Performance of Recycled Rubber Modified Binders in Warm Mix Asphalt Mixtures

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ABSTRACT. *The past few years have seen the introduction of the warm mix asphalt (WMA) technology in efforts to reduce the required energy for the production and construction of the asphalt concrete layer. The basic principle of the WMA technology is to lower the mixing and compaction temperatures of the produced mixture through lowering the viscosity-temperature relationship of the asphalt binder.*

This paper evaluates the performance of terminal blend tire rubber-modified binder in WMA mixtures manufactured with two WMA technologies; Advera and Sasobit. The evaluation consisted of measuring the mechanistic properties of mixtures with and without moisture damage. The resistance of the mixtures to moisture damage was evaluated in terms of the impact of multiple freeze-thaw cycling on the dynamic modulus property.

The paper presents the results of the study showing the performance of terminal blend tire rubber-modified binder in WMA mixtures as compared to WMA manufactured with neat and polymer-modified binders. The use of terminal blend tire rubber-modified binder with WMA mixtures significantly improves their resistance to moisture damage in terms of increased retained strength/modulus and reduced tensile/vertical strains within the asphalt layer. Among all mixture evaluated in this study, the best performance was obtained from the terminal blend tire rubber-modified mixtures treated with hydrated lime. This observation was true for control, WMA-Advera, and WMA-Sasobit mixtures.

KEYWORDS: *recycled rubber, warm mix asphalt, moisture damage, dynamic modulus, mechanistic analysis*

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1. Introduction

Warm mix asphalt (WMA) technologies are increasingly being investigated for their impact on asphalt performance. WMA technologies allow asphalt mixtures to be produced and placed at temperatures lower than the temperatures used for conventional asphalt produced without the additives. However, the reduced production temperatures may hinder the evaporation of moisture from aggregates leading to an increased potential for moisture damage.

The National Center for Asphalt Technology (NCAT) has done a significant amount of research with regards to the applicability of WMA additives to typical paving operations. In 2005, NCAT studied the applicability of Sasobit, an organic wax and Aspha-min, a zeolite or water-bearing additive (i.e. similar to Advera) in WMA (Hurley and Prowell, 2006). The NCAT study evaluated two aggregate sources (granite and limestone) with two binder types (PG 64-22 and PG 58-28). To study the effects of residual moisture, NCAT added moisture to the aggregate at a rate of three percent above the aggregate absorption value before the aggregate was heated. To study the effects of aging on WMA mixtures, NCAT evaluated samples that were subjected to short-term aging prior to compaction of 2 – 5 hours at110 °C and long-term aging of 5 days at 85 °C. The prepared samples were then tested for strength gain by means of tensile strength (TS) testing and tensile strength ratio (TSR) after a single freeze-thaw (F-T) cycle. The TSR is the ratio of the TS after one F-T cycle over the un-conditioned TS.

The moisture damage analysis revealed that the Sasobit WMA mixtures could exhibit lower TS than the control asphalt. The addition of liquid anti-strip (LAS) to the Sasobit WMA mixtures resulted in reduced TS and TSR values but significantly higher than the control asphalt. Despite the increase in TSR values, it is still debatable whether the addition of the LAS reduced the potential for moisture damage in the Sasobit mixtures due to the reduction in TS values. The aging evaluation revealed that the strength varied between control asphalt and Sasobit WMA mixtures at different aging times and this variation was aggregate dependent. The Sasobit WMA mixtures showed reduced strengths when compared to the control asphalt. At the long-term aged condition, no significant differences existed between the Sasobit WMA mixtures and the control asphalt.

The moisture damage analysis revealed that the Aspha-min WMA mixtures could exhibit lower TSR values as compared to control asphalt. The mixtures with Aspha-min did not meet the minimum TSR criteria for Superpave mixtures of 0.80. It was assumed the lower TSR values may have been a result of the residual moisture. The moisture damage experiment was repeated with dry aggregates which also showed that the Aspha-min WMA mixtures did not meet the Superpave TSR criteria. The addition of LAS to the Aspha-min WMA mixtures resulted in reduced TSR values. NCAT researchers theorized that the reduced TSR values may have been due to the LAS thinning the binder and reducing the binder viscosity. NCAT also evaluated the moisture sensitivity of mixtures with hydrated lime. The addition of hydrated lime to the Aspha-min WMA mixtures increased the TSR values but not to the level of the Superpave criteria. The aging evaluation revealed no significant differences in strength gain between the Aspha-min WMA mixtures and the control asphalts.

From the laboratory evaluation of Sasobit and Aspha-min WMA mixtures, NCAT researchers concluded that WMA additives tended to reduce the TS and TSR values of asphalt and thus may decrease the resistance of asphalts to moisture damage.

Clemson University conducted a laboratory study regarding the moisture damage of WMA mixtures and the use of liquid anti-strip additives (Xiao et al, 2009). Clemson researchers tested three aggregate sources, one water-bearing additive (Aspha-min), one binder (PG 64-22) and three additives (two LAS and a hydrated lime). The researchers found that the addition of Aspha-min lowered the TS and TSR values of the asphalts. The LAS increased the moisture-conditioned TS of the Aspha-min mixtures, but the resulting TSR did not meet the South Carolina Department of Transportation TSR criteria of 0.85, except in one of six cases. In general, Aspha-min mixtures without anti-strip additive did not meet the TSR criteria. The addition of hydrated lime was effective at increasing TS values of the Aspha-min mixtures to acceptable levels. The TS testing indicates that the Aspha-min additive increases the potential for moisture damage, but that the moisture damage potential can be effectively reduced with hydrated lime.

In 2011 researchers at the University of Nevada investigated the impact of residual moisture in the aggregates on the moisture damage of WMA mixtures made with Advera and Sasobit (Wong, 2011). Residual moisture was defined as the moisture from the stockpiled aggregates that does not completely evaporate in the drum as WMA mixing temperatures are lower than those used during typical asphalt mixtures production. It was hypothesized that the residual moisture, in the coated aggregates may result in a moisture susceptible asphalt mix.

