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16. Abstract Since the introduction of warm mix asphalt (WMA) in the United States, a variety of different technologies and processes have been developed and used to achieve proper mixing and compaction at reduced temperatures compared to conventional hot mix asphalt (HMA). A better understanding of the effect of WMA additives and reduced aging on the rheology of asphalt binders is a crucial step towards the successful implementation of WMA. This report presents the findings from a study conducted to investigate the influence of chemical WMA additives and reduced short-term aging on the properties of asphalt binders, mortars, and mixtures. A detailed description of the findings relevant to asphalt binders modified using warm mix additives is presented in the Interim Report. This report presents the details of the test methods and findings relevant to mortars and mixtures prepared using warm mix additives. Findings from this study indicate that certain WMA additives tend to exacerbate the reduced stiffness and early age rutting resistance in warm mix binders. The long-term aged WMA binders had similar or slightly reduced resistance to low-temperature cracking compared to conventional binders. Also, WMA with reclaimed asphalt had similar low temperature cracking resistance as compared to a similar HMA with reclaimed asphalt. Tests on asphalt mortars indicated that the WMA additives significantly affected the fatigue cracking resistance of one of the two binders. Tests on full asphalt mixtures indicate that in most cases the rutting and moisture damage resistance of WMA mixtures was similar to or less than the corresponding control HMA. Findings based on the tests conducted using asphalt mortars and asphalt mixtures were qualitatively consistent with the findings based on the tests conducted using asphalt binders.					
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Chapter 1. Introduction and Background

1.1 Introduction

Several technologies have been introduced during the last decade in the United States to produce asphalt mixtures at temperatures that are 30° to 50°C lower (54° to 90°F lower) than conventional mixing and compaction temperatures. These mixtures are referred to as *warm mix asphalt* (WMA) mixtures. Several different additive technologies may be used to produce WMA mixtures. These additives include chemicals, organic compounds, water-bearing zeolite particles, or introduction of water during mixing to cause foaming. Several field demonstration projections based on one or more of these technologies have been executed in Texas and other states over the past few years. WMA is also being increasingly used in conjunction with reclaimed asphalt pavement (RAP) materials. The National Cooperative Highway Research Program (NCHRP) has sponsored two projects on the development and validation of a WMA mix design procedure. Several independent research studies have made broad comparisons between the engineering properties and performance of WMA mixtures to conventional hot mix asphalt (HMA) mixtures. However, very little work investigates the effect of WMA additives on the performance-related properties of the asphalt binder or the long-term impact of using such additives in asphalt binders and mixtures. In addition, work needs to be performed to evaluate the effectiveness of using recycled materials in conjunction with the WMA technology. The overall goal of this study was to bridge these knowledge gaps.

More specifically, the main objectives of this study were to

- evaluate the impact of different WMA additives on the rheology and performance related properties of a carefully selected set of asphalt binders including the impact of long-term aging and RAP materials on these properties,
- extend the evaluations conducted using the asphalt binders to a limited set of asphalt mortars and mixtures, and
- provide recommendations for the use of WMA additives to produce WMA mixtures to ensure that the performance of the WMA mixture was at par to an equivalent HMA.

1.2 Overview of the Research Plan

This research study comprised four main elements. The first element was to identify and select asphalt binders based on their chemical diversity. The two chemical attributes selected for testing were natural wax content and acid content. These two attributes were selected for the possible physico-chemical interactions that could occur between the WMA additives and the asphalt binder. The second element was to evaluate the rheological and performance-related properties of the asphalt binders modified using the chemical WMA additives. The third element was to evaluate the fatigue cracking resistance and moisture damage resistance of asphalt mortars prepared using one aggregate and a subset of the binder-additive combinations used in the binder study. The fourth element of the study was to evaluate a limited number of full asphalt mixtures prepared using the WMA additives to corroborate the findings from the binder and mortar study. The interim report presents a detailed description of the first two elements, which

are also briefly summarized in the following subsection. This report presents a detailed description of the tests conducted and findings from these tests for the last two elements of this research project (mortar and mixture testing).

1.3 Summary of Findings from Binder Testing

Several combinations of asphalt binders and WMA additives were evaluated for their workability (based on viscosity measurements), rutting resistance (based on the Superpave $G^*/\sin\delta$ parameter and the non-recoverable compliance), fatigue cracking resistance (based on the Superpave $G^*\sin\delta$ parameter and fracture tests on this asphalt binders), and resistance to low temperature cracking (based on stiffness and creep compliance). The following is a summary of the findings from this study. Details relevant to these findings can be found in the Interim Report.

Results from binder testing indicate that the rolling thin film oven (RTFO) residues of the WMA additive-binder pairs (with the exception of Sasobit) typically had a $G^*/\sin\delta$ that was 80% or less than that of the HMA binder counterpart, indicating a reduced resistance to permanent deformation or rutting. Moreover, the non-recoverable compliance (J_{nr}) measured using the multiple stress creep and recovery (MSCR) test demonstrated that WMA additives (except Sasobit) interacted with asphalt binders to reduce the WMA's stiffness and ability to resist permanent deformation; this effect was in addition to the reduced stiffness resulting from the reduced aging of WMA binders. For example, for about half of the 24 additive-binder combinations tested, the stiffness loss was due to the additive itself in addition to the stiffness loss attributed to the reduced aging of the WMA binders. The influence of WMA additives on the resistance to permanent deformation was more pronounced for the binders with high natural wax content. For instance, for the PG76 binders, short-term aging at reduced temperatures resulted in an increase in the J_{nr} value by two to eight times compared to the controls. For the same binders, a combination of the WMA additive and reduced short-term aging time and temperatures resulted in a J_{nr} value that was 5 to 50 times that of the control. This result indicates a significantly reduced resistance to permanent deformation. To summarize, the findings presented in the interim report for the RTFO-aged binders indicate that most of the WMA binders had a reduced resistance to permanent deformation. In many cases the decrease in rutting resistance of the WMA binders (compared to HMA) was caused by the additive itself in addition to reduced aging.

The pressure aging vessel (PAV) residues of approximately half of the WMA additive-binder pairs showed a decrease in fracture energy compared to the fracture energy of a similar binder representing an HMA. Based on the Superpave criterion of $G^*\sin\delta$ for PAV-aged binders, the fatigue cracking resistance of WMA binders was very similar to the fatigue cracking resistance of HMA binders. However, it must be recognized that the current Superpave criterion of $G^*\sin\delta$ is not an accurate representation of the fatigue cracking resistance of the asphalt binders, in particular for modified asphalt binders. Reduced short-term aging, as in the case of a WMA, did not have a significant influence on either the stiffness or m-value of binders after PAV aging. This suggests that the low temperature cracking resistance of the WMA binders will be similar to that of the control after long-term aging. In other words, binders with the WMA additives that were subjected to reduced short-term aging followed by PAV aging had similar or slightly reduced thermal cracking resistance compared to the control.

1.4 Scope of Report

Based on the aforementioned findings, the focus of the next task of this project was to evaluate the influence of WMA additives and aging on the mechanical properties and performance of WMA and HMA mixtures. Tests were conducted on two types of WMA and HMA mixtures: asphalt mortars or fine aggregate matrix and full asphalt mixtures. In this study, FAM or asphalt mortar is defined as a composite of the asphalt binder and fine aggregates that pass the #16 ASTM sieve. Chapter 2 of this report presents the tests and results obtained by testing FAM mixtures. Chapter 3 of this report presents tests and results pertaining to the full asphalt mixtures. Chapter 4 presents a summary of conclusions based on the findings from the binder, mortar, and mixture testing.

Chapter 2. Fatigue Cracking and Moisture Damage Resistance of Asphalt Mortars

2.1 Introduction

Fatigue cracking, thermal cracking, rutting, and moisture-induced damage are the most prevalent forms of distresses in asphalt pavements. Several studies have been conducted in the past few decades to (i) better understand the mechanisms of the aforementioned distresses, (ii) accurately quantify and predict the resistance of materials to these distresses from a design stand point, and (iii) engineer material modification and production techniques that will result in an overall longer serviceable life of asphalt pavements. These studies have been conducted over several different length scales (e.g., binders, mastics, mortars, and mixtures). In particular, several researchers have used asphalt mortars or fine aggregate matrix (FAM) to quantify the fatigue cracking, rutting, and moisture damage resistance of asphalt composites with different modified binders, fillers, or additives (Kim & Little 2005; Branco et al. 2008; Masad et al. 2008). Although testing a FAM mixture does not provide a direct measurement of the mixture properties, it does present several advantages particularly when the objective of the study is to investigate the effect of different modifiers and/or fillers on the performance of the composite. First, it is more time- and cost-efficient to fabricate and test FAM specimens as compared to full asphalt mixtures. Second, the FAM specimens are designed to incorporate fine aggregate particles (typically passing #16 ASTM sieve) from the same source and in a relative proportion similar to that of the intended full asphalt mixture. This ensures that any physico-chemical interactions between the asphalt binder and the aggregate particles are accounted for while evaluating the FAM specimens. Third, due to the large surface area of the finer sized particles, distresses such as crack growth and moisture-induced damage are concentrated in the mortar fraction of the full asphalt mixture. Therefore, evaluating the FAM amplifies the effect of additives and binder-aggregate interactions on these distresses. Owing to these advantages, the FAM specimens were used to evaluate the effect of using different WMA additives and reduced mixing temperatures on the fatigue cracking and moisture damage resistance of asphalt mixtures.

An important factor in the context of fatigue cracking resistance of WMA and conventional HMA mixtures is the aging of the asphalt binder. Oxidative aging of asphalt binders is known to increase the stiffness of the binder, reduce its ductility, and possibly affect its resistance to fatigue induced cracking. In practice, however, test specimens used to evaluate the fatigue cracking resistance of asphalt mixtures or mortars are typically only short-term aged prior to compaction. This is because of the extensive time required to simulate long-term aging in asphalt mixtures in a laboratory environment. For example, the AASHTO R30 recommends long-term aging of compacted asphalt mixtures at 85°C (185°F) for 120 hours. The extent and uniformity of aging in compacted samples when subjected to such limited aging times can be questioned. For example, in order to evaluate the effect of long-term aging on asphalt mixtures, Morian et al. (2011) aged test specimens for 3, 6, and 9 months at 60°C (140°C). Therefore, a relevant question that arises is whether the relative fatigue cracking resistance of different mixtures (as determined only after short-term aging) changes significantly after long-term aging.

A testing plan was designed to evaluate the influence of WMA production temperatures and additives on the fatigue cracking and moisture damage resistance of asphalt mortars or FAM mixtures. The findings from this testing plan would also allow us to compare the stiffness and fatigue cracking resistance of asphalt mortars before and after long-term aging.

2.2 Materials and Tests

In order to achieve the aforementioned objectives, the experimental plan shown in Table 2.1 was developed to conduct tests on FAM specimens. Two binders and four different WMA additives were used. The binders used were a PG76-28 and a PG64-22 and were obtained from local refineries in Texas. The PG76-28 was a binder with a relatively higher wax and acid content compared to other binders used in the state of Texas. The PG64-22 had a lower wax and intermediate acid content compared to other binders used in the state of Texas. These two binders are referred to as PG76-28HW and PG64-22BLW in the interim report. The WMA technologies used were an organic wax based additive (Sasobit[®]), a moisture based additive that is intended to improve workability by micro-foaming (Advera[®]), and two chemical technologies (Evotherm 3G[®] and Rediset WMX[®]). In addition to mixtures using the four WMA additives, a control mix and a mix with dehydrated Advera were also used. The dehydrated Advera was used as a control for the mixture produced using the Advera WMA technology in order to isolate the effect of water trapped in the zeolite particles from the effect of the particles itself. Dehydrated Advera was obtained by placing approximately 40 g (1.4 oz) of the additive in an oven at 150°C (302°F) for 24 hours immediately prior to adding it to the asphalt binder. Note that although only two different binders were used in this study, the combination of the binders with the different WMA additives resulted in modified binders with significantly different rheological properties as well as resistance to permanent deformation and fatigue cracking. The detailed properties of these binders and the significant differences are documented in the interim report.

Table 2.1: Test matrix for FAM or mortar specimens to evaluate fatigue cracking resistance and moisture-induced damage

Variables	Aged+ (Dry and after 24 hrs moisture conditioning)	Extended Aged++ (Dry)
Control A ¹	B1A1, B2A1	B1A1, B2A1
Sasobit	B1A1, B2A1	B1A1, B2A1
Evotherm 3G	B1A1, B2A1	B1A1, B2A1
Rediset WMX	B1A1, B2A1	B1A1, B2A1
Advera	B1A1, B2A1	B1A1, B2A1
Dry Advera	B1A1, B2A1 ²	B1A1, B2A1 ²

¹ Mixing at conventional mixing temperatures (all others at conventional mixing temperatures—20°C or 36°F).

² The tests on dry Advera were used to evaluate the effect of the residual particles in the mix.

+ Loose mix will be aged for 4 hours before compaction at mixing temperatures (hot mix for Control A and WMA for others).

++ In addition to +, loose mix is aged for 30 days at 60°C (140°F) in the environmental room to simulate extended aging.

B1 = PG76-28

B2 = PG64-22B

A1 = Limestone aggregate

A limestone aggregate was used for this study. The aggregate was obtained from a quarry in Buda, Texas. A Type C mixture following a typical dense gradation was designed in accordance with the 2004 TxDOT specbook (TxDOT 2004). The aggregate gradation for mortar essentially followed the same relative proportions of different sizes as the full asphalt mixture with the only difference being that aggregates passing #16 were used to produce the FAM

mixtures. Table 2.2 presents the final gradation of the FAM mixture. The optimum binder content for the Type C dense graded asphalt mixture using the PG64-22 binder was determined to be 5.5%. This binder content was then used to estimate the binder content for the mortar (the mixture passing #16 sieve size) using the following procedure. Approximately 7000 g (15.4 lb) of the Type C mixture was prepared with 5.5% of the PG64-22 binder. The loose mix was then carefully spread over a large surface area and the particles were separated by hand to the extent possible while the mix was still hot. After the loose mix cooled down, a rubber mallet was used again to separate the particles in the loose mix. The separated loose mix (Figure 2.1) was then sieved using ASTM sieve #16 and the fine aggregate mixture passing sieve #16 was ignited in the ignition oven in accordance with AASHTO T308. The binder content for the material passing the number #16 sieve was found to be 7.6%. This binder content was used to produce FAM mixes with the two binders (PG64-22 and PG76-28) and with/without WMA additives. This method to determine the binder content in the FAM mixtures was similar to that proposed by Sousa et al. (2011).

