THE BENEFITS OF HYDRATED LIME IN HOT MIX ASPHALT

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National Lime Association

LIME

The Versatile Chemical

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

Thus, hydrated lime is an additive that increases pavement life and performance through multiple mechanisms. This document summarizes a project which was sponsored by the National Lime Association to consolidate recent studies, as well as to update previous literature compilations on hydrated lime's use as an antistrip agent.

Various methods are used to add hydrated lime to HMA. They range, for example, 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 also summarizes studies evaluating different modes of application. Because different methods have been used successfully, preferred modes of application vary from state to state. Addition of lime into a drum mixer can be effective and is commonly practiced in Georgia, for example. Treatment of aggregates is also effective--either as a slurry to dry aggregate or as dry hydrated lime to wet aggregate. Marination of treated aggregates generally improves performance (especially if clay fines are present) and is practiced in Utah, for example.

Because current tests for evaluating additives are based solely on short-term retained strengths following moisture conditioning (e.g., AASHTO T 283), there is not a consistent correlation between laboratory test results and observed field performance. This is not surprising because the long-term performance of an asphalt pavement is influenced by factors other than reduced moisture sensitivity (e.g., resistance to load-induced fatigue cracking). A pressing need exists for the development of a simple and repeatable test that can evaluate the multi-functional 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 pavement performance.

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." An 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, it is generally the case that 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 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.

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.

Because hydrated lime had been used by states prior to the 1970s, several states (including Georgia, Nevada, Texas, Virginia, and Utah) began using lime to solve their water susceptibility problems. Lime has become a popular antistrip agent in the United States as indicated by a telephone survey conducted in 1998. As shown in Table 1, at least 15 states presently use hydrated lime in HMA.

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).

A number of other test methods have also 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.

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).

It is important that the air voids and the degree of saturation be controlled in whatever test method is used. The vacuum level and freeze-thaw cycles to stress the bond at the interface of the asphalt binder and aggregate must also be controlled. Figure 3 indicates the importance of the freeze-thaw cycle, Figure 4 the effect of multiple freeze-thaw cycles, and Figure 5 the importance of controlling the saturation level.

The Lottman test (AASHTO T 283) with a single freeze-thaw cycle is the best standardized test presently used in the United States. Multiple freeze-thaw cycles may be used to increase precision. Based on a 1991 survey of states and provinces in North America, AASHTO T 283 and other tensile strength ratio (TSR) tests are perceived to be the most effective (see Figure 6).

LIME AS AN ANTISTRIP AGENT

A number of additives to reduce moisture sensitivity and stripping are used in the United States. The most widely used antistrip additive is hydrated lime. Others include liquid amines and diamines, liquid polymers, portland cement, fly ash, and flue dust. Pavement contractors usually prefer liquid antistrip additives as they are relatively easy to use. Figure 7 shows results from the freeze-thaw pedestal test indicating the relative antistripping properties of various types of additives. Figure 8 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 9 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 2 [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 3). 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 [Aschebrener and Far (1994)].

A study conducted by Oregon State University for the Oregon DOT demonstrates that both fatigue and rutting resistance can be improved with lime [Kim et. al., (1995)]. Figure 10 indicates that the addition of hydrated lime will increase the fatigue life of a pavement as determined by a laboratory fatigue test. Figures 11 and 12 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 13 and 14 [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 15 [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 5. Some of these cores were from pavements more than 10 years old. Average tensile strengths of these core samples are shown on Figure 16. The effectiveness of lime as an antistripping agent is demonstrated from these field data.

Virginia conducted field evaluations of pavements that were three to four years old—see Figure 17 [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.[1]

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.

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[1] Two years later, a different set of pavements was 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-antistrip-treated HMA sections (Figure 18). However, this study was conducted on non-experimental test sections – in contrast to the earlier, more scientifically-structured study.

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 stability 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 13 and 14 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 3) and Georgia (Table 6) 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 7) 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 19 and indicates that lime substantially increases the viscosity (stiffness) of asphalt cement binders. The property represented in Figure 19 is the parameter G*/sin d which has been adopted by the Strategic Highway Research Program (SHRP) as an indicator of rut resistance. An increase in this parameter increases the stiffness of the HMA (Figures 13 and 14) and reduces the rutting potential. The increase in viscosity 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 20. 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.

Recent studies evaluated the changes in rheology, aging kinetics, and oxidative hardening created by adding lime to HMA [Little, (1996) and Lesueur, Little, and Epps, (1998)]. Extensive binder and mixture tests measured improvements in high temperature performance (rutting resistance), fatigue cracking resistance, and low temperature fracture. Lesueur, Little, and Epps (1998) conclude 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) reduced oxidative hardening, (b) improved rut resistance (Figure 21), (c) improved low-temperature fracture toughness (Figure 22), and (d) improved fracture fatigue resistance (Figure 23).

Buttlar et al., (1998) used micromechanics to assess the mechanical properties of mineral fillers combined with bitumen to form mastics. They conclude 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.

Hydrated lime and lime slurry added to reclaimed asphalt has been shown to improve the aging kinetics and general rheological properties of reclaimed and recycled asphalt [Wisnewski, (1996)]. Furthermore, the addition of lime slurry in the cold milling and cold in-place recycling process has proved to be very beneficial [Rogge et al., (1995)].

Extensive research at the Western Research Institute (WRI) shows that age hardening of asphalt can be reduced by the addition of hydrated lime (Figure 24) [Petersen et al., (1987)]. As little as one-half of one percent hydrated lime by dry weight is needed to achieve a reduction in age hardening. This reduction in hardening has been confirmed in a field study conducted by the Utah DOT (Figure 25) [Jones (1997)].

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 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 et al., (1998) 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.

Work at WRI (1997) 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 soluble 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.

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 [Goacelon et al., (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 26 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. This program will continue and will be complemented with field pavement performance and cost evaluations.

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.

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, (1997)].

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. A discussion of general field operations appears in Appendix A.

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 slurries 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 more efficient and effective ways of introducing hydrated lime into the HMA mixing process.

ADDITION OF LIME IN THE HOT MIX OPERATION

University of Nevada

Three studies, which were conducted by the University of Nevada, simulated field lime addition practices. Results are shown on Figures 8 [Epps (1992)], 27 [Waite et al., (1986)], and 28 [Nevada DOT(1998)]. Figure 8 indicates that the use of lime slurry on dry aggregate results in higher retained resilient modulus and tensile strength (after AASHTO T 283 conditioning). Results shown on Figures 27 and 28 show the resilient modulus values before and after conditioning when tested using the AASHTO T 283 method.

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 indicates that the use of marination produces higher retained properties than the use of dry lime on damp or wet aggregate (see Figures 29 to 32). Both Nevada and Utah use dry lime additions to damp or wet aggregates with and without marination. The method selected depends on the presence of plastic fines.

Georgia DOT

Georgia DOT conducted a laboratory study to determine the benefits of using lime dry or in slurry form [Collins (1998)]. Both dry and slurry addition methods provided benefits to the aggregate-asphalt mixtures used (see Figure 33). 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.

NCHRP Survey

NCHRP conducted a survey of states and provinces on processes used to add lime [Hicks (1991)]. Respondents prefer to use dry lime on moist aggregates or to use lime slurry rather than dry lime on dry aggregate (Figure 34).

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 35). For drum mixers, the addition of lime to the cold feed and to aggregates prior to stockpiling was effective (Figure 36). 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.

Nevada DOT

The Nevada Department of Transportation recently tested laboratory and field-produced mixtures for a large number of projects [Nevada DOT (1997)]. These data include projects in which dry lime was mixed with damp aggregates in both non-marinated and marinated aggregate stockpile operations. Dry strength and retained strength after AASHTO T 283 testing are shown in Tables 8 and 9. The retained strength results for field-mixed samples suggest that benefits can be obtained from marination. However, retained strength tests for laboratory samples are not consistent. "Dry" tensile strengths (before conditioning) are reduced for both the laboratory and field-mixed samples using the marination process.

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).

TxDOT

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 only to the fine aggregate fraction, only to 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 37). 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 38). (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.) Lime treatment is very effective in reducing moisture susceptibility (Figure 39).

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 40).

Stockpile Carbonation

The lime carbonation (reaction with CO_2 to form $CaCO_3$) 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 (1992). For up to 180 days, carbonation was minimal at depths greater than three inches (Figure 41).

CONCLUSIONS

It has been proved 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.

Over the last several years, evidence has begun to compound 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 proved 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 proved 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.

Asphalt tests require further refinements. 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 more effective and efficient ways of adding hydrated lime at the HMA production site.

In the meantime, highway engineers and contractors should reconsider hydrated lime’s role in improving the long-term performance of pavements:

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.

APPENDIX A: GENERAL FIELD OPERATIONS

Hydrated lime is typically delivered by truck. The lime is off-loaded pneumatically into field storage equipment, which includes vertical silos, horizontal tanks, and a variety of truck trailers. The storage capacity should be large enough for uninterrupted HMA production during the off-loading of lime.

Lime transfer, lime metering, water metering, and mixing systems are needed to control the addition of lime. Dry lime transfer methods include pneumatic means, screw conveyors, and belt conveyors. The most popular lime delivery method presently used is the screw conveyor to feed the lime from the storage silo to the mixing area. Lime slurry with high water contents can be transported without substantial separation.

Lime-metering devices include vane feeders, hoppers and vane feeders, belt scales, weigh hopper, load cell hopper, load cell screw conveyor, and in-line flow meter. The vane feeder and hopper are used frequently in the United States.

Water is needed to activate the lime and to help in the lime-aggregate mixing process. Most HMA mixing facilities do not use water-metering systems other than simple water valves. Calibration of these valves should be performed. Metering systems are desirable.

Continuous pugmill mixers, which are commonly in service for cement stabilization projects, have been used extensively in the United States for adding lime to HMA. "End of belt" mixers have been used when the lime is stockpiled prior to entering the HMA mixing operation.

After mixing, the lime-treated aggregate is usually placed on the weigh belt in a drum mixer operation or on a charging belt for the dryer of the batch mixer. Some agencies allow the introduction of lime into the drum after the aggregate has been mostly dried and just prior to the application of the asphalt cement. This method may increase the resistance of the mixture to stripping; however, the maximum benefit of using lime will be achieved when it is mixed with the aggregate in the presence of water.

Precautions should be taken to avoid the creation of lime dust. All transfer points for the lime should be equipped with dust-abatement equipment. Personal protection clothing and safety equipment should be available. The other construction operations of HMA storage, transportation, lay down, and compaction are the same as for typical operations.

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Table 1. States Using Hydrated Lime in HMA (1998 Telephone Survey).

State	Remarks
Arizona	General use
California	Limited use
Colorado	General use
Florida	Use in friction courses only
Georgia	General and extensive use
Iowa	Primary pavements only
Mississippi	General use
Missouri	Use in friction course only
Montana	General use
Nevada	General use
New Mexico	General use
Oregon	Limited use
South Carolina	General and extensive use
South Dakota	General use
Utah	General use

Table 2. Relative Behavior of Lime and Liquid Antistrip Additives in Georgia [After Collins (1988)].

Type Mix	**Treatment**	**Stability**	**Flow**	**Control**	**Tensile Strength Conditioned**	**% Retained**
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 3. Deformation (mm) After 20,000 Passes for Samples Treated with Various Anti-Stripping Treatments in Colorado [After 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 4. Comparison of Tensile Strength Ratios of Specimens (Freeze-Thaw Only) with Field Performance in Terms of Moisture Susceptibility [After Collins et al. (1997)].

Aggregate	**Tensile Strength Ratio (TSR)**		**Field Performance**
	AASHTO T 283	GDT - 66 (Georgia Method)	
Source 2	47.9 (39.2)[a]	102 (70.6)	Excellent
Source 4	63.2 (67.8)	92.8 (76.4)	Good
Source 1	78.5 (99.2)	92.7 (89.0)	Good to Fair
Source 3	84.5 (87.5)	81.8 (138.8)	Fair to Poor

[a] The values in parentheses are tensile strengths (psi).

Table 5. Tabulations of Stripping Rate [After Watson (1992)].

