Performance Characteristics of Liquid and Lime-Treated Asphalt Mixtures

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ABSTRACT: An extensive laboratory experiment was conducted to evaluate the impact of liquid and lime additives on the moisture sensitivity of asphalt mixtures from five different sources around the United States. Three types of mixtures were evaluated from each source: un-treated, liquid-treated, and lime-treated. The measured properties of the fifteen mixtures included the dynamic modulus master curves at the unaged and aged stages and their resistances to moisture damage. The measured dynamic modulus properties and moisture sensitivity characteristics are then used in a mechanistic analysis of a typical asphalt pavement to assess the impact of liquid and lime treatments on the rutting and fatigue performance The analyses of the laboratory generated data on all fifteen mixtures showed the significant impact of the lime in improving the moisture resistance of asphalt mixtures from all five sources as compared to that of the liquid additives. On the other hand the mechanistic analysis showed that the lime-treated asphalt pavements from all five sources significantly out-performed the un-treated and liquid-treated pavements in both rutting and fatigue. In addition, the mechanistic analysis showed that adding liquid anti-strip to some asphalt pavements may reduce their rutting and fatigue performance.

KEY WORDS: Asphalt mixtures, asphalt pavements, lime, liquid, moisture sensitivity, moisture damage, dynamic modulus, freeze-thaw cycles.

1 INTRODUCTION

Asphalt mixtures are composite materials comprised of two major ingredients; aggregate and asphalt binder. Through the crushing operation of the aggregates, the fractured aggregate takes on a variety of shapes and sizes. The function of the binder is to completely coat the aggregate creating a stable mixture of aggregate and asphalt which resists the imposed stresses induced by the highway traffic and environment.

Once in service, asphalt pavements are subjected to continuously changing environmental conditions and traffic wheel loads. The environment plays an important role in conditioning the pavement due to the presence of moisture, the fluctuations in temperature, and aging of asphalt mixtures. When environmental impacts are combined with the imposed stresses from the repeated traffic loads, a physical separation between the asphalt binder and aggregate may begin to occur. As the binder is displaced, moisture moves in to capture the aggregate's surface.

The resistance of asphalt mixtures to moisture damage is very critical to its long-term performance. Moisture damage manifests itself as a reduction in the overall strength or stiffness of the mixture. Therefore, if an asphalt mixture is susceptible to moisture damage, it could eventually fail in any of the four failure modes i.e. rutting, fatigue, thermal cracking, and raveling.

To handle the problem of moisture damage, many highway agencies have resorted to specifying anti-stripping additives in an attempt to increase adhesion at the aggregate-asphalt interface. The primary goal of an anti-strip additive is to eliminate the moisture sensitivity of the asphalt mixture through improving the bond between the asphalt binder and the aggregate. This binder-aggregate bond is a fundamental property of the asphalt mixture which cannot be evaluated through testing of the individual components (i.e. binder or aggregate). Another major consideration when evaluating an anti-strip additive is its ability to maintain good mixture properties. In other words, the additive must not eliminate the moisture sensitivity problem at the expense of other desirable mixture(s) properties. For example, a successful anti-strip additive would maintain the flexibility of the asphalt mixture at low and intermediate temperatures and its stability at high temperatures.

Anti-strip additives can be categorized into two major groups: liquid and lime. Liquid anti-stripping additives are chemical surfactants that reduce the aggregate's surface tension promoting better surface coverage. The asphalt is used as a carrier of these liquid additives. Hydrated lime is an additive to the aggregates that can be applied either in a dry or slurry states. Hydrated lime tends to change the surface chemistry or molecular polarity of the aggregate surface.

2 BAKGROUND

Research studies in Colorado and Texas used the Hamburg wheel tracking device to assess the moisture sensitivity of asphalt mixtures. The objective of the Hamburg test is to assess the ability of the asphalt mix to withstand 20,000 repetitions of the loaded wheel without experiencing severe rutting. As the asphalt mix is loaded with the steel wheel, it goes through the creep region and the stripping region. The creep region is where the rutting per wheel pass is very low while the stripping region is where the rutting per wheel pass increases significantly. The separation point between the two regions is the stripping inflection point. The Colorado study showed that lime consistently improved the resistance of asphalt mixtures to moisture damage while using liquid additives may or may not lead to favorable performance (Aschenbrener and Far, 1994). The Texas study indicated that the lime-treated asphalt mixtures are expected to exhibit minor rutting and never experience severe moisture damage that leads to stripping problems (Izzo and Tahmoressi, 1999). The lime-treated mixtures in the Texas study never reached the stripping inflection point while the liquid-treated mixtures experienced severe rutting.

Research studies in Nevada, South Dakota, California, and Idaho measured the impact of moisture damage on the engineering properties of asphalt mixtures. The Nevada study used both the tensile strength and the resilient modulus properties to evaluate the impact of lime and liquids on the moisture damage of one asphalt mixture from Nevada and one mixture from California (Pickering et al. 1992). The conclusions of the mechanistic analysis that was conducted using the data generated from this research confirmed that lime treatment of the Nevada and California mixtures leads to superior performing asphalt pavements at both the un-damaged and moisture-damaged conditions.

The South Dakota study evaluated the resilient modulus properties of lime and liquid treated asphalt mixtures under multiple freeze-thaw cycling (Tohme et al. 2004). This study showed that while the lime-treated mixtures retain good level of resilient modulus after 18 cycles of freeze-thaw, the un-treated and liquid-treated mixtures loose almost 100 percent of their initial un-conditioned modulus within 6-9 freeze-cycles. This study also showed significant increase in the rutting resistance coupled with the increase in the moisture-conditioned tensile strength property of the lime-treated asphalt mixtures which will lead to pavements that are highly resistant to rutting, fatigue, and thermal cracking.

The California study showed that the lime-treated mixture provided higher tensile strength and fatigue resistance at the dry stage and maintained these higher properties throughout the entire moisture conditioning process of 0, 4, 8, and 12 months (Lu and Harvey, 2006). This indicates that the lime-treated mix will start with a better performing asphalt pavement and maintains its superior performance through the long-term field conditioning process leading to a significantly better life cycle cost-benefit ratio than the control and liquid-treated pavement. The Idaho study showed the potential increase in rutting as a function of multiple freeze-thaw cycling of the liquid-treated mix is significantly higher than that of the lime-treated mix (Sebaaly et al. 2007). Additionally, the liquid-treated mix deteriorated at a higher rate than the lime-treated mix. The study showed that overall, the lime-treated mix is more stable, less susceptible to rutting, and less susceptible to moisture damage while having similar resistance to fatigue cracking as compared to the liquid-treated mix.

2 EXPERIMENTAL PLAN

The research effort described in this paper evaluated the properties of un-treated, liquid-treated, and lime-treated asphalt mixtures from five different sources throughout the United States as summarized in Table 1. Four out of the five evaluated mixtures used neat asphalt binders and one mixture used a polymer-modified binder. All five sources used the same source of hydrated lime (type N) while the liquid anti-strip additives were selected by the agencies based on past experience.

Table 1: Sources and properties of the mixtures.

Source State	Type of Mix	Type of Aggregate	Asphalt Binder		
			PG Grade	Polymer-modified	Acid-Modified
Alabama (AL)	Dense	Limestone	PG67-22	No	No
California (CA)	Dense	Siliceous	PG64-16	No	No
Illinois (IL)	Dense	Dolomite Limestone	PG64-22	No	No
South Carolina (SC)	Dense	Granite	PG64-22	No	No
Texas (TX)	Dense	Gravel	PG76-22	Yes-SBS	No

3 MIX DESIGNS

Each mixture source has three independent mix designs: un-treated, liquid-treated, and lime-treated. All mixtures were designed following the Superpave volumetric mix design method with a medium traffic level that is equivalent to 3–10 millions equivalent single axle loads (ESAL). The $N_{initial}$, N_{design}, and N_{max} for all mix designs were; 8, 100, and 160, respectively. Designing all mixtures to the same level allowed comparisons across the entire matrix. The mix design moisture sensitivity criteria consisted of a minimum unconditioned tensile strength (TS) of 480 kPa at 25°C and a minimum retained tensile strength ratio (TSR) for the treated mixtures of 80%.