For the FAM mixes containing the PG76-28 binder, the control mixtures (including dehydrated Advera) were mixed at 163°C (325°F) and compacted at 143°C (289°F) while the mixtures with the warm mix additives were mixed at 143°C (289°F) and compacted at 123°C (253°F). For the FAM mixes containing the PG64-22, the control mixtures were mixed at 143°C and compacted at 123°C, whereas the mixtures with the warm mix additives were mixed at 123°C (253°F) and compacted at 103°C (217°F). Note that in each case, the mixing temperature denotes the temperature of the aggregate. The binder temperature for the control and modified binders was the same prior to adding it to the aggregates.

Table 2.2: Gradation of the FAM mixes

Sieve Size	FAM Gradation (% Retained)
#16	0
#30	36.7
#50	26.3
#200	24.8
Pan	12.6

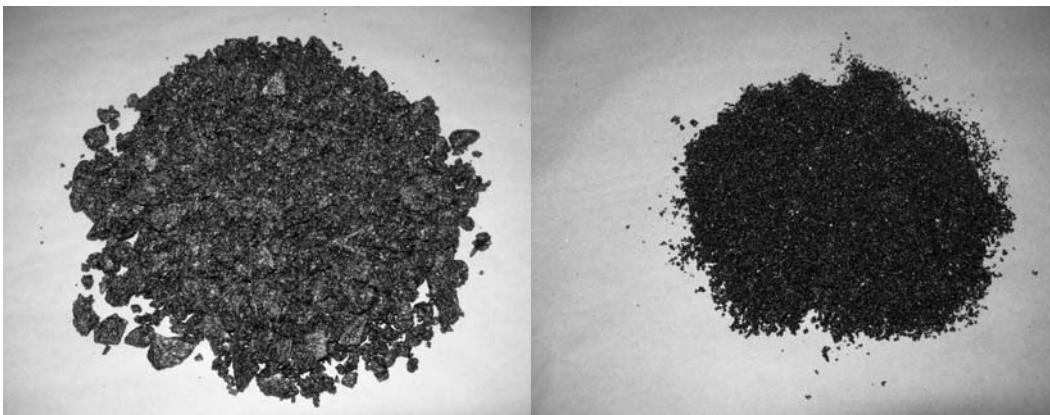


Figure 2.1: Loose asphalt mixture before (left) and after sieving on #16 sieve to obtain fine aggregate particles (right)

2.3 Short and Long-Term Aging and Compaction Mortars

The mixing and compaction temperatures for the WMA mixtures used in this study represents a 20°C reduction (36°F reduction) from the mixing and compaction temperatures used for the control mixtures. This corresponds well with the typical reduction in mixing and compaction temperatures associated with the production of WMA. The control and WMA mixtures were short-term aged for 4 hours at their corresponding compaction temperatures. The short-term aging time of 4 hours was selected following the current practice in Texas for short-term aging of WMA mixtures. In order to serve as a control, the HMA was also short-term aged for 4 hours. Following the short-term aging, the loose mix was separated into two batches. One batch was immediately used for compaction with the Superpave Gyratory Compactor (SGC) and the other batch was subjected to further aging in an environmental room for 30 days at 60°C (140°F). The basis for the choice of this combination of temperature and duration is discussed later in this subsection. The SGC was used to compact the loose FAM mix to produce a specimen that was 152.4 mm (6 inch) in diameter and approximately 60 mm (2.36 inch) in height. The ends of the SGC compacted specimen were sawed to achieve 40 mm (1.57 inch) height. Approximately 20 smaller specimens, each with a diameter of 12.5 mm (0.5 inch), were drilled out of the SGC specimen. The air void content of the finished FAM test specimens were determined to be 7% $\pm$ 0.5%. Figure 2.2 illustrates a typical SGC compacted specimen with a number of FAM test specimens that were drilled out of the SGC specimens.



Figure 2.2: Typical FAM test specimens cored out of a Superpave gyratory compacted specimen

An important part of this study was to determine the duration and temperature for which the loose FAM mixture must be aged to simulate a reasonable degree of extended aging. For this study a reasonable degree of extended aging was defined as the aging conditions (temperature and duration) that, when applied to a thin film of asphalt binder at atmospheric pressure, would result in a level of oxidation comparable to that of the PAV-aged binder. The following paragraphs present the literature review and tests conducted to determine the combination of temperature and duration for the extended aging of the loose mix. The authors recognize that the PAV-aged binder itself is not the most accurate representation of the extent of long-term aging in asphalt pavements and also that binder aging can change in the presence of aggregates (Chen & Huang 2000; Morian et al. 2011). However, as mentioned above, the objective of this study was to compare the relative fatigue cracking resistance and stiffness of different composites before and after being subjected to a reasonable degree of extended aging.

Long-term aging of asphalt binders or aging that occurs during the service life is commonly simulated in the laboratory using the PAV. Harrigan et al. (1994) recommend the use of the PAV at 90 to 110°C (194 to 230°F) at a pressure of 20 atmosphere of air for 20 hours to simulate long term aging. Glover et al. (2005) compared the long-term aging simulated using the PAV to the long-term aging simulated at higher than room temperature and atmospheric pressure. They reported that aging of thin films of asphalt binders for approximately 35 days at 60°C (140°F) and atmospheric pressure was equivalent to aging in the PAV for 20 hours at 90 to 110°C (194 to 230°F) and 20 atmospheres. The “equivalency” was established by comparing carbonyl area measured using Fourier Transform Infra-red (FTIR) spectroscopy and rheological properties such as zero shear viscosity.

The results presented by Glover et al. (2005) were verified for a subset of the binders and modifiers that were used in this study. Samples of the RTFO-aged PG64-22 binder with and without the warm mix additives (Sasobit, Evotherm 3G, and Rediset) were further aged in the environmental room as well as using the PAV. Aging in the PAV was carried out in accordance with ASTM D6521, where 50 grams (1.76 oz) of RTFO residue were placed into the PAV pans and aged for 20 hours at 100°C (212°F). Aging in the environmental room was carried out by placing 66 g (2.33 oz) of each RTFO-aged sample in aluminum trays measuring 22 cm (8.7 inch) by 30 cm (11.8 inch) and allowing the binder to age in the environmental room with an approximate film thickness of 1 mm (0.039 inch) at 60°C (140°F) for 30 days.

The degree of oxidation in the binder from the PAV as well as the environmental room was investigated by measuring the carbonyl area using the FTIR spectroscopy. FTIR spectroscopy is a robust and accurate noninvasive in-situ method that can provide data identifying the various functional groups present in the material. Several researchers have used the FTIR in the past to gauge the extent of oxidation in asphalt binders. For example, Chen and Huang (2000) used the carbonyl area from the FTIR spectra to quantify aging in different binders mixed with different fillers. Glover et al. (2005) used the carbonyl area as a metric for oxidation while comparing the extent of oxidation from different methods of aging.

The attenuated total reflection (ATR) method was used to obtain the FTIR spectra of the binders aged in the environmental room and PAV. The OPUS software was used to run the tests and calculate the integration areas under the peak corresponding to the carbonyl functional group. The carbonyl area, in arbitrary units, was computed as the area under the absorption spectrum between wavelengths of 1671.03 and 1720.05 cm^{-1} . Figure 2.3 compares the carbonyl area of the binders aged as a thin film in the environmental room at 60°C (140°F) after 22, 35, and 67 days, to the carbonyl area of the binders aged in the PAV. Results of the carbonyl area measurement for the control binder and the binder modified with Sasobit indicate that approximately 35 days of aging in the environmental room produced levels of oxidative aging that were similar to that for the PAV residue. The binder modified with the surfactant based WMA additives (Cecabase, Evotherm 3G, and Rediset) had slightly higher levels of oxidation after PAV aging compared to their oxidation levels after 35 days aging condition in the environmental room at 60°C (140°F). The results were consistent with the earlier findings reported by Glover et al. (2005). Additional details documenting the comparison of aging in the environmental room to that of the PAV are documented in other literature (Trujillo 2011). Therefore, for this study aging of the loose FAM mixtures for 30 days at 60°C (140°F) was considered to provide an adequate level of extended aging (note that the particles in the loose FAM mixture have a binder film that is much less than 1 mm or 0.039 inch).

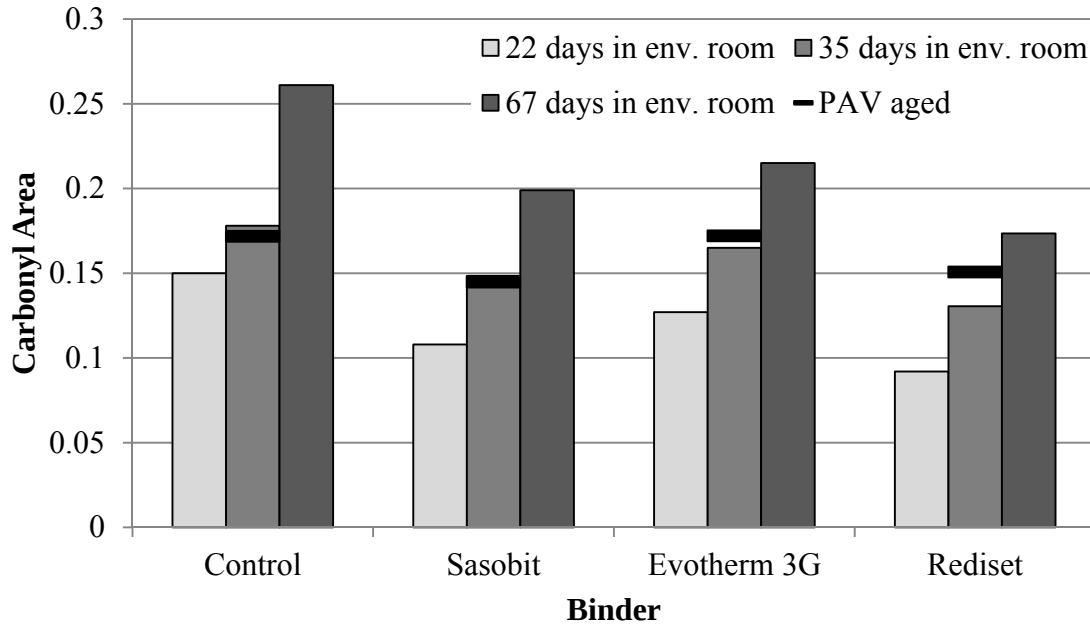


Figure 2.3: Carbonyl area of PG64-22 binder aged in the environmental room and pressure aging vessel

2.4 X-Ray CT Scanning

In this study, loose asphalt mortar was long-term aged in an environmental room and then compacted. The internal structure of an asphalt mixture is known to play a significant role in influencing the mechanical properties and the resistance of the mixture to major distresses, including rutting, fatigue cracking, thermal cracking, and low-temperature cracking. In the context of this study, a relevant concern was whether the loose mix compacted after long-term aging had the same internal structure (geometric alignment of aggregate particles within the matrix) as the mix compacted only after short-term aging. In order to address this concern, the authors conducted X-ray CT analysis of a limited number of FAM specimens compacted after short-term and long-term aging. This subsection briefly summarizes the metrics that were used to compare the internal structure of the test specimens analyzed from these two aging conditions.

The term internal structure of an asphalt concrete mixture refers to the content and spatial distribution of asphalt, aggregates, and air-voids (Masad et al. 1999). In a previous study, Bhasin et al. (2011) used X-ray CT images to determine the three-dimensional fabric tensor of the mastic within a mortar or asphalt mixture. They used the fabric tensor and star length distribution (SLD) to compute the (i) degree of anisotropy, (ii) average star length in the preferred direction, and (iii) average of variation in star lengths along different directions. Their study also showed that these metrics were sensitive to the mixture properties and method and of compaction. In this study, these metrics were used to compare the internal microstructure of the mortar specimens compacted after short-term aging to the mortar specimens compacted after short and long-term aging.

The aforementioned metrics to compare the internal structure of the asphalt mortars were computed using digital images acquired by a high resolution X-ray CT scanner. Grayscale digital images obtained using the X-ray CT scanner were processed to three intensity levels that

reflected the air voids, matrix (binder with fines passing #200 sieve), and fine aggregate particles in the FAM specimen according to procedures described in Bhasin et al. (2011). The SLD was calculated by randomly selecting 1000 points within the matrix. Lines were drawn emanating from each point along 512 predefined orientations in 3 dimensions until the lines encountered a boundary. The lengths of these lines were measured at all orientations and points to obtain the SLD. A three-dimensional rose diagram of the mean star length (along a given orientation) provides a visual representation of the geometry (Figure 2.4). The SLD was also used to compute the fabric tensor and the three metrics described above. Details of the methods used to obtain these metrics are beyond the scope of this report and can be found in other literature (Bhasin et al. 2011). Table 2.3 presents a summary of these metrics for two different mixtures using the same asphalt binder (PG 76-28) compacted after short-term aging and long-term aging. The coefficient of variation for each metric between the four FAM specimens was very small. This result indicates that the FAM specimens had very similar internal structures even when compacted after long-term aging.