DATE OF EVALUATION	**NUMBER OF CORES RATED**	**STRIPPING RATING (% RECEIVING RATING)**
July, 1983	37 5	None (88.1%) Slight (11.9%)
January, 1984	49 6	None (89.1%) Slight (10.9%)
July, 1984	56 6 1	None (88.9%) Slight (9.5%) Moderate (1.6%)
January, 1985	59 5 4 1	None (85.5%) Slight (7.2%) Slight+ (5.8%) Moderate (1.5%)
July, 1985	102 6 4	None (77.3%) Slight (19.7%) Moderate (3.0%)
January, 1986	111 25 2	None (80.4%) Slight (18.1%) Moderate (1.5%)
January, 1987	120 16 3	None (86.3%) Slight (11.5%) Moderate (2.2%)
January, 1988	37 6	None (86.)%) Slight (14.0%)
January, 1990	33 2 6	None (80.0%) Slight (4.9%) Moderate (14.6%)
January, 1992	10 3 4	None (58.8%) Slight (17.7%) 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 6. Number of Cycles Corresponding to 7.5 mm and 5.0 mm Rutting in Specimens Tested by ASTEC Asphalt Pavement Tester [After 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 7. 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 8. Nevada Department of Transportation Laboratory Mix Design [After Nevada DOT (1998)].

Item	**Non-marinated**	**Marinated**
No. of Samples	21	34
• Dry Strength	112	101
o % below 65 psi	0.0	0.0
o % below 75 psi	9.5	2.9
• Retained Strength, %	90	88
o % below 70	0.0	0.0
o % below 80	19.0	17.6

Table 9. Nevada Department of Transportation Field (Behind Paver) Samples [After Nevada DOT (1998)].

Item	**Non-marinated**	**Marinated**
No. of Samples	114	118
• Dry Strength	118	93
o % below 65 psi	1.8	11.9
o % below 75 psi	4.4	21.2
• Retained Strength, %	76	89
o % below 70	29.8	3.4
o % below 80	57.9	16.1

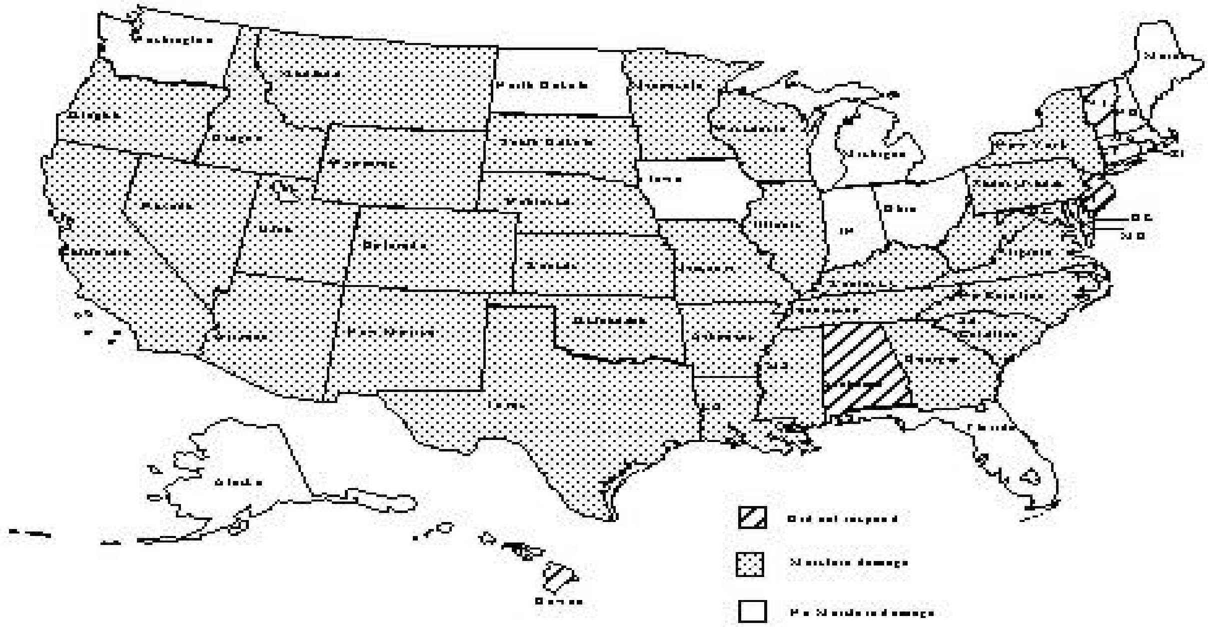


Figure 1. Extent of Moisture Damage in the United States [After Hicks (1991)].

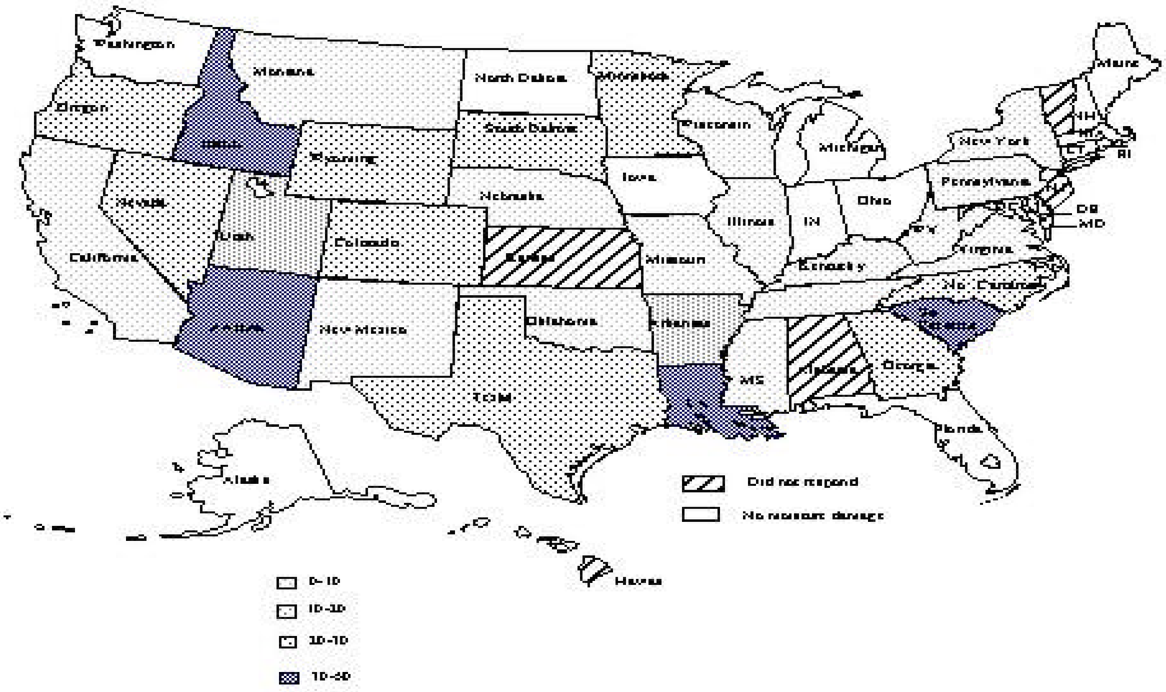


Figure 2. Percentage of Pavements Experiencing Moisture Related Distress by State [After Hicks (1991)].

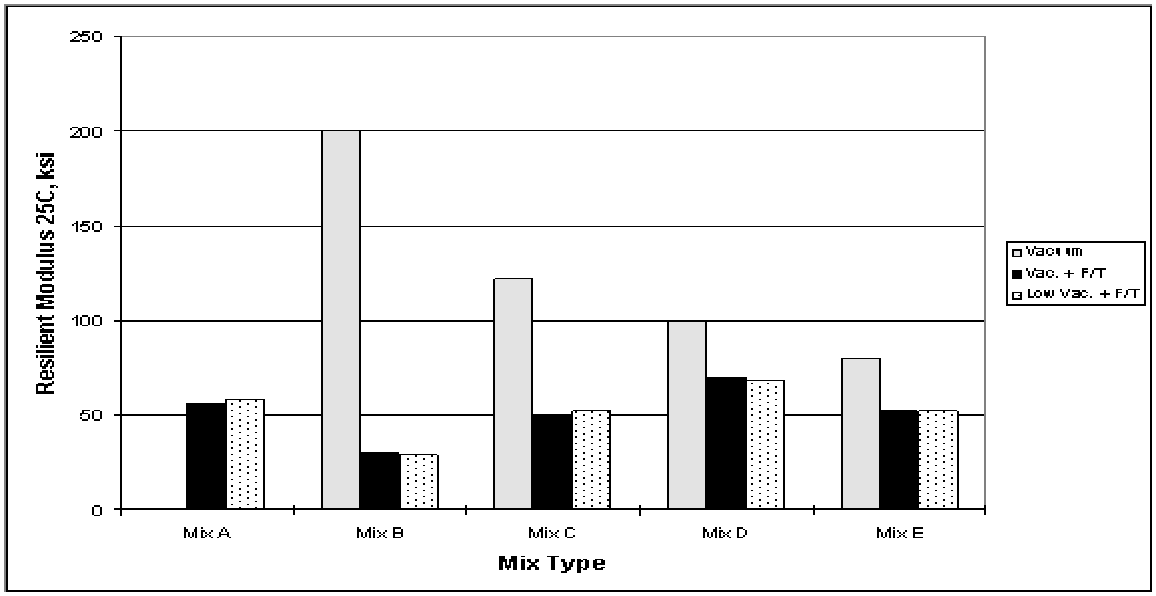


Figure 3. Effect of Freeze-Thaw on Resilient Modulus [After Epps et al. (1992)].

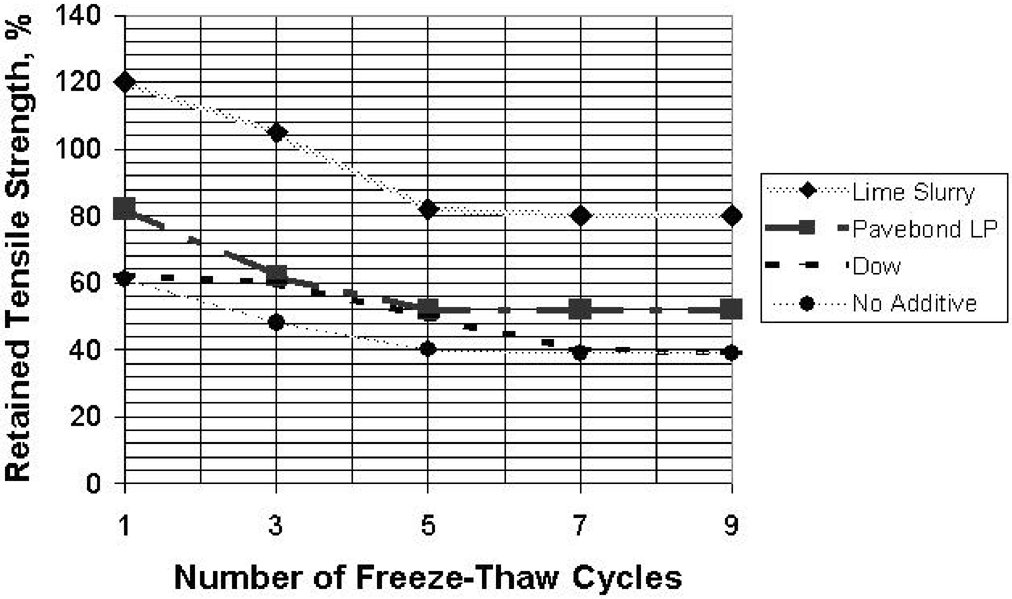


Figure 4. Effect of the Number of Freeze-Thaw Cycles on Retained Tensile Strength for Various Additives [Epps et al. (1992)].

