TOPIC 4

Treatments

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In the presence of water, asphalt-aggregate mixtures can experience a loss of bond between the asphalt binder and the aggregate (adhesion). In addition, the asphalt binder may experience changes in properties (strength, stiffness, viscosity, etc.) when water is present (cohesion). Loss of bond or changes, or both, in the properties of the asphalt binder can result in significant engineering property changes in hot-mix asphalt mixtures and premature distress in pavements.

A number of premature pavement performance problems were experienced in the United States in the middle and late 1970s and into the 1980s. This distress resulted in significant expenditures for rehabilitation and maintenance. Raveling, rutting, alligator cracking, bleeding, longitudinal cracking, and transverse cracking were some of the forms of pavement distress experienced during that period. Rutting was a relatively common form of premature distress during this period. The relatively large number of pavements experiencing some form of premature distress was in part responsible for the Strategic Highway Research Program (SHRP) and the resulting Superpave™ binder specification and mixture design method.

CAUSES OF PREMATURE DISTRESS

Premature pavement distress during this period of time has been attributed to several factors, including

1. Increase in truck traffic volumes,
2. Increase in truck weights,
3. Increase in tire pressure,
4. Changes in asphalt binder properties (both chemical and physical),
5. Changes in aggregate properties,
6. Construction practices,
7. Pavement design considerations, and
8. Moisture sensitivity.

Other factors have been identified by various authors but are not included in the list.

Truck traffic volume has increased significantly on our nation’s highways. Increases in commerce as well as a shift from rail transport to highway transport are among the major driving forces. Truck weights in some states have increased and, in part, contribute to the premature distress. Truck tire pressures increased from approximately 70 psi in the 1960s to an average of 100 psi by the late 1970s. Tires are used in Europe and Asia with inflation pressures of 135 psi and above. The types of truck tires also changed during that period.

The oil embargo, which started in late 1973, resulted in a different slate of crude oil being used in a number of refineries throughout the United States. Asphalt binders produced by some refineries changed significantly during that period.

Aggregate sources are continually changing, and in some cases the quality of aggregates has declined. Aggregate quality and type are related to water sensitivity problems in hot-mix asphalt.

The quality of construction has improved since the mid-1980s as quality control and quality assurance types of specifications have been used by more states. Improvements in in-place air voids, joint density, and general quality control associated with asphalt binder content, aggregate gradation, and segregation have occurred since the early 1980s.

The more widespread use of open-graded friction courses, and in some areas interlayers constructed with chip seals or fabrics, resulted in hot mixes subjected to increased moisture contents over longer periods of time. The use of these types of materials caused premature distress in some pavements during the 1970s and 1980s.

MOISTURE SENSITIVITY AND PREMATURE DISTRESS

Moisture sensitivity was identified as a major contributor to premature distress on several pavements in the Intermountain West and the Southeastern United States in the late 1970s. Research programs on water sensitivity were initiated by NCHRP and several states in the middle and late 1970s. Field experimental projects were conducted in the early 1980s. Significant amounts of research were conducted in the 1980s and early 1990s. A renewed interest in moisture sensitivity and in particular the relationship between laboratory testing and field performance started in the late 1990s and continues today.

Raveling, rutting, alligator cracking, and bleeding are forms of hot-mix asphalt pavement distress that can be caused in part by moisture sensitivity problems. Raveling, or the loss of aggregate from the surface of the pavement, is generally associated with water sensitivity, aging of the asphalt binder, and low asphalt binder contents, among other factors. Raveling is a common form of pavement distress in the Intermountain West. Some areas of the Intermountain West experience nearly 300 air freeze–thaw cycles annually. A significant number of these freeze–thaw cycles occur in the presence of moisture.

Rutting has been related to moisture sensitivity in hot-mix asphalt as a result of the loss of strength due to the presence of moisture. Often the rutting is associated with some bleeding of the asphalt surface, and raveling can also be present. Several pavements in the Southeastern United States experienced rutting that was associated with high pavement temperature and moisture. Rutting in other areas of the United States has been related to moisture, particularly when chip seals, interlayers, and open-graded friction courses are used without high-quality hot-mix asphalt.

Fatigue is associated with load repetitions and is experienced in those pavements with relatively high stresses or strains due to traffic. A reduction in the stiffness of the hot-mix asphalt (resilient modulus or dynamic modulus) in a pavement can result in stresses and strains in the hot-mix asphalt that exceed the fatigue capacity of the hot mix. Moisture can contribute a reduction in the stiffness of the hot-mix asphalt.

TREATMENTS FOR MOISTURE SENSITIVITY PROBLEM

The potential for a hot-mix asphalt to have moisture sensitivity problems is related to the properties of the asphalt binder, properties of the aggregate, hot-mix asphalt characteristics, climate, traffic, construction practices, and pavement design considerations. For a particular project, the climate and traffic volumes cannot be controlled. Construction practices and pavement design considerations can be controlled to a limited extent. From a practical standpoint, the selection of the asphalt binder and aggregate for a particular project is based largely on availability and economics. Mixture designs can be developed with moisture sensitivity as one of the controlling factors.

For most projects, an asphalt binder and aggregate are selected and the mixture design is developed. The mixture is then tested for moisture sensitivity and, if not accepted, a "treatment" of some type is selected based on experience and laboratory testing. The hot-mix asphalt is judged to be acceptable if it meets certain laboratory test criteria. Some public agencies require all hot-mix asphalt mixtures to be treated for moisture sensitivity. Other public agencies require that the field-produced hot-mix asphalt meet certain laboratory test criteria as part of the test strip process or during production of the hot-mix asphalt for the project, or both.

A survey conducted by Aschenbrener in August 2002 indicated that 25 states use a liquid antistripping agent, 13 states use hydrated lime, and 7 states use either a liquid or hydrated lime (*1*).

A variety of treatments are available to improve the water sensitivity of a particular hot-mix asphalt. These treatments can be conveniently grouped into those that are added or applied to the asphalt binder and those that are applied to the aggregate. Although the treatments are typically added or applied to the asphalt binder and the aggregate, their physicochemical effect is on both the asphalt binder and aggregate.

Treatments Added to the Asphalt Binders

A variety of chemicals are being used to reduce the moisture sensitivity of hot-mix asphalt. The majority of chemicals presently used are alkyl amines and are sold under a variety of brand names. These chemicals are added directly to the asphalt binder either at the refinery or asphalt terminal, or at the contractor's asphalt facility during production of the mix with an in-line blending system. These types of chemical additives are generally referred to as "liquid antistrip agents or adhesion agents." Liquid antistrip agents are not only used in hot-mix asphalt but are commonly used in cold-applied, asphalt-bound patching materials, in asphalt binders used for chip seals, and in the binder used for precoating the aggregates in chip seals.

There is evidence that some polymers can act as antistrip agents. Polymers are typically blended with the asphalt binder at the refinery or terminal and supplied to the hot-mix asphalt producer.

The physicochemical properties of the liquid antistrip agents and the polymers that are added to the asphalt binders are discussed elsewhere in these conference proceedings. The physicochemical interaction between these types of antistrip agents and the asphalt binder and aggregate is also discussed elsewhere in these conference proceedings.

Treatments Applied to the Aggregates

Hydrated lime, portland cement, fly ash, flue dust, and polymers have been added to aggregates to provide resistance to moisture in hot-mix asphalt mixtures. Typically, these materials are added to the aggregate and mixed before the introduction of the asphalt binder in the hot-mix asphalt production process. In some cases, hydrated lime or portland cement has been added in the drum mixing operation at the point of entry of the asphalt binder to the heated aggregate.

Hydrated lