# The Benefits of
# HYDRATED LIME IN HOT MIX ASPHALT

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# THE BENEFITS OF HYDRATED LIME IN HOT MIX ASPHALT

## SUMMARY

Hydrated lime in hot mix asphalt (HMA) creates multiple benefits. A considerable amount of information exists in the current literature on hydrated lime's ability to control water sensitivity and its well-accepted ability as an antistrip to inhibit moisture damage. However, recent studies demonstrate that lime also generates other effects in HMA. Specifically, lime acts as an active filler, anti-oxidant, and as an additive that reacts with clay fines in HMA. These mechanisms create multiple benefits for pavements:

1. Hydrated lime reduces stripping.
2. It acts as a mineral filler, stiffening the asphalt binder and HMA.
3. It improves resistance to fracture growth (i.e., it improves fracture toughness) at low temperatures.
4. It favorably alters oxidation kinetics and interacts with products of oxidation to reduce their deleterious effects.
5. It alters the plastic properties of clay fines to improve moisture stability and durability.

The ability of lime to improve the resistance of HMA mixtures to moisture damage, reduce oxidative aging, improve the mechanical properties, and improve resistance to fatigue and rutting, has led to observed improvements in the field performance of lime-treated HMA pavements. Life cycle cost analyses have shown that using lime results in approximate savings of $20/ton of HMA mix while field performance data showed an increase of 38% in the expected pavement life.

Several highway agencies have proven the effectiveness of lime with cold-in-place recycled mixtures. Lime treatment of the CIR mixtures increases their initial stability which allows the early opening of the facility to traffic and improves their resistance to moisture damage which significantly extends the useful life of the pavement.

Various methods are used to add hydrated lime to HMA. They range from adding dry lime to the drum mixer at the point of asphalt binder entry, to adding lime to aggregate followed by "marination" for several days. This report summarizes studies evaluating different modes of application. Because different methods have been used successfully, preferred modes of application vary from state to state. In 2003, the NLA produced an overview of how to add lime to HMA mixtures based on site visits (http://www.lime.org/howtoadd.pdf).

Hydrated lime is an additive that increases pavement life and performance through multiple mechanisms. This document consolidates recent studies and updates previous literature compilations on hydrated lime's multiple benefits.

## BACKGROUND

### DEFINITIONS AND MECHANISMS

Stripping is commonly defined as "loss of adhesion between the aggregate surface and asphalt cement binder in the presence of moisture." HMA may experience loss of strength in the presence of moisture without visible evidence of debonding because water may affect the cohesive strength of the asphalt binder. Thus, the terms "water susceptibility" and "water sensitivity" are often used to designate the loss of strength or other properties of HMA in the presence of moisture.

The water susceptibility of HMA is controlled by:

- Aggregate properties
- Asphalt cement binder properties
- Mixture characteristics
- Climate
- Traffic
- Construction practices
- Pavement design considerations

It is usually the aggregate properties that dominate the water susceptibility properties of an HMA. Although asphalt cement properties may also affect water susceptibility, generally an aggregate-related water susceptibility problem cannot be overcome by selecting an unmodified asphalt cement binder with superior antistripping properties.

Problem pavements under high traffic levels normally experience more rapid premature distress than similar pavements under low traffic loading. Compacted mixtures with high air voids are generally more likely to experience stripping than pavements that are compacted to low air void contents.

The hot and wet climates of the southern United States and the cold and relatively dry climates of the western United States experience the most dramatic stripping problems. In the southeastern states, the combination of high temperatures (low asphalt viscosity) and wet weather (in the summer months) cause stripping. The mountain and high desert areas of the west experience severe stripping problems due to moisture, freeze-thaw cycles (up to 230 air freeze-thaw cycles annually), and aggregates that have poor adhesion to asphalt in the presence of moisture. Most other regions also experience moisture problems that can manifest themselves through incompatibility between binders and aggregates and/or loss of cohesion in the bitumen due to moisture penetration.

Pavements with open-graded friction courses and interlayers (fabric, chip seals, etc.) have experienced premature distress due to stripping. In fact, failures of asphalt pavements within weeks of placing chip seals have occurred relatively frequently.

The physical-chemical mechanisms responsible for stripping in asphalt-aggregate mixtures are complex and may never be fully understood. Detachment, displacement, emulsification, pore water pressure, hydraulic scouring, and asphalt-aggregate interfacial physical-chemistry have been proposed to define the cause of water susceptibility problems. Additional research will be needed for a full understanding of the basic mechanisms. Nonetheless, the research presented in this report demonstrates lime’s potential for creating multiple benefits in HMA and effecting significant improvements in pavement performance.

## HISTORY – OBSERVED U.S. PAVEMENT PROBLEMS

In the late 1970s, a number of premature asphalt pavement failures occurred in the southeastern and western United States. Stripping was identified as a major problem, but its rather sudden appearance has never been fully explained. Probable causes included: changes in properties of asphalts associated with the Arab oil embargo of the mid 1970s, increases in traffic, drum mixing equipment, open graded friction courses, paving fabrics, and aggregate characteristics.

A National Cooperative Highway Research Project (NCHRP), which was completed in 1991, presented a more comprehensive review of moisture damage problems [Hicks (1991)]. About 70 percent of the responding state and province departments of transportation in North America experienced moisture damage problems in their pavements. Figure 1 shows that all regions reported moisture damage. Figure 2 shows the percentage of pavements experiencing moisture-related distress by state.

The major types of premature distress included: rutting or permanent deformation in the wheel paths, bleeding in selected areas of the pavement, and alligator cracking. Millions of dollars of rehabilitation were necessary and research efforts were initiated to solve this problem.

Since the 1991 survey, many more states have identified moisture as a significant cause of pavement damage. In 2002, the Colorado Department of Transportation conducted a survey to identify the actions that various agencies take in combating moisture damage of HMA mixtures [Aschenbrener (2002)]. This survey included 50 state departments of transportation, 3 FHWA Federal Land offices, the District of Columbia, and 1 Canadian province. It was determined that 82% of the agencies require some sort of antistrip treatment. Figure 3 shows the distribution of the various techniques used for moisture damage treatment. Since the publication of the 2002 survey, additional states have begun treating asphalt mixes for stripping, such as Kansas, and Vermont. After years of alternate treatment methods to address pavement damage, and after a thorough study of alternate methods, the Nebraska DOT chose to specify hydrated lime exclusively as the preferred method of treatment for their pavements.

## TEST METHODS TO ASSESS STRIPPING AND MOISTURE DAMAGE

These moisture damage problems stimulated considerable research in the United States in the late 1970s and during the 1980s. NCHRP projects were initiated to develop improved water sensitivity tests for HMA [Lottman (1978), Lottman (1982), and Tunnicliff and Root (1982)]. The present AASHTO and ASTM test methods were developed based on this research (AASHTO T 283 and ASTM D 4867).

Additional research was conducted in the 1990s and 2000s under the Strategic Highway Research Program (SHRP), NCHRP project 9-13; "Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design," and NCHRP project 9-34; "Improved Conditioning Procedure for Predicting the Moisture Susceptibility of HMA Pavements."

Numerous test methods have been developed to determine the water susceptibility of HMA and other types of asphalt aggregate combinations. Most of the tests are intended for use during the mixture design process and are not suitable for quality control and quality assurance purposes. For the most part, extensive data are not available to correlate laboratory tests and field performance.

Laboratory tests for water susceptibility can be grouped into three mixture categories: loose, representative, and compacted.

- Loose mixture tests include soaking and boiling tests (e.g., ASTM D 3625) performed on loose or uncompacted mixtures.

- Representative mix tests are performed on a selected portion of the aggregate fraction (for example the fine aggregate). One example is the "pedestal freeze-thaw test."

- Compacted mix tests comprise most of the testing presently performed in the United States. The immersion compression (ASTM D 1075), Root-Tunnicliff (ASTM D 4867), and Lottman (AASHTO T 283) tests are the most widely used. AASHTO T 283 with 6-inch diameter samples is part of the volumetric mixture design protocol for Superpave.

- Also under the compacted mix category, the environmental conditioning system (ECS) developed in the SHRP research and the Hamburg wheel tracking device are the latest group of tests to be introduced to assess the moisture susceptibility of HMA mixtures. A common feature among these two tests is that they attempt to simulate field conditions. The ECS simulates field conditions by simultaneously applying repeated loads and moisture flow while the Hamburg device applies repeated tire loads over a submerged HMA sample.

Important features of a water sensitivity test include: compaction of the HMA to an air void content typical of that which is achieved at the time of construction (six to eight percent), ensuring that the sample is exposed to water (using a vacuum saturation procedure), and exposing the sample to a severe test environment (freeze-thaw cycle or cycles). Recent developments through the ECS and Hamburg tests attempted to incorporate simulations of field loading conditions into the laboratory testing process.

It is important that the air voids and the degree of saturation be controlled in whatever test method is used. The vacuum saturation level and freeze-thaw cycles to stress the bond at the interface of the asphalt binder and aggregate must also be controlled. Figure 4 indicates the importance of the freeze-thaw cycle, Figure 5 the effect of multiple freeze-thaw cycles, and Figure 6 the importance of controlling the saturation level.

Figure 7 summarizes the findings of the 1991 survey of states and provinces in North America, which indicate that the AASHTO T 283 test with modulus or tensile strength ratio is the most effective method [Hicks (1991)]. The 2002 Colorado DOT survey also collected data on the type of test used to measure moisture susceptibility and the stage at which the test is conducted [Aschenbrener (2002)]. It was found that 87% of the agencies test the HMA mix for moisture sensitivity. Figure 8 presents the various testing techniques that the agencies use to evaluate moisture susceptibility of HMA mixtures. Figure 9 shows the stage at which the agencies test for moisture susceptibility: 62% test at the mix design stage only and 38% test at both the mix design and construction stages. The survey also concluded that 20% of the agencies continue to fund research on moisture damage of HMA mixtures.

Based on the 1991 and 2002 surveys, the AASHTO T 283 and other tensile strength ratio (TSR) tests are perceived to be the most effective. The AASHTO T 283 with a single freeze-thaw cycle is the best standardized test presently used in the United States. The use of multiple freeze-thaw cycles have shown to increase precision and to improve correlations with actual field performance. The percentages of agencies using the various tests, based on the 2002 survey, are summarized below:

- 82 % use tensile test (AASHTO T 283, ASTM D 4867, or similar),
- 10% use a compression test (AASHTO T 115 or similar),
- 4% use a retained stability test (typically the Marshall stability), and
- 4% use wheel-track tests (either the Hamburg or the APA) and tensile tests.

## LIME AS AN ANTISTRIP AGENT

A number of additives to reduce moisture sensitivity and stripping are used in the United States. Hydrated lime is widely used as an antistrip additive. Others include liquid additives (e.g. amines, diamines, and polymers), portland cement, fly ash, and flue dust. Pavement contractors usually prefer liquid antistrip additives as they are relatively easy to use. Figure 10 shows results from the freeze-thaw pedestal test indicating the relative antistripping properties of various types of additives. These data show that some liquid antistrip additives reduce the resistance of HMA mixtures to moisture damage. Figure 11 shows the results of Lottman tests on Nevada HMAs, which contain different types of antistrip additives [Epps (1992)]. The higher retained strength after Lottman conditioning when hydrated lime is added illustrates its value in reducing moisture damage.

Figure 12 illustrates that the relative effectiveness of liquid antistrip agents and lime depends on the aggregate type and the test method used to evaluate the HMA [Kennedy and Ping (1991)]. In general, the more severe the laboratory test method, the more demonstrable the differences between lime and liquid antistrip agents.

The relative effect of lime versus various liquid antistrip agents in Georgia HMA mixtures is shown in Table 1 [Collins (1988)]. The conditioned samples reported in this table were subjected to vacuum saturation without freeze-thaw cycles. Values reported are state-wide average values. In all but one case, lime outperformed the other antistripping agents.

Colorado used the Hamburg wheel tracking device to evaluate the relative effectiveness of different types of antistripping agents (Table 2). The addition of hydrated lime produced mixtures that passed the test acceptance criteria for all four HMAs. Some of the liquid antistrip agents did not produce satisfactory results [Aschenbrener and Far (1994)].

A study conducted by Oregon State University for the Oregon DOT demonstrated that both fatigue and rutting resistance can be improved with lime [Kim et. al., (1995)]. Figure 13 indicates that the addition of hydrated lime will increase the fatigue life of a pavement as determined by a laboratory fatigue test. Figures 14 and 15 show that lime reduces permanent deformation or rutting of pavements. These data also indicate that lime performs better than liquid antistrip materials.

Results of laboratory studies on California aggregates are shown in Figures 16 and 17 [Epps (1992)]. The antistrip benefits of adding lime to these aggregates and this asphalt binder are evident. The modified Lottman test (AASHTO T 283) was used in this study.

Results of a survey of perceptions of the effectiveness of various antistripping agents are shown on Figure 18 [Hicks (1991)]. Lime has a higher effectiveness rating than liquid antistrip agents (amines), polymers, and portland cement.

Georgia DOT conducted a field evaluation program involving more than 125 paving projects [Watson (1992)]. Core samples (of lime-treated HMA) were obtained from these projects and a visual evaluation of stripping was made--see Table 3. Some of these cores were from pavements more than 10 years old. Average tensile strengths of these core samples are shown on Figure 19. The effectiveness of lime as an antistripping agent is demonstrated by the constant level of the tensile strength of the field cores as a function of pavement age.

Virginia conducted field evaluations of pavements that were three to four years old—see Figure 20 [Maupin (1995)]. Of the 12 pavements included in the study, the pavements in which lime was used as an antistrip 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 HMA sections displayed lower water sensitivity than the sections that were treated with chemical liquid additive. Two years later, a different set of pavements were sampled and evaluated after five to six years of service [Maupin (1997)]. Results from this study indicate little difference between the lime-treated and liquid-anti-strip-treated HMA sections as shown in Figure 21. However, this study was conducted on non-experimental test sections – in contrast to the earlier, more scientifically-structured and well-designed study.

Tarrer (1996) investigated the bitumen-aggregate bond and concluded that, in the field, the water at the surface of the aggregate has a high pH and therefore most liquid antistrip agents remain at the surface because they are water soluble at high pH levels. To overcome being washed away, the liquid antistripping agents must be given time to cure (in excess of three hours). In contrast, hydrated lime cures rapidly (within 15 to 30 minutes) and forms water insoluble compounds. Hydrated lime creates a very strong bond between the bitumen and the aggregate, preventing stripping at all pH levels. Tarrer also found that hydrated lime reacted with silica and alumina aggregates in a pozzolanic manner that added considerable strength to the mixture.

In 1996 Ishai and Craus compared the impact of six different fillers on the durability of HMA mixtures under moisture conditioning [Ishai and Craus (1996)]. The durability index was defined as the average strength loss area enclosed between the durability curve and initial strength line. The researchers found that mixtures with non-active fillers are much more sensitive to binder contents than mixtures with active filers. Using the relationships between durability index and binder contents for the various fillers, the researchers recommended the optimum binder contents for the various fillers to achieve the optimum durability of the mixture. The data in Table 4 indicate that by using hydrated lime as a filler in HMA mixtures, the optimum binder content for maximum durability is a minimum of 0.5% lower than any other filler. This reduction in the optimum binder content translates into direct construction cost savings.

Tahmoressi reported on a Texas DOT study to evaluate the impact of lime treatment on the performance of limestone mixtures in Texas under the Hamburg wheel tracking device [Tahmoressi (2002)]. 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 percent 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 HMA mixtures to rutting under the Hamburg wheel tracking device conducted by the Texas DOT. TxDOT uses a Hamburg failure criterion of a 12.5 mm rut depth under 20,000 load cycles. Table 5 summarizes the TxDOT data which indicate that limestone, gravel, and igneous aggregates all show significant increase in the number of mixes passing the TxDOT Hamburg criterion by the addition of lime regardless of the binder grade.

The South Dakota DOT compared the performance of various antistrip additives on two field projects [Sebaaly et al. (2003)]. Each project included a control section and five sections treated with lime, liquid, and ultrapave (UP) additives. Figures 22 and 23 show the performance of the field mixtures under multiple freeze-thaw cycling in the laboratory. The resilient modulus (Mr) is an engineering property that describes the stress-strain relationship of the HMA mix. A reduction in the Mr property under multiple freeze-thaw cycling leads to an increase in the strains experienced by the HMA mixture due to traffic induced stresses. As the HMA pavement is subjected to higher strains, its tendency to experience rutting and fatigue cracking would increase. The data show that mixtures treated with hydrated lime performed significantly better than the control, UP5000, and the liquid antistrip mixtures at both locations.

Moisture damage was identified as the cause of failure of HMA mixtures with two different aggregates at the Logan International Airport in Boston. The impacts of lime treatment of the two mixtures and an additional mixture with a third aggregate were evaluated using multiple freeze-thaw cycling and loading under the Model Mobile Load Simulator 3 (MMLS3) [Mallick et al. (2005)]. The MMLS3 subjects the six-inch diameter samples to repeated tire loads of 607 lbs and 100 psi while submerged under 140oF water. The tensile strength (TS) property was used to measure the impact of both multiple freeze-thaw cycling and the MMLS3 trafficking. Table 6 shows that the addition of hydrated lime significantly improved the unconditioned and conditioned TS and TSR of mixtures. It was concluded that lime treatment was effective in improving the resistance of the mixtures to moisture damage induced by hot-wet trafficking (MMLS3) and under multiple freeze-thaw cycling.

In 2005 the Idaho DOT constructed a field project on SH67 to evaluate the impact of lime and liquid antistrip on the mechanical properties of an Idaho HMA mix [Sebaaly et al. (2005)]. Both the lime and liquid mixtures were evaluated under multiple freeze-thaw cycling in the laboratory as shown in Figure 24. The lime mix started at a higher dry Mr property and maintained good modulus properties over the entire 21 freeze-thaw cycles. The liquid mix fully disintegrated after 22 freeze-thaw cycles. The results of a mechanistic analysis summarized in Table 7 show that, as a result of multiple freeze-thaw cycling, the liquid mix will have 220 percent increase in potential rutting as compared to the lime mix having only 65 percent potential increase in rutting. Table 8 summarizes the following mechanical properties of the lime and liquid mixtures:

- Dynamic modulus in compression as an indicator of rutting resistance
- Dynamic modulus in tension as an indicator of moisture damage
- Rate of dynamic creep as an indicator of fatigue resistance

Based on the mechanical properties of the lime and liquid mixtures at the moisture conditioned and unconditioned stages, the researchers concluded that the lime mix is stiffer, less susceptible to rutting, and less susceptible to moisture damage while having similar fatigue cracking compared to the liquid mix.

A recent study by the North Carolina DOT evaluated the use of lime as an anti-strip additive for mitigating moisture sensitivity of asphalt mixes containing baghouse fines (BHF) [Tayebali and Shidhore (2005)]. The NCDOT uses a tensile strength ratio of 85% as a failure criterion following the AASHTO T-283 method without the freeze-thaw cycle. Figure 25 shows that the use of 1.0 percent hydrated lime improved the TSR ratios of mixtures from the high 60s to the 85-95 percent range which comply with the NCDOT TSR criterion. The researchers used the simple shear tester to measure the permanent shear strains under 5,000 cycles of shear stresses and used the measured shear strains to estimate rut depth. The data in Table 9 show that the lime treatment of the mixtures reduced the estimated rut depth at the dry and wet stages.

## EXTENDED BENEFITS OF LIME IN HMA

Not only does the addition of lime provide antistripping benefits, but it also:

1. Acts as a mineral filler to stiffen the asphalt binder and HMA;
2. Improves resistance to fracture growth (i.e., improves fracture toughness) at low temperatures;
3. Favorably alters oxidation kinetics and interacts with products of oxidation to reduce their deleterious effects; and
4. Alters the plastic properties of clay fines to improve moisture sensitivity and durability.

The filler effect of the lime in the asphalt reduces the potential of the asphalt to deform at high temperatures, especially during its early life when it is most susceptible to rutting. The hydrated lime filler actually stiffens the asphalt film and reinforces it. Furthermore, the lime makes the HMA less sensitive to moisture effects by improving the aggregate-asphalt bond. This synergistically improves rut resistance. As the HMA ages due to oxidation, hydrated lime reduces not only the rate of oxidation but also the harm created by the products of oxidation. This effect keeps the asphalt from hardening excessively and from becoming highly susceptible to cracking (through fatigue and low temperature (thermal) cracking). Synergistically, the filler effect of the hydrated lime dispersed in the asphalt improves fracture resistance and further improves cracking resistance.

In addition to these benefits, adding hydrated lime to marginal aggregates that have plastic fines can improve the aggregate through the mechanisms of cation exchange, flocculation/agglomeration, and pozzolanic reactions. These reactions result in a change in the characteristics of the fines so that they are no longer plastic but act as agglomerates held together by a “pozzolanic cement” [Little (1987)]. This process makes the aggregate fines much less susceptible to moisture by reducing their ability to attract and hold water.

## THE BENEFITS OF HYDRATED LIME AS A MINERAL FILLER AND IN MITIGATING THE EFFECTS OF OXIDATIVE AGING

This section presents research on the multifunctional benefits of hydrated lime in more detail. Research has been conducted throughout the world--in the United States, Europe, Australia, and South Africa.

### UNITED STATES RESEARCH

Figures 16 and 17 indicate that the addition of hydrated lime to HMA increases stiffness [Epps (1992)]. This helps to distribute and reduce the stresses and strains in the pavement structure created by traffic loads and generally reduces rutting (permanent deformation) potential. The results of laboratory wheel tracking tests conducted in Colorado (Table 2) and Georgia (Table 10) indicate that hydrated lime increases resistance to rutting and permanent deformation [Aschenbrener and Far, (1994) and Collins et al., (1997)]. Creep tests in Texas (Table 11) also clearly show that hydrated lime promotes high temperature stability, thereby increasing resistance to rutting [Little (1994)].

The mineral filler effect on asphalt is shown in Figure 26 and indicates that lime substantially increases the stiffness of asphalt cement binders. The property represented in Figure 26 is the parameter

G*/sin δ, which has been adopted by the Superpave performance grade (PG) system for asphalt binders as an indicator of rut resistance. An increase in this parameter increases the stiffness of the HMA and reduces the rutting potential. The increase in stiffness of the asphalt binder also increases resistance to water susceptibility. The synergistic effects of moisture resistance and improved stiffness are demonstrated by the creep test results in Figure 27. The experiment used a siliceous aggregate from Natchez, Mississippi treated with a lime slurry in the stockpile - a marination process. The stockpile was about 90 days old when it was used to produce the HMA. The creep tests were conducted after the mix was subjected to vacuum saturation. The untreated mix is extremely moisture susceptible and creeps at an accelerated rate (tertiary creep) after about 2,500 seconds of loading. The lime-treated mix maintains excellent creep properties (maintaining steady state behavior) and never enters tertiary creep.

Research studies conducted in the 1990s evaluated the impact of lime on the improvements in high temperature performance (rutting resistance), fatigue cracking resistance, and low temperature fracture [Little (1996), Lesueur et al. (1998), and Lesueur and Little (1999)]. These studies concluded that:

1. Hydrated lime is not simply an inert filler but reacts with the bitumen. The lime particles actually adsorb polar components of the bitumen. This adsorbed inter-layer makes hydrated lime a very effective additive. The level of the bitumen-lime reaction was found to be bitumen dependent.
2. The “active” filler effect has a graduated temperature sensitivity. At high temperatures the filler effect is most pronounced; it is considerably less at temperatures near the glass transition of the bitumen. This very positive characteristic allows the bitumen to resist flow-damage at high temperatures and yet to relax at low temperatures, dissipating energy by flow in lieu of fracturing.
3. A physico-chemical interaction between the hydrated lime and the bitumen can be verified by (a) rheological models, (b) nuclear magnetic resonance, and (c) scanning electron microscopy.
4. The physico-chemical interaction is a fundamental mechanism that provides a basis to explain the multifunctional effects of lime in bitumen. These effects include: (a) improved rut resistance (Figure 28), (b) improved low-temperature fracture toughness (Figure 29), and (c) improved fracture fatigue resistance (Figure 30).

Extensive research at the Western Research Institute (WRI) shows that age hardening of asphalt binders can be reduced by the addition of hydrated lime [WRI (1997)]. In 1987, Petersen et al. evaluated two asphalt binders modified with limestone and hydrated lime at 20 percent by weight of binder. The untreated and treated binders were aged at 113$^{o}$C in the thin film accelerated aging test. Table 12 summarizes the high temperature properties of the untreated and treated binders. For both binders, the addition of hydrated lime increases the un-aged complex modulus, reduces the aged complex modulus, and significantly reduces the aging index (Figure 31). Table 13 summarizes the measured low temperature properties of the untreated and treated aged binders from the same experiment. In both cases, the lime treatment of the binders almost doubled the percent elongation of the aged binders while it maintained similar modulus to the untreated binder. This translates in significant improvements in the resistance of the aged binders to thermal cracking. The results of this research indicate that lime treatment would improve the resistance of fresh pavements to permanent deformation through an increase in the un-aged high temperature complex modulus and improves the resistance of the aged pavement to thermal cracking through the reduced aging index. Since the behavior of HMA mixtures at low temperatures is mainly controlled by the properties of the aged binder, lime treatment would produce HMA pavements that are highly resistant to thermal cracking.

In other research efforts, the WRI researchers attempted to resolve some of issues surrounding the laboratory testing of recovered asphalt binders from field-aged mixtures [Huang et al. (2002) and Huang and Robertson (2004)]. Extracting and recovering an asphalt binder from a lime-treated HMA mixture using powerful solvents would destroy any lime-induced molecular structuring that may be present in the mix. Another question would be where does the lime go after the binder is recovered. Furthermore, there is no assurance that the rheological properties measured in the recovered asphalt binder are representative of the actual in-place properties of the lime-treated asphalt in the pavement. In light of these issues, the WRI researchers aged the untreated and lime-treated binders in the pressure aging vessel (PAV) at 60$^{O}$C to simulate the temperature ranges encountered in the field. The PAV aging intervals were for 100, 400, 800, and 2000 hours. The rheological properties of the un-aged and aged binders were measured at 25$^{O}$C and 60$^{O}$C and 10 rad/s. Two asphalt binders and two grades of hydrated lime were used in the study. Both binders were treated with 20 percent by weight of binder with the two grades of lime. Figure 32 presents the relationship between aging time and aging index which is defined as the ratio of the viscosity after PAV aging over the viscosity before aging. The data in Figure 32 indicate that the lime was highly effective in reducing the aging index of the AAD-1 binder. Lime treatment was not as effective with the ABD binder which is not a typical binder. It is well recognized that lime treatment would improve the aging characteristics of most asphalt binders.

The WRI research adds further credibility to the bitumen-hydrated-lime interaction. WRI’s research demonstrates that carboxylic acids in bitumens hydrogen bond very strongly with hydroxyl groups on siliceous aggregates. However, the hydrogen bonds are very sensitive to disruption by water. Conversion of carboxylic acids within the bitumen to insoluble salts prior to mixing with aggregate should prevent adsorption of the water-sensitive free acids on the aggregate. WRI further notes that the conversion of all acidic materials in the bitumen to water-insensitive calcium salts at the time of bitumen production would be preferred.

Furthermore, this reduction in hardening has been confirmed in a field study conducted by the Utah DOT (Figure 33) [Jones (1997)].

Buttlar et al., (1999) used micromechanics to assess the mechanical properties of mineral fillers combined with bitumen to form mastics. They concluded that a rigid layer adsorbed to the filler explains the ability of the filler to result in stiffening ratios that are greater than would be predicted based on volumetric concentrations alone. Based on the equivalent rigid layer analysis, physico-chemical reinforcement effects play a dominant role throughout the range of filler-to-bitumen ratios encountered in practice. Hydrated lime shows a much higher level of physico-chemical reinforcement than baghouse fillers. They further conclude that the surface activity of hydrated lime--and hence physico-chemical stiffening potential--is quite high and that the flaky shape and rough surface texture of hydrated lime also contribute to stiffening effects which exceed those predicted by volume-based models. The work of Buttlar et al., (1999), Lesueur, Little and Epps (1998), Lesueur and Little (1999), Hoppman (1998), and Vanelstraete and Verhasselt (1998) are consistent and in agreement on this topic.

Johannson (1998) performed an extensive review of the literature of lime in bitumen and conducted additional research on the reaction of hydrated lime with bitumen. Some of Johannson's most significant findings are:

1. Adding 20 percent hydrated lime by mass of binder produces a significant increase in creep stiffness but does not increase physical hardening. Furthermore, the lime-modified bitumen demonstrates a greater potential for dissipating energy through deformation (at low temperature) than the unmodified bitumen. This is a positive effect at low temperatures because it reduces fracture potential.
2. Although the filler effect increases low temperature stiffness, fracture toughness is substantially increased. Fracture toughness is the energy expended in fracturing a material. Lesueur and Little (1999) also demonstrated that at low temperatures lime does not negatively impact relaxation but substantially increases fracture toughness.
3. Hydrated lime reduces the effects of age-hardening more so at high temperatures than at low temperatures.

Little and Petersen (2005) synthesized several decades of research considering the rheological and mechanical contributions imparted to asphalt mixtures by the addition of hydrated lime. They concluded that due to its chemical activity, hydrated lime added as part of the mineral filler, improves stiffness at high temperatures while toughening mixes at low temperatures. Mixtures containing hydrated lime can accommodate more fatigue than either unfilled systems or those containing equivalently sized limestone. They observed that "the impact of hydrated lime as a filler and its proven ability to resist damage is probably due to a complex interaction of effects related to a physical filler and the way in which hydrated lime affects the micro-structural nature of the bitumen."

## EUROPEAN RESEARCH

### French Research

French researchers recognize the effects of hydrated lime in HMA in improving stiffening as well as the aggregate-asphalt bond. The Jean Lefevre-Metz Company and the Laboratoire Central des Ponts et Chaussées (LCPC) in Saint Quentin, verified that hydrated lime makes asphalt road courses more stable and reduces rutting [Mauget (1998)].

### German Research

The practical effectiveness of hydrated lime in HMA to improve moisture sensitivity and stiffening is accepted in Germany. Field research on two road sections (L 280 near Grevenbroich and B 7N near Wuppertal-Dornap) confirms that the addition of 1.0 to 1.5 percent hydrated lime by weight of the mixture can substantially improve rut resistance [Radenberg (1998)]. Figure 34 illustrates the results of wheel tracking tests from the Wuppertal-Dornap pavements.

### Belgian Research

The Centre de Recherches Routiéres (CRR) in Belgium has verified that lime creates a significant improvement in adhesion between binders and aggregates [Verhasselt (1996)]. CRR also identifies an improvement in resistance to the effects of oxidative hardening [Verhasselt & Choquet (1993)].

The most significant research in Belgium monitored 15 test zones on the wearing course of the N5 between Neuville and Mariembourg for up to 10 years following construction [Choquet & Verhasselt (1993)]. In cooperation with a Dutch workgroup, Belgian researchers determined that after about seven years the asphalt zones that had been modified with hydrated lime were in significantly better condition than zones made with unmodified conventional bitumens. (The zones in which hydrated lime was used performed comparably with zones where a polymer-modified bitumen was used.)

