MECHANISTIC PROPERTIES OF 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 asphalts. The basic principle of the WMA technology is to lower the mixing and compaction temperatures of the produce asphalt through lowering the viscosity-temperature relationship of the bitumen.

The objective of this research effort was to evaluate the impact of WMA additives on the resistance of asphalts to moisture damage and permanent deformation. In addition, the low mixing temperature of WMA tends to leave access moisture inside the aggregates which is referred to as "residual moisture". The study evaluated the impact of residual moisture in the aggregates and the interaction of WMA additives with polymer, recycled tire rubber, and anti-strip additives that are commonly to improve the long-term performance of asphalt pavements. The resistance of the mixtures to moisture damage was evaluated in terms of the impact of multiple freeze-thaw cycles on the dynamic modulus. And the resistance to permanent deformation was evaluated in term of the flow number.

The study showed that WMA mixtures can be designed to provide excellent resistance to moisture damage and permanent deformation if the right combination of WMA additive, bitumen modifier, and anti-strip additive is selected. This study showed that the terminal blend tire rubber-modified bitumen combined with hydrated lime can provide the best performing control asphalt and WMA mixtures leading to highly sustainable asphalt pavements.

Keywords: warm mix asphalt, moisture damage, rutting, residual moisture

1. INTRODUCTION

In effort to build sustainable asphalt pavements through conserving energy and reducing emissions, warm mix asphalt (WMA) technologies are increasingly being investigated for their impact on asphalt performance. WMA technologies allow asphalts to be produced and placed at temperatures lower than the temperatures used for conventional asphalt produced without the additives. In general, WMA additives improve workability and compactability of asphalts to the point that they can be produced at lower temperatures. The reduced production temperatures create two major concerns: a) hinder the evaporation of moisture from aggregates leading to an increased potential for moisture damage in asphalt pavements and b) impair the hardening of the bitumen leading to permanent deformation failure of asphalt pavements. This paper documents a research effort that investigated both of these concerns.

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 [1, 2, 3]. 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 ^{o}C and long-term aging of 5 days at 85 ^{o}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 [4]. 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.

2. OBJECTIVE

The intention of this research effort is to evaluate the use of WMA additives with typical neat, polymer-modified (PM), and terminal blend tire rubber-modified (TR) bitumen that are commonly used in the states of Nevada and California in the western region of the United States. The research evaluated the resistance of WMA mixtures to moisture damage and permanent deformation. It should be clearly noted that the terminal blend tire rubber-modified bitumen is different than the crumb rubber-modified (CRM) bitumen in that the TR bitumen is blended at the terminal and shipped to the asphalt plant ready to be used while the CRM bitumen 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 bitumens are modified with tire rubber. This research only evaluated WMA and control asphalts made with the TR bitumen.

3. SCOPE

The experimental program of this research effort consisted of three major parts:

1. Part I: Evaluate the impact of residual moisture in the aggregates on the properties of WMA.
2. Part II: Evaluate the impact of anti-strip additives on the moisture damage of WMA.
3. Part III: Evaluate the permanent deformation characteristics of WMA.

4. MIX DESIGNS

The bitumens used in this research consisted of a neat PG64-22, polymer-modified PG64-28PM, and terminal blend tire rubber-modified PG64-28TR. The aggregate came from a hard rock quarry in northern Nevada that supplies asphalt aggregates to Nevada and California. The control asphalts 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 bitumen at a rate of 0.5 % by weight of bitumen.

The optimum bitumen contents that were obtained for the control asphalts were verified for WMA mixtures using the procedure outlined in reference 5. Table 1 summarizes the mix design information for the control asphalt and WMA mixtures. The optimum bitumen contents are similar for control asphalts and WMA mixtures and for both types of anti-strip additive.

Table 1: Summary of mix designs

Mix Type	Treatment	Optimum Bitumen 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

The procedure outlined in reference 5 proposes the use of aging index, aggregate coating, and compactability criteria to determine the mixing and compaction temperatures for the various WMA mixtures. These procedures were followed in this research and the results are shown in Figure 1. The aging index of each bitumen 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 bitumen 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 [6]. A WMA mixing temperature that resulted in 98 % aggregate coating was deemed acceptable for WMA production. The compactability of the WMA mixture was represented by the number of gyrations to 8 % air voids (i.e. 92 % 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 % 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 % relative density. The WMA compaction temperature was deemed appropriate if the number of gyrations to 92 % relative density at the compaction temperature minus 30 °C was less than 125 % 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 % 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 % by weight of bitumen was sufficient for the PG64-22 and PG64-28TR mixtures while the rate had to be increased to 3.0 % by weight of bitumen 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 ^{o}C while they only reduced the mixing and compaction temperatures of the modified mixtures by 17 – 25 ^{o}C.

