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Influence of extended aging on the properties of asphalt composites produced using hot and warm mix methods

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HIGHLIGHTS

- We used an environmental room to simulate extended aging of asphalt composites.
- Fine aggregate mixtures (mortars) compacted after short-term and long-term aging had similar internal microstructures.
- We examined stiffness and fatigue lifer of WMA and HMA mixtures.
- We compared fatigue life rankings of short-term and long term aged mixtures.

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ABSTRACT

Fatigue cracking resistance of asphalt binders and composites is influenced by the presence of modifiers and aging conditions. This paper presents the findings from a study conducted to evaluate the fatigue cracking resistance of asphalt mortars or fine aggregate matrix (FAM) as influenced by two factors: (i) the presence of warm mix additives with reduced short-term aging temperatures and (ii) the influence of long-term aging of the mix. Combinations of two binders with four different warm mix additives and one aggregate type were used to evaluate the first factor. The second factor was evaluated by subjecting the loose mix to extended aging in an environmental room at high temperatures. X-ray CT analysis were conducted on a limited number of samples compacted before and after extended aging to ensure that the internal structure of the specimen did not change significantly and the differences in performance could be attributed to aging of the mix. A dynamic mechanical analyzer (DMA) was used to evaluate the fatigue cracking resistance of the FAM test specimens. The stiffness and the fatigue cracking resistance of the FAM specimens were compared before and after long-term aging. Results indicate that the specific binder–additive pair governed the influence of the warm mix additive on the fatigue cracking life of the FAM specimens. More importantly, results also indicate that the rank order of the short-term aged mixtures, in terms of their fatigue cracking resistance, did not change significantly after long-term aging. The ranking of fatigue cracking resistance of short-term aged specimens using different binders correlated well with the ranking of fatigue cracking resistance of long-term aged specimens.

1. Introduction

Warm Mix Asphalt (WMA) has gained interest in United States and other countries due to the environmental and financial benefits associated with lower production temperatures. This interest has prompted the transportation agencies in the United States to conduct several research studies in order to facilitate the implementation of this technology. Most recent studies have focused on the influence of WMA additives and production temperatures on asphalt binder and mixture performance [1–3]. In these studies, different WMA additives, foaming technologies, and a variety of unmodified and polymer modified binders were considered. A common theme throughout these studies is that binders used in WMA are likely to have reduced stiffness and increased susceptibility to permanent deformation due to the reduced temperatures associated with short-term aging. Most of the studies also show that binders with WMA additives had similar resistance to thermal cracking despite the initial reduction in the production temperature and concomitant oxidation. Several research studies have also been conducted on the moisture damage resistance of WMA mixtures and typically reported reduced performance compared to an equivalent HMA [4,5]. However, there is no reported evidence of moisture-related failure in field projects using WMA mixtures placed in the US [6]. More importantly, research studies have also investigated and reported that reduced temperature for short-term

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aging appeared to have a significant effect on the fatigue cracking resistance of binders and mixtures. This effect was also reported to be dictated by the type of WMA additive and binder [7].

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 the asphalt mortar or FAM to quantify the fatigue cracking, rutting and moisture damage resistance of asphalt composites with different modified binders, fillers or additives [8–10]. 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. These advantages have led several researchers to use FAM mixtures to evaluate different aspects of asphalt mixture performance [8–10].

An important factor in the context of fatigue cracking resistance of asphalt 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 [11]. The oxidation of the binder creates carbonyl compounds, mainly by oxidizing aromatic compounds in the naphthene aromatic, polar aromatic, and asphaltene fractions. An increase in the polar fractions in turn leads to stiffening of the binder seen as increase in the elastic modulus and viscosity [11]. 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. For example, the AASHTO R30 recommends long-term aging of compacted asphalt mixtures at 85 °C for 120 h. The extent and uniformity of aging in compacted specimens 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. [12] aged test specimens for 3, 6, and 9 months at 60 °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?

This paper presents the findings from a study conducted to evaluate the influence of mixture production temperatures and additives on the fatigue cracking resistance of asphalt mortars or FAM mixtures. An important objective of this study was not only to evaluate the fatigue cracking resistance of different FAM mixtures modified using the warm mix additives, but also to compare the stiffness and fatigue cracking resistance of asphalt mortars before and after long-term aging.

