IMPACT OF LIME ON PAVEMENT PERFORMANCE

Hot mix asphalt (HMA) pavements are subjected to continuously changing traffic wheel loads and environmental conditions. Figures 1 shows the state of stresses in a typical HMA pavement consisting of surface and base layers over the natural subgrade. The shear, compression, and bending stresses are caused by the traffic load while the thermal tension is caused by the environment. In addition, the environment affects the pavement due to the presence of moisture, the fluctuations in temperature, and aging of the HMA mix. When environmental actions are combined with the imposed stresses from the repeated traffic loads moisture damage can occur and causes a reduction in pavement life due to the formation of rutting and cracking failures.

To prevent moisture damage, many states and other agencies have resorted to specifying anti-stripping additives in an attempt to increase adhesion at the aggregate-asphalt interface. Anti-strip additives can be categorized into two major groups: liquid and solid. Lime is the most common solid anti-stripping additive used in HMA. Long term performance of HMA pavements treated with liquid and lime showed that liquid maybe effective in reducing the moisture sensitivity of the mixture while lime can, simultaneously reduce the moisture sensitivity of the mix and improve its resistance to rutting and cracking.

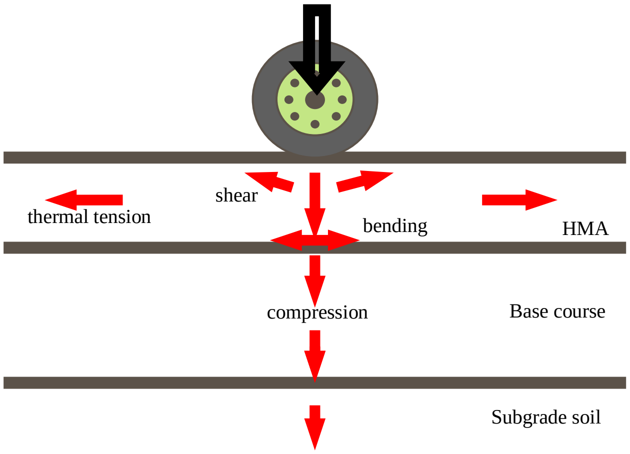


Figure 1. Stresses within a typical HMA pavement

This document summarizes the largest study of its kind to evaluate the multifunctional impact of lime and liquid additives on HMA pavements. 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 HMA mixture. This study extended the evaluation to cover the impact of lime and liquid additives on the structural performance of the HMA mixtures and their impact on the long term performance of typical HMA pavements.

Study Methodology

The Principal Investigators for the study were Dr. Peter Sebaaly from the University of Nevada, Reno and Dr. Dallas Little from the Texas A&M University. The laboratory testing of the mixtures were conducted in the Pavements/Materials Laboratory of the University of Nevada under the supervision of Dr. Elie Hajj.

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 HMA mixtures that were evaluated in this study.

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

Agency	**Type of Mix**	**Type of Aggregate**	**Asphalt Binder**			**Liquid Anti-strip**	**Lime**
			PG Grade	**Polymer-modified**	**Acid-Modified**		
Alabama	Dense	Limestone	PG67-22	No	No	Polyamine derived	Type "N" normal hydrate 95% CaO
California	Dense	Siliceous	PG64-16	No	No	Polyamine derived	
Illinois	Dense	Dolomite Limestone	PG64-22	No	No	Amidoamine derived	
South Carolina	Dense	Granite	PG64-22	No	No	Amidoamine derived	
Texas	Dense	Gravel	PG76-22	Yes-SBS	No	Amino acid based	

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% 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 permanent deformation: relationship between permanent strain in the HMA 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 HMA 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 185°F 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. For example, in the case of resistance to permanent deformation, the HMA 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 HMA mixtures were evaluated at the aged stage because cracking is a long-term distress mode. The E* of the HMA mixtures were evaluated under both the unaged and aged stages to cover the entire life span of the HMA pavement.