Vanelstraete and Verhasselt (1998) compared the effects of hydrated lime with limestone of identical size and gradation. Rheological measurements were made prior to and following aging of the mastic. Their conclusions are in close agreement with Lesueur, Little, and Epps (1998) that hydrated lime reduces temperature susceptibility of the mastic, that mastics with hydrated lime are significantly stiffer at higher temperatures than the limestone-filled mastics (whereas little stiffness difference exists at low temperatures), and that lime's active filler effect is graduated until it becomes highly effective at high temperatures. They document an increase in stiffness modulus of about 50 percent at 60°C. Their study also shows that the increase in stiffness modulus subsequent to construction aging is considerably smaller for the mastics with hydrated lime than for those with the identically-sized limestone filler. The effects of hydrated lime are especially important for wearing courses and porous asphalt mixtures where deterioration by aging is one of the main causes of road deterioration.

## Czech Research

The Institute for Road Construction in Prague studied the influence of hydrated lime on HMA and constructed several test pavement sections to determine the long-term behavior of hydrated lime in HMA [Luxenburk (1998)]. About 18.5 percent hydrated lime by weight of the binder was added to mixtures and tested with the Nottingham Asphalt tester and by rutting tests. The results clearly show that hydrated lime improves stability and increases rutting resistance due to the filler effect, especially at elevated temperatures of between 30°C and 40°C.

## Dutch Research

The Netherlands stipulates the use of hydrated lime in some porous asphalt mixes largely to prevent sedimentation in these high asphalt binder content mixtures. In a research program at the Technical University Delft, stripping and Marshall stability tests were performed on different types of bitumens and aggregates with various contents of hydrated lime [Hopman (1996)]. All specimens containing hydrated lime show less stripping and improved stability. The best results were in mixtures where the mineral filler fraction (typically seven percent by weight of the mixture) contains 10 to 15 percent (of the filler fraction) hydrated lime. In the Netherlands, hydrated lime is typically added to hot mix as a component of the mineral filler fraction. After mixing, not all of the hydrated lime is in "direct" contact with the surface of the aggregate, but some becomes part of the binder itself. To ensure development of the necessary bond strength between the asphalt binder and the aggregate, fillers with a higher portion of hydrated lime (approximately 25 percent by weight) are used for porous asphalts. (For traditional dense-graded mixes, the hydrated lime portion of the filler is about 10 percent.) The Dutch researchers believe that the improved bond between the asphalt and aggregate is the primary cause of improved performance.

Some of the most powerful research in recent years to demonstrate a lime-bitumen interaction was performed by Hopman et al., (1998). Results are similar to those reported by Lesueur, Little, and Epps (1998). Hopman et al., used light absorption measurements and gel-permeation chromatography (GPC). Both methods show a significant change in generic composition of the bitumen after the addition of lime--indicating that lime is an "active" filler.

### Spanish Research

Researchers in Spain and Argentina recently compared the impact of hydrated lime on the aging characteristics of asphalt binders and mixtures [Recasens et al. (2005)]. The aging process consisted of placing the compacted HMA sample in the oven at 80$^{o}$C for 0, 2, 4, and 7 days. The asphalt binder was extracted from the HMA mix after 2 and 7 days of oven aging and tested for penetration, absolute and kinematic viscosities, and softening point. Table 14 summarizes the properties of the recovered aged binder which show that the hydrated lime significantly reduces the aging rate of the asphalt binder. The study also evaluated the impact of hydrated lime and calcium carbonate on the aging rate of HMA mixtures. The impact of aging on the brittleness of the HMA mix was evaluated through a direct tension test on a notched Marshall sample at 20$^{o}$C. The specific energy of fracture was obtained as the area under the load displacement curve divided by the area of the fracture of the sample. A higher specific energy of fracture indicates a more brittle HMA mix with a lower resistance to cracking. The data showed that after 7-days of oven aging, the HMA mix with hydrated lime had a specific energy of fracture that is 10 and 30 percent lower than the un-filled mix and the mix with calcium carbonate, respectively. The combination of lower binder properties and lower specific energy of fracture with time indicates the protective characteristics of hydrated lime against aging which ensures a better long term durability of the HMA mix.

## PLASTICITY OF FINE AGGREGATE AND COATINGS

Aggregates that are used for HMA can contain plastic clays and clay coatings. While generally not desirable, economic considerations sometimes dictate their use in HMA. Lime is an effective chemical additive for reducing the plastic characteristics of clay soils and is commonly used for treating soils with plasticity index above about 10 [NLA (1999)]. Ion exchange on the clay surface (involving calcium ions), flocculation and agglomeration of the clay minerals, and pozzolanic reactions are responsible for the effectiveness of lime [Little (1995)].

## EFFECTIVENESS OF LIME IN COLD IN-PLACE RECYCLING

Recycling of the existing pavement offers an attractive approach for effectively dealing with the distressed pavement surface. A severely cracked pavement presents a challenge for the design engineer due to its potential of reflecting the cracks through the new overlay. Recycling of the existing surface would delay the problem of reflective cracking and a strong base would result in the requirement of a thinner overlay.

Cold in-place recycling (CIR) is defined as the pulverization of the top 2" – 3" of the existing HMA layer, mixing it with emulsion and repaving the mix on the site. The objectives of the CIR process can be summarized as follows:

- Reduce the brittleness of the aged existing mixture,
- Provide a mixture with enough stability for early traffic, and
- Improve the moisture sensitivity of the mixture.

Achieving the above objectives is critical since any HMA mixture selected for CIR is expected to have experienced moisture damage and/or aging. The combination of these two conditions results in a CIR mixture that is highly susceptible to moisture damage. Several laboratory and field studies have shown that the addition of hydrated lime to CIR mixtures significantly improves their early stability and moisture sensitivity.

Cross evaluated the impact of hydrated lime slurry on the moisture sensitivity of CIR mixtures in Kansas [Cross (1999)]. The AASHTO T-283 with one freeze-thaw cycle was used to moisture condition the tensile strength and resilient modulus samples. Figure 35 shows the retained tensile strength and resilient modulus ratios (i.e. ratio of conditioned over unconditioned property) of the various CIR mixtures. The data show that the hydrated lime slurry has a significant impact on the retained tensile strength ratio while not as significant on the retained resilient modulus ratio except for the high float emulsion where the hydrated lime slurry showed a significant impact on both ratios. The research also evaluated the impact of hydrated lime slurry on the rut resistance of CIR mixture as measured in the asphalt pavement analyzer (APA) at the dry and underwater conditions. Figure 36 presents the increase in rut depth from the dry to the underwater conditions which shows the significant impact of the hydrated lime slurry in reducing the percent change in the rut depth of the CIR mixtures.

As a follow-up to this study, the Kansas DOT constructed field test sections in 1997 to evaluate the long-term performance of CIR mixtures treated with lime slurry and fly ash [Fager (2004)]. The Kansas researchers concluded the following: "The fly ash section cracked soon after construction and had more cracking than the lime slurry section. Cracking in the lime slurry section occurred much later….the lime slurry section outperformed the fly ash test section."

In the late 1990s, the Nevada DOT started looking into recycling most of the low-medium volume roads. A mix design procedure for CIR mixtures was developed to provide early stability and resistant to moisture damage [Sebaaly et al. (2004)]. Table 15 summarizes the mix design data from three different CIR projects. A good level of early stability was defined as an Mr value above 150 ksi, and a good resistance to moisture damage was defined as a retained-strength ratio above 70%. Based on the mix designs data in Table 15, the Nevada researchers concluded that in order to achieve early stability and to improve resistance of the mixtures to moisture damage, lime treatment of the CIR mixtures was needed. Currently, Nevada DOT mandates the use of lime in all CIR mixtures which has led to excellent field performance [Sebaaly et al. (2004)].

## IMPACT OF LIME ON THE MECHANICAL PROPERTIES OF HMA MIXTURES

Mechanical properties of HMA mixtures play a major role in pavement design, analysis, and performance. They govern the relationships between traffic loads and pavement responses and the long term performance of pavement structures under the combined action of traffic and environment. Typical mechanical properties of HMA mixtures include the modulus as a function of temperature and loading rate, and fatigue and rutting performance relationships. As the pavement engineering community moves closer to the implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG), the knowledge of the mechanical properties of HMA mixtures becomes a high priority.

An ideal HMA mix can be characterized as having good modulus properties under the anticipated field conditions and excellent fatigue and rutting resistance. When such an ideal mix is incorporated into a mechanistic-based pavement design, excellent long term performance can be realized along with significant cost savings. Several materials and mix design factors influence the magnitude of the mechanical properties of HMA mixtures, such as: binder grade, aggregate gradation and quality, volumetric properties of the mix, and any modifications to the binder or the aggregate. Lime treatment of HMA mixtures has been shown to positively influence the mechanical properties of HMA mixtures.

Researchers at Texas A&M University evaluated the impact of rest periods on the healing of HMA mixtures [Si et al. (2002)]. Different rest periods were introduced into the uniaxial fatigue testing of untreated and lime treated mixtures with river gravel and crushed limestone mixtures from Texas. It is believed that rest periods during fatigue testing better simulate field conditions since repeated traffic loading in the field always occurs after the pavement has time to recover. The healing index was defined as the percent increase in the stiffness of the HMA mix after the introduction of the rest period. The researchers concluded that the degree of healing is mixture dependent and the ability of a mixture to heal is largely related to binder properties. The addition of hydrated lime to the mixtures tested generally improved the healing potential of the mixtures.

Little and his colleagues used the torsional fatigue test to evaluate the impact of lime treatment on the fatigue life of sand asphalt mixtures [Little and Kim (2002) and Kim et al. (2003)]. The data in Table 16 show that the effect of hydrated lime as a filler increased the high strain fatigue life of the sand asphalt mix with binder AAD-1 by approximately 240 percent and the fatigue life of the sand mix with binder AAM-1 by approximately 100 percent. Researchers also used the cumulative dissipated energy as an indication of fatigue resistance which showed that the addition of lime increased the fatigue resistance by 588 and 442 percent for the AAD-1 and AAM-1 binders, respectively.

Researchers at the University of Nevada evaluated the impact of hydrated lime on the mechanical properties of HMA mixtures and assessed the differences among the various lime application techniques [McCann and Sebaaly (2003)]. Three different mixtures were evaluated with four lime application methods along with a control mix (i.e. no-lime). The four methods of lime applications were: dry lime on moist aggregates with and without 48 hours marination and lime slurry with and without 48 hours marination. Table 17 summarizes the data based on the resilient modulus, tensile strength, and resistance to permanent shear strains. It should be noted that the label "NOT DIFFERENT" means that the no-lime mix has similar property to the lime- treated mix and the label "DIFFERENT" means that the no-lime mix has a property that is significantly lower than the lime-treated mix. The data in Table 17 indicate that prior to moisture conditioning, the two mixtures had similar mechanical properties in the majority of the cases. However, when the mixtures were moisture conditioned with one or 18 freeze-thaw cycles, the mechanical properties of the no-lime mixtures were significantly lower than those of the lime-treated mixtures. In addition, the study concluded that the four methods of lime applications did not have any significant impact on the mechanical properties of the HMA mixtures.

In an effort to incorporate lime-treated HMA mixtures into the AASHTO MEPDG, Bari and Witczak measured the effect of lime on the dynamic modulus (E*) of HMA mixtures [Bari and Witczak (2005)]. The AASHTO MEPDG uses E* as the primary material property for HMA mixtures. Therefore, any impact of lime-treatment on the E* property of HMA mixtures will introduce changes in the design of the pavement structure. The research measured the E* properties of seventeen different mixtures sampled from six different project sites across the United States: six mixtures contain no lime and eleven mixtures had hydrated lime up to 3% by dry weight of aggregate. The data in Table 18 show that the addition of hydrated lime increases the dynamic modulus of the HMA mix between 17 and 50 percent. The researchers concluded that the E* of a lime treated HMA mixture (1-2% lime) will be approximately 1.25 times the E* of untreated mixtures independent of temperature and/or time rate of load.

Significant increases in the modulus, fatigue and rut resistance of the HMA mix leads to reduced layer thickness and better long term performance. In the mechanistic pavement design process, the effects of an increased modulus and improved resistance to fatigue and rutting are accumulated exponentially. In other words, the higher modulus would result in lower strains in the HMA layer. When the lower strains are introduced into the improved fatigue and rutting relationships, a significant improvement in the performance of the pavement is realized.

## IMPACT OF LIME ON PAVEMENT LIFE AND LIFE CYCLE COSTS

The impact on pavement life and its life cycle costs is the ultimate measure by which the effectiveness of an additive can be assessed. Regardless of how effective the additive is in improving the properties of the various components or the entire HMA mix, the ultimate challenge is to construct a less expensive pavement that will last longer. Therefore, the final link in assessing the effectiveness of lime on HMA pavements is to take the improvements that lime introduces on the various components and translate them into extension in pavement life and lower life cycle costs. This task is huge and requires evaluating multiple levels of material properties, pavement designs, and long term field performance. Currently, there are two studies that have attempted to achieve such a goal using two different approaches. These studies are summarized below.

Hicks and Scholz developed a life cycle cost analysis (LCCA) model to compare the life cycle costs for HMA pavements with and without lime [Hicks and Scholz (2003)]. The researchers surveyed ten state DOTs and collected data on the following topics: reasons for using lime in HMA mixtures, the cost of adding lime in HMA mixtures, and the field performance of HMA mixtures. Table 19 presents the reasons identified by the various DOTs for the use of Lime in HMA mixtures. Reducing stripping was the most important attribute of using lime in HMA mixtures for all DOTs followed by altering the properties of fines. Improve aging resistance, stiffening the binder, and improve fracture toughness were ranked as lower importance which may be a direct result of the lack of information on the impact of lime on these properties.

Table 20 lists typical costs of adding lime into HMA mixtures in terms of the added cost per ton of mix. The cost of adding lime does not significantly vary among locations, but it significantly varies between non-marinated and marinated mixtures.

The research developed a computerized LCCA model that incorporates initial costs, maintenance costs, and salvage values along with the performance of HMA pavements with and without lime to compare the effectiveness of adding lime. Table 21 summarizes the deterministic LCCA of HMA pavements with and without lime on interstates and state highways in the ten surveyed states. The study was based on data gathered from states that use lime to treat HMA mixtures with known stripping problems. The LCCA data showed that the antistripping benefits of using lime in HMA mixtures results in a wide range of savings with an approximate average saving of $2.00/yd$^2$. This translates into an approximate saving of $20/ton of HMA mix which compares very favorably with the average additional costs of using lime of $1.25/ton for non-marinated and $4.00/ton for marinated (ranges are presented in Table 21).

The researchers also conducted a probabilistic LCCA of HMA pavements with and without lime. The probabilistic analysis accounts for the inherent variabilities in materials properties and cost and in the predicted field performance. The probabilistic analysis showed similar results to the deterministic analysis with one additional finding: in 79 to 96 percent of the time, the life cycle costs of HMA pavements with lime are less expensive than the life cycle costs of HMA pavements without lime. In other words, there is a 79 to 96 percent chance that using HMA mixtures with lime will be less expensive than using HMA mixtures without lime.

Sebaaly and colleagues used the impact of lime on the performance of HMA mixtures in the laboratory and in the field to predict the impact of lime on pavement life [Sebaaly at al (2003)]. Lime treated and untreated pavement sections were sampled, and their properties were evaluated using laboratory tests. Pavement performance data from the pavement management system (PMS) were used to compare the field performance of lime-treated and untreated sections. Finally, the data from the laboratory evaluation of field sections were used in the AASHTO Pavement Design Guide to assess the impact of lime on the design life of flexible pavements in Nevada.

The laboratory portion of the research concluded that the lime treatment of Nevada’s aggregates significantly improves the moisture resistance of HMA mixtures. The study showed the lime-treated HMA mixtures become significantly more resistant to multiple freeze-thaw cycles than do the untreated mixtures. Lime-treated mixtures showed excellent properties for locations in the wheelpath and between the wheelpaths, which indicates that lime treatment helps HMA mixtures in resisting the combined action of environmental and traffic stresses.

The field portion of the research used PMS data to compare the field performance of projects that were constructed with untreated and lime-treated mixtures. The common feature among the projects that were compared is that they were constructed on the same highway facility, which implies that they received the same traffic and environmental stresses. The performance of the projects was compared in terms of their present serviceability index (PSI) as developed from the AASHO Road Test. The PSI is presented on a scale of 0 to 5 with 4.2 rating representing a newly constructed flexible pavement and a PSI below 2.0 indicating a rough road in need of major rehabilitation. The performance of the untreated versus lime-treated pavements was evaluated using the following criteria:

1. Comparison of the change in average PSI value,
2. Comparison of the occurrence of the low PSI values, and
3. Comparison of the impact of the occurrence of the low PSI value on the average PSI value.

Criterion 1 represents the need to perform maintenance activities throughout the service life of the pavement. Criterion 2 represents the frequency of maintenance activities. Criterion 3 is introduced to assess whether the occurrence of a low PSI is an isolated event or a predominant one. For example, if the occurrence of the low PSI value did not affect the average

PSI, the low PSI value existed at an isolated milepost within the project, and it did not represent the conditions of the majority of the project. However, if the occurrence of the low PSI value affected the average PSI, the low PSI value existed on the majority of the mileposts within the project. This concept is clearly shown in Figure 37, in which low PSI values significantly affected the average PSI for the untreated mixture. For the lime-treated mixture, low PSI values did not affect the average PSI. This indicates that the low PSI value represented the conditions of the majority of the mileposts of the untreated mixtures, and the low PSI value on the lime-treated mixtures represented only an isolated milepost within the entire project.

Table 22 summarizes the field performance of the untreated and lime-treated mixtures in terms of the three established criteria and on the basis of the PSI trends of the untreated and lime-treated sections. The data in Table 22 were evaluated on the basis that a good-performing pavement section would have none to moderate reduction in the average PSI, none to moderate occurrence of low PSI, and an insignificant impact of the low PSI. Based on the pavement management system (PMS) data and the analysis summarized in Table 22, the researchers concluded that the lime-treated mixtures performed better than the untreated mixtures under all three criteria and for all the evaluated projects. From these findings, it was concluded that lime treatment of HMA mixtures in Nevada resulted in better-performing HMA pavements.

The last step in evaluating the performance of lime in HMA mixtures was to quantify its impact on the actual pavement life. To achieve this, the researchers used the data from the laboratory evaluation of the field projects in the AASHTO Guide for Design of Pavement Structures in conjunction with the following three assumptions:

1. The sixth freeze-thaw cycle was selected to represent the critical stage for the damage of HMA mixtures.
2. The percent reduction in the resilient modulus (Mr) is proportional to the percent reduction in the layer coefficient ($a_1$), except if the cores failed after the sixth freeze-thaw cycle, then the $a_1$ will be assigned a value of 0.1.
3. The reduced Mr exists during 4 month of the year and the weighted $a_1$ will be used to represent the relative strength of the HMA layer.

Table 23 summarizes the data generated from the structural design analysis. The step of converting the increase in the Equivalent Single Axle Loads (ESAL) into pavement life assumes that Nevada DOT expects an 8-year life from untreated HMA mixtures, and therefore any percentage increase in the ESALs due to lime treatment is directly converted into an increase in pavement life over the 8-year period.

On the basis of the data generated from the AASHTO design guide analysis and the trends shown by the PMS data, it was concluded that the lime treatment of Nevada’s HMA mixtures would increase the pavement life by an average of 3 years. This result represents an average increase of 38% in the expected pavement life, which compares very favorably with the percent increase in the cost of HMA mixtures of 10% ($4/ton) due to lime treatment of aggregates and the 48-hours marination that is mandated by the Nevada DOT.

In 1995, the Texas DOT formed a joint industry-TxDOT task group to identify issues associated with the unsatisfactory performance of HMA pavements made with crushed siliceous gravel aggregates in northeast Texas [Tahmoressi and

Scullion (2002)]. The task group made several recommendations to improve the performance of such pavements. One of these recommendations is to require antistrip agent in all mixtures. As a result of this recommendation, several HMA pavements were constructed in northeast Texas with both liquid antistrip and lime additives.

In 2001, the task group evaluated the performance of 38 HMA pavements in northeast Texas using both the Hamburg wheel tracking device and visual performance surveys. Table 24 summarizes the findings of the 2001 evaluations. In this table the data is separated into three groups [Tahmoressi and Scullion (2002)]. The first group contains all of the pavements that had less than 5 mm rut depth. The second group shows pavements with a rut depth of more than 5 mm, but less than 12.5 mm. The third group contains all projects with more than 12.5 mm rut depth. At the time of evaluation, TxDOT used a maximum allowable rut depth in the Hamburg test of 12.5 mm.

Tahmoressi and Scullion concluded: “The majority of pavements in the first group (less than 5 mm rut depth) contained lime. Only two pavements with lime did not fall in this group. These two pavements had 6.1 and 8.0 mm of rutting, two of the better performers in the second group. The pavements in the second group (rut depth between 5 and 12.5 mm) displayed more distresses than the first group. The distresses were mostly of a cracking nature. The pavements in the third group had the lowest average visual performance rating of the three groups. Of the 18 projects in this group, 15 used crushed siliceous gravel coarse aggregates. Half of these pavements used liquid antistripping additives, and the other half did not use any additives. None of the sections that used lime fell into this bottom group.”

The conclusions of the TxDOT study further support the findings of other highway agencies and researchers; that lime treatment of aggregates improves the long term performance of HMA pavements and increases their useful service life.

## METHODS USED TO ADD LIME TO HMA

Lime can be added to HMA during the production process by a number of different methods. This review describes current field practices and presents research evaluating their effectiveness. In 2003, the NLA produced a report on how to add lime to HMA mixtures based on site visits in four states (http://www.Lime.org/howtoadd.pdf).

Techniques used to add lime to HMA range from adding dry lime to the drum mixer at the point of asphalt binder entry to adding lime to aggregate followed by “marination” for several days. Quicklime should not be added to HMA unless it first has been completely hydrated. If quicklime remains unhydrated in the HMA, it will change to Ca(OH)2 when it comes into contact with water during the service life of the pavement. This reaction (i.e., changing from CaO to Ca(OH)2) is expansive and will create a volume change in the HMA and losses in strength and performance.

Lime can be successfully proportioned and mixed in HMA in both batch and drum mixers. In Georgia, dry lime is typically added at the point in the drum mixer where the asphalt binder is introduced.

Dry lime can be added to dry aggregate and to wet aggregate. Moisture levels in wet aggregate are typically about two to three percent above the saturated surface dried condition of the aggregate. Moisture ionizes the lime and helps distribute it on the aggregate surface. Lime-treated aggregates can be stockpiled for "marination" or can be conveyed directly to the drying and mixing portion of the HMA production unit.

Lime slurries made from hydrated lime or quicklime have also been used. Lime-slurried aggregates are conveyed directly to the drying and mixing portion of the HMA facility or placed into stockpiles for marination. The use of lime slurry has several advantages: improved resistance of the treated hot mix to stripping; reduced dusting associated with the addition of dry lime to the aggregate; and, improved distribution of the lime on the aggregate. However, the use of lime slurries adds more water than is typically used for conventional lime applications and can substantially increase the water content of the aggregate prior to entering the drying and mixing portions of the HMA facility. Increased fuel consumption and reduced HMA production can result. The use of lime slurries also requires purchasing or renting specialized equipment to prepare the lime slurry at the site of the mixing operation.

Marinating or stockpiling treated aggregate prior to re-entry into the HMA facility is fairly common in California, Nevada, and Utah. The advantages of marination include: a reduction in moisture content while the aggregate is stockpiled; the lime treatment can be performed separately from the HMA production with some economic advantage; and an improvement in the resistance to moisture can result (particularly when aggregates have clays present in their fines or have clay coatings). The treatment of aggregates followed by marination also allows for the use of the lime on only problematic or strip-prone aggregate. For example, a fine aggregate may be highly water sensitive while coarse aggregates may not be water sensitive.

Disadvantages of marination include: additional handling of the aggregate; additional space for both lime-treated and untreated stockpiles; and lime can be washed from the aggregate during marination. Carbonation of the lime in stockpiles of aggregate does not appear to be a major problem, as it usually occurs only on the surface of the stockpile.

Adding dry lime to the asphalt binder and storing the lime-modified binder prior to mixing with the aggregate has not been practiced in the field. However, recent research demonstrates the potential effectiveness of this approach [Lesueur and Little (1999)].

## LABORATORY AND FIELD STUDIES ASSESSING METHODS OF LIME ADDITION

Forming a mastic of a homogeneous blend of hydrated lime in bitumen has been shown to provide substantial improvement in high temperature stiffness, low temperature toughness, rut resistance, and reduced hardening effects [Lesueur and Little (1999)]. Based on these findings and confirmation in other studies, research is currently underway to investigate additional ways of introducing hydrated lime into the HMA mixing process.

## ADDITION OF LIME IN THE HOT MIX OPERATION

### University of Nevada, Reno

Two studies, which were conducted by the University of Nevada, simulated field lime addition practices [Waite et al., (1986), and McCann and Sebaaly (2003)]. Figure 38 shows the resilient modulus values before and after conditioning when tested using the AASHTO T 283 method for HMA mixtures treated with different types of lime and different methods of application. The data from the study conducted by McCann and Sebaaly summarized in Table 17 indicate that, for the aggregates and binders studied, the method of lime application does not affect the moisture sensitivity of the mix.

## Nevada DOT

The Nevada DOT conducted a study to evaluate the impact of lime application method on the properties of HMA mixtures [Epps Martin et al. (2003)]. The three years of data presented in Table 25 lead to the conclusion that, by requiring marination, the percent of field mixtures failing the retained strength ratio is significantly reduced from a 3-year average of 18 percent to 3 percent (Table 25). It is believed that two reasons led to this finding: a) marination during field operations allows the contractor to concentrate on treating the aggregates, because they are separated from the rest of the mix production process; and b) marination improves the properties of aggregates having plastic fines. NDOT also evaluated the impact of marination period on the moisture sensitivity of HMA mixtures. Table 26 summarizes the moisture sensitivity properties of HMA mixtures at various marination periods. The data from this study showed that longer marination times will not improve the resistance of HMA mixtures to moisture damage. In the majority of the cases, prolonging the marination time significantly reduced the retained strength ratio. Based on this finding, NDOT mandated a minimum of 48 hours and a maximum of 60 days of marination time.

## Utah DOT

The Utah Department of Transportation has performed both AASHTO T 283 and immersion compression tests on aggregates treated with lime by different methods [Betenson (1998)]. This laboratory research indicated that the use of marination produces higher retained properties than the use of dry lime on damp or wet aggregate (see Figures 39 to 42).

## Georgia DOT

Georgia DOT conducted a laboratory study to determine the benefits of using lime dry or in slurry form [Collins (1988)]. Both dry and slurry addition methods provided benefits to the aggregate-asphalt mixtures used (see Figure 43). Having noted only minor differences between the two methods of addition, Georgia DOT elected to add dry lime in drum mixers near the asphalt binder feed line towards the end of the drum.

## Texas Hot Mix Asphalt Pavement Association and Texas DOT

The Texas Department of Transportation (TxDOT) and the Texas Hot Mix Asphalt Pavement Association conducted a field experimental project to study various methods of adding lime to batch and drum mixers [Button and Epps (1983)]. Tests at batch mixers indicated that the use of lime slurry produced the best results, although dry lime added to damp aggregate was also beneficial (Figure 44). For drum mixers, the addition of lime to the cold feed and to aggregates prior to stockpiling was effective (Figure 45). The addition of dry lime to the drum mixer, however, was not effective in this study--probably because special lime-addition equipment was not used for this field test. The benefits of stockpiling or marination are also evident from these data.

In 1999, TxDOT conducted a study to evaluate the effectiveness of the different methods of adding lime to HMA mixture [Tahmoressi and Mikhail (1999)]. The study evaluated laboratory prepared mixtures under the Modified Lottman test and the Hamburg wheel tracking device. The Texas researchers concluded that there is no significant difference between the different methods of adding lime on the resistance of the HMA mix to moisture induced damage (Figure 46). They recommended that TxDOT allows the addition of dry lime to dry aggregates in the mixing drum or pugmill prior to asphalt addition.

## ADDITION OF LIME TO SELECTED FRACTIONS OF STOCKPILES

One of the benefits of adding lime to stockpiles of aggregates is the opportunity for separate treatment of those aggregate fractions that are water susceptible. A secondary benefit is the potential for treating one aggregate fraction at a higher concentration of lime and then introducing the lime to the other aggregate fraction during the HMA production process. One of the potential disadvantages of pretreating and stockpiling the aggregates--carbonation of the hydrated lime--has not been found to be significant (see below).

### Texas DOT

The effectiveness of treating individual stockpiles was studied as part of the extensive field and laboratory program performed by TxDOT and the Texas Hot Mix Asphalt Pavement Association [Button (1984)]. For one series of tests, lime slurry was added to only the fine aggregate fraction, to only the coarse aggregate fraction, and to the entire aggregate. All were held in stockpiles for up to 30 days. Hydrated lime was an effective antistrip additive for all lime addition methods (Figure 47). The length of time between mixing the lime with aggregate and mixing the treated aggregate with an asphalt binder did not significantly change the effectiveness.

In 1982, TxDOT performed a field research project to investigate the effectiveness of pretreating only the sand fraction of an aggregate with lime (i.e., the effectiveness of the lime being transferred from the fine aggregate to the coarse aggregate) during the aggregate blending, drying, and mixing operations at a HMA production facility [Kennedy et al., (1982) and (1983)]. The pretreatment of the sand fraction reduces the water sensitivity of the mixture (see Figure 48). (Stockpiling the lime-treated sand for a period of 28 weeks was not detrimental to the effectiveness of the lime.) Sufficient lime was added to a moist sand to produce lime concentrations in the total aggregate that ranged from approximately 0.3 to 1.5 percent by dry weight of aggregate. Approximately 25 percent sand was used to produce the HMA.

### Mississippi DOT

The Mississippi DOT pretreated a crushed gravel with a lime slurry in 1993 [Little (1994)]. Longer stockpile storage times (up to 90 days) produced mixes with acceptable characteristics. The asphalt mix contained 65 percent pretreated gravel, 10 percent No. 8 limestone, 10 percent agricultural limestone, 15 percent coarse sand, and 5.8 percent asphalt binder. Samples of the aggregate and asphalt binder were tested using AASHTO T 283 to determine water sensitivity after various time periods of storage in stockpiles (marination). (Over 11 inches of rain fell during the stockpiling operation.) Extended lime treatment is very effective in reducing moisture susceptibility (Figure 49).

### National Center for Asphalt Technology

An extensive study to investigate the effectiveness of lime additions to only the fine aggregate fraction was performed in 1993 by the National Center for Asphalt Technology [Hansen et al., (1993)]. Three fine aggregates and a single coarse aggregate (a Georgia granite) were used in the study. Twenty percent sand was used in the mixtures, which were tested by the ASTM D 4867 and AASHTO T 283 methods. Laboratory lime addition techniques included lime slurry and dry lime added to a moist aggregate. Lime is an effective antistrip agent when added to the fine aggregate fraction (Figure 50).

### Stockpile Carbonation

The lime carbonation (reaction with CO2 to form CaCO3) that occurs in a lime-treated stockpile can potentially increase water sensitivity because carbonated lime is unable to react with HMA or fines. Two studies demonstrate that carbonation is generally not a problem. In 1993, TxDOT evaluated lime-treated field sand that had been stockpiled for seven months [Little (1993)]. There was no evidence of carbonation or deterioration in lime concentrations. Graves evaluated carbonation in lime-treated aggregates [Graves (1992)]. For up to 180 days, carbonation was minimal at depths greater than three inches (Figure 51).

## CONCLUSIONS

It has been proven through laboratory and field testing that hydrated lime in HMA substantially reduces moisture sensitivity. Lime enhances the bitumen-aggregate bond and improves the resistance of the bitumen itself to water-induced damage. Recent surveys document the success and acceptance of lime in HMA throughout the United States.

The ability of lime to improve the resistance of HMA mixtures to moisture damage, reduce oxidative aging, improve mechanical properties, and improve resistance to fatigue and rutting, has led to observed improvements in the field performance of lime-treated HMA pavements. Life cycle cost analyses have shown that using lime results in approximate saving of $20/ton of HMA mix while field performance data showed an increase of 38% in the expected pavement life.

Several highway agencies have proven the effectiveness of lime with cold-in-place recycled mixtures. Lime treatment of the CIR mixtures increased their initial stability which allows the early opening of the facility to traffic and it improves their resistance to moisture damage which significantly extended the useful life of the pavement.

Laboratory and field performance studies conducted over the last several years shows that hydrated lime improves the rheology of the mastic and produces multifunctional and synergistic benefits in the mixture. Work in the United States and in Europe has proven that hydrated lime can substantially improve the resistance of the HMA to permanent deformation damage at high temperatures. Hydrated lime also substantially improves low temperature fracture toughness without reducing the ability of the mastic to dissipate energy through relaxation. Recent research demonstrates that hydrated lime is indeed an “active” filler that interacts with the bitumen; and some of the mechanisms responsible have been identified. It has been shown that there are high and low temperature rheological benefits in adding hydrated lime to the HMA mastic. It has been proven that there are also benefits of reduced susceptibility to age hardening and improved moisture resistance. Clearly hydrated lime is an attractive multifunctional additive to HMA.

Current tests to evaluate additives are based solely on short-term retained strengths following moisture conditioning (e.g., AASHTO T 283). This does not represent long-term performance of an asphalt, which is influenced by factors other than reduced moisture sensitivity (e.g., resistance to load-induced fatigue cracking or low temperature cracking). There is a pressing need for a simple and repeatable test that can evaluate the multifunctional aspects of pavement performance. Such a test will result in substantial savings because it will more accurately identify those additives that are capable of improving long-term asphalt pavement performance.

Hydrated lime may be added in the HMA production process in several ways. Many different methods have been used successfully. The experience of the states and contractors currently dictates the preferred manner of lime addition. Research activities are underway to investigate additional ways of adding hydrated lime at the HMA production site. Extensive laboratory and field performance studies conducted over the past few decades indicate that using lime in HMA mixture will generate the following properties:

1. Lime reduces stripping.
2. It acts as a mineral filler to stiffen the asphalt binder and HMA, which reduces rutting.
3. It improves resistance to fracture growth (i.e., improves fracture toughness) at low temperatures.
4. It reduces aging by favorably altering oxidation kinetics and interacting with products of oxidation to reduce their deleterious effects.
5. It alters the plastic properties of clay fines to improve moisture stability and durability.

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Table 1. Relative Behavior of Lime and Liquid Antistrip Additives in Georgia [Collins (1988)].

| Type Mix | Treatment | Stability | Flow | Tensile Strength, 77°F, psi | | |
|---|---|---|---|---|---|---|
| | | | | Unconditioned | Conditioned | Ratio (%) |
| Base | Lime | 2777 | 10.9 | 94.6 | 88.7 | 93.8 |
| | Liquid Additive | 2515 | 10.8 | 89.2 | 78.6 | 88.1 |
| B | Lime | 2685 | 10.6 | 91.2 | 87.3 | 95.7 |
| | Liquid Additive | 2380 | 11.1 | 91.6 | 79.7 | 87.0 |
| E | Lime | 2616 | 10.4 | 92.9 | 87.9 | 94.6 |
| | Liquid Additive | 2315 | 10.8 | 94.0 | 78.2 | 83.2 |
| F | Lime | 2487 | 10.4 | 89.9 | 88.0 | 97.9 |
| | Liquid Additive | 2392 | 11.6 | 85.1 | 73.5 | 86.4 |
| G | Lime | 2247 | 10.3 | 103.0 | 102.4 | 99.1 |
| | Liquid Additive | 2109 | 10.0 | 101.1 | 80.4 | 79.5 |
| H | Lime | 2325 | 11.0 | 104.0 | 85.5 | 82.2 |
| | Liquid Additive | 2272 | 10.7 | 86.7 | 74.4 | 85.8 |

Table 2. Deformation (mm) After 20,000 Passes for Samples Treated with Various Anti-Stripping Treatments in Colorado [Aschebrener and Far (1994)].

| | No Treatment | 1 % Hydrated Lime | Additive "A" | | Additive "B" | |
|---|---|---|---|---|---|---|
| | | | Type 1 | Type 2 | Type 1 | Type 2 |
| Mix 1 | (17.0)[1] | 1.4 | 2.2 | 3.1 | 6.3 | 7.4 |
| Mix 2 | (>20) | 2.3 | 8.1 | 8.4 | 5.3 | (14.6) |
| Mix 3 | (>20) | 2.5 | (13.7) | 8.5 | (>20) | (12.4) |
| Mix 4 | 8.7 | 2.3 | 6.2 | 4.7 | 5.0 | 4.3 |

[1] Parentheses indicates that the mixture failed due to excessive deformation.

Table 3. Tabulations of Stripping Rate in Field Samples [Watson (1992)].

| DATE OF EVALUATION | NUMBER OF CORES RATED | STRIPPING RATING (% RECEIVING RATING) |
|---|---|---|
| July, 1983 | 37<br>5 | None (88.1%)<br>Slight (11.9%) |
| January, 1984 | 49<br>6 | None (89.1%)<br>Slight (10.9%) |
| July, 1984 | 56<br>6<br>1 | None (88.9%)<br>Slight (9.5%)<br>Moderate (1.6%) |
| January, 1985 | 59<br>5<br>4<br>1 | None (85.5%)<br>Slight (7.2%)<br>Slight+ (5.8%)<br>Moderate (1.5%) |
| July, 1985 | 102<br>6<br>4 | None (77.3%)<br>Slight (19.7%)<br>Moderate (3.0%) |
| January, 1986 | 111<br>25<br>2 | None (80.4%)<br>Slight (18.1%)<br>Moderate (1.5%) |
| January, 1987 | 120<br>16<br>3 | None (86.3%)<br>Slight (11.5%)<br>Moderate (2.2%) |
| January, 1988 | 37<br>6 | None (86.0%)<br>Slight (14.0%) |
| January, 1990 | 33<br>2<br>6 | None (80.0%)<br>Slight (4.9%)<br>Moderate (14.6%) |
| January, 1992 | 10<br>3<br>4 | None (58.8%)<br>Slight (17.7%)<br>Moderate (23.5%) |

The degree of stripping was rated according to the following:

- None (No evidence of stripping)
- Slight (some stripping, primarily on coarse particles)
- Moderate (considerable stripping on coarse particles; moderate stripping on fine particles)
- Severe (severely stripped on fine and coarse particles)

Table 4. Recommended Binder Contents for Optimum Durability of HMA Mixtures [Ishai and Craus (1996)].

| Rate of Filler Activity | Examples of Fillers | Surface Activities of the Fillers | | Binder Content for Optimum Durability |
|---|---|---|---|---|
| | | Heat of Adsorption (cal/gr).$10^{-2}$ | Spec Heat of Adsorption (cal/m$^2$) | |
| High | Hydrated Lime | >30 | >0.55 | $\omega_{opt}$ |
| Intermediate | Limestone<br>Dolomite<br>Sandstone | 8 – 30 | 0.30 – 0.55 | $\omega_{opt}$ + 0.5% |
| Low | Basalt | <8 | <0.30 | $\omega_{opt}$ + 1.0% |

Table 5. Impact of Lime Treatment on the Performance of Texas HMA Mixtures under the Hamburg Wheel Tracking Device [Tahmoressi (2002)].

| Binder Grade | Aggregate Type | No. of Mixes | No. Passed | % Passed |
|---|---|---|---|---|
| PG 64-22 | Gravel – no lime | 3 | 0 | 0 |
| | Gravel – lime | 16 | 7 | 44 |
| | Igneous – no lime | 3 | 0 | 0 |
| | Igneous – lime | 6 | 5 | 83 |
| | Limestone – no lime | 13 | 2 | 15 |
| | Limestone – lime | 14 | 4 | 29 |
| | All – no lime | 19 | 2 | 11 |
| | All - lime | 36 | 16 | 44 |
| PG 70-22 | Gravel – no lime | 11 | 6 | 55 |
| | Gravel – lime | 12 | 8 | 67 |
| | Igneous – no lime | 2 | 2 | 100 |
| | Igneous – lime | 10 | 10 | 100 |
| | Limestone – no lime | 15 | 5 | 33 |
| | Limestone – lime | 35 | 19 | 54 |
| | All – no lime | 28 | 13 | 46 |
| | All - lime | 57 | 37 | 65 |
| PG 76-22 | Gravel – no lime | 13 | 7 | 54 |
| | Gravel – lime | 35 | 32 | 91 |
| | Igneous – no lime | 8 | 7 | 88 |
| | Igneous – lime | 31 | 31 | 100 |
| | Limestone – no lime | 18 | 14 | 78 |
| | Limestone – lime | 35 | 32 | 91 |
| | All – no lime | 39 | 28 | 72 |
| | All - lime | 101 | 95 | 94 |

Table 6. Tensile Strength Properties of Untreated and Lime Treated Mixtures on the Logan International Airport [Mallick et al. (2005)].

| **Treatment** | **Property** | **Aggregate/Mixture** | | |
|---|---|---|---|---|
| | | **A** | **B** | **C** |
| | TS of Unconditioned mix (kPa) | 807 | 1025 | 925 |
| None | TS after MMLS3 Loading (kPa) | 649 | 954 | 727 |
| | TS after 1 FT Cycle (kPa) | 800 | 950 | 750 |
| | TS after 10 FT Cycles (kPa) | 633 | 586 | 334 |
| | TSR after MMLS3 (%) | 80 | 93 | 79 |
| | TSR after 1 FT Cycle (%) | 99 | 93 | 81 |
| | TSR after 10 FT Cycles (%) | 78 | 57 | 36 |
| | TS of Unconditioned mix (kPa) | 1001 | 1177 | 761 |
| Hydrated Lime | TS after MMLS3 Loading (kPa) | 1334 | 1381 | 1343 |
| | TS after 1 FT Cycle (kPa) | 960 | 1010 | 800 |
| | TS after 10 FT Cycles (kPa) | 979 | 1126 | 530 |
| | TSR after MMLS3 (%) | 133 | 117 | 176 |
| | TSR after 1 FT Cycle (%) | 96 | 86 | 105 |
| | TSR after 10 FT Cycles (%) | 98 | 96 | 70 |
| | | | | |

Table 7. Impact of Multiple Freeze-thaw Cycling on the Rutting Potential of Liquid and Lime Mixtures from the Idaho SH67 Project [Sebaaly et al. (2005)].

| **F-T Cycles** | **Increase in Potential for Rutting at .5 million ESALs (%)** | |
|---|---|---|
| | **Liquid Mix** | **Lime Mix** |
| 0 | na | na |
| 3 | 0 | 0 |
| 6 | 3 | 0 |
| 9 | 55 | 0 |
| 12 | 40 | 10 |
| 18 | 150 | 55 |
| 21 | 220 | 65 |
| | | |

Table 8. Mechanical Properties of Lime and Liquid Mixtures from the Idaho SH67 Project [Sebaaly et al. (2005)].

| **Mixture** | **Moisture Conditioning** | **Dynamic Modulus in Compression, 10 rad/sec, ksi, 25C** | **Dynamic Modulus in Tension, 10 rad/sec, ksi, 25C** | **Rate of Dynamic Creep, (microns/cycle), 25C** |
|---|---|---|---|---|
| Lime Mix | Unconditioned | 964 | 374 | 0.46 |
|  | Conditioned | 726 | 301 | 0.57 |
| Liquid Mix | Unconditioned | 712 | 294 | 0.48 |
|  | Conditioned | 539 | 205 | 0.64 |
|  |  |  |  |  |

Table 9. Plastic Shear Strains at 5,000 Cycles and Corresponding Rut Depth of North Carolina Mixtures, 50°C [Tayebali and Shidhore (2005)].

| **Type of Mix** | **Lime %** | **Plastic Shear Strain (%)** |  | **Estimated Rut Depth (in)** |  |
|---|---|---|---|---|---|
| **Bone BHF %** |  | **Dry** | **Wet** | **Dry** | **Wet** |
| 1.5 | 0 | 1.86 | 2.00 | 0.20 | 0.22 |
| 6.5 | 0 | 1.42 | 1.78 | 0.16 | 0.20 |
| 5.5 | 1 | 1.33 | 1.40 | 0.15 | 0.15 |
| **Enka BHF %** |  |  |  |  |  |
| 1.5 | 0 | 1.55 | 1.78 | 0.17 | 0.20 |
| 6.5 | 0 | 1.71 | 1.61 | 0.19 | 0.18 |
| 5.5 | 1 | 1.33 | 1.37 | 0.15 | 0.15 |
|  |  |  |  |  |  |

Table 10. Number of Cycles Corresponding to 7.5 mm and 5.0 mm Rutting in Specimens Tested by ASTEC Asphalt Pavement Tester [Collins et al. (1997)].

| | **Specimens with Lime** | | **Specimens without Lime** | |
|---|---|---|---|---|
| **Aggregate** | **Vacuum Saturation** | **Freeze-Thaw** | **Vacuum Saturation** | **Freeze-Thaw** |
| Source 1 | 7803[c] (2240)[d] | 5000 (1467) | 1748 (5000) | 5609 (2166) |
| Source 2 | 3685 (1303) | 5242 (1796) | 3310 (1177) | 3507 (931) |
| Source 3 | 2974 (1065) | 2332 (680) | 1805 (736) | 452 (302) |
| Source 4 | 2496 (734) | 4240 (1242) | 1983 (732) | 2045 (579) |

[c] The first figure is the number of cycles corresponding to 7.5 mm failure criteria

[d] The figure in parentheses is the number of cycles corresponding to 5.0 mm failure criteria

Table 11. Summary of Creep Test Data Evaluated According to the Procedure Developed by Little et al. (1994).

| | **1-Hour Strain, in./in., $,_p$** | | **1-Hour Creep Modulus, $E_c$, psi** | | **Properties of Steady State Region of Creep Curve** | | |
|---|---|---|---|---|---|---|---|
| | **From Test** | **Criterion** | **From Test** | **Criterion** | **From Test** | **Criterion** | **Tertiary Creep** |
| C1[1] | 0.020 | Failure | -- | Failure | -- | -- | Yes |
| C2 | 0.009 | HRS[3] | 2,200 | HRS | 0.40 | HRS | Yes |
| C3 | Failure | -- | -- | -- | -- | -- | -- |
| L1[2] | 0.0018 | HRR[4] | 10,500 | HRR | 0.20 | HRR | No |
| L2 | 0.052 | MRR[5] | 3,750 | MRR | 0.25 | MRR | No |
| L3 | 0.0032 | HRR | 6,110 | HRR | 0.20 | HRR | No |

[1] - C1 - Control sample 1 - mixture without lime

[2] - LI - Lime -treated sample 1

[3] - HRS - High rut susceptibility

[4] - HRR - High rut resistance

[5] - MRR - Moderate rut resistance

Table 12. Comparison of High Temperature Properties of the Un-aged and Aged Binders [Petersen et al. (1987)]

| **Asphalt** | **Treatment** | **G*, 60C, 10rad/sec, kPa** | **Phase Angle (deg)** | **Viscosity, 60C, P** | **Aging Index*** |
|---|---|---|---|---|---|
| Un-aged Boscan | None | 1.33 | 84.6 | 838 | |
| | 20% Limestone | 2.30 | 83.9 | 1450 | |
| | 20% HL | 3.20 | 83.4 | 2020 | |
| Un-aged West Texas Maya blend | None | 1.85 | 85.6 | 1170 | |
| | 20% Limestone | 2.56 | 85.3 | 1610 | |
| | 20% HL | 2.60 | 86.4 | 1640 | |
| Aged Boscan | None | 2.25 | 72.1 | 179000 | 214 |
| | 20% Limestone | 5.46 | 69.0 | 433000 | 299 |
| | 20% HL | 0.68 | 82.1 | 54000 | 27 |
| Aged West Texas Maya blend | None | 4.99 | 70.3 | 396000 | 338 |
| | 20% Limestone | 1.46 | 66.5 | 1160000 | 720 |
| | 20% HL | 1.07 | 82.5 | 84900 | 52 |

* Ratio of aged binder viscosity over un-aged binder viscosity

Table 13. Comparison of Low Temperature Properties of the Aged Binders [Petersen et al. (1987)].

| **Asphalt** | **Treatment** | **Temperature (C)** | **Elongation (%)** | **Tensile Stress (kPa)** | **Modulus (kPa) x $10^4$** |
|---|---|---|---|---|---|
| Boscan | None | -5 | 10.6 | 560 | 2.24 |
| | | -10 | 4.8 | 830 | 3.68 |
| | 20% Limestone | -5 | 4.0 | 1,000 | 6.19 |
| | | -10 | 2.8 | 1,680 | 11.3 |
| | 20% HL | -5 | 15+ | 680 | 2.06 |
| | | -10 | 11.7 | 1,170 | 4.37 |
| West Texas Maya blend | None | -5 | 5.5 | 650 | 3.24 |
| | | -10 | 4.4 | 1,340 | 4.89 |
| | 20% Limestone | -5 | 4.0 | 1,580 | 8.74 |
| | | -10 | 0.75 | 1,310 | 15.6 |
| | 20% HL | -5 | 13.0 | 920 | 4.06 |
| | | -10 | 8.3 | 2,170 | 6.12 |

Table 14. Impact of Hydrated Lime on the Properties of the Recovered Aged Binder from HMA Mixtures in Spain [Rescasens et al. (2005)].

| **Property** | **0-days oven aging @ 80°C** | | **2-days oven aging @ 80°C** | | **7-days oven aging @ 80°C** | |
|---|---|---|---|---|---|---|
| | **None** | **HL** | **None** | **HL** | **None** | **HL** |
| Penetration (0.1 mm) | 78 | 79 | 43 | 47 | 34 | 37 |
| Viscosity @60°C (P) | 1900 | 1600 | 4800 | 3700 | 6300 | 4900 |
| Viscosity@ 135°C (P) | 3.9 | 4.2 | 5.2 | 6.1 | 7.6 | 6.2 |
| Softening Point (C) | 51 | 48 | 57 | 53 | 62 | 55 |

Table 15. Mix Design Properties of the Nevada CIR Mixtures [Sebaaly et al. (2004)].

| **Project** | **Emulsion** | **Emulsion Content (%)** | **No Lime** | | **1.5% Lime** | |
|---|---|---|---|---|---|---|
| | | | **Unconditioned Mr at 77°F (ksi)** | **Mr Ratio* (%)** | **Unconditioned Mr at 77°F (ksi)** | **Mr Ratio* (%)** |
| US-50 | ERA-25 | 0.8 | 83 | 18 | 236 | 100 |
| | | 1.3 | 58 | 32 | 209 | 100 |
| | | 1.8 | 40 | 100 | 189 | 90 |
| | CMS-2S | 0.8 | 162 | 98 | 261 | 100 |
| | | 1.3 | 98 | 100 | 204 | 100 |
| | | 1.8 | 70 | 100 | 126 | 100 |
| | ERA-75 | 0.8 | 134 | 52 | 262 | 100 |
| | | 1.3 | 64 | 49 | 164 | 100 |
| | | 1.8 | 60 | 35 | 165 | 100 |
| US-95 | ERA-25 | 1.7 | 394 | 95 | 547 | 100 |
| | | 2.2 | 383 | 67 | 377 | 100 |
| | | 2.7 | 237 | 85 | 242 | 100 |
| | CMS-2S | 1.7 | 589 | 60 | 641 | 100 |
| | | 2.2 | 399 | 100 | 485 | 100 |
| | | 2.7 | 429 | 66 | 373 | 100 |
| | ERA-75 | 1.7 | 425 | 100 | 652 | 100 |
| | | 2.2 | 543 | 100 | 716 | 100 |
| | | 2.7 | 497 | 87 | 707 | 66 |
| NV-396 | ERA-25 | 1.2 | 168 | 26 | 635 | 100 |
| | | 1.7 | 130 | 37 | 571 | 89 |
| | | 2.2 | 82 | 45 | 441 | 100 |
| | CMS-2S | 1.2 | 413 | 5 | 621 | 67 |
| | | 1.7 | 319 | 7 | 523 | 89 |
| | | 2.2 | 308 | 15 | 495 | 100 |
| | ERA-75 | 1.2 | 318 | 16 | 484 | 100 |
| | | 1.7 | 260 | 34 | 521 | 100 |
| | | 2.2 | 205 | 54 | 430 | 100 |

$$* \text{ Mr ratio} = \frac{\text{Mr at } 77^{o}\text{F conditioned samples}}{\text{Mr at } 77^{o}\text{F unconditioned samples}} \times 100$$

Table 16. Impact of Hydrated Lime on the Torsional Fatigue Life of Sand Asphalt Mixtures [Little and Kim (2002)].

| Strain (%) | Binder: AAD-1 | | | Binder: AAM-1 | |
|---|---|---|---|---|---|
| | Neat | Limestone Filler | Hydrated Lime Filler | Neat | Hydrated Lime Filler |
| 0.2 | 34,555[a] | 65,610 (90)[b] | NA | 20,660 | 36,210 (75) |
| 0.28 | 10,060 | 18,843 (87) | 45,960 (357) | 4,510 | 11,235 (150) |
| 0.40 | 3,860 | 7,577 (96) | 13,110 (240) | 2,110 | 4,210 (100) |

a: average number of loading cycles until fatigue failure

b: percent increase in fatigue life compared to unfilled mix

Table 17. Impact of Lime Treatment and Lime Application Methods on the Mechanical Properties of Nevada's HMA Mixtures [McCann and Sebaaly (2003)].

| Property | No-Lime vs. Lime Treated Mixtures | | | Lime Application Method |
|---|---|---|---|---|
| | Conditioning | | | One and 18 freeze-thaw cycles |
| | None | One Freeze-thaw cycle | 18 Freeze-thaw cycles | |
| Resilient Modulus | 11 out of 12<br>NOT DIFFERENT | 9 out of 12<br>DIFFERENT | 12 out 12<br>DIFFERENT | 30 out 36<br>NOT DIFFERENT |
| Tensile Strength | 8 out 12<br>NOT DIFFERENT | 11 out 12<br>DIFFERENT | 12 out of 12<br>DIFFERENT | 31 out 36<br>NOT DIFFERENT |
| Permanent Shear Strain | 7 out of 12<br>NOT DIFFERENT | 12 out of 12<br>DIFFERENT | 12 out of 12<br>DIFFERENT | 36 out of 36<br>NOT DIFFERENT |

Table 18. Ratio of E* with Lime to E* without Lime [Witczak and Bari (2004)].

| Temperature (F) | Hydrated Lime Content (percent of dry weight of aggregate) | | | | |
|---|---|---|---|---|---|
| | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
| 14 | 1.24 | 1.07 | 1.31 | 1.33 | 1.34 |
| 40 | 1.12 | 1.10 | 1.21 | 1.43 | 1.22 |
| 70 | 1.26 | 1.31 | 1.06 | 1.91 | 1.31 |
| 100 | 1.21 | 1.51 | 1.15 | 1.39 | 1.30 |
| 130 | 1.24 | 1.09 | 1.14 | 1.45 | 1.25 |
| Average | 1.21 | 1.22 | 1.17 | 1.50 | 1.28 |
| STD | 0.06 | 0.19 | 0.09 | 0.23 | 0.05 |
| CV | 5 | 16 | 8 | 15 | 4 |

Table 19. Reasons for Using Lime in HMA Pavements [Hicks and Scholz (2003)].

| Agency | Resist Stripping | Improve Aging Resistance | Stiffen Binder | Improve Fracture Toughness | Alter Properties of Fines |
|---|---|---|---|---|---|
| Arizona | 1 | 3 | 2 | 3 | 2 |
| California – Dist 2 | 1 | 2 | 3 | 1 | 1 |
| Colorado | 1 | 3 | 3 | 3 | 1 |
| Georgia | 1 | 3 | 3 | 3 | 3 |
| Mississippi | 1 | 1 | 2 | - | 3 |
| Nevada | 1 | 3 | 3 | 2 | 1 |
| Oregon | 1 | 2 | 3 | 3 | 3 |
| South Carolina | 1 | 2 | 2 | 2 | 2 |
| Texas | 1 | 3 | 2 | 3 | 2 |
| Utah | 1 | 2 | 2 | 2 | 2 |

Level of Importance:
1 = very important
2 = moderately important
3 = less important

Table 20. Typical Costs for Adding Lime into HMA Mixtures based on Contractor Surveys [Hicks and Scholz (2003)].

| Agency | Contractor | Method Used | % Lime Used | Added Cost $/Ton-Mix |
|---|---|---|---|---|
| Arizona | FNF | Non-Marinated | 1.0 | 1.00 |
| | Kiewit-Pacific | Non-Marinated | 1.0 | 1.00 – 1.50 |
| California | FNF | Marinated | 0.7 – 1.2 | 3.75 – 4.25 |
| | Granite | Marinated | 0.7 – 1.2 | 4.00 – 4.50 |
| | Kiewit-Pacific | Marinated | 0.7 – 1.2 | 4.00 |
| Colorado | Lafarge | Non-Marinated | 1.0 | 1.00 – 1.25 |
| Georgia | APAC | Non-Marinated | 1.0 | 1.25 – 1.50 |
| Mississippi | APAC | Non-Marinated | 1.0 | 1.25 – 1.50 |
| Nevada | FNF | Non-Marinated | 1.5 | 1.00 – 1.50 |
| | | Marinated | 1.5 | 3.75 – 4.25 |
| | Granite | Non-Marinated | 1.5 | 1.25 – 1.50 |
| | | Marinated | 1.5 | 2.75 – 4.50 |
| Oregon | Kiewit-Pacific | Non-Marinated | 1.0 | 1.25 – 1.50 |
| | Morse Brothers | Non-Marinated | 1.0 | 1.25 – 1.50 |
| South Carolina | APAC | Non-Marinated | 1.0 | 1.25 – 1.50 |
| Texas | APAC | Non-Marinated | 1.0 – 1.5 | 1.00 – 1.50 |
| | F.M. Young | Non-Marinated | 1.0 – 1.5 | 1.00 – 1.50 |
| Utah | Granite | Non-Marinated | 1.0 – 1.5 | 1.25 – 1.50 |
| | Staker | Non-Marinated | 1.0 – 1.5 | 1.25 – 1.50 |

Table 21. Summary of the Life Cycle Cost Analysis of HMA Pavements with and without Lime based on the Deterministic Approach [Hicks and Scholz (2003)].

| Agency | Life Cycle Cost, $/yd$^2$ (Net Present Value) Lime-Treated Alternative | Life Cycle Cost, $/yd$^2$ (Net Present Value) Non-Treated Alternative | Savings Associated with Using Lime $/yd$^2$ | Savings Associated with Using Lime $/lane-mile |
|---|---|---|---|---|
| a) Interstates | | | | |
| Arizona | 14.18 | 15.34 | 1.16 | 8,188 |
| California | 24.83 | 28.25 | 3.42 | 24,075 |
| Colorado | 20.52 | 24.51 | 3.99 | 28,067 |
| Georgia | 20.65 | 24.79** | 4.14 | 29,155 |
| Mississippi | 7.65 | 9.05** | 1.40 | 9,897 |
| Nevada | 11.48 | 19.69*** | 8.21 | 57,775 |
| Oregon | 12.34 | 13.91 | 1.57 | 11,019 |
| South Carolina | 20.90 | 21.53** | 0.63 | 4,421 |
| Texas | 8.40 | 8.11 | 0.29 | 2,100 |
| Utah | 17.30 | 22.92*** | 5.62 | 39,530 |
| b) State/Federal Lands Highways | | | | |
| Arizona | 5.37 | 7.61 | 2.24 | 15,769 |
| California | 24.18 | 27.45 | 3.27 | 23,018 |
| Colorado | 9.47 | 10.50 | 1.03 | 7,256 |
| FHWA | 7.69* | 8.01* | 0.32 | 2,297 |
| Georgia | 7.71 | 9.28** | 1.57 | 11,093 |
| Mississippi | 7.20 | 7.74** | 0.54 | 3,786 |
| Nevada | 10.01 | 10.92*** | 0.91 | 6,426 |
| Oregon | 11.68 | 14.59 | 2.91 | 20,519 |
| South Carolina | 21.71 | 25.96** | 4.25 | 29,958 |
| Texas | 9.03 | 9.60 | 0.57 | 3,974 |
| Utah | 15.99 | 18.81*** | 2.82 | 19,904 |

* Federal Lands Highways only.

** Not used by agency; life of non-lime alternative to be 2 years less than lime-treated alternative.

*** Not used by agency, but agency estimated relative life of non-lime alternative.

Table 22. Summary of the Performance of Field Projects based on Pavement Management System [Sebaaly et al. (2003)].

| State Region | Route | Mixture | Year of Const. | Reduction in PSI | Occurrence of low PSI | Impact of Low PSI |
|---|---|---|---|---|---|---|
| South: Las Vegas Area | I-15 | Untreated | 1984 | Moderate (after 4th year) | Frequent | Insignificant |
| | I-15 | Lime-Treated | 1992 | None | None | Insignificant |
| | US-95 | Untreated | 1986 | Severe | Frequent | Significant |
| | US-95 | Lime-Treated | 1996 | None | Infrequent | Insignificant |
| North: Reno Area | I-80 | Untreated | 1983 | Severe (years 3, 5, 6) | Frequent | Significant |
| | I-80 | Lime-Treated | 1990 | Moderate (years 3 and 6) | Moderate | Insignificant |
| | I-80 | Untreated | 1984 | Moderate (years 2 and 5) | Frequent | Significant |
| | I-80 | Lime-Treated | 1994 | None | Frequent | Insignificant |

Table 23. Impact of Lime Treatment on Pavement Life in Nevada based on AASHTO Design Guide [Sebaaly et al. (2003)].

| **Project** | **Mr (ksi)** | | **Reduced $a_1$** | **Weighted $a_1$** | **SN** | **ESALs Millions** | **Increase in ESALs** | **Increase in Pav. Life (%)** |
|---|---|---|---|---|---|---|---|---|
| | Uncond. | 6th Cycle | | | | | | |
| Pecos-untreated | 1900 | 104 | 0.02 | 0.24 | 3.44 | 1.850 | 70 | 6** |
| US-95-treated | 1100 | 460 | 0.15 | 0.28 | 3.74 | 3.120 | | |
| Russell-untreated | 1900 | 270 | 0.05 | 0.25 | 3.54 | 2.210 | 14* | 1 |
| Sunset-treated | 1050 | 193 | 0.07 | 0.26 | 3.60 | 2.415 | | |
| SR-599-treated | 1250 | 345 | 0.10 | 0.27 | 3.64 | 2.600 | | |
| Plumas-untreated | 970 | 0 | 0.01 | 0.23 | 3.44 | 1.850 | 40 | 3 |
| Greens-Untreated | 910 | 0 | 0.01 | 0.23 | 3.44 | 1.850 | | |
| SR-516-treated | 1700 | 383 | 0.08 | 0.26 | 3.64 | 2.600 | | |

* Average percent increase in ESALs for the two lime-treated projects as compared with the untreated project.
** Increase in pavement life is based on an average of 8-year life for untreated projects.

