Comparative Life Cycle Cost Analyses of Asphalt Pavements Treated with Anti-Stripping Additives

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ABSTRACT

A comprehensive study was conducted to evaluate the impact of liquid and lime additives on the performance of asphalt pavements 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 and their resistance to rutting and fatigue at the undamaged and moisture damaged conditions. The measured performance properties of the mixtures were used in the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) to conduct 20 years structural designs for actual projects selected from the five sources of mixtures. For each project, a total of three structural designs were established by changing the type of mix used in the asphalt layer e.g. un-treated, liquid-treated, and lime-treated. The MEPDG structural designs were used with typical cost figures for the three types of mixtures to estimate the costs of the three types of structural designs for each project. The percent cost savings/additional costs were estimated relative to the cost of the asphalt pavement with the un-treated asphalt mixtures. Overall, the use of lime additives in asphalt mixtures resulted consistently in significant savings that sometime was as high as 45%. On the other hand, the use of liquid anti-strip additives in asphalt mixtures may either result in savings between 13 and 32% or an additional cost, in some cases as high as 50%. The additional cost for the liquid-treated mixes was observed for mixtures that were not considered moisture sensitive as measured by AASHTO T283.

INTRODUCTION

Moisture damage is commonly defined as "loss of adhesion between the aggregate surface and asphalt binder in the presence of moisture." Asphalt mixtures may also experience loss of strength in the presence of moisture without visible evidence of debonding because water may affect the cohesive strength of the asphalt mastic. The resistance of asphalt mixtures to moisture damage is controlled by: aggregate properties, asphalt binder properties and mixture characteristics.

The hot and wet climates of the southern part of North America and the cold and relatively dry climates of the western part of North America lead to the most dramatic moisture damage problems. In the southeastern region, the combination of high temperatures (low asphalt viscosity) and wet weather (in the summer months) cause moisture damage. The mountain and high desert areas of the west experience severe moisture damage problems due to moisture, freeze-thaw cycles and aggregates that have poor adhesion to asphalt. Most other regions also experience moisture damage problems that can manifest themselves through incompatibility between binders and aggregates and/or loss of cohesion in the bitumen due to moisture penetration.

A number of additives to reduce moisture damage of asphalt mixtures are used in the United States and Canada. Hydrated lime is widely used as an anti-strip additive. Others include liquid additives (e.g. amines, diamines, and polymers), portland cement, fly ash, and flue dust.

In 1991, Kennedy and Ping [1] found that the relative effectiveness of liquid anti-strip agents and lime depends on the aggregate type and the test method used to evaluate the asphalt mixture. A study conducted by Oregon State University for the Oregon Department of Transportation demonstrated that both fatigue and rutting resistance can be improved with lime [2]. Additionally, Researchers found that lime performed better than liquid anti-strip materials.

Virginia conducted field evaluations of pavements that were three to four years old [3]. Of the twelve pavements included in the study, the pavements in which lime was used as an anti-strip agent had only “very slight” to “slight” stripping as determined from core samples obtained from the pavements and from visual evaluations of the pavement surface. The lime-treated asphalt sections displayed lower moisture damage than the sections that were treated with the chemical liquid additive. Two years later, a different set of pavements were sampled and evaluated after five to six years of service [4]. The results from this study indicated little difference between the lime-treated and liquid anti-strip treated asphalt sections

Tahmoressi reported on a Texas Department of Transportation (TxDOT) study to evaluate the impact of lime treatment on the performance of limestone asphalt mixtures in Texas under the Hamburg wheel tracking device [5]. The study evaluated the performance of Texas mixtures using soft, moderate, and hard limestone aggregates with PG64-22, PG70-20, and PG76-22 binders. The research concluded that the addition of 1% hydrated lime reduces the Hamburg rut depth by 50% for all binder grades and it is equivalent to raising the PG binder grade by one grade. The report also presented extensive data on the resistance of asphalt mixtures to rutting under the Hamburg wheel tracking device conducted by the Texas DOT. The data indicated that limestone, gravel, and igneous aggregates all show significant increase in the number of mixes passing the TxDOT Hamburg criterion (12.5 mm rut depth under 20,000 load cycles) by the addition of lime regardless of the binder grade.

The South Dakota Department of Transportation compared the performance of various antistrip additives on two field projects [6, 7]. Each project included a control section and five sections treated with lime, liquid, and ultrapave (UP) additives. The data indicated that mixtures treated with hydrated lime performed significantly better than the control, UP5000 and the liquid anti-strip mixtures at both locations.

OBJECTIVES

Typically, lime and liquid are used as additives to combat moisture damage, and therefore, their impact is only evaluated with respect to their influence on the moisture sensitivity of the asphalt mixture. This study extended the evaluation to cover the impact of lime and liquid additives on the structural performance of the asphalt mixtures and their impact on the long term performance of typical asphalt pavements. The designed structures with un-treated and treated asphalt mixtures were then used to conduct a comparative life cycle cost analysis (LCCA) of the various pavements.

EXPERIMENTAL PROGRAM

All testing and evaluations were conducted on laboratory-produced asphalt mixtures. Aggregates and binders were obtained from five different sources (Table 1): Alabama (AL), California (CA), Illinois (IL), South Carolina (SC), and Texas (TX) to produce asphalt mixtures that were evaluated in this study. Virgin aggregates and virgin asphalt binders were mixed and compacted in the laboratory following the recommended mixing and compaction temperatures based on the temperature-viscosity relationship of the asphalt binder used in the mix.

Table 1. Properties of the Mixtures Recommended by the Participating States.

<table>
<tr><th rowspan="2">State Agency</th><th rowspan="2">Type of Aggregate</th><th colspan="3">Asphalt Binder</th><th rowspan="2">Liquid Anti-strip</th><th rowspan="2">Lime</th></tr>
<tr><th>PG Grade</th><th>Polymer-modified</th><th>Acid-Modified</th></tr>
<tr><td>Alabama</td><td>Limestone</td><td>PG67-22</td><td>No</td><td>No</td><td>Polyamine derived</td><td rowspan="5">Type “N” normal hydrate 95% CaO</td></tr>
<tr><td>California</td><td>Siliceous</td><td>PG64-16</td><td>No</td><td>No</td><td>Polyamine derived</td></tr>
<tr><td>Illinois</td><td>Dolomite Limestone</td><td>PG64-22</td><td>No</td><td>No</td><td>Amidoamine derived</td></tr>
<tr><td>South Carolina</td><td>Granite</td><td>PG64-22</td><td>No</td><td>No</td><td>Amidoamine derived</td></tr>
<tr><td>Texas</td><td>Gravel</td><td>PG76-22</td><td>Yes-SBS</td><td>No</td><td>Amino acid based</td></tr>
</table>

Three mix designs were conducted for each material source: un-treated, liquid-treated, and lime-treated mixtures. All mix designs were conducted following the Superpave Volumetric Mix Design Method. The types of liquid additive were selected by each participating state agency (i.e. materials source) and were added at the rate of 0.5% by weight of binder. A single lime source was used for all five aggregate sources. 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. Table 2 summarizes the moisture sensitivity data for the five sources of mixtures as evaluated with the AASHTO T283 test at the mix design stage.

Table 2. Moisture Sensitivity of the Various Mixtures.

Mixture Type	Tensile Strength Ratio (%)				
	Alabama	**California**	**Illinois**	**S. Carolina**	**Texas**
Un-treated	81	72	82	61	61
Liquid-treated	83	91	85	81	100
Lime-treated	90	95	87	87	98

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% tensile strength ratio (TSR) while the mixtures from Alabama and Illinois did not require any additive. The TSR data showed that the experiment includes 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 following performance properties were evaluated for all 15 mixtures [5 aggregate sources x 3 treatments (none, liquid, and lime)]:

- Resistance to moisture damage: relationship between dynamic modulus (E*) and multiple freeze-thaw (F-T) cycles.
- Resistance to rutting: relationship between permanent strain in the asphalt mix and number of load repetitions under triaxial testing conditions at the un-conditioned and moisture-conditioned stages.
- Resistance to fatigue cracking: relationship between bending strain in the asphalt mix and number of load repetitions to failure under beam fatigue testing conditions at the un-conditioned and moisture-conditioned stages.