2. Materials and tests

In order to achieve the aforementioned objectives, the experimental plan shown in Table 1 was developed to conduct tests on FAM specimens. Two binders and four WMA technologies were used. The binders used were a PG76-28 and a PG64-22 obtained from local refineries within the state of Texas, USA. 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 the four WMA technologies, a control mix and dry Advera were also used. The dry 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. Dry Advera was obtained by spreading 40 g of the additive on a PAV pan and placing it in an oven at 150 °C for 24 h immediately prior to adding it to the asphalt binder. The temperature and duration used to remove the moisture from Advera was based on preliminary tests using Thermogravimetric Analysis (TGA). The preliminary tests using the TGA demonstrated that this duration of heating was more than adequate to remove all the moisture that can escape from the zeolite particles at this temperature. The binders modified with dry Advera were mixed with aggregates using the HMA production temperatures. A qualitative observation was that the mixture had similar workability compared to the control-HMA mixture produced at the same temperature. 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 other literature [3].

The additives were blended with the asphalt binder using a low shear mixer. Dosage and mixing time of the additives were in accordance with the recommendations provided by their respective producers. The additives were added manually and slowly into the asphalt binder to achieve a homogenous distribution of the additive. The additives were blended into the asphalt binder using a digital overhead mixer equipped with a four blade propeller, and stirred for 30 min. Additives were not added directly into the asphalt concrete mixing bucket to avoid the variability that may be incurred due the inconsistency between asphalt binder and mixture blending procedures, especially for such small quantities. Quantities of the additives used to mix with the binders are presented in Table 2. The modified binders were later mixed with the aggregates to produce the FAM mixtures.

A limestone aggregate was used for this study. The aggregate was obtained from a quarry located in Buda, Texas. A Type C mixture following a typical dense gradation was designed in accordance with the specifications followed by the TxDOT (Texas Department of Transportation) [13]. The aggregate gradation for the asphalt mortar or FAM essentially follows the same relative proportions of different sizes as the full asphalt mixture with the only difference being that aggregates passing #16 are used to produce the FAM mixtures. Table 3 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 of the Type C mixture was prepared with 5.5% of the PG64-22 binder. The loose mix was then carefully spread out 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 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 was the binder content that was used to produce FAM mixes using the two binders (PG64-22 and PG76-28) with/without WMA additives. This method to determine the binder content in the FAM mixtures was similar to that proposed by Sousa et al. [14].

Fine aggregates passing sieve #16 and following the gradation shown in Table 3 were mixed with the different binders (with and without WMA additives) to produce the FAM mixtures. For the PG76-28 binder, the control mixtures (including dry Advera) were mixed at 163 °C and compacted at 143 °C, and the mixtures with the warm mix additives were mixed at 143 °C and compacted at 123 °C. For 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 and compacted at 103 °C. 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.

2.1. Short and long-term aging of asphalt binders and mortars

The mixing and compaction temperatures for the WMA mixtures represent a 20 °C temperature reduction from the mixing and compaction temperatures used for the control mixtures. This corresponds well with the typical drop in mixing

Table 1
DMA testing of mortars for stiffness, fatigue life and moisture damage.

Variables	Short-term aged[+] (dry and after 24 h moisture conditioning)	Long-term aged[++] (dry)
Control A[a]	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	B1A1, B2A1

B1 = PG76-28, B2 = PG64-22 and A1 = limestone aggregate.
[a] Mixing at conventional temperatures (all others at WMA temperatures).
[+] Loose mix will be aged for 4 h before compaction at mixing temperatures (hot mix for control A and WMA for others).
[++] In addition to short-term aging, loose mix was aged for 30 days at 60 °C in the environmental room to simulate extended aging.

Table 2
Dosage of additives added to the asphalt binder by weight.

Additives	Percent by weight
Sasobit®	1.5
Advera®	5.0
Evotherm® 3G	0.5
Rediset® WMX	2.0
Dry Advera®	5.0

Table 3
Fine aggregate mixture design gradation.

Sieve size	FAM gradation (% retained)
#30	36.7
#50	26.3
#200	24.8
Pan	12.6

and compaction temperatures associated with the production of WMA. The control and WMA mixtures were short-term aged for 4 h at their corresponding compaction temperatures. The short-term aging time of 4 h was selected following the current practice in the state of Texas for short-term aging of WMA mixtures. In order to serve as a control, the HMA was also short-term aged for 4 h. 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. 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 150 mm in diameter and approximately 60 mm in height. The ends of the SGC compacted specimen were sawed to achieve 40 mm height. Approximately 20 smaller specimens, each of 12.5 mm diameter, were drilled out of the SGC specimen. The air void content of the finished FAM test specimens were determined to be 7% ± 0.5%.

