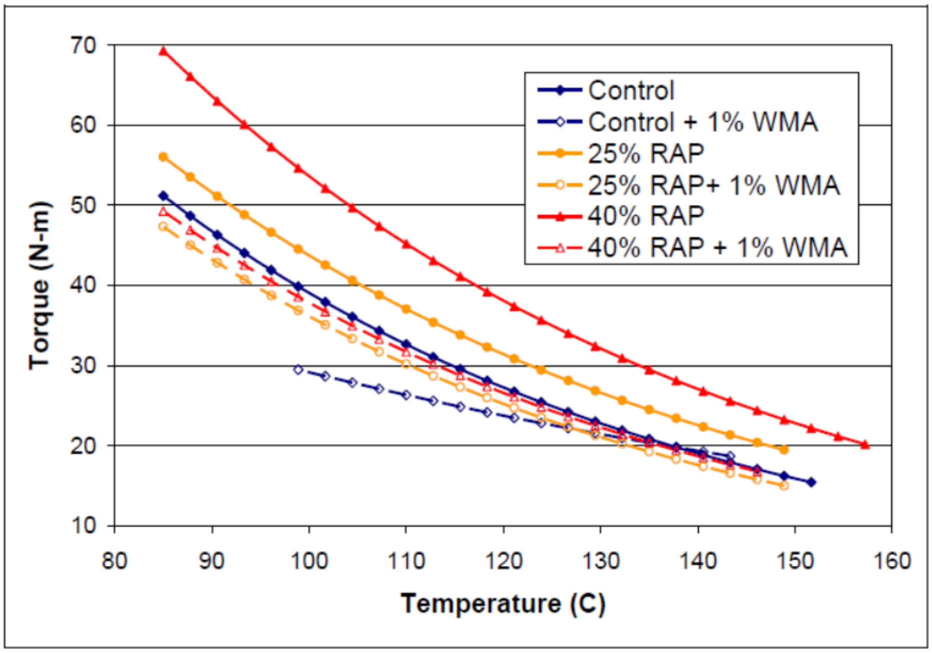
Because of the potential decrease in mixture workability due to the incorporation of RAP in the mixtures, workability evaluations of each of the mixtures were completed. These evaluations were conducted using a HMA workability device developed by the University of Massachusetts Dartmouth Highway Sustainability Research Center (HSRC). This device is known as the Asphalt Workability Device (AWD) and has been used previously to evaluate high percentage RAP mixtures as well as mixtures incorporating WMA additives (*7*,*27*).

The AWD operates on the torque measurement principles that have been previously established (*40*). The AWD rotates the loose HMA mixture at a constant speed (15 rpm for this study) and separately records the resultant torque exerted on a pug mill style paddle shaft embedded into the mixture. Concurrently, the surface and internal temperatures of the mixture are recorded. As the mixture cools in ambient conditions, the torque exerted on the shaft increases, thereby giving an indication of the workability of the mixture at different temperatures.

Each of the mixtures in this study was mixed and aged (four hours) at the mixing and compaction temperatures previously outlined, respectively. After completion of aging, the loose mixture was tested in the AWD.

From the AWD test data for each mixture, a best fit exponential line was fitted to the raw data. This fit line was then utilized to develop a model curve plotted over the AWD test temperature range in which torque and temperature data were collected. This temperature range included the anticipated field placement and compaction temperatures of the mixture. The model curves are shown in Figure 9. Note that mixtures exhibiting lower torque values are considered more workable.

Figure 1: ARGG Workability Test Results



The data for the mixtures without the WMA technology showed the expected trend: as the amount of RAP incorporated into the mixture was increased there was a corresponding decrease in mixture workability (i.e., increase in torque) over the temperatures tested. The mixtures with the WMA technology, for the majority, showed the same trend with the exception of the control with WMA at higher temperatures, which showed marginally higher torque vales than the 25% and 40% RAP mixtures. Overall, comparison of the mixtures with and without WMA indicated that the addition of the WMA greatly improved the workability of the mixtures with RAP to a level similar to the control mixture without RAP and WMA.

5.3 Thin Lift Mixtures with High RAP, RAS, and/or WMA for Pavement Preservation

5.3.1 Stiffness - Dynamic Modulus

Complex dynamic modulus |E*| testing was conducted to determine changes in mixture stiffness due to the incorporation of RAP, RAS and/or the WMA technology. Test specimens were placed in the AMPT device and subjected to a sinusoidal (haversine) axial compressive stress at the different temperatures and frequencies. The resultant recoverable axial strain (peak-to-peak) was measured. From this data the dynamic modulus was calculated.

Three replicate dynamic modulus specimens were fabricated in the SGC for each mixture at a target air void level of 7.0 ± 1.0%. Each specimen was subsequently prepared for dynamic modulus testing in AMPT in accordance with AASHTO TP62 “Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)” (*30*) and the draft specification provided in NCHRP Report 614 “Proposed Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor” (*41*). Each specimen was tested at temperatures of 4°C (39°F), 20°C (68°F), and 35°C(95°F) and loading frequencies of 10 Hz, 1 Hz, 0.1 Hz and 0.01 Hz (35°C only) (*41*). The results of the dynamic modulus testing are shown in Figures 10 through 12.