All mixtures were short term aged prior to compaction (loose mix) for 4 hours in the oven at the compaction temperature. The long term aging of the mixtures followed the Superpave recommendation which consisted of subjecting the compacted samples to 85^{o}C temperatures for 5 days in a forced draft laboratory oven. Mixtures that were only subjected to short term aging are referred to as "unaged" and mixtures that were subjected to both short and long term aging are referred to as "aged". Some of the properties were evaluated at both the unaged and aged stages while others were only evaluated at a single stage. In the case of resistance to rutting, the asphalt mixtures were evaluated at the unaged stage because permanent deformation is an early pavement life (short-term) distress mode. On the other hand, the fatigue resistances of the asphalt mixtures were evaluated at the aged stage because cracking is a long-term distress mode. The E* of the asphalt mixtures were evaluated under both the unaged and aged stages to cover the entire life span of the asphalt pavement.

MOISTURE CONDITIONING

Both unaged and aged compacted asphalt mixtures were subjected to moisture conditioning which consisted of the following process:

- Subject the compacted samples to 75% water saturation.
- Subject the saturated samples to multiple freeze-thaw (FT) cycling wherein one F-T cycle consists of freezing at -18^{o}C for 16 hours followed by 24 hours thawing at 60^{o}C and 2 hours at 25^{o}C.
- Conduct testing after F-T cycles: 1, 3, 6, 9, 12, and15.

IMPACT OF MOISTURE DAMAGE ON STIFFNESS

The impact of moisture damage on the stiffness of the various mixtures was evaluated in terms of measuring the dynamic modulus (E*) of the mixtures after multiple F-T cycles. The E* of the asphalt mix is measured at multiple temperatures and multiple loading frequencies to simulate the combined impact of mixed traffic under variable environmental conditions. The E* master curves were developed using the data obtained from the dynamic modulus test (AASHTO TP62 and PP62). The E* represents the overall stiffness of the asphalt mix. A low E* indicates a weak mix while a high E* indicates a strong mix. E* at 10 Hz represents highway traffic loading, a 40^{o}C temperature and unaged stage is critical for rutting, while a 21^{o}C temperature and aged stage is critical for fatigue cracking. Figures 1 – 5 show the measured E* at various F-T cycles for the fifteen mixtures at the unaged and aged stages.

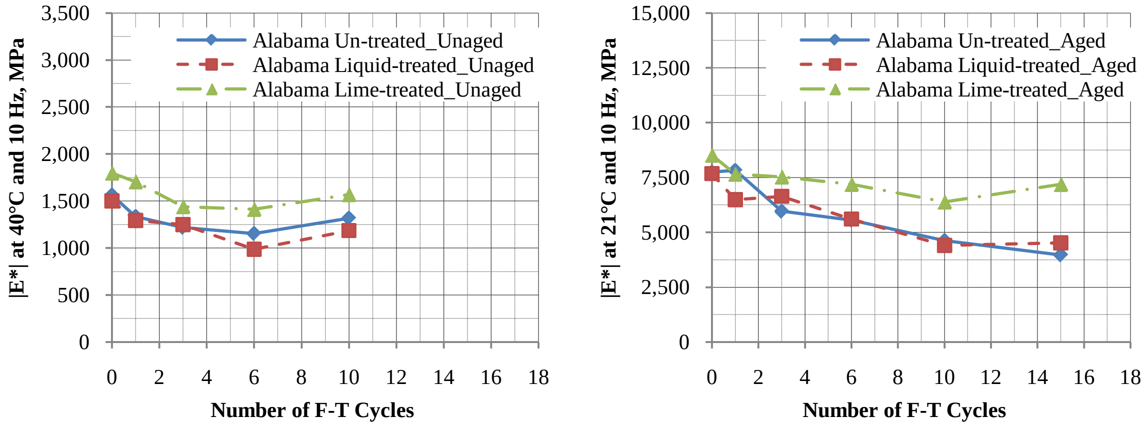


Figure 1. E* as a function of F-T cycles for the Alabama mixtures.

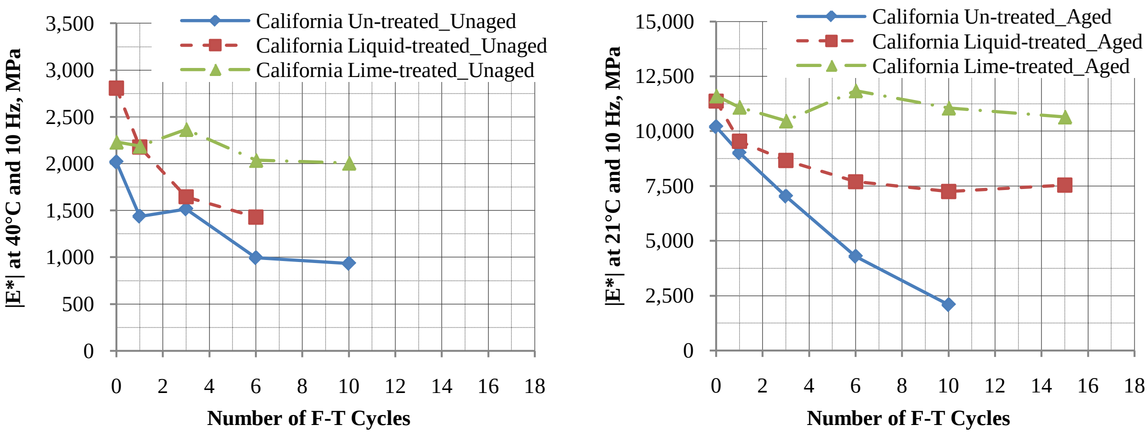


Figure 2. E* as a function of F-T cycles for the California mixtures.

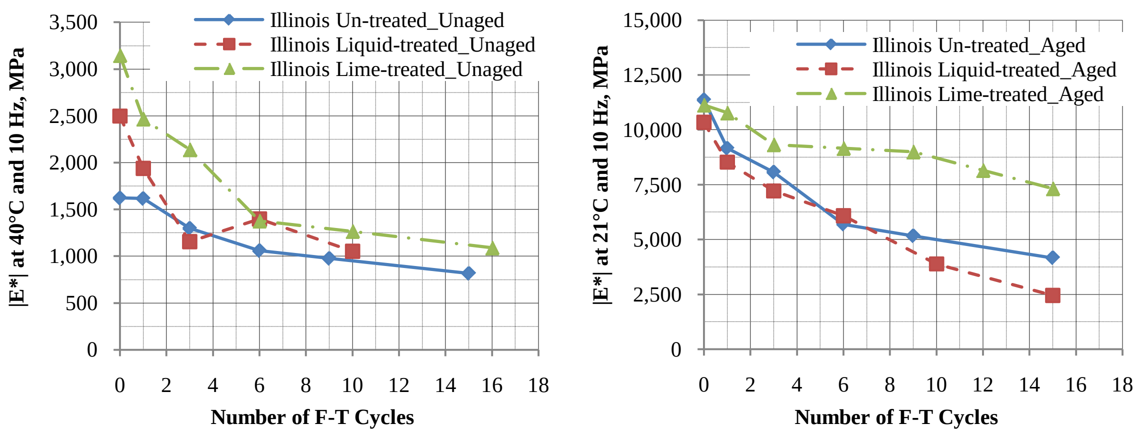


Figure 3. E* as a function of F-T cycles for the Illinois mixtures.