The lime was added to the mixtures in the form of dry hydrated lime on wet aggregate (3% moisture above the saturated surface dry condition) at the rate of 1% by dry weight of aggregate. The liquid anti-strip additives were selected by the source state and were blended into the asphalt binder in the laboratory at the rate of 0.5% by weight of binder.

Table 2 summarizes the mix design information for all the evaluated mixtures. In summary, the mix designs showed that the mixtures from California, South Carolina, and Texas required additives to pass the Superpave moisture sensitivity criterion of 80% TSR while the mixtures from Alabama and Illinois did not require any additive. The following TSR values were measured on the un-treated mixtures: Alabama – 81, California – 72, Illinois – 82, South Carolina – 61, and Texas – 61. The TSR data showed that the experiment included two mixtures that can be classified as highly moisture sensitive (SC and TX), one mix that is moderately moisture sensitive (CA), and two mixtures that are not moisture sensitive (AL and IL). This provided a wide range of mixtures to be evaluated in the study.

Table 2: Mix design information for all mixtures.

Source State	Mix	Optimum Binder Content (%)	Tensile Strength at 25^{o}C, kPa		Tensile Strength Ratio (%)
			unconditioned	conditioned	
Alabama	un-treated	4.04	779	634	81
	liquid-treated	3.92	752	621	83
	lime-treated	3.95	827	752	90
California	un-treated	4.47	1,475	1,069	72
	liquid-treated	4.28	1,241	1,131	91
	lime-treated	4.23	1,131	1,069	95
Illinois	un-treated	4.61	951	772	82
	liquid-treated	4.92	931	793	85
	lime-treated	4.70	1,027	889	87
S. Carolina	un-treated	5.33	1,048	634	61
	liquid-treated	5.28	1,062	862	82
	lime-treated	4.71	1,117	972	87
Texas	un-treated	4.70	1,096	676	61
	liquid-treated	4.55	772	772	100
	lime-treated	4.78	1,069	1,055	98

The data in Table 2 show that the addition of lime increased both the unconditioned, except for the California mix, and conditioned TS, and therefore, generating stronger and more durable mixtures. The addition of lime to the California mix reduced its unconditioned TS value at 25^{o}C from 1,477 to 1,132 kPa. Even-though this behavior is not typical of lime-treated mixtures, the California lime-treated mix still exhibited a relatively high unconditioned TS value relative to the other treated mixtures that were evaluated in this study. The impact of adding the liquid anti-strip was inconsistent among the five mixtures. When looking at the TSR data, it can be seen that the addition of both liquid and lime improved the TSR values regardless of the TSR values of the un-treated mixtures. In other words, the addition of liquid and lime benefitted both the moisture sensitive mixtures and non-sensitive mixtures.

4 RESISTANCE OF MIXTURES TO MOISTURE DAMAGE

Since the E* is the fundamental engineering property of asphalt mixtures that is used in the mechanistic-empirical pavement design guide (MEPDG) to evaluate the performance of asphalt pavements, the E* versus freeze-thaw (F-T) cycles was used to estimate the impact of moisture damage on the strength characteristics of asphalt mixtures (NCHRP, 2004). The E* property of the various mixtures were evaluated under various combinations of loading frequency and temperature. The test is conducted at frequencies of: 25, 10, 5, 0.5, 0.1 Hz and at temperatures of: 4, 21, 38, and 55°C. Using the visco-elastic behavior of an asphalt mixture (i.e. interchangeability of the effect of loading rate and temperature) the master curve can be used to identify the appropriate E* for any combination of pavement temperature and traffic speed.