Moisture Conditioning

Moisture conditioning of the mixtures consisted of the following process:

- Subject the compacted samples to 75% water saturation.
- Subject the saturated samples to multiple freeze-thaw cycling wherein one freeze-thaw cycle consists of freezing at 0°F for 16 hours followed by 24 hours thawing at 140°F and 2 hours at 77°F.
- Subject each sample to the required number of freeze-thaw cycles.

- Conduct testing after cycles: 1, 3, 6, 9, 12, and15.

Impact of Moisture Damage on Modulus

The E* of the HMA mix is measured at multiple temperatures and multiple loading frequencies to simulate the combined impact of mixed traffic and variable environmental conditions. The E* represents the overall stiffness of the HMA 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 104^{o}F temperature is critical for rutting, while a 70^{o}F temperature is critical for fatigue cracking. Figures 2a – 2e show the measured E*at 104^{o}F at various F-T cycles for the fifteen mixtures at the unaged stage. Similar data were also measured on all fifteen mixtures at the aged stage.

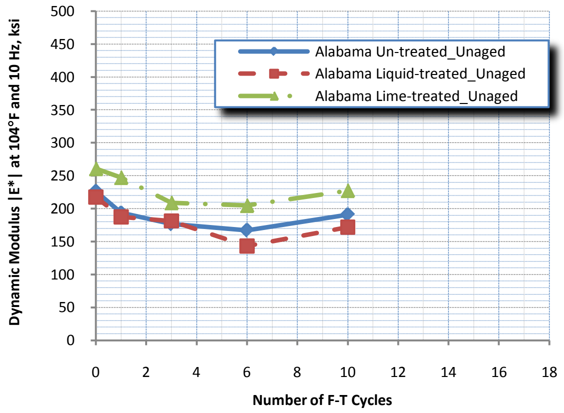


Figure 2a. relationship between E* and F-T cycles for Alabama mixtures

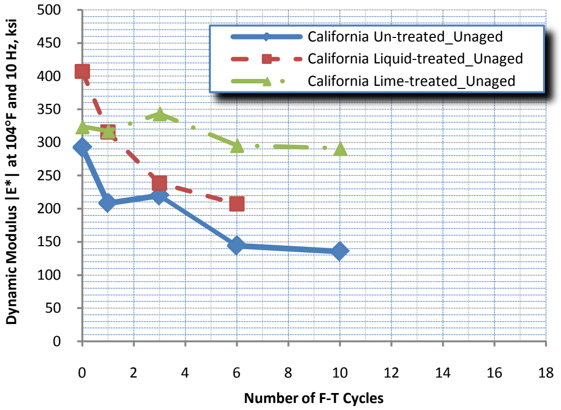


Figure 2b. Relationship between E* and F-T cycles for California mixtures

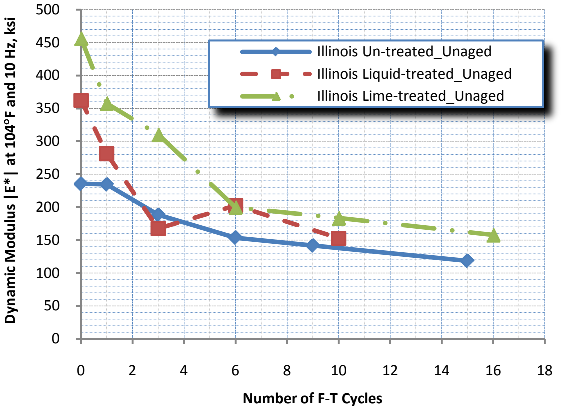


Figure 2c. Relationship between E* and F-T cycles for Illinois mixtures

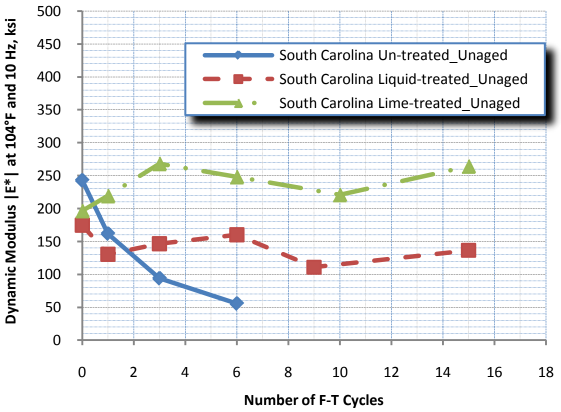


Figure 2d. Relationship between E* and F-T cycles for S. Carolina mixtures

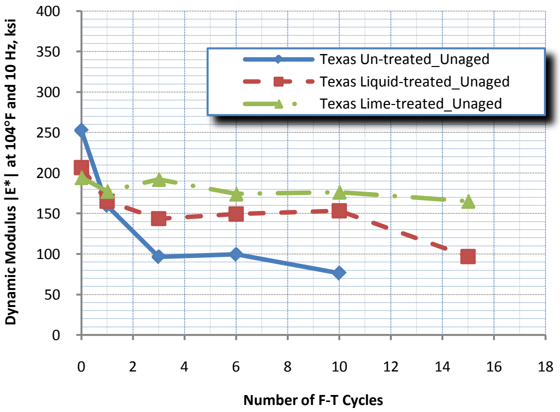


Figure 2e. Relationship between E* and F-T cycles for Texas mixtures

The data in the above figures 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.

The data in the graphs and Table 2 clearly show the significant improvement in the E* properties of the lime-treated mixtures as compared with 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 the 6 F-T cycles for both the unaged and aged stages. The ratio of the conditioned E* over the unconditioned E* is also shown in Table 2 which indicates that