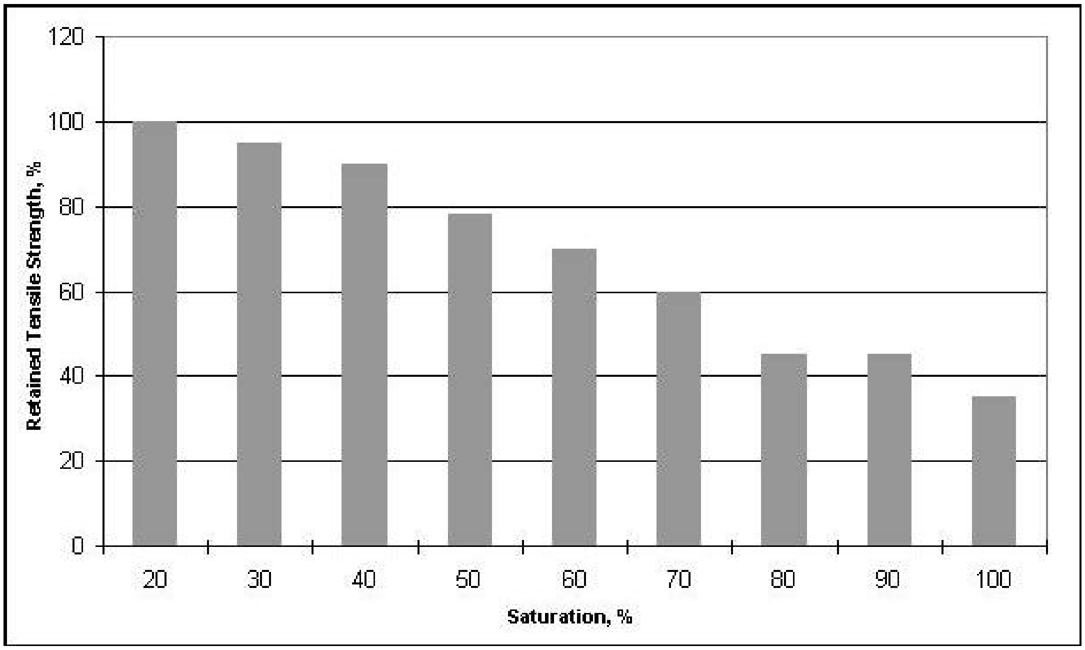
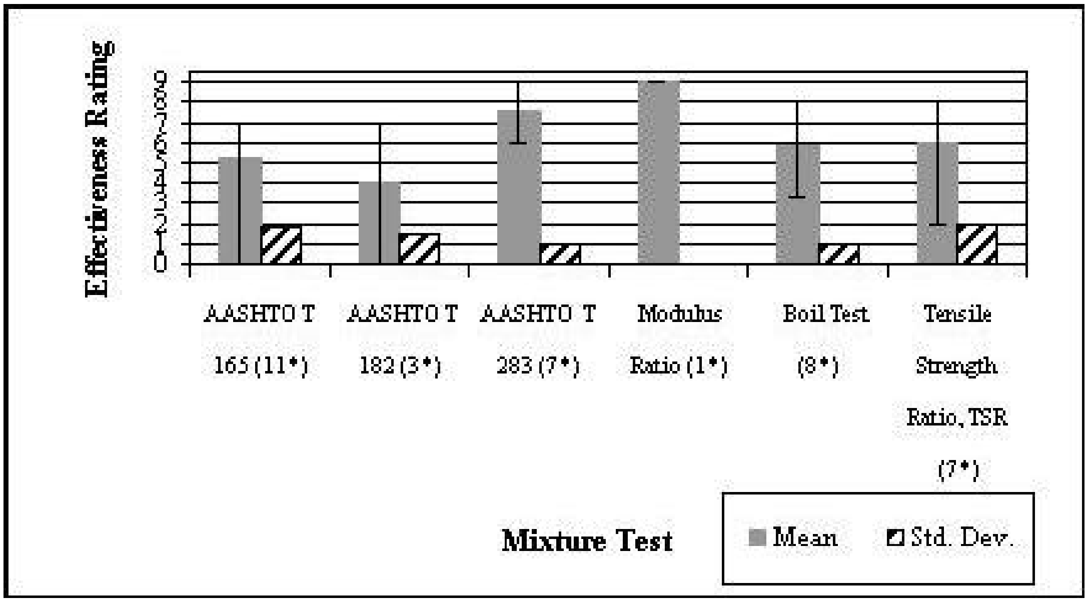


Figure 5. Effect of Degree of Saturation on the Tensile Strength Ratio [After Kennedy and Ping (1991)].



* Note: numbers in parentheses represent number of responses & error bars represent lowest and highest ratings received

Figure 6. Relative Effectiveness of Mixture Tests Procedures to Identify Moisture-Related Problems [After Hicks (1991)].

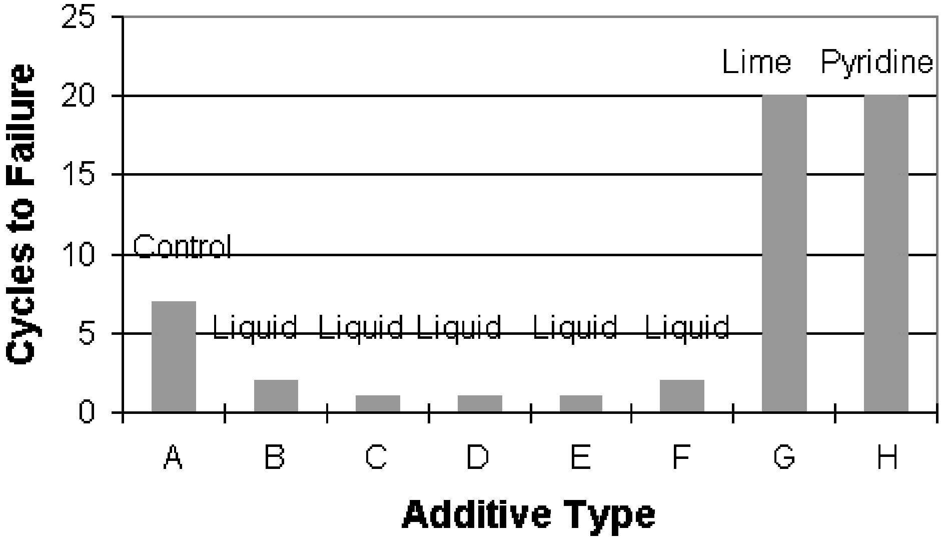


Figure 7. Effect of Selected Modifiers on Moisture Damage as Measured by the Freeze-Thaw Pedestal Test [After Kennedy and Ping (1991)].

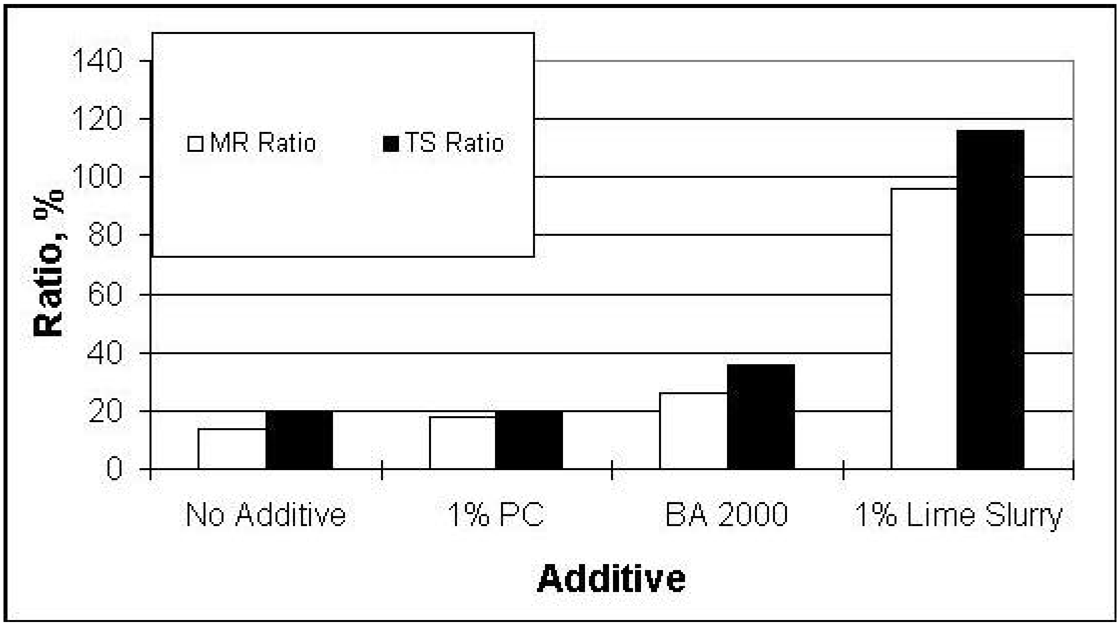


Figure 8. Effect of Various Additives on the Retained Strength (Following Lottman Conditioning) of Asphalt Mixtures with 6.0% Asphalt Cement [After Epps (1992)].

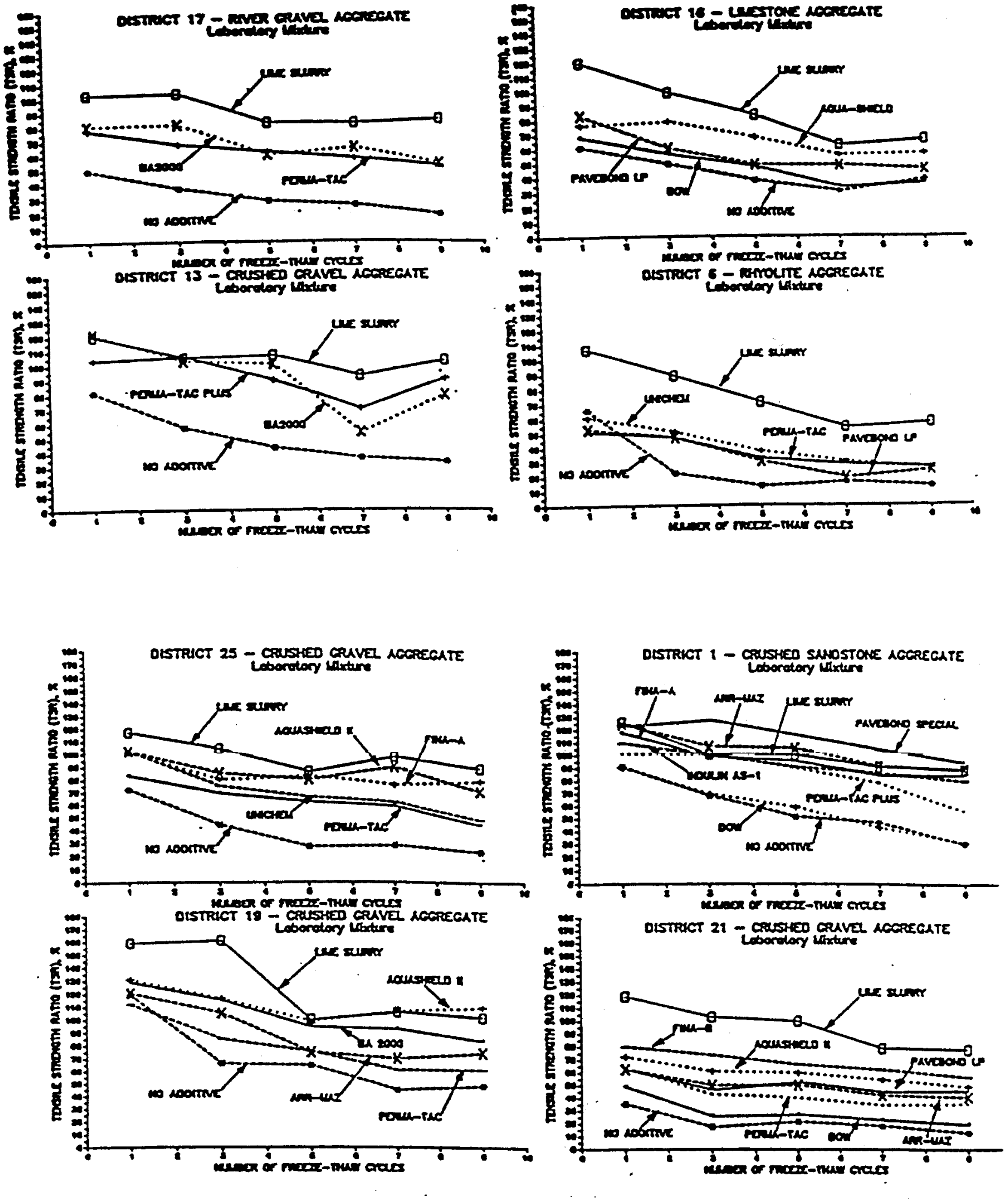


Figure 9. Multiple Freeze-Thaw Cyclic Tests Results for Laboratory Mixtures Comparing Severity of Tests Method on the Ability to Differentiate Between Lime and Other Anti-Strip Additives [After Kennedy and Ping (1991)].

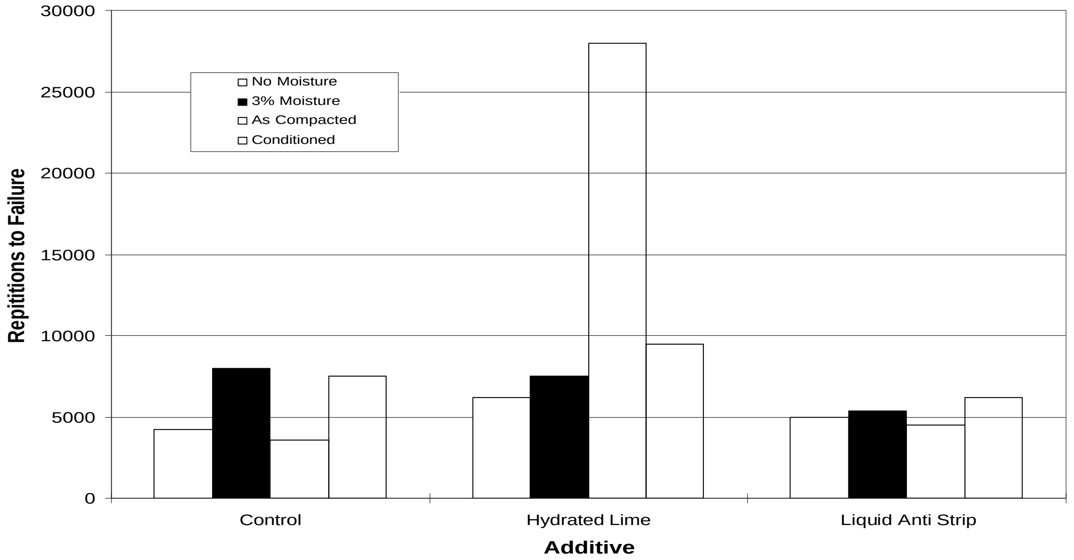


Figure 10. The Effect of Additives on Fatigue Life - Oregon Department of Highways Field Study [After Kim et al. (1995)].