Figure 10: Dynamic Modulus Comparison – Thin Lift Control & 40% RAP

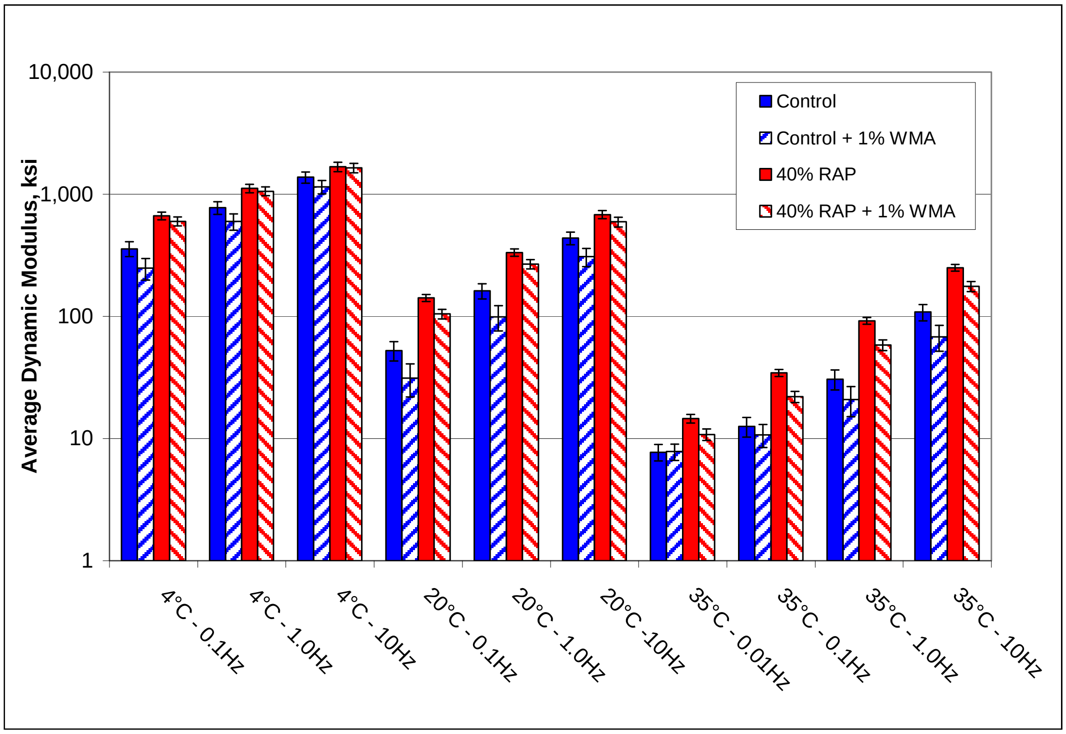


Figure 2: Dynamic Modulus Comparison – Thin Lift Control & 35% RAP + 5% RAS

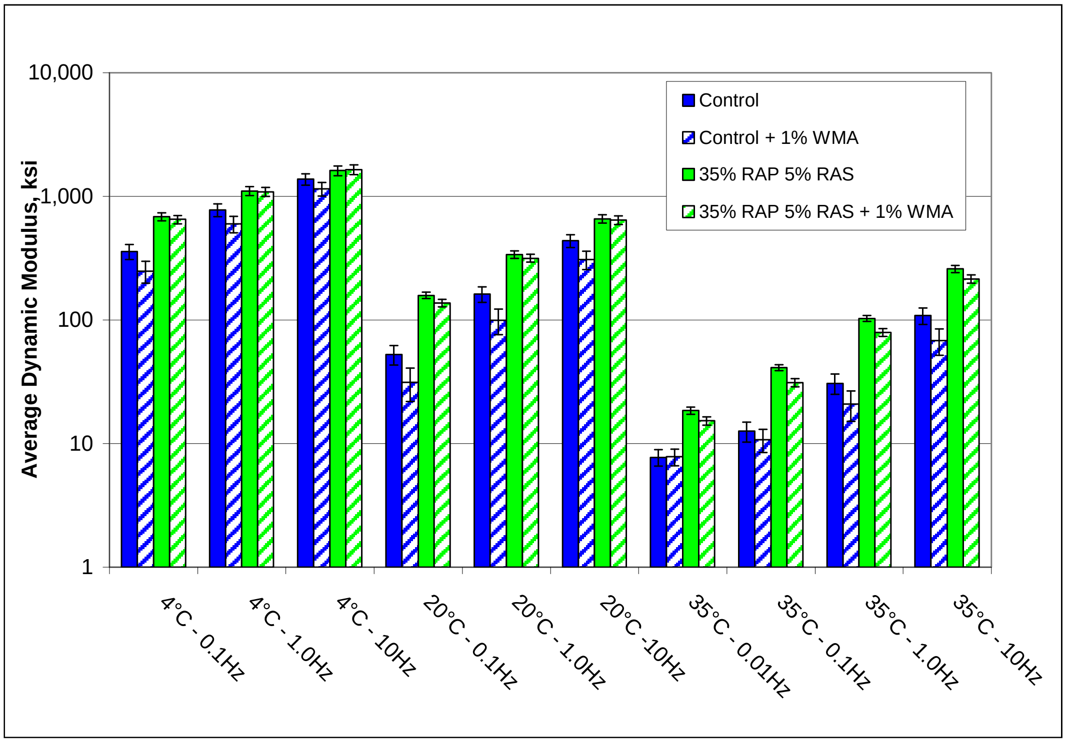
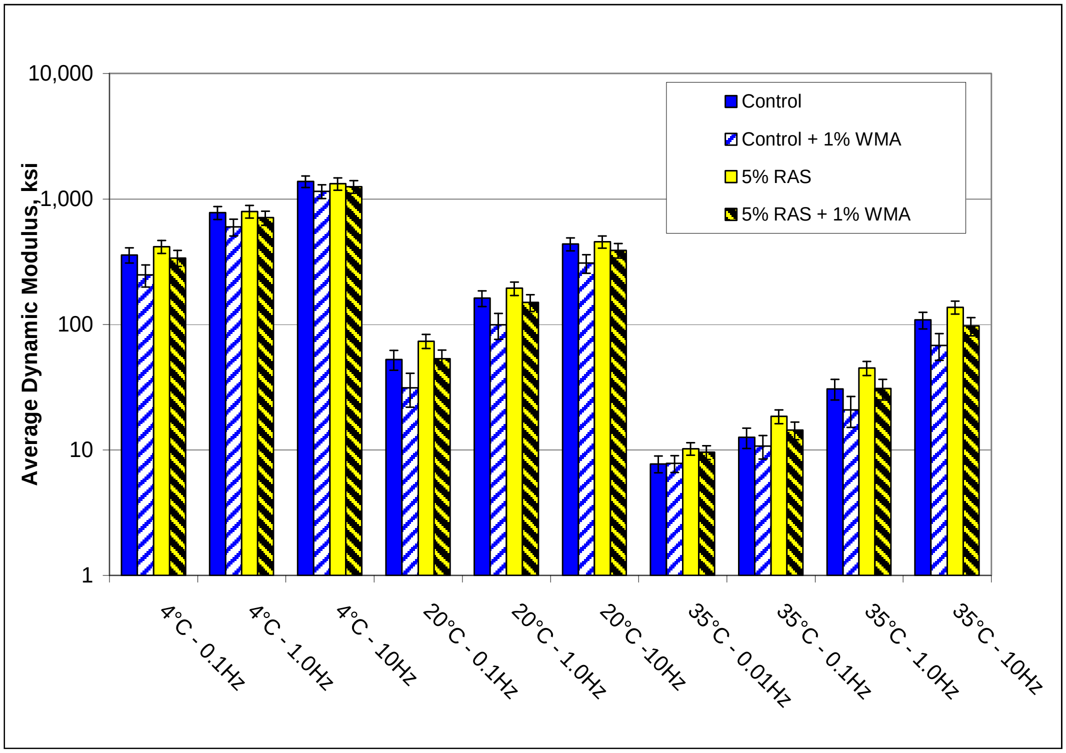


Figure 3: Dynamic Modulus Comparison – Thin Lift Control + 5% RAS



The error bars on the dynamic modulus results shown in Figures 10 through 12 are 95% confidence intervals. Error bars that overlap indicate that the modulus values are not significantly different. The results indicated, for the majority, that the addition of 40% RAP and 35% RAP + 5% RAS increased the mixture stiffness significantly as compared to the control. The 5% RAS mixture did not show a significant increase in mixture stiffness. This may be attributed to a lower percentage of binder being replaced for this mixture. Comparing the results for the mixtures with and without the WMA technology indicated, for all mixtures tested, that the mixture stiffness decreased for the mixtures incorporating the WMA technology. This is likely a result of less aging due to reduced mixing and compaction (aging) temperatures.

5.3.2 Reflective Crack Testing - Overlay Test

Because the mixture stiffness increased due to the increased amount of RAP and/or RAS in the mixtures, these mixtures could be more susceptible to reflective cracking. Therefore, all mixtures were tested for their reflective cracking resistance utilizing the OT.

The OT is a device designed to evaluate the cracking potential of asphalt mixtures. The device applies tension loading to the test specimen while recording load, displacement, temperature and time (*38*). Research studies have been conducted that outline the use of this device for evaluating cracking susceptibility of asphalt mixtures (*42, 43*).

Trimmed gyratory specimens for this test had an air void level of 7.0 ± 2.0% as required in the TxDOT specification Tex-248-F (*38*). Specimens without the WMA technology were mixed at 144ºC (291ºF) and then aged four hours at the compaction temperature of 132ºC (270ºF). All specimens containing the WMA technology were mixed at 124ºC (255ºF) and then aged four hours at the compaction temperature of 112ºC (235ºF).

The TxDOT specification (Tex-248-F) was followed for testing the mixtures with the OT (*38*). Mixtures for this study were tested with a joint opening (displacement) of 0.06 cm (0.025 in), test temperature of 15ºC (59°F) and a failure criteria of 93% reduction in the load measured during the first cycle or 1,200 cycles (whichever occurred first). The results of the testing are shown in Table 19. Generally, mixtures exhibiting more cycles to failure exhibit more cracking resistance.

The OT test results indicated that the mixtures incorporating RAP and/or RAS reduced the reflective cracking resistance of the mixture as compared to the control. The trend was consistent between mixtures with and without the WMA technology as the reflective cracking resistance decreased as the amount of RAP and/or RAS in the mixture increased. Finally, it was shown that mixtures incorporating the WMA technology had less of a reduction in the reflective cracking resistance. This is likely a result of less aging (due to the reduced mixing and compaction temperatures) and therefore less mixture stiffness.

Table 19: Thin Lift Overlay Tests Results

Mixture	Average OT Cycles to Failure	Standard Deviation of OT Results
Control	1,004	278
40% RAP	3	1
5% RAS	308	102
35% RAP + 5% RAS	22	5
Control + 1% WMA	936	373
40% RAP + 1% WMA	143	91
5% RAS + 1% WMA	297	124
35% RAP + 5% RAS + 1% WMA	63	29

5.3.3 Low Temperature Cracking Resistance - Asphalt Concrete Cracking Device (ACCD)

It is generally expected that the resultant binder in mixtures with RAP and/or RAS will be stiffer than the binder in mixtures with no recycled materials. The low temperature cracking resistance of asphalt mixtures is highly dependent on the stiffness of the binder; hence, the mixtures were tested to determine their low temperature cracking characteristics using the Asphalt Concrete Cracking device (ACCD).

The ACCD operates on the basic principle that as the temperature of the specimen is lowered, the asphalt mixture attempts to contract. This contraction is prevented by the presence of the ACCD ring, which causes tensile stress in the sample and corresponding compression in the ACCD ring. This stress continues to accumulate until the specimen breaks. A plot of data collected during the tests (strain resulting from the thermal tensile stress on the ACCD ring versus temperature) is utilized to determine the cracking temperature of the mixture. A more thorough explanation of the ACCD, corresponding specimen preparation and data analysis is available in previous research (*44, 45).*

For this study, two ACCD specimens per mixture were compacted. The target air voids content of the specimen was 9 ± 1% which was consistent with previous research (*44*). Table 20 presents the low temperature cracking results for all the mixtures tested using the ACCD. The inclusion of RAP, RAS or RAP and RAS in the mixtures did not change the low temperature cracking dramatically. As compared to the control mixtures, the difference in cracking temperature was within 1 - 2°C (34 - 36°F). The same was observed for the mixtures incorporating the WMA technology. Overall, the ACCD results indicated that the use of the recycled materials, at the percentages tested, with and without the WMA technology did not have an adverse effect on the low temperature characteristics of the mixtures.

Table 20: Thin Lift ACCD Test Results

Mixture	ACCD Cracking Temperature
Control	-38.5ºC (-37.3ºF)
40% RAP	-37.0ºC (-34.6ºF)
5% RAS	-38.8ºC (-37.8ºF)
35% RAP + 5% RAS	-37.0ºC (-34.6ºF)
Control + 1% WMA	-39.3ºC (-38.7ºF)
40% RAP + 1% WMA	-39.8ºC (-39.6ºF)
5% RAS + 1% WMA	-40.5ºC (-40.9ºF)
35% RAP + 5% RAS + 1% WMA	-39.3ºC (-38.7ºF)

5.3.4 Moisture Susceptibility Testing – Hamburg Wheel Tracking Device (HWTD)

The HWTD was used to measure the effects of high RAP content and/or RAS or WMA technology on the moisture susceptibility of the mixtures. Previous research (*27*) has suggested that moisture susceptibility might be a concern for WMA mixtures. Therefore, in order to understand the performance of these mixtures, they were subjected to moisture susceptibility testing in the HWTD.

Testing was conducted in accordance with AASHTO T324 "Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)" (*9*). Test specimens were fabricated to 7.0 ± 2.0% air voids. Specimens without the WMA technology were mixed at 144ºC (291ºF) and then aged four hours at the compaction temperature of 132ºC (270ºF). All specimens containing the WMA technology were mixed at 124ºC (255ºF) and then aged four hours at the compaction temperature of 112ºC (234ºF). In this test, a steel wheel loads the specimen and the corresponding rut depth is recorded. The rut depth versus numbers of passes of the wheel is plotted to determine the SIP. The SIP gives an indication of when the test specimen begins to exhibit stripping (moisture damage).

Testing in the HWTD was conducted at a test temperature of 40ºC (104ºF). This temperature was selected over 50ºC (122ºF) due to the fact that a lower PG binder grade virgin binder (PG52-28) was utilized. The specimens were tested at a rate of 52 passes per minute after a soak time of 30 minutes at the test temperature. Testing terminated at 20,000 wheel passes or until visible stripping was noted. Table 21 shows the results of the moisture susceptibility testing.

Table 21: Thin Lift HWTD Tests Results

Mixture	Stripping Inflection Point
Control	16,800
40% RAP	NONE
5% RAS	NONE
35% RAP + 5% RAS	NONE
Control + 1% WMA	6,200
40% RAP + 1% WMA	NONE
5% RAS + 1% WMA	9,800
35% RAP + 5% RAS + 1% WMA	NONE

For mixtures without WMA technology, the results indicated that mixtures containing RAP and/or RAS without WMA technology performed better than their corresponding control mixtures. The reason for the failure of the control mixture was likely a result of the softer PG52-28 binder that was utilized in the mixture design. The remaining mixtures passed the tests. This indicated there was a degree of blending between the stiffer binder in the RAP and/or RAS with the virgin binder added, thus increasing the overall mixture stiffness.
The control mixture and 5% RAS with WMA technology did not perform as well as the same mixture without the technology. Overall, the data suggested that the 40% RAP and 35% + 5% RAS mixtures passed the test with and without the WMA technology and at a reduced mixing and compaction temperature.

5.3.5 Extracted Binder Performance Grade

The binder for each mixture was extracted, recovered and graded in accordance with AASHTO T164, T170 and R29 respectively. The results of this grading are shown in Table 22.

Table 22: Extracted Binder Grading Results

Mixture	Continuous Grade	PG Grade
Control	62.2-31.2	58-28
40% RAP	72.4-27.9	70-22
5% RAS	65.6-32.2	64-28
35% RAP + 5% RAS	77.5-25.9	76-22
Control + 1% WMA	56.4-32.6	52-28
40% RAP + 1% WMA	64.2-30.9	64-28
5% RAS + 1% WMA	60.9-32.7	58-28
35% RAP + 5% RAS + 1% WMA	71.1-27.9	70-22

The results indicated that RAP or RAS improved the high temperature grade of the extracted binder for all the mixtures tested with or without WMA technology. This improvement was as much as three full grades for the mixtures without WMA technology (control PG58-28 vs. 35% RAP + 5% RAS PG76-22) and mixtures with WMA technology (control PG52-28 vs. 35% RAP + 5% RAS PG70-22). Correspondingly, the results indicated that the low temperature grade of the extracted mixture binder either remained the same as the control (PGXX-28) or was reduced by one full grade to a PGXX-22. These low temperature reductions typically occurred at higher amounts of RAP and/or RAS. Comparing the results for the mixtures with and without WMA technology showed reduced high temperature grades for all the mixtures tested as compared to the mixtures without WMA technology. This indicated that the reduced mixing and aging temperatures for the mixture with WMA technology reduced the amount of binder aging (stiffening). Overall, the data indicated that the addition of RAP and/or RAS to the mixtures improved the high temperature grade of the binder by up to three temperature grades while maintaining the low temperature grade or reducing it by one grade.