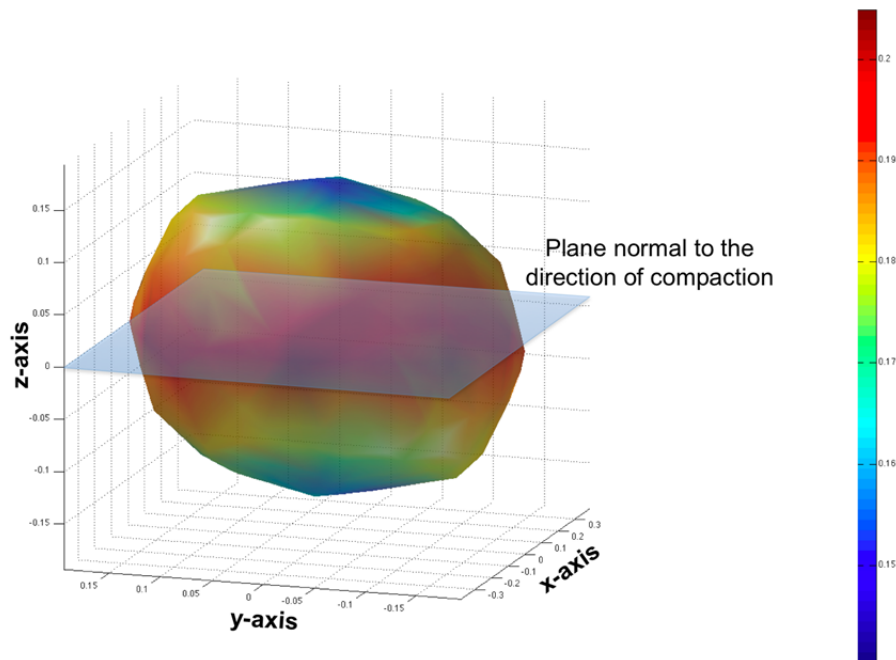


Figure 2.4: Typical three-dimensional rose diagram showing the average distribution of the matrix between the particles (fine aggregates) in a mortar specimen

2.5 Moisture Conditioning

As indicated in Table 2.1, the short-term aged and compacted FAM specimens were also evaluated for their fatigue cracking resistance after moisture conditioning. Moisture conditioning of the FAM specimens was carried out as follows. Three replicate specimens for the same type of mix were placed in a vacuum container that was approximately 50 mm (2 inch) deep and half filled with water. A vacuum pump was used to apply vacuum for 15 minutes. After 15 minutes, the specimens were placed in a water bath at room temperature ($23 \pm 1^\circ\text{C}$ / $73 \pm 1.8^\circ\text{F}$) for 24 hours. The level of saturation in the FAM specimens was determined volumetrically and found to be within 80 and 90% for most samples.

Table 2.3: Metrics that compare the internal structure of FAM specimens compacted after short-term and long-term aging

Mix Type	DA	Average star length in preferred direction	Average coefficient of variation in star lengths
1 STA	1.22	0.18	70.9
2 STA	1.19	0.16	69.0
3 LTA	1.15	0.17	69.9
4 LTA	1.23	0.17	71.4
Coeff. of variation	3%	3%	2%

2.6 Mechanical Testing

The linear viscoelastic properties and resistance of the test specimens to fatigue cracking were measured at 23+/-1°C (73+/-1.8°F) using Bohlin's C-VOR model dynamic shear rheometer. Shear oscillations following a sinusoidal wave form at a low stress amplitude of 15 KPa (2.17 psi) were applied for 10 minutes at a frequency of 10 Hz to determine the undamaged complex modulus, G^* , and phase angle δ of the FAM specimens. Shear oscillation following a sinusoidal waveform with high-stress amplitude of 275 KPa (39.9 psi) was then applied at a frequency of 10 Hz until specimen failure to determine the fatigue cracking resistance of the mortar specimens.

2.7 Results

2.7.1 Influence of WMA additives and temperature on fatigue cracking life

At least two replicates of FAM specimens were tested for stiffness and fatigue cracking resistance using the dynamic mechanical analyzer after short-term and long-term aging. The mean values and the coefficient of variation of the stiffness, G^* , and fatigue life are presented in Table 2.4 for the short-term aged specimens and in Table 2.5 for the long-term aged specimens. Figures 2.5 through 2.8 also illustrate these results for mortar specimens using the two binders at different levels of aging. In this study, fatigue life was defined as the number of load cycles to achieve 50% of the initial modulus of the specimen. Note that all tests were conducted using a constant stress amplitude. This approach can result in rank orders that differ from those created when the tests are conducted using a constant displacement (e.g., overlay test). This difference occurs because in the displacement controlled tests, softer materials develop smaller internal stresses that inhibit the nucleation and propagation of fatigue cracks.

An ANOVA and a Fisher's LSD test were performed with 95% reliability to determine whether any significant difference developed between the test results for the control and WMA fine aggregate mixtures, either in the short-term or long-term aging conditions. The data presented in Tables 2.4 and 2.5 show that the stiffness of at least some of the modified mixtures using the PG76-28 binder was significantly different from the control HMA. The stiffness of all WMA mixtures produced using PG64-22 binder were similar to the control HMA. In other words, for the PG64-22 binder, WMA technologies did not have a significant effect on mixture stiffness.

The statistical analysis of the data also showed that for the short-term aged mixtures at least some of the additives affected the fatigue life of the test specimens compared to the control. However, after long-term aging, the fatigue cracking lives for the control and modified mixtures were similar for the PG76-28 binder mixture but different for the mixtures with the PG64-22 binder. In general the data suggests that the stiffness or fatigue life of long-term aged WMA mixture is similar to or lower than that of the HMA mixture, depending on the type of binder used.

Results for the FAM mixtures produced using PG76-28 binder are consistent with several of the research studies conducted on plant-produced WMA mixtures. For instance, a study conducted by Johnson et al. (2006) on the fatigue cracking resistance of plant-produced WMA mixtures found that WMA mixtures have either similar or better resistance to fatigue cracking. Johns et al. (2010) also evaluated the fatigue resistance of plant-produced WMA mixtures and found that the use of a WMA technology did not affect the fatigue resistance of the asphalt mixture. However, fatigue life of WMA mixtures produced using PG64-22 was significantly different (and in some cases less) compared to the control. This result suggests that each binder-additive pair can create differing mechanical response of the material.

Table 2.4: Relative change in stiffness and fatigue life after short-term aging

Binder	Modification	Complex Modulus, G*			Fatigue Life, N _f		
		G* [x10 ⁸ Pa]	COV	Diff. from Control ⁺	N _f [10 ³]	COV	Diff. from Control ⁺
PG64-22	Control HMA	9.71	1%	N/A	37.26	11%	N/A
	Sasobit	10.97	0%	N	10.84	8%	Y
	Evotherm 3G	9.55	15%	N	23.74	48%	N
	Advera	9.33	3%	N	5.24	30%	Y
	Dry Advera	11.16	7%	N	44.36	29%	N
	Rediset WMX	9.01	6%	N	26.56	7%	N
PG76-28	Control HMA	4.43	8%	N/A	2.19	3%	N/A
	Sasobit	4.18	2%	N	3.95	45%	N
	Evotherm 3G	2.77	7%	Y	4.72	20%	N
	Advera WMA	2.77	4%	Y	3.46	15%	Y
	Dry Advera WMA	4.72	9%	N	0.84	22%	N
	Rediset WMX	3.30	5%	Y	2.29	12%	Y

⁺Note: Statistically significant difference at $\alpha = 0.05$

Table 2.5: Relative change in stiffness and fatigue life after long-term aging

Binder	Specimen	Complex Modulus, G*			Fatigue Life, N _f		
		G* [x10 ⁸ Pa]	COV	Diff. from Control ⁺	N _f [10 ³]	COV	Diff. from Control ⁺
PG64-22	Control HMA	11.49	5%	N/A	30.38	12%	N/A
	Sasobit	12.38	5%	N	15.19	31%	Y
	Evotherm 3G	9.13	9%	N	17.55	16%	Y
	Advera	10.50	16%	N	10.78	25%	Y
	Dry Advera	12.48	13%	N	39.08	2%	Y
	Rediset WMX	10.84	12%	N	13.84	4%	Y
PG76-28	Control HMA	10.20	28%	N/A	1.97	35%	N/A
	Sasobit	9.67	3%	N	2.05	29%	N
	Evotherm 3G	7.09	30%	N	2.34	36%	N
	Advera WMA	5.91	19%	Y	1.98	50%	N
	Dry Advera WMA	8.41	12%	N	1.53	52%	N
	Rediset WMX	4.78	38%	Y	2.57	23%	N

⁺Note: Statistically significant difference at $\alpha = 0.05$

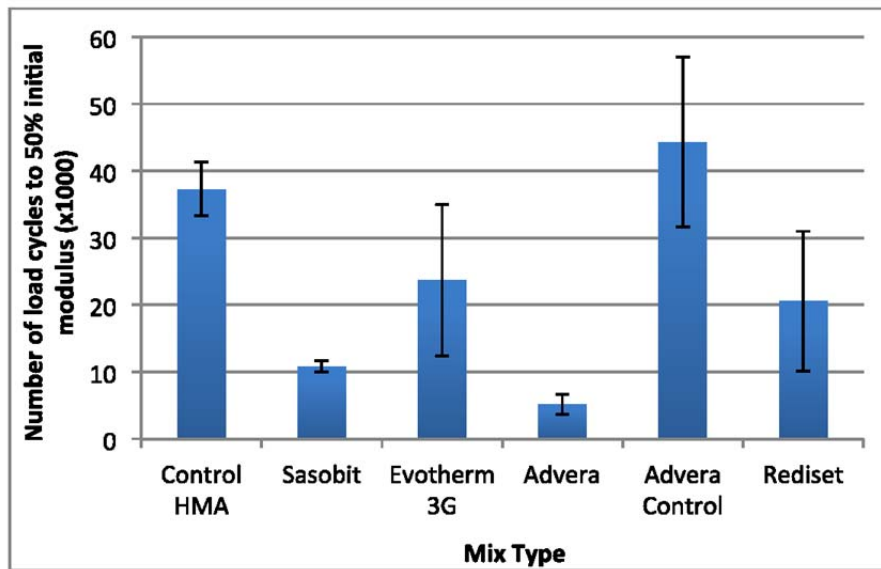


Figure 2.5: Fatigue cracking life of FAM specimens using the PG64-22 binder after four hours of short-term aging (based on a stress controlled test)

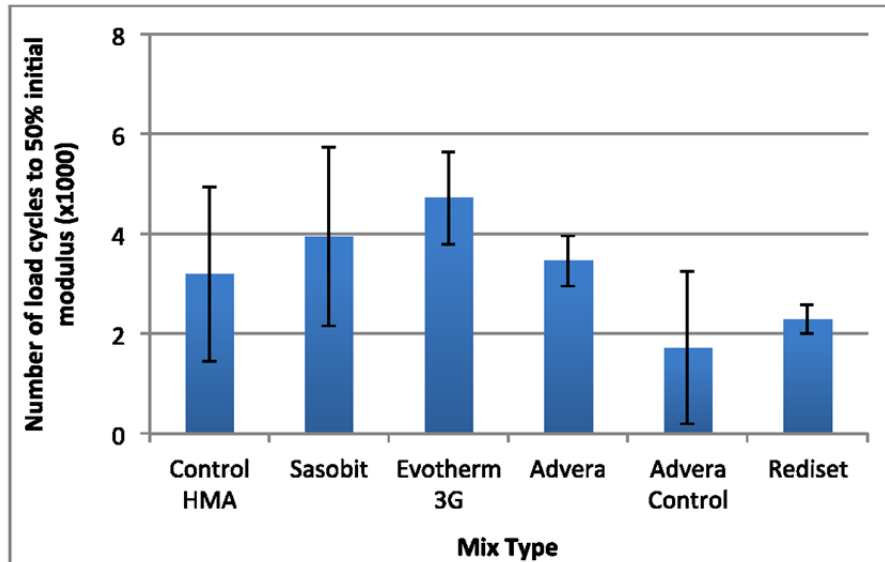


Figure 2.6: Fatigue cracking life of FAM specimens using the PG76-28 binder after four hours of short-term aging (based on a stress controlled test)

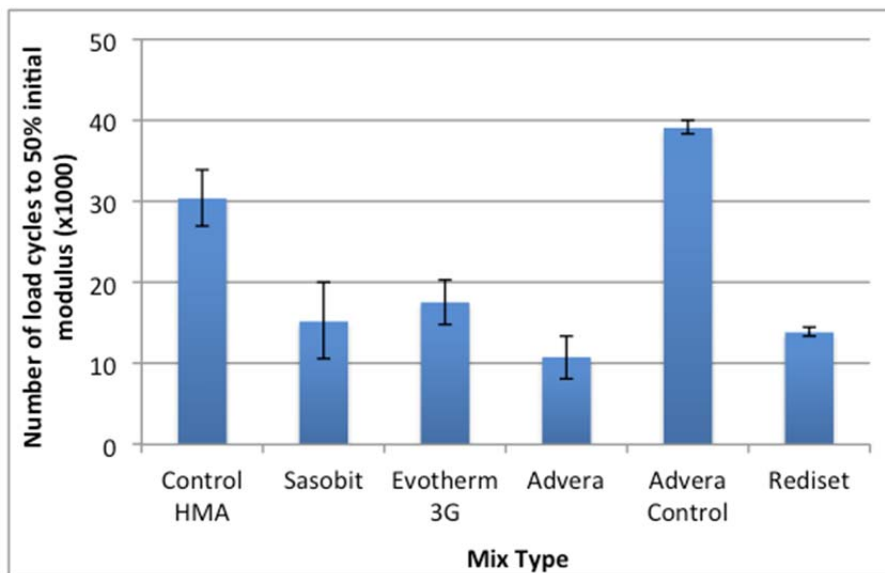


Figure 2.7: Fatigue cracking life of FAM specimens using the PG64-22 binder after four hours of long-term aging (based on a stress controlled test)

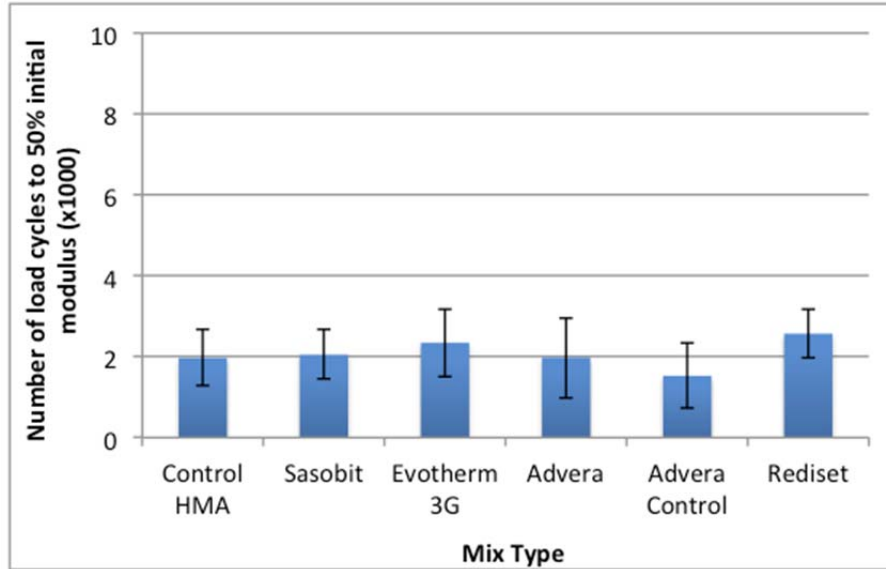


Figure 2.8: Fatigue cracking life of FAM specimens using the PG76-28 binder after four hours of long-term aging (based on a stress controlled test)

2.7.2 Comparison of short-term aged and long-term aged fatigue cracking resistance

WMA mixtures are produced and compacted at temperatures lower than those of conventional HMA mixtures that may result in a softer asphalt binder. The reduction in production temperature of WMA mixtures causes a reduction in binder oxidation in the short term. However, after the WMA mixtures are compacted and placed in the field, they will be subjected to the same temperature and weather conditions as that of HMA mixtures. The objective of conducting this test was to quantify the effect of WMA technologies on the stiffness and fatigue cracking life of the mortar specimens. According to Bonaquist (2011), the effect of binder oxidation on the fatigue life of mixtures is not well known. Therefore, one of the main goals of this study was also to evaluate whether the relative stiffness and fatigue cracking resistance of different mixes change after being long-term aged in the presence of the fine aggregate and mineral filler.

Stiffness, G^* , and fatigue cracking life of FAM specimens after short-term aging are compared with the stiffness and fatigue life of FAM specimens after long-term aging in Figures 2.9 and 2.10, respectively. In addition, Figure 2.11 compares the rankings of the 12 different mixtures in terms of their fatigue life before and after long-term aging. The data points represent identical materials after short-term and long-term aging.

The results demonstrate that the stiffness and fatigue life of short-term aged mixtures were well related to the respective properties of the long-term aged mixtures. In particular, the rank of the mixtures in terms of their fatigue cracking resistance did not change after long-term aging. Figure 2.10 shows that the fatigue cracking rankings of the specimens before long-term aging correlates well after long-term aging. That is, the relative fatigue cracking resistance of different mixtures did not change significantly after long-term aging.

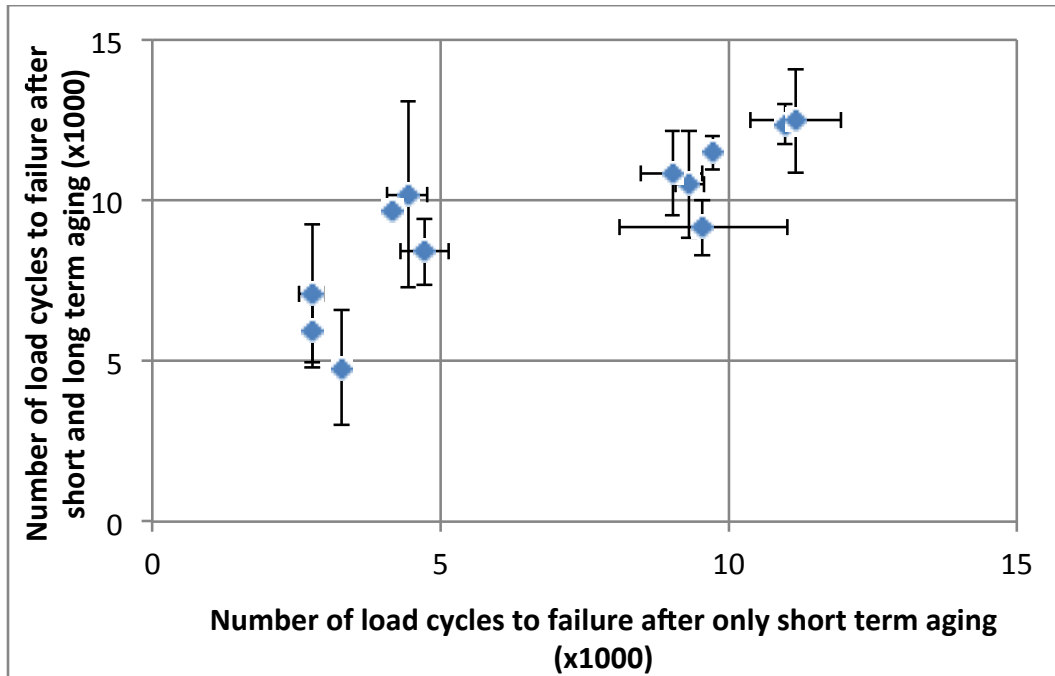


Figure 2.9: Comparison of G^* before and after long-term aging for different FAM specimens

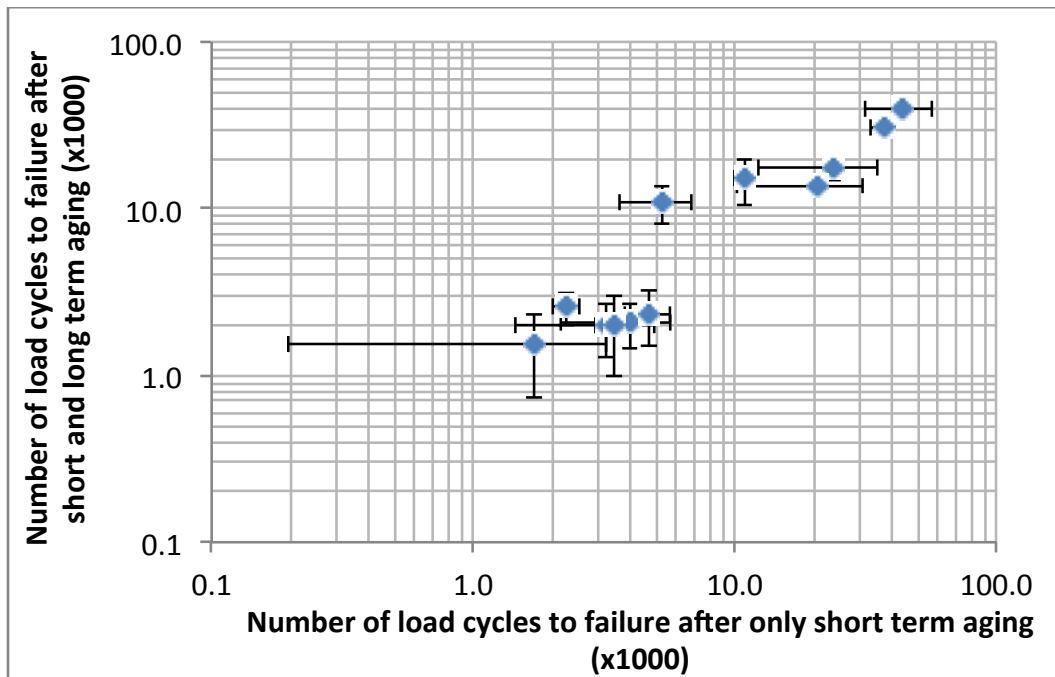


Figure 2.10: Comparison of fatigue life before and after long-term aging for FAM specimens

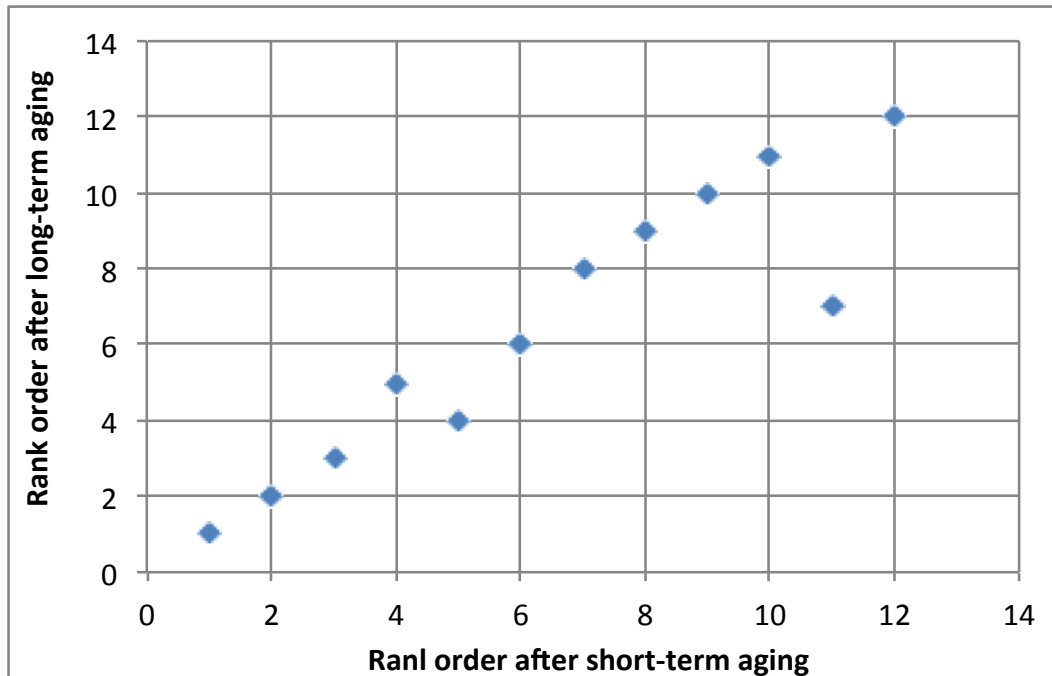


Figure 2.11: Ranking based on fatigue cracking resistance for FMA specimens before and after long-term aging

2.7.3 Moisture damage resistance

One of the objectives of this task was also to evaluate the moisture damage resistance of WMA and hot mix FAM specimens. This was quantified as (i) the ratio of the undamaged complex modulus of the moisture-conditioned specimen to the unconditioned specimen and (ii) the ratio of the fatigue cracking life of the moisture conditioned specimen to the unconditioned specimen. Figures 2.12 and 2.13 illustrate these metrics for the different combinations of binders and warm mix additives as well as the control. The test results show that moisture susceptibility of the FAM specimens was affected by a combination of the WMA additives and mixing temperatures. The control mixtures representing the HMA produced the best results for all combinations that were tested. Moisture conditioning had minimal effect on the reduction in stiffness of the HMA mixtures. The effect of moisture on the fatigue cracking life of the specimens produced using the PG64-22 binder was similar for most additives except Advera WMA. For the specimens produced using the PG76-28 binder, Advera WMA resulted in the largest reduction in stiffness due to moisture conditioning, and Sasobit resulted in the largest reduction in fatigue cracking life due to moisture conditioning. Comparison with the dehydrated Advera indicates that some of the observed performance differences could be due to the interaction with the zeolite particles.

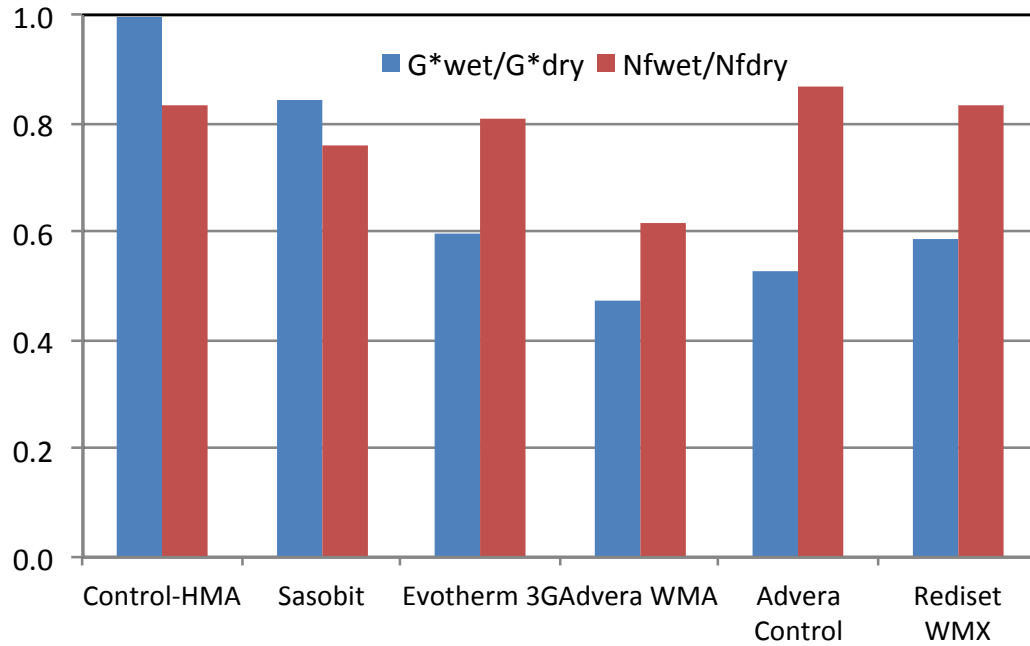


Figure 2.12: Moisture damage resistance based on stiffness and fatigue cracking life for FAM specimens with the PG64-22 binder

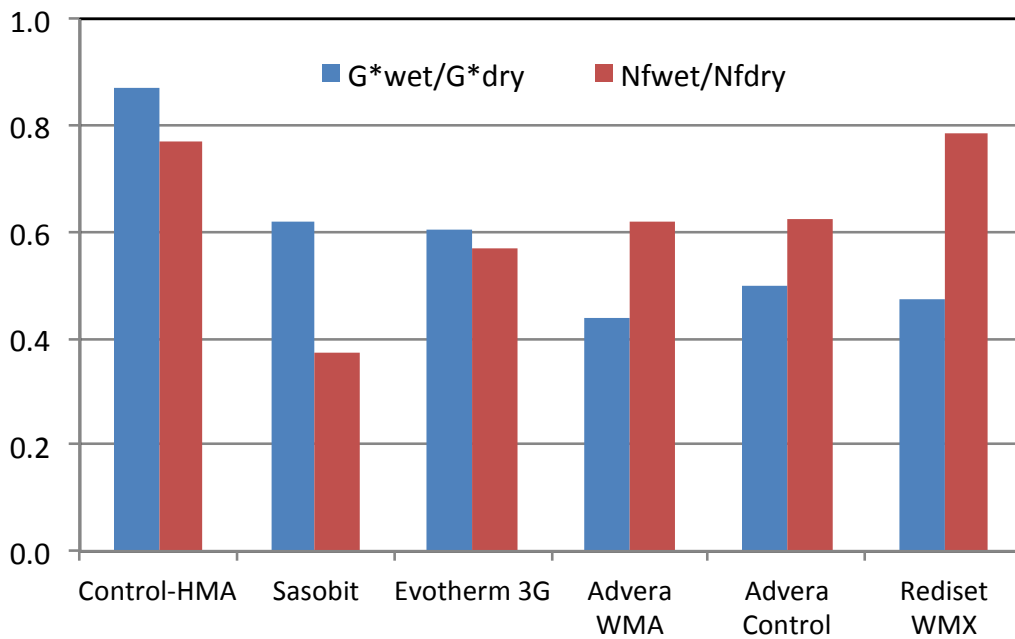


Figure 2.13: Moisture damage resistance based on stiffness and fatigue cracking life for FAM specimens with the PG76-28 binder

2.8 Summary

In this part of the study, one aggregate, two binders, and four WMA additives were used to evaluate the fatigue cracking characteristics of fine aggregate mixtures after short-term and long-term or extended aging conditions. Extended aging of the FAM mixtures was achieved by conditioning the loose mix in an environmental room for 30 days at 60°C (140°F). FTIR results for asphalt binders show that these aging conditions oxidize the binder to levels comparable to that of the PAV aging procedure. X-ray CT analyses showed that the samples compacted after long-term aging had a similar internal structure compared to samples compacted after short-term aging. The following conclusions were reached based on the mechanical tests conducted on the FAM specimens.