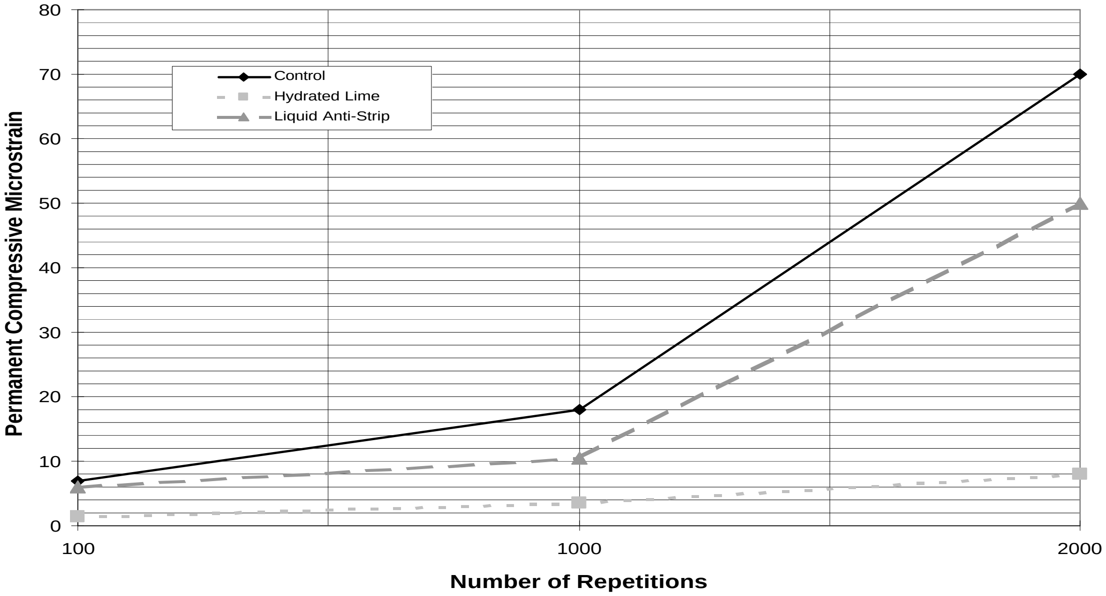


Figure 11. Effect of Additives (<u>Without</u> Moisture) on Permanent Deformation - Oregon Department of Highways Field Study [After Kim et al. (1995)].

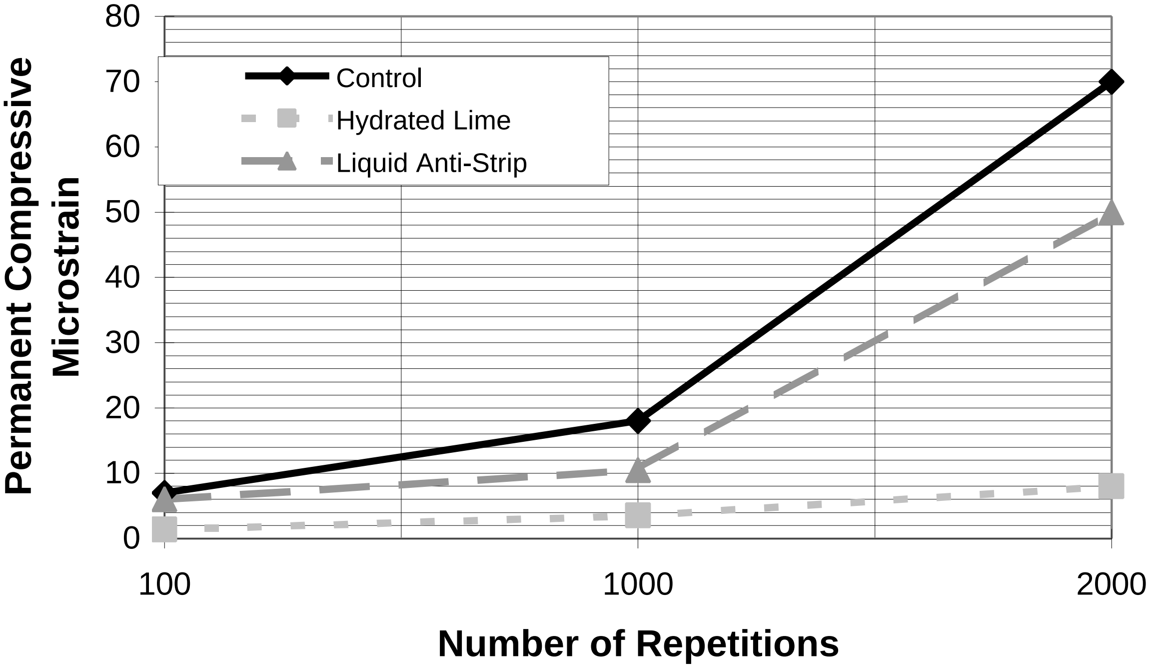


Figure 12. Effect of Additives (<u>With</u> Moisture) on Permanent Deformation - Oregon Department of Highways Field Study [After Kim et al. (1995)].

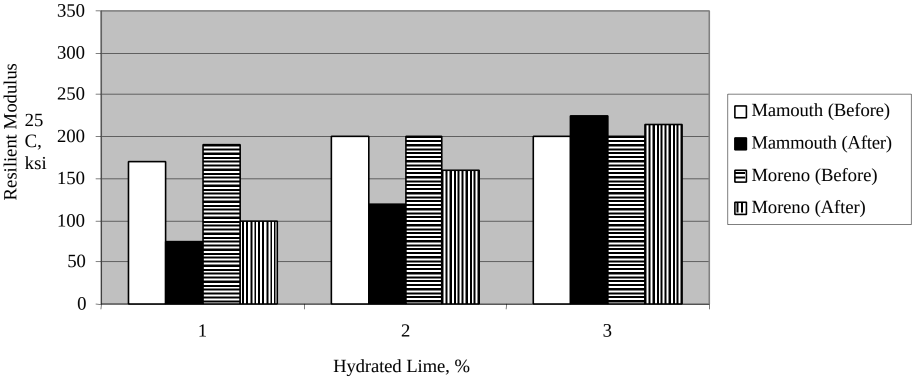


Figure 13. Effect of Hydrated Lime on the Resilient Moduli Before and Following Lottman Conditioning for Truckee and Grass Valley, California Mixtures [After Epps et al.(1992)].

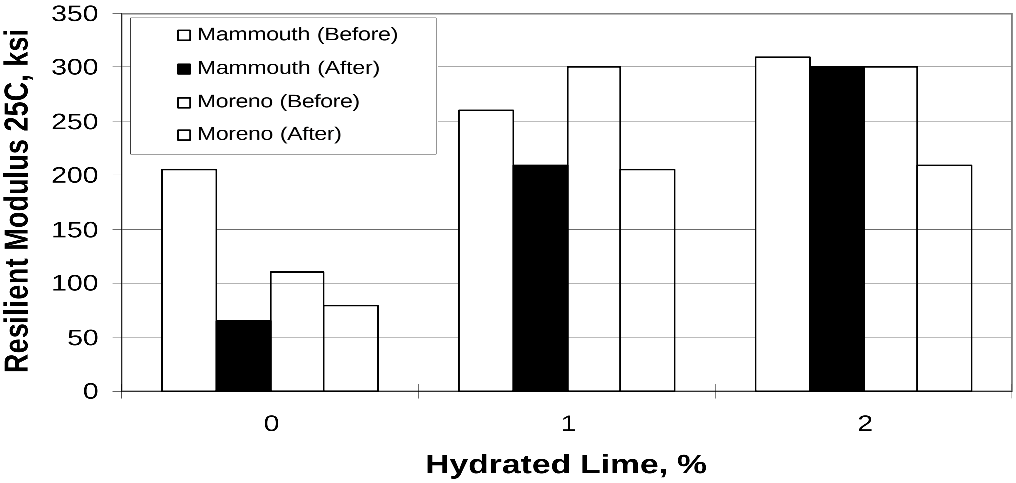
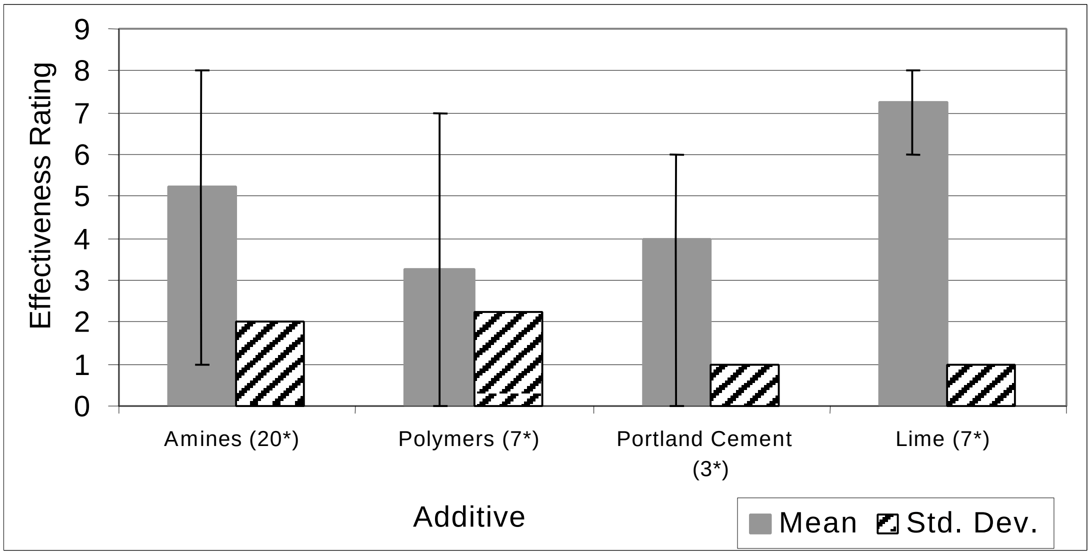


Figure 14. Effect of Hydrated Lime on the Resilient Moduli Before and Following Lottman Conditioning for Mammoth and Monroe, California Mixtures [After Epps et al.(1992)].



* Note: numbers in parentheses represent number of responses & error bars represent lowest and highest ratings received

Figure 15. Relative Effectiveness of Additives in Eliminating or Reducing Moisture Problems [After Hicks (1991)].

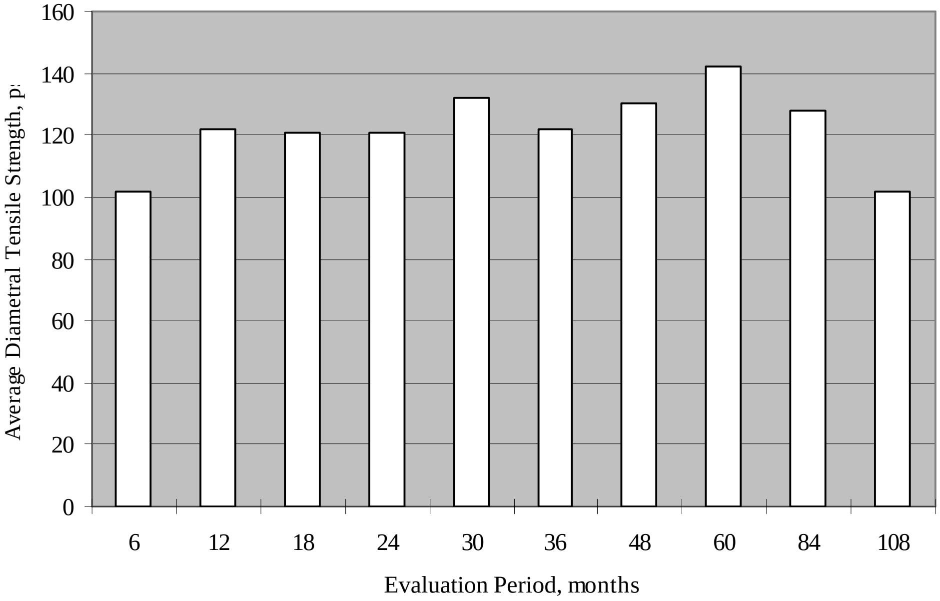


Figure 16. Effect of Time on the Average Diamentral Tensile Strength Based on Core from Georgia Field Study [After Watson (1992)].