the lime-treated mixtures from all five sources generally maintained a higher ratio than the un-treated and liquid-treated mixtures at both unaged and aged stages. In summary, the data in Table 2 show that the lime-treated mixtures maintained a significantly higher E* property after subjected to moisture in terms of magnitude and retained ratio for all mixtures and at both the unaged and aged stages. This finding indicates that the lime-treated mixtures are stronger and more durable than the un-treated and liquid-treated mixtures.

Table 2. Dynamic Modulus of various Mixes at 10 Hz.

State	**Mix**	**Unaged E^*, (ksi) at 104°F**			**Aged E^* (ksi) at 70°F**		
		0 F-T	**6 F-T**	**Ratio E_{6FT}/E_{0FT}**	**0 F-T**	**6 F-T**	**Ratio E_{6FT}/E_{0FT}**
Alabama	Un-treated	226	167	74%	1,123	806	72%
	Liquid-treated	218	143	66%	1,113	813	73%
	Lime-treated	261	205	79%	1,236	1,043	84%
California	Un-treated	292	144	49%	1,479	622	42%
	Liquid-treated	407	207	51%	1,649	1,116	68%
	Lime-treated	324	296	91%	1,683	1,717	102%
Illinois	Un-treated	235	154	66%	1,648	826	50%
	Liquid-treated	362	203	56%	1,500	881	59%
	Lime-treated	456	200	44%	1,614	1,328	82%
South Carolina	Un-treated	243	56	23%	754	275	36%
	Liquid-treated	175	160	91%	749	560	75%
	Lime-treated	197	248	126%	1,037	958	92%
Texas	Un-treated	253	99	39%	870	508	58%
	Liquid-treated	207	149	72%	848	603	71%
	Lime-treated	194	174	90%	852	843	99%

Predicting Performance of HMA Pavements

Predicting the performance of HMA pavements can be achieved in two different approaches: a) predicting performance based on the E* property alone and b) predicting performance based on E* property and mixtures mechanical characteristics. In the first approach, the E* properties of the fifteen mixtures are used to calculate the compressive and bending strains within the HMA layer of a typical HMA pavement which are then used in nationally calibrated models for rutting and fatigue. In the second approach, the E* properties and the mixtures-specific rutting and fatigue models are used to conduct the structural designs for specific projects from the five materials sources.