Generally, the fatigue life of mixtures with warm mix additives were similar to or lower than that of the control mixtures, depending on the type of the binder-additive pair. This result suggests the need to carefully and continually investigate the fatigue cracking resistance of asphalt mixtures produced using WMA technologies. The results were consistent with the findings from the binder tests that indicated that the binder resistance to fracture was dependent on each binder-WMA additive pair. Several binder-additive pairs that demonstrated a reduced fracture resistance (compared to control) from the binder test also demonstrated a reduced fracture resistance (compared to control) in the mortar test.

The complex shear modulus as well as the fatigue life (number of load cycles to failure) for the different binder-additive combinations before long-term aging correlated well with these properties measured after long-term aging. The results from this study indicate that the rank order of fatigue cracking resistance of the mixtures did not change significantly after long-term aging. This finding is consistent with Morian et al. (2011), who reported that different binders aged at nearly the same rate in compacted specimens aged for long durations of time. The authors recognize that this data is limited, based as it is on two source binders that were modified using different methods and one aggregate. In particular, the presence of different aggregates may affect the rate at which the binders age in the mix. The results must not be construed to diminish the importance of evaluating the fatigue cracking resistance after long term aging of the mix. However, when limited resources are available to compare different binders and/or additives with the same aggregate, a comparison of the fatigue cracking resistance of the mixes even after short-term aging may be reasonable.

Chapter 3. Stiffness and Resistance to Fracture, Rutting, and Moisture Damage in WMA Mixtures

3.1 Introduction

Chapter 2 of this report presented the details and findings pertaining to the effect of WMA additives and mixing temperature on the stiffness, fatigue cracking resistance, and moisture-induced damage of asphalt mortars. This chapter presents the findings from the last component of this study. The objective of this part of the study was to corroborate the findings based on the binder and mortar tests by measuring the mechanical properties of a limited number of full asphalt mixtures. The mechanical properties and methods used to evaluate these properties are

- stiffness or complex modulus measured in the indirect tension mode at different frequencies at intermediate temperatures,
- rutting resistance and moisture damage resistance measured using the Hamburg wheel-track test at elevated temperature, and
- fracture resistance based on the indirect tensile strength at low temperatures.

3.2 Materials

Full mixtures were prepared using two different binders, one aggregate, and four different WMA technologies. The binders used were the PG76-28 and the PG64-22, which were also used for FAM testing as described in Chapter 2. The WMA additives and controls were also similar to those used for FAM testing: Sasobit[®], Advera[®], Evotherm 3G[®], and Rediset WMX[®]. The two controls were a regular hot mix with no additives and a hot mix with dehydrated Advera.

3.3 Experimental Methods, Analytical Methods, and Results

3.3.1 Hamburg Wheel Tracking Device

The Hamburg wheel-tracking device (HWTD) was used to evaluate the rutting and moisture damage resistance of a limited number of WMA mixtures compared to the HMA mixtures. Another objective of conducting these tests was to evaluate whether the findings reported from the binder tests were generally in agreement with the mixture tests. The HWTD is a torture test that is used to assess the rutting and moisture damage susceptibility of HMA. This test is performed by oscillating a 203.2-mm (8.0-inch) diameter and 47-mm (1.85-inch) wide steel wheel loaded with 71.7 kg (158 lb.) over a Superpave Gyratory Compactor (SGC) compacted specimen, 63.55 mm (2.5 inches) in height submerged in water at 50°C (122°F). Permanent deformation of each specimen is recorded with reference to the number of passes of the loaded wheel. For this study, the test was conducted for 20,000 passes or until the sample reached a maximum deformation of about 12.5 mm (about 0.5 inch). Mixtures showing excessive susceptibility to moisture damage tend to undergo stripping and usually exhibit a sudden increase in the slope of the curve for rut depth versus number of passes after a certain number of cycles. Figure 3.1 shows typical deformation curves for samples that exhibit either little or significant moisture damage in a Hamburg test.

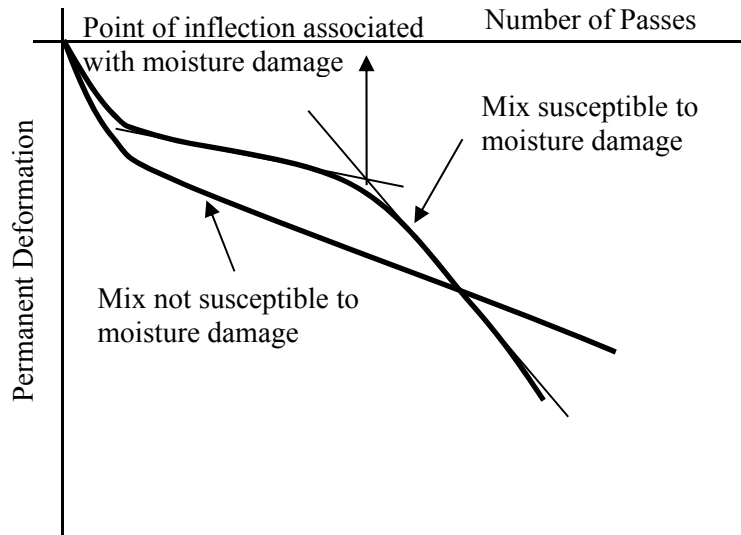


Figure 3.1: Schematic of the two different responses from the Hamburg wheel-tracking test

For the mixes that undergo moisture damage, the following method was adopted to determine the number of passes at which moisture damage commenced. After a number of initial passes (typically ranging from 200 to 300), the rate of deformation of the mix becomes constant. Failure due to moisture damage is identified by a sudden increase in the rate of deformation as the test progresses. Equations of the two best-fit lines corresponding to each linear zone (before and after incipient moisture damage) are determined. The abscissa of the point of intersection of these two lines is considered an estimate of the number of passes at which moisture damage begins. In the following sections of this report, this will be referred to as the point at which moisture damage starts, although in reality this point refers to the number of cycles when the effect of moisture damage is apparent (damage may have started several cycles earlier).

Four replicates of each mixture design were tested using the HWTD, with two replicates under each loading wheel. Figure 3.2 illustrates the typical results from a WMA mixture that demonstrated moisture-induced damage. Figures 3.3 and 3.4 present the results (rutting and inflection point) for the mixtures with the PG64-22 and PG76-28 binders. All WMA mixtures showed similar or lower rutting and moisture damage resistance compared to the control HMA. Note that the Advera control was a hot mix control used to evaluate the effect of residual particles and not a WMA. The reduced rutting resistance was more significant for the mixtures with the PG76-28 binder.

The results from the HWTD were consistent with the results from the binder test presented in the interim report. For the PG64-22 binder, the non-recoverable compliance (Jnr) values for the binders with the Evotherm, Sasobit, and Rediset additives were similar to the Jnr value of the control binder representing the hot mix. HWTD results show that the mixtures that the mixtures with these binder-additive combinations had similar rutting resistance. For the PG76-28 binder, the Jnr values for the binders with Evotherm, Sasobit, and Rediset additives were higher compared to the Jnr for the control binder, indicating an increased susceptibility to rutting. HWTD results show that the mixtures with these binder-additive combinations did in fact have an increased susceptibility to rutting compared to the control.

The results pertaining to the moisture sensitivity of different mixtures based on the HWTD results were similar to the results for moisture sensitivity of different FAM specimens (from Chapter 2) based on the fatigue cracking life of dry and moisture conditioned specimens. In general, in both cases (FAM testing and HWTD) the WMA mixtures demonstrated a similar or increased susceptibility to moisture-induced damage compared to the control. For example, based on the fatigue testing of FAM specimens, WMA mixtures with the PG76-28 binder had higher susceptibility to moisture-induced damage compared to the control, with the Rediset mix being relatively better than the other WMA mixes. This was similar to the results from the HWTT.

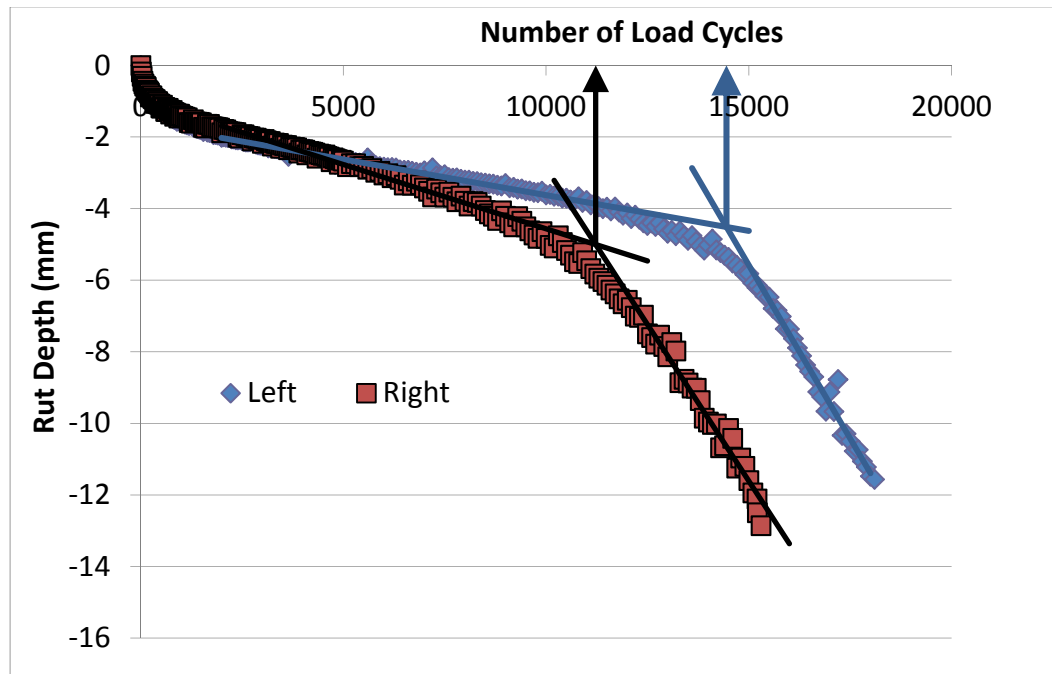


Figure 3.2: Typical data from one of the WMA mixture specimens with inflection points for moisture-induced damage

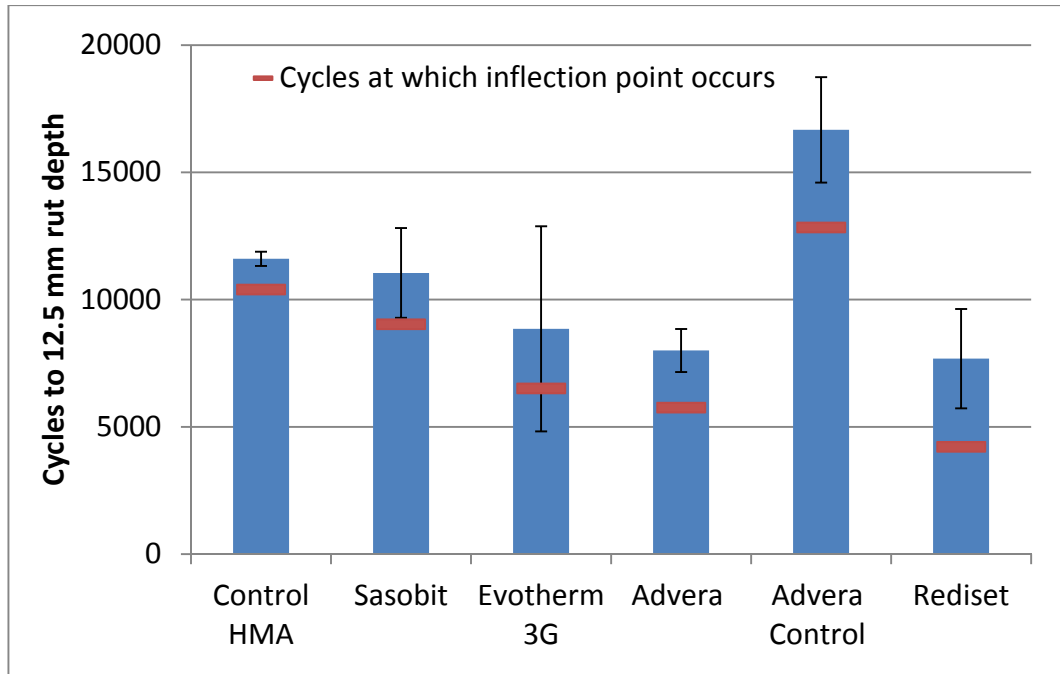


Figure 3.3: Rutting resistance and inflection point for moisture damage on asphalt mixtures with PG64-22 binder