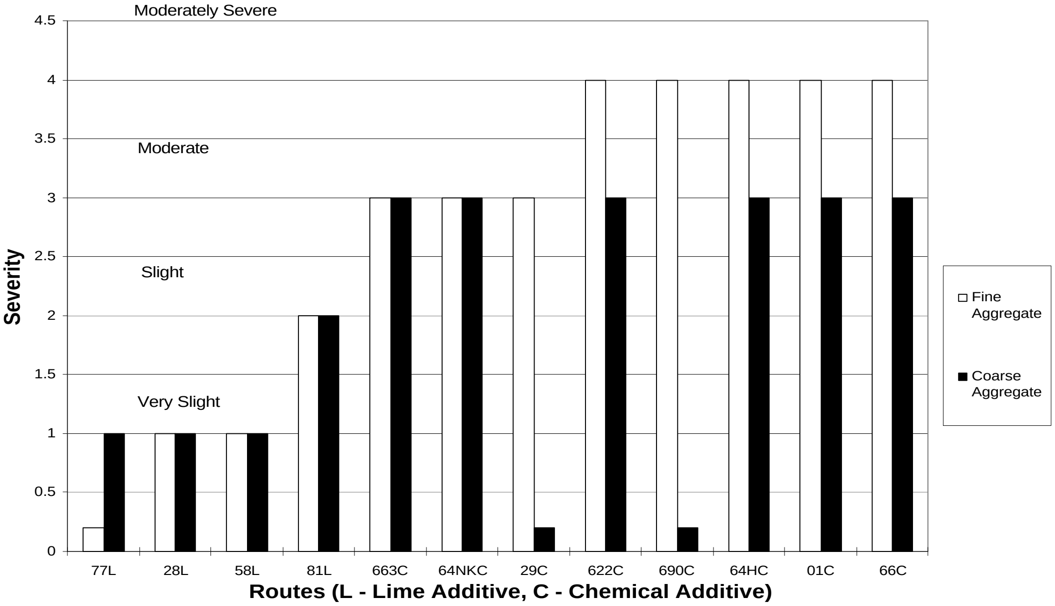


Figure 17. Severity of Stripping as Determined by Maupin for Virginia Pavements [After Maupin (1995)].

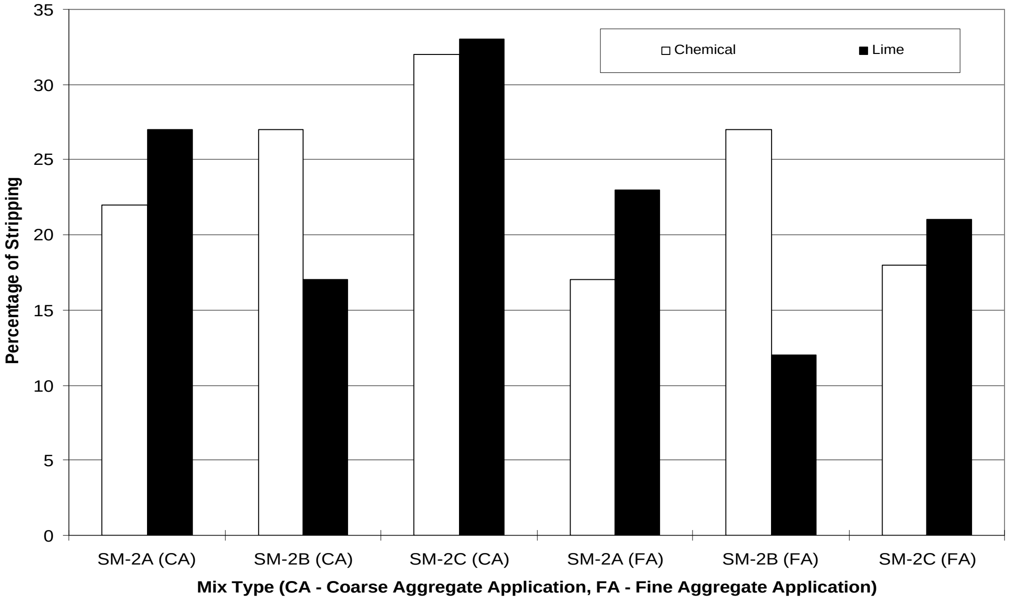


Figure 18. Average Stripping in Aggregates [After Maupin (1997)].

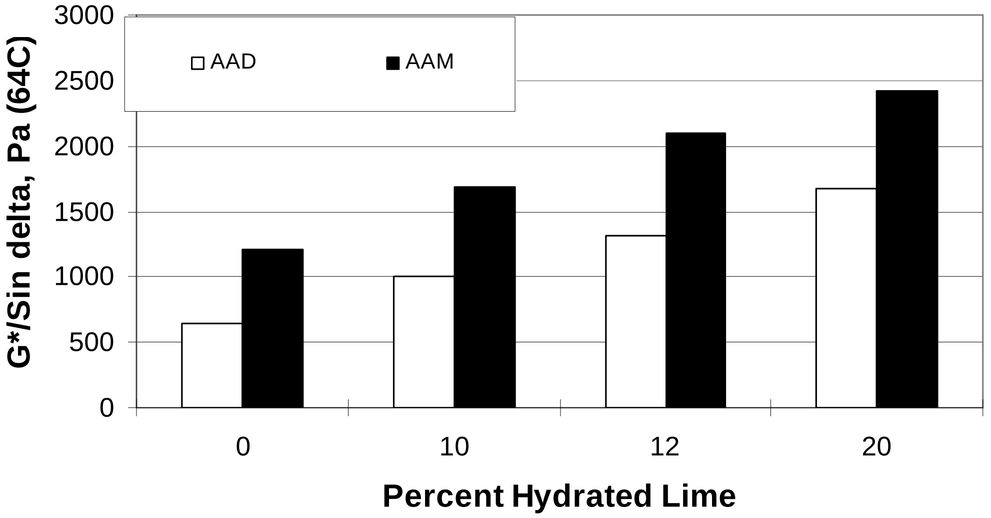


Figure 19. Effect of the Addition of Hydrated Lime on
Asphalt Binder Rheology, G*/sin d [After Little (1996)].

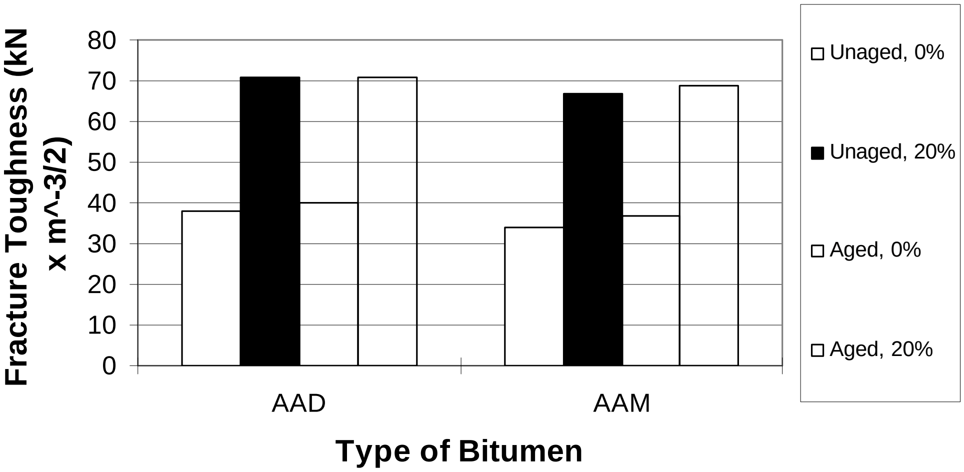


Figure 20. Creep Strains Measured After Lottman Conditioning on Natchez, Mississippi, Asphalt Mixture [After Little (1994)].

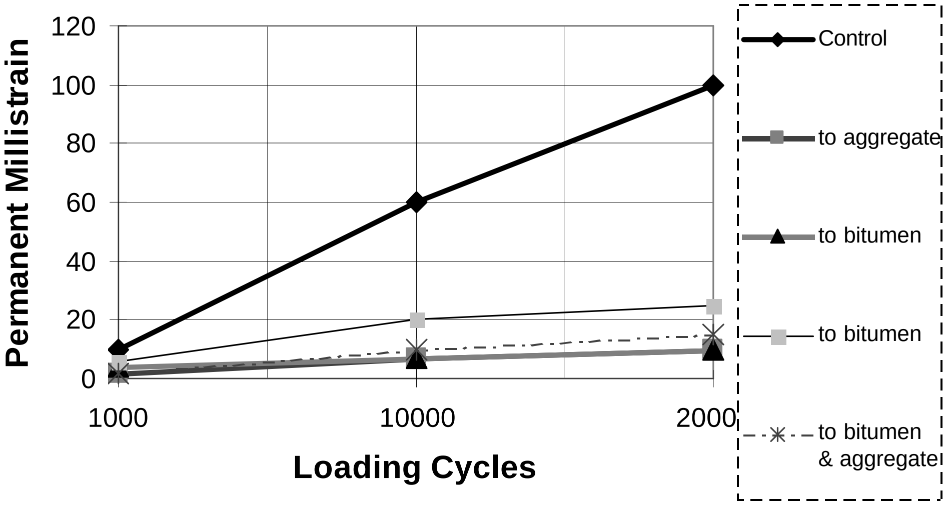


Figure 21. Lime Added to Hot Mix in Various Modes (to the Aggregate or to the Bitumen) Strongly Affects the Rut Resistance of the Mixture Even Under High Temperature and Moisture [After Lesueur et al. (1998)].

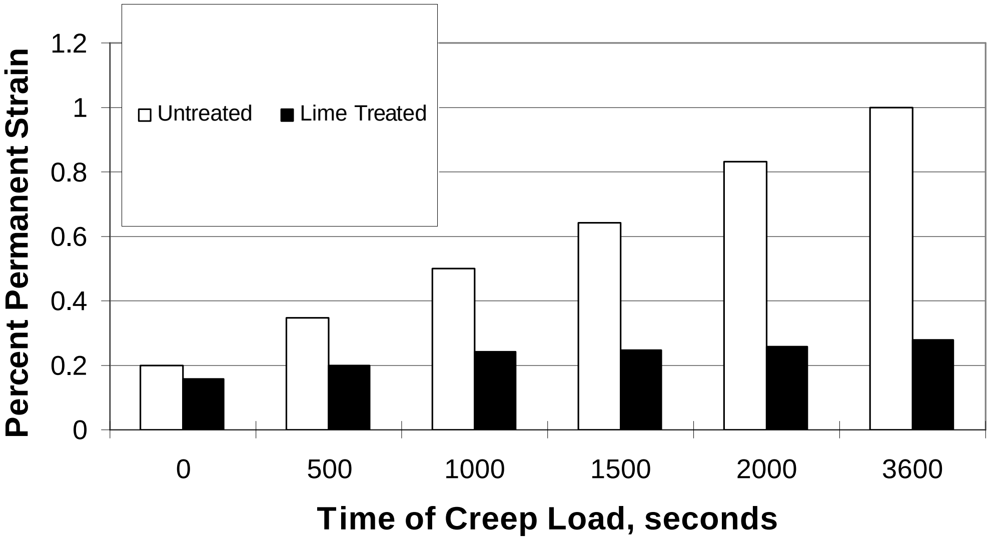


Figure 22. Hydrated Lime Improves Low Temperature Toughness of the Lime-Modified Bitumen [After Lesueur et al. (1998)].