a) Predicting Performance Based on E Properties and National Models*

Predicting the rutting and fatigue performance of the various mixtures when used in HMA pavements requires the estimation of the compressive and bending strains in the HMA layer as shown in Figure 1. The moisture damaged E* (i.e. after 6 F-T) properties of the fifteen mixtures were used to calculate the compressive and bending strains within the HMA layer of a typical HMA pavement (6” HMA over 10” crushed aggregate base). The rutting and fatigue performance of the pavements were estimated using the nationally calibrated rutting and fatigue performance models included in the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG). Figures 3a and 3b below show the ratios of rutting and fatigue lives of the typical pavements when using HMA mixtures from the five sources. The ratio of rutting life for the SC source was not predicted because its E* property at 104^{o}F after 6 F-T cycles was extremely low as shown in Table 2 (56 ksi for un-treated vs. 248 ksi for lime-treated). The life ratio is calculated as the number of load repetitions of the treated pavement over the load repetitions of the un-treated pavement. A ratio above 1.0 indicates the treated pavement will survive more load repetitions than the un-treated pavement while a ratio below 1.0 indicates the treated pavement will survive less load repetitions than the un-treated pavement.

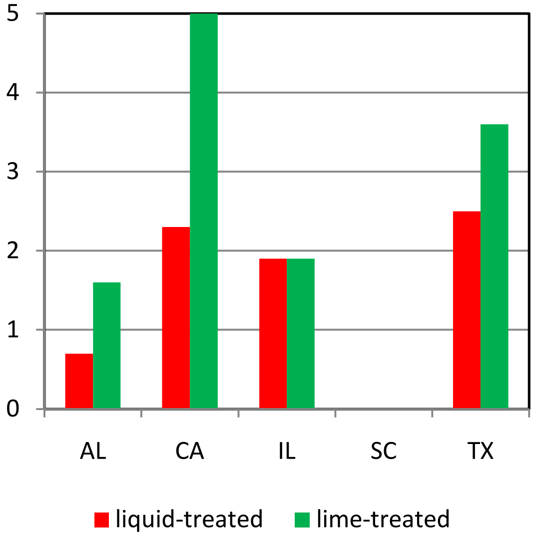


Figure 3a. Ratio of rutting life

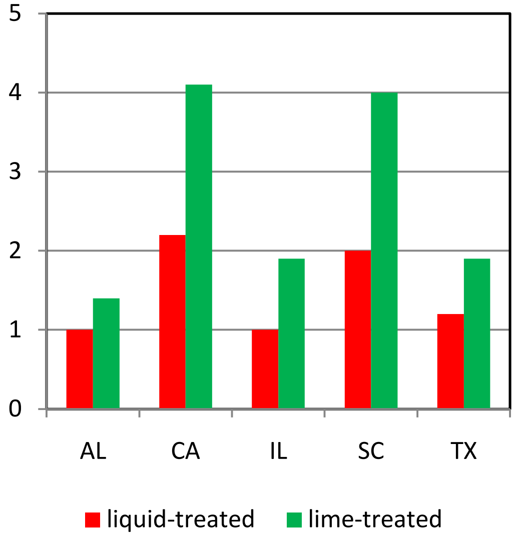


Figure 3b. Ratio of fatigue life

The performance data for the typical pavements based on the nationally calibrated MEPDG models show that the lime-treated mixtures significnlaty out-perform the liquid-treated mixtures in both rutting and fatigue for all pavements except for the rutting life of the IL mix. The liquid-treated pavement in AL will have a lower rutting life than the un-treated pavement.

b) Predicting Performance Based on E Properties and Mixtures Specific Models*

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 MEPDG for projects where the evaluated mixtures will be used. In order to complete this analysis, the five participating agencies were asked to provide information regarding location, traffic, and roadbed soil for projects where the evaluated mixtures will be used. The E* properties of the fifteen mixtures that were evaluated as part of the moisture damage experiment were used in this analysis. In addition the rutting and fatigue characteristics at the un-damaged and moisture-damaged conditions of the fifteen mixtures were evaluated using the tests described below.