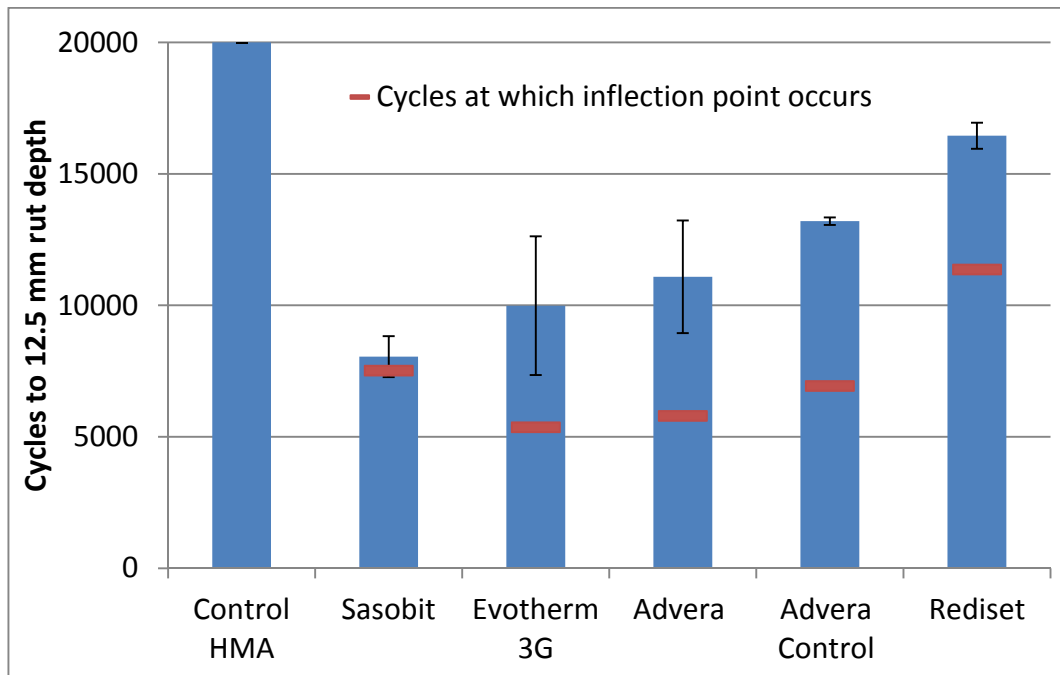


Figure 3.4: Rutting resistance and inflection point for moisture damage on asphalt mixtures with PG76-28 binder

3.3.2 Dynamic modulus in indirect tension mode

The dynamic modulus of the different asphalt mixtures was measured at $23 \pm 0.5^\circ\text{C}$ ($73 \pm 0.9^\circ\text{F}$) at frequencies of 10Hz, 5Hz, 1Hz, and 0.1Hz. The following is a brief description of the procedures used to fabricate the specimens, conduct the dynamic modulus test, and analyze the results.

Three specimens—152.4 mm (6 in.) in diameter and approximately 125 mm (approximately 5 in.) high—of each mixture type were compacted using the SGC. The ends of the SGC compacted specimens were cut to obtain a single 101.6 mm (4 inch) specimen. Each specimen was then cut again in two halves to obtain two 50.8 mm (2 inch) specimens. At least four test specimens were fabricated for each mixture type. The air voids of the finished specimens were measured and found to be $7 \pm 1\%$. Eight metallic strain gauge holders were affixed on the two sides of each test specimen. The strain gauge holders accommodate four strain gauges with two strain gauges on each face of the specimen. The two strain gauges on each face are at right angles to each other with one of the strain gauges oriented along the direction of the loading axis. The strain gauge holders were affixed to the specimen using a metal template to ensure proper alignment and orientation. Figure 3.5 illustrates the test specimen in a servo-hydraulic loading frame with the two strain gauges on the front face of the specimen. A gauge length of 50.8 mm (2 inch) was used in all cases. The actual height of each specimen was also measured for use in calculations related to the complex modulus.

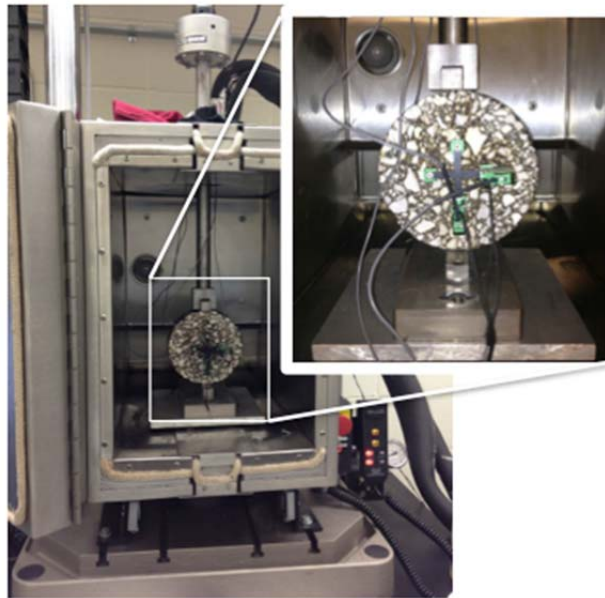


Figure 3.5: Setup used to measure dynamic modulus in indirect tension mode

The test specimen was placed in the loading frame and aligned such that one pair of strain gauges was directly in line with the centerline of the loading axis. Compressive loads were applied to the test specimen via a loading strip that was 19 mm (0.75 inch) wide. The load strip was hinged from the top to avoid non-uniform stress distribution that may be due to any unevenness on the loading surface. A seating load of 0.05 kN was applied to the test specimen. After applying the seating load, conditioning cycles were applied to the specimen using a stress amplitude of 0.01 kN and a frequency of 25 Hz frequency. The test was then conducted by

applying 100 cycles at 10 Hz, 50 cycles at 5 Hz, 20 cycles at 1 Hz, and 10 cycles at 0.1 Hz. A 30 second rest period was introduced between each loading frequency. Also, only the data from the last 10 cycles for the 25 Hz and 10 Hz and last 5 cycles from the 1 and 0.1 Hz frequencies of loading were analyzed to avoid the initial transient effect. The load amplitude was adjusted for different frequencies such that the maximum strain experienced by the horizontal strain gauges was typically within 200 micro-strains.

The data were analyzed to obtain the applied load amplitude, the strain amplitude from the two vertical strain gauges, and the strain amplitude from the two horizontal strain gauges. The raw data collected from the data acquisition system was fit to equation 3.1. In equation 3.1, $y(t)$ represents the load or strain as it changes with time t , f is the known frequency of loading in Hz, and a , b , c , and p are fitting constants that represent the mean of the amplitude at the start of the data capture, slope of the shift in the mean amplitude (indicative of rate of accumulated deformation in the specimen), amplitude of the parameter y , which could be load or strain from one of the four strain gauges, and phase shift in the data, respectively. The fitted load or strain amplitude is then used for further analysis. Figures 3.6 and 3.7 illustrate the typical raw data (circles) collected from the data acquisition system as well as the fitted functions (continuous line) for the load and one of the four strain gauges, respectively.

$$y(t) = a + bt + c \sin(2\pi ft + p) \quad 3.1$$

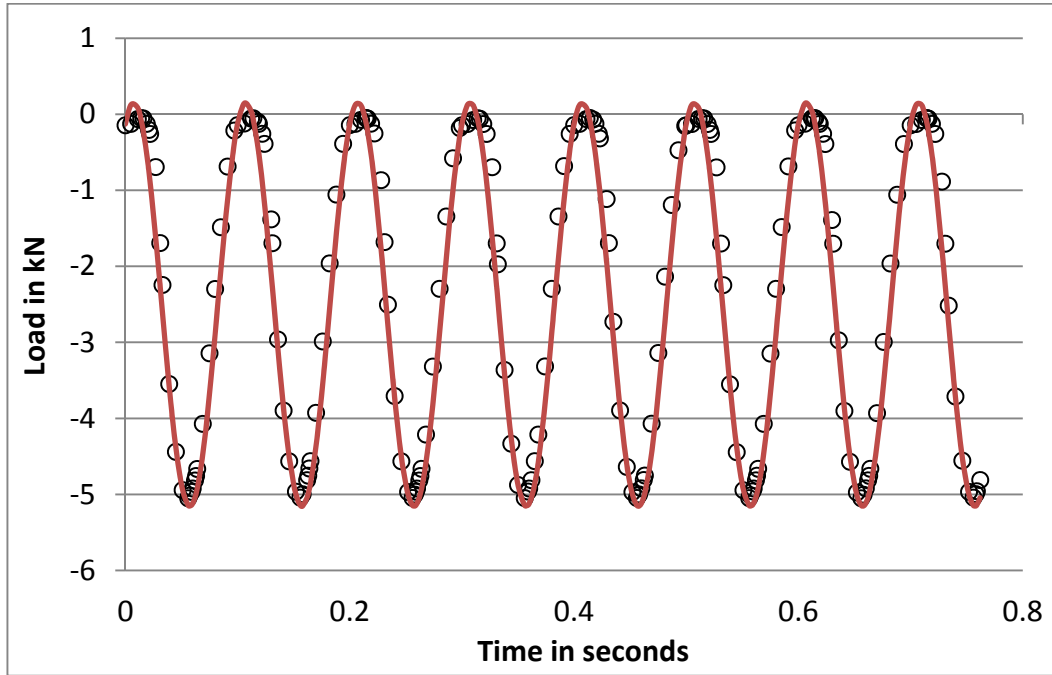


Figure 3.6: Typical raw data and fitted wave form for load

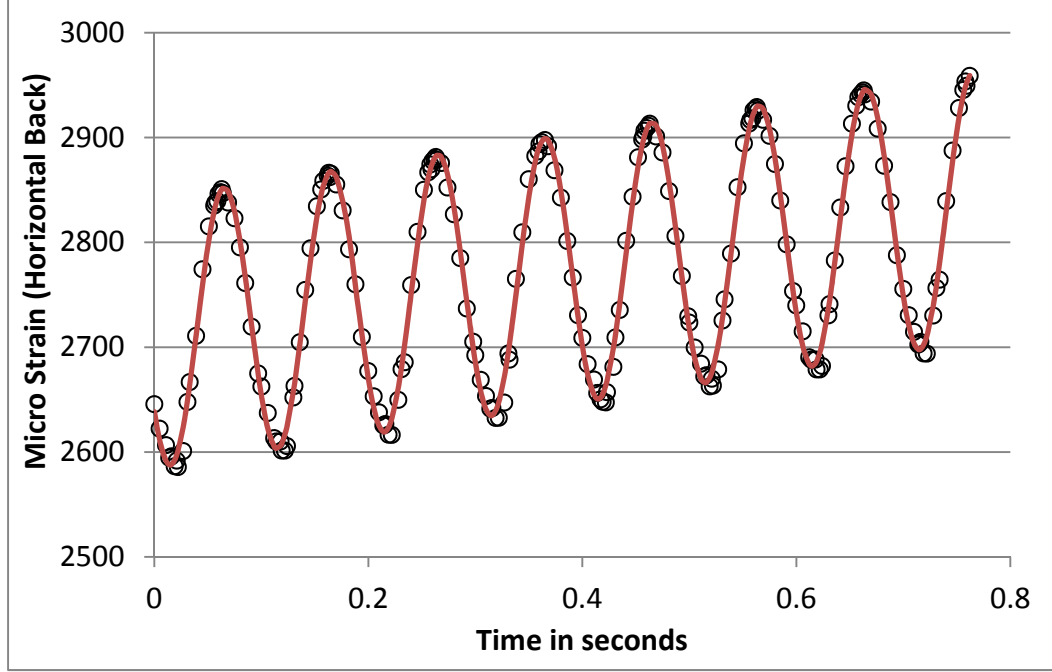


Figure 3.7: Typical raw data and fitted wave form for strain gauges (the values on the y-axis are not absolute micro-strains but are relative to initial value at the start of the test)

Kim et al. (2004) presented an analytical solution to determine the dynamic modulus using the applied load amplitude, the measured horizontal strain amplitude, and the measured vertical strain amplitude in the indirect tension mode. The complex modulus, $|E^*|$, in this case is computed from Equation 3.2. In this equation, P_0 is the load amplitude, V_0 is the displacement amplitude in the vertical direction, and U_0 is the displacement direction in the horizontal direction. The horizontal and vertical displacement amplitudes can be calculated using the strain amplitudes in the respective directions and the gauge lengths. The parameter a in Equation 3.2 is the width of the loading strip and d is the thickness of the specimen. The terms $\beta_1, \gamma_1, \beta_2$ and γ_2 are constants that are functions of the gauge length and specimen geometry. The constants provided by Kim et al. (2004) were not applicable for the geometry used in this study. Therefore, these constants were calculated using their respective definitions (Table 3.1).

$$|E^*| = 2 \frac{P_0}{\pi a d} \frac{\beta_1 \gamma_2 - \beta_2 \gamma_1}{\gamma_2 V_0 - \beta_2 U_0} \quad 3.2$$

Table 3.1: Geometry constants used for dynamic modulus calculations

Specimen dia. (mm)	Gauge length (mm)	β_1	β_2	γ_1	γ_2
152.4	50.8	-0.0198	-0.00617	0.0054	0.0172

Equation 3.2 and the geometric constants shown in Table 3.1 were then used to compute the dynamic modulus of the different mixtures included in this study. At least two replicate specimens were used for each mixture type. Figures 3.8 and 3.9 illustrate the dynamic modulus of the different mixtures as a function of frequency. In terms of stiffness, with one exception, all WMA mixtures had a stiffness that was similar to or less than the control HMA. The differences between the HMA and the WMA are more exaggerated at lower frequencies. This is clearly seen when the complex modulus for the WMA mixtures is normalized by the complex modulus for the control HMA at each frequency. Figures 3.10 and 3.11 illustrate the normalized dynamic modulus for the mixtures with these two binders.