The multiple F-T cycling followed the procedure outlined in AASHTO T-283 at multiple stages (AASHTO 2009). A total of three samples, at the selected number of F-T cycles, from each mix were evaluated following the procedure outlined below:

- Measure the unconditioned E* master curve (i.e., 0 F-T cycles).
- Subject the samples to 75% saturation.
- Subject the saturated samples to multiple freeze-thaw cycling wherein one freeze-thaw cycle consists of freezing at -18°C for 16 hours followed by 24 hours thawing at 60°C and 2 hours at 25°C.
- Subject each sample to the required number of freeze-thaw cycles.
- Conduct E* testing after F-T cycles: 1, 3, 6, 9, 12, and 15.

The E* master curves were evaluated at the unaged and at the long-term aged stages to capture the behavior of the asphalt mixtures at their early and late ages (Sebaaly et al. 2009). The long-term aging of the mixtures followed the Superpave recommendation which consisted of subjecting the compacted E* samples to 85°C temperature for 5 days in a forced draft laboratory oven. Figures 1 – 5 show the E* for the various mixtures as a function of F-T cycles at 10 Hz loading frequency, representing highway traffic, and temperatures of 40°C and 21°C. The unaged modulus at 40°C represents the property of the mix for rutting analysis (i.e. early age and high temperature) and the aged modulus at 21°C represents the property of the mix for fatigue analysis (i.e. late age and intermediate temperature). Examining the E* data in Figures 1 – 5 leads to the observation that the E* property become lower as the mixtures are subjected to multiple F-T cycles at both the unaged and aged stages. However, the lime-treated mixtures show smaller reduction in the E* property as a function of F-T cycling. In addition, the E* property data are basically indicating that the impact of the multiple F-T cycling on the mixtures varies depending on the type of additive and the aging stage of the mix.

The measured E* property as a function of F-T cycles shown in Figures 1-5 indicate that all mixtures exhibit significant reductions in the E* through the first 6 F-T cycles. After the 6th F-T the relationship between E* and F-T becomes flat. Based on these observations, it was concluded that the 6th F-T represents the full moisture damage state of all mixtures.

Table 3 summarizes the E* property of the various mixtures at the unconditioned stage (0 F-T) and after 6 F-T cycles. The data in Table 3 clearly show the significant difference between the E* properties of the lime-treated mixtures and the other mixtures. For example, the Texas mix shows a higher unconditioned E* (i.e. 0 F-T) for the un-treated than the treated mixtures, however, the E* property of the un-treated mix significantly dropped after 6 F-T cycles for both the unaged and aged stages. The ratio of the conditioned E* over the conditioned E* is also shown in Table 3 which indicates that the lime-treated mixtures from all five sources maintained a higher ratio than the un-treated and liquid-treated mixtures at both unaged and aged stages. In summary, the data in Table 3 shows that the lime-treated mixtures maintained a significantly higher E* property after moisture damage in terms of magnitude and retained ratio for all mixtures and at both the unaged and aged stages.