The resistance of the of HMA pavements to rutting depends on the interaction between the HMA's E* at high temperatures and the magnitude of the shear and compression strains within the HMA layer as it is subjected to repeated loads. In simple terms, rutting in the HMA layer is the product of the permanent strain (ε_p) times the thickness of the HMA layer (i.e. $\varepsilon_p x H_{HMA}$). The magnitude of ε_p is directly related to the magnitude of the compression and shear strains within the HMA layer represented by the vertical and inclined arrows in Figure 1. The smaller the vertical and inclined arrows within the HMA layer in Figure 1, 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:

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

Repeated Load Triaxial Test

Due to the triaxial nature of the RLT test, it activates both the shear and compression stresses within the HMA mix as represented by the inclined and vertical arrows in Figure 1. Figure 4 shows typical rutting models for two of the mixtures that were evaluated in this study.

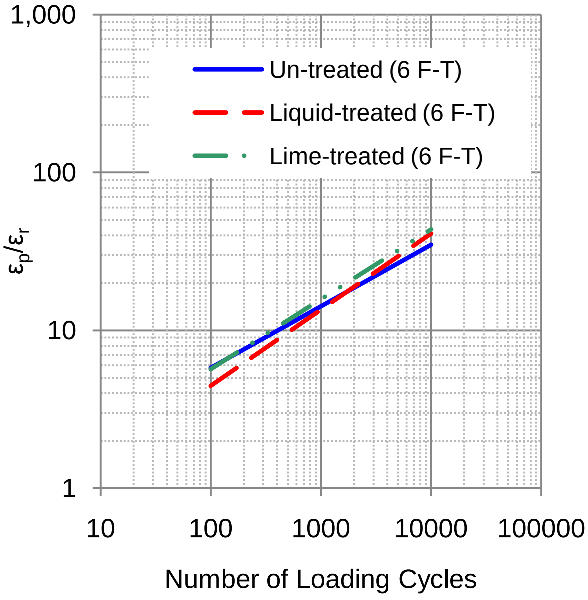


Figure 4a. Rutting Models for the IL Mixtures

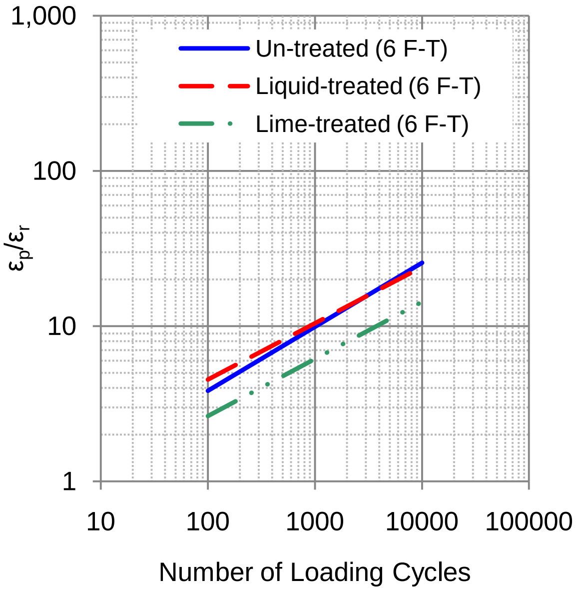


Figure 4b. Rutting Models for the TX Mixtures

In general, the lower the RLT curve the higher the resistance of the mixture to permanent deformation. The rutting models for the Illinois mixtures shown in Figure 4a indicate that the addition of liquid and lime did not make a significant impact on the rutting resistance of the mixture. On the other hand, the rutting models for the Texas mixtures shown in Figure 4b indicate that the addition of lime significantly improved the rutting resistance of the mixture. The difference in the impact of lime on the rutting resistance of the Illinois and Texas mixtures can be attributed to the fact that the Illinois mixture was classified as not moisture sensitive while the Texas was classified as highly moisture sensitive.