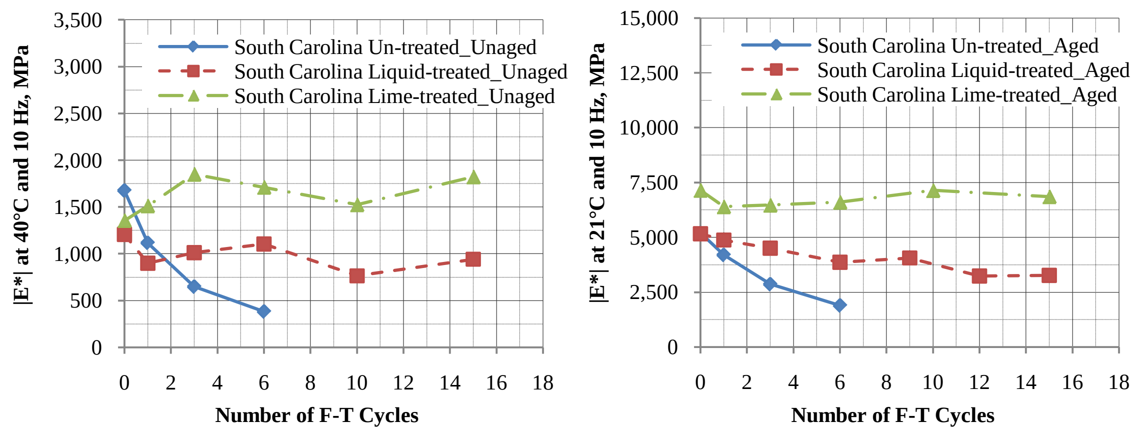


Figure 4. E* as a function of F-T cycles for the South Carolina mixtures.

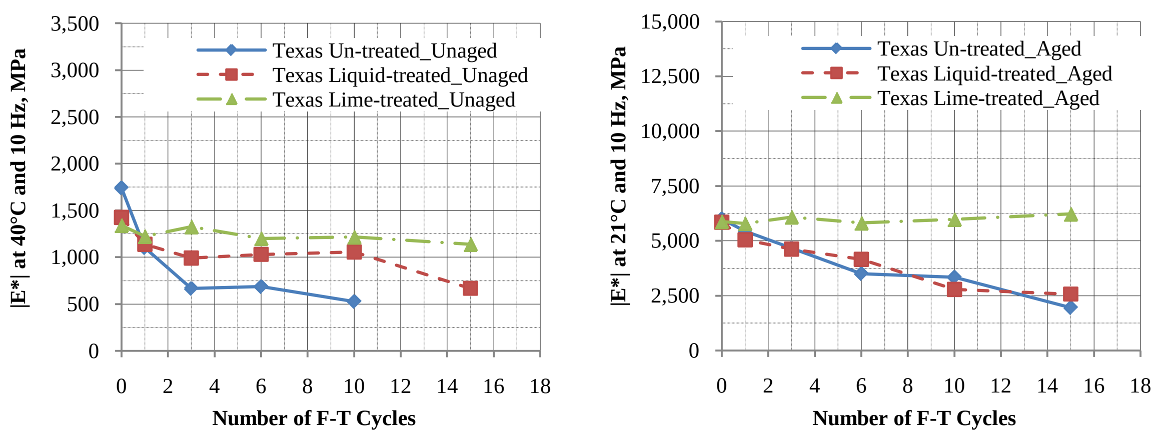


Figure 5. E* as a function of F-T cycles for the Texas mixtures.

The data in Figures 1 – 5 show a significant reduction in the E* property as a function of multiple F-T cycling. The un-treated mixtures from California, South Carolina, and Texas could not withstand the entire set of 15 F-T cycles. In summary, the data indicate that as the various mixtures are subjected to multiple F-T cycling, the lime-treated mixtures of all five sources hold their E* properties significantly better than the un-treated and liquid-treated 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 the 6 F-T cycles.

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 or complete failure such as the case with SC un-treated mixture. Based on these observations, it was concluded that the 6th F-T represents the full moisture damage state of all mixtures. 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.

PERFORMANCE CHARACTERISTICS OF MIXTURES

The performance characteristics of the asphalt mixtures were evaluated in terms of their resistance to rutting and fatigue cracking. The rutting and fatigue characteristics of the mixtures were evaluated by using the Repeated Load Triaxial (RLT) (AASHTO TP79) test and the beam fatigue test (AASHTO T321) performed on laboratory prepared samples, respectively. The rutting and fatigue characteristics of the mixtures were evaluated at the un-damaged (i.e. 0 F-T) and moisture-damaged (i.e. 6 F-T) stages.

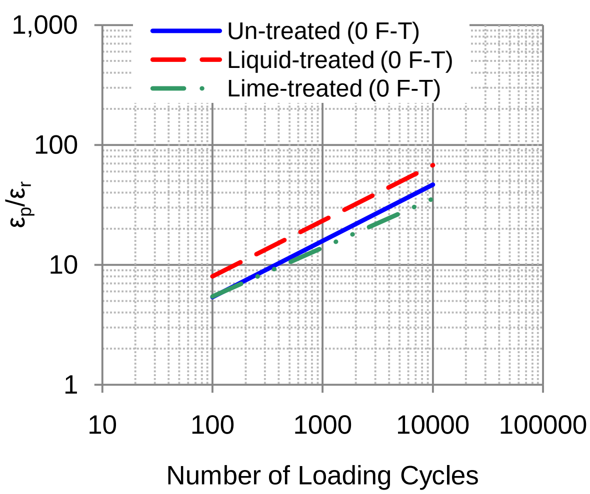
In simple terms, rutting in the asphalt layer is the product of the permanent strain (ε_p) times the thickness of the asphalt layer (i.e. $\varepsilon_p x H_{asphalt}$). The magnitude of ε_p is directly related to the magnitude of the resilient compressive strain within the asphalt layer generated by the moving truck load. The smaller the vertical resilient strain within the asphalt layer, the lower the ε_p. The repeated load triaxial (RLT) test was used to establish the relationship between the ε_p, ε_r, and number of load repetitions (N_r) at a temperature (T) for each of the fifteen mixtures. The form of the relationship is shown below:

$$\frac{\varepsilon_p}{\varepsilon_r} = a(N_r)^b(T)^c$$

Figures 6 – 10 show the rutting models for the mixtures that were evaluated in this study. The lower the rutting model the higher the resistance of the mixture to rutting. A review of the rutting models shown in Figures 6 – 10 indicates the following:

- At the un-damaged stage (i.e. 0F-T); the liquid additive reduced the rutting resistance of the AL, IL, and SC mixtures while the impact of lime additive was insignificant on all mixtures.

- At the moisture-damaged stage (i.e. 6 F-T); both liquid and lime reduced the rutting resistance of the AL mixtures and had no impact on the CA, IL, and SC. And lime significantly improved the rutting resistance of the TX mixtures while the liquid had no impact.



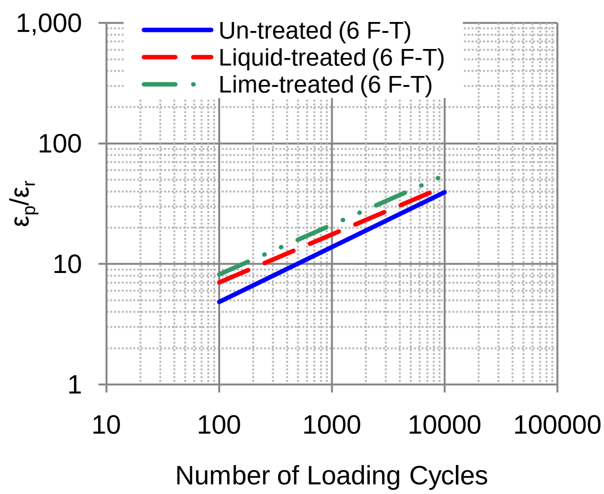


Figure 6. Rutting Characteristics at 40°C for the Alabama Mixes at 0 and 6 F-T Cycles.