This page left intentionally blank.

6.0 Pilot Specifications/Protocols Developed Based on the Research

Based on this research, pilot specification and protocols for use by MassDOT were developed.

6.1 Superpave 9.5 mm Green Sustainable High Performance Thin Overlay (GSHPThinOL) Specification

A pilot specification for a 9.5 mm Green Sustainable High Performance Thin Overlay (GSHPThinOL) was developed. This GSHPThinOL is intended to be a pavement preservation strategy used to extend a pavement's service life without improving its structural capacity. This mixture is a preventive maintenance strategy that can be applied to pavements in good condition that do not require structural rehabilitation. The GSHPThinOL should have a final thickness of 0.75 to 1.5 inches (19.0 mm to 37.5 mm). The composition of the mixture shall incorporate a rubber modified asphalt binder and up to 40% RAP can be included in the mixture.

The pilot specification shown in the Appendix (Section 9.1) addressed: surface preparation, material properties (binder, aggregate, tack coat), mixture design requirements, RAP testing requirements, performance criteria for the asphalt binder in terms of thermal cracking and mixture performance criteria in terms of reflective cracking, thermal cracking, fatigue cracking and rutting.

6.2 Sampling and Testing Protocols for Warm Mix Asphalt Mixtures in Massachusetts

Due to the increasing number of WMA technologies on the market and those already being utilized, MassDOT requested that a protocol be developed to evaluate new and existing types of WMA technologies. Therefore, a protocol entitled "Sampling and Testing Protocols for Warm Mix Asphalt Mixtures in Massachusetts" was developed.

As shown in the Appendix (Section 9.2), the protocol addresses aggregate sampling and testing requirements, binder sampling and testing requirements, WMA additive sampling requirements, mixture performance testing requirements, mixture production information required, procedures for loose mix sampling, loose mix reheating, plant compacting of samples and collection of field cores.

This page left intentionally blank.

7.0 Discussion of Results

7.1 Effect of Temperature & Time on the Moisture Susceptibility of WMA Mixtures

The focus of this portion of the study was to measure the effect of aging time and temperature on the moisture susceptibility of different WMA mixtures using the HWTD and ESR. Based on the data, the following observations were made:

1. The results of the moisture susceptibility testing in the HWTD indicated that performance of the control and WMA mixtures improved as the aging time increased.

2. Mixtures failing the HWTD test at the intermediate and low temperatures were retested with the incorporation of anti-strip agents (chemical and hydrated lime). The results indicated, for the majority, that the moisture susceptibility performance of the control and WMA mixture improved due to the anti-strip. This finding indicates that it is possible for a WMA mixture's susceptibility to moisture damage to be remedied with the addition of anti-strip additives.

3. Dynamic modulus testing was conducted on control and WMA mixtures aged at the 129ºC (265ºF) and 113ºC (235ºF) temperature levels with 4 and 8 hour aging periods. This testing was conducted to assess any reduction in stiffness associated with moisture damage. For the majority, the WMA mixtures had a larger ESR ratio at the 113ºC (235ºF) for both aging periods relative to the 129ºC (265ºF). This trend requires further investigation to determine its cause and potential applicability to other WMA mixtures. Furthermore, the mixtures with Advera and Evotherm had a substantial increase in their ESR at 113ºC (235ºF) in comparison to 129ºC (265ºF). The cause of this occurrence requires further investigation. Overall, the ESR results at the lower temperature that is typically associated with WMA mixture placement showed that WMA mixtures performed similarly to the control mixture.

7.2 Performance Characteristics of Asphalt Rubber Gap Graded (ARGG) Mixtures with RAP and/or WMA

Based on the research conducted to design and evaluate an ARGG mixture that incorporated high RAP content and a WMA technology, the following observations were made:

1. For the majority, an ARGG control mixture incorporating RAP (25% and 40%) with and without a WMA technology was able to be developed and met the desired volumetric specifications. However, the amount of time the RAP was heated prior to

specimen mixing had a significant effect on the mixture volumetrics. A four hour heating time was recommended.

2. The dynamic modulus and mixture master curve data indicated that an addition of 25% and 40% RAP to the control mixture resulted in an increase in mixture stiffness at 20ºC and 40ºC (68°F and 104°F). This stiffness increase was mitigated through the use of the WMA technology and corresponding reduced aging temperatures. The addition of the WMA technology to the control mixture had little to no effect on the mixture’s stiffness.

3. Generally, the results of the beam fatigue tests in strain control indicated that the resistance to fatigue cracking of the mixtures decreased with the incorporation of higher amounts of RAP. The same trend was also apparent with the incorporation of a WMA technology.

4. Reflective cracking test results from the OT indicated that mixtures incorporating 25% and 40% RAP were more susceptible to reflective cracking as compared to the control mixtures. For the RAP mixtures, the addition of the WMA technology did not yield a better reflective cracking resistance.

5. The addition of any percentage of RAP and/or the addition of the WMA technology to the ARGG control mixture had no significant impact on the moisture susceptibility or rutting potential of the mixture.

6. The workability evaluation indicated that as the amount of RAP incorporated into the ARGG control mixture was increased there was a corresponding decrease in mixture workability. Comparison of the mixtures with and without the WMA technology indicated that the addition of the WMA greatly improved the workability of the ARGG control mixtures with RAP to a level similar to the ARGG control mixture without RAP or WMA. Therefore, the use of a WMA technology should be considered when field compactability may be an issue with these types of mixtures.

7. It is recommended to further investigate and develop a procedure to determine the proper drop in temperatures for asphalt rubber mixtures that incorporate WMA, as the temperature drop may have been a contributing factor to the reduced cracking performance of the mixture incorporating WMA technology.

8. Overall, the data indicated that high amounts of RAP and/or the use of WMA technology may reduce the cracking resistance of the ARGG mixture. The addition of RAP and/or WMA did not negatively impact the moisture susceptibility or rutting of the mixture. The workability of the mixtures was improved when using the WMA technology. Further investigations are needed to validate these results with different types of AR binders and WMA technologies.

7.3 Thin Lift Mixtures with High RAP, RAS, and/or WMA for Pavement Preservation

Based on the research conducted to design and evaluate thin lift mixtures for pavement preservation that incorporate high RAP content, RAS and WMA technology, the following observations were made:

1. Superpave 9.5 mm mixtures were able to be designed that incorporated high RAP content, RAS, high RAP content and RAS and redesigned incorporating a wax-based WMA technology. These mixtures met the Superpave 9.5 mm gradation and volumetric requirements.