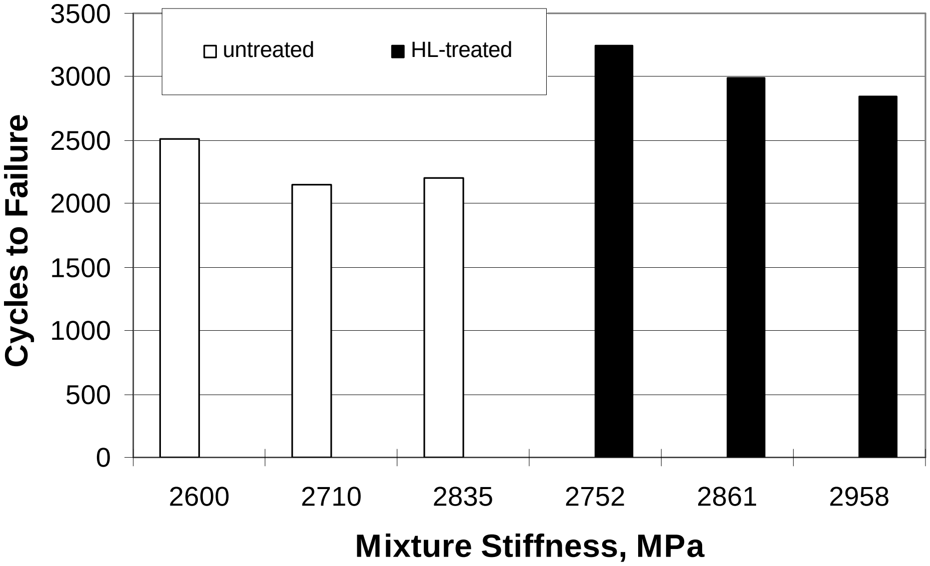


Figure 23. Hydrated Lime Added to the Bitumen Improves the Toughness of the Bitumen and Improves Fatigue Life When Compared to the Identical Mixture Without Lime [After Lesueur et al. (1998)].

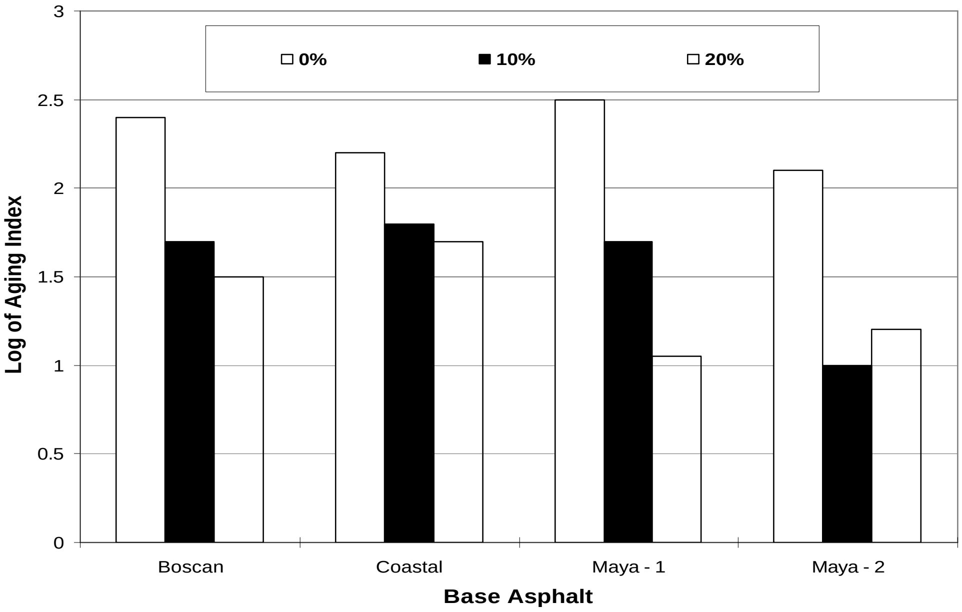


Figure 24. Effect of Hydrated Lime in Reducing the Aging Index of Asphalt Binders [After Petersen et al. (1987)]

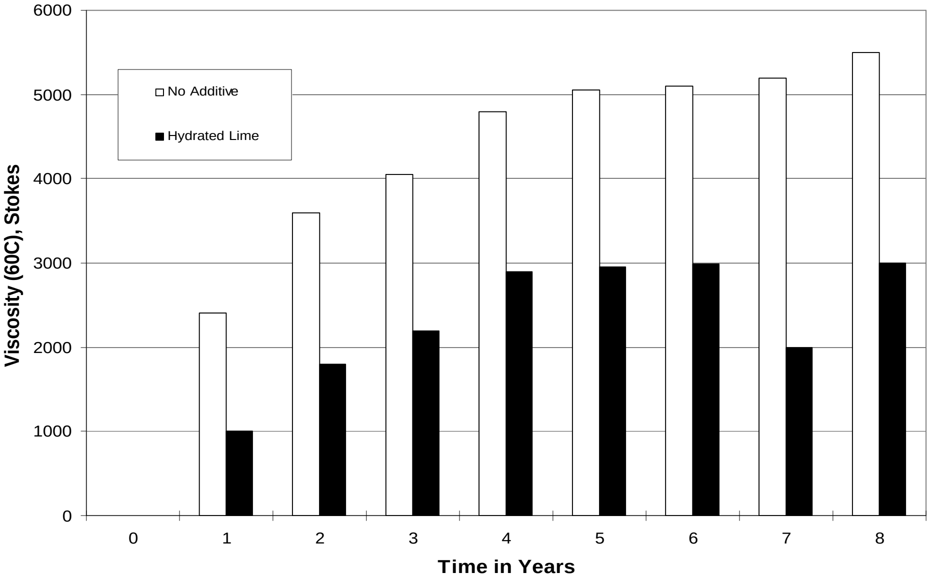


Figure 25. Field Data Demonstrating the Effect of Hydrated Lime on the Hardening of Asphalt Binder Based on Utah Data [After Jones (1997)].

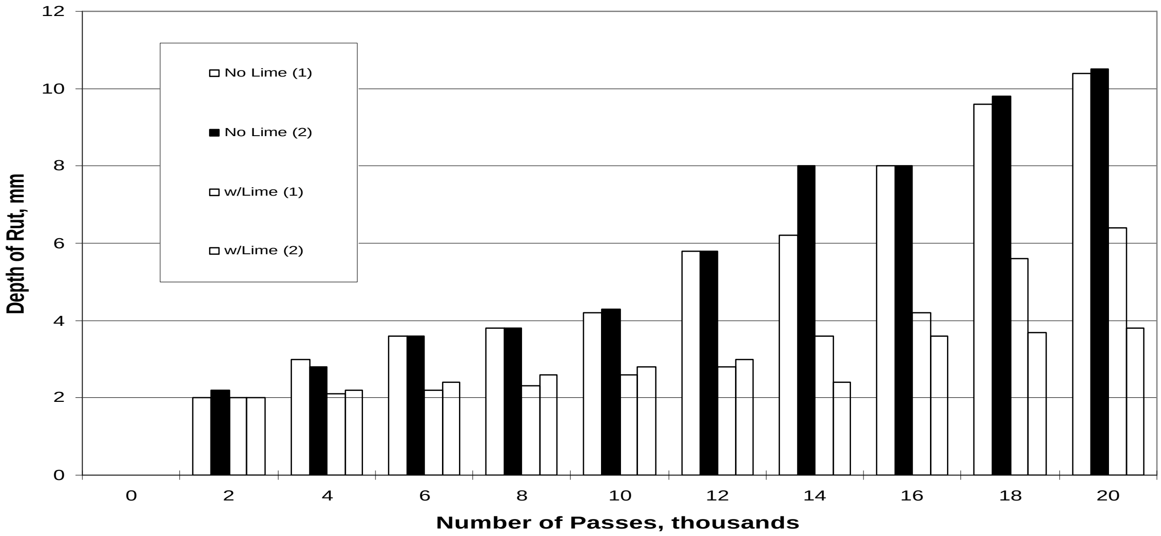


Figure 26. Results of Rut Tracking Tests from Wuppertal-Dornap, Germany [After Radenberg (1998)].

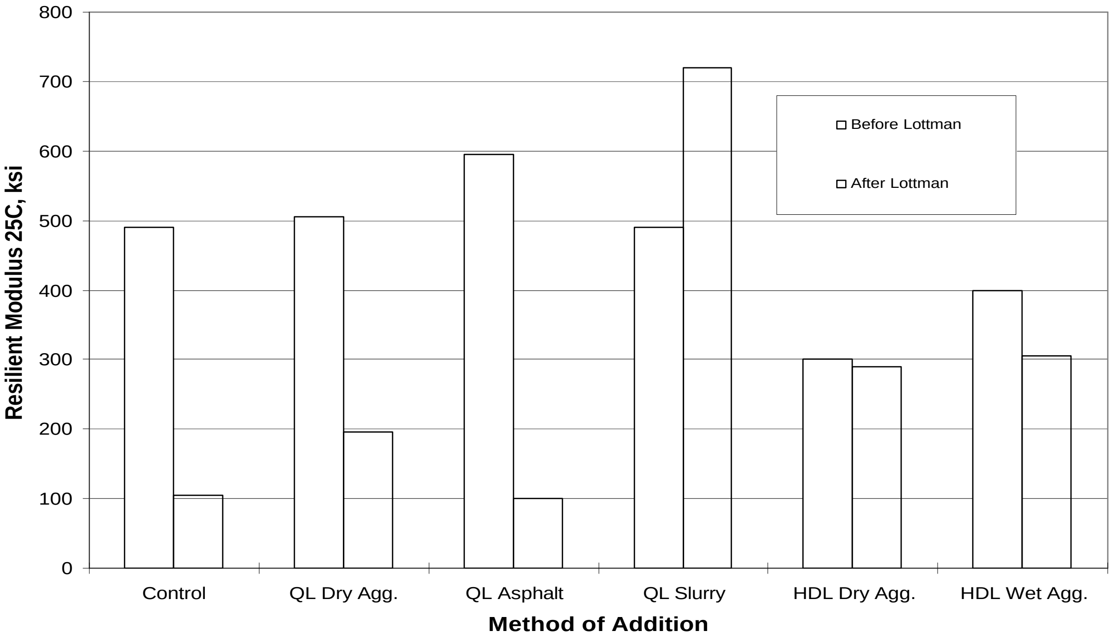


Figure 27. Effect of the Method of Hydrated Lime Addition on the Retained Resilient Modulus After Lottman Conditioning [After Waite et al. (1986)].

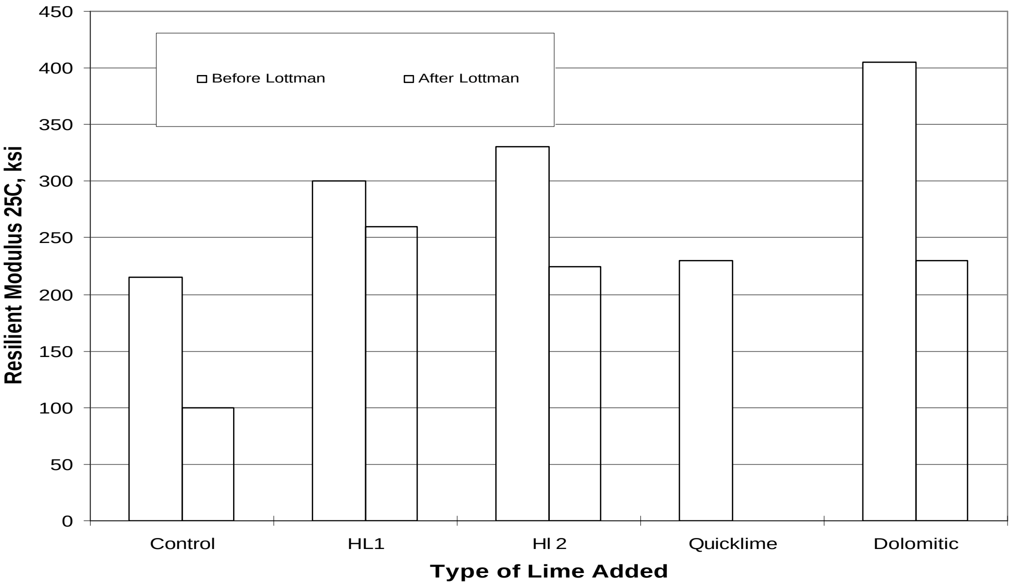


Figure 28. Effect of Type of Lime Added to Dry Aggregate on the Resilient Modulus [After Nevada DOT (1998)].

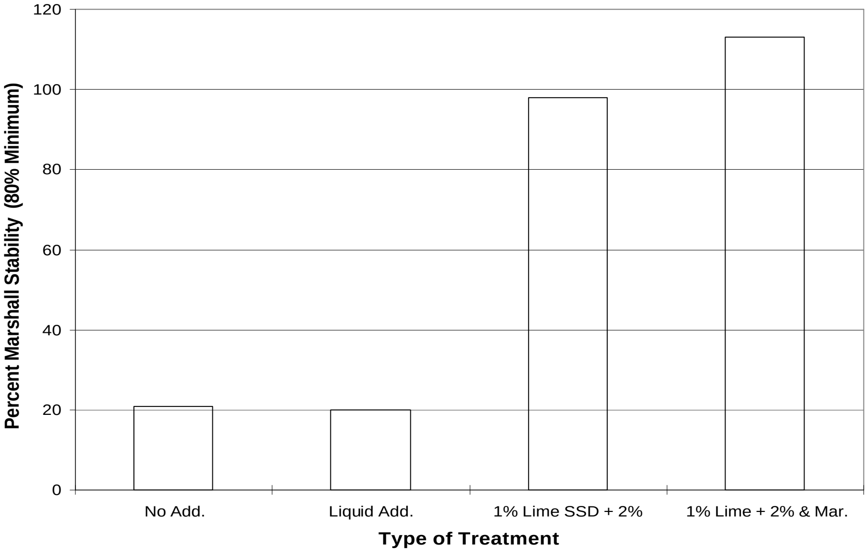


Figure 29. Effect of the Type of Additive and Method of Addition on the Retained Tensile Strength of Materials from SR-50, Millard County Line to Salina, Utah [After Betenson (1998)].