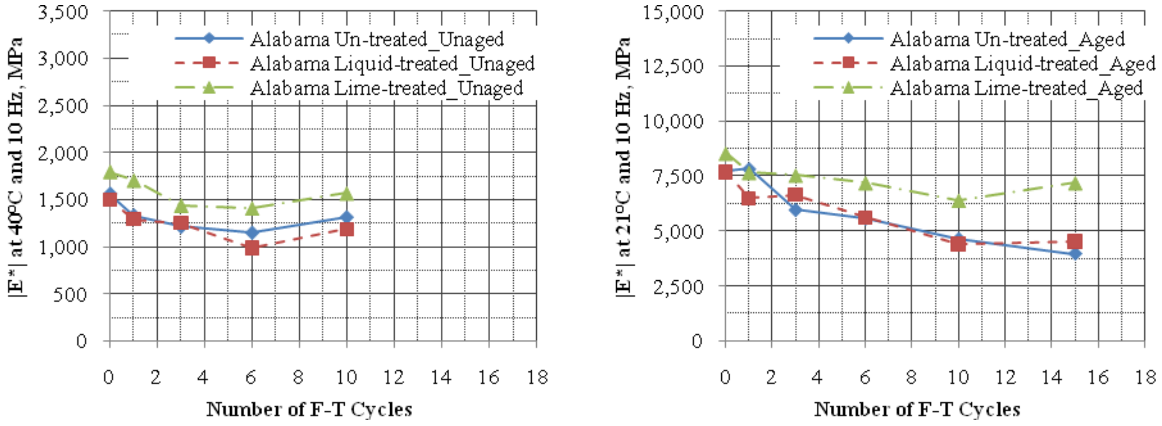

Figure 1: E* as a function of F-T cycles for the Alabama mixtures.

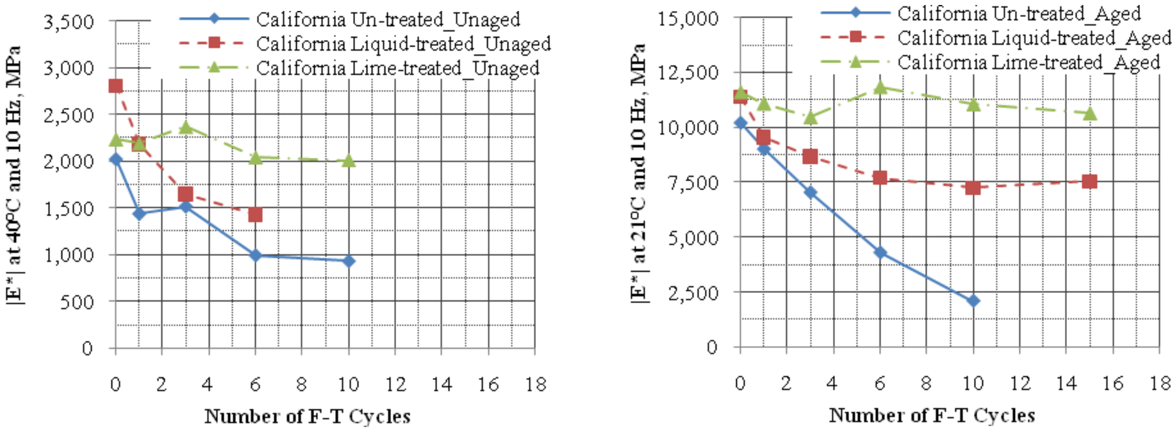

Figure 2: E* as a function of F-T cycles for the California mixtures.

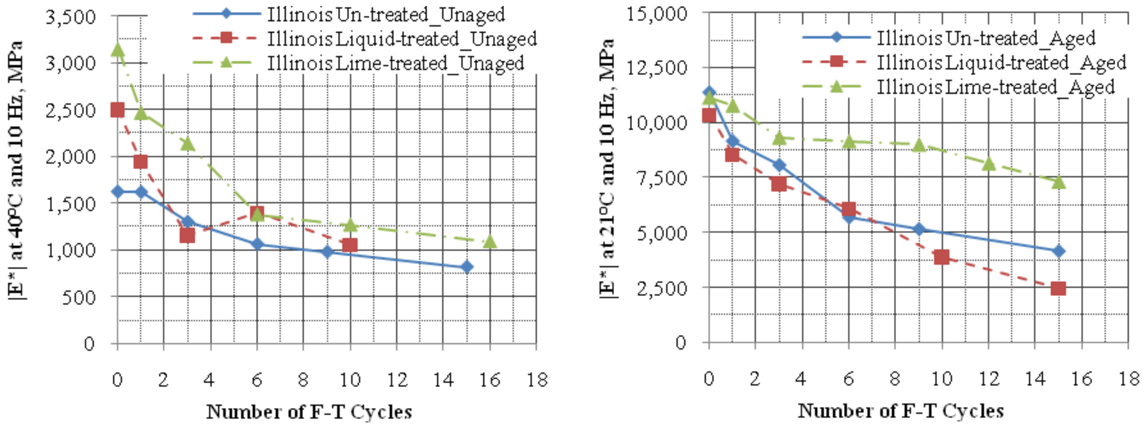

Figure 3: E* as a function of F-T cycles for the Illinois mixtures.