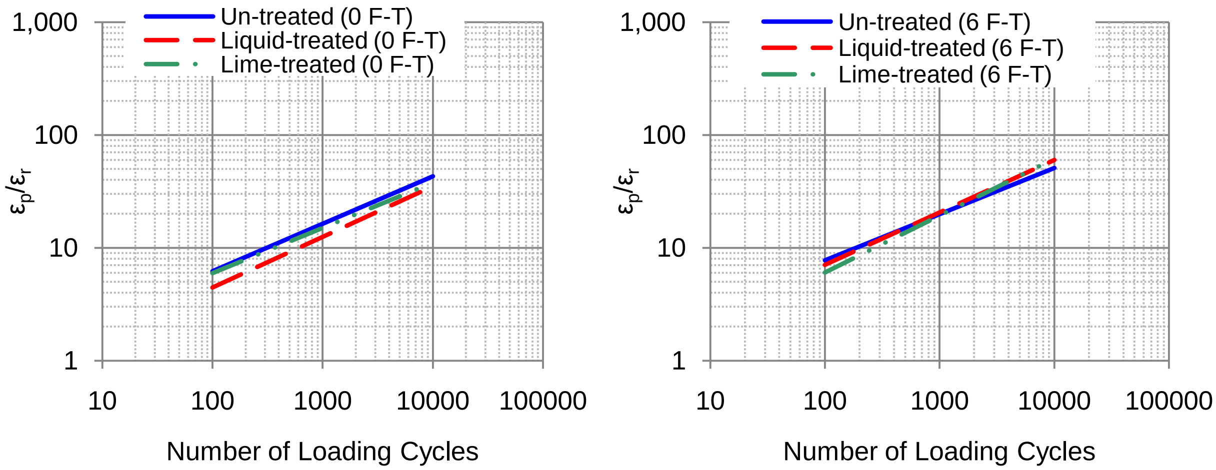


Figure 7. Rutting Characteristics at 40°C for the California Mixes at 0 and 6 F-T Cycles.

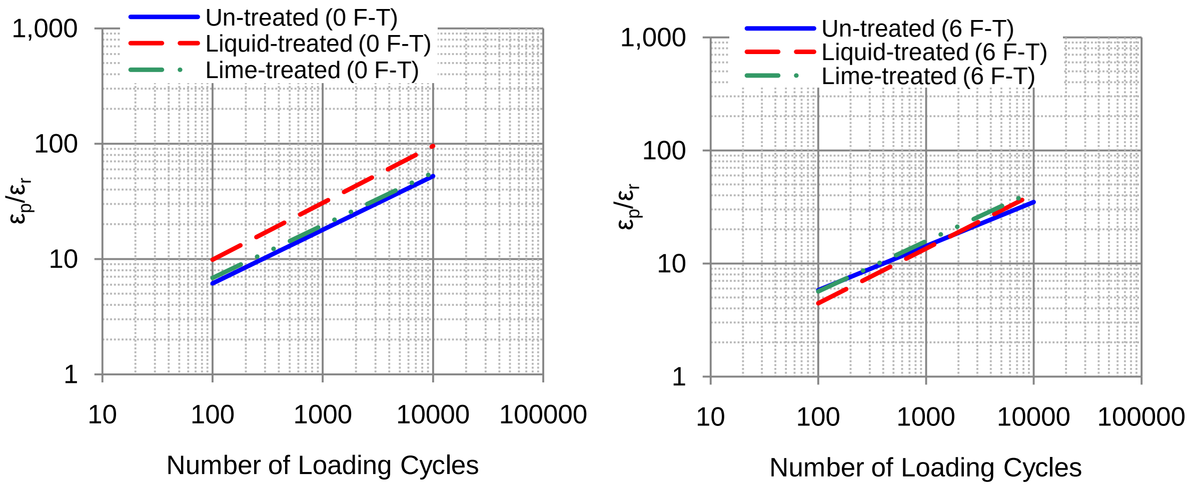


Figure 8. Rutting Characteristics at 40°C for the Illinois Mixes at 0 and 6 F-T Cycles.

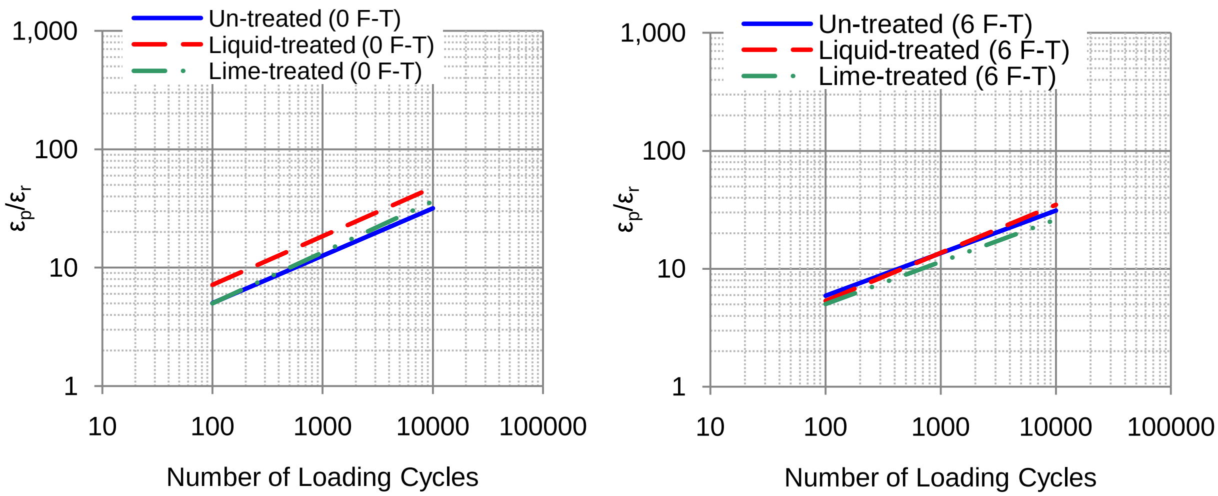


Figure 9. Rutting Characteristics at 40°C for the S. Carolina Mixes at 0 and 6 F-T Cycles.

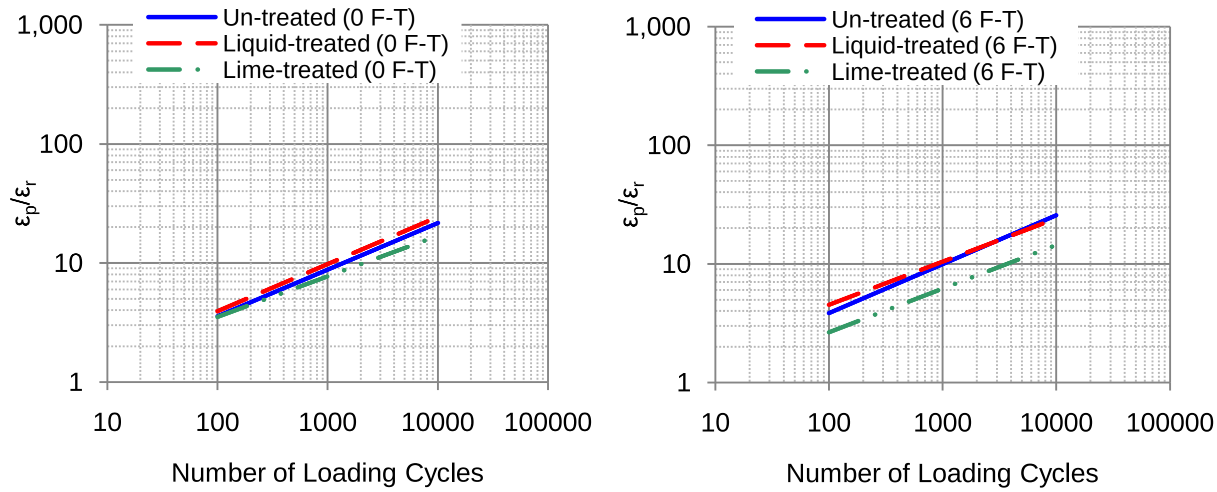


Figure 10. Rutting Characteristics at 40°C for the Texas Mixes at 0 and 6 F-T Cycles.

The resistance of the asphalt mix to fatigue cracking depends on the magnitude of the bending strain (ε_t) at the bottom of the asphalt layer as it is subjected to repeated loads. The smaller the bending strain (ε_t), the higher the fatigue life of the asphalt mix. The flexural beam fatigue test was used to establish the relationship between the ε_t, E*, and number of load repetitions (N_f) for each of the fifteen mixtures. The form of the relationship is shown below:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t}\right)^{k_2} \left(\frac{1}{E*}\right)^{k_3}$$

Figures 11 – 15 show the fatigue models for all mixtures that were evaluated in this study. The higher the fatigue curve the better the resistance of the mixtures to fatigue cracking. A review of the fatigue models shown in Figures 11 – 15 indicates the following:

- At the un-damaged stage (i.e. 0F-T); both liquid and lime had no impact on the fatigue resistance of AL, CA, and TX mixtures while they both improved the fatigue resistance of the IL mixtures. And the lime additive reduced the fatigue resistance of the SC mixtures while the liquid had no impact.