The residual moisture in the aggregate ranged from 0.15 to 0.77 percent by weight of aggregate depending on the WMA mixing temperature. The amount of residual moistures coincided very well with the WMA mixing temperatures; the higher the mixing temperature the lower the residual moisture and vise versa. The study evaluated the impact of residual moisture on the dynamic modulus (E*) property of the mixtures at the un-conditioned stage and after 1 and 6 freeze-thaw (F-T) cycles. The study concluded that the residual moisture has an impact on the E* of the WMA mixtures, with the Advera WMA experiencing more significant impact. In the case of the Sasobit

WMA, the mixtures with residual aggregates showed similar or higher un-conditioned E* but when the mixtures were subjected to 1 and 6 F-T cycles, their E* properties dropped significantly. It was recommended that any evaluation of the impact of moisture damage on WMA mixtures should include residual moisture in the aggregate.

2. Problem Statement

It is evident that most of the past research on rubber modified mixtures has been conducted on HMA mixtures and the great majority research on WMA mixtures has been conducted with neat asphalt binders. Therefore, there is a great need to assess the performance of rubber modified mixtures with the WMA technologies.

3. Objective

The intention of this research effort was to evaluate the use of terminal blend tire rubber-modified (TR) binder with WMA mixtures and to compare its performance with WMA mixtures made with neat and polymer-modified (PM) binders. The research evaluated the resistance of WMA mixtures to moisture damage and its impact on pavement responses.

It should be clearly noted that the terminal blend tire rubber-modified binder is different than the crumb rubber-modified (CRM) binder in that the TR binder is blended at the terminal and shipped to the asphalt plant ready to be used while the CRM binder is typically blended and cured at the asphalt plant prior to mixing which requires additional equipment at the plant. However, both the TR and CRM binders are modified with tire rubber. This research only evaluated WMA and control asphalts made with the TR binder.

4. Mix Design

The asphalt binders used in this research consisted of a terminal blend tire rubber-modified PG64-28TR, neat PG64-22, and polymer-modified PG64-28PM. The aggregate came from an andesitic basalt quarry in northern Nevada that supplies asphalt aggregates to Nevada and California. A control asphalt mixture was produced with each binder at normal mixing and compaction temperatures as obtained from the binder-specific viscosity temperature chart. As recommended by the 2011 study at the University of Nevada, the evaluations were conducted using aggregates with residual moisture as summarized in Table 1.

Mix Type	Residual Moisture in Aggregates (%)		
	PG64-22	PG64-28PM	PG64-28TR
Control Asphalt	0.00	0.00	0.00
WMA-Advera	0.77	0.13	0.25
WMA-Sasobit	0.68	0.2	0.15

Table 1. *Measured Residual Moisture in Aggregates*

The control asphalt mixtures were designed using the Hveem mix design method as per Nevada and California specifications. Two anti-strip additives were evaluated in this research effort for mitigating potential moisture damage: hydrated lime and liquid anti-strip. Dry lime on damp aggregate was added at a rate of 1.0 % by dry weight of aggregate. The liquid additive was blended in the binder at a rate of 0.5 % by weight of binder.

The National Cooperative Highway Research Program (NCHRP) project 9-43 recommended the use of aging index, aggregate coating, and compactability criteria to determine the mixing and compaction temperatures for the various WMA mixtures (NCHRP, 2008). These procedures were followed in this research and the results are shown in Figure 1.

The aging index of each binder was used to determine the minimum mixing temperature that a WMA mixture can be subjected to before the reduction in mixing temperature impacts the resulting binder grade. The aggregate coating of the various mixtures was evaluated using the American Association of State Highway and Transportation Officials (AASHTO) T195 standard method for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures (AASHTO 2009). A WMA mixing temperature that resulted in 98 percent aggregate coating was deemed acceptable for WMA production.

The compactability of the WMA mixture was represented by the number of gyrations to 8 percent air voids (i.e. 92 percent relative density) by means of the Superpave gyratory compactor. Compactability samples were mixed at the proposed mixing temperature, cured for two hours at the proposed compaction temperature and then compacted to 92 percent relative density. In this study, the compaction temperature for the WMA mixtures was defined as the mixing temperature reduced by 14 °C. Another set of samples was prepared and cured for two hours at the compaction temperature and allowed to cool to 30 °C below the proposed compaction temperature before compaction to 92 percent relative density. The WMA compaction temperature was deemed appropriate if the number of gyrations to 92 percent relative density at the compaction temperature minus 30 °C was less than 125 percent of the value at the compaction temperature.

It should be noted that in the case of the Advera, the supplier recommended rate of 0.3 percent by total weight of mix was sufficient to achieve the desired reduction in the mixing and compaction temperatures. In the case of Sasobit, the supplier recommended rate of 1.5 percent by weight of binder was sufficient for the PG64-22 and PG64-28TR mixtures while the rate had to be increased to 3.0 percent by weight of binder for the PG64-28PM to achieve the desired reduction in the mixing and compaction temperatures. In general, the WMA additives reduced the mixing and compaction temperature of the neat mixtures by 25 – 30 °C while they only reduced the mixing and compaction temperatures of the modified mixtures by 17 – 25 °C.

The optimum binder contents that were obtained for the control asphalt mixtures were verified for WMA mixtures using the procedures discussed above. Table 2 summarizes the mix design information for the control asphalt and WMA mixtures. For each binder type, the optimum binder contents are similar for control mixtures and WMA mixtures and for both types of anti-strip additive.

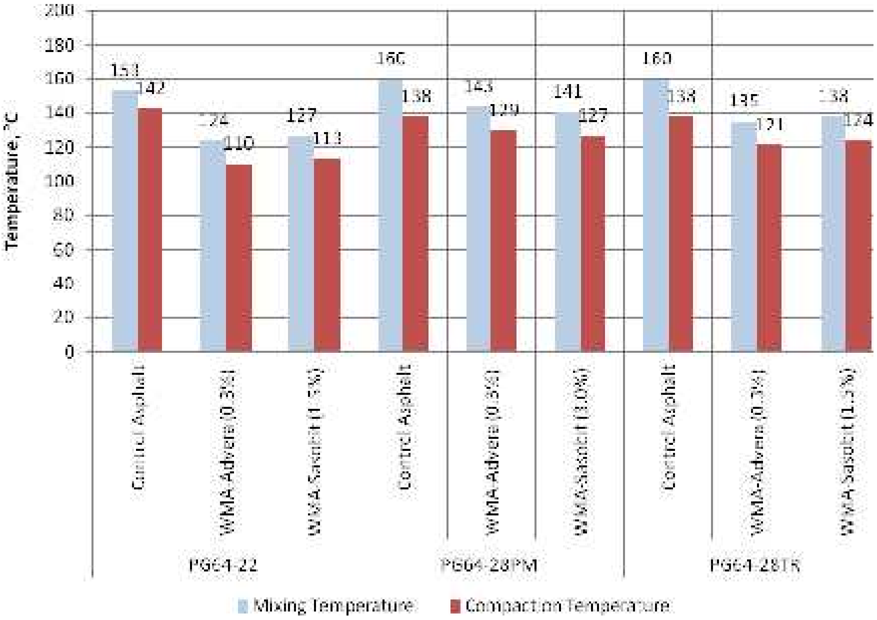

Figure 1. *Mixing and Compaction Temperatures for various Mixtures*

Mix Type	Treatment	Optimum Binder Content, percent dry weight of aggregate (%)		
		PG64-22	PG64-28PM	PG64-28TR
Control Asphalt	Un-treated	5.7	5.8	5.7
	Lime-treated	5.6	5.6	5.6
	Liquid-treated	5.7	5.8	5.7
WMA-Advera	Un-treated	5.7	5.8	5.7
	Lime-treated	5.6	5.6	5.6
	Liquid-treated	5.7	5.8	5.7
WMA - Sasobit	Un-treated	5.7	5.8	5.7
	Lime-treated	5.6	5.6	5.6
	Liquid-treated	5.7	5.8	5.7

Table 2. *Summary of Mix Designs*

5. Laboratory Testing Methods

The various laboratory testing methods that were used in this research effort are briefly described below:

5.1 Freeze-Thaw Cycles

Freeze-thaw cycling was used to simulate the impact of short and long-term moisture damage on control mixtures and WMA mixtures. Each F-T cycle consisted of the following steps:

1. Subject the compacted sample to 70 – 80 percent saturation
2. Freeze the saturated sample at -18 ^{o}C for 16 hours
3. Thaw the frozen sample at 60 ^{o}C for 24 hours
4. Repeat steps 2 and 3 to achieve the desired number of F-T cycles

5.2 Tensile Strength

The tensile strength (TS) of the mixtures was evaluated using the indirect tensile strength test which loads the asphalt sample in the diametral direction and measures the maximum load at failure. The maximum load is then used to calculate the TS as the tensile stress at the center of the sample. The loading rate of the TS test is 50 mm/min. The values of TS and tensile strength ratio (TSR) have been typically used to assess the short-term moisture damage of asphalts.

5.3 Dynamic Modulus

The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) uses the dynamic modulus (E*) master curve to evaluate the structural response of the flexible pavement under various combinations of traffic loads, speed, and environmental conditions (NCHRP, 2004). The E* test consists of testing 100 mm x 150 mm cylindrical sample under uniaxial state of stress. Under zero confining pressure, a sinusoidal deviator stress is applied. The sinusoidal axial deformation is measured over the middle 100 mm of the sample by two linear variable differential transformers (LVDTs) placed 180 degrees apart. The sinusoidal strain is calculated as the ratio of the deformation over the 100 mm gauge length times 100. The amplitude of the E* is calculated as the ratio of the maximum sinusoidal stress over the maximum sinusoidal strain. The E* property of the various mixtures is measured under multiple combinations of loading frequency of 25, 10, 5, 0.5, 0.1 Hz and temperature of 4, 21, 38, and 55 °C as specified by AASHTO TP 62 (AASHTO, 2009). Using the viscoelastic behavior of asphalt mixtures (i.e. interchangeability of the effect of loading rate and temperature) the master curve is developed as specified by AASHTO PP 61 (AASHTO, 2009). The master curve can be used to identify the appropriate E* for any combination of pavement temperature and traffic speed. The E* property provides an indication of the general quality of asphalt mixtures. The relationship between E* and the number of F-T cycles gives an excellent indication of the resistance of a mixture to moisture damage.

6. Analysis of Mixtures Properties

The resistances of the various mixtures to moisture damage were evaluated at the short-term and long-term stages. The un-conditioned and conditioned (i.e. after 1 F-T cycle) TS were used to evaluate the short-term moisture damage. The TSR was determined as the ratio of the TS after 1 F-T cycle over the unconditioned TS times 100. The unconditioned E* and E* after 6 F-T cycles were used to evaluate long-term moisture damage.

Figures 2 – 4 summarize the short-term moisture damage of the various mixtures. The numbers over the bars represent the average values while the whiskers represent the range of measurements. The data in Figure 2 show that only the PM and TR control and Sasobit WMA mixtures pass the Superpave criteria of minimum TSR of 80 percent without additive. The data in Figures 3 show that the addition of lime significantly improved the TSR for all mixtures well above the Superpave criteria. The data in Figure 4 show that the addition of liquid anti-strip moderately improved the TSR for all mixtures with the PG64-22 Advera WMA TSR remained below the Superpave criteria.