2. Dynamic modulus testing indicated that the incorporation of high RAP content and/or RAS caused an increase in the stiffness of the mixtures. The stiffness increase was significant for the 40% RAP and 35% RAP + 5% RAS mixtures with and without WMA technology. Mixtures incorporating the WMA technology showed generally lower dynamic modulus values than the mixture without the technology. This was likely due to less mixture aging for the WMA technology mixture due to reduced mixing and compaction (aging) temperatures. Overall, the mixture dynamic modulus data agrees with the percent binder replacement value calculated, as the 40% RAP and 35% RAP + 5% RAS mixtures had larger amounts of binder replaced (39.9% and 49.8% respectively) and therefore would be expected to exhibit higher mixture stiffness.

3. Reflective cracking results obtained from the OT indicated that mixtures incorporating the RAP and/or RAS had reduced reflective cracking resistance as compared to the control. The addition of the WMA technology increased the reflective cracking resistance of the mixtures, but these mixtures also did not exhibit the same performance as the control mixture with the WMA technology.

4. Low temperature cracking resistance test results indicated that the addition of RAP, RAS and/or WMA technology did not have a negative impact on the low temperature performance of the mixtures as compared to the control.

5. Moisture susceptibility results indicated, for the majority, that the mixtures incorporating RAP and/or RAS had improved moisture susceptibility relative to the control mixtures. Additionally, mixtures incorporating WMA technology showed similar performance improvements over the control mixture with WMA technology.

6. Binder grading performed on extracted mixture binder indicated that the addition of RAP and/or RAS to the mixtures, at the percentages used in this study, improved the high temperature grade of the binder by up to three temperature grades while maintaining the low temperature grade or reducing it by one grade. The addition of WMA technology to the mixtures helped reduce the magnitude of the changes in the binder grade which is likely a result of the reduced aging experienced for these mixtures.

7. Overall, the results indicated that mixtures incorporating RAP and/or RAS performed similarly to the control mixtures except for reflective cracking resistance. This suggests that further research is needed to investigate the use of a polymer modified binder or another binder that can add elasticity to these mixtures.

8.0 References

1. Mogawer, W.S. and Austerman, A.J., "Laboratory and Field Evaluation of Warm Mix Asphalt Technology to Determine its Applicability for Massachusetts." Final Report. Massachusetts Department of Transportation, February 2008.

2. Hurley, G. C., Prowell, B.D., "Evaluation of Sasobit for Use in Warm Mix Asphalt." National Center for Asphalt Technology (NCAT), *NCAT Report 05-06*, June 2005.

3. Xie, H., Cooley, L.A., and Huner, M. H., "4.75 mm NMAS Stone Matrix Asphalt (SMA) Mixtures." National Center for Asphalt Technology (NCAT), *NCAT Report 03-05*, December 2003.

4. National Asphalt Pavement Association (NAPA), "Designing and Constructing SMA Mixtures – State-of-the-Practice." National Asphalt Pavement Association (NAPA), Quality Improvement Series 122, 1999.

5. National Asphalt Pavement Association (NAPA), "Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses." National Asphalt Pavement Association (NAPA), Information Series 115, 2002.

6. Mogawer, W.S. and Austerman, A.J., "Phase II: Implementation of Superpave Technology in Massachusetts." Final Report. Massachusetts Highway Department, December 2006.

7. Mogawer, W.S., Austerman, A.J., and Bonaquist, R., "Laboratory Development and Field Trials of Thin-Lift Hot Mix Asphalt Overlays Incorporating High Percentages of Reclaimed Asphalt Pavement with Warm Mix Asphalt Technology." Canadian Technical Asphalt Association (CTAA) Proceedings, Moncton - New Brunswick, November 2009, pp. 73-97.

8. Austerman, A.J. "Laboratory and Field Evaluation of Warm Mix Asphalt." Master Thesis, University of Massachusetts Dartmouth, North Dartmouth, MA, January 2009.

9. American Association of State Highway and Transportation Officials (AASHTO), "Standard Specifications for Transportation Materials and Methods of Sampling and Testing." American Association of State Highway and Transportation Officials, Washington, D.C. 30th Edition, 2010.

10. Austerman, A.J., Mogawer, W.S., and Bonaquist, R., "Investigation of the Influence of Warm Mix Asphalt Additive Dose on the Workability, Cracking Susceptibility, and Moisture Susceptibility of Asphalt Mixtures Containing Reclaimed Asphalt Pavement." Canadian Technical Asphalt Association (CTAA) Proceedings, Moncton - New Brunswick, November 2009, pp. 51-71.

11. Hurley, G., and Prowell, B., "Evaluation of Aspha-min® Zeolite for Use in Warm Asphalt Mixes." National Center for Asphalt Technology (NCAT), *NCAT Report 05-04*, Auburn University, Auburn, AL, 2005.

12. Cooper, S. B., "Characterization of HMA Mixtures Containing High Recycled Asphalt Pavement Content with Crumb Rubber Additives." Master Thesis, Louisiana State University, Baton Rouge, LA, December 2008.

13. Bonaquist, R., "Laboratory Evaluation of Hot Mix Asphalt (HMA) Mixtures Containing Recycled or Waste Product Materials Using Performance Testing." *Publication FHWA-PA-2005-006+98-32(19)*, Pennsylvania Department of Transportation, Office of Planning and Research, 2005.

14. McDaniel, R., Shah, A., Huber, G., and Gallivan, V., "Investigation of Properties of Plant-Produced RAP Mixtures." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1998, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp.103-111.

15. Daniel, J., and Pochily, J., "Can We Make More Use of RAP? A Study of Extracted Binder Properties in NH, VT and Maine RAP Mixes." Presented at the 2009 Northeast Asphalt User Producer Group (NEAUPG) Annual Meeting, South Portland, ME October 8, 2009. http://www.neaupg.uconn.edu/pdf/09_Binder_Study_daniel-pochily.pdf. (Accessed June 6, 2011).

16. American Society for Testing and Materials, "Annual Book of ASTM Standards." ASTM International, Volume 04.03, 2008.

17. Walker, D., "Understanding How Tires are used in Asphalt." Rubber Form Recycled Products, LLC.
http://www.rubberform.com/news.php?id=108 (Accessed June 15, 2011).

18. Xiao, F., Amirkhanian, S., and Juang, C. H., "Rutting Resistance of Rubberized Asphalt Concrete Pavements Containing Reclaimed Asphalt Pavement Mixtures." *American Society of Civil Engineers (ASCE) Journal of Materials in Civil Engineering*, 19, 475, 2007.

19. Bonaquist, R., "Mix Design Practices for Warm Mix Asphalt." National Cooperative Highway Research Program (NCHRP), *NCHRP Report 691*, 2011.

20. "Road Science: Thin is In." *Better Roads*, Randall-Reilly Publishing Co. LLC, January 2010.
www.betterroads.com/road-science-thin-is-in/ (Accessed June 30, 2010).

21. Chou, Y. J., Datta, D., and Pulugurta, H., "Effectiveness of Thin Hot Mix Asphalt Overlay on Pavement Ride and Condition Performance." *Report No. FHWA/OH-2008/4*, Federal Highway Administration, U.S. Department of Transportation and Ohio Department of Transportation, April 2008.

22. Al-Qadi, I. L., Carpenter, S., Roberts, G., Ozer, H., Elseifi, M., and Trepanier, J., “Determination of Usable Residual Asphalt Binder in RAP.” *Research Report No. FHWA-ICT-09-031*, Federal Highway Administration, U.S. Department of Transportation and Illinois Department of Transportation, January 2009.

23. Daniel, J.S. and Chehab, G.R., “Use of RAP Mixtures in the Mechanistic Empirical Pavement Design Guide.” Transportation Research Board 2008 Annual Meeting CD-ROM, Transportation Research Board of the National Academies, Washington, D.C., 2008.