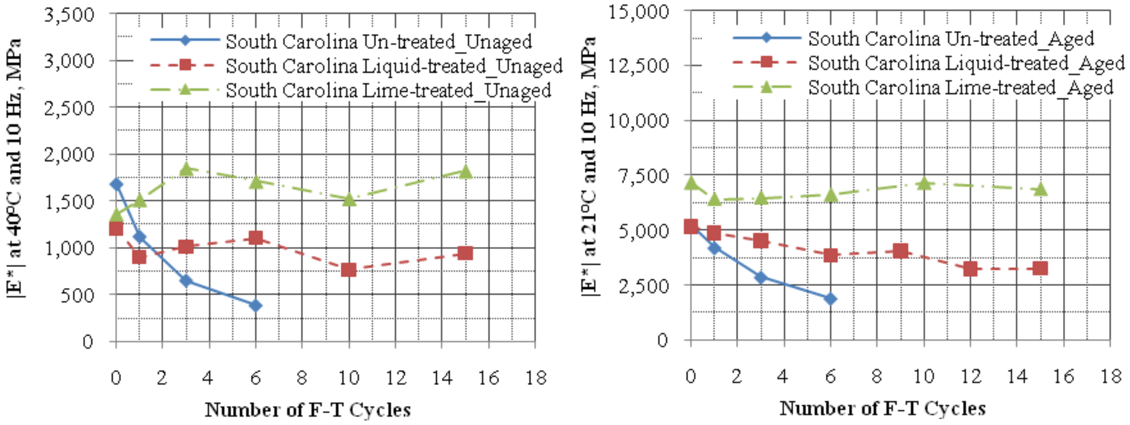

Figure 4: E* as a function of F-T cycles for the South Carolina mixtures.

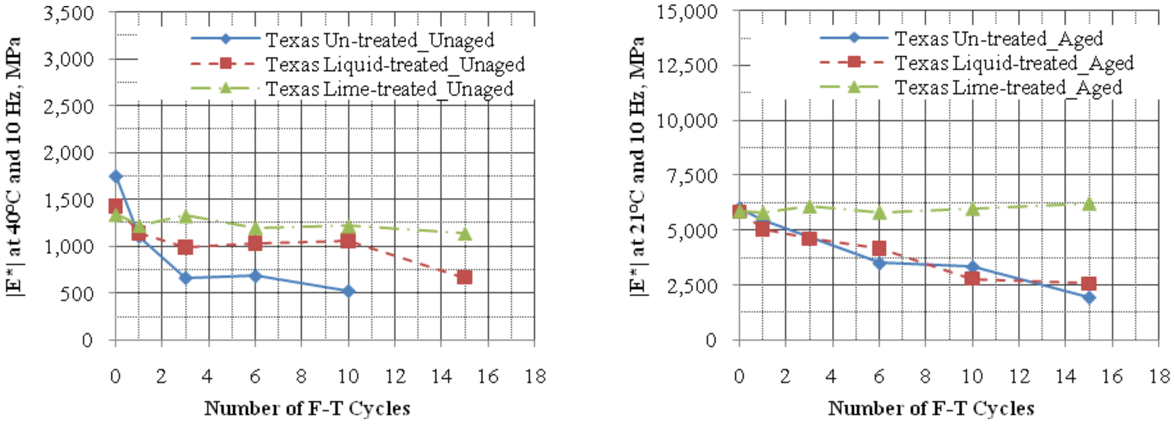

Figure 5: E* as a function of F-T cycles for the Texas mixtures.

Table 3: Dynamic modulus of various mixtures at 10 Hz.