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) which when applied to a thin film of asphalt binder at atmospheric pressure would result in a level of oxidation that is comparable to that of the pressure aging vessel (PAV) aged binder. The following paragraphs present the literature review and tests that were 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 [12,15]. 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 pressure aging vessel or PAV. Harrigan et al. [16] recommend the use of the PAV at 90–110 °C at a pressure of 20 atmosphere of air for 20 h to simulate long-term aging. Glover et al. [11] compared the long-term aging simulated using the PAV to the long-term aging simulated at higher than room temperature (60 °C) and atmospheric pressure. They reported that aging of thin films of asphalt binders for approximately 35 days at 60 °C and atmospheric pressure was equivalent to aging in the PAV for 20 h at 90–110 °C 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. [11] 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 g of RTFO residue were placed into the PAV pans and aged for 20 h at 100 °C. Aging in the environmental room was carried out by placing 66 g of each RTFO-aged sample in aluminum trays measuring 22 cm by 30 cm and allowing the binder to age in the environmental room with an approximate film thickness of 1 mm at 60 °C 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 FT-IR 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 [15] used the carbonyl area from the FTIR spectra to quantify aging in different binders mixed with different fillers. Glover et al. [11] 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}. Fig. 1 compares the carbonyl area of the binders aged as a thin film in the environmental room at 60 °C for 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. The results were consistent with the earlier findings reported by Glover et al. [11]. Additional details documenting the comparison of aging in the environmental room to that of the PAV are documented in other literature [17]. Therefore, for this study aging of the loose FAM mixtures for 30 days at 60 °C 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).

It must be noted that although accelerated aging using higher pressures was considered, it was decided that the mortars be aged under atmospheric pressure as a first step for this study. The rationale for this is as follows. The relationship between asphalt oxidation, pressure and absolute temperature was given by Liu [18] as shown in following equation:

$$\frac{dCA}{dt} = AP^{\alpha}\mathrm{EXP}\left(-\frac{E}{RT}\right) \quad (1)$$

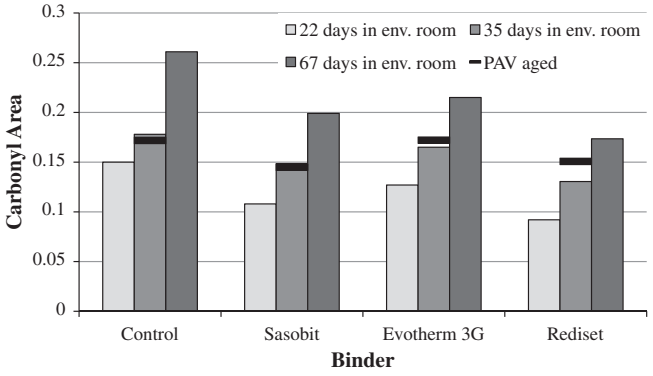

Fig. 1. Carbonyl area of PG64-22 binder aged in the environmental room and PAV.

where P is pressure, T is absolute temperature, CA is the carbonyl area used as a quantitative indicator of the extent of oxidation, t is time, and A, α, and E are constants that are characteristics of each asphalt binder. This equation shows that relative hardening rates measured in the PAV may be different from those observed on roadways. Glover et al. [11] compared aging index of binders aged in the PAV with binders aged in thin films in a 60 °C environmental room for 135 days. For a given binder, it is expected that the two methods would yield different levels of aging. However, it was also observed that the relative level of aging between different binders was different for the two methods. For example, binders that showed similar level of aging in the PAV had very different levels of aging when oxidized in the environmental room at atmospheric pressure and vice versa. In the context of Eq. (1), this is most likely because the material parameter α could differ from one binder to another. Consequently, different binders (with different values of α) would age at different rates when subjected to higher pressures. In the context of this study, it is possible that binders modified using different WMA additives may oxidize at different rates when subjected to higher pressures. Therefore, for this study, it was decided to simulate extended aging using an environmental room at atmospheric pressure although the use of higher pressures must be investigated for future work.