Table 24. Performance of HMA Pavements in Northeast Texas based on Hamburg Rut Depth and Visual Performance Rating [Tahmoressi and Scullion (2002)].

| Project | Layer | Hamburg Rut Depth (mm) @20,000 cycles | Age (years) | Visual Performance Rating | Antistrip Agent | Coarse Aggregate Mineralogy | Screening Mineralogy |
|---|---|---|---|---|---|---|---|
| Atlanta – 4 | 1 | 0.6 | 6 | 100 | Lime | Gravel | Gravel |
| Atlanta – 9 | 1 | 0.6 | 5 | 100 | Liquid | Limestone | Limestone |
| Atlanta – 8 | 1 | 1.0 | 5 | 100 | Liquid | Sandstone | Sandstone |
| Atlanta – 14 | 1 | 1.3 | 4 | 95 | Lime | Gravel | Gravel |
| Atlanta – 16 | 1 | 1.3 | 4 | 55 | Lime | Sandstone | Sandstone |
| Atlanta – 11 | 1 | 1.8 | 5 | 95 | Lime | Igneous | Igneous |
| Atlanta – 2 | 1 | 2.1 | 6 | 70 | Lime | Gravel | Gravel |
| Atlanta – 12 | 1 | 2.5 | 4 | 95 | Lime | Gravel | Gravel |
| Atlanta – 15 | 1 | 3.0 | 4 | 100 | Liquid | Sandstone | Sandstone |
| Atlanta – 3 | 1 | 4.7 | 6 | 65 | Liquid | Sandstone | Sandstone |
| Atlanta – 13 | 1 | 4.8 | 4 | 85 | Lime | Gravel | Gravel |
| **Average** | | **2.2** | **4.8** | **87.3** | | | |
| Tyler – 3 | 1 | 6.1 | 4 | 95 | Lime | Gravel | Limestone |
| Lufkin – 8 | 1 | 6.2 | 5 | 85 | Liquid | Gravel | Limestone |
| Atlanta – 10 | 1 | 8.0 | 5 | 70 | Lime | Quartzite | Quartzite |
| Tyler – 6 | 1 | 8.0 | 6 | 95 | Liquid | Limestone | Limestone |
| Atlanta – 1 | 1 | 8.1 | 7 | 70 | Liquid | Gravel | Gravel |
| Atlanta – 5 | 1 | 8.9 | 5 | 100 | Liquid | Limestone | Limestone |
| Tyler – 4 | 1 | 10.3 | 9 | 65 | None | Sandstone | Sandstone |
| Lufkin – 3 | 2 | 10.5 | 5 | 70 | None | Limestone | Limestone |
| Atlanta – 18 | 2 | 11.2 | 5 | 70 | Liquid | Gravel | Gravel |
| **Average** | | **8.6** | **5.7** | **80.0** | | | |
| Tyler – 5 | 1 | 13.0 | 12 | 70 | None | Limestone | Limestone |
| Atlanta – 17 | 2 | 13.9 | 6 | 65 | Liquid | Limestone | Limestone |
| Lufkin – 6 | 1 | 15.8 | 8 | 55 | None | Gravel | Limestone |
| Atlanta – 6 | 1 | 16.6 | 6 | 80 | Liquid | Gravel | Gravel |
| Lufkin – 5 | 1 | 18.2 | 10 | 70 | None | Gravel | Limestone |
| Atlanta – 7 | 1 | 18.5 | 7 | 70 | Liquid | Gravel | Gravel |
| Tyler – 1 | 1 | 19.2 | 8 | 100 | Liquid | Gravel | Limestone |
| Lufkin – 2 | 1 | 20.5 | 10 | 85 | None | Gravel | Limestone |
| Tyler – 7 | 1 | 36.2 | 6 | 40 | Liquid | Igneous | Igneous |
| Lufkin – 4 | 1 | 43.9 | 4 | 40 | Liquid | Gravel | Limestone |
| Tyler – 2 | 1 | 56.8 | 8 | 90 | Liquid | Gravel | Gravel |
| Lufkin – 3 | 1 | 59.5 | 5 | 70 | None | Limestone | Limestone |
| Lufkin – 8 | 2 | 83.3 | 6 | 85 | Liquid | Gravel | Limestone |
| Tyler – 8 | 1 | | 9 | 70 | Liquid | Gravel | Gravel |
| Lufkin – 1 | 2 | | 9 | 50 | None | Gravel | Limestone |
| Lufkin – 7 | 1 | | 7 | 40 | None | Gravel | Limestone |
| Tyler – 9 | 1 | | 9 | 55 | None | Gravel | Limestone |
| Lufkin – 1 | 1 | | 8 | 50 | None | Gravel | Limestone |
| **Average** | | **32.0** | **7.7** | **65.8** | | | |

Table 25. Nevada DOT Moisture Sensitivity Data of 97-99 HMA Mixtures [Epps Martin et al. (2003)].

| Property | Mix Design | | | | | | Field Mixtures | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Marinated | | | Non-marinated | | | Marinated | | | Non-marinated | | |
| | 97 | 98 | 99 | 97 | 98 | 99 | 97 | 98 | 99 | 97 | 98 | 99 |
| No. of samples | 39 | 80 | 70 | 28 | 13 | 7 | 118 | 312 | 370 | 114 | 95 | 61 |
| Uncond. Tensile strength, psi [1] | 101 | 87 | 99 | 122 | 121 | 140 | 94 | 88 | 97 | 118 | 143 | 131 |
| Fail @ 65 psi, % | 0 | 14 | 0 | 0 | 0 | 0 | 12 | 9 | 1 | 2 | 0 | 0 |
| Strength Ratio, % [2] | 84 | 90 | 94 | 81 | 84 | 86 | 89 | 90 | 94 | 76 | 82 | 81 |
| Fail @ 70% | 13 | 1.3 | 1.4 | 25 | 15 | 0 | 3.4 | 2.2 | 3.8 | 30 | 16 | 8 |

1 Average unconditioned tensile strength.

2 average retained strength ratio

Table 26. NDOT Moisture Sensitivity Properties of HMA Mixtures at Various Marination Times [Epps Martin et al. (2003)].

| Agg. Source | Binder Grade | 48 hours | | 45 days | | 60 days | | 120 days | |
|---|---|---|---|---|---|---|---|---|---|
| | | Strength | Ratio | Strength | Ratio | Strength | Ratio | Strength | Ratio |
| Lockwood | AC-20 | 107 | 88 | 138 | 40 | 146 | 30 | 139 | 43 |
| | AC-20P | 75 | 85 | 101 | 38 | 72 | 46 | 96 | 50 |
| | PG64-28 | 70 | 74 | 101 | 36 | 93 | 47 | 110 | 61 |
| Dayton | AC-20 | 115 | 96 | 138 | 62 | 110 | 61 | 109 | 79 |
| | AC-20P | 82 | 95 | 85 | 70 | 75 | 63 | 91 | 75 |
| | PG64-28 | 79 | 93 | 107 | 66 | 88 | 66 | 91 | 65 |
| Lone Mtn | AC-20 | 164 | 91 | 142 | 96 | 138 | 100 | 143 | 97 |
| | AC-20P | 124 | 103 | 133 | 91 | 120 | 100 | 116 | 96 |
| | PG64-28 | 100 | 90 | 127 | 63 | 104 | 68 | 92 | 69 |
| Suzie Creek | AC-20 | 82 | 85 | 88 | 70 | 90 | 76 | 116 | 44 |
| | AC-20P | 52 | 133 | 60 | 89 | 67 | 74 | 62 | 66 |
| | PG64-28 | 62 | 111 | 74 | 96 | 71 | 70 | 87 | 30 |

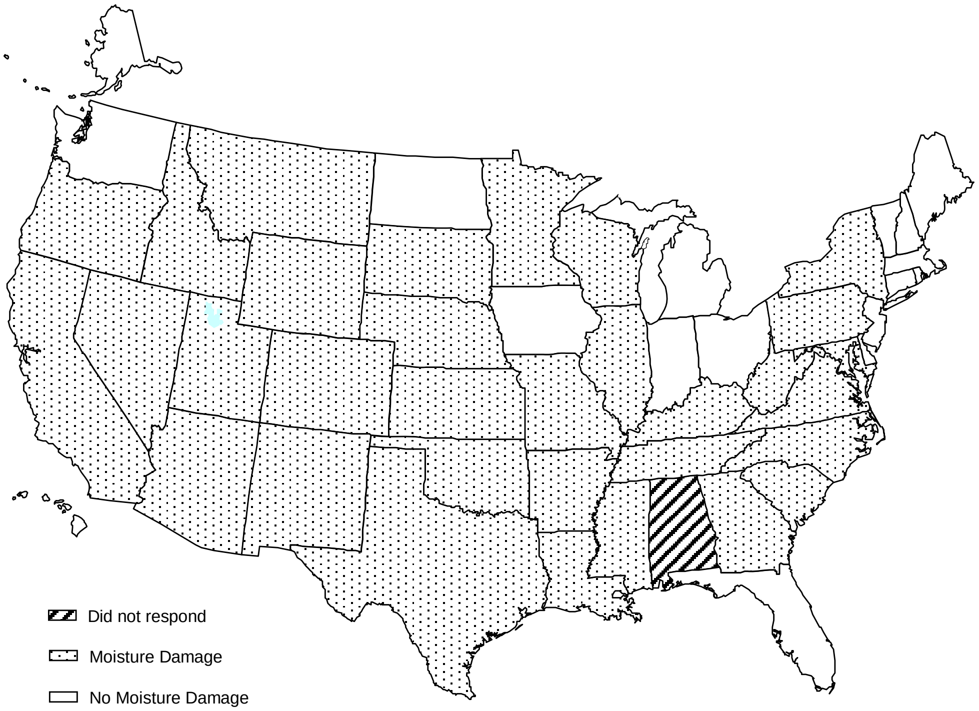


Figure 1. Extent of Moisture Damage in the United States [Hicks (1991)].

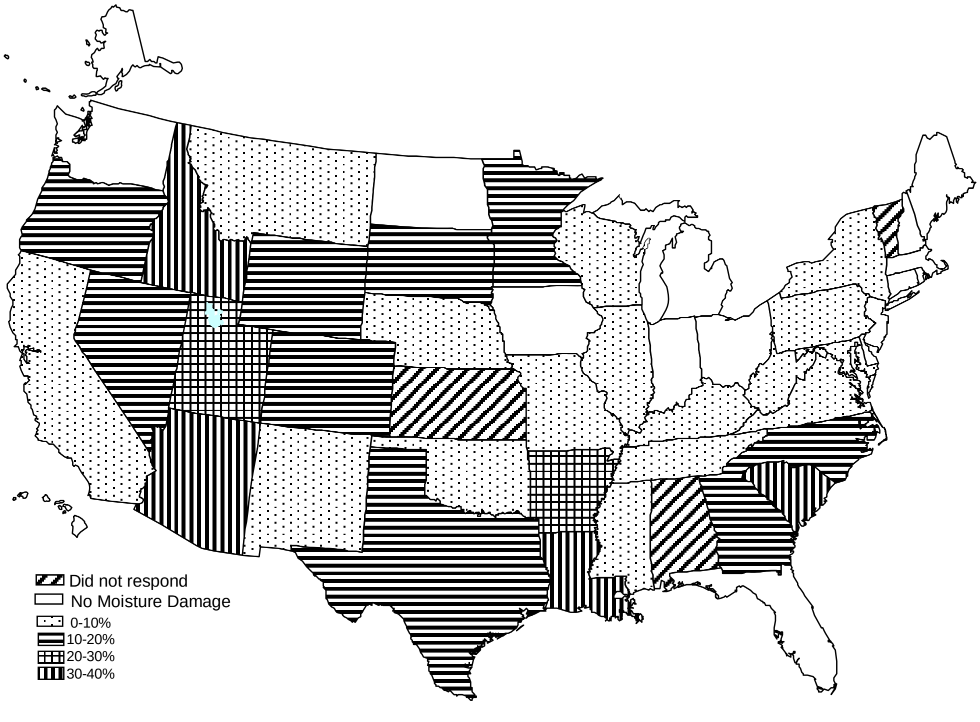


Figure 2. Percentage of Pavements Experiencing Moisture Related Distress by State [Hicks (1991)].

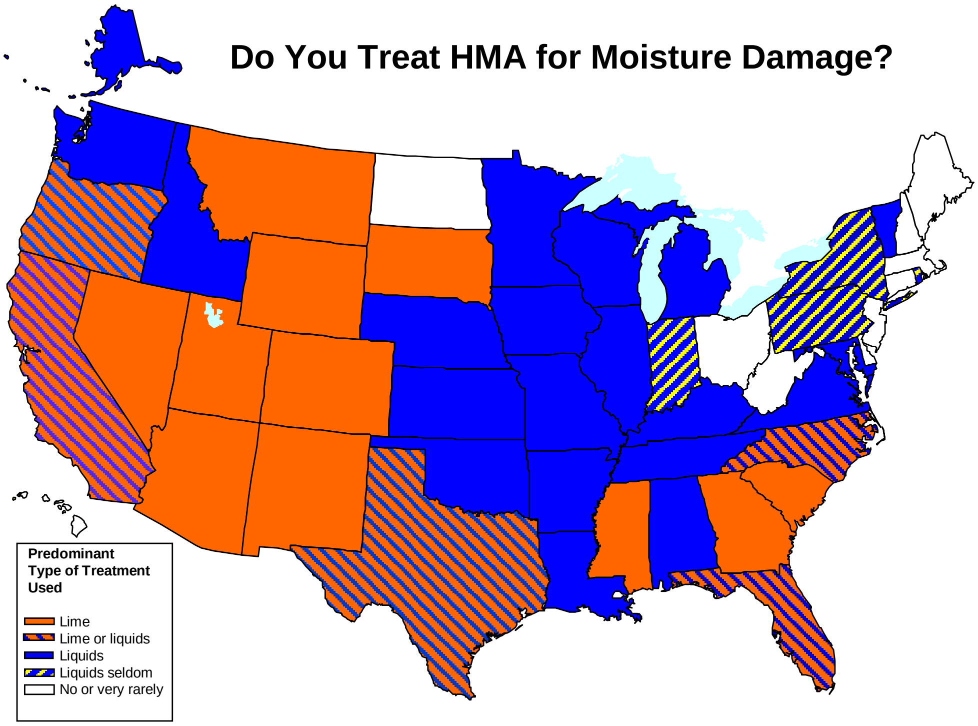


Figure 3. Distribution of Moisture Damage Treatments [Aschenbrener (2002)].

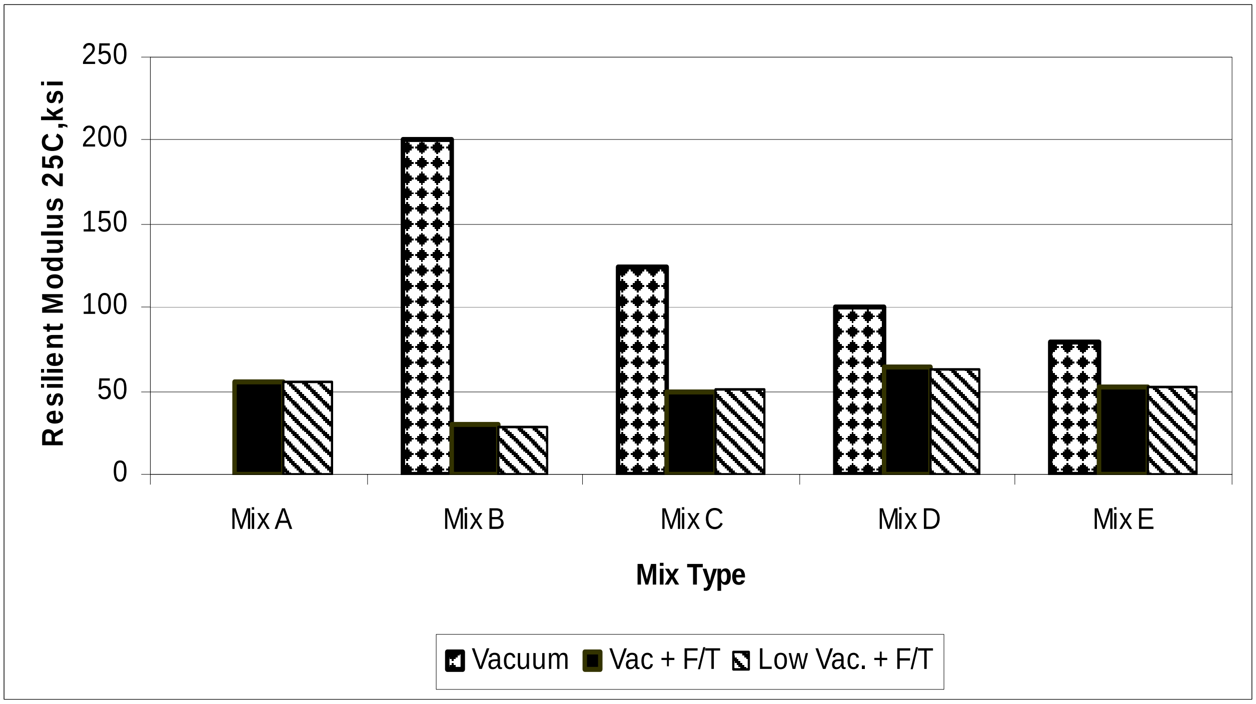


Figure 4. Effect of Freeze-Thaw on Resilient Modulus [Epps et al. (1992)].

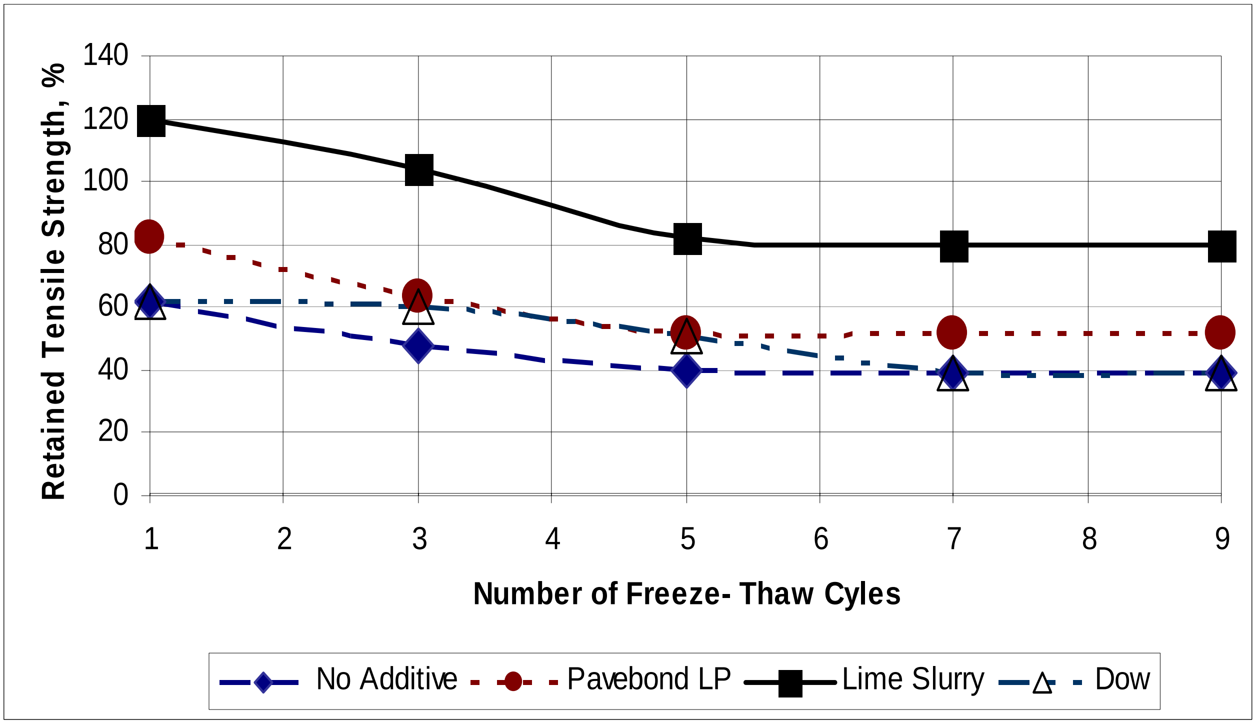


Figure 5. Effect of the Number of Freeze-Thaw Cycles on Retained Tensile Strength for Various Additives [Epps et al. (1992)].

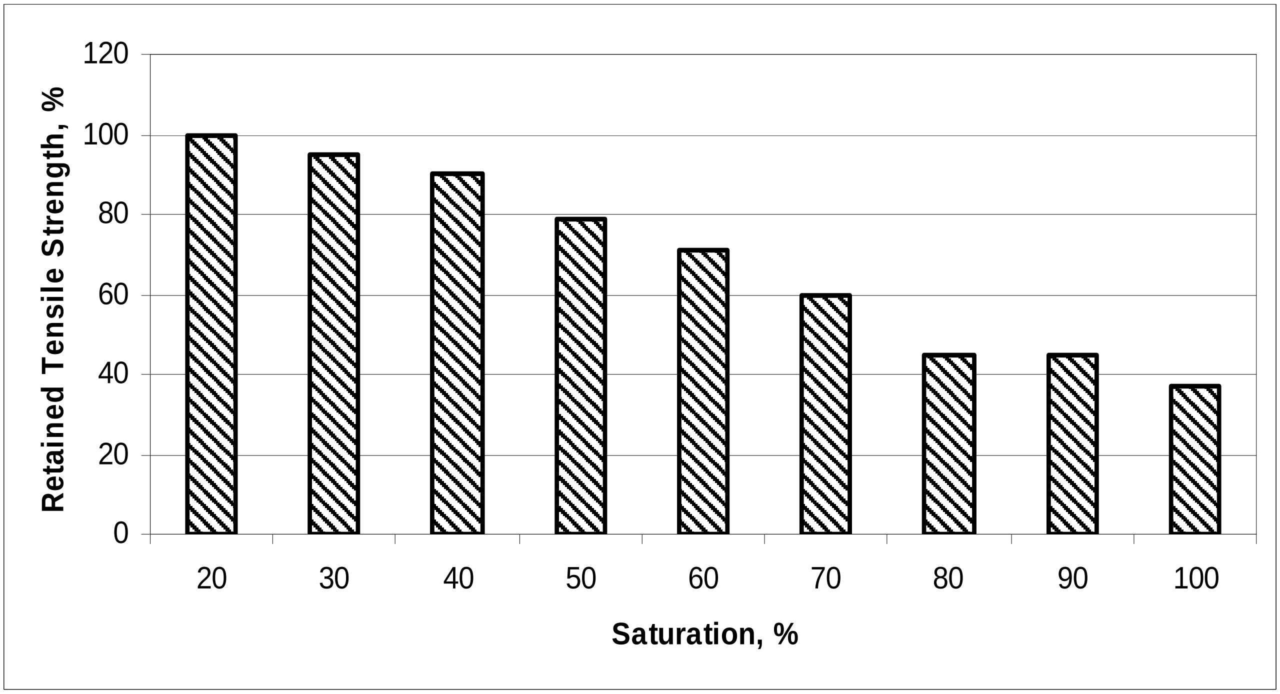
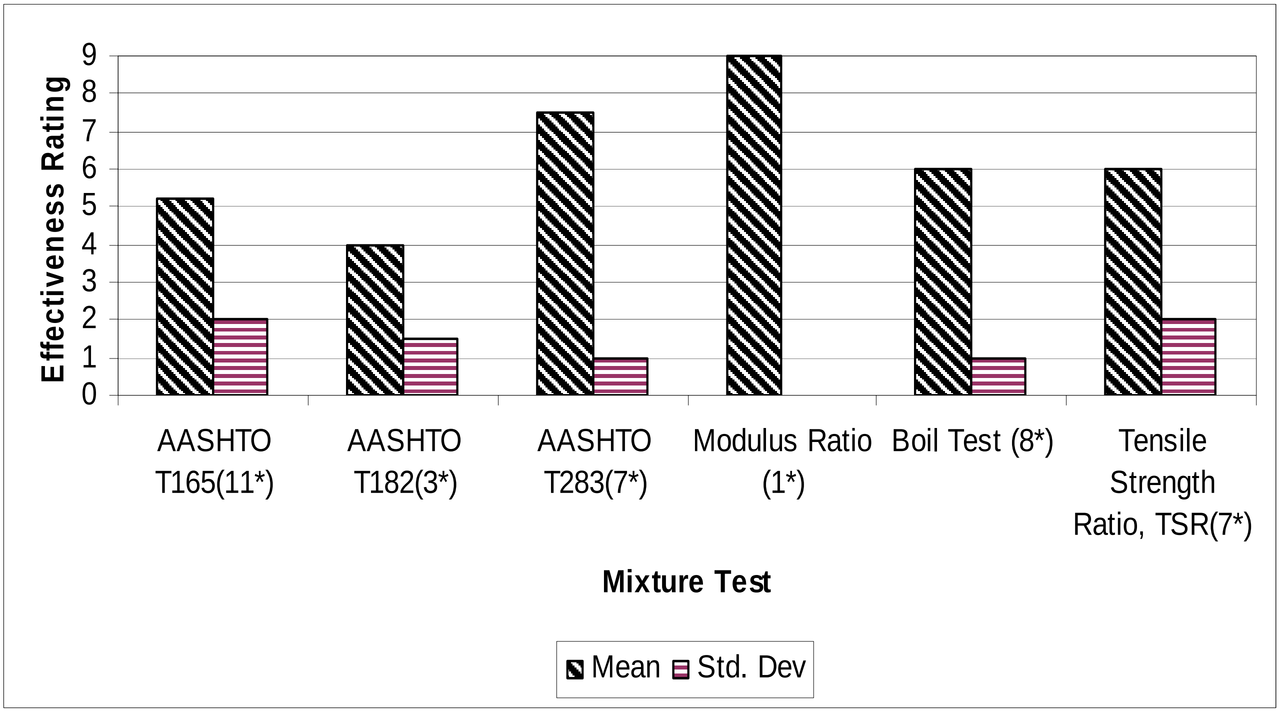


Figure 6. Effect of Degree of Saturation on the Tensile Strength Ratio [Kennedy and Ping (1991)].



* Note: numbers in parentheses represent number of responses.

Figure 7. Relative Effectiveness of Mixture Tests Procedures to Identify Moisture-Related Problems [Hicks (1991)].

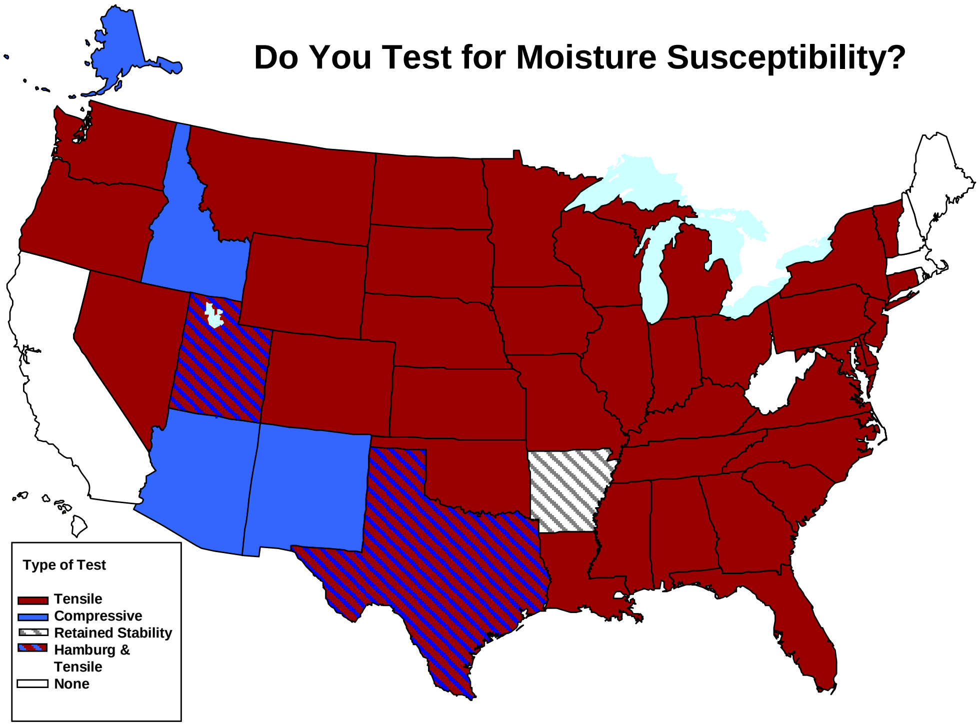


Figure 8. Type of Tests used to Assess Moisture Susceptibility of HMA Mixtures [Aschenbrener (2002)].

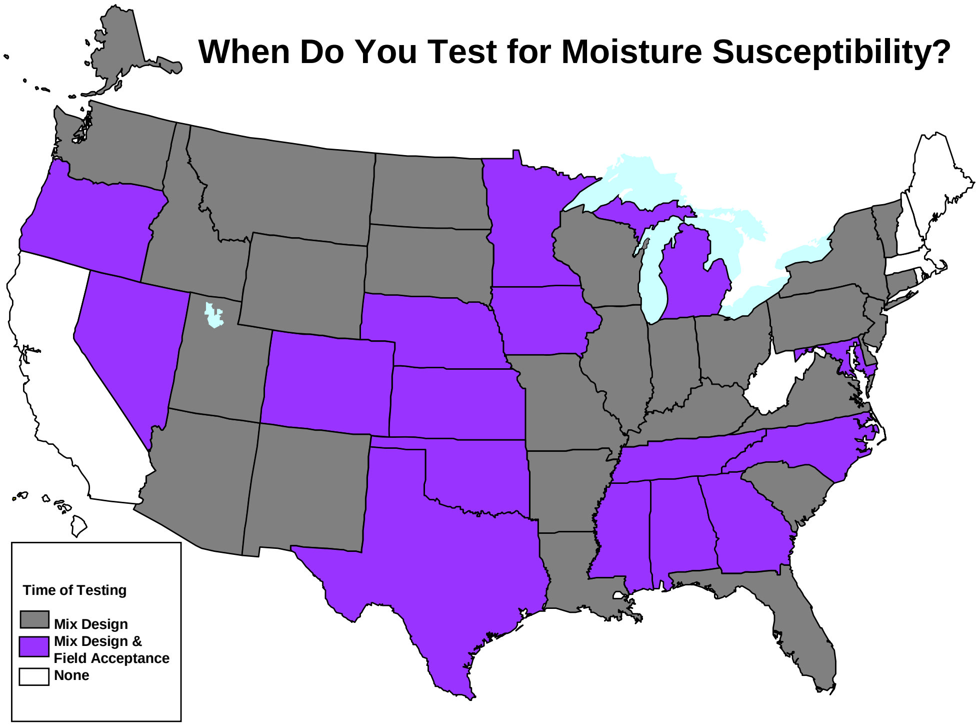


Figure 9. Testing Stage for Moisture Susceptibility of HMA Mixtures [Aschenbrener (2002)].

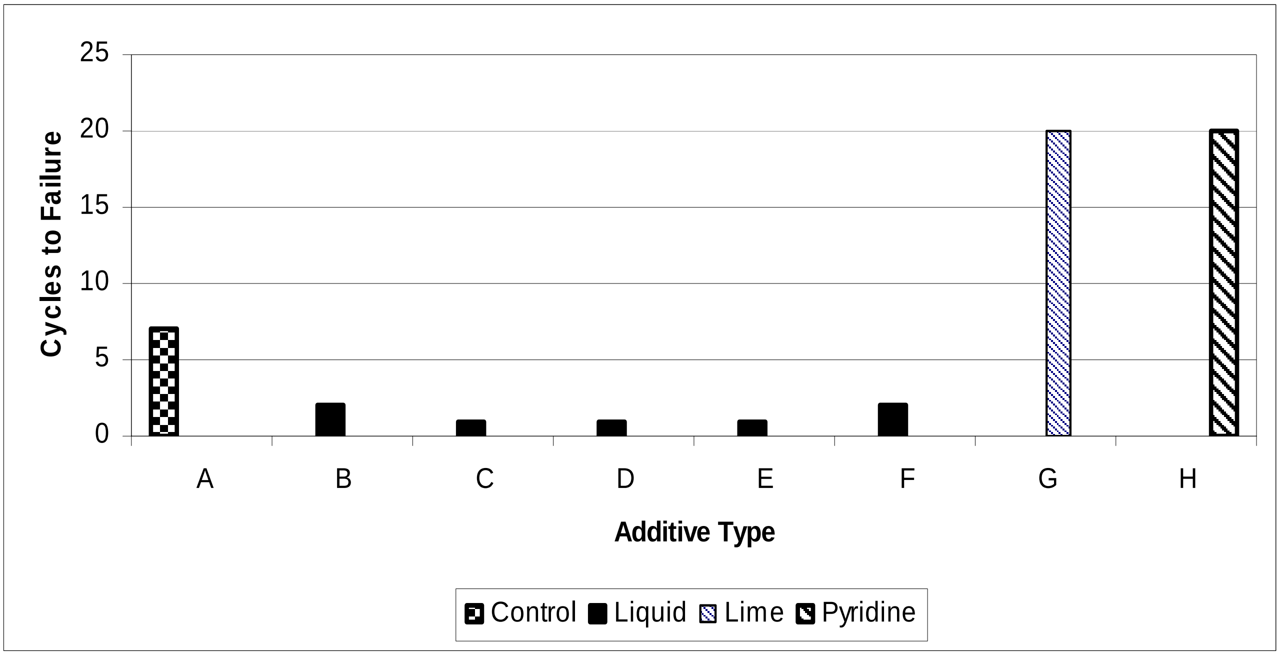


Figure 10. Effect of Selected Modifiers on Moisture Damage as Measured by the Freeze-Thaw Pedestal Test [Kennedy and Ping (1991)].

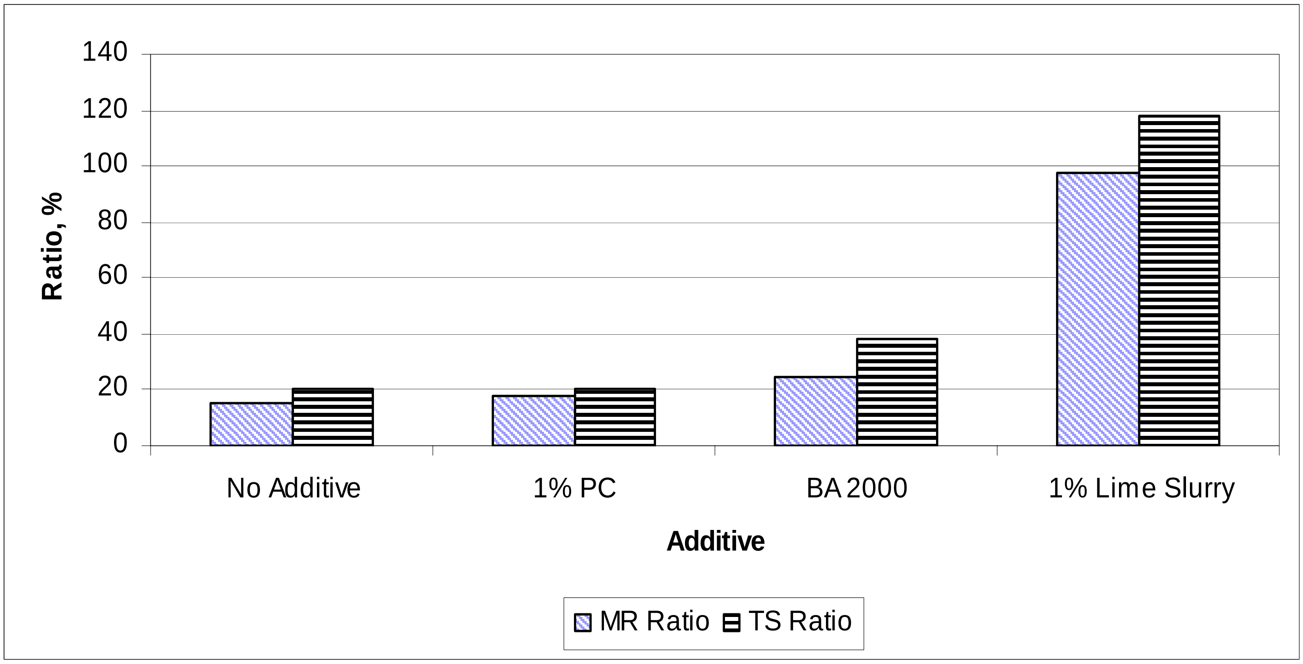


Figure 11. Effect of Various Additives on the Retained Strength (Following Lottman Conditioning) of Asphalt Mixtures with 6.0% Asphalt Cement [Epps (1992)].

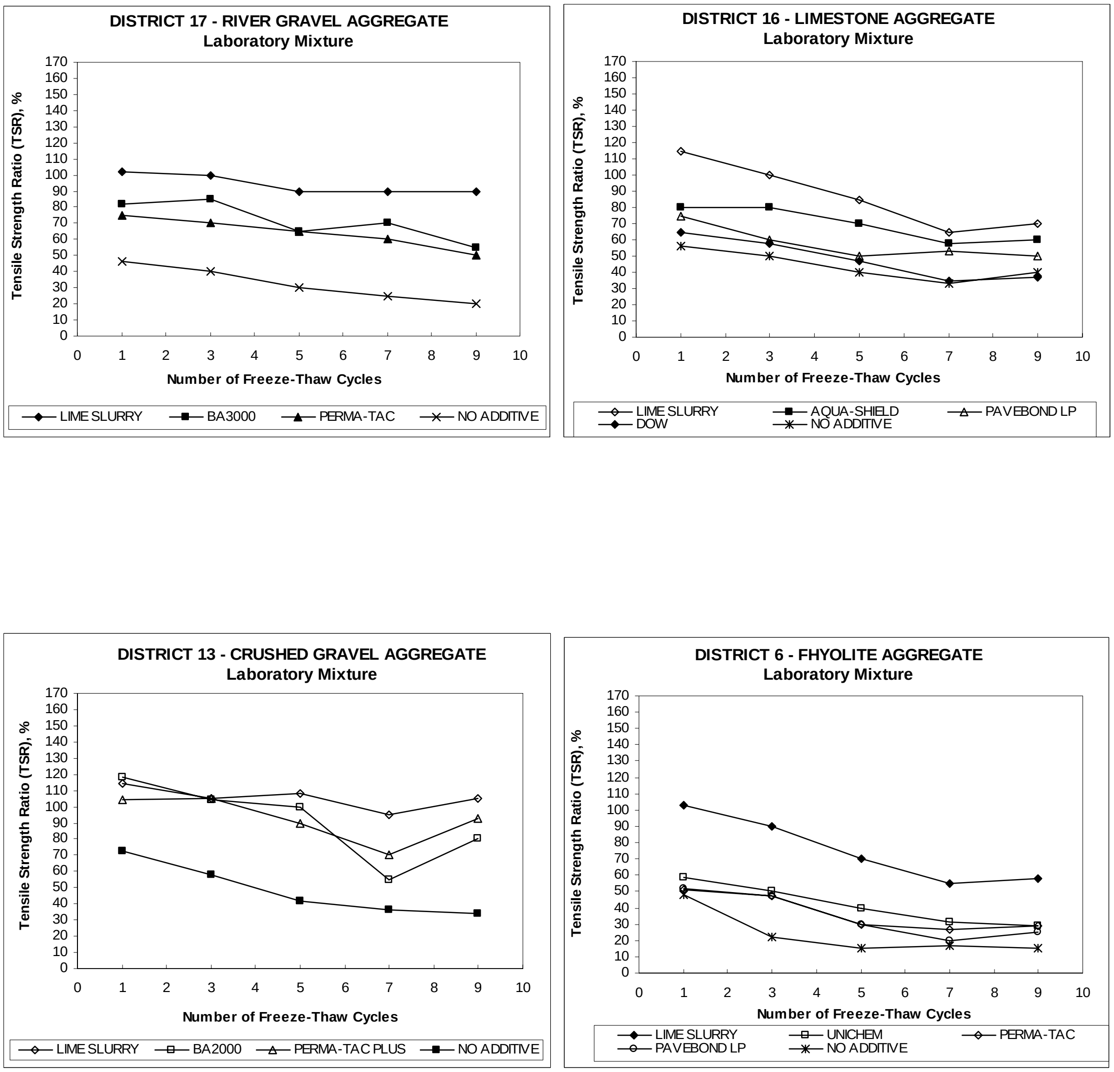
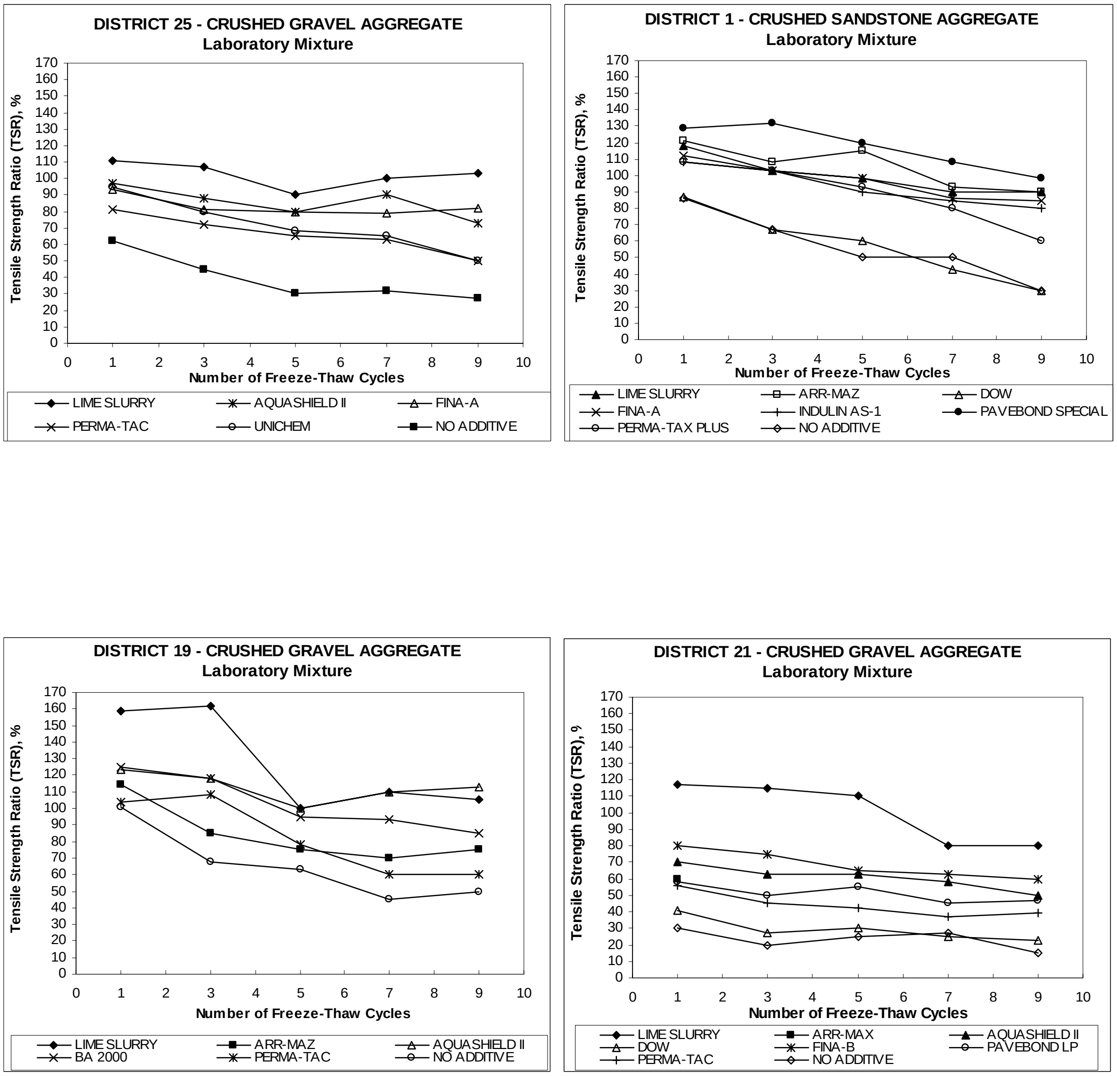


Figure 12. Multiple Freeze-Thaw Cyclic Tests Results for Laboratory Mixtures Comparing Severity of Tests Method on the Ability to Differentiate Between Lime and Other Anti-Strip Additives [Kennedy and Ping (1991)]. (continued on next page)


DISTRICT 25 - CRUSHED GRAVEL AGGREGATE Laboratory Mixture

DISTRICT 1 - CRUSHED SANDSTONE AGGREGATE Laboratory Mixture

DISTRICT 19 - CRUSHED GRAVEL AGGREGATE Laboratory Mixture

DISTRICT 21 - CRUSHED GRAVEL AGGREGATE Laboratory Mixture

Figure 12. Multiple Freeze-Thaw Cyclic Tests Results for Laboratory Mixtures Comparing Severity of Tests Method on the Ability to Differentiate Between Lime and Other Anti-Strip Additives [Kennedy and Ping (1991)] (continued).

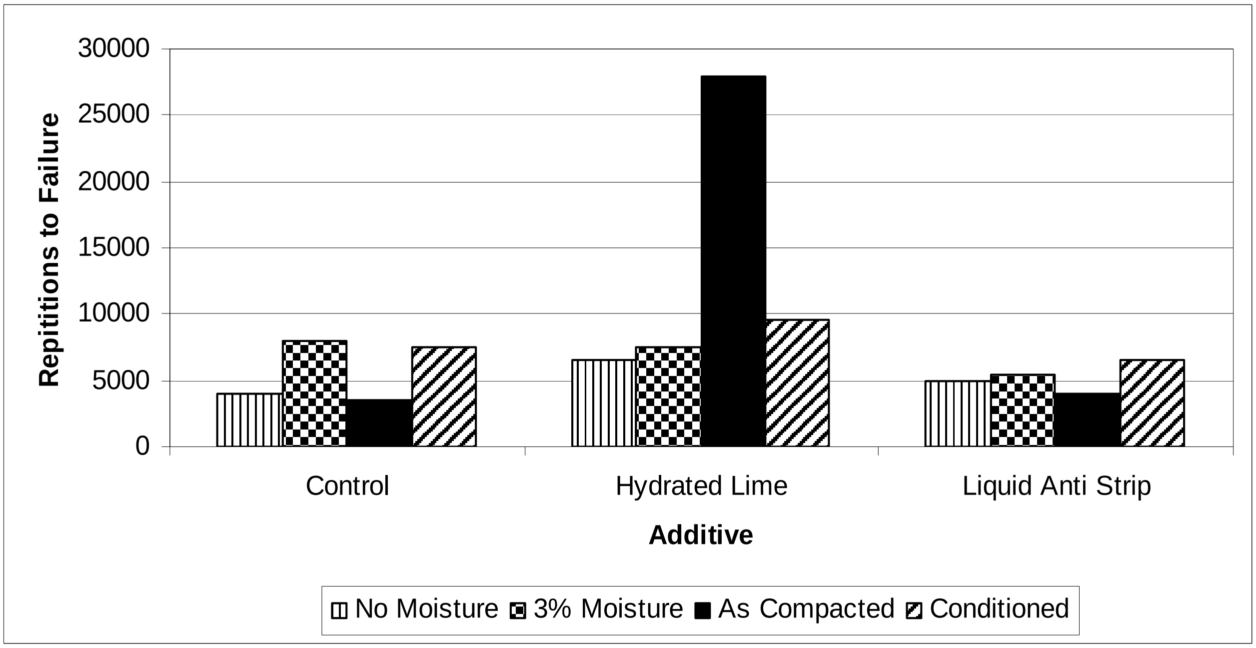


Figure 13. The Effect of Additives on Fatigue Life - Oregon Department of Highways Field Study [Kim et al. (1995)].

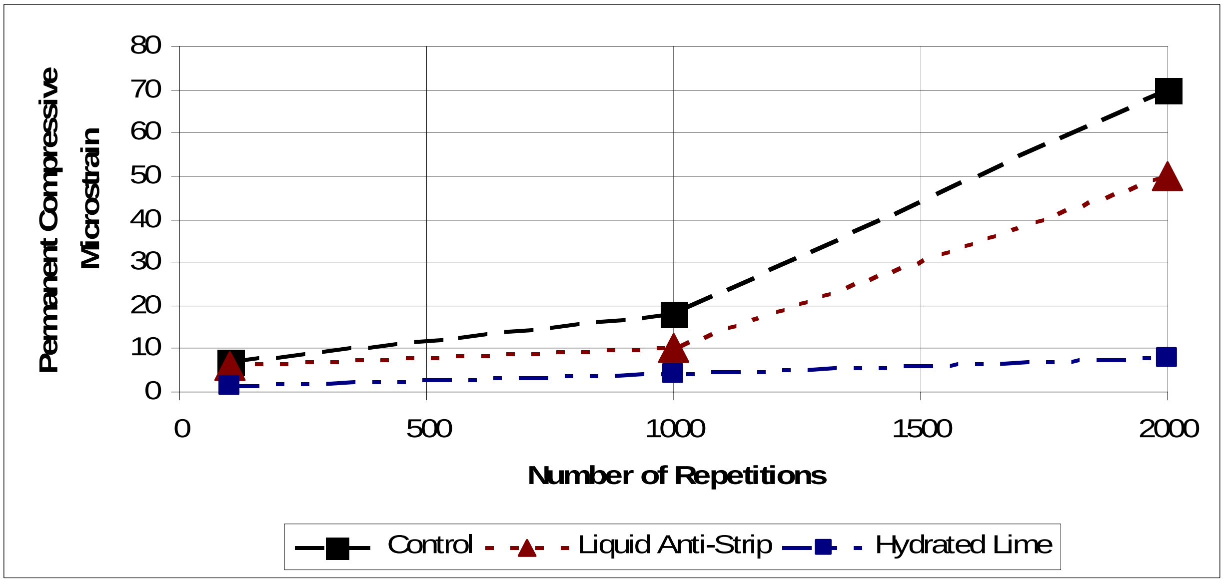


Figure 14. Effect of Additives (Without Moisture) on Permanent Deformation - Oregon Department of Highways Field Study [Kim et al. (1995)].

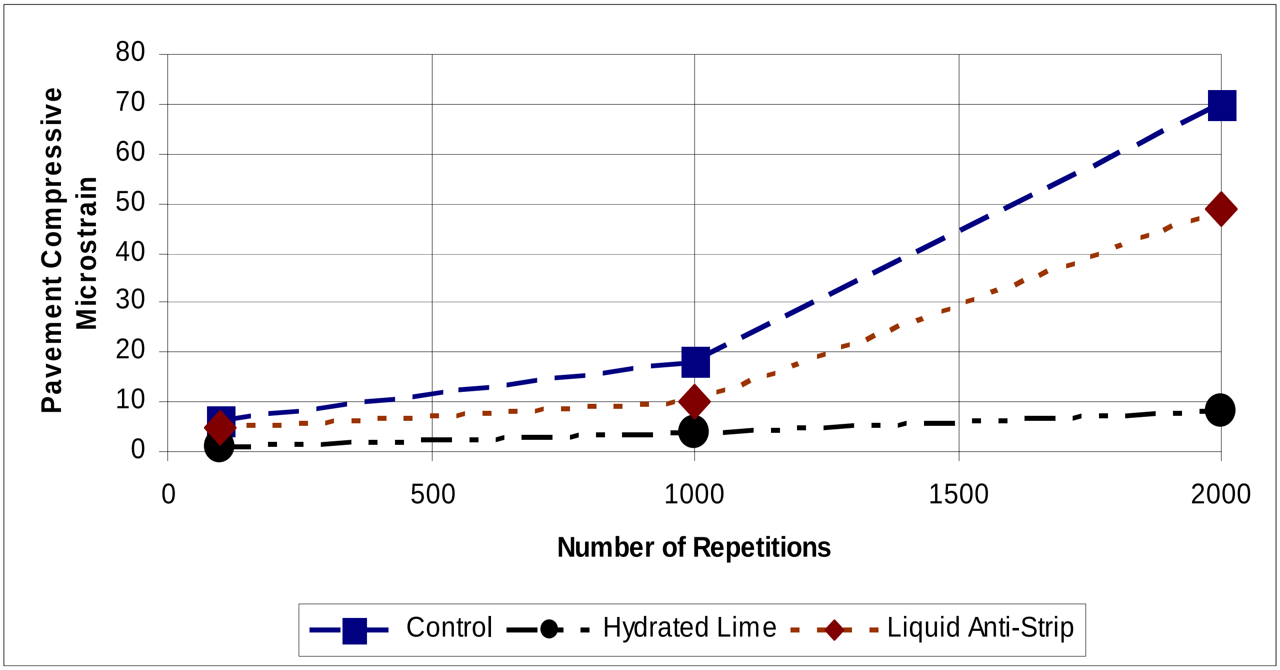


Figure 15. Effect of Additives (With Moisture) on Permanent Deformation - Oregon Department of Highways Field Study [Kim et al. (1995)].

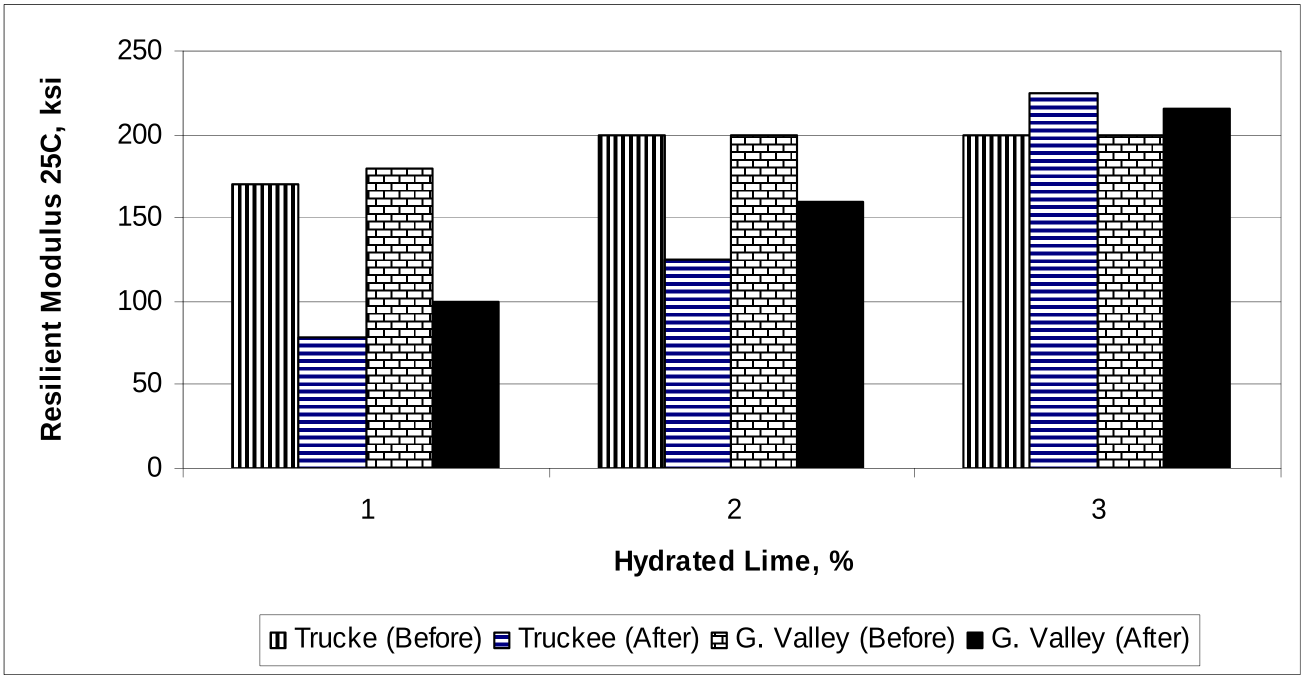


Figure 16. Effect of Hydrated Lime on the Resilient Moduli Before and Following Lottman Conditioning for Truckee and Grass Valley, California Mixtures [Epps et al.(1992)].

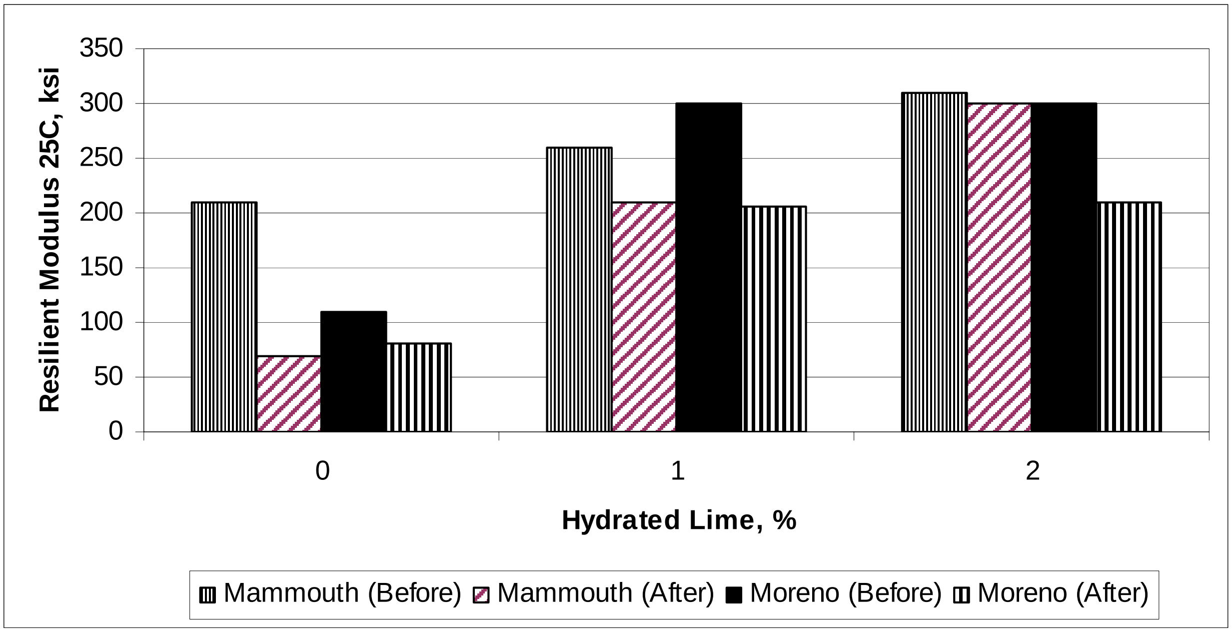
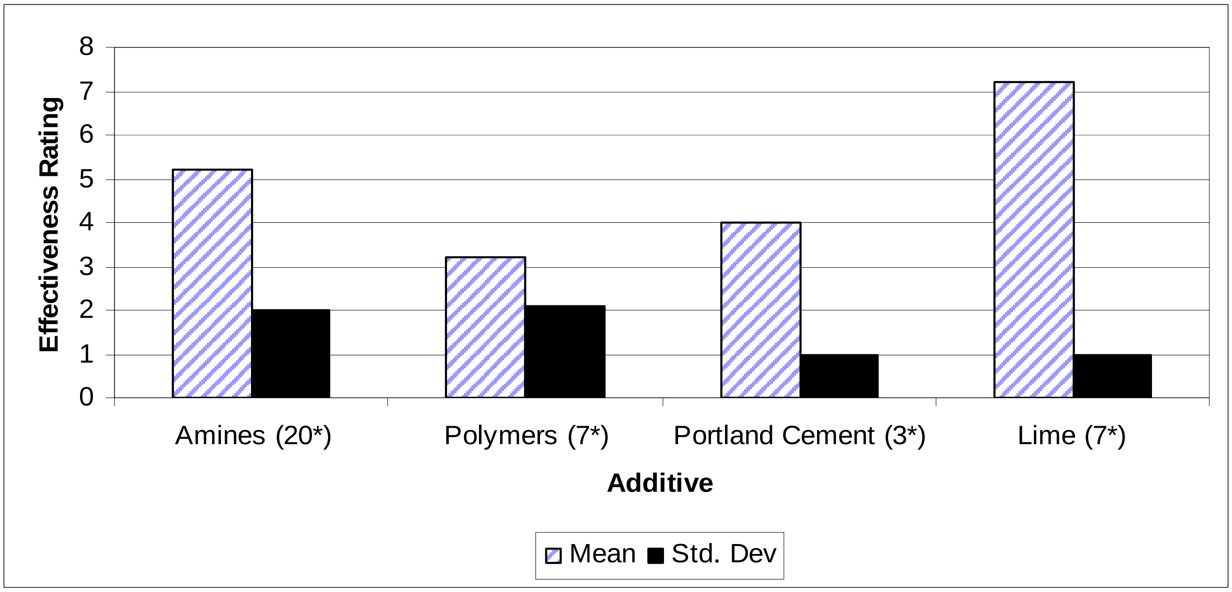


Figure 17. Effect of Hydrated Lime on the Resilient Moduli Before and Following Lottman Conditioning for Mammoth and Moreno, California Mixtures [Epps et al.(1992)].



* Note: numbers in parentheses represent number of responses.

Figure 18. Relative Effectiveness of Additives in Eliminating or Reducing Moisture Problems [Hicks (1991)].

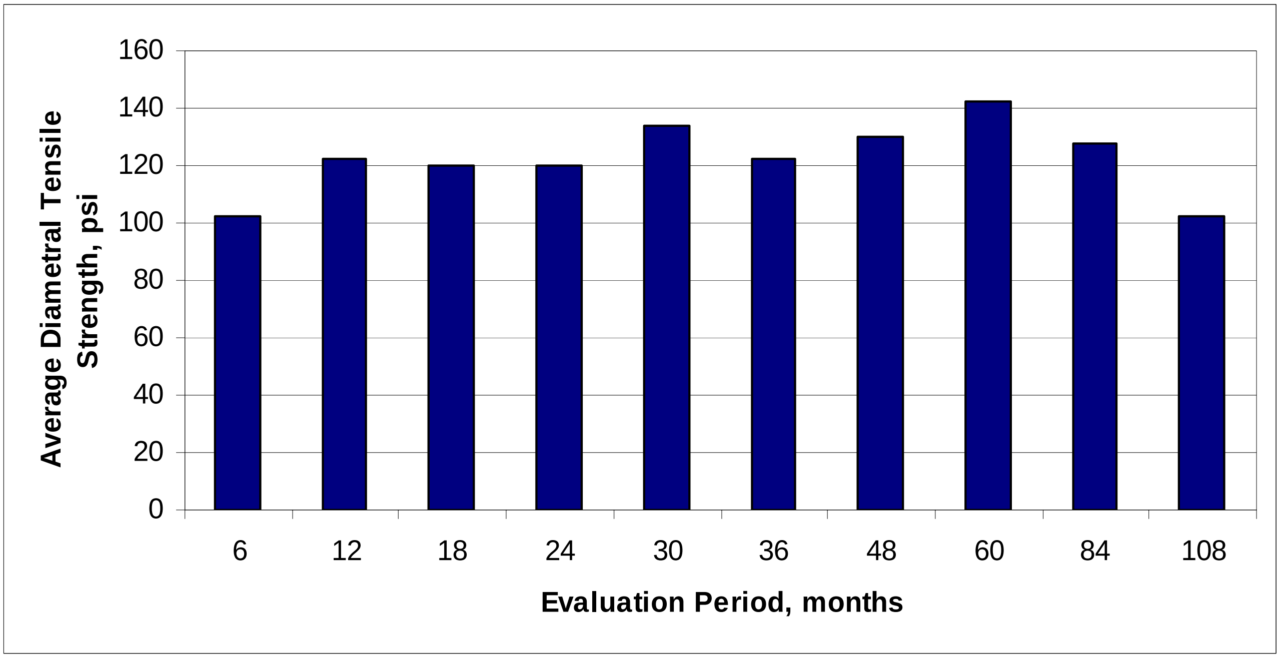


Figure 19. Effect of Time on the Average Diamentral Tensile Strength Based on Core from Georgia Field Study [Watson (1992)].

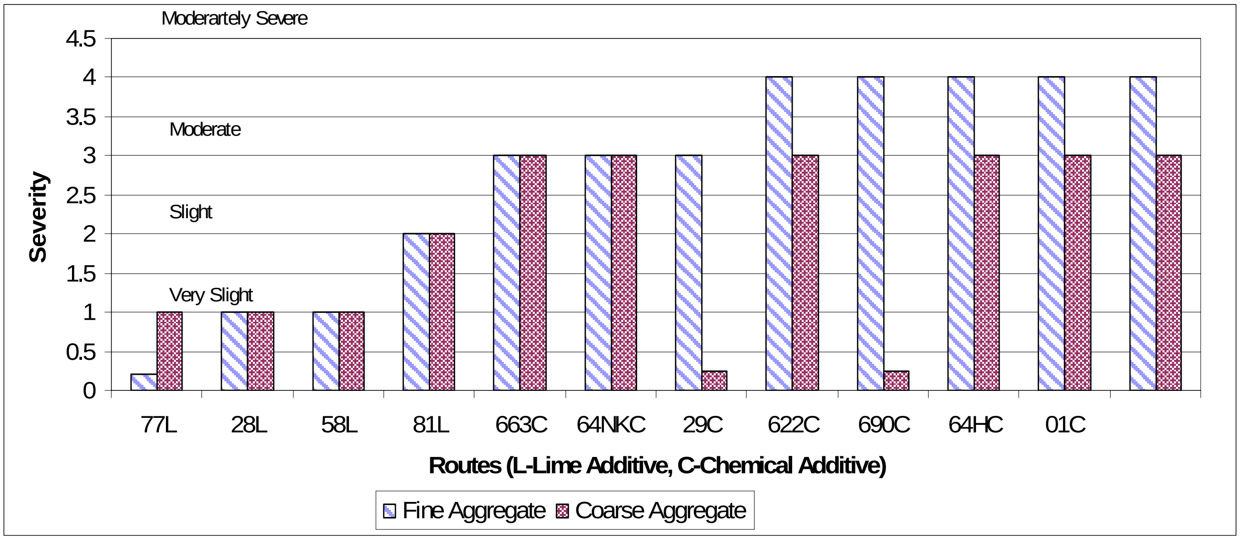


Figure 20. Severity of Stripping as Determined by Maupin for Virginia Pavements [Maupin (1995)].

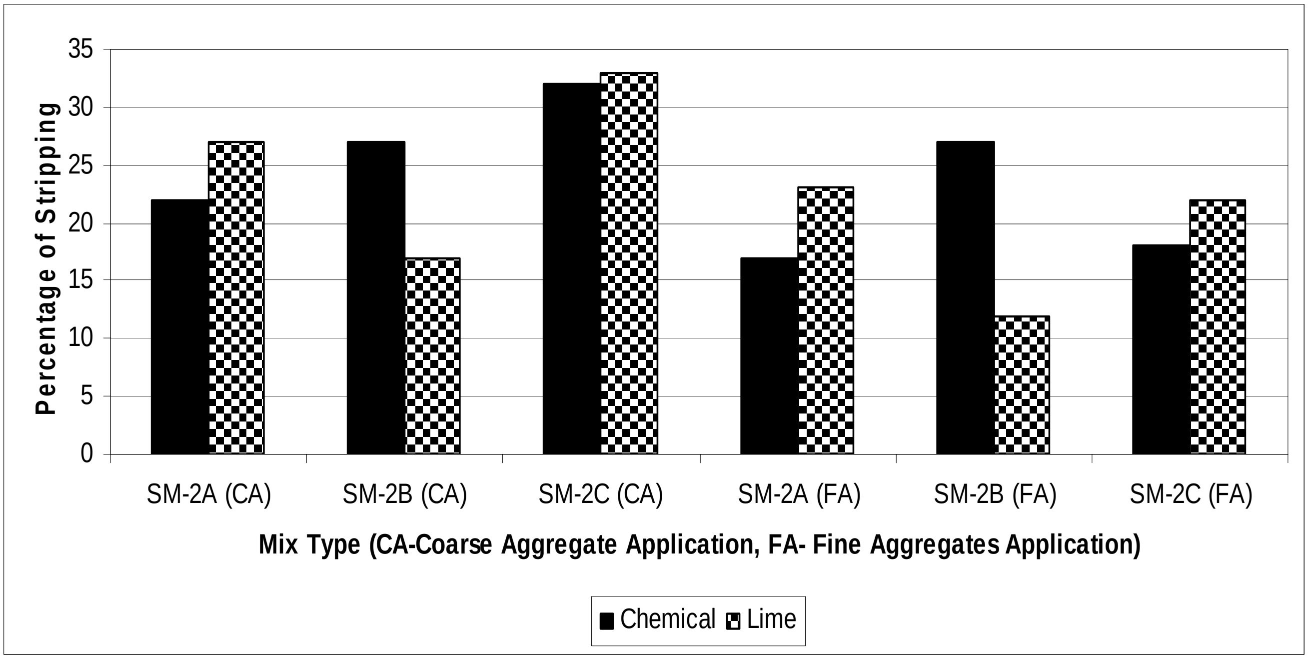


Figure 21. Average Stripping in Aggregates [Maupin (1997)].

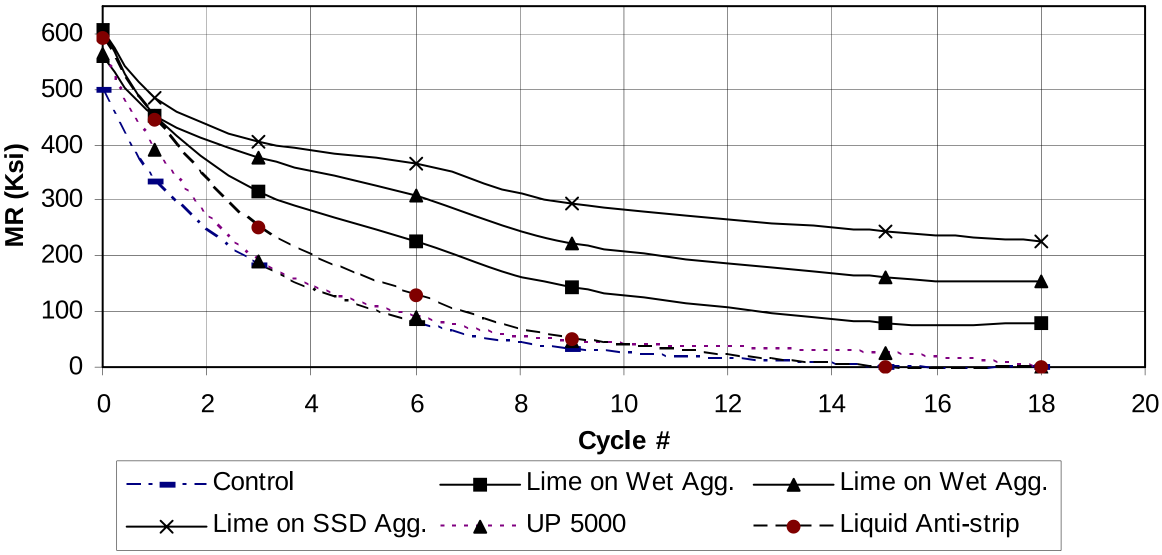


Figure 22. Mr Property as a Function of Freeze-Thaw Cycles for the Mixtures on SD 314 [Sebaaly et al. (2003)].

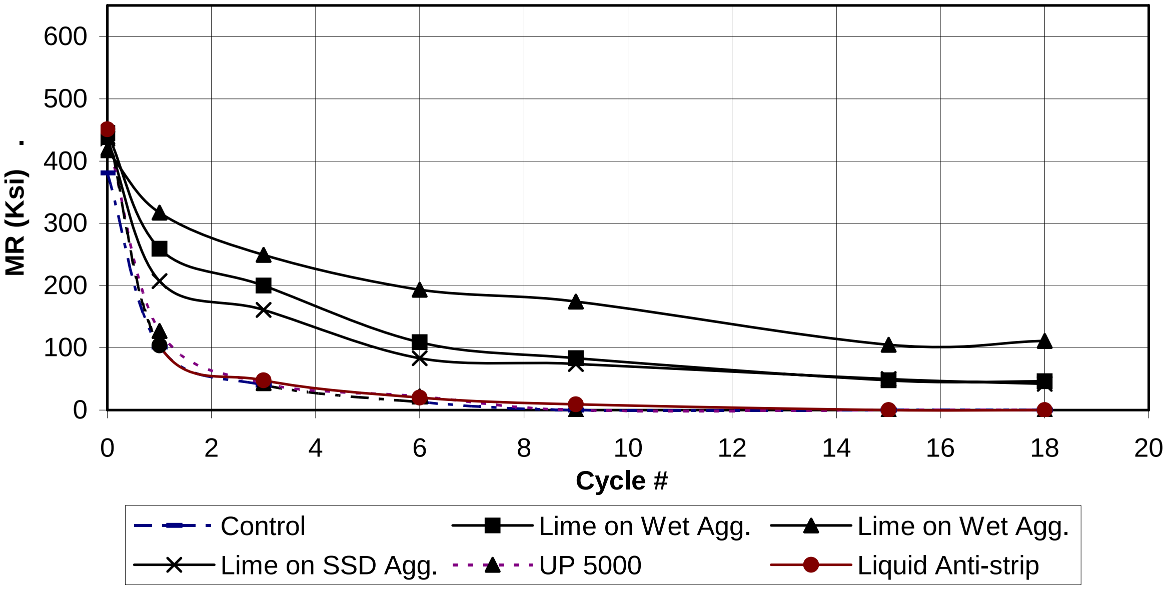


Figure 23. Mr Property as a Function of Freeze-Thaw Cycles for the Mixtures on US 14 [Sebaaly et al. (2003)].

*Note: two replicate sections were constructed using the lime on wet aggregate technique on each project.

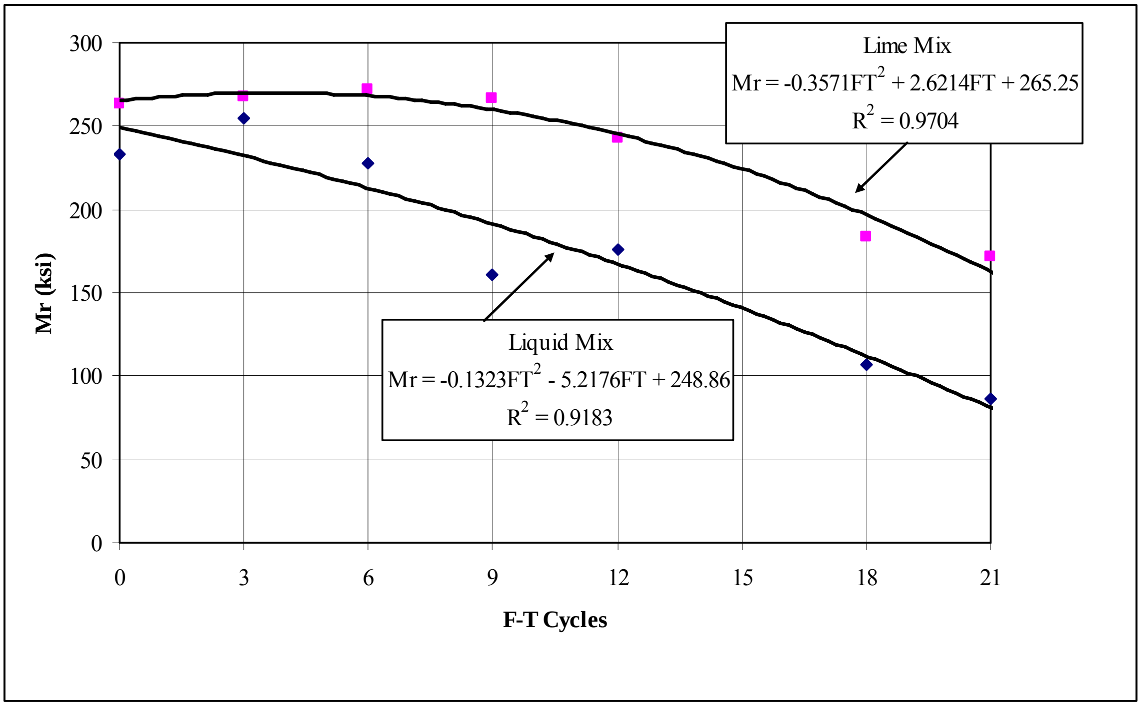


Figure 24. Relationship between Mr and Freeze-Thaw Cycles for Idaho SH67 Mixtures [Sebaaly et al. (2005)].

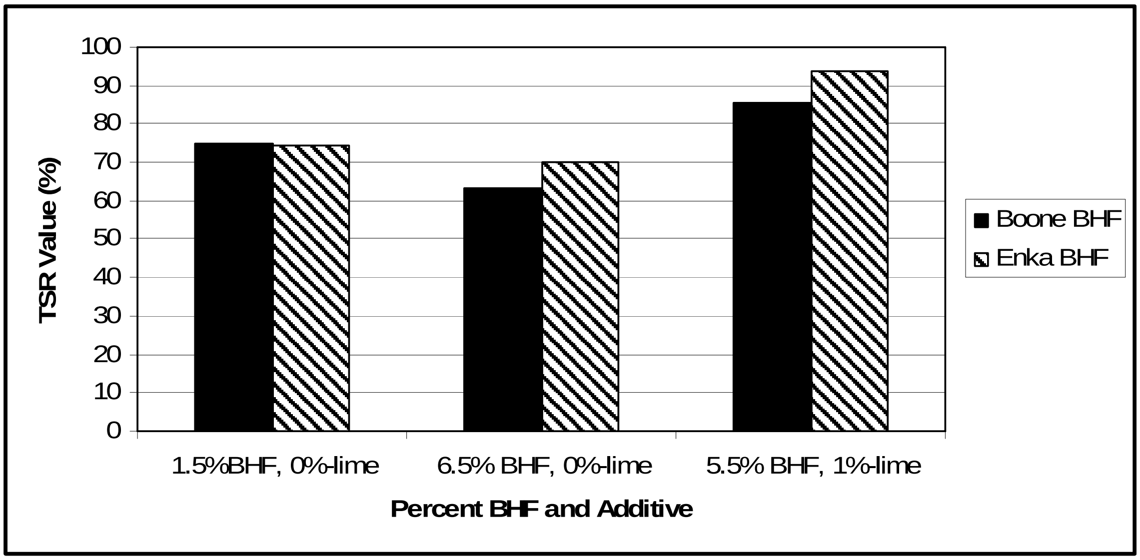


Figure 25. TSR Values of the North Caroline Mixtures with Baghouse Fines [Tayebali and Shidhore (2005)].

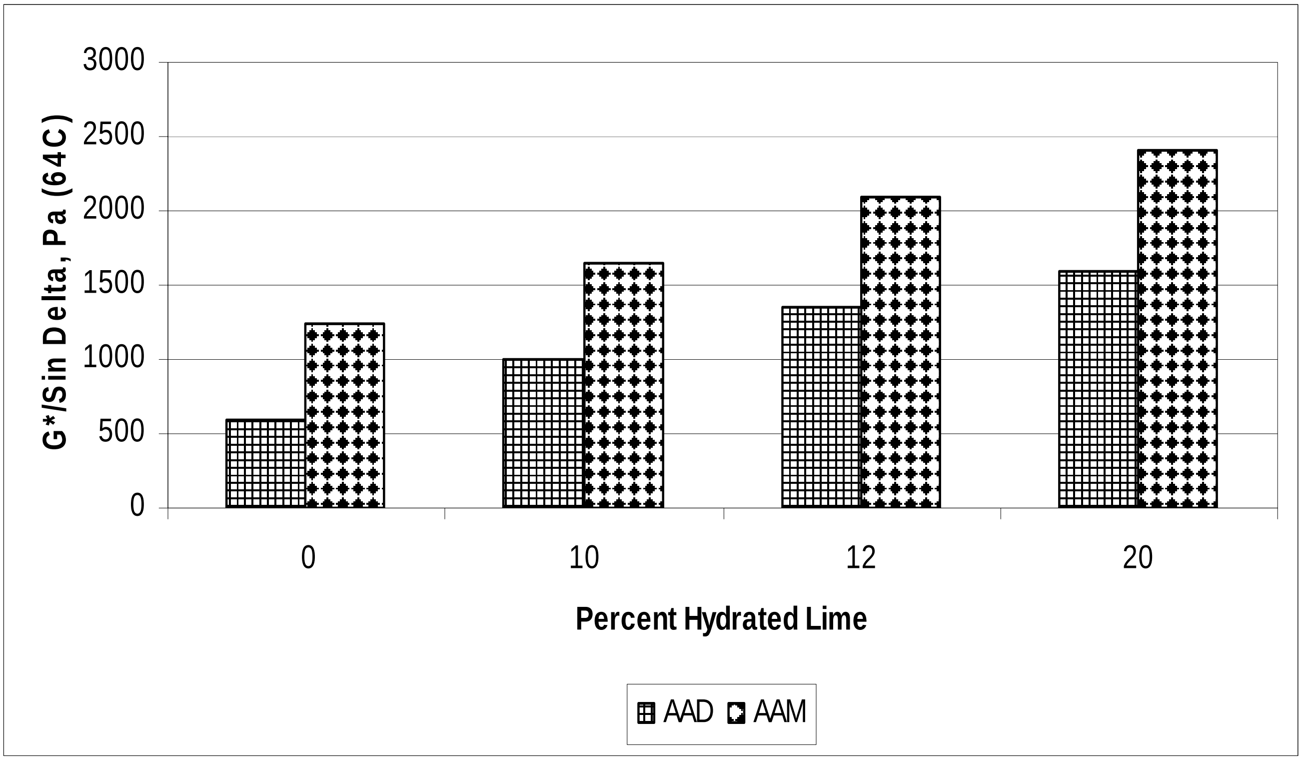


Figure 26. Effect of the Addition of Hydrated Lime (percent by weight of binder) on Asphalt Binder Rheology, G*/sin δ [Little (1996)].

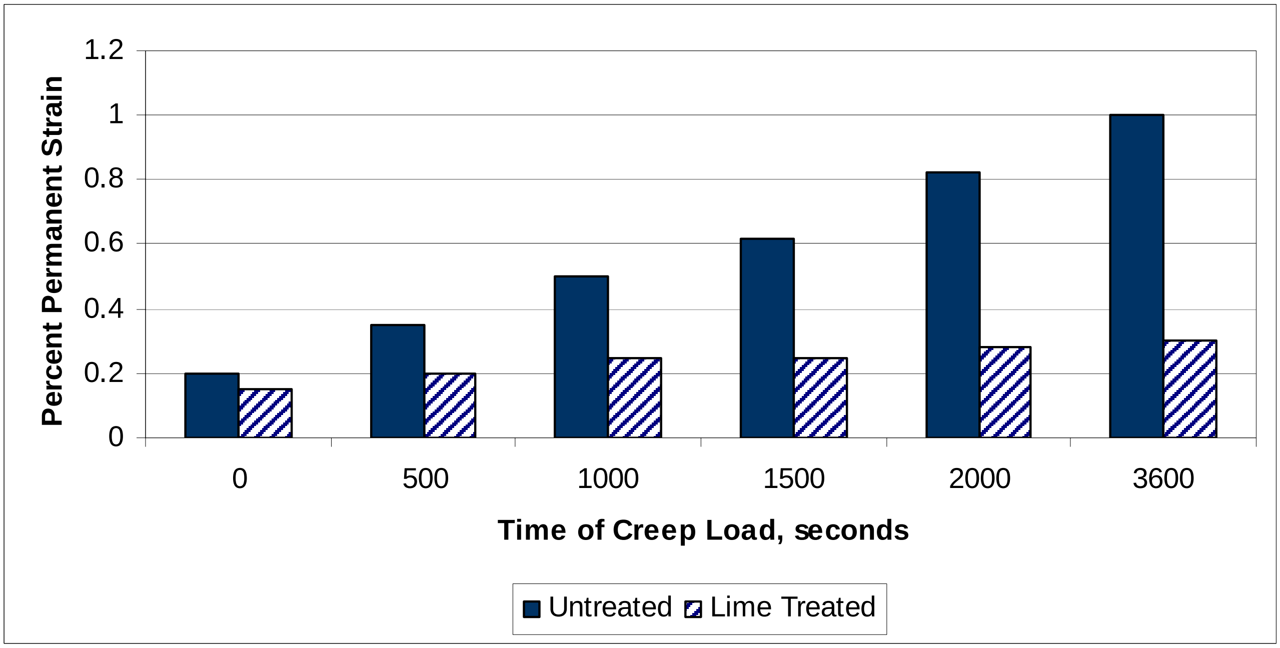


Figure 27. Creep Strains Measured After Lottman Conditioning on Natchez, Mississippi, Asphalt Mixture [Little (1994)].

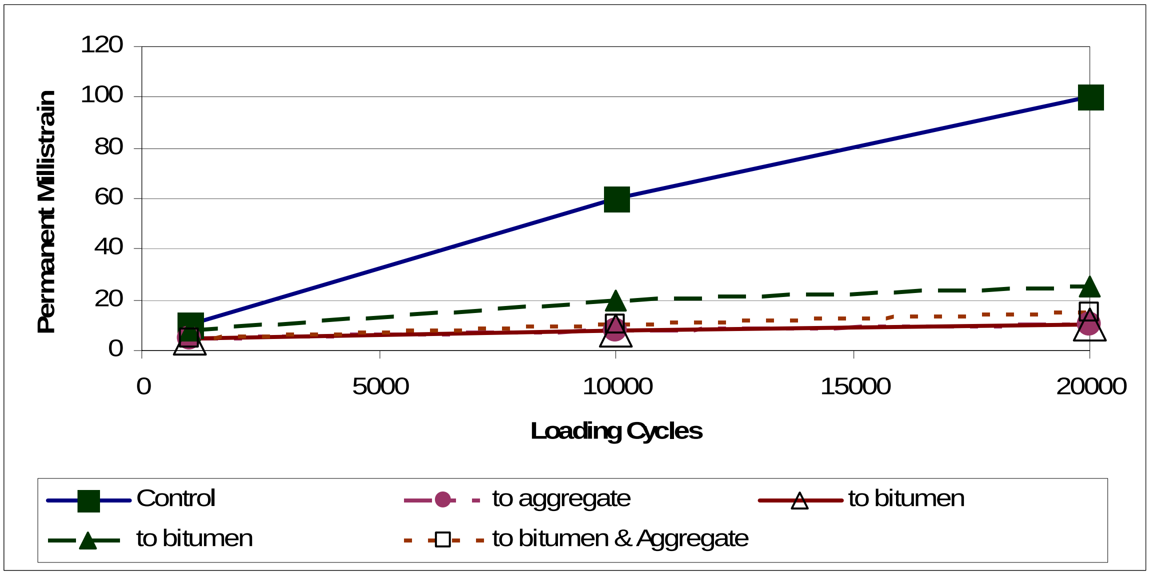


Figure 28. Lime Added to Hot Mix in Various Modes (to the Aggregate or to the Bitumen) Strongly Affects the Rut Resistance of the Mixture Even Under High Temperature and Moisture [Lesueur et al. (1998)].

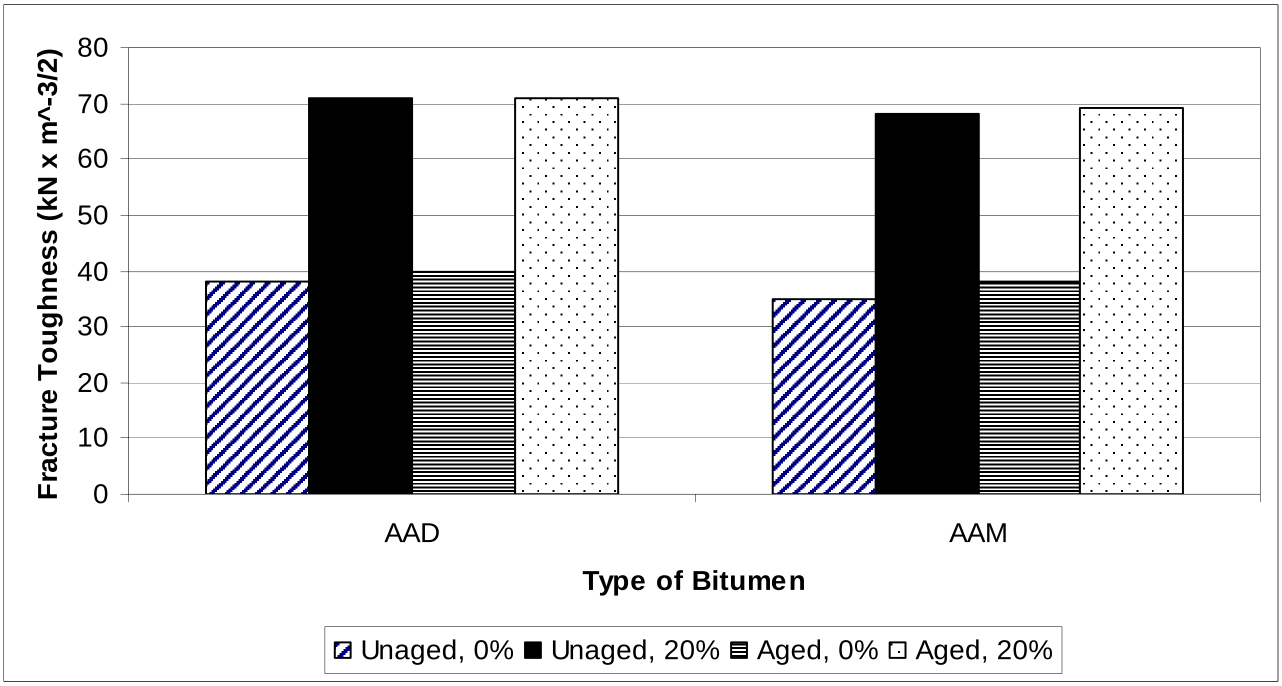


Figure 29. Hydrated Lime Improves Low Temperature Toughness of the Lime-Modified Bitumen [Lesueur and Little (1999)].

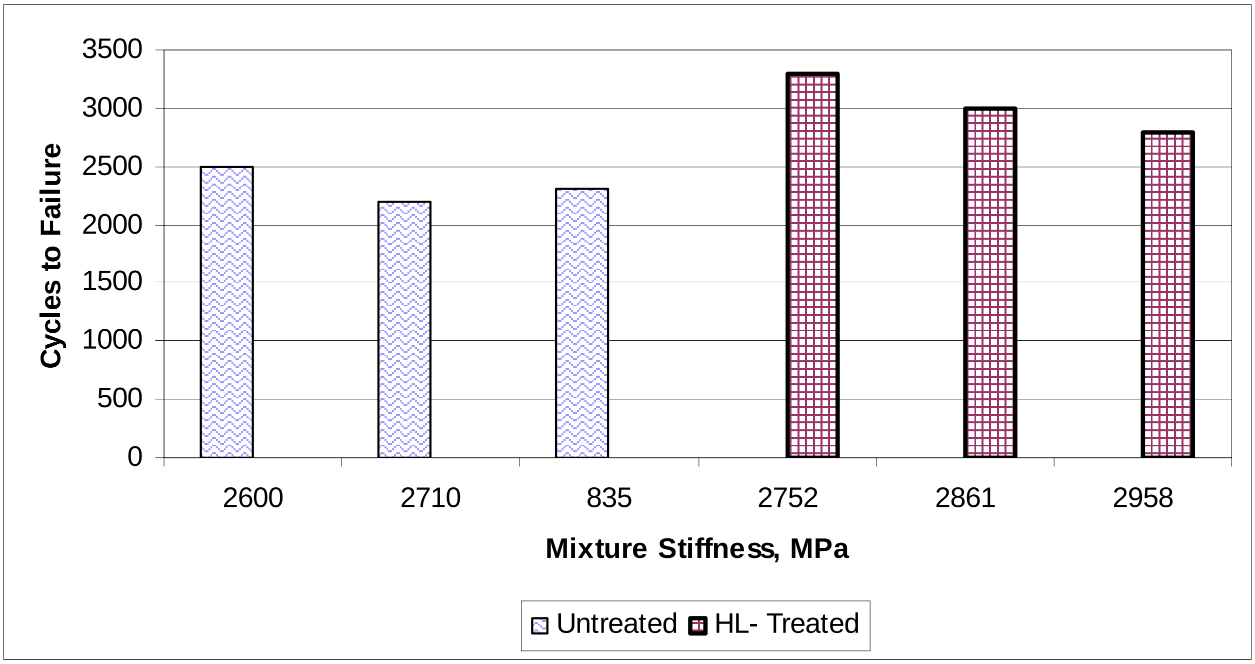


Figure 30. Hydrated Lime Added to the Bitumen Improves the Toughness of the Bitumen and Improves Fatigue Life When Compared to the Identical Mixture Without Lime [Lesueur and Little (1999)].