- At the moisture-damaged stage (i.e. 6 F-T); both liquid and lime improved the fatigue resistance of the CA, IL, and TX mixtures. The impact of liquid and lime on the fatigue resistance of the SC mixtures was inconsistent: they improved the resistance under high strains and reduced the resistance under low strains. This inconsistent impact was also observed by the liquid on the AL mixtures. Such inconsistent impact makes it very complicated to assess the fatigue behavior of the asphalt mixtures under mixed traffic loads.

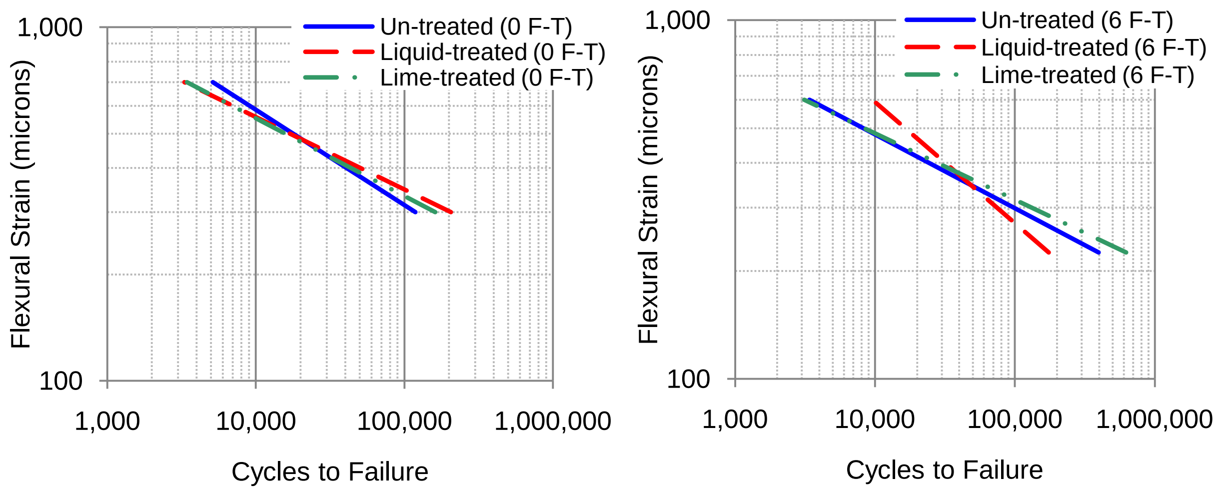


Figure 11. Fatigue Characteristics at 21°C for the Alabama Mixes at 0 and 6 F-T Cycles

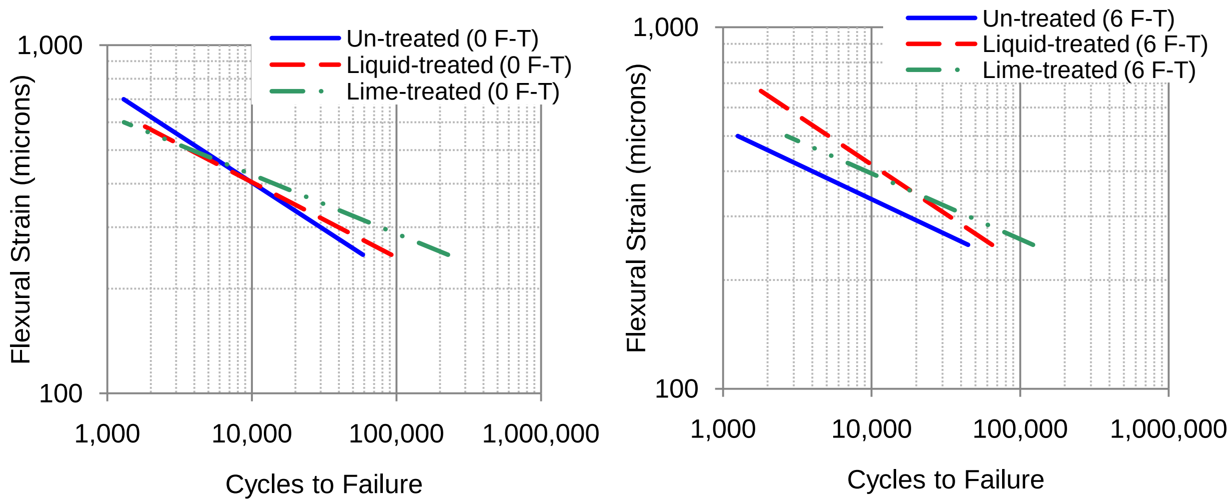


Figure 12. Fatigue Characteristics at 21°C for the California Mixes at 0 and 6 F-T Cycles

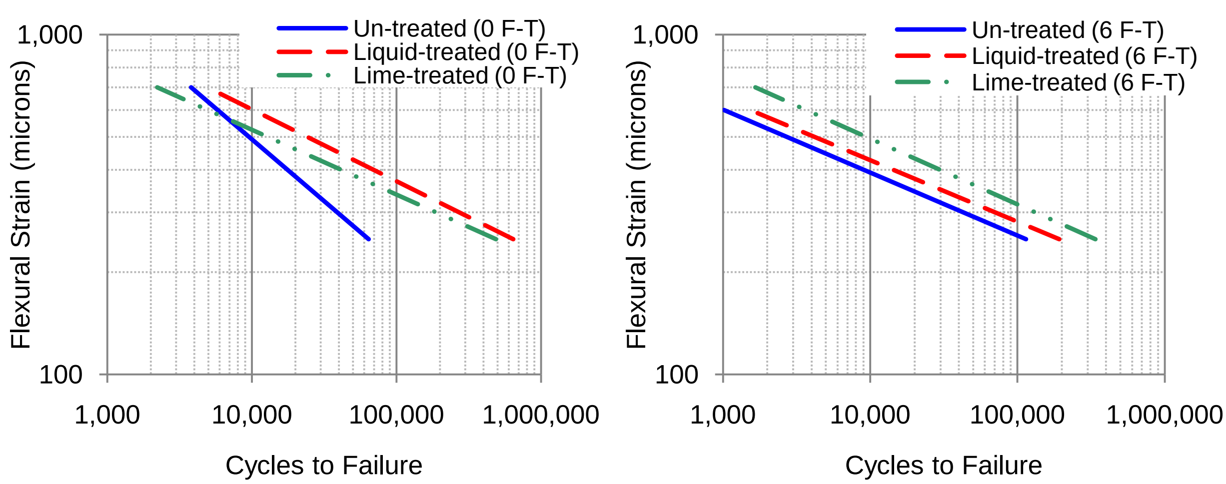


Figure 13. Fatigue Characteristics at 21°C for the Illinois Mixes at 0 and 6 F-T Cycles

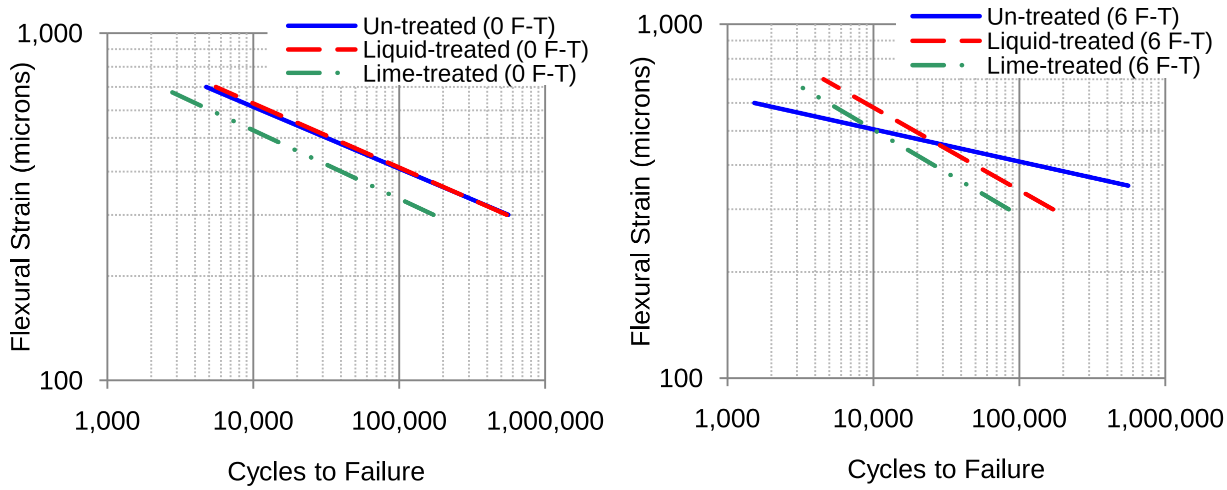


Figure 14. Fatigue Characteristics at 21°C for the S. Carolina Mixes at 0 and 6 F-T Cycles