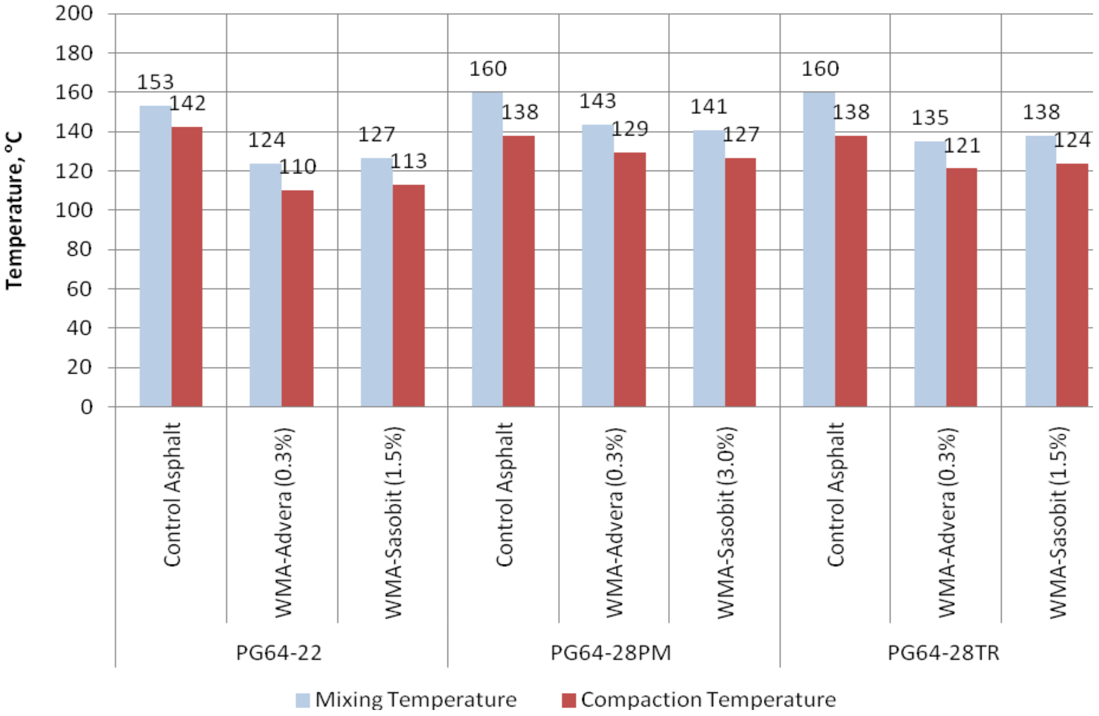

Figure 1: Mixing and compaction temperatures for various mixtures

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 asphalt 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 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 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. 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 [6]. 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 [6]. 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.

5.3 Flow Number

The resistances of the various mixtures to permanent deformation were evaluated using the Flow Number (FN) Test. The FN test consists of testing 100 mm x 150 mm cylindrical sample under uniaxial state of stress. Under zero confining pressure, a repeated haversine deviator stress of 600 kPa is applied for 0.1 second followed by a 0.6 second rest period. The axial deformation of the sample is measured over the middle 100 mm of the sample by two linear variable differential transformers (LVDTs) placed 180 degrees apart. The LVDTs measure both the resilient and permanent deformations. The axial permanent strain is calculated as the ratio of the permanent deformation over the 100 mm gauge length times 100. The FN tests for all mixtures were conducted at a temperature of 58 ^{o}C. The FN is defined as the number of load cycles at which the mixture starts its tertiary flow which is defined as a large increase in the rate of permanent strain as a function of load repetitions.