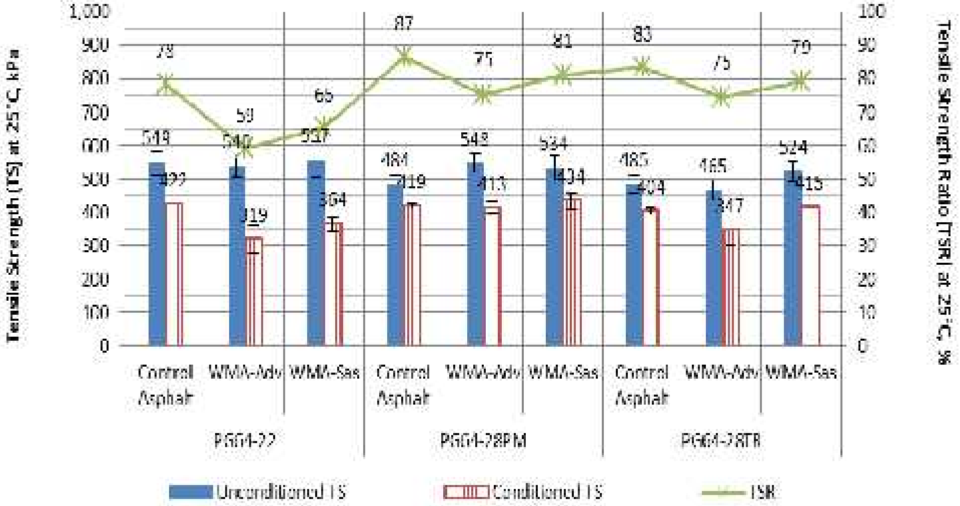

Figure 2. *Tensile Strength Properties of the Un-treated Mixtures*

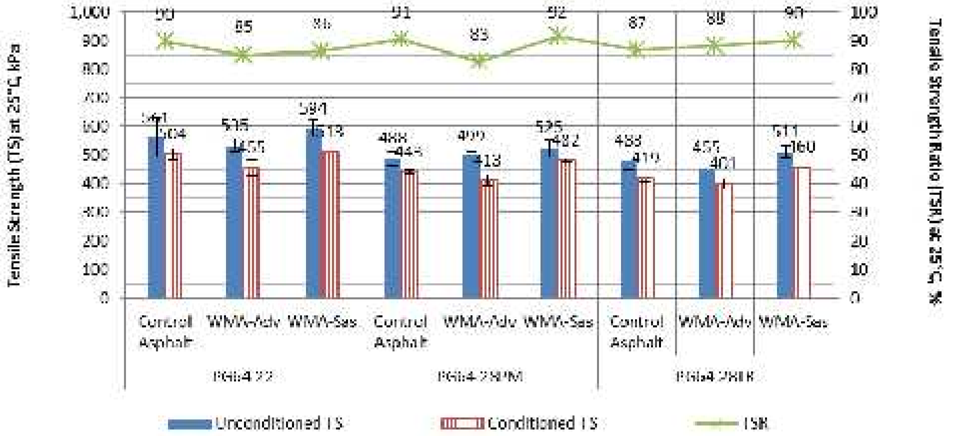

Figure 3. *Tensile Strength Properties of the Lime-Treated Mixtures*

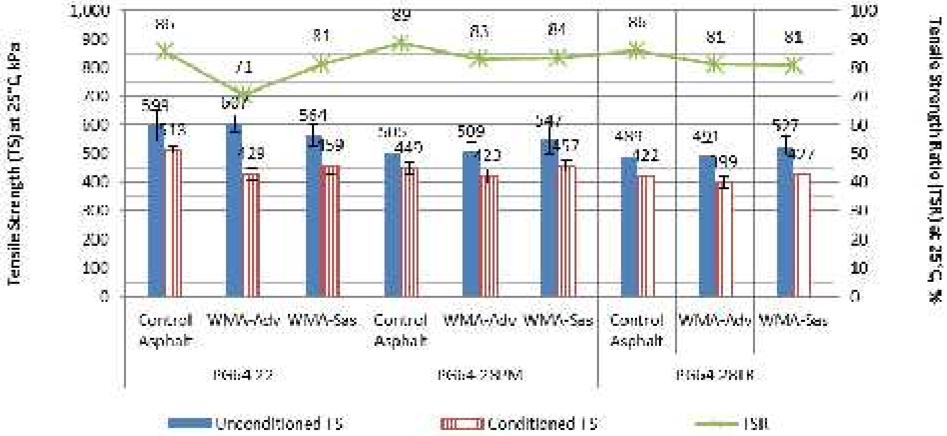

Figure 4. *Tensile Strength Properties of the Liquid-Treated Mixtures*

Figures 5 – 7 show the long-term moisture damage in terms of the un-conditioned E* (i.e. 0 F-T cycles) and E* after 6 F-T cycles for all mixtures. The ECR was determined as the ratio of the E* after 6 F-T cycle to the un-conditioned E* times 100. Overall, the data show that E* decreases as the mixtures are subjected to 6 F-T cycles. Based on the test results, the following trends were observed:

- The neat PG64-22 control and WMA mixtures showed the highest un-conditioned E* property with significant reductions in E* after 6 F-T cycles.
- The un-treated Advera WMA mixtures experienced the largest reduction in E* after 6 F-T cycles.
- The un-treated Sasobit WMA mixtures experienced moderate reduction in E* after 6 F-T cycles.
- The lime additive significantly improved the long-term resistance to moisture damage of all control and WMA mixtures. Previous research studies have shown that lime also improves the strength and performance characteristics of asphalt mixtures (Sebaaly et al, 2010).
- The liquid additive moderately improved the long-term resistance to moisture damage of control and WMA mixtures except for the PG64-28TR Advera WMA mix which did not experience any improvement (Figure 7 shows the ECR curve for the liquid-treated Advera WMA mix overlapping the un-treated curve).

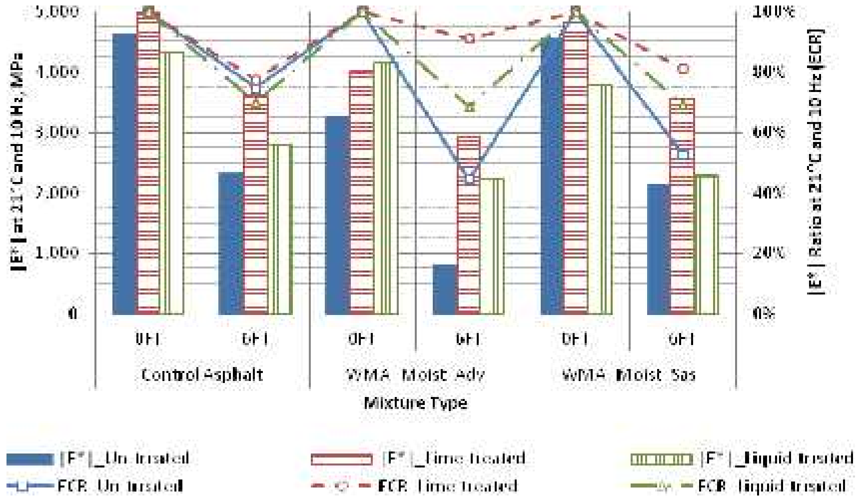

Figure 5. *Impact of Long-term Moisture Damage on the Dynamic Modulus of PG64-22 Mixes*

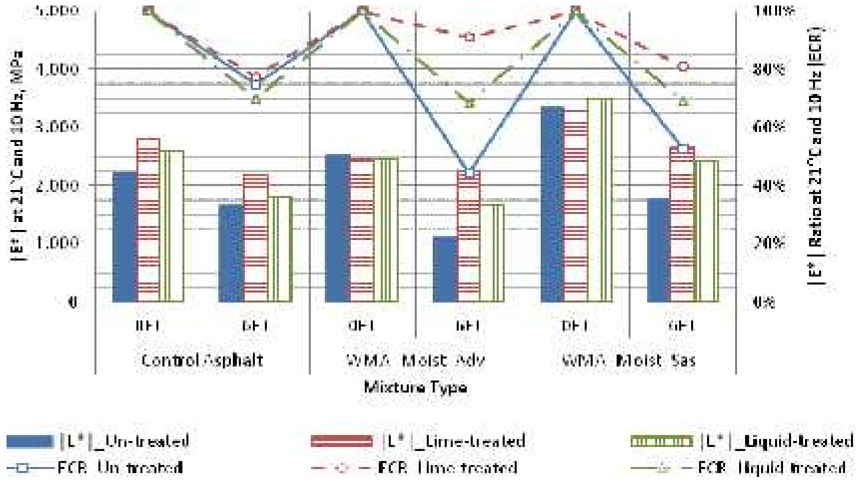

Figure 6. *Impact of Long-term Moisture Damage on the Dynamic Modulus of PG64-28PM Mixes*

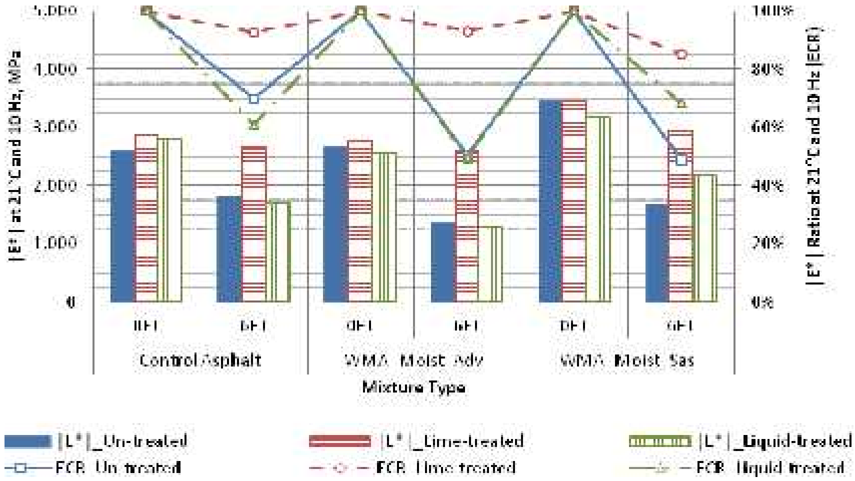

Figure 7. *Impact of Long-term Moisture Damage on the Dynamic Modulus of PG64-28TR Mixes*

7. Mechanistic Analysis of Pavements

This section of the paper presents the mechanistic analyses of flexible pavements constructed with the neat, PM, and TR mixtures. For each of the three types of mixture, the control and two WMA mixtures were evaluated. The analyses used the undamaged (i.e. 0 F-T) and moisture-damaged (i.e. 6 F-T) E* properties of the various mixtures to evaluate the response parameters of asphalt pavements that are considered critical to fatigue and rutting of the asphalt layer. The following pavement structures were analyzed with the layout shown in Figure 8.

- Asphalt layer: 150 mm thick, modulus varies depending on the type of mix used and moisture damage stage
- Crushed aggregate base layer: 254 mm thick, modulus = 138 MPa
- Subgrade layer: infinite, modulus = 55 MPa

The loading consisted of a single axle load of 80 kN with dual tires at an inflation pressure of 828 kPa. The values of the E* for the various mixtures were obtained from the dynamic modulus master curves at 0 and 6 F-T cycles for a loading frequency of 10 Hz. The E* properties at 21°C and 40°C were used for fatigue and rutting analysis, respectively. The temperatures of the E* were selected to represent the critical conditions for fatigue cracking of intermediate temperature and permanent deformation of high temperature.

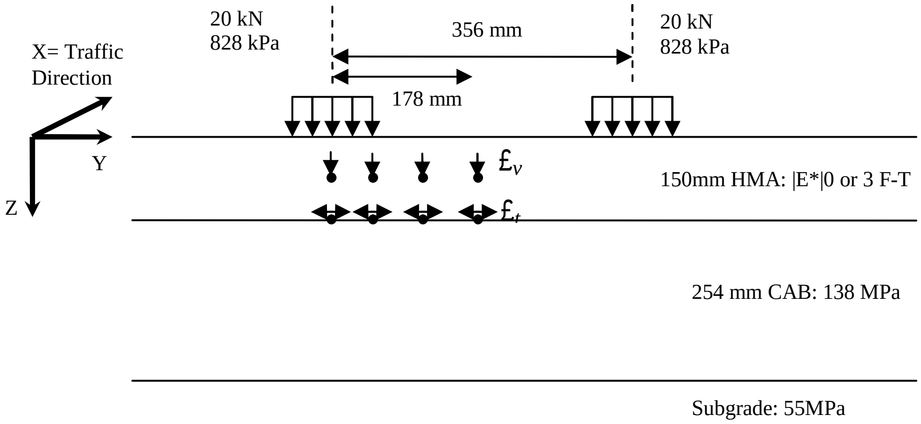

Figure 8. *Flexible Pavement Structure used in the Mechanistic Analyses*

The AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) relates bottom-up fatigue cracking to the tensile strain at the bottom of the asphalt layer and the permanent deformation in the asphalt layer to the vertical compressive strain at the middle of the asphalt layer (NCHRP, 2004). The following combinations were included in the mechanistic analysis:

- Pavement structure: one level
- Asphalt mixture: 9 levels
    - three binder grades: PG64-22, PG64-28PM, PG64-28TR
    - three WMA additives: none, Advera, Sasobit
- Moisture damage: 2 levels
    - un-damaged: 0 F-T cycles
    - damaged: 6 F-T cycles
- Anti-strip additive: 3 levels
    - None
    - Hydrated lime
    - Liquid

Total Pavements: (1 structure)x(9 mixtures)x(2 moistures)x(3 additives) = 54

The properties of the 54 pavement structures along with the loading conditions were used in the multi-layer elastic solution to calculate the maximum tensile strain ($£_t$) at the bottom of the asphalt layer and the maximum vertical compressive strain ($£_v$) at the middle of the asphalt layer for all 54 pavements.

Table 3 summarizes the E* properties of the various mixtures that were used in the mechanistic analyses. It should be recognized that the E* at 21^{o}C were used for the $£_t$ calculations and the E* at 40^{o}C were used for the $£_v$ calculations. In the MEPDG, the calculated strains are inputed into the performance models of the HMA layer to estimate the fatigue and rutting performance of the HMA pavement. Since the fatigue and rutting performance models were outside the scope of this study, only pavement responses (i.e. $£_t$ and $£_v$) for the various pavements at the un-damaged and moisture-damaged stages were evaluated and compared to each others.

Table 4 summarizes the calculated $£_t$ and $£_v$ for all 54 pavements. The data in Tables 3 and 4 show the clear impact of moisture damage on the measured E* properties and the generated strains in all pavements. The E* at both temperatures decrease and both the $£_t$ and $£_v$ increase as the control and WMA mixtures are subjected to the 6 F-T cycles.

The magnitudes of $£_t$ and $£_v$ are impacted by several factors, including; magnitude of load and pressure, thickness of pavement layers, and the modulus of the various pavement layers. In this analysis, most of these factors were kept constant such as the load and pressure, thickness of pavement layers, and modulus of base and subgrade. The major difference among the various pavements is the modulus of the asphalt layer which is impacted by the binder grade, WMA additive, and the anti-strip additive.

Mixture ID	Anti-strip Additive	WMA Additive	0 F-T		6 F-T	
			E*, 21^{o}C (MPa)	E*, 40°C (Mpa)	E*, 21^{o}C (Mpa)	E*, 40°C (Mpa)
PG64-22	None	None	4632	2331	1322	590
		Advera	3278	814	657	214
		Sasobit	4542	2139	1116	569
	Lime	None	4962	3600	1314	875
		Advera	4019	2910	825	611
		Sasobit	4808	3556	1217	871
	Liquid	None	4315	2795	1150	660
		Advera	4135	2241	770	450
		Sasobit	3792	2276	1007	520
PG64-28PM	None	None	2229	1668	568	400
		Advera	2522	1118	530	253
		Sasobit	3351	1767	934	396
	Lime	None	2812	2176	563	417
		Advera	2455	2233	454	410
		Sasobit	3284	2656	801	624
	Liquid	None	2601	1818	579	360
		Advera	2455	1683	513	320
		Sasobit	3501	2425	1008	531
PG64-28TR	None	None	2612	1829	545	436
		Advera	2664	1353	554	309
		Sasobit	3468	1699	772	385
	Lime	None	2870	2660	480	471
		Advera	2788	2595	452	460
		Sasobit	3465	2953	671	551
	Liquid	None	2821	1721	555	306
		Advera	2565	1278	430	252
		Sasobit	3178	2175	678	418