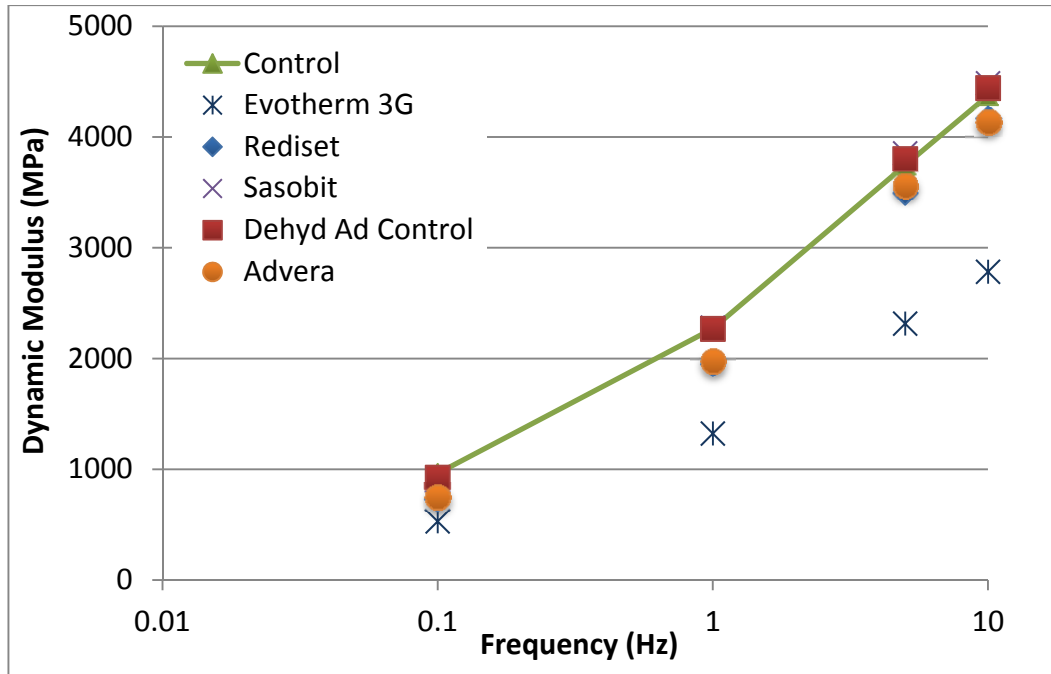


Figure 3.8: Different modulus of different WMA mixtures (Evotherm, Rediset, Sasobit and Advera) and HMA controls (Control and Dehydrated Advera) using the PG64-22 binder

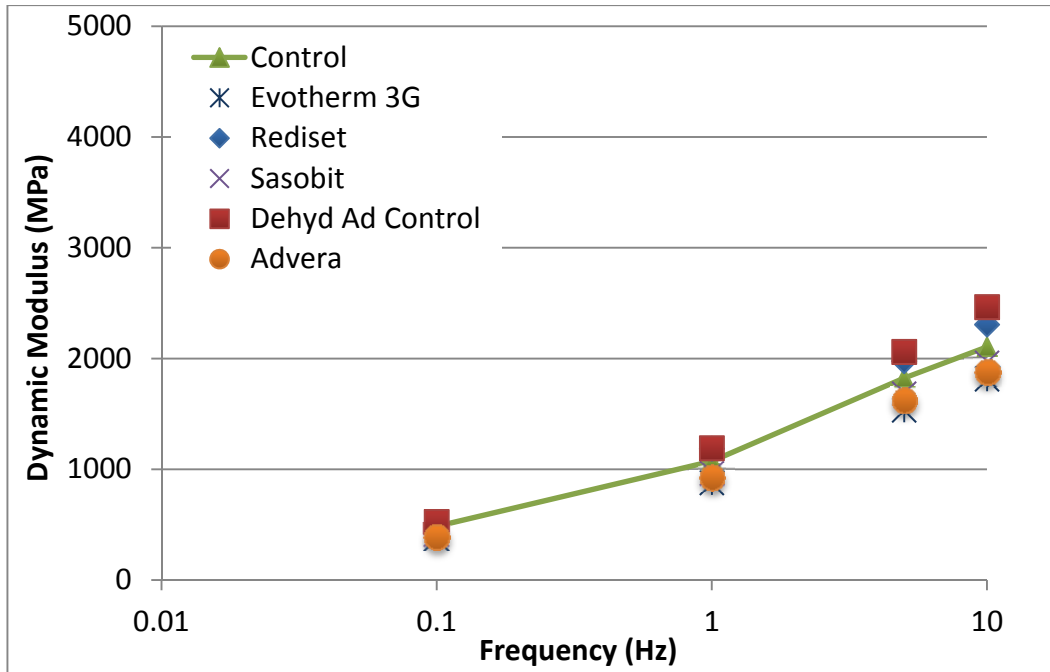


Figure 3.9: Different modulus of different WMA mixtures (Evotherm, Rediset, Sasobit and Advera) and HMA controls (Control and Dehydrated Advera) using the PG76-28 binder

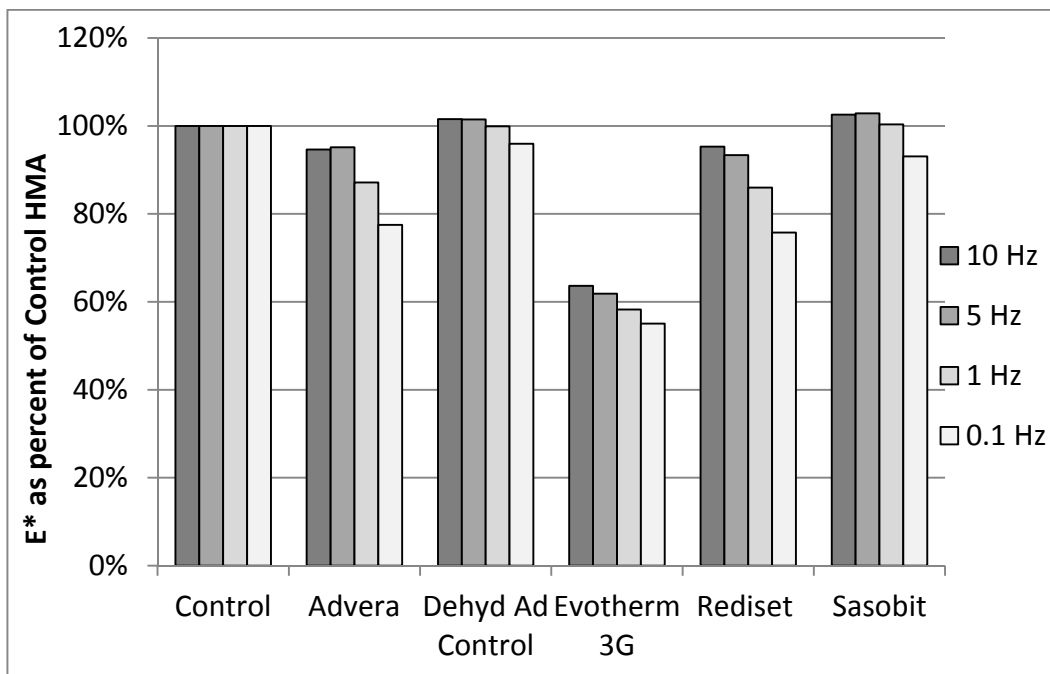


Figure 3.10: Dynamic modulus of different WMA and HMA mixtures normalized with the HMA control using the PG64-22 binder

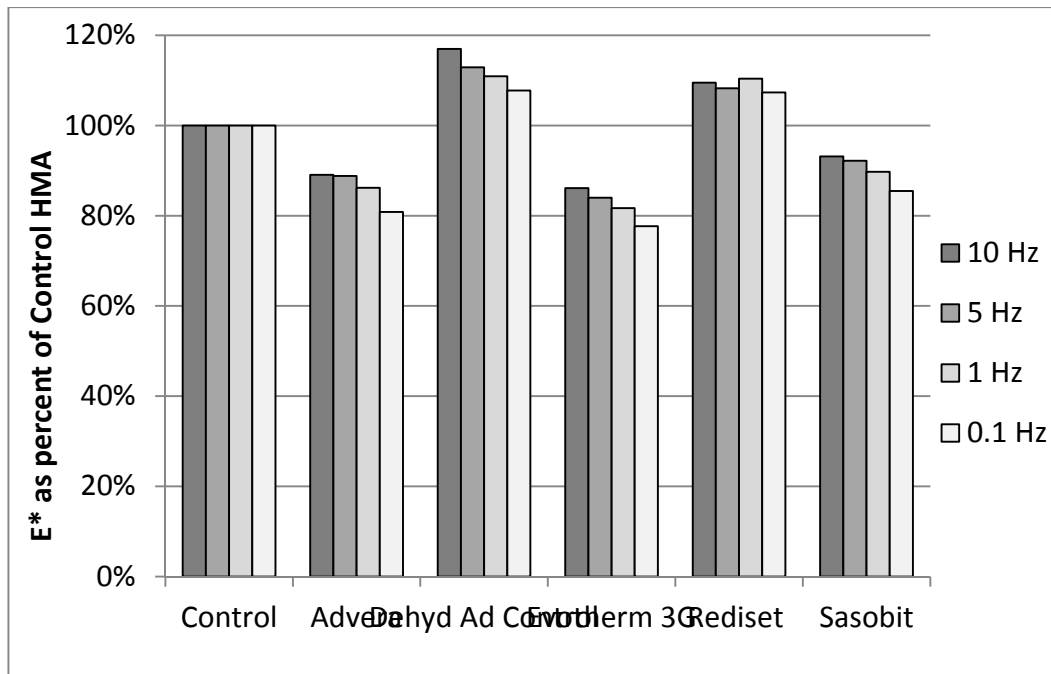


Figure 3.11: Dynamic modulus of different WMA and HMA mixtures normalized with the HMA control using the PG76-28 binder

Another observation was that although the two mixtures with the PG64-22 and PG76-28 binder had similar binder content, aggregate gradation, and air voids, the latter was less stiff than the former at room temperature. This could be attributed to a combination of two possible reasons. First, both the PG64-22 and PG76-28 binder must meet a maximum stiffness requirement ($G^* \sin \delta$) at an intermediate temperature (that differs by 3°C or 5.4°F for the two binders) and not a minimum stiffness requirement. In other words, the difference in the stiffness at the high temperature is not as much at intermediate temperatures. Second, an examination of the test specimens showed that the limestone aggregate used in this study was absorbing more of the PG64 grade binder than the PG76 binder. Figure 3.12 shows an image of the test specimens with these two binder types.



Figure 3.12: Test specimens using the PG64 (top row) and PG76 binders (bottom row); specimens with the PG64 binder suggest higher binder absorption

3.3.3 Indirect tensile strength at low temperatures

Since the dynamic modulus test described in the previous section is a non-destructive test, the same specimens were used for the indirect tensile strength test. All test specimens were stored at room temperature for 48 hours after the completion of the dynamic modulus test. After this time, the specimens were then stored in an environmental room at 4°C (39.2°F) for a duration of 48 hours. The indirect tensile strength was measured at this temperature. The low temperature was selected to be above the freezing point of water to avoid the potential interaction and effect due to freeze thaw action. A constant rate mechanical loading frame was used to conduct the strength test. A load cell and a digital data acquisition system were used to record the load data as a function of time. The frame applies a displacement at a constant rate of 50 mm/minute (2 in./minute). Figure 3.13 illustrates the loading frame with a typical test specimen. Figure 3.14 illustrates a typical load versus time and displacement versus time curve for a test specimen. The maximum or peak normal load was used as a metric to compare the strength of the different asphalt mixtures.

Figures 3.15 and 3.16 compare the strength of the different WMA mixtures to the HMA controls for mixtures prepared using the PG64-22 and PG76-28 binder. These results indicate that in all cases, the strength of the WMA mixtures was similar to or less than that of the control HMA mix. The findings from these mixtures tests are qualitatively similar to the findings from the binder fracture tests and the fatigue tests conducted on FAM mixtures.