6. ANALYSIS OF DATA FROM PART I

One concern regarding WMA is that the moisture from the stockpiled aggregates does not completely evaporate in the drum as WMA mixing temperatures are lower than those used during typical asphalt production. The retained moisture, defined as residual moisture, in the bitumen-coated aggregates may result in a moisture susceptible asphalt. The residual moisture was determined in the laboratory as the moisture remained in the aggregate after heating the wet aggregate to the WMA mixing temperature. This process involves treating the aggregate blend for 15 – 18 hours with water at 2 % above the combined aggregate absorption. Then, the saturated aggregate were dried for a calibrated time period in an oven set to the WMA mixing temperature and their moisture content was measured. The calibrated time period is the time for a similarly wet aggregate sample to reach constant dry mass in an oven set at the corresponding typical asphalt temperature. The residual moisture in the aggregate varied by mixture depending on the WMA mixing temperature as listed in Table 2. The residual moistures coincide very well with the mixing temperatures shown in Figure1; the higher the mixing temperature the lower the residual moisture and vise versa. The objective of Part I is to evaluate the impact of residual moisture on the moisture resistance of control asphalt and WMA mixtures.

Table 3 summarizes the experiment that was completed to achieve the objective of Part I. The WMA mixtures were evaluated with and without residual moisture. The control asphalts did not include any residual since the aggregates will be completely dry at the elevated mixing temperatures of the control asphalts.

Table 2: Measured residual moisture in aggregates

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 3: Experimental plan for part I

Bitumen	WMA additive	Residual Moisture	Dynamic Modulus, E*, Master Curve		
			E* dry	E* after 1 F-T	E* after 6 F-T
Neat PG64-22	None	No	X	X	X
	Advera	No	X	X	X
		Yes	X	X	X
	Sasobit	No	X	X	X
		Yes	X	X	X
Polymer-modified PG64-28PM	None	No	X	X	X
	Advera	No	X	X	X
		Yes	X	X	X
	Sasobit	No	X	X	X
		Yes	X	X	X
Terminal blend tire rubber-modified PG64-28TR	None	No	X	X	X
	Advera	No	X	X	X
		Yes	X	X	X
	Sasobit	No	X	X	X
		Yes	X	X	X

Figures 2 -4 summarize the impact of residual moisture in terms of its affect on the E* property of the mixtures at the un-conditioned stage and after 1 and 6 F-T cycles. The WMA mixtures labeled as “moist” represent the mixtures that include residual moisture. The left axis represents the E* and the right axis represents the E* ratio (ECR) defined as the ratio of the E* after 1 or 6 F-T cycles over the un-conditioned E* (i.e. 0 F-T). The E* property at 21 °C and 10 Hz were selected to represent intermediate pavement temperature and highway loading rate, respectively.

In order to assess the impact of residual moisture, the E* and ECR of the moist mixtures should be compared with the E* of the corresponding control asphalt and WMA mix without residual moisture. The data in Figures 2 – 4 show that the residual moisture has an impact on the E* and ECR of the WMA mixtures, with the Advera WMA experiencing more significant impact. In the case of the Sasobit WMA, the moist mixtures 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. Based on the observations made from the data in Figures 2 – 4, it was concluded that the residual moisture in the aggregate impacts the E* of the WMA mixtures. Therefore, the evaluation of the impact of moisture damage on WMA mixtures should include residual moisture.