24. Daniel, J.S. and Lachance, A., “Mechanistic and Volumetric Properties of Asphalt Mixtures with RAP.” Transportation Research Board 2005 Annual Meeting CD-ROM, Transportation Research Board of the National Academies, Washington, D.C., 2005.

25. Scholz, T. V., “Preliminary Investigation of RAP and RAS in HMAC.” *Final Report SR 500-291*, Oregon Department of Transportation, February 2010.

26. Hurley, G.C. and Prowell, B.D., “Evaluation of Potential Processes for Use in Warm Mix Asphalt.” *Journal of the Association of Asphalt Paving Technologists*, Vol. 75, 2006, pp. 41-90.

27. Austerman, A.J., Mogawer, W.S., and Bonaquist, R., “Investigation of the Influence of Warm Mix Asphalt Additive Dose on the Workability, Cracking Susceptibility, and Moisture Susceptibility of Asphalt Mixtures Containing Reclaimed Asphalt Pavement.” In *Canadian Technical Asphalt Association (CTAA) Proceedings.* Moncton - New Brunswick, pp. 51-71, November 2009.

28. Christopher, R. and Epps, J., “Energy, Emissions, Material Conservation and Prices Associated with Construction, Rehabilitation and Material Alternatives for Flexible Pavement.” Transportation Research Board 2010 Annual Meeting CD-ROM, Transportation Research Board of the National Academies, Washington, D.C., 2010.

29. Li, X., Marasteanu, M.O., Williams, R.C., and Clyne, T.R., “Effect of RAP (Proportion and Type) and Binder Grade on Properties of Asphalt Mixtures.” In Transportation Research Board 2008 Annual Meeting CD-ROM, Transportation Research Board of the National Academies, Washington, D.C., 2008.

30. American Association of State Highway and Transportation Officials. 2008 AASHTO Provisional Standards. American Association of State Highway and Transportation Officials (AASHTO).Washington, D.C., June 2008 Edition.

31. Arizona Department of Transportation (ADOT), “Section 413 Asphaltic Concrete (Asphalt-Rubber),” Standard Specifications, 2000. http://www.azdot.gov/Highways/ConstGrp/Contractors/PDF/2000_Standard_Spec/Sec401_417.pdf (Accessed June 15, 2011).

32. Mogawer, W.S., Austerman, A.J., and Roussel, M., "Performance Characteristics of Asphalt Rubber Mixtures Containing RAP and Warm Mix Asphalt Technology." Proceedings of the 2nd International Warm-Mix Conference, St. Louis, MO, October 2011.

33. Dukatz, E., "Wisconsin RAM Specification." Presented at RAP Expert Task Group (ETG) Meeting, Auburn, AL, May 20, 2010.

34. Izzo, R. and Tahmoressi, M., "Evaluation of the Use of the Hamburg Wheel-Tracking Device for Moisture Susceptibility of Hot Mix Asphalt." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1681, Transportation Research Board of the National Academies, Washington, D.C., 1999, pp. 76-85.

35. Solaimanian, M., Fedor, D., Bonaquist, R., Soltani, A., and Tandom, V., "Simple Performance Test for Mixture Damage Prediction in Asphalt Concrete." *Journal of the Association of Asphalt Paving Technologists*, Vol. 75, 2006, pp. 345-380.

36. Nadkarni, A., Kaloush, K., Zeiada, W., and Biligiri, K., "Using Dynamic Modulus Test to Evaluate Moisture Susceptibility of Asphalt Mixtures." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2127, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 29-35.

37. Mogawer, W.S., Corderio, P. and Austerman, M.G., "Phase I: Implementation of Superpave in Massachusetts." Final Report, Massachusetts Highway Department, December 31, 2000.

38. Texas Department of Transportation (TxDOT), "Test Procedure for Overlay Test." TxDOT Designation Tex-248-F, January 2009. ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit248.pdf (Accessed June 15, 2011).

39. Mogawer, W.S., Austerman, A.J., Kassem, E., and Masad, E., "Moisture Damage Characterization of Warm Mix Asphalt Mixtures." *Journal of the Association of Asphalt Paving Technologist* (AAPT), Vol. 80, 2011b, pp. 491-526.

40. Gudimettla, J., Cooley, L., and Brown, E., "Workability of Hot Mix Asphalt." National Center for Asphalt Technology (NCAT), *NCAT Report 03-03,* Auburn, AL, 2003.

41. Bonaquist, R., "Refining the Simple Performance Tester for Use in Routine Practice." National Cooperative Highway Research Program (NCHRP), *NCHRP Report 614,* Transportation Research Board of the National Academies, Washington, D.C., 2008.

42. Zhou, F., Hu, S., Scullion, T., Chen, D., Qi, X., and Carlos, G., "Development and Verification of the Overlay Tester Based Fatigue Cracking Prediction Approach." *Journal of the Association of Asphalt Paving Technologist,* Vol. 76, pp. 627-662, 2007.

43. Zhou, F., Hu, S., Chen, D., and Scullion, T., "Overlay Tester: A Simple Performance Test for Fatigue Cracking." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2001, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp.1-8.

44. Kim, S., Sargand, S., and Wargo, A., "A Simple Test Procedure for Evaluating Low Temperature Crack Resistance of Asphalt Concrete." *Publication FHWA/OH-2009/5*, Ohio Department of Transportation, November 2009.

45. Kim, S., Wargo, A., and Powers, D., "Asphalt Concrete Cracking Device to Evaluate Low Temperature Performance of HMA." *Journal of the Association of Asphalt Paving Technologists*, Vol. 79, 2010.

This page left intentionally blank.

9.0 Appendices

9.1 Superpave 9.5 mm Green Sustainable High Performance Thin Overlay (GSHPThinOL) Specification

Date XX/XX/XX

Superpave 9.5 mm Green Sustainable High Performance Thin Overlay (GSHPThinOL) Specifications

Description

A Superpave 9.5 mm Green Sustainable High Performance Thin Overlay (GSHPThinOL) is a pavement preservation strategy used to extend a pavement's service life without improving its structural capacity. This mixture is a preventive maintenance strategy that can be applied to pavements in good condition that do not require structural rehabilitation. The GSHPThinOL ranges from 0.75 to 1.5 inch (19.0 mm to 37.5 mm) in thickness.

Composition of the mixture for the GSHPThinOL shall be coarse aggregate, fine aggregate, mineral filler (if needed) and a rubber modified asphalt binder. Also, up to 40% RAP can be included in the mixture. The mixture without RAP and the mixture with RAP will be designated as mixtures A and B, respectively. Both mixtures will incorporate a WMA technology that incorporates a rejuvenator.

Surface Preparation of Existing Pavement

It is recommended that the existing pavement surface be prepared as outlined in NAPA Information Series 135 Table 1 "Suggested Approaches to Surface Preparation Prior to Thin Overlay Based on Distresses."

Materials

All materials must be approved by the agency prior to production and placement of the GSHPThinOL.

Rubber Modified Asphalt Binder

The rubber modified asphalt binder shall have a high temperature performance grade equal to or higher than the one specified by the state or region were the GSHPThinOL will be placed. The low temperature performance grade will be one grade colder than specified by the state or the region were the GSHPThinOL will be placed. For example, if a state specifies a PG 64-22, the high temperature performance grade for the GSHPThinOL will be a PG64 or higher and low temperature performance grade will be a PGXX-34 or colder. The asphalt supplier shall provide testing in accordance with AASHTO R29 "Grading or Verifying the Performance Grade of an Asphalt Binder" Section 6.0 – Test Procedure for Grading an Unknown Asphalt Binder and AASHTO M320 to verify the performance grade of the asphalt binder. Additionally, the modified asphalt binder shall be tested in the Asphalt Binder Cracking Device (ABCD) to determine the thermal cracking temperature of the binder. The thermal cracking temperature of the binder shall be equal to or colder than the low temperature performance grade of the binder.

Aggregate
The aggregate blend for the GSHPThinOL shall meet the entire Superpave aggregate consensus properties requirement list in Table 5 of AASHTO M323 "Superpave Volumetric Mix Design" and the source property requirements noted in Table 23. The aggregate blend shall be classified as coarse or fine as outlined in AASHTO M323 Section 6.1.3 – Gradation Classification.

Table 23: Superpave Source Property Requirements

Test	**Applicable Method**	**Limitations**
LA Abrasion, % loss	AASHTO T96 or ASTM C131	40% max.
Sodium Sulfate Soundness, % loss	AASHTO T104 or ASTM C88	16% max.

Mineral Filler
Mineral filler, if necessary, in addition to that naturally present in the aggregate, shall meet the requirements of AASHTO M17 or ASTM D242.

Tack Coat
Tack coat shall either be polymer modified emulsion or the performance grade asphalt binder specified by the state DOT suitable for the location where the mixture will be placed.

Job Mix Formula
The GSHPThinOL mixture shall be a Superpave 9.5 mm mixture conforming to the gradation and asphalt binder content requirements detailed in Table 24.

Table 24: Mixture Requirements for a GSHPThinOL

Sieve Designation	**Percent by Mass Passing**	**Production Tolerances**
12.5 mm (1/2")	100	± 6
9.5 mm (3/8")	90 – 100	± 6
4.75 mm (#4)	≤ 90	± 6
2.36 mm (#8)	32 – 67	± 4
0.075 mm (#200)	2 – 10	± 1
Asphalt Binder %	Min. 6.5	± 0.3

AASHTO R35 “Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt” shall be used to develop a mixture that will meet the specified design criteria in accordance with AASHTO M323 “Standard Specification for Superpave Volumetric Mix Design.” A copy of all design test data used in developing the mix design, including graphs, shall be submitted with the mixture design. The job mix formula shall establish the percentage of aggregate passing each sieve and the percentage of polymer modified binder to be added to the aggregate. Also, all mixtures shall meet the volumetric properties outlined in AASHTO M323 Table 6. No change in the job-mix formula may be made without prior written approval.

In addition to the criteria previously noted, the mixture will satisfy the following criteria outlined in Table 25 and Table 26, depending on whether or not RAP is included in the mixture.

Table 25: Mixture A (No RAP)

Property	Device/Test	Criteria
Thermal cracking temperature of the modified asphalt binder	Asphalt Binder Cracking Device (ABCD)	Equal to or colder than the low temperature performance grade of the binder
Thermal cracking temperature of extracted binder from the mixture	Asphalt Binder Cracking Device (ABCD)	± one grade from the low temperature performance grade of the binder
Thermal cracking temperature of mixture	Thermal Stress Restrained Specimen Tensile Strength Test (TSRST) - AASHTO TP10-93	± 6°C from the low temperature performance grade of the binder
Cracking	Overlay Test -TxDOT Test Designation Tex-248-F	Mixtures shall exhibit average overlay test cycles to failure (93% load reduction) ≥ 300
Fatigue Life*	Flexural Beam - AASHTO T321	≥100,000 cycles
Rutting	Hamburg Wheel Tracking Device at 45°C - AASHTO TP 324	Average rut depth is ≤ 12.5 mm at 10,000 loading cycles

**It is preferred that the strain level should be equal to the strain in the existing HMA layer or alternatively use a strain level in the range of 1200 to 300 micro strain.*

Table 26: Mixture B (If RAP is included in the mixture)

Property	Device/Test	Criteria
Thermal cracking temperature of the modified asphalt binder	Asphalt Binder Cracking Device (ABCD)	Equal to or colder than the low temperature performance grade of the binder
Thermal cracking temperature of extracted binder from the mixture	Asphalt Binder Cracking Device (ABCD)	± one grade from the low temperature performance grade of the binder
Thermal cracking temperature of mixture	Thermal Stress Restrained Specimen Tensile Strength Test (TSRST) - AASHTO TP10-93	± 6°C from the low temperature performance grade of the binder
Cracking	Overlay Test -TxDOT Test Designation Tex-248-F	Mixtures containing RAP shall exhibit average overlay test cycles to failure (93% load reduction) within ± 10% of the overlay test cycles to failure of control specimens without RAP [minimum of three test specimens per mixture]
Fatigue Life*	Flexural Beam - AASHTO T321	≥100,000 cycles
Rutting	Hamburg Wheel Tracking Device at 45°C - AASHTO TP 324	Average rut depth is ≤ 12.5 mm at 10,000 loading cycles

**It is preferred that the strain level should be equal to the strain in the existing HMA layer or alternatively use a strain level in the range of 1200 to 300 micro strain.*

<u>Reclaimed Asphalt Pavement (RAP)</u>

The amount of RAP in the mixture will be limited to 40% RAP or the amount of RAP corresponding to 1% binder replaced, whichever is less. The percent binder replaced shall be calculated by the following equation:

$$\text{Binder Replacement, \%} = \frac{(\text{Percent Binder in the RAP}) \times (\text{Percent RAP in Mixture})}{\text{Total Percent Binder in Mixture}}$$

Fractionated RAP is preferred, but not required. RAP shall be clean and free of all foreign material. The maximum size of RAP should correspond to the NMAS used in the mixture (9.5 mm). All volumetric properties are the same as for the mixture without RAP (mixture A).

Extensive testing of the RAP material shall be completed prior to the mixture design. Copies of all test results must be submitted with the GSHPThinOL mixture design for the Job Mix Formula (JMF) approval. No material may be added to the RAP stockpiles after the requisite testing samples have been taken. Table 27 outlines the required RAP testing and the corresponding number of replicates (random sampling shall be used throughout).

Table 27: Required RAP Testing

Test	Applicable Method	Number of Replicates
Binder Content	AASHTO T308 (Ignition Oven) or AASHTO T164 (Centrifuge)	4
Extraction and Recovery of RAP Binder	AASHTO T319 (Rotovap) or T170 (Abson)	Replicates sufficient to provide quantity adequate for subsequent binder testing
Determine Performance Grade of Extracted Binder	AASHTO R29 - Section 6.0	4
Recovered RAP Aggregate Gradation	AASHTO T11 & AASHTO T27	4
Specific Gravity of Recovered RAP Aggregates	AASHTO T84 & T85	4
Maximum Theoretical Specific Gravity of RAP	AASHTO T209	4

No changes in the source, location or type of RAP will be permitted once the JMF has been approved.

---End Specification---

9.2 Sampling and Testing Protocols for Warm Mix Asphalt Mixtures in Massachusetts

Sampling and Testing Protocols for Warm Mix Asphalt Mixtures in Massachusetts

The required sampling and testing protocols for WMA mixtures (and corresponding HMA mixtures to be used for comparative purposes) for MassDOT projects are outlined in this document. These sampling and testing protocols shall be performed during the development of the mixture design in the laboratory and on specimens fabricated from reheated mixture collected during production. Field cores should also be tested periodically after the WMA mixture has been in service for one year.