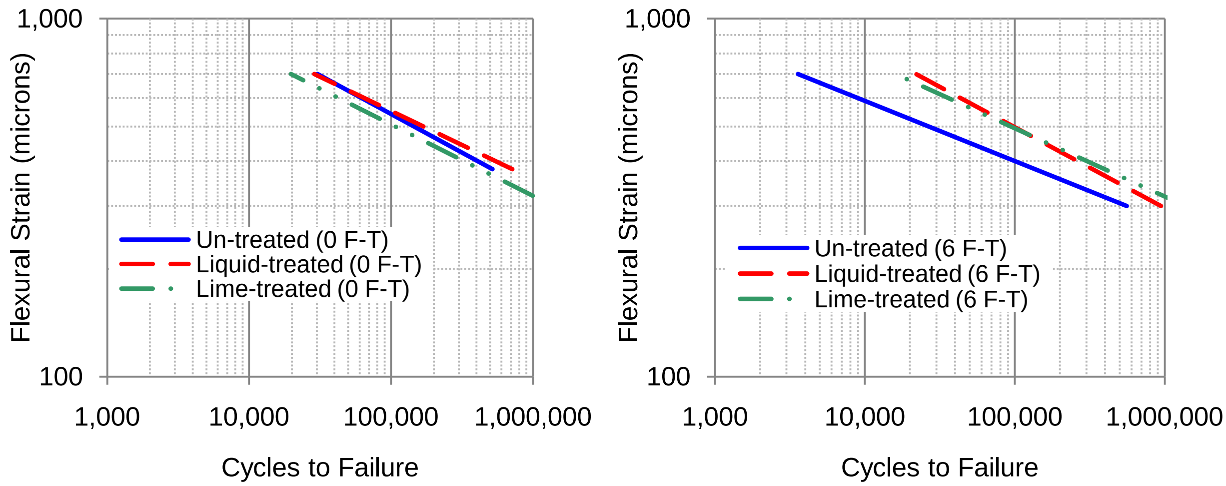


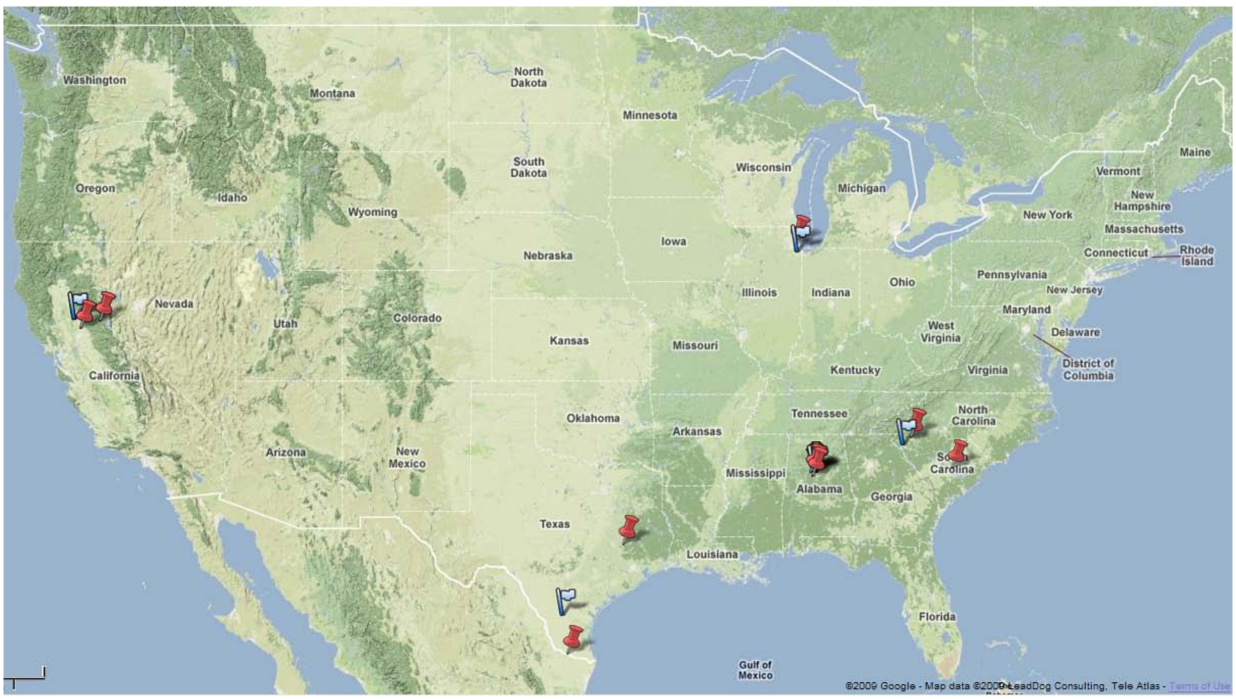
Figure 15. Fatigue Characteristics at 21°C for the Texas Mixes at 0 and 6 F-T Cycles

MECHANISTIC-EMPIRICAL STRUCTURAL DESIGNS

The objective of this analysis is to use the specific properties of the various mixtures in terms of E*, rutting characteristics, and fatigue characteristics to conduct structural designs using the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) for projects where the evaluated mixtures will be used. To conduct the structural designs, the MEDPG requires information on: Traffic, Climate, Materials Properties, and Performance Models.

Using these information, the MEPDG calculates the mechanistic responses of the asphalt pavement in terms of tensile strain at the bottom of the asphalt layer and vertical resilient strain throughout the asphalt layer. The calculated strains are then input into the performance models of the asphalt layer that were developed in this study to estimate the rutting and fatigue performance of the asphalt pavement.

Each participating state was asked to identify 1 – 2 project locations where the evaluated mixtures will most likely be used. In order to complete this analysis, the five participating agencies were asked to provide information regarding location, traffic, and roadbed soil for their selected projects. Figure 16 shows the locations of the recommended projects along with the locations of the aggregate sources from all five participating states. The MEPDG was used to conduct a 20 years structural design for asphalt pavements at each location using all three types of asphalt layers: un-treated, liquid-treated, and lime-treated. The structural designs were conducted based on un-damaged and moisture-damaged conditions of the asphalt layer. The dynamic modulus properties at 0 F-T cycles were used to represent the un-damaged conditions and the dynamic modulus properties at 6 F-T cycles were used to represent the moisture-damaged conditions of the asphalt layer.



Aggregate source Project location

Figure16. Locations of Field Projects and Aggregate Sources.

Each participating state was asked to provide traffic information for the recommended project locations. Only South Carolina provided project specific average daily truck traffic (ADTT) distributions while the MEPDG default ADTT distributions were used for the other four states. The default values provided by the MEPDG software were used for the hourly truck traffic distributions for all five states.

The MEPDG considers the effects of climatic variables on pavement responses and pavement performance. Moisture and temperature profiles are predicted through the Enhanced Integrated Climatic Model (EICM) module incorporated into the MEPDG software. A specific climatic station was identified based on the location of each project and used by the MEPDG to extract the required climatic information.

The MEPDG software requires the E* master curve for the asphalt layer. The dynamic modulus master curves that were measured for the un-treated, liquid-treated, and lime-treated mixtures were used in the MEPDG software to represent the three types of mixtures from each of the five states. As mentioned earlier, the E* master curves at 0 F-T cycles were used to represent the un-damaged conditions and the E* master curves at 6 F-T cycles were used to represent the moisture-damaged conditions of the asphalt layer.

A typical crushed aggregate dense graded base (CAB) was used with a resilient modulus (Mr) of 30,000 psi for all projects in the five participating states. This value is a representative Mr value for crushed aggregate at optimum density and moisture content. The Enhanced Integrated Climatic Model (EICM) is used to modify the representative Mr for the seasonal effect of climate.

A Level 3 analysis was used for the subgrade which means that a representative resilient modulus is assigned by the MEPDG software based on the AASHTO classification of the subgrade material. A relatively lower modulus value was assigned to the subgrade at the Illinois site because of its historically low California Bearing Ratio (CBR). Table 3 summarizes the modulus values assigned to the subgrades for the various projects.

Table 3. Assigned Subgrade Resilient Modulus for the various Projects.

Subgrade	Alabama		California	Illinois	South Carolina		Texas	
	US31	SR7	PLA28	Chicago	SC12	SC161	FM396	SH30
Type	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	A-2-4	A-7-6	A-6
Resilient Modulus* (MPa)	90	90	90	60	90	140	80	100

* Representative modulus at optimum density and moisture content

The rutting and fatigue performance models that were developed in this study for the three mixtures from every state were used in the MEPDG to estimate the rutting and fatigue performance of the asphalt pavements. The performance models at the 0 F-T cycles were used to conduct the design at the un-damaged condition and the 6 F-T cycles were used to conduct the designs at the moisture-damaged condition. The models used in the MEPDG designs are shown in Figures 6 – 15.

MEPDG Structural Designs

The MEPDG structural design was conducted for each project location within the five participating state. At each location, the following process was followed:

- The design life was set at 20 years for all projects.
- The rutting failure criterion was set at 6.25mm rut depth in the asphalt layer.
- The fatigue failure criterion was set at 25% fatigue of the pavement surface.
- Conduct structural designs for the un-damaged condition using the 0 F-T cycles properties and performance models for each of the three HMA mixtures: un-treated, liquid-treated, and lime-treated.

- Conduct structural designs for the moisture-damaged condition using the 6 F-T cycles properties and performance models for each of the three HMA mixtures: un-treated, liquid-treated, and lime-treated.
- In each case of the un-damaged and moisture-damaged conditions, select the structural design that satisfy both the rutting and fatigue criteria.

In the case of the South Carolina project on SC12, the MEDPG was unable to recommend a structural design for the un-treated mix at the moisture-damaged condition due to extremely low dynamic modulus property of the un-treated mix after moisture conditioning (i.e. Figure 4).

The next step of the analysis was to identify the mix condition that controlled the structural design for each project that provides the 20 years performance life. For this step, the thicker structural design between the un-damaged and moisture-damaged conditions was selected for each project. Since the thickness of the base layer was kept constant within each project, the thicker structural designs were simply the ones having the thicker asphalt layer. Table 4 summarizes the structural designs that provided the 20 years performance life for all projects along with an indication on the condition that controlled the final design, e.g. un-damaged or moisture-damaged and rutting or fatigue. Figure 17 shows the percent change in the thickness of the asphalt layer due to the use of liquid and lime additives for the various projects. A positive percent change indicates that the use of the treated mix resulted in a reduction in the asphalt layer as compared with the un-treated mix while a negative percent change indicates the opposite.

Table 4. MEPDG 20 Years Structural Designs for all Project Locations.

State	Location	HMA Mixture	Structural Design		Control Condition/ Control Distress
			HMA (cm)	Base (cm)	
Alabama	US31 (4.6×10^6 ESALs, 1438 ADTT)	un-treated	22	28	un-damaged/rutting
		liquid-treated	33	28	un-damaged/rutting
		lime-treated	17	28	moisture-damaged/rutting
	SR7 (2.8×10^6 ESALs, 910 ADTT)	un-treated	18	23	un-damaged/rutting
		liquid-treated	27	23	moisture-damaged/rutting
		lime-treated	15	23	moisture-damaged/rutting
California	PLA28 (1.6×10^6 ESALs, 360 ADTT)	un-treated	24	20	moisture-damaged/fatigue
		liquid-treated	20	20	moisture-damaged/fatigue
		lime-treated	15	20	neither/neither
Illinois	Chicago (3.7×10^6 ESALs, 1050 ADTT)	un-treated	22	25	un-damaged/rutting & fatigue
		liquid-treated	27	25	un-damaged/rutting
		lime-treated	15	25	Moisture-damaged/rutting
S. Carolina	SC12 (9.6×10^6 ESALs, 2170 ADTT)	un-treated	*	30	moisture-damaged/rutting
		liquid-treated	35	30	un-damaged/rutting
		lime-treated	33	30	un-damaged/rutting
	SC161 (7.1×10^6 ESALs, 2360 ADTT)	un-treated	39	25	moisture-damaged/rutting
		liquid-treated	32	25	un-damaged/rutting
		lime-treated	30	25	un-damaged/rutting
Texas	FM396 (7.8×10^6 ESALs, 872 ADTT)	un-treated	35	28	moisture-damaged/rutting
		liquid-treated	23	28	moisture-damaged/rutting & fatigue
		lime-treated	18	28	un-damaged/rutting & fatigue
	SH30 (3.3×10^6 ESALs, 824 ADTT)	un-treated	34	23	moisture-damaged/rutting
		liquid-treated	25	23	moisture-damaged/rutting & fatigue
		lime-treated	18	23	un-damaged/rutting & fatigue

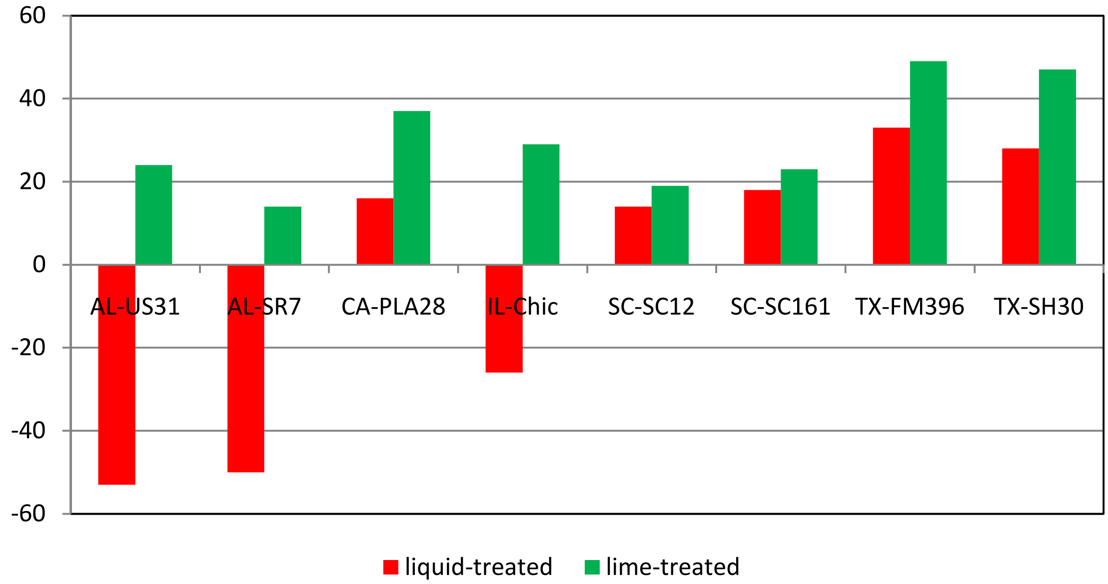


Figure 17. Percent Reduction in the Thickness of the Asphalt Layer

LIFE CYCLE COST ANALYSIS

The MEPDG designs recommended the required thickness of the asphalt layer for the un-treated and treated pavements for a constant design life of 20 years. This converts the change in intial construction costs into equivalent life cycle costs. The following figures were used in the cost analysis:

- Unit cost of un-treated asphalt mix: US$65.0/ton of mix
- Unit cost of liquid-treated asphalt mix: US$65.5/ton of mix
- Unit cost of lime-treated asphalt mix: US$68.4/ton of mix

The above unit costs are based on the cost of asphalt binder of US$650 per ton at the hot mix plant and the cost of aggregate of US$15 per ton at the hot mix plant. The unit cost of the liquid-treated asphalt mix was calculated based on the cost of the liquid additive of US$0.70/ton of mix without any additional cost for the production of the liquid-treated asphalt mix. The unit cost of the lime-treated asphalt mix was calculated based on the cost of lime of US$1.25/ton of mix and the additional costs of plant modifications and equipment of US$3.75/ton of mix.