The resistance of the of HMA pavements to fatigue depends on the interaction between the HMA's E* at intermediate temperatures and the magnitude of the bending strain (ε_t) at the bottom of the HMA as it is subjected to repeated loads. The smaller the horizontal arrow at the bottom of the HMA layer in Figure 1, the higher the fatigue life of the HMA pavement. The flexural beam fatigue test was used to establish the relationship between the ε_t, E*, and number of load repetitions (N_f) at a temperature (T) for each of the fifteen mixtures. The form of the relationship is shown below:

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

Flexural Beam Test

Figure 5 shows typical fatigue models for two of the mixtures that were evaluated in this study.

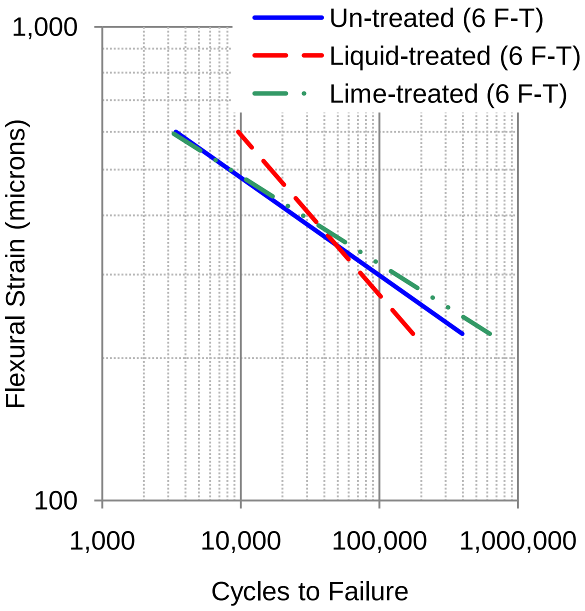


Figure 5a. Fatigue Models for the AL Mixtures

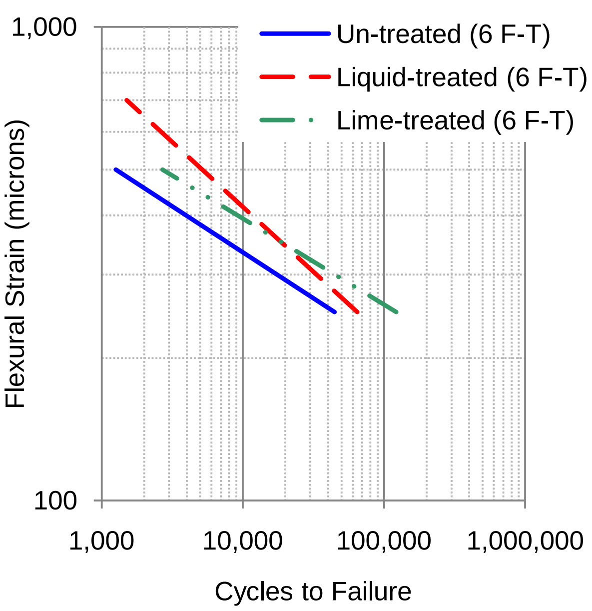


Figure 5b. Fatigue Models for the CA Mixtures

The higher the fatigue curve the better the resistance of the mixtures to fatigue cracking. Figures 5a and 5b show that the liquid additive created a significant change in the slope of the fatigue curves for the Alabama and California mixtures. Such behavior leads to differing fatigue resistance of the mixtures under high strains versus low strains which makes it very complicated to assess the potential performance of the mixtures under mixed traffic. On the other hand, the addition of lime did not impact the fatigue resistance of the Alabama mixtures, which is considered as not moisture sensitive, while it significantly improved the fatigue resistance of the California mixtures without changing the slope.