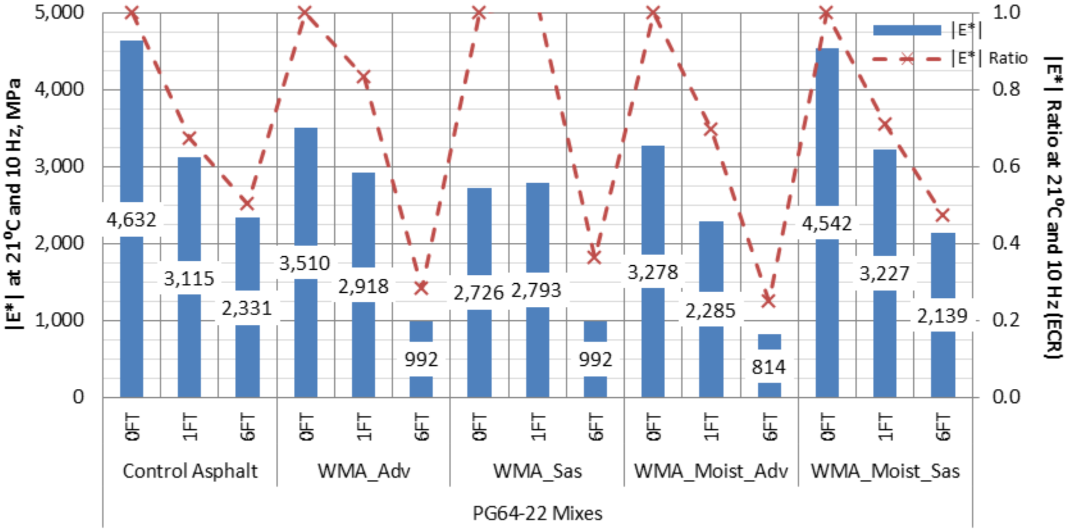

Figure 2: Impact of residual moisture on the dynamic modulus of PG64-22 mixes

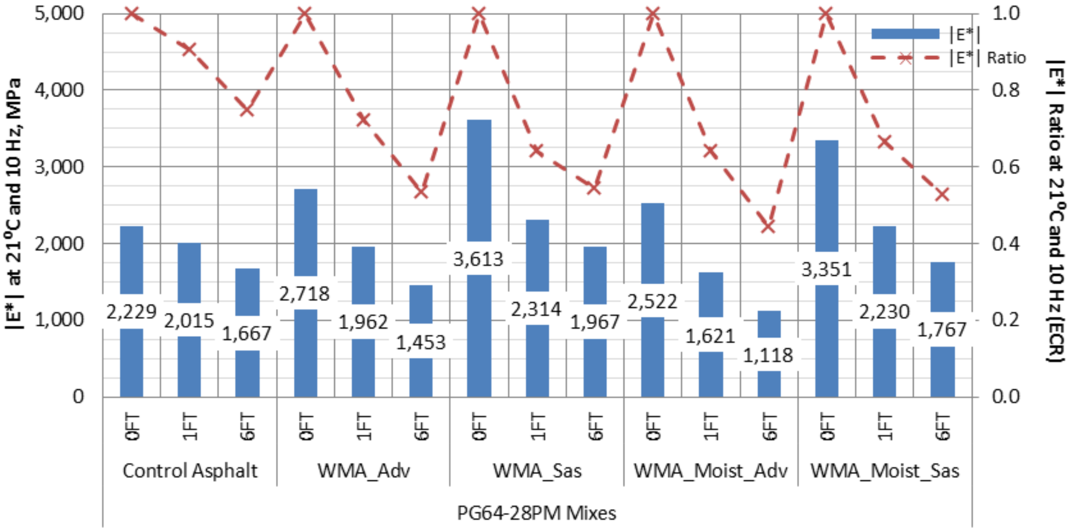

Figure 3: Impact of residual moisture on the dynamic modulus of PG64-28PM mixes

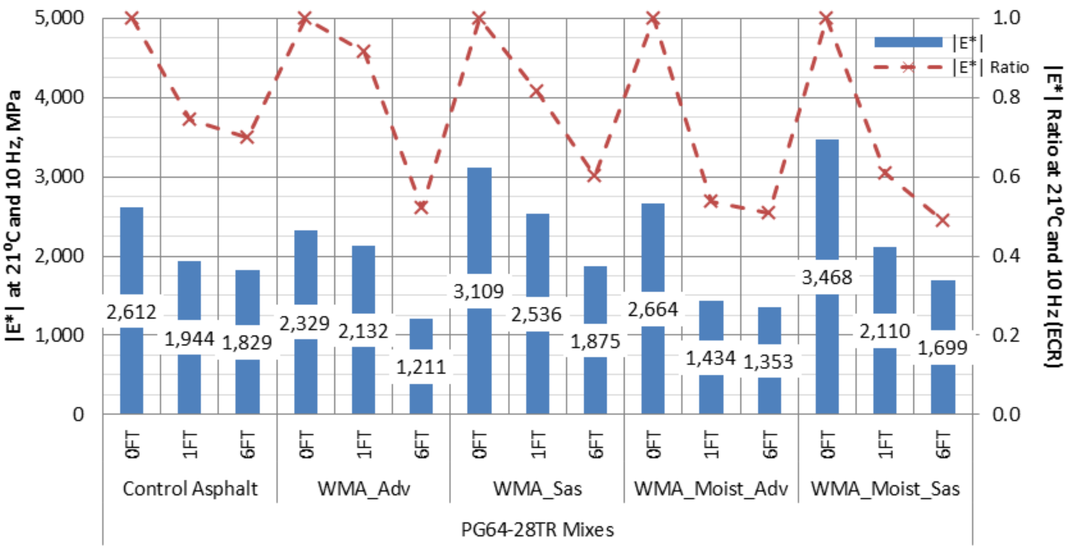

Figure 4: Impact of residual moisture on the dynamic modulus of PG64-28TR mixes

7. ANALYSIS OF DATA FROM PART II

The objective of Part II was to determine if the use of an anti-stripping additive will improve the moisture resistance of the various mixtures. Two types of anti-stripping additives were used: lime and liquid. Aggregates with residual moisture were used to prepare the various WMA mixes. 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 unconditioned E* and E* after 6 F-T cycles were used to evaluate long-term moisture damage.