The life cycle cost savings realized due to the reduction in the thickness of the asphalt layer when treated mixtures are used are presented in Figure 18 in terms of the percent savings. The percent savings were calculated using the changes in the thickness of the asphalt layer along with the unit cost for each mixture type. A positive percent savings indicates that the use of the treated mix resulted in a reduction in the initial construction cost of the pavement as compared with the un-treated mix while a negative percent savings indicates the opposite.

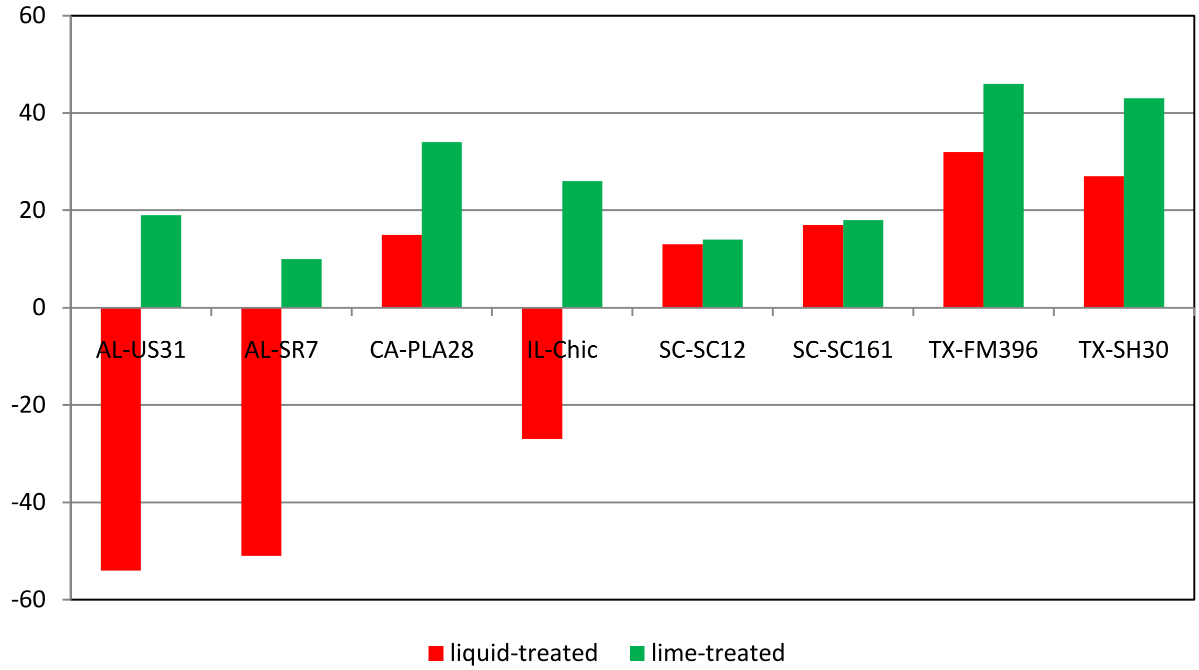


Figure 18. Cost Savings of Treated Asphalt Mixtures as Compared with Un-treated Mixtures

SUMMARY AND CONCLUSIONS

This experiment evaluated the impact of lime and liquid additives on the resistance of asphalt mixtures to moisture damage, rutting, and fatigue cracking. A total of five different sources of asphlat mixtures were evaluated. Three different types of mixtures were evaluated from each source: untreated, liquid-treated, and lime-treated. The strength properties in terms of E* and the resistance to rutting and fatigue cracking of the mixtures were compared at the un-damaged and moisture-damged stages. Finally, the strength properties of the mixtures along with their rutting and fatigue characteristics were used in the AASHTO MEPDG to design actual asphalt pavements at locations where the evaluated materials will be used. The resulted structrual designs were then used in a life cycle cost analysis that compared the various alternatives of constructing the asphalt pavements. The analysis of the data generated in this research effort led to the folloiwng cocnlsuions:

- The use of lime significantly improved the resistance of asphalt mixtures to moisture damage whether the aggregate source is labeled as moisture sensitive or not.

- The use of liquid additive marginally improved the resistance of asphalt mixtures to moisture damage.

- The impact of both lime and liquid additives on the resistance of asphalt mixtures to rutting was marginal. The reason for the marginal impact is due to the fact that the rutting resistance of asphalt mixture is primarily controlled by the gradation and texture of the aggregates. And, by simply adding lime or liquid to the mix will not significantly impact neither the gradation nor the texture of the aggregates.

- Both liquid and lime improved the fatigue resistance of the moisture-damaged mixtures. But the improvement in fatigue resistance of some mixtures was dependent on the level of tensile strain which is directly related to the level of traffic loads.

- The mechanistic-empirical structural design process as conducted by the MEPDG allows the pavement engineer to combine the influence of stiffness (E*) and performance characteristics of the mixtures on the final design of the asphalt pavement. As shown in the rutting and fatigue models, the life of the asphalt pavement depends on the generated strains within the asphalt layer. On the other hand, the magnitude of the generated strains within the asphalt layer dependent on the stiffness of the mix. Therefore, an asphalt mix that will hold a high level of stiffness after moisture damage will result in lower strains and longer pavement life. Based on these concepts, the MEPDG designs showed significant reductions in the thickness of the asphalt layer when lime-treated mixtures were used which translated into significant cost savings as identified below:

    - The use of lime additives in HMA mixtures resulted in significant savings, in some cases more than 45%. The savings were realized in all mixtures regardless of their anticipated level of moisture sensitivity.
    - The use of liquid anti-strip additives in HMA mixtures may result in additional cost, in some cases as high as 50%. The additional costs were realized in mixtures that did not require liquid additives to pass the Superpave moisture sensitivity criterion of TSR≥80% such the AL and IL mixtures.
    - The data generated on the four mixtures from Alabama, California, Illinois, and S. Carolina show that lime is highly compatible with the use of neat asphalt binders and will always results in savings on the order of 13-34%.
    - The data generated on the mixtures from Texas show that the lime is highly compatible with the use of polymer-modified binders and will result in savings on the order of 40-45% which is significantly higher than the savings that could be realized with the use of the liquid anti-strip.

REFERENCES

1. Kennedy, T. W. and W. V. Ping. Evaluation of Effectiveness of Antistripping Additives in Protecting Asphalt Mixtures from Moisture Damage. In *Proceedings of Technical Sessions*: *Journal of the Association of Asphalt Paving Technologists, Vol. 60,* Seattle, WA, 1991, pp. 230 – 263.

2. Kim, O. X., Bell, C.A., and R. G. Hicks. The Effect of Moisture on the Performance of Asphalt Mixtures. In *American Society for Testing and Materials: Special Technical Publication STP-899*, Philadelphia, 1995, pp. 51-72.

3. G. W. Maupin, Jr. Effectiveness of Antistripping Additives in the Field. Virginia Transportation Research Council, Report No. VTRC 96-R-5, September 1995.

4. G. W. Maupin, Jr. Follow-up Field Investigation of the Effectiveness of Antistripping Additives in Virginia. Virginia Transportation Research Council, Report No. VTRC 97-TAR6, January 1997.

5. M. Tahmoressi. Effects of Hydrated Lime on Hamburg Properties of Limestone Mixtures. Research Report, PaveTex Engineering and Testing, Inc., 2002.

6. Sebaaly, P. E., Tohme, P., Hitti, E., Stansburry, K., and J. Epps. Asphalt Concrete Antistripping Techniques. South Dakota DOT Study SD99-10, Final Report, Pierre, SD, 2003.

7. Tohme, P., Sebaaly, P. E., Hajj, E. Y., and D. Johnston. Effectiveness of Antistrip Additives for Bituminous Mixtures. In *International Journal of Pavements, Vol. 3, No. 1-2*, 2004, pp. 50-62.