Figure 3.13: Setup to measure the indirect tensile strength of the WMA and HMA mixtures

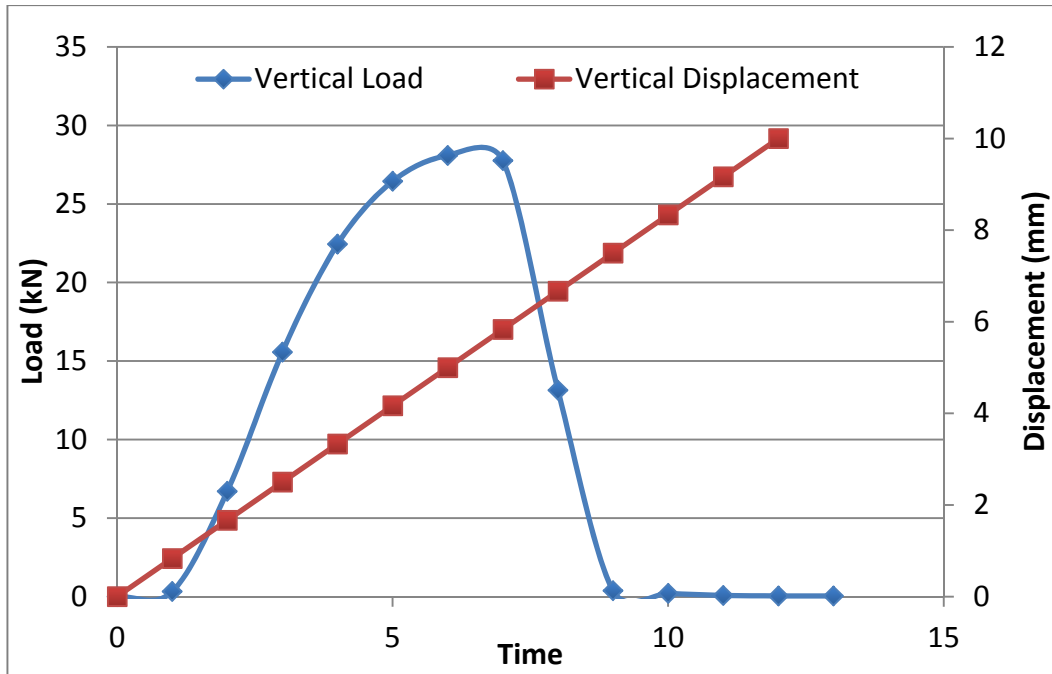


Figure 3.14: Typical load and displacement versus time curves for the indirect tensile strength test

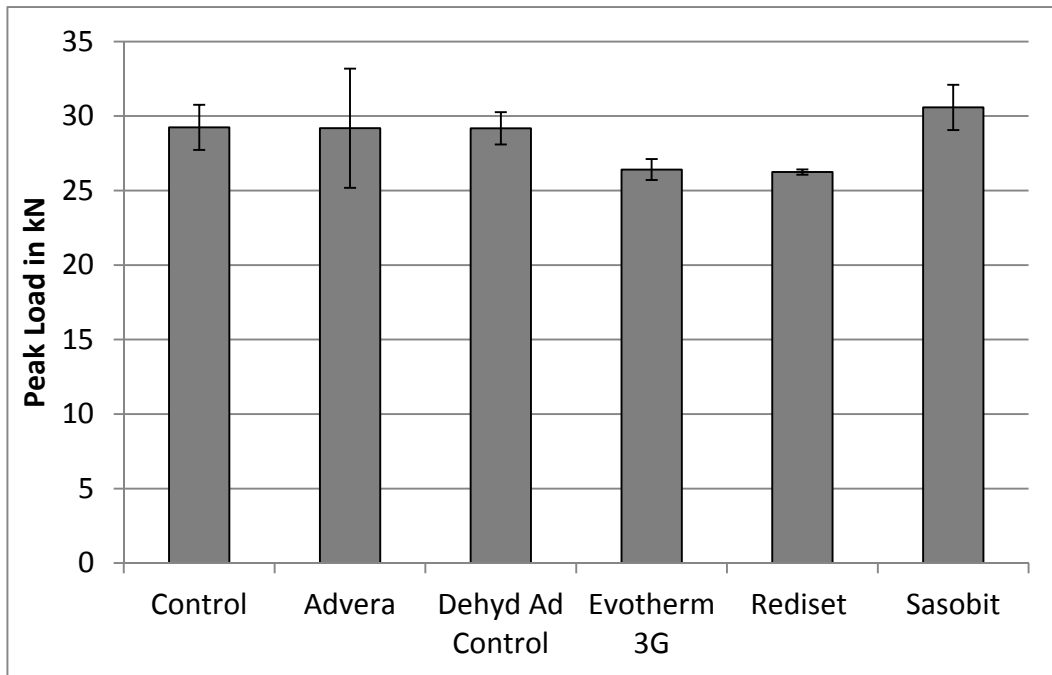


Figure 3.15: Peak load until failure for the mixes with PG64-22 binder

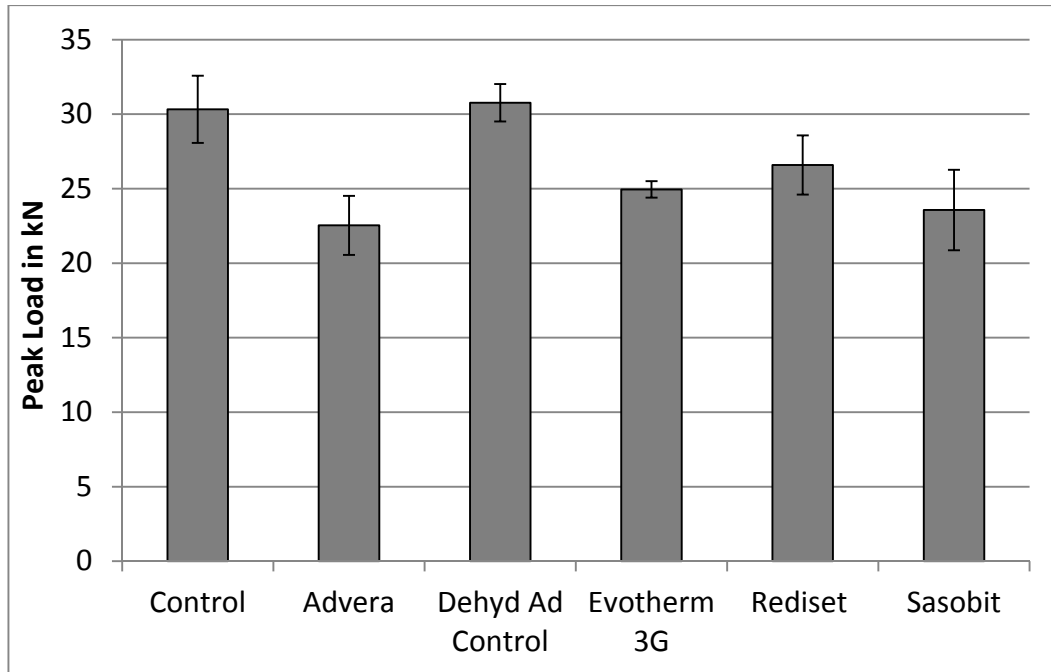


Figure 3.16: Peak load until failure for the mixes with PG76-28 binder

3.4 Summary

In this part of the study, one aggregate, two binders, and four different WMA additives were used to compare the mechanical properties of the WMA mixtures to control HMA mixtures. These tests were also conducted to corroborate the findings based on the binder and mortar (or FAM) tests. The fracture resistance at low temperatures, stiffness at intermediate temperatures, and rutting and moisture damage resistance at high temperatures were measured for the full asphalt mixtures.

Results show that the WMA mixtures had a lower rutting resistance compared to a similar HMA mixture. Results from the HWTT on the rutting performance of asphalt mixtures were also consistent with the results based on the testing of asphalt binders using the multiple stress creep and recovery test. The HWTT was also used to evaluate the moisture damage resistance of WMA mixtures. While the WMA mixtures with the PG64-22 binder demonstrated similar or increased susceptibility to moisture-induced damage compared to the HMA control, the WMA mixtures with the PG76-22 binder demonstrated consistently increased moisture susceptibility compared to the HMA control. The moisture sensitivities from the HWTT were consistent with the moisture sensitivities measured using the fatigue cracking test on dry and moisture-conditioned mortar or FAM specimens. Results based on the dynamic modulus testing of asphalt mixtures indicate that stiffness of the WMA mixtures was similar to or less than the stiffness of a similar HMA. The differences were more exaggerated at lower loading rates.

Chapter 4. Conclusions and Recommendations

The main objective of this research study was to evaluate the influence of warm mix additives on the rheology and performance characteristics of asphalt binders with emphasis on the effects of long-term aging and use of recycled asphalt binder. To achieve this objective, the asphalt binders were first screened based on their chemical makeup. The selected asphalt binders were combined with different WMA additives and evaluated for their mechanical properties. Subsets of these binders were also used to evaluate the effect of long-term aging and the effect of using recycled asphalt binder on performance characteristics. Tests were also conducted using a limited number of sand-asphalt mortars and full asphalt mixtures to further corroborate the findings from the binder study.

4.1 Conclusions

Some of the findings from this study are as follows.

4.1.1 Workability

- Viscosities of the unaged binder modified using the warm mix additives were similar to or, in most cases, less than the viscosities of the control binders.
- Warm mix additives were very beneficial in reducing the viscosity of binders that were aged for twice the duration of conventional RTFO aging. This was particularly significant for binders with high natural wax content (these are typically binders with a high temperature grade of 70 or 76). These tests simulate a scenario where loose mix is stored in a heated silo for prolonged duration of time and/or transported over long distances.

4.1.2 Rutting resistance

- For three of the four binders modified using Sasobit, the $G^*/\sin\delta$ parameter was similar to the control. For 22 out of 24 combinations of binder and warm mix additives other than Sasobit that were tested, the $G^*/\sin\delta$ was reduced to 80% of the $G^*/\sin\delta$ for the control binder or less. Results based on the non-recoverable compliance using the multiple stress creep recovery test were also consistent with those based on the $G^*/\sin\delta$ parameter. These results were also consistent with the results based on the Hamburg wheel-tracking test (HWTT) conducted on full asphalt mixtures using some of the same binder-WMA additive pairs.
- Comparison with the control binders with reduced aging revealed that Sasobit compensated for the effect of reduced aging on early age stiffness and rutting resistance. However, certain other warm mix additives further aggravated the effect of reduced aging on early age stiffness and rutting resistance. In other words, for about half the binder-warm mix additive combinations, stiffness loss occurred due to the presence of the additive itself; this was in addition to the stiffness loss that was due to reduced aging.

4.1.3 Stiffness and fatigue cracking resistance at intermediate temperatures

- Binders modified using the warm mix additive and long-term aged using the PAV had similar or lower values of $G^*\sin\delta$ compared to their respective controls. It must be noted that this finding does not necessarily imply that the fatigue cracking resistance of warm mix binders is similar to or better than the control. Recent research studies have shown that the $G^*\sin\delta$ may not be an effective parameter to characterize binder fatigue.
- A subset of long-term aged binders was evaluated using a thin film fracture test. For 10 out of 16 combinations of binder and warm mix additives, the fracture energy was reduced to 80% of the fracture energy of the control binder or less. Tests on long-term aged asphalt mortar specimens using some of the same binder-WMA additive combinations also indicated that certain binder-WMA additives could reduce the fatigue cracking resistance of the asphalt composite. For example, presence of the WMA additives significantly affected the fatigue cracking resistance of asphalt mortars with the PG64-22 binder but no significant difference as found in the fatigue cracking life of asphalt mortars with the same WMA additives and the PG76-28 binder.
- The dynamic modulus of WMA mixtures was in most cases similar to or slightly less than that of a similar HMA. The difference in the dynamic modulus was more exaggerated at slower rates of loading (which can also be interpreted as higher temperatures).

4.1.4 Moisture-induced damage

- Based on the results from the HWTT, six out of eight mixtures with different binder-WMA additive combinations resulted in a reduced resistance to moisture-induced damage compared to the HMA control. This was also the case when the resistance to moisture-induced damage was quantified as the ratio of fatigue cracking life of moisture conditioned specimens to dry specimen in the mortar specimens.

4.1.5 Rate of aging

- Binders modified using the warm mix additive were RTFO aged (control at 163°C/325°F and warm mix at 143°C/289°F) and subsequently aged in an environmental room at 60°C/140°F for a period of 132 days. Binder samples were analyzed and tested intermittently as they were being aged in the environmental room. Spectroscopic analysis of these binders indicated that the binders modified using the warm mix additive and RTFO aged at lower temperatures had significantly lower oxidative aging compared to the control initially. However, after 132 days, the extent of oxidative aging in the modified binders was not very different from that of the control.

4.1.6 Influence of recycled asphalt binder

- One question related to the use of WMA is whether a combination of the RAP binder and WMA can help mitigate the risk of fatigue and thermal cracking after

long-term aging. To this end, warm mix additives were combined with virgin binder and laboratory produced recycled binder. This blend, along with a control, was further subjected to RTFO and PAV aging and evaluated (control was RTFO aged at 163°C/325°F and warm mix at 143°C/289°F). Results indicate that based on the stiffness at 60 seconds and the “m” parameter, the low temperature cracking resistance of a combination of warm mix binders with recycled asphalt was in most cases similar to that of the control hot mix binder with recycled asphalt. These results are for the best case scenario when the recycled binder has the same chemical makeup (other than extent of oxidation) and is fully blended with the virgin binder.

4.2 Recommendations

The following recommendations are made based on the findings from this study:

- Each binder-WMA additive pair must be treated as a modified binder that is likely to have performance-related properties very different from the original binder.
- The rutting resistance of WMA is relatively lower than the rutting resistance of a similar HMA, which is primarily attributed to reduced aging and addressed using RAP in the mixture. However, neither the cause nor the remedy is universally applicable. For example, findings from this study indicate that most WMA additives exacerbate the reduced rutting resistance that is due to reduced aging. Findings from this study also indicate that wax-based additives such as Sasobit can compensate for the reduced rutting resistance with certain (but not all) binders. In such cases, it may not be necessary to use RAP.
- To the extent possible, a proposed job mix formula for a WMA must be evaluated for its fatigue cracking resistance (with the mix incorporating the additive) prior to being approved for construction. Results from this and other studies have shown that the fatigue cracking resistance of asphalt mixtures can be affected by the type of asphalt binder and WMA additive used. In addition, the use of a “mode independent” parameter to evaluate fatigue cracking resistance must also be considered. Simply put, the findings from this study in combination with other studies indicate that, depending on the mode of loading for a fatigue test (load versus displacement controlled), the same set of asphalt mixtures can achieve different rankings. For example, a displacement-controlled mode of loading to evaluate the fatigue cracking resistance of asphalt mixtures is likely to reflect a greater number of load cycles to failure for a softer mix than for a stiffer mix.
- In most cases, the use of RAP with WMA does not offer any significant improvement in the resistance to low temperature cracking after long-term aging as compared to the use of RAP with a conventional HMA. Certain WMA additives may present limited advantages but these must be evaluated on a case-by-case basis. To the extent possible, a WMA with RAP must be treated as an HMA with RAP. In light of the increasing trend in the use of WMA with RAP as green mixes, it is important the future studies further investigate the interaction of RAP binder with the virgin binder and the subsequent impact on fatigue and thermal cracking resistance.

- Results indicate that most WMA mixtures tend to be relatively more moisture sensitive as compared to a similar HMA mixture. Increased moisture sensitivity compared to a control does not necessarily imply that a mixture cannot be used, because the moisture sensitivity of a WMA can still be within allowable limits. However, if an HMA is known to have moisture sensitivity issues, then the use of a WMA based on the HMA design must be used with caution or avoided.

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