Life Cycle Cost Analysis for New Designs

The life cycle cost analysis started by conducting structural designs for the various pavements using the AASHTO MEPDG with the following process for each project location:

- Use the project-specific traffic and environmental conditions.
- Keep the thickness of the base and the strengths of the base and subgrade constant.
- Use the un-treated, liquid-treated, and lime-treated mixtures in the HMA layer along with their corresponding E* properties, rutting characterics, and fatigue cahracteristics.
- Design the thickness of the HMA layer for each type of mix under the un-damaged and moisture-damaged conditions.
- Select the most conservative structrual design for each type of mix: un-treated, liquid-treated, and lime-treated.

The MEPDG designs recommend the required thickness of the HMA 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 HMA mix:	\$5.12/yd^2-in (\$65.0/ton of HMA)
Unit cost of liquid-treated HMA mix:	\$5.16/yd^2-in (\$65.5/ton of HMA)
Unit cost of lime-treated HMA mix:	\$5.39/yd^2-in (\$68.4/ton of HMA)

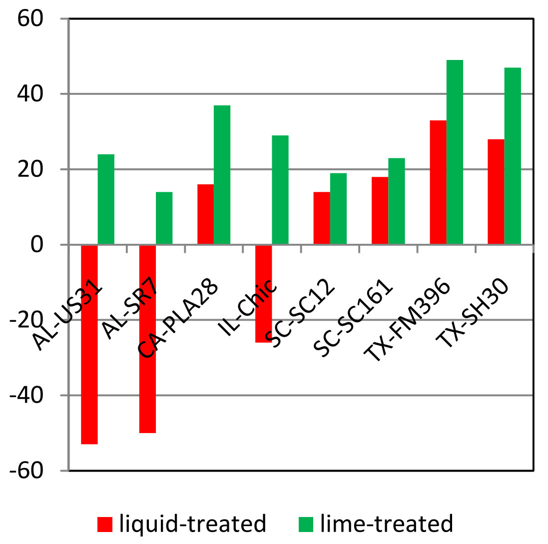
The recommended MEPDG structural designs are presented below (left side) in terms of the percent change in the thickness of the HMA layer for the liquid- and lime-treated mixtures relative to the thickness of the HMA layer for the un-treated mix. A positive percent change indicates that the use of the treated mix resulted in a reduction in the HMA layer as compared with the un-treated mix while a negative percent change indicates the opposite. The life cycle cost savings realized due to the reduction in the thickness of the HMA layer when treated mixtures are used are also presented below (right side) in terms of the percent savings. The percent savings were calculated using the changes in the thickness of the HMA 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.

In summary, the results generated from this study lead to the following conclusions:

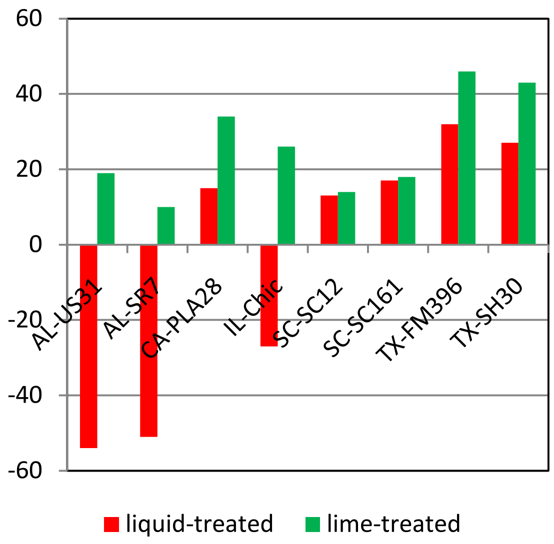
- The use of lime additives in HMA mixtures resulted in significant savings, in some cases more than 45%.
- The use of liquid anti-strip additives in HMA mixtures may result in additional cost, in some cases as high as 50%.
- The data generated on the four mixtures from Alabama, California, Illinois, 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.

- These data show that the use of lime additives will always improve the performance of the HMA pavement to a magnitude that always outweighs its cost.