Table 3. *E* Properties used in the Mechanistic Analyses.*

Mixture ID	WMA Additive	Anti-strip Additive	0 F-T		6 F-T	
			£$_t$, 21^{o}C (micro)	£$_v$, 40°C (micro)	£$_t$, 21^{o}C (micro)	£$_v$, 40°C (micro)
PG64-22	None	None	203	335	306	801
		Advera	251	713	499	2430
		Sasobit	206	402	321	764
	Lime	None	194	338	238	522
		Advera	222	556	270	771
		Sasobit	198	366	239	525
	Liquid	None	212	389	276	709
		Advera	218	600	313	1079
		Sasobit	230	448	310	919
PG64-28PM	None	None	313	835	365	1227
		Advera	293	901	440	2025
		Sasobit	248	487	354	1239
	Lime	None	275	843	318	1172
		Advera	297	1067	313	1194
		Sasobit	251	575	284	753
	Liquid	None	288	818	349	1377
		Advera	297	934	363	1566
		Sasobit	242	448	299	899
PG64-28TR	None	None	287	874	348	1114
		Advera	284	858	404	1624
		Sasobit	243	598	361	1278
	Lime	None	272	1003	284	1025
		Advera	277	1071	288	1052
		Sasobit	243	696	267	863
	Liquid	None	275	857	359	1644
		Advera	290	1131	414	2034
		Sasobit	256	689	318	1166

Table 4. *Calculated Tensile and Compressive Strains*

Figures 9 – 14 present the strain ratios for the three types of mixture; PG64-22, PG64-28PM, and PG64-28TR. The strain ratio is defined as the ratio of the strain (i.e. $£_t$ or $£_v$) of the moisture-damaged asphalt layer (i.e. after 6 F-T) over the strain ($£_t$ or $£_v$) of the undamaged asphalt layer. For each mixture type, the strain ratios for the un-treated, lime-treated, and liquid-treated mixtures are presented. The higher the strain ratio, the more damaged the asphalt mix is due to the 6 F-T cycles. The following summarizes the observations from Figures 9 – 14:

- Tensile strains at the bottom of the PG64-22 layer (Figure 9):
  - un-treated WMA-Advera mix experienced the highest moisture damage, un-treated control and WMA-Sasobit mixtures experienced the same moisture damage
  - liquid-treated control and WMA mixtures experienced moderate moisture damage
  - lime-treated control and WMA mixtures experienced the least moisture damage

- Tensile strains at the bottom of the PG64-28PM layer (Figure 10):
  - un-treated WMA-Advera and WMA-Sasobit mixtures experienced the highest moisture damage, and un-treated control mix experienced low moisture damage
  - liquid-treated WMA-Advera and WMA-Sasobit mixtures experienced moderate moisture damage while the liquid-treated control mix experienced increased moisture damage as compared to un-treated
  - lime-treated control and WMA mixtures experienced the least moisture damage

- Tensile strains at the bottom of the PG64-28TR layer (Figure 11):
  - un-treated WMA-Advera and WMA-Sasobit mixtures experienced the highest moisture damage, and un-treated control mix experienced moderate moisture damage
  - liquid-treated WMA-Advera experienced high moisture damage and liquid-treated control and WMA-Sasobit mixtures experienced moderate moisture damage
  - lime-treated control and WMA mixtures experienced the least moisture damage

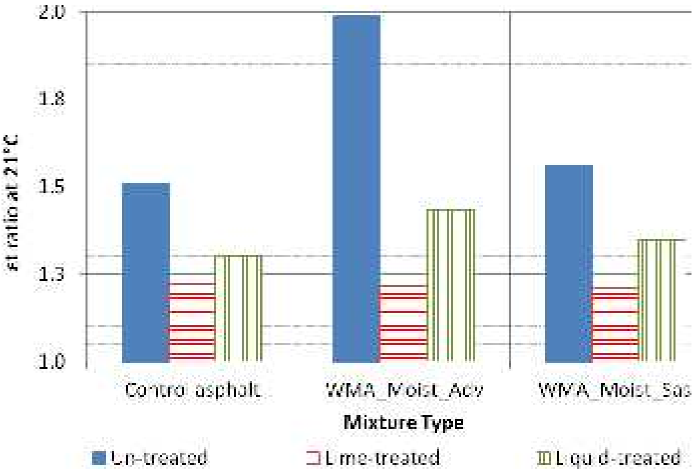

Figure 9. *Tensile Strain Ratios for the PG64-22 Mixtures*

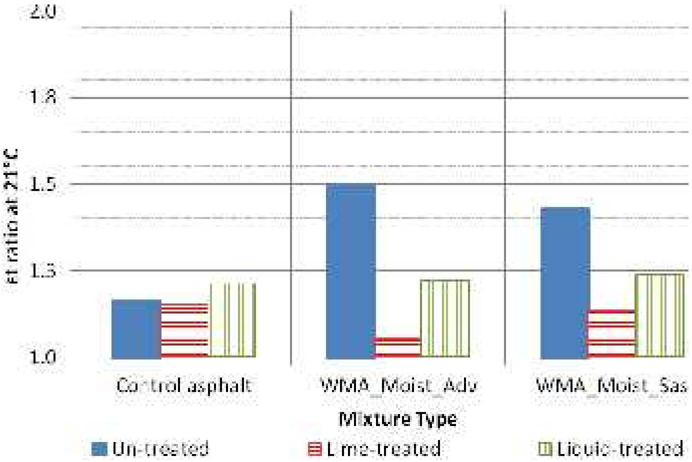

Figure 10. *Tensile Strain Ratios for the PG64-28PM Mixtures*

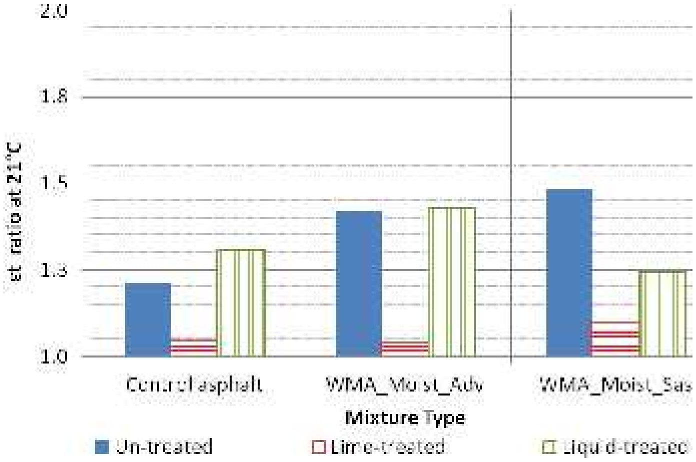

Figure 11. *Tensile Strain Ratios for the PG64-28TR Mixtures*

- Vertical strains at the middle of the PG64-22 layer (Figure 12):
  - un-treated WMA-Advera mix experienced the highest moisture damage followed by the un-treated control the un-treated WMA-Sasobit mixtures
  - liquid-treated mixtures experienced moderate moisture damage with the liquid-treated WMA-Sasobit mix experiencing slightly higher moisture damage than the un-treated WMA-Sasobit mix
  - lime-treated control and WMA mixtures experienced the least moisture damage