I. Aggregates

Sampling:
Each aggregate stockpile shall be sampled by the contractor in accordance with AASHTO T2 "Sampling of Aggregates." It is also recommended that one (1) 55-gallon drum of each aggregate stockpile utilized in each mixture be sampled and retained by the contractor for any future testing requirements (if necessary).

Testing:
The tests to be completed for each aggregate stockpile are summarized in Table 28 as follows:

Table 28: Aggregate Stockpile Tests

Aggregates			
Test/Test Parameter	**Test Method/Reference**	**Title**	**Notes**
Wet Wash	AASHTO T11	Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing	Testing to be Completed by the Contractor
Sieve Analysis	AASHTO T27	Sieve Analysis of Fine and Coarse Aggregates	Testing to be Completed by the Contractor
Bulk Specific Gravity / Absorption	AASHTO T84 AASHTO T85	Specific Gravity and Absorption of Fine Aggregate/Specific Gravity and Absorption of Coarse Aggregate	Testing to be Completed by the Contractor
Moisture Content	AASHTO T255	Total Evaporable Moisture Content of Aggregate by Drying	Testing to be Completed by the Contractor
Superpave Consensus and Source Properties	ASTM D5821 AASHTO T304 Method A ASTM D4791 AASHTO T176 AASHTO T96 AASHTO T104	Coarse Aggregate Angularity Uncompacted Voids in Fine Aggregate Flat and Elongated Particles Sand Equivalent LA Abrasion Soundness	Testing to be Completed by the Contractor

II. Asphalt Binder

Sampling:

The asphalt binder used in the production of the WMA and HMA mixtures shall be sampled by the contractor in accordance with AASHTO T40 “Sampling Bituminous Materials.” This sampling shall include the virgin binder (without the WMA additive) and the mixed WMA binder (virgin + WMA additive) if applicable.

It is recommended that the asphalt binder be sampled from the liquid asphalt binder tanks at the HMA plant prior to the start of each mixture’s production. For each binder, a minimum of twenty (20) one-gallon specimens shall be sampled into uncoated metal containers for testing and future work (if necessary). After sampling, the asphalt binder shall be stored in a temperature controlled environment, with air temperatures not exceeding 25ºC (77ºF).

The supplier, source and any additional pertinent information (modifier type, amount, etc.) for each asphalt binder shall be reported.

Testing:
The tests to be completed for each binder are summarized in Table 29 as follows:

Table 29: Binder Tests for Virgin, Mixed (Virgin + WMA Additive) and Extracted Mixture Binder

Virgin Binder			
Test/Test Parameter	**Test Method/ Reference**	**Title**	**Notes/Remarks**
Performance Grade	AASHTO R29 & AASHTO M320	Grading or Verifying the Performance Grade of an Asphalt Binder & Performance-Graded Asphalt Binder	Testing to be Completed by DOT
Binder Modulus (G*) & Binder Master Curve	No Formal Method Established	N/A	Testing to be Completed by DOT
Softening Point	AASHTO T53	Softening Point of Bitumen (Ring-and-Ball Apparatus)	Testing to be Completed by DOT
Thermal Cracking Temperature	Asphalt Binder Cracking Device (ABCD)	Kim, S., Wysong, Z., and Kovach, J.,"*Low-Temperature Thermal Cracking of Asphalt Binder by Asphalt Binder Cracking Device.*" Transportation Research Record Issue No.1962 (2006).	Testing to be Completed by DOT
Critical Cracking Temperature	AASHTO R49-09	Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders	Testing to be Completed by DOT
Multiple Stress Creep Recovery	AASHTO MP19-10	Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test	Testing to be Completed by DOT

III. Warm Mix Additive

The contractor shall sample and provide sufficient quantity of the Warm Mix Additive that will be utilized during production to complete the required binder and mixture testing. Also the contractor shall supply relevant Material Safety Data Sheet information, handling instructions, method for introducing the WMA additive into the mixture in the laboratory, and appropriate dosage rate.

The exact quantity of the WMA additive required will be determined by the DOT as the amount required may vary by WMA type (waxes, liquids, etc.).

IV. Mixture Testing

Tests to be completed for each mixture are summarized in Table 30 as follows. Additionally, binders shall be extracted from the mixtures and tested using the tests listed in Table 29.

Table 30: Mixture Tests

Mixtures			
Test	**Reference**	**Title**	**Notes/Remarks**
Dynamic Modulus	AASHTO TP62 AASHTO TP79	Determining Dynamic Modulus of Hot Mix Asphalt Concrete Specimens Determining the Dynamic Modulus and Flow Number for Hot-Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)	Testing to be Completed by DOT
Low Temperature Cracking	AASHTO TP10	Thermal Stress Restrained Specimen Test	Testing to be Completed by DOT
Push-Pull Fatigue Test (S-VECD)	No Formal Method Established	Proposed Standard Method of Test for Determining the Damage Characteristic Curve of Asphalt Concrete from Direct Tension Cyclic Fatigue Tests	Testing to be Completed by DOT
Moisture Sensitivity	AASHTO T283	Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage	Testing to be Completed by DOT
Moisture Sensitivity	AASHTO T324	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)	Testing to be Completed by DOT

V. Mixture Production Information

During production, the contractor shall be asked to collect and provide the following information:

- Plant type and model
- Production rate (tons per hour)
- Description of method of introducing WMA additive(s)
- Type of WMA used
- Dosage of WMA used
- Production rate
- Aggregate discharge temperature
- Mixture discharge temperature
- Temperature of asphalt binder
- Storage time in silo
- Temperature of mix leaving plant
- Haul time to project
- Mix laydown temperature
- Material Transfer Vehicle (MTV) utilized
- Fuel consumption data for both HMA and WMA
- Haul distance/Haul time
- Paver type and model

VI. Loose Mix, Plant Compacted Specimens, and Field Cores

Loose Mix

Prior to the mix leaving the plant, it is requested that twenty (20) five-gallon metal buckets of loose mix be collected for each mixture produced. If possible, loose mix should be collected prior to any silo storage; if this is not possible, the storage temperature and time at that storage temperature should be noted with each sample. Collected loose mix shall be cooled to room temperature and then stored in a stable, environmentally controlled room with air temperatures less than 25ºC (77ºF).

Loose mix shall be compacted as soon as possible (within one month) after production to limit potential aging of the loose mix. The compacted specimens shall be wrapped and sealed in plastic and stored in a stable, environmentally controlled room with air temperatures less than 25ºC (77ºF). The compacted specimens (from the sampled loose mix) shall be tested within one month after compaction (within two months from the time of initial production). The mixtures will be tested following the tests listed in Table 30.

Reheating

Reheating of loose mix for sample fabrication shall be conducted at the placement temperatures.

Plant Compacted Specimens

The contractor will be requested to compact a minimum of ten (10) gyratory specimens to a height of 170 mm tall at a compacted air void level of 7.5% to 8.5%. If the contractor's gyratory compactor does not have the capability to compact 170 mm specimens consistently, 120 mm specimens should be compacted to an air void level of 6.5% to 7.5%. Compacted specimens should be stored in a stable, environmentally controlled room with air temperatures less than 25ºC (77ºF). Specimens shall be wrapped and sealed in plastic wrap until testing. Specimens shall be cut to the appropriate test dimensions within one week of testing. Testing of compacted specimens shall be conducted within two months of production.

--End Protocol---