2.2. X-ray CT scans

In this study, loose asphalt mortar was long-term aged in an environmental room and then compacted. It is well recognized that the internal structure of an asphalt mixture plays 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 [19]. In a previous study, Bhasin et al. [20] 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 the fine aggregate particles in the FAM specimen according to procedures described in Bhasin et al. [20]. The star length distribution was calculated by randomly selecting 1000 points within the matrix. Lines were drawn emanating from each point along 512 predefined orientations in three dimensions until the lines encountered a boundary. The lengths of these lines were measured at all orientations and points to obtain the star length distribution. A three dimensional rose diagram of the mean star length (along a given orientation) provides a visual representation of the geometry (Fig. 2). The star length distribution 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 paper and can be found in other literature [20]. Table 4 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 indicates that the FAM specimens had very similar internal structures even when compacted after long-term aging.

2.3. Mechanical tests

The linear viscoelastic properties and resistance of the test specimens to fatigue cracking were measured at 23 ± 1 °C using the dynamic shear rheometer from Bohlin (model designation CVOR). Shear oscillations following a sinusoidal wave form at a low stress amplitude of 15 kPa were applied for 10 min 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 a high stress amplitude of 275 kPa were then applied at a frequency of 10 Hz until specimen failure to determine the fatigue cracking resistance of the mortar specimens. Note that this high level of stress was selected because the FAM or mortar matrix typically experiences local stresses that are several times higher than far-field stresses and also to ensure that the fatigue tests would be completed within a reasonable amount of time.

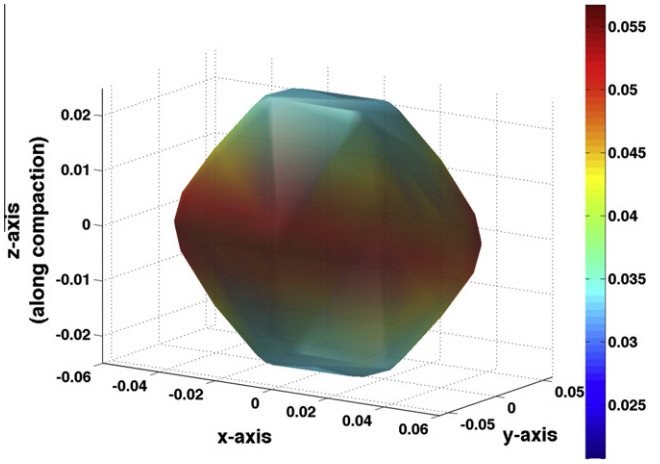

Fig. 2. Typical rose diagram showing the average three dimensional distribution of the matrix between the particles (fine aggregates) in a mortar specimen.

Table 4
Metrics that compare the internal structure of FAM specimens compacted after short-term aging and long-term aging.

Mix type	DA	Average star length in preferred direction	Average of 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
Coefficient of variation in metric between different mix types →	3%	3%	2%

3. Results

3.1. Statistical analysis of test results

At least two replicates of FAM specimens were conducted in the DMA test setup 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 5 for the short-term aged specimens and in Table 6 for the long-term aged specimens. In this study, fatigue life was defined as the number of load cycles to achieve 50% of the initial modulus of the specimen.

An ANOVA and Fisher's LSD test was performed with 95% reliability to determine if there was any significant difference among the test results between the control and WMA fine aggregate mixtures either in the short-term or long-term aging conditions. The data presented in Tables 5 and 6 show that the stiffness of at least some of the modified mixtures using the PG76-28 binder were 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 the stiffness of mixtures. The mixes produced using PG64-22 binders showed higher stiffness values and fatigue life compared to mixes produced using PG76-28 binders. This was despite the fact that both mixtures had similar gradations and binder contents. The reason for the higher stiffness and fatigue lives exhibited by PG64-22 mixes compared to PG76-22 mixes is due to the differences in the percentages of asphalt binder that was absorbed. Notably, the percentage of binder absorbed by the PG64 mixes was higher than the percentage of binder absorbed by the PG76 mixes. As the percent

Table 5
Relative change in stiffness and fatigue life after short-term aging.

Binder	Modification	Complex modulus, G^*			Fatigue life, N_f		
		G^* ($\times 10^8$ 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

[+] Statistically significant difference at $\alpha = 0.05$, N/A-not applicable, Y-significant, N-not significant.

Table 6
Relative change in stiffness and fatigue life after long-term aging.

Binder	Specimen	Complex modulus, G^*			Fatigue life, N_f		
		G^* ($\times 10^8$ 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

[+] Statistically significant difference at $\alpha = 0.05$.

of binder absorbed by the aggregates increases, the mixture has less effective binder, resulting in higher stiffness and potentially different susceptibility to fatigue cracking [21]. A more detailed discussion on these differences is presented elsewhere [22].