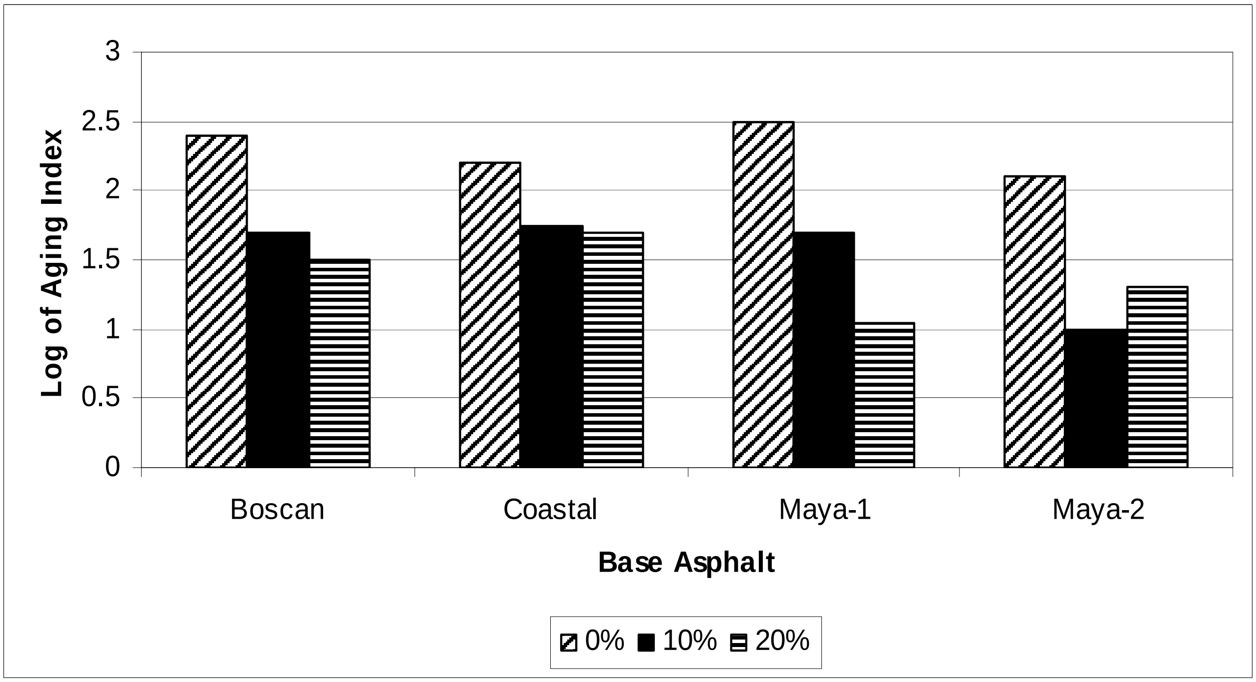
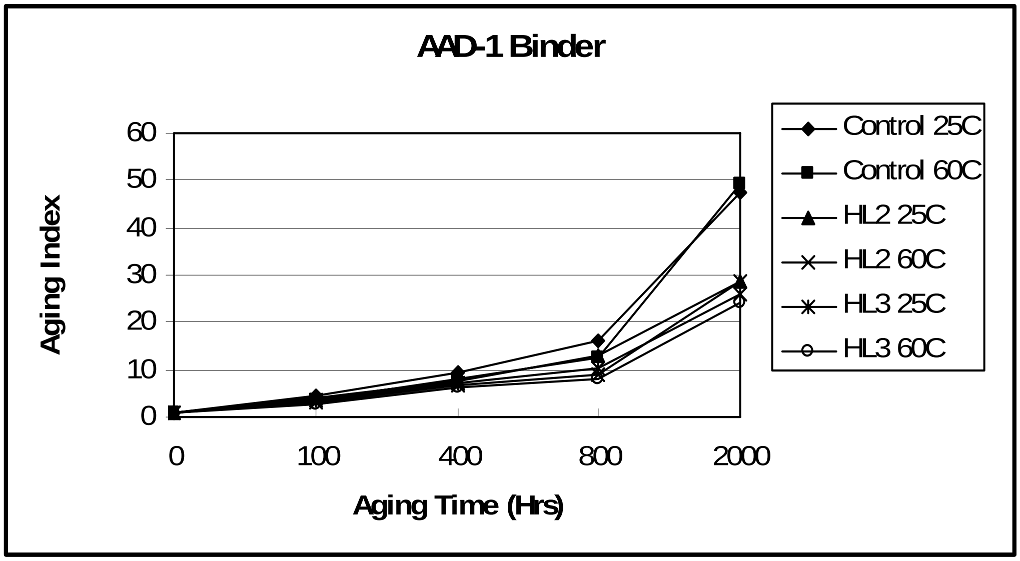


Figure 31. Effect of Hydrated Lime in Reducing the Aging Index of Asphalt Binders [Petersen et al. (1987)]



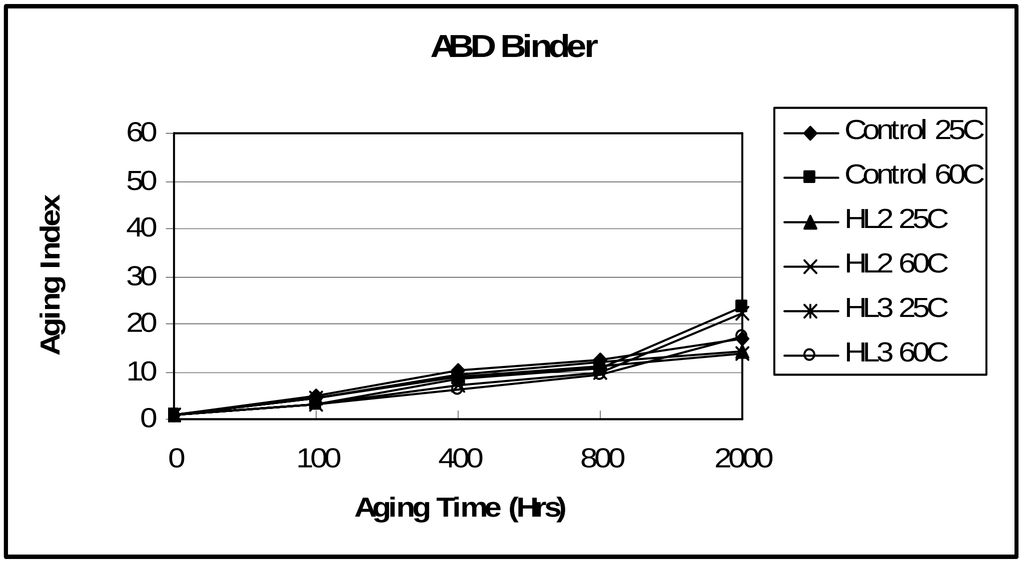


Figure 32. Aging Index of Untreated and Lime-Treated Asphalt Binders [Huang et al. (2002].

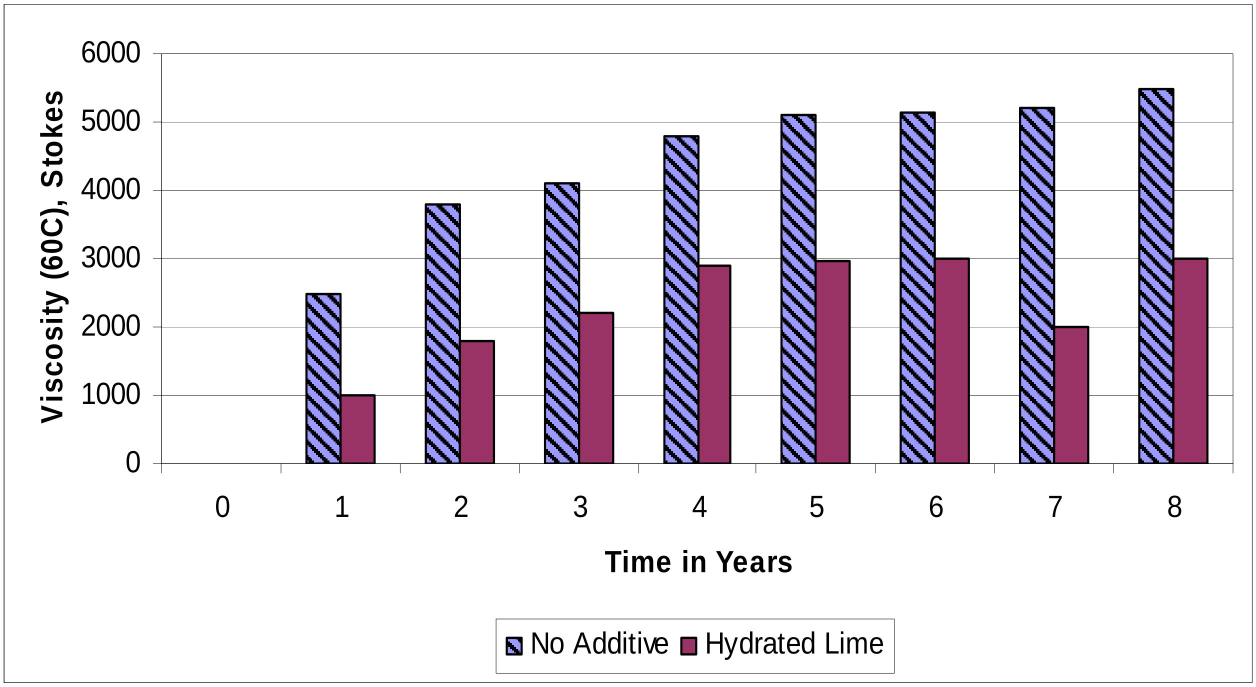


Figure 33. Field Data Demonstrating the Effect of Hydrated Lime on the Hardening of Asphalt Binder Based on Utah Data [Jones (1997)].

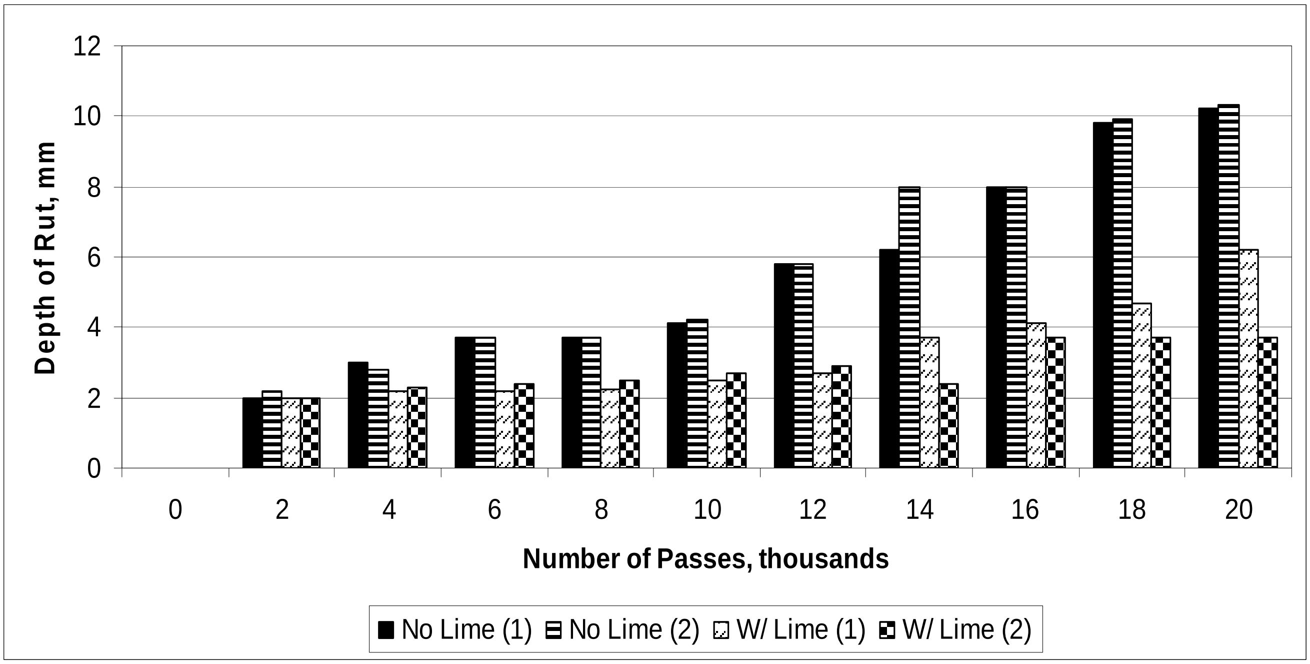


Figure 34. Results of Rut Tracking Tests from Wuppertal-Dornap, Germany [Radenberg (1998)].

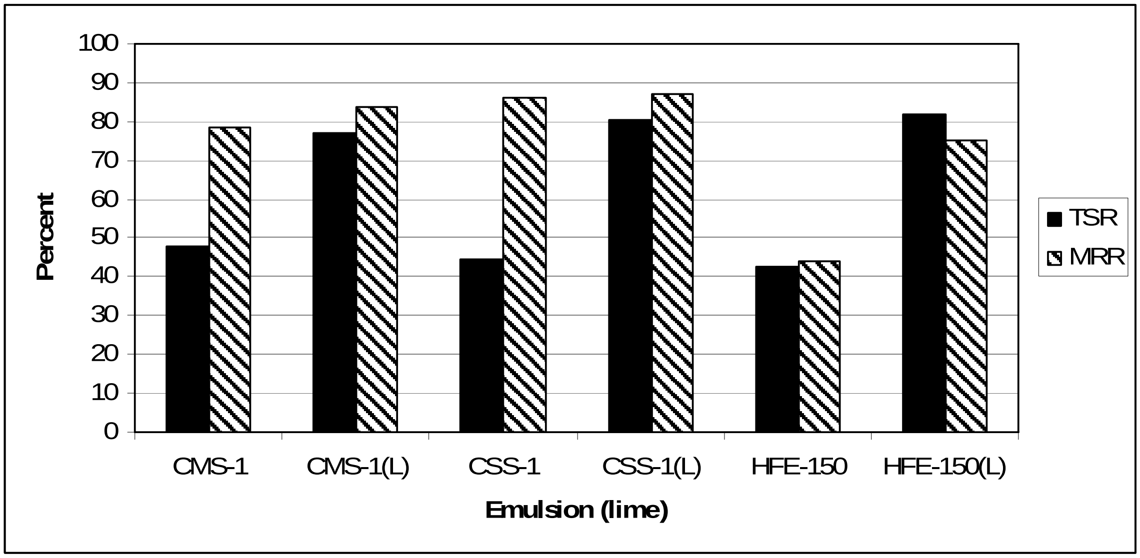


Figure 35. Tensile Strength Ratio (TSR) and Resilient Modulus Ratio (MRR) of Kansas CIR Mixtures [Cross (1999)].

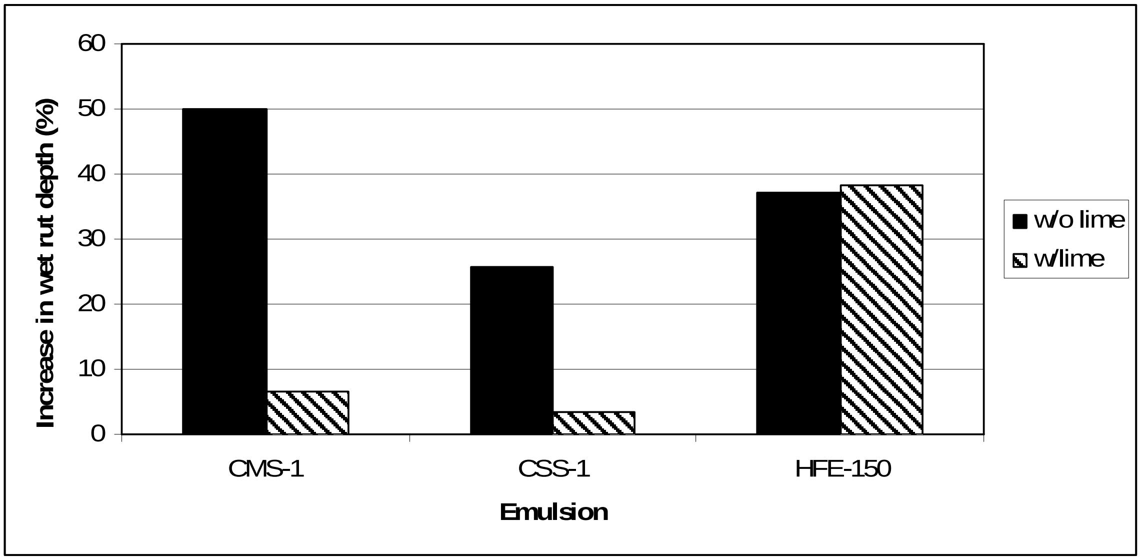
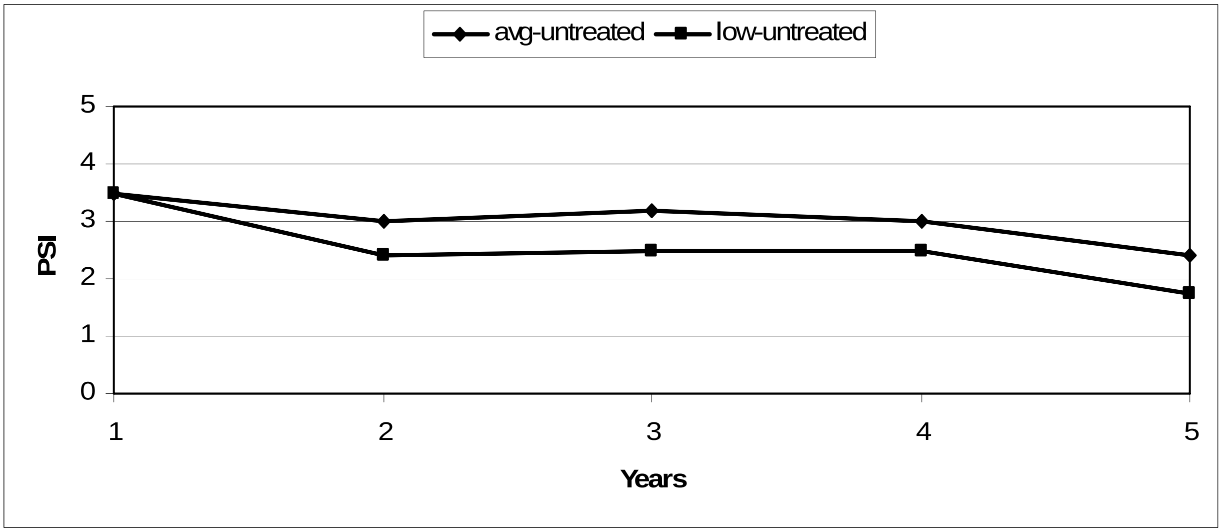


Figure 36. Percent Increase in Rut Depth of Kansas CIR Mixtures in the APA Underwater after 8,000 Cycles [Cross (1999)].



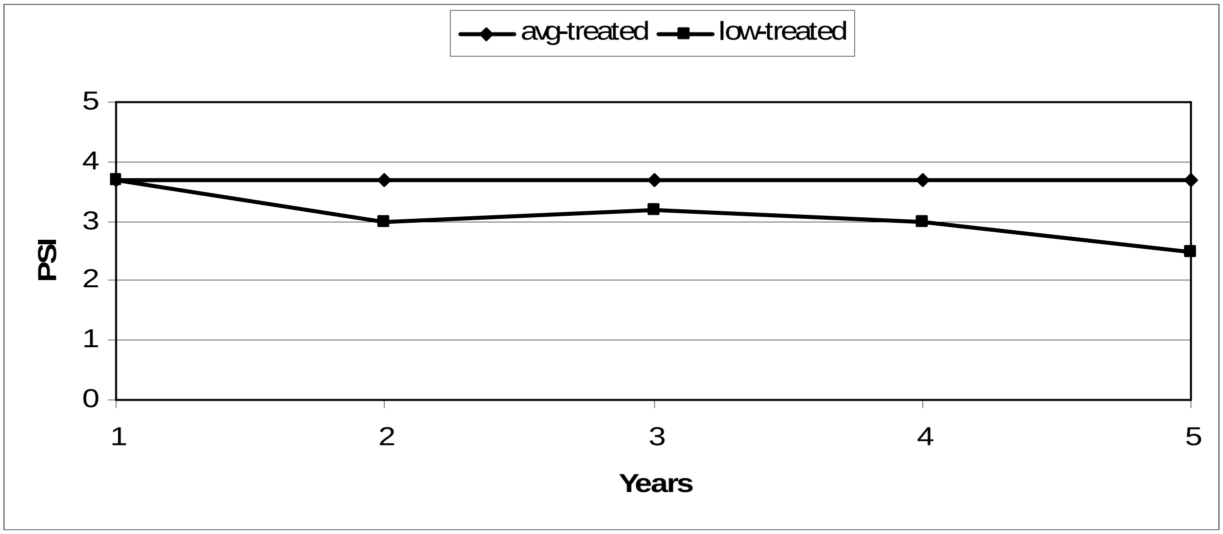


Figure 37. Average and Low Values of PSI for Untreated and Lime-Treated Mixtures on I-80 in Northern Nevada [Sebaaly et al. (2003)].

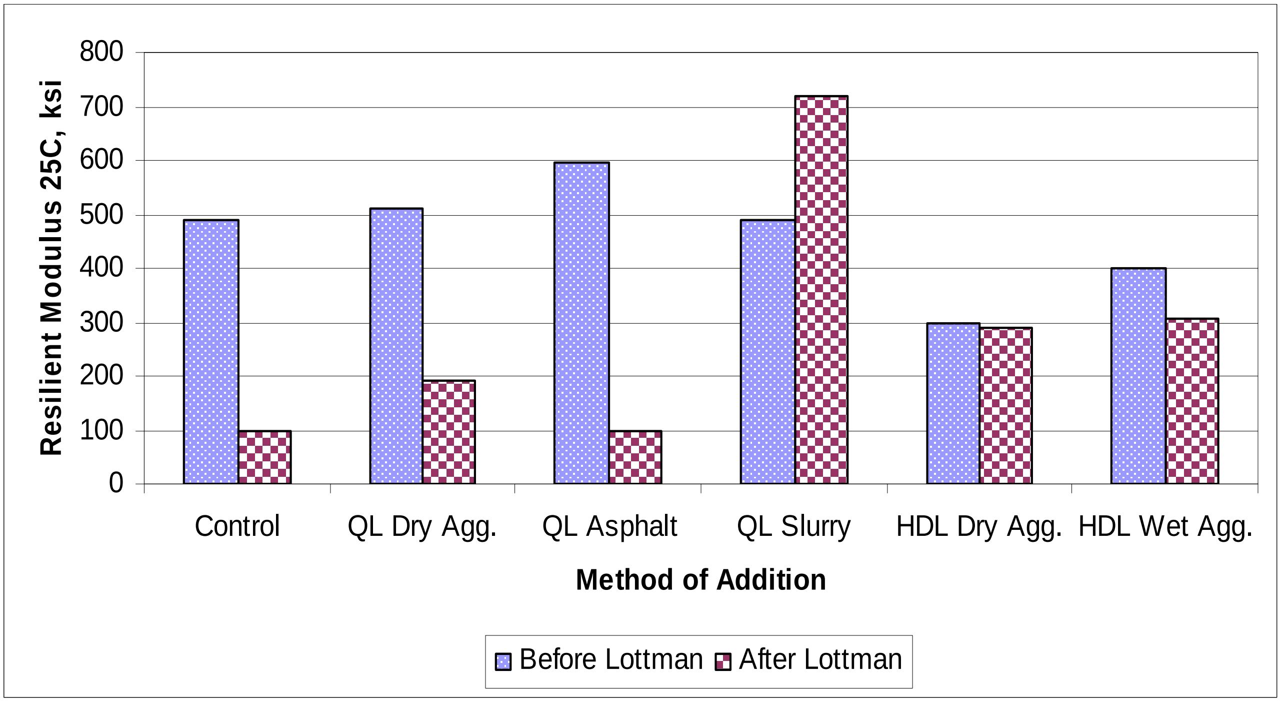


Figure 38. Effect of the Method of Hydrated Lime Addition on the Retained Resilient Modulus After Lottman Conditioning [Waite et al. (1986)].

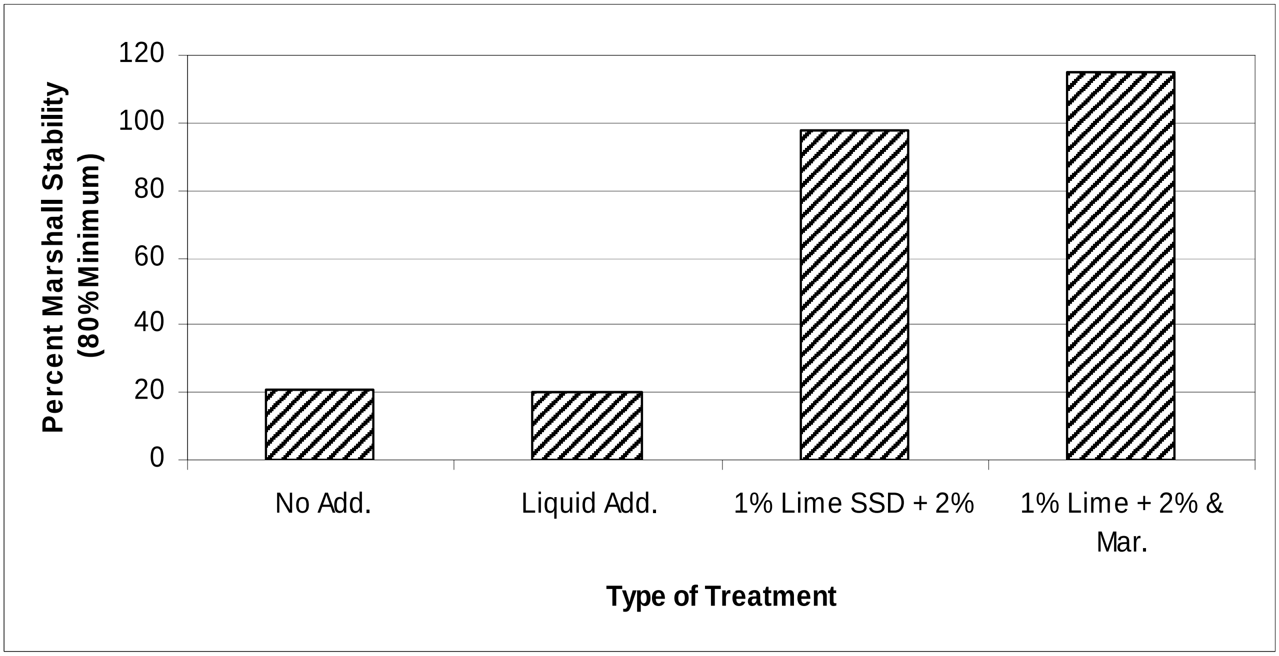


Figure 39. Effect of the Type of Additive and Method of Addition on the Retained Tensile Strength of Materials from SR-50, Millard County Line to Salina, Utah [Betenson (1998)].

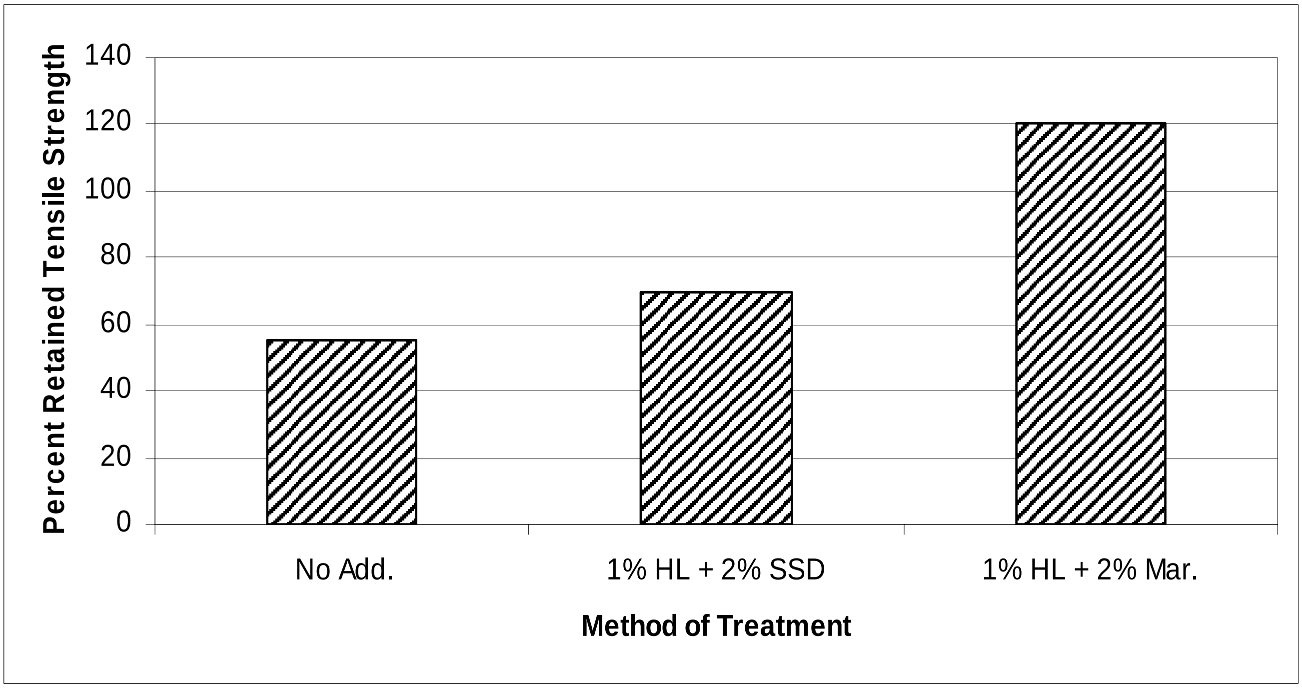
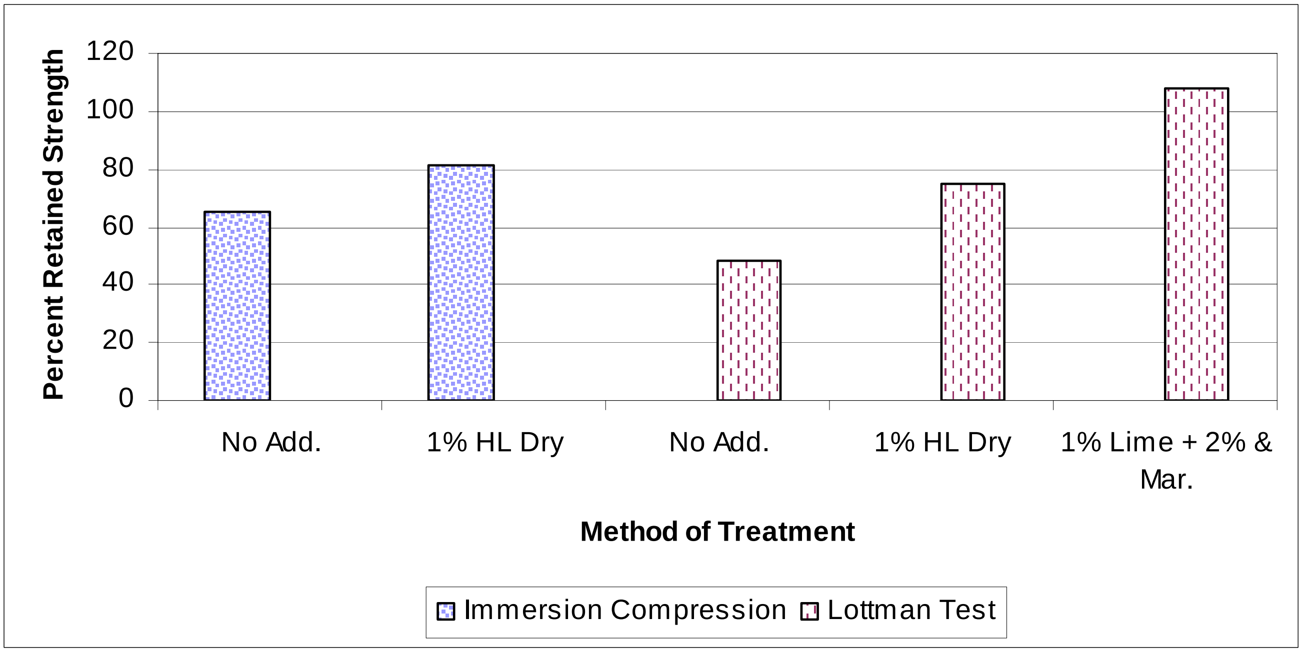
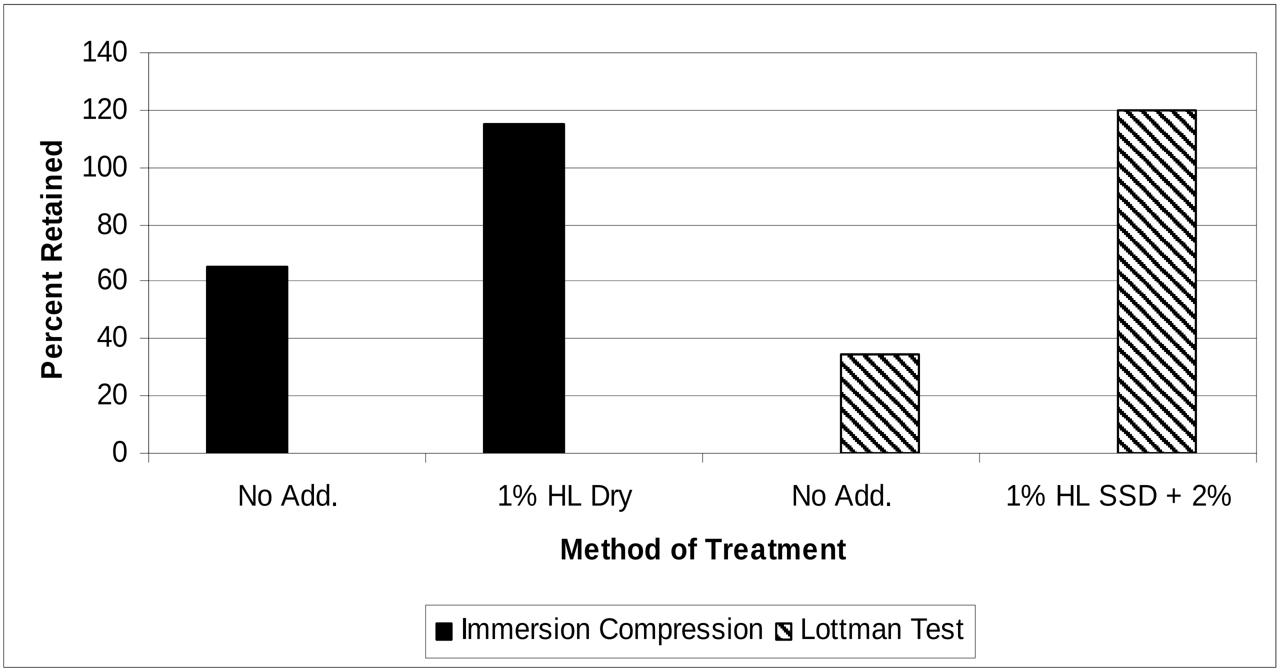


Figure 40. Effect of Method of Lime Addition on Tensile Strength Ratio for Materials from I-70 Wetwater to Colorado Line, Utah DOT [Betenson (1998)].