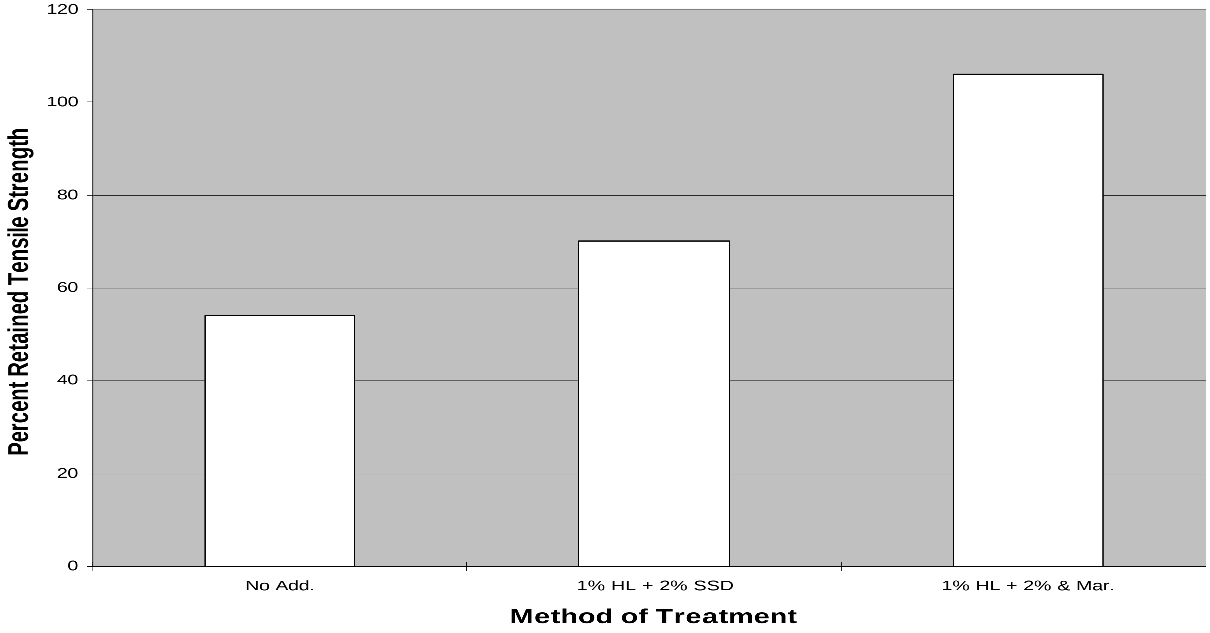


Figure 30. Effect of Method of Lime Addition on Tensile Strength Ratio for Materials from I-70 Wetwater to Colorado Line, Utah DOT [After Betenson (1998)].

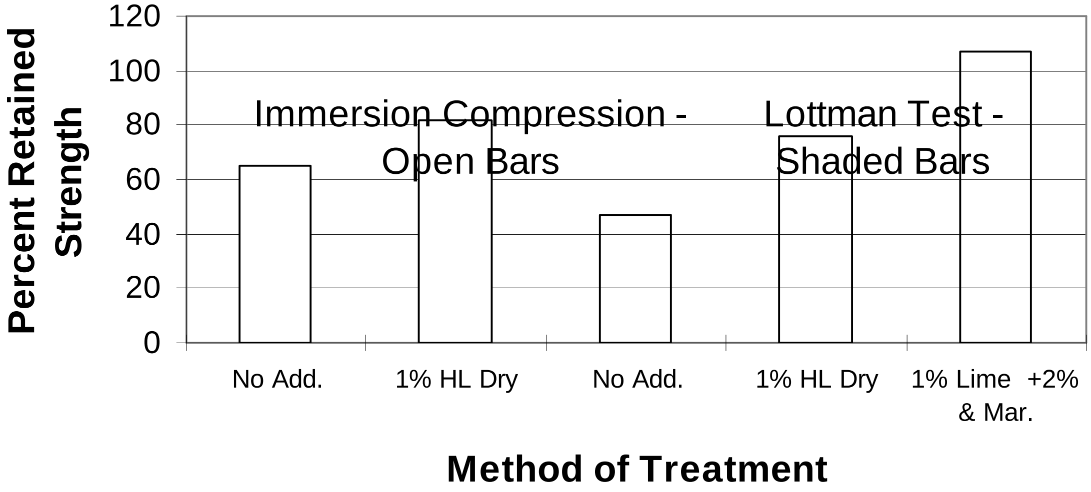
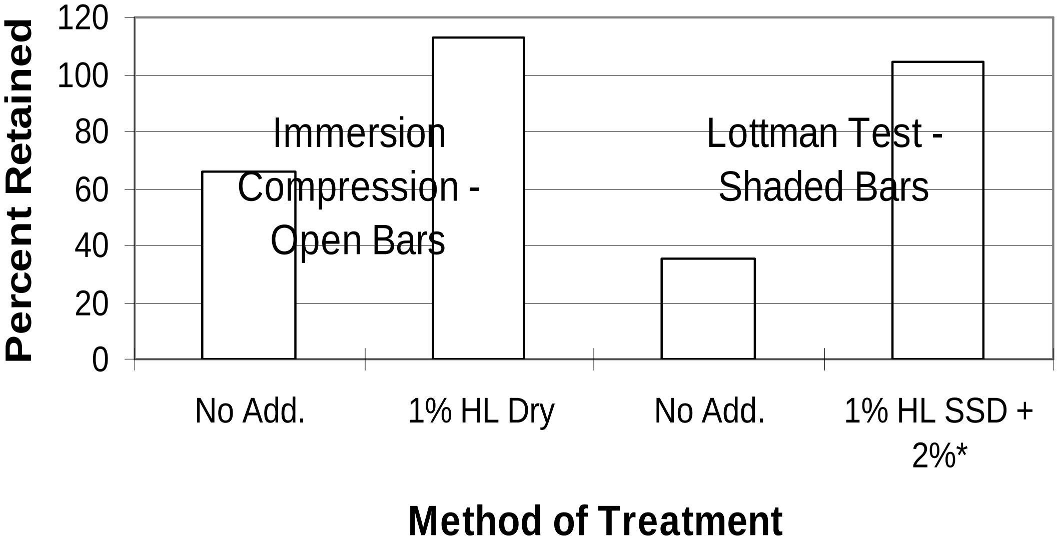


Figure 31. Effect of Method of Lime Addition on the Retained Compressive and Tensile Strengths for Main Street in Richfield, Utah [After Betenson (1998)].



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

Figure 32. Effect of Method of Lime Addition on Retained Compressive and Tensile Strength for I-70 Spring Canyon to Wide Hollow, Utah [After Betenson (1998)].

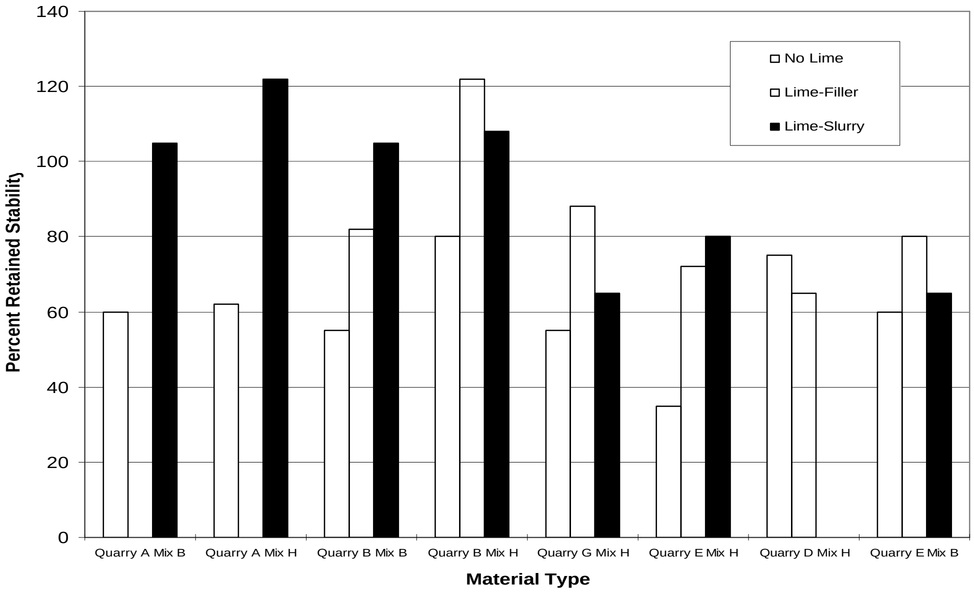


Figure 33. Effect of the Addition of Lime and Method of Addition on the Retained Stability for Georgia DOT Mixtures [After Collins (1988)].

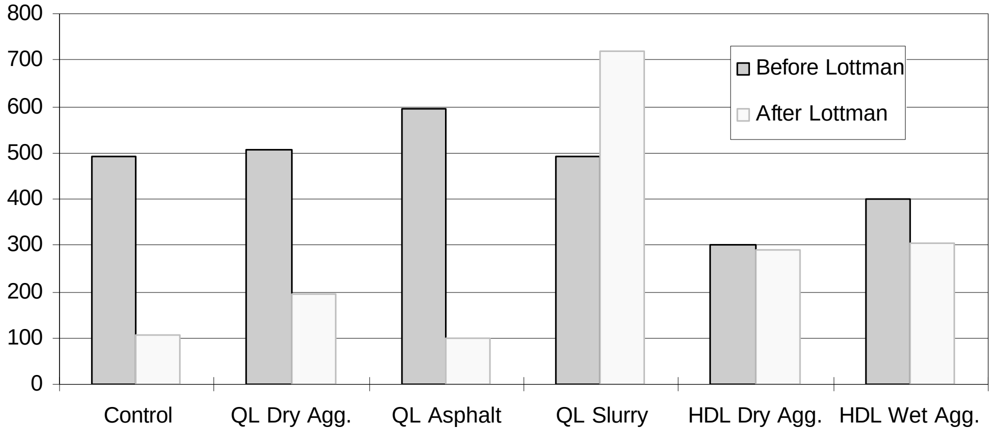


Figure 34. Relative Effectiveness of Lime Treatment of Aggregate by Method of Lime Addition [After Hicks (1991)].

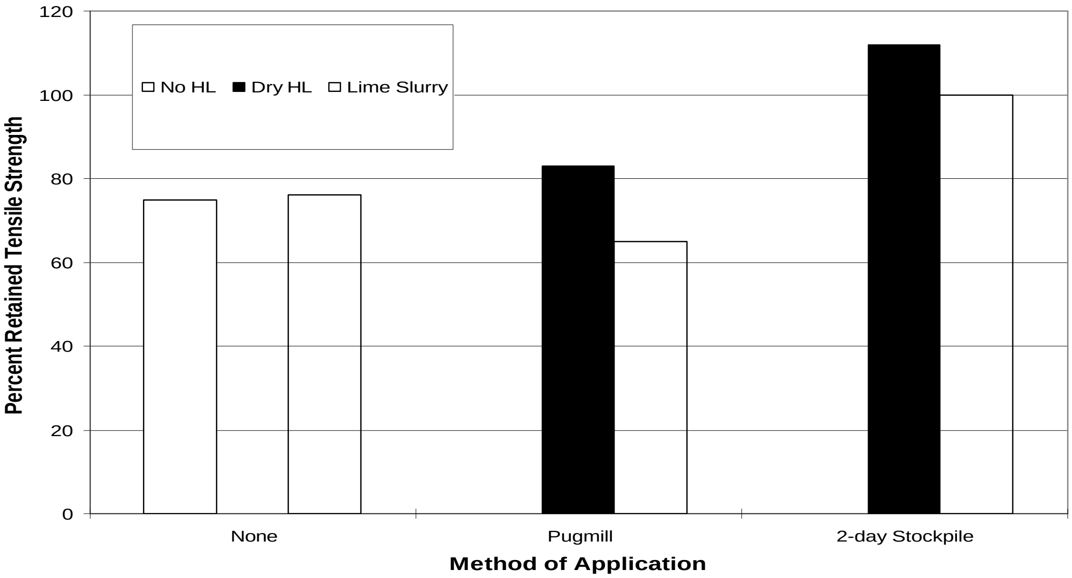


Figure 35. Effect of Method of Application on Retained Tensile Strengths of Batch Plant Operations in Texas [After Button and Epps (1983)].