Figures 5 – 7 summarize the short-term moisture damage of the various mixtures. The data in Figure 5 show that only the PM and TR control and Sasobit WMA mixtures pass the Superpave criteria of minimum TSR of 80 % without additive. The data in Figures 6 show that the addition of lime significantly improved the TSR for all mixtures well above the Superpave criteria. The data in Figure 7 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.

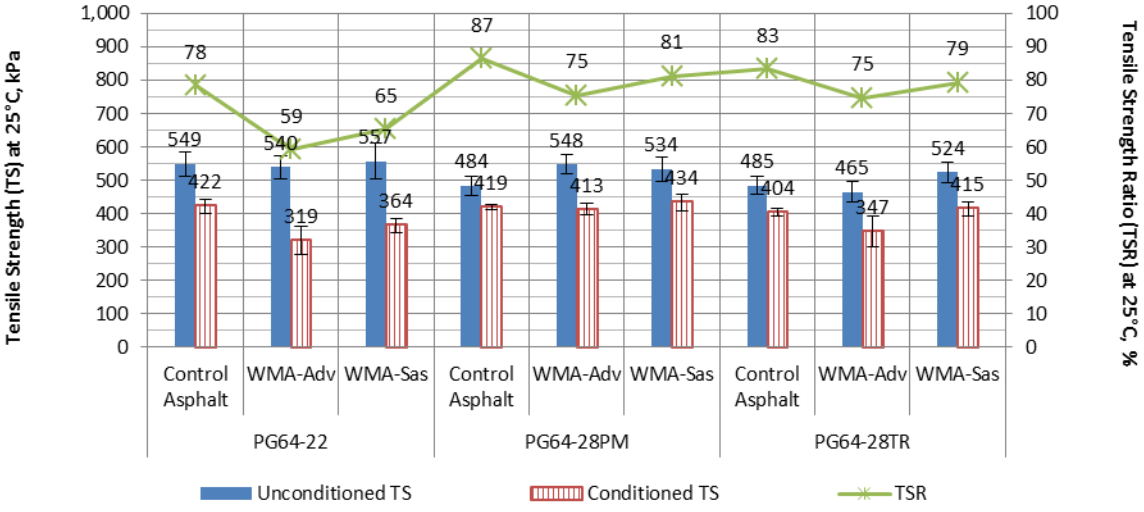

Figure 5: Tensile strength properties of the un-treated mixtures

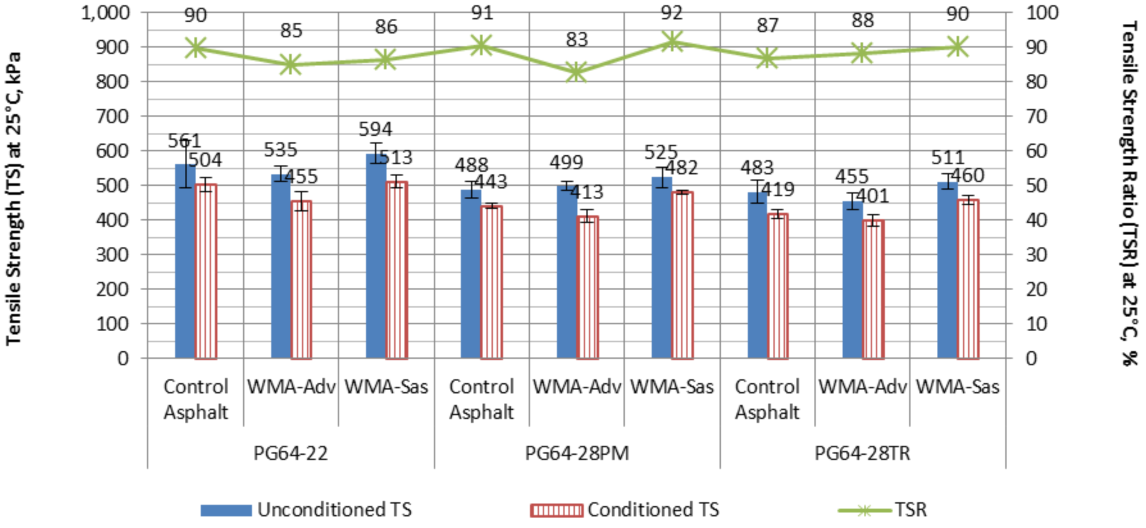

Figure 6: Tensile strength properties of the lime-treated mixtures

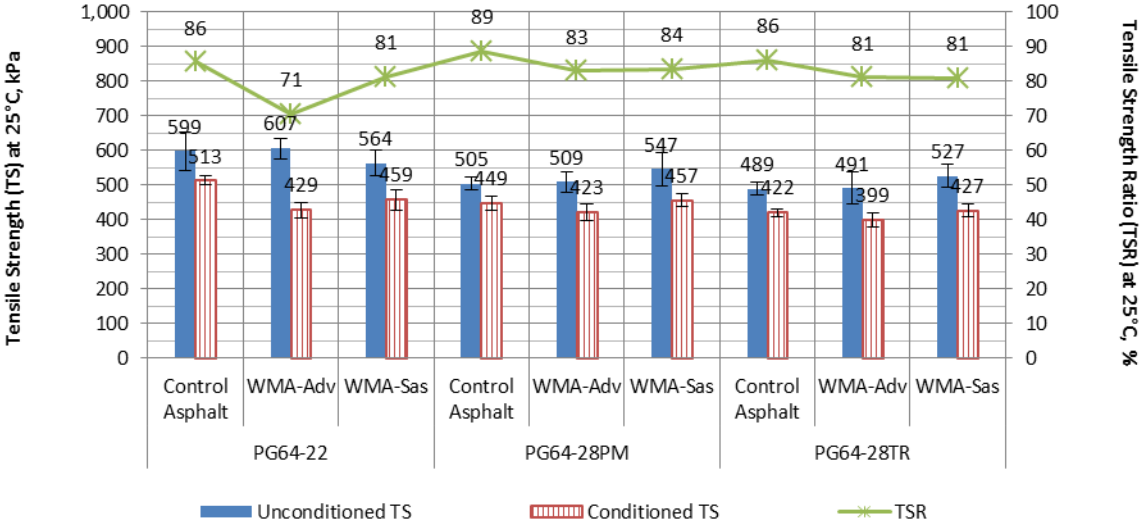

Figure 7: Tensile strength properties of the liquid-treated mixtures

Figures 8 – 10 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.
- 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 10 shows the ECR curve for the liquid-treated Advera WMA mix overlapping the un-treated curve).

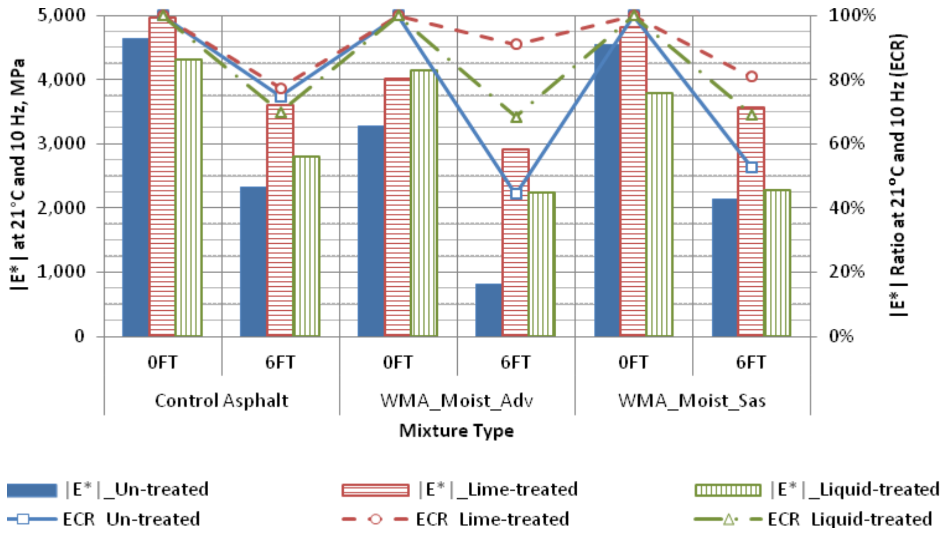

Figure 8: Impact of long-term moisture damage on the dynamic modulus of PG64-22 mixes