* 2% & Mar.: 2% moisture above SSD with marination.

Figure 41. Effect of Method of Lime Addition on the Retained Compressive and Tensile Strengths for Main Street in Richfield, Utah [Betenson (1998)].



*   SSD + 2% = saturated surface dry plus 2% additional water

Figure 42. Effect of Method of Lime Addition on Retained Compressive and Tensile Strength for I-70 Spring Canyon to Wide Hollow, Utah [Betenson (1998)].

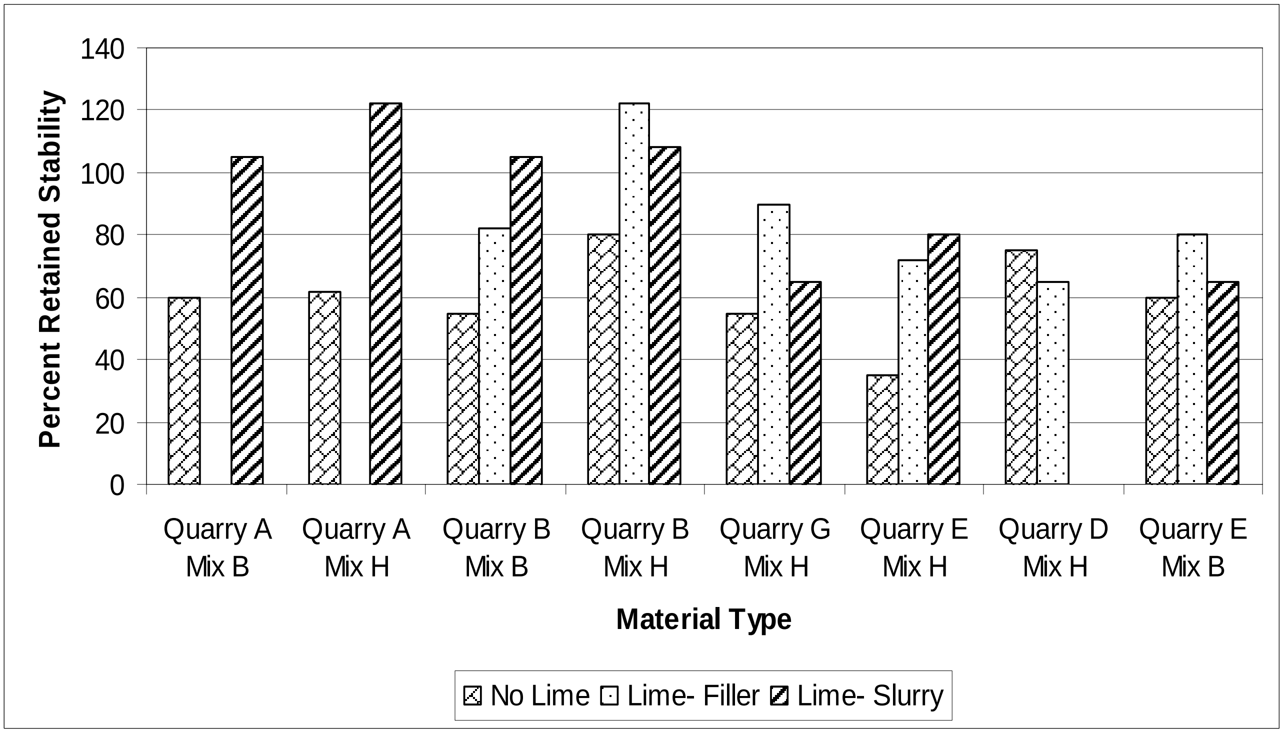


Figure 43. Effect of the Addition of Lime and Method of Addition on the Retained Stability for Georgia DOT Mixtures [Collins (1988)].

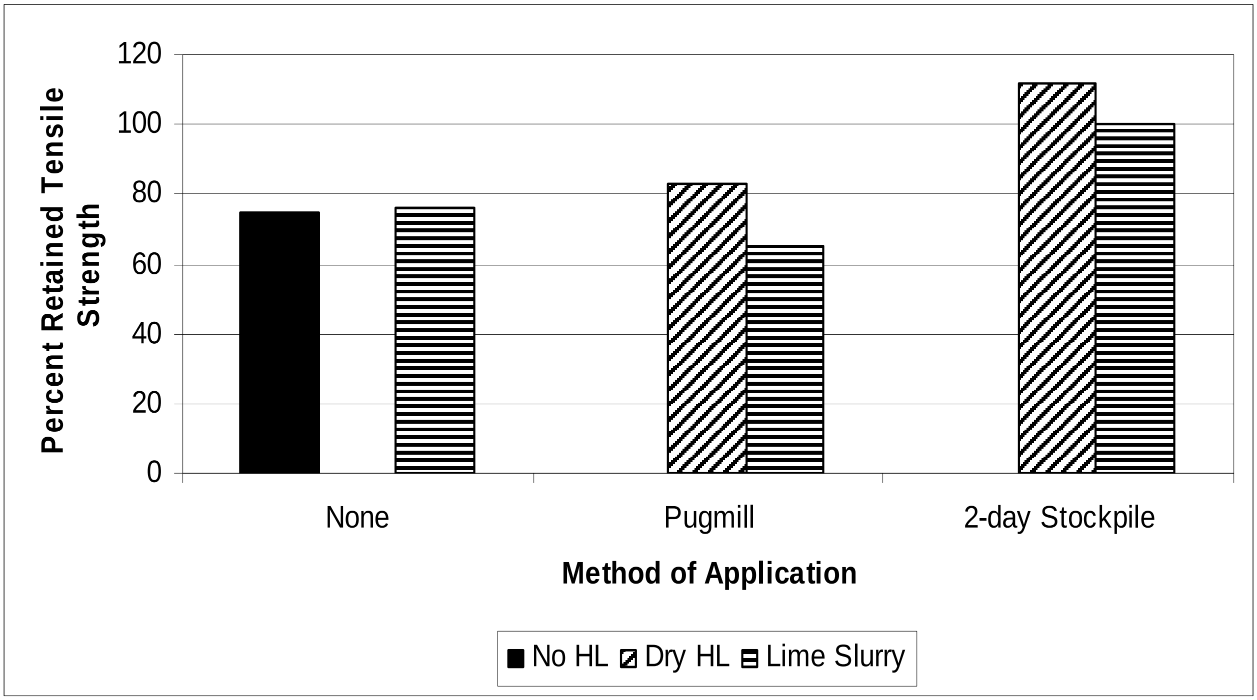


Figure 44. Effect of Method of Application on Retained Tensile Strengths of Batch Plant Operations in Texas [Button and Epps (1983)].

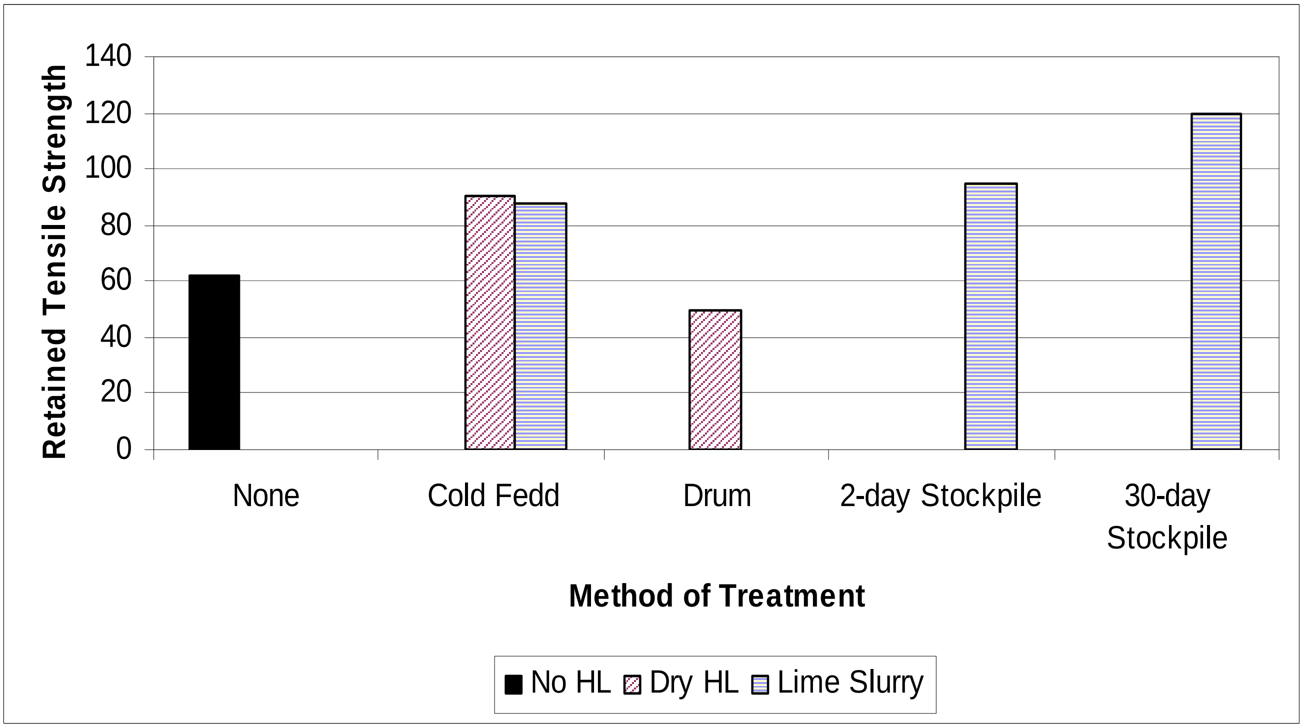


Figure 45. Effect of Addition of Lime to Drum Plant Operations [Button and Epps (1983)].

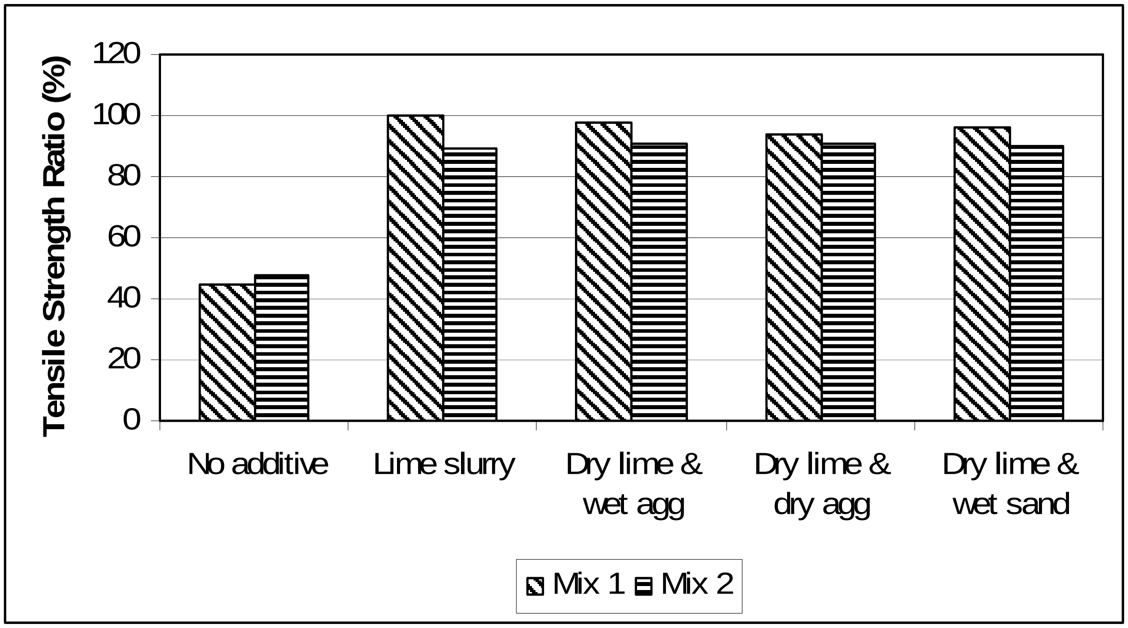
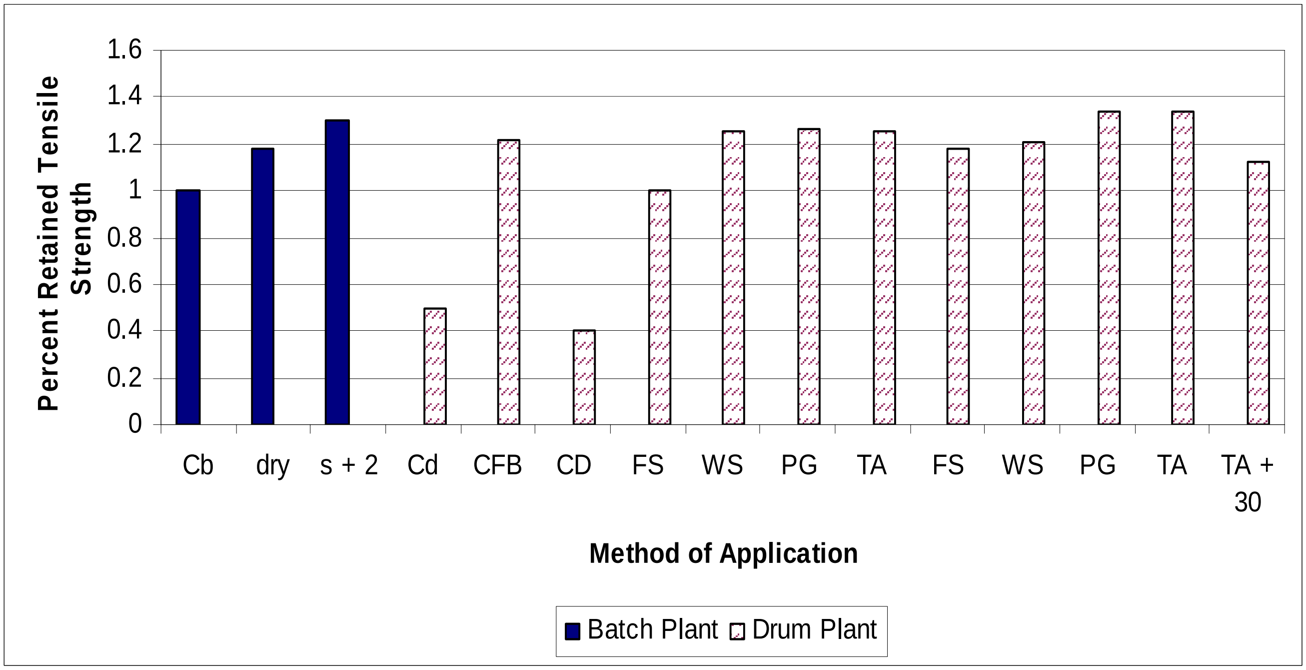


Figure 46. Impact of Lime Addition Method [Tahmoressi and Mikhail (1999)].



Cb = No Lime, Dry = Dry Lime in Pugmill, S + 2 = Slurry on Total Aggregate + 2-Days in Stockpile, Cd = Control + No Lime, CFB = Dry Lime on Total Aggregate at Cold Feed Belt, CD = Dry Lime at Center Drum Through Fines Feeder, FS = Slurry on Field Sand at Cold Feed Belt, WS = Slurry on Washed Sand at Cold Feed Belt, PG = Slurry on Pea Gravel at Cold Feed Belt, TA = Slurry on Total Aggregate at Cold Feed Belt,
TA + 30 Day = Slurry on Total Aggregate + 30-Days in Stockpile

Figure 47. Effect of Method of Addition of Lime on Tensile Strength Ratio for Batch and Drum Plants [Button (1984)].

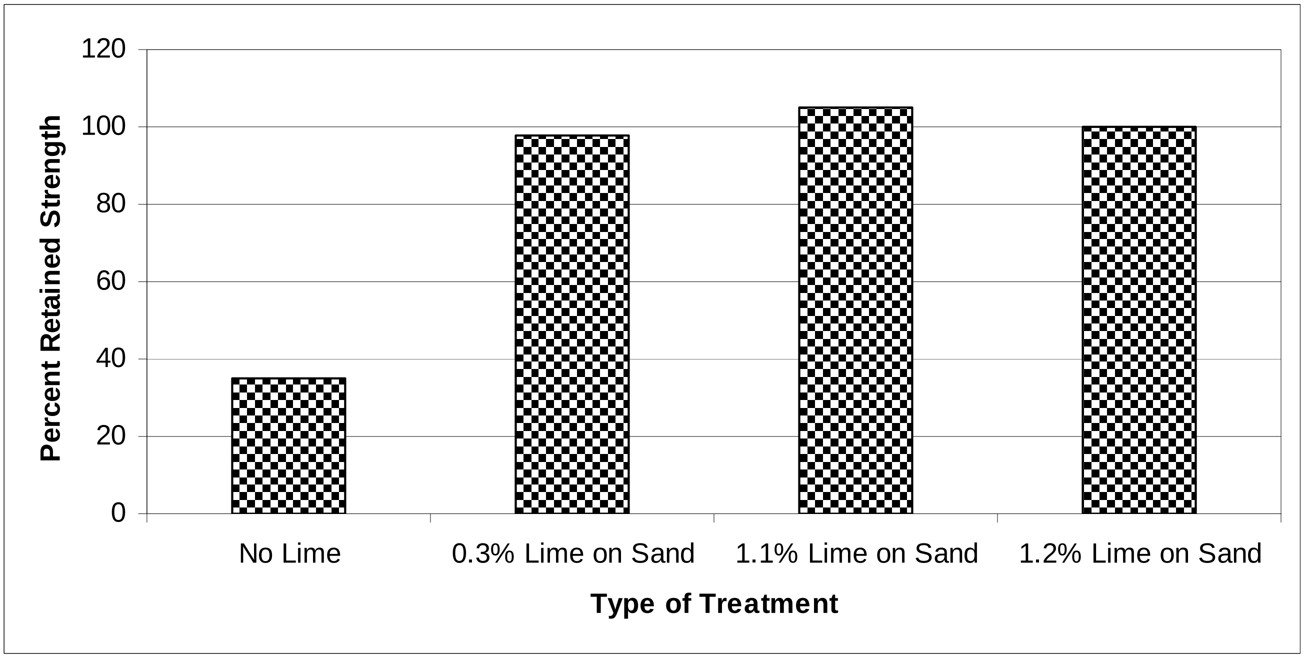


Figure 48. Effect of Amount of Lime Added to Field Sand [Kennedy et al. (1982)].

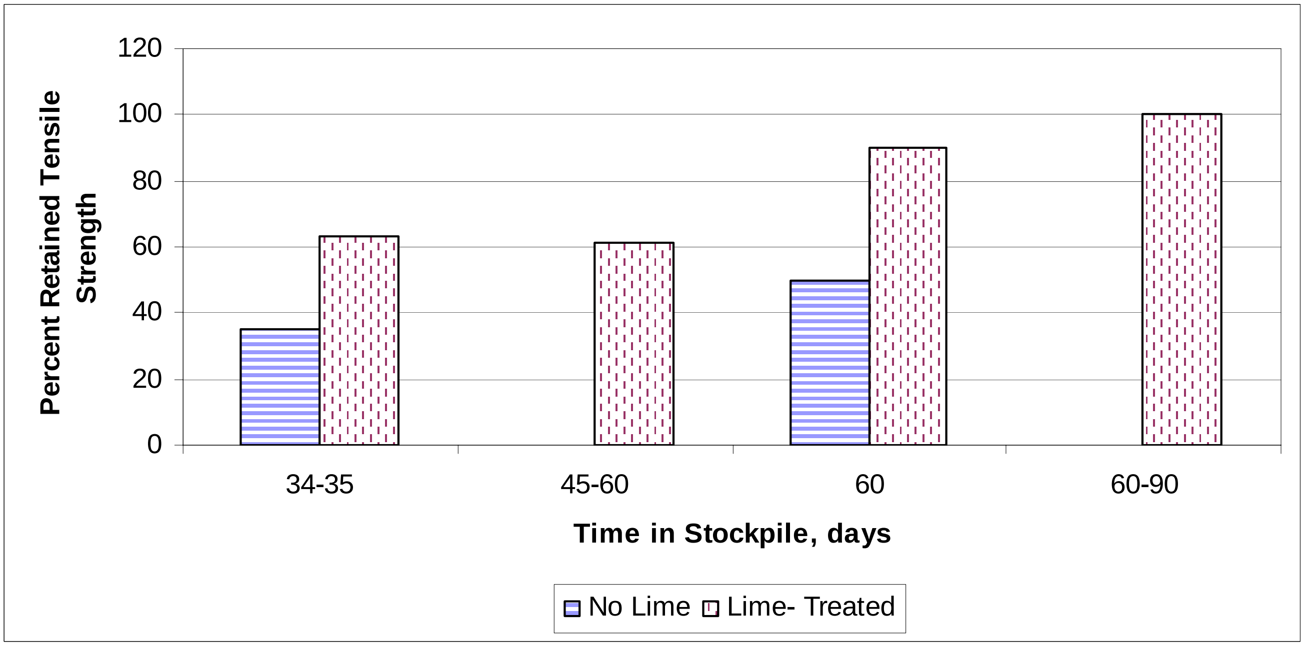


Figure 49. Effect of Time of Stockpile Marination on the Tensile Strength Ratio of Mississippi Siliceous River Gravel Aggregate [Little (1994)].

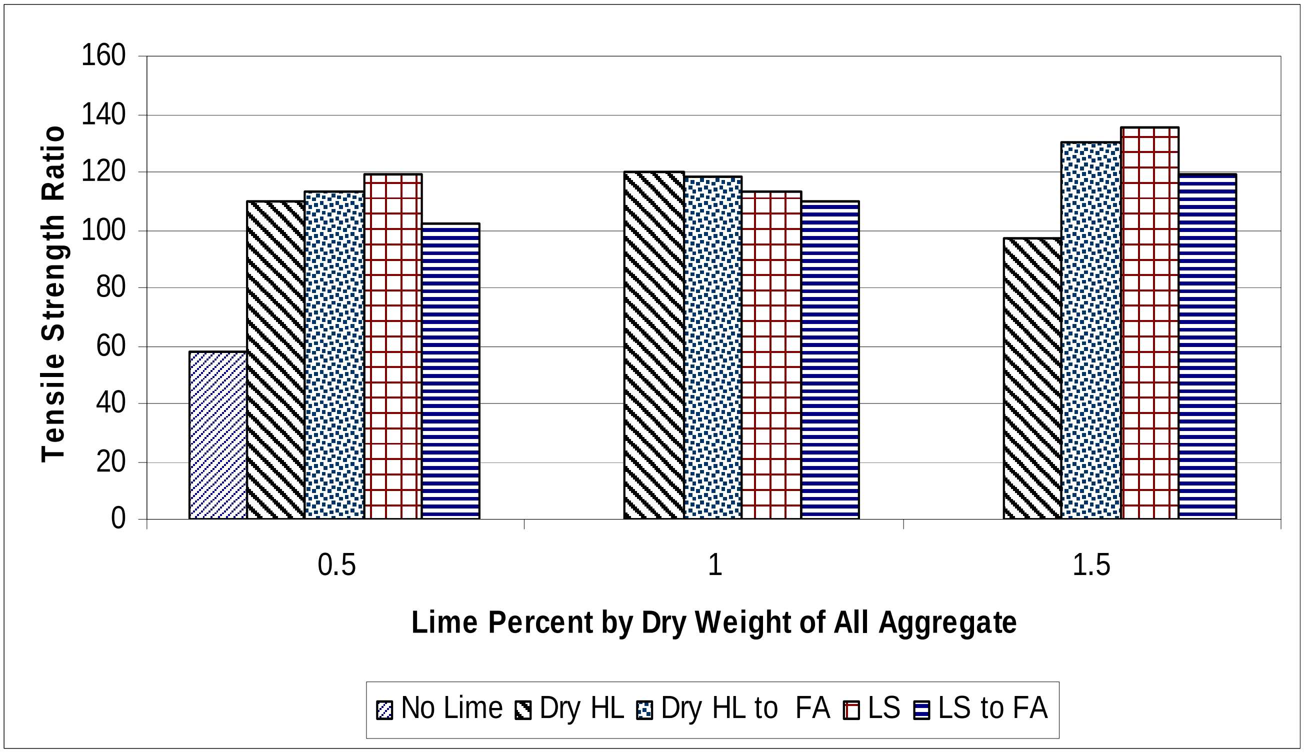


Figure 50. Effect of Method of Lime Addition and Percent of Lime Added to Granite Aggregate [Hanson et al. (1993)].

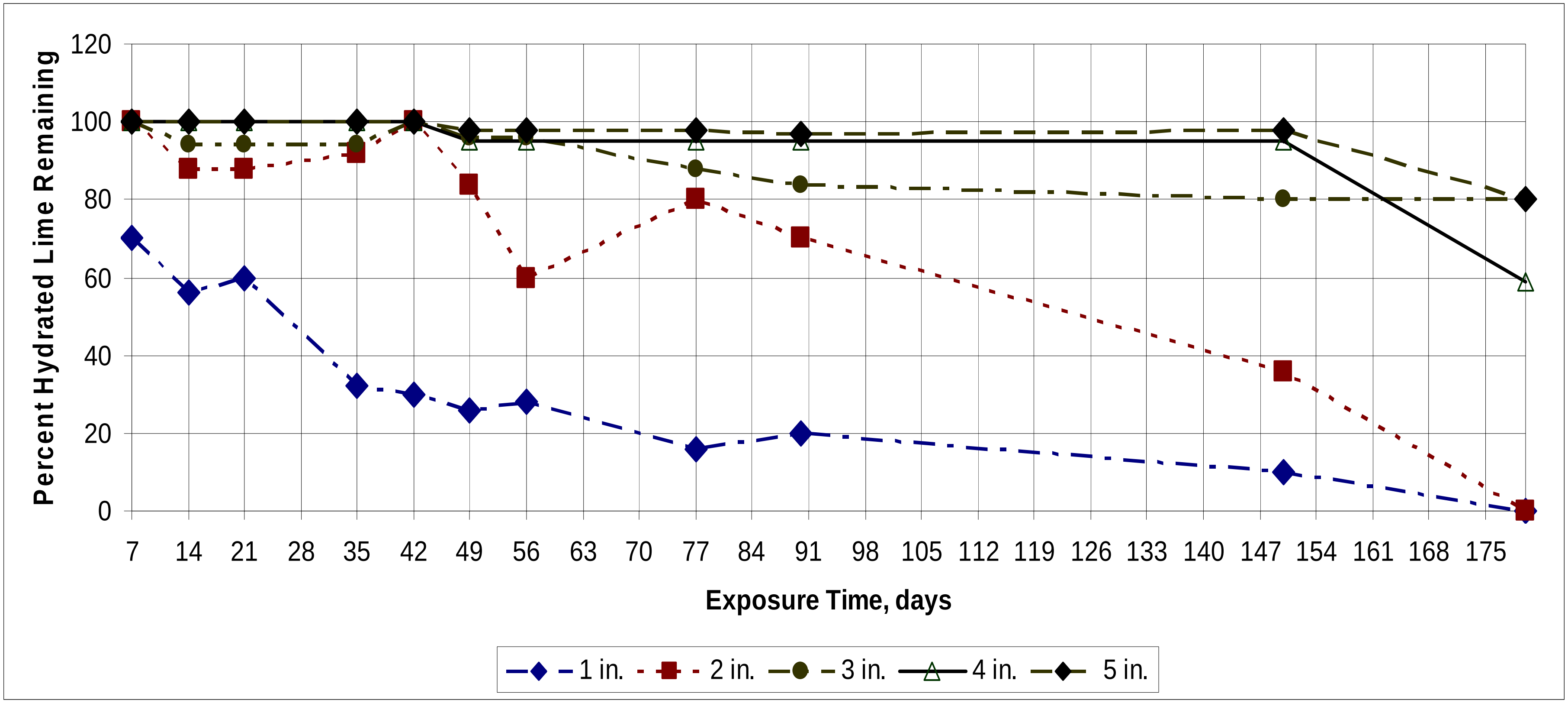


Figure 51. Effect of Exposure Time and Stockpile Carbonation on the Active $Ca(OH)_2$ Remaining [Graves (1992)].