State	Mix	Unaged E^* at 40ºC, MPa			Aged E^* at 21ºC, MPa		
		0 F-T	6 F-T	E_{6FT}/E_{0FT}^*	0 F-T	6 F-T	E_{6FT}/E_{0FT}^*
Alabama	Un-treated	1,558	1,151	74%	7,743	5,557	72%
	Liquid-treated	1,503	986	66%	7,674	5,605	73%
	Lime-treated	1,800	1,413	79%	8,522	7,191	84%
California	Un-treated	2,013	993	49%	10,197	4,289	42%
	Liquid-treated	2,806	1,427	51%	11,369	7,695	68%
	Lime-treated	2,234	2,041	91%	11,604	11,838	102%
Illinois	Un-treated	1,620	1,062	66%	11,363	5,695	50%
	Liquid-treated	2,496	1,400	56%	10,342	6,074	59%
	Lime-treated	3,144	1,379	44%	11,128	9,156	82%
South Carolina	Un-treated	1,675	386	23%	5,199	1,896	36%
	Liquid-treated	1,207	1,103	91%	5,164	3,861	75%
	Lime-treated	1,358	1,710	126%	7,150	6,605	92%
Texas	Un-treated	1,744	683	39%	5,998	3,503	58%
	Liquid-treated	1,427	1,027	72%	5,847	4,158	71%
	Lime-treated	1,338	1,200	90%	5,874	5,812	99%

$^*E_{6FT}$: E* after 6 F-T cycles, E_{0FT}: E* after 0 F-T cycles

5 IMPACT OF MOISTURE DAMAGE ON PERFORMANCE

The impact of moisture damage on the performance of asphalt mixtures was evaluated through mechanistic analysis of a typical asphalt pavement. The analyses used the moisture damaged E* property after 6 F-T cycles of the various mixtures to evaluate the response parameters of asphalt pavements that are considered critical to rutting and fatigue of the asphalt layer. The following pavement structures were analyzed.

Asphalt layer: 150 mm thick, modulus varies depending on the type of mix used
Crushed aggregate base layer: 250 mm thick, modulus = 170 MPa
Subgrade layer: infinite, modulus = 69 MPa

The loading consisted of a single axle load of 80 kN with dual tires at an inflation pressure of 690 kPa. The values of the E* for the various asphalt mixtures are obtained from the data summarized in Table 3 after 6 F-T cycles. Again the unaged E* property is used for the rutting analysis and the aged E* property is used for the fatigue analysis. Using the three types of asphalt mixtures from each of the five sources resulted in 15 different pavement structures.

The AASHTO MEPDG relates the permanent deformation of the asphalt layer to the vertical strain at the middle of the layer and fatigue cracking to the tensile strain at the bottom of the asphalt layer. The properties of the pavement structures along with the loading conditions were used in the multi-layer elastic solution to calculate the vertical strain at the middle of the asphalt layer and the tensile strain at the bottom of the asphalt layer for all 15 pavements. The calculated strains were used in the general rutting and fatigue models recommended by the MEPDG to calculate the rutting and fatigue life of the various pavements (NCHRP, 2004). Finally, the ratio of the rutting/fatigue life of the liquid- and lime-treated pavements over the rutting/fatigue life of the un-treated pavement were calculated for each aggregate source. Table 4 summarizes the results of the mechanistic analysis in terms of the calculated strains and ratios of life for all the evaluated pavements.

A ratio above 1.0 indicates the additive improved the life of the pavement while a ratio below 1.0 indicates the additive reduced the life of the pavement. The data in Table 4 indicate that the liquid and lime improved the rutting and fatigue life of the pavements from all sources except for the liquid-treated pavement from Alabama. The liquid-treated pavement from Alabama showed a rutting life ratio of 0.7 and a fatigue life ratio of 1.0 indicating that the liquid-treated pavement will only survive 70 percent of the rutting life and 100 percent of the fatigue life of the un-treated pavement. It should be noted that the Alabama mix was labeled as non-moisture sensitive due to its high TSR (i.e. 81) at the un-treated stage.