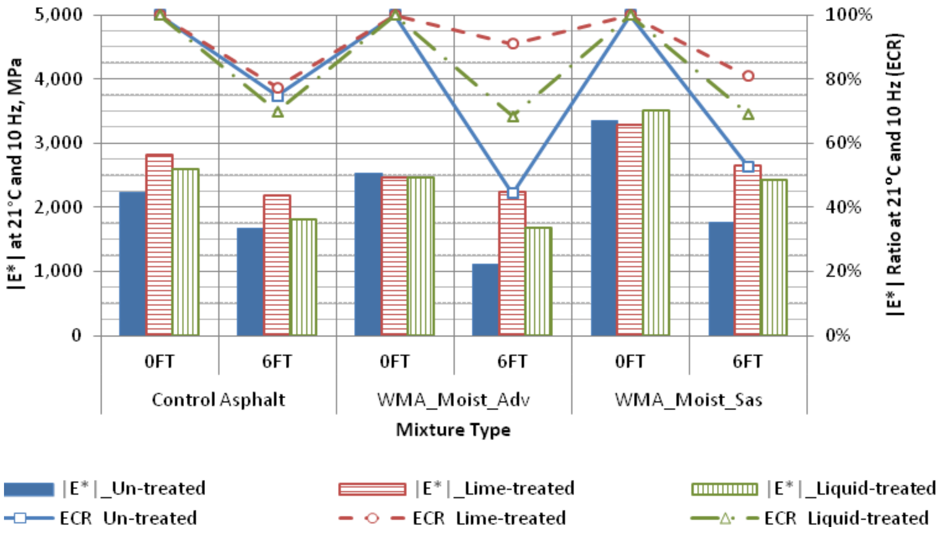

Figure 9: Impact of long-term moisture damage on the dynamic modulus of PG64-28PM mixes

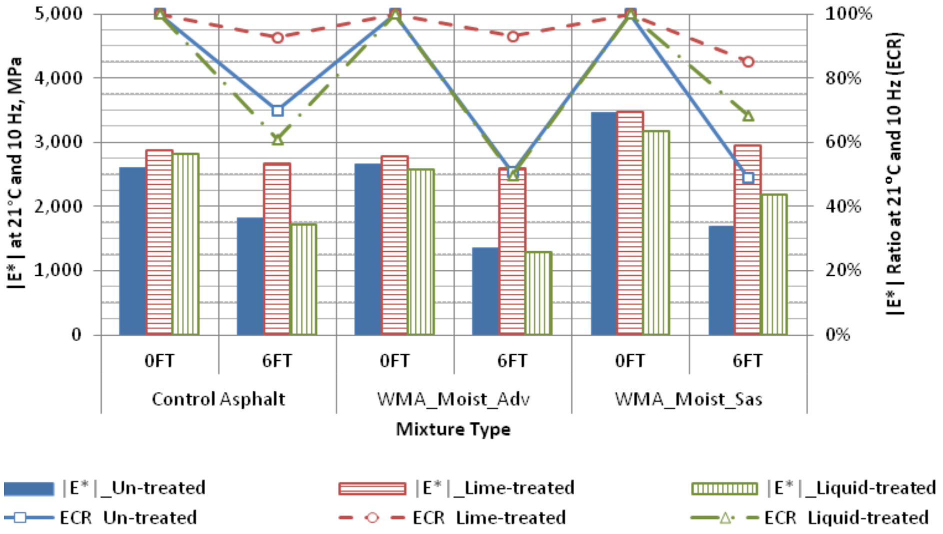

Figure 10: Impact of long-term moisture damage on the dynamic modulus of PG64-28TR mixes

8. ANALYSIS OF DATA FROM PART III

The objective of Part III was to evaluate the resistance of the control and WMA mixtures to permanent deformation using the FN test. The resistance to permanent deformation was selected due to the concern that the lower temperatures of the WMA mixtures may not provide enough stiffening of the bitumen during the early life of the asphalt pavement. Figure 11 shows the FN of the various mixtures at the 58 °C which represents the critical temperature for permanent deformation of bitumen with a high PG temperature of 64 °C which is the case for the mixtures evaluated in this study. The FN test was conducted on un-conditioned mixtures.

A higher FN indicates that the mixture was able to withstand higher number of load repetitions prior to exhibiting tertiary flow. An examination of the data in Figure 11 leads to the following observations:

- The neat PG64-22 Advera WMA mix showed the lowest resistance to permanent deformation which could not be improved with neither lime nor liquid additives.
- The neat PG64-22 control and Sasobit WMA mixtures showed similar resistance to permanent deformation with and without additive.
- The lime additive significantly improved the resistance to permanent deformation of all PM and TR mixtures.
- The FN of the lime-treated PG64-28PM Sasobit mix is significantly higher than the FN of all other mixtures. It is hypothesized that the 3 % Sasobit that was included in the PG64-28PM mix to achieve the desired temperatures has interacted positively with the lime to create a very highly stable mix.
- The liquid additive did not show any significant improvement in the resistance to permanent deformation for any of the evaluated mixtures except for the PG64-22 control mix. In fact the liquid additive reduced the resistance to permanent deformation of some mixtures.

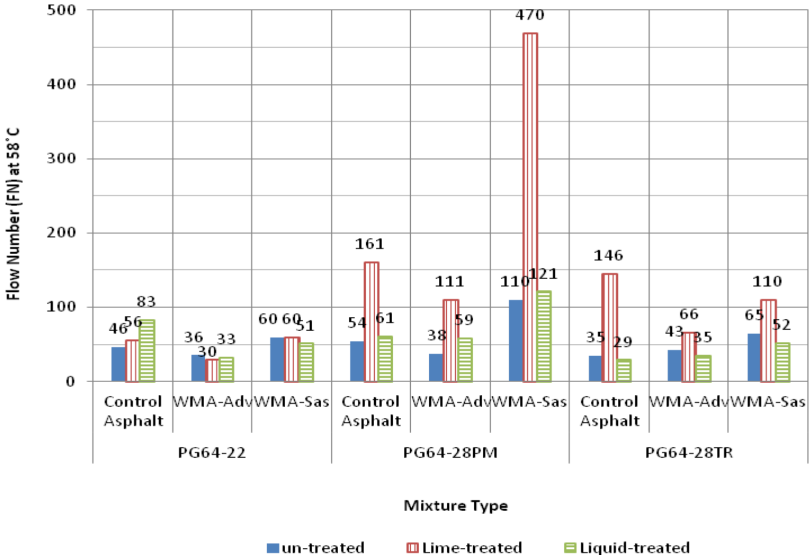

Figure 11: Flow Number (FN) of the various mixtures

9. SUMMARY AND CONCLUSIONS

The research effort documented in this paper conducted an extensive laboratory experiment that evaluated the impact of WMA additives on the performance of asphalts in terms of their resistance to moisture damage and permanent deformation. The unique features of this research include; a) evaluation of the impact of residual moisture, b) evaluation of polymer and tire rubber modified asphalts, evaluation of short and long-term moisture damage, c) evaluation of the impact of anti-strip additives, and d) evaluation of permanent deformation using the FN test.

Based on the analyses of the data generated from the three parts of the research, the following conclusions can be made:

- The residual moisture remaining in the aggregates due to the lower mixing temperature of the WMA could have a significant impact on the WMA properties and their resistance to moisture damage. However, the level of the impact varies as a function of the type of WMA additive and the type of bitumen. Therefore, it is highly recommended to ensure that the aggregates be completely dry prior to mixing of WMA in the plant to avoid potential damage to the long-term performance of the pavement.

- The use of anti-strip additive can improve the resistance of the WMA to both short and long-term moisture damage and to permanent deformation. However, the effectiveness of the additive depends on its type as summarized below;

- The addition of hydrated lime to the control asphalts and WMA mixtures evaluated in this study significantly improved the resistance of the mixtures to short and long-term moisture damage and to permanent deformation.
- The addition of liquid anti-strip additive to the control asphalts and WMA mixtures evaluated in this study had a marginal improvement on some mixtures while it negatively impacted others. Therefore, the addition of liquid anti-strip additive to WMA mixtures should be very carefully assessed prior to its final incorporation in the mix to avoid adverse effects on the properties of the mixtures.

In summary, this research effort showed that sustainable asphalt pavements can be effectively constructed through the identification of an optimum system of bitumen modification, WMA additive, and anti-strip additive. The data generated from this research showed that the combination of terminal blend tire rubber modified bitumen, WMA additives, and hydrated lime can generate highly sustainable asphalts that are resistant to moisture damage and permanent deformation. The measured significant improvements in the performance properties of the identified asphalts significantly out-weigh the additional costs associated with the inclusion of the three major components. In addition, the potential increase in pavement life from the combined technologies will result in significant reductions in emissions and energy costs, which is expected to outweigh the energy cost required to produce the desired additives, leading to truly sustainable asphalt pavements.

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