- Vertical strains at the middle of the PG64-28PM layer (Figure 13):
  - un-treated WMA-Advera and WMA-Sasobit mixtures experienced the highest moisture damage, and un-treated control mix experienced low moisture damage
  - liquid-treated WMA-Sasobit mixture experienced high moisture damage while the liquid-treated control and WMA-Advera mixtures experienced moderate moisture damage
  - lime-treated control and WMA mixtures experienced the least moisture damage

- Vertical strains at the middle of the PG64-28TR layer (Figure 14):
    - un-treated WMA-Advera and WMA-Sasobit mixtures experienced the highest moisture damage, and un-treated control mix experienced low moisture damage
    - liquid-treated control and WMA mixtures experienced high moisture damage
    - lime-treated control and WMA mixtures experienced the least moisture damage

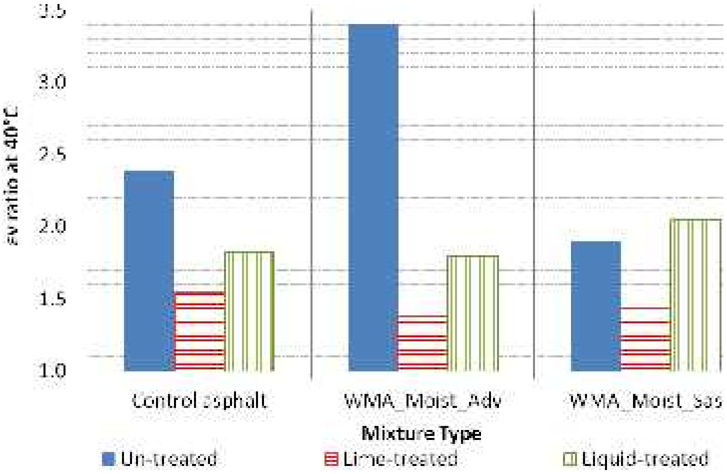

Figure 12. *Vertical Strain Ratios for the PG64-22 Mixtures*

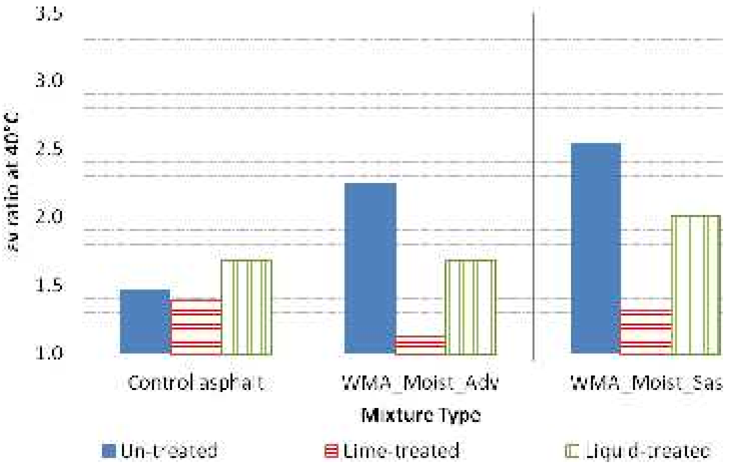

Figure 13. *Vertical Strain Ratios for the PG64-28PM Mixtures*

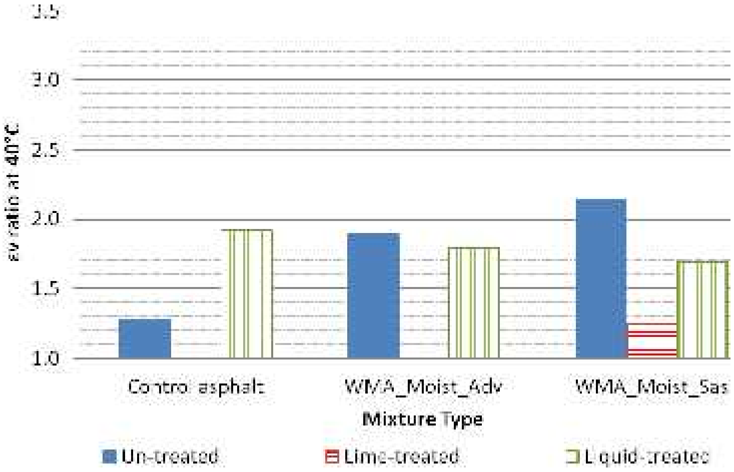

Figure 14. *Vertical Strain Ratios for the PG64-28TR Mixtures*

8. Conclusions and Recommendations

The use of terminal blend tire rubber-modified binder with WMA mixtures significantly improves their resistance to moisture damage in terms of increased retained strength/modulus and reduced tensile/vertical strains within the asphalt layer.

Among all mixture evaluated in this study, the best performance was obtained from the terminal blend tire rubber-modified mixtures treated with hydrated lime. This observation was true for control, WMA-Advera, and WMA-Sasobit mixtures.

However, the addition of liquid anti-strip additive to the control and WMA mixtures evaluated in this study had a marginal improvement on some mixtures while it negatively impacted others.

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