Percent Change in HMA Thickness



Percent Savings

Life Cycle Cost Analysis for Rehabilitated Pavements

Figure 6 shows a cracked HMA pavement subjected to an overlay. Temperature changes create horizontal movements on the tip of the cracks in the old HMA layer while traffic loads create vertical movements at the same location. In addition, traffic loads also generate horizontal and vertical movements at the bottom of the HMA overlay. Because of the full bond condition at the interface between the HMA overlay and the old HMA layer, the four components are transferred to the new HMA mix. Superimposing all four components of movements will greatly increase the potential of the cracks to reflect through the HMA overlay. Therefore, the performance life of the entire pavement in Figure 6 will be controlled by the ability of the HMA overlay to resist rutting, fatigue, thermal, and reflective cracking.

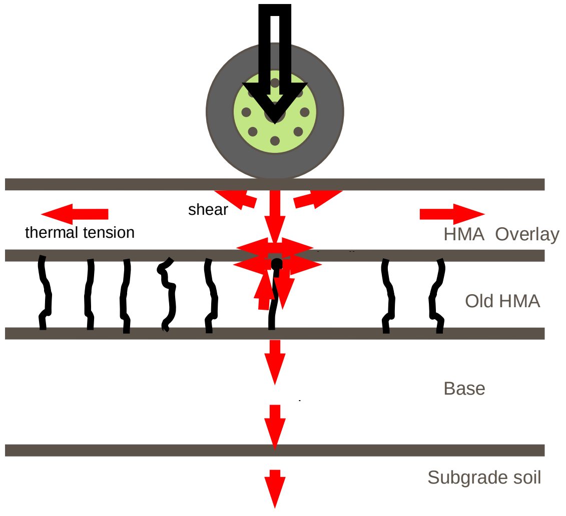
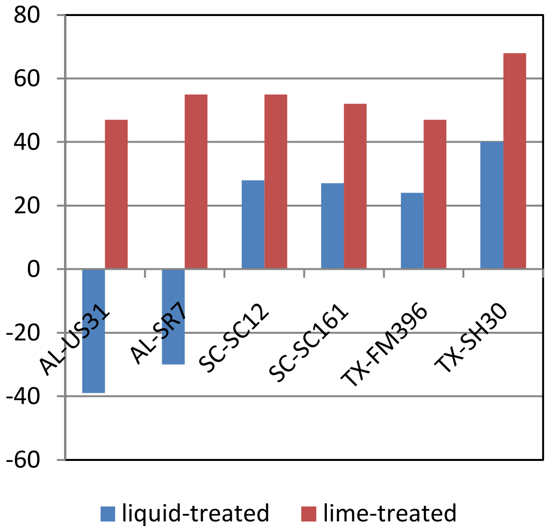


Figure 6. **Stresses within an overlaid HMA pavement**

The Rubber Pavement Association (RPA) Overlay Design Model was used to evaluate the resistance to reflective cracking of the un-treated, liquid-treated, and lime-treated mixtures from all five sources. The RPA model utilizes the E* property and the fatigue characteristics of the various HMA mixtures to evaluate their long term performance as they are placed over cracked HMA pavements. The final result of the RPA model is the required 10-years design thickness of the overlay for the design ESALs. The climatic conditions and the properties of base and subgrade layers were similar to the ones used for the project locations for the design of new HMA pavements.

The life cycle cost savings realized due to the reduction in the thickness of the HMA layer overlay when treated mixtures are used are presented on the right in terms of the percent savings. The percent savings were calculated using the changes in the thickness of the HMA overlay 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 construction cost of the overlay as compared with the un-treated mix while a negative percent savings indicates the opposite. In the case of the California and Illinois projects, the overlay design with the un-treated mixtures was un-achievable. Therefore, a true percent savings could not be calcuated for these two projects. In summary, the use of hydrated lime in HMA overlays results in savings in the range of 40-65% while the use of liquid anti-strip may result in additional cost as high as 40%. In addition, the savings realized by the use of liquid anti-strip are always significnalty lower than the savings realized by the use of hydrated lime.



Percent Savings

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