The ratios of rutting life for the S. Carolina pavement were not calculated because the un-treated mix experienced a very low moisture-damaged (i.e. after 6 F-T) modulus at 40^{o}C indicating that the un-treated mix will not result in a reasonable structural design that can resist rutting in the asphalt layer.

When comparing the impact of lime versus the impact of liquid, the data in Table 4 show that the lime is significantly more effective than the liquid additive in both the rutting and fatigue performance. The lime-treated mixtures significantly improved the rutting and fatigue performance of the pavements from all five sources. On the other hand the impact of the liquid on the fatigue life was marginal (i.e. ratios of 1.0 and 1.2) for three out of five mixtures.

Table 4: Results of the mechanistic analysis

Source	HMA Mix	Vertical strain at middle of HMA		Tensile strain at bottom of HMA	
		Micro-strain	Ratio of rutting life	Micro-strain	Ratio of fatigue life
Alabama	Un-treated	328	-	138	-
	Liquid-treated	387	0.7	137	1.0
	Lime-treated	263	1.6	116	1.4
California	Un-treated	384	-	163	-
	Liquid-treated	260	2.3	111	2.2
	Lime-treated	178	5.0	82	4.1
Illinois	Un-treated	357	-	136	-
	Liquid-treated	265	1.9	130	1.0
	Lime-treated	267	1.9	99	1.9
South Carolina	Un-treated	na	-	262	-
	Liquid-treated	343	na	174	2.0
	Lime-treated	215	na	123	4.0
Texas	Un-treated	577	-	185	-
	Liquid-treated	370	2.5	166	1.2
	Lime-treated	313	3.6	134	1.9

The additional cost to treat asphalt mixtures with liquid and lime are 1 and 5 percent, respectively. These additional costs should be compared with the increase in performance life of the asphalt pavements. The ratios of the lime-treated pavements range from 1.6 to 5.0 while the ratios of the liquid-treated pavements range from 0.7 to 2.5. Comparing the significant improvements in the performance life of the lime-treated pavements with the possibility of a liquid additive reducing or not improving the performance life of some pavements, it can be concluded that the lime-treated pavements offer more consistent and much superior design than the liquid-treated pavements.

6 CONCLUSIONS

This research effort conducted an extensive laboratory evaluation of liquid- and lime-treated asphalt mixtures from five different sources located throughout the U.S. The TSR data showed that the experiment included two mixtures that can be classified as highly moisture sensitive (SC and TX), one mix that is moderately moisture sensitive (CA), and two mixtures that are not moisture sensitive (AL and IL). This provided a wide range of mixtures to be evaluated in the study. The evaluation used the most advanced testing techniques to evaluate the impact of moisture damage on the strength and performance of asphalt mixtures. Based on the analysis of the data generated in this study, the following conclusions can be made:

- The use of both liquid and lime additives improved the moisture sensitivity of the asphalt mixtures as measured by the TSR following AASHTO T283 method.
- As the mixtures were subjected to further moisture damage induced through multiple F-T cycling, the un-treated and liquid-treated mixtures had significantly reduced their strength properties (i.e. E*). On the other hand, the lime-treated mixtures maintained higher strength properties for the entire 15 F-T cycles for all five sources.

- The sixth F-T cycle seems to indicate the point after which most of the mixtures hold a steady value of E*. This indicates that the sixth F-T represents an effective moisture conditioning stage for the various mixtures. It should be noted that the use of multiple F-T cycles is not meant to mimic the actual field conditioning process but to accelerate the moisture damage in a manner that can be measured under laboratory conditions.
- The mechanistic analysis of a typical asphalt pavement and using the general rutting and fatigue models recommended by the MEPDG indicated that lime-treated asphalt pavements significantly out-performed both un-treated and liquid-treated HMA pavements. In addition, using liquid-treated mixtures in some asphalt pavements may reduce their performance life.

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