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 mixtures with PG76-28 binder 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 Johnston et al. [7] on the fatigue cracking resistance of plant-produced WMA mixtures found that WMA mixtures have either similar or better resistance to fatigue cracking. Jones et al. [23] 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 demonstrates that each binder–additive pair can significantly affect the mechanical response of the material, and varying the material type may produce a bigger change in fatigue life than varying the production temperature. The results also suggest the need to keep monitoring fatigue cracking resistance of pavements constructed using WMA technologies.

3.2. Comparison of short and long-term aged FAM test results

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 affect of WMA technologies on the stiffness and fatigue cracking life of the mortar specimens. According to Bonaquist [24] 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. In the context of this study, short-term aged mortars were aged as a loose mix for only 4 h prior to compaction and testing whereas long-term aged mortars were further aged for 30 days at 60 °C prior to compaction and testing.

Stiffness, G^*, and fatigue cracking life of FAM specimens after short-term aging were compared with the stiffness and fatigue life of FAM specimens after long-term aging in Figs. 3 and 4, respectively. In addition, Fig. 5 compares the rankings of the 12 different mixtures in terms of their fatigue life before and after long-term

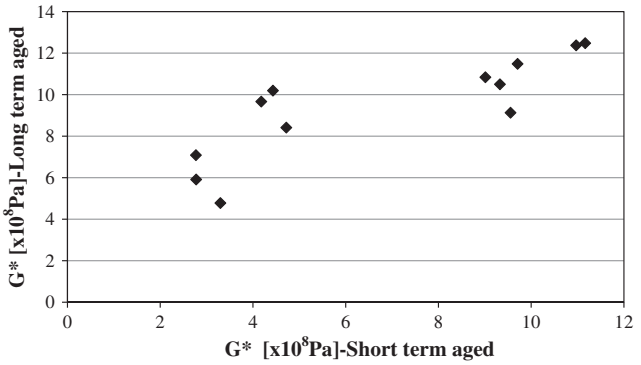

Fig. 3. Comparison of G^* before aging and after long-term aging for the different FAM specimens.

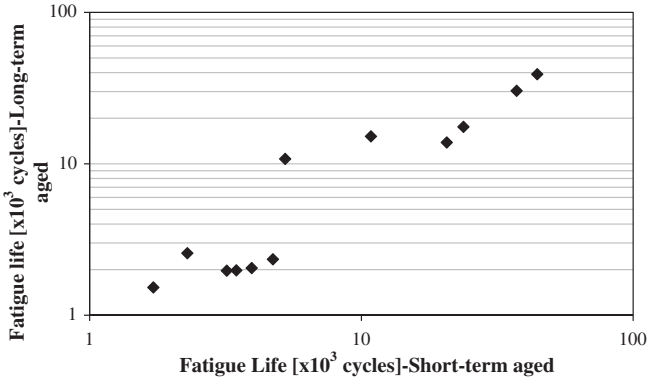

Fig. 4. Comparison of fatigue life before and after long-term aging for FAM specimens.

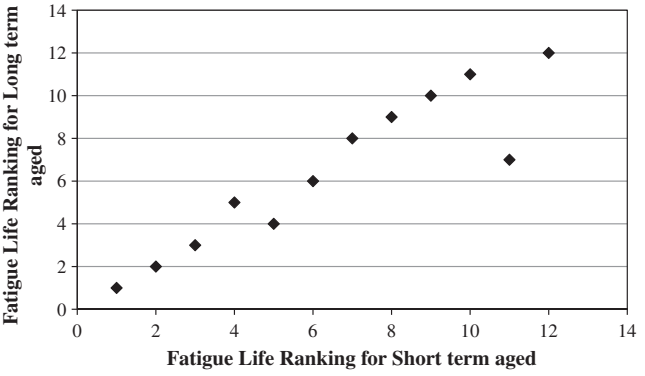

Fig. 5. Fatigue life ranking of FAM specimens before and after long term aging.

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. Fig. 5 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. This shows that short-term aged specimens may be used for evaluating relative fatigue cracking resistance of the mixes.

4. Concluding remarks

In this 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.

- FTIR results on asphalt binders show that these aging conditions oxidize the binder to levels comparable, although not exact, 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. Generally, 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 suggests the need to carefully and continually investigate the fatigue cracking resistance of asphalt mixtures produced using WMA technologies.
- 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.

5. Discussion

The mechanical test results were consistent with Morian et al. [12] 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 is only limited data and based 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 binder ages in the mix. The results must in no way 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.

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