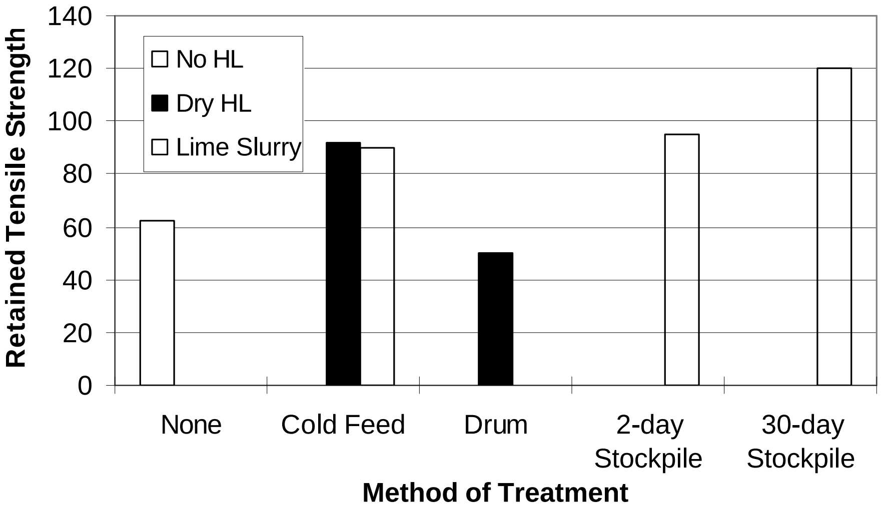
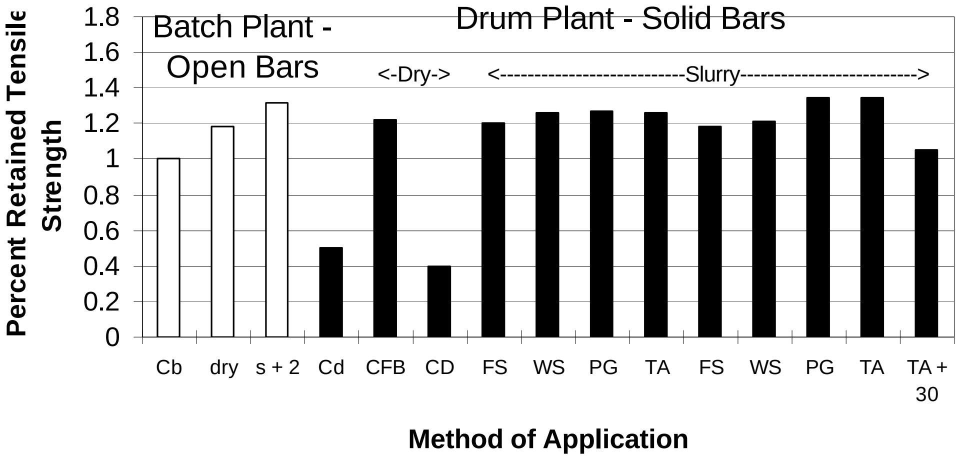


Figure 36. Effect of Addition of Lime to Drum Plant Operations [After Button and Epps (1983)].



Cb = No Lime, Dry = Dry Lime in Pugmill, S + 2 = Slurry on Total Aggregate + 2-Days in Stockpile, Cd = Control + No Lime, DFB = 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 37. Effect of Method of Addition of Lime on Tensile Strength Ratio for Batch and Drum Plants [After Button (1984)].

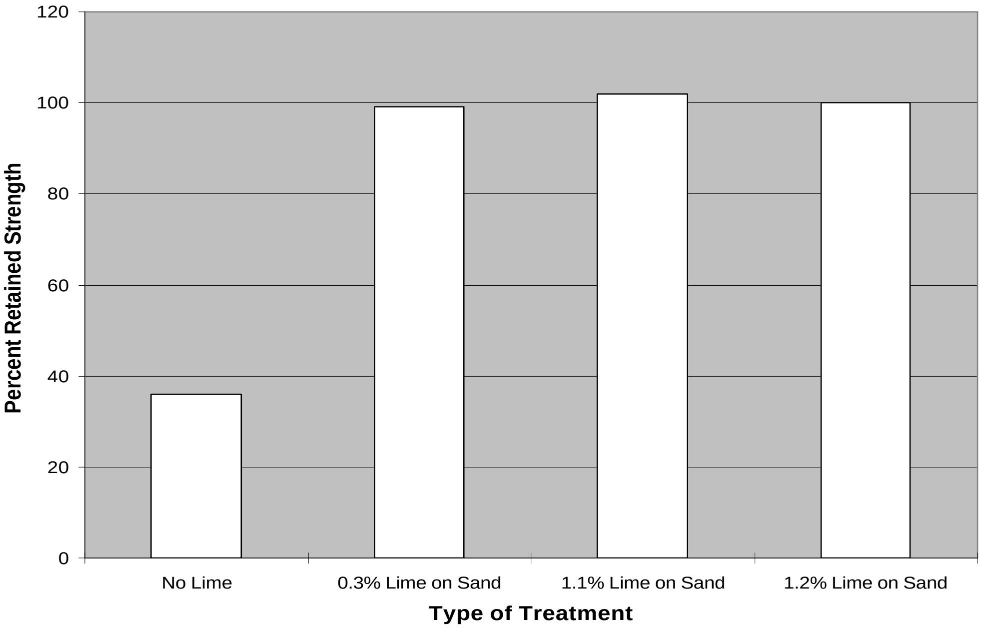


Figure 38. Effect of Amount of Lime Added to Field Sand [After Kennedy et al. (1982)].

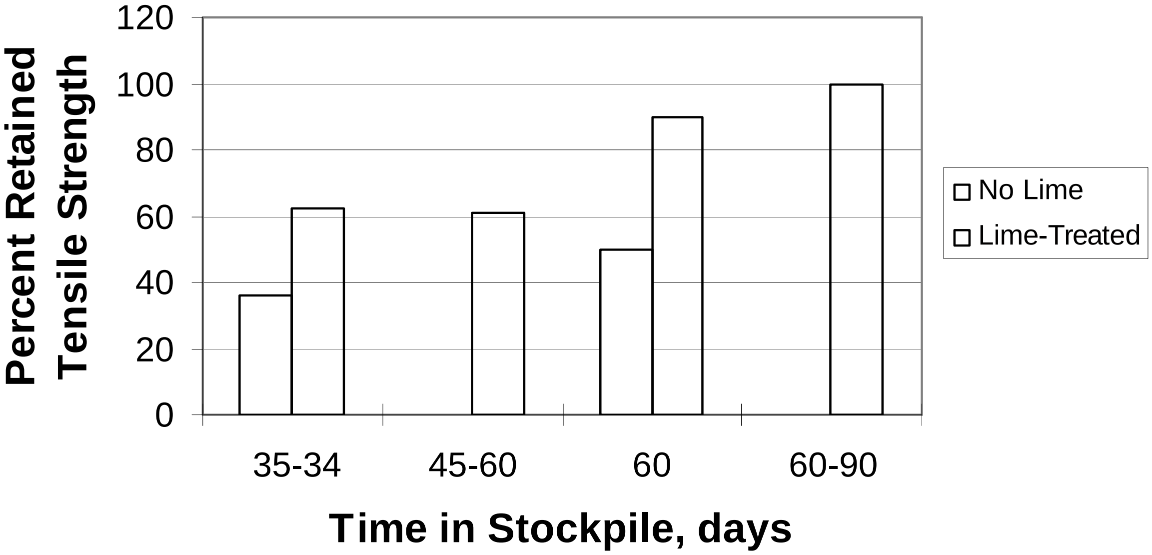


Figure 39. Effect of Time of Stockpile Marination on the Tensile Strength Ratio of Mississippi Siliceous River Gravel Aggregate [After Little (1994)].

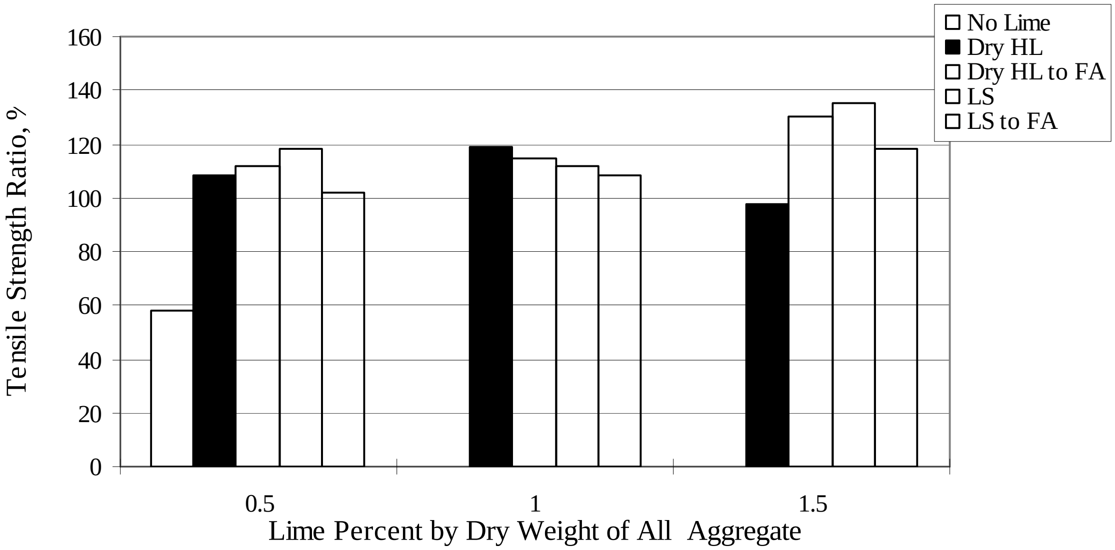


Figure 40. Effect of Method of Lime Addition and Percent of Lime Added to Granite Aggregate [After Hanson et al. (1993)].

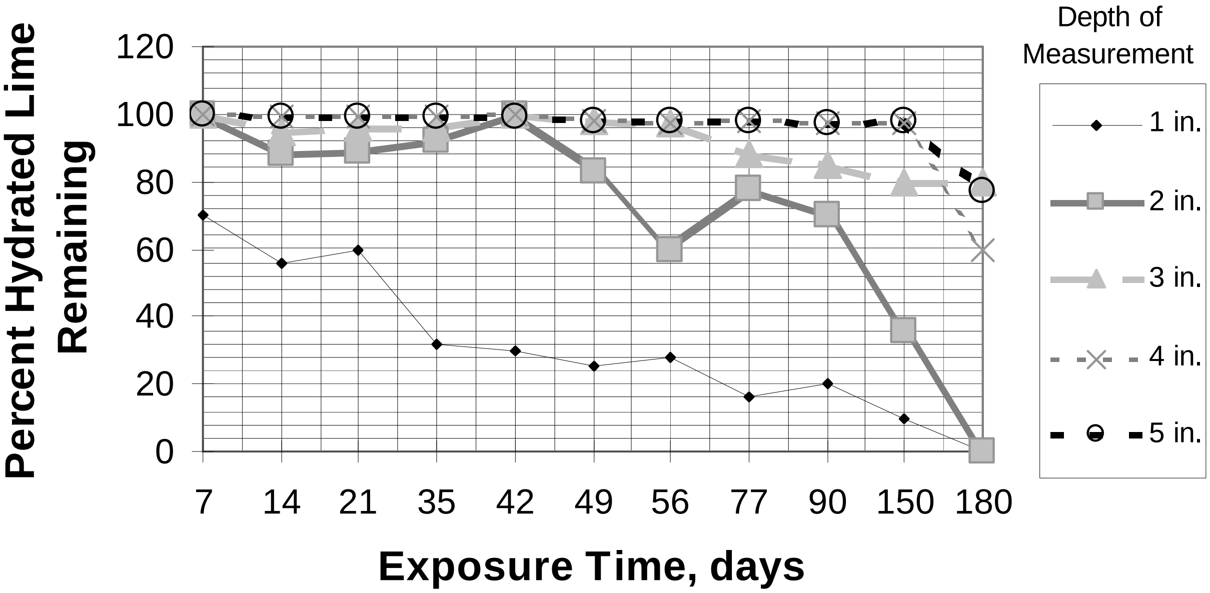


Figure 41. Effect of Exposure Time and Stockpile Carbonation on the Active $Ca(OH)_2$ Remaining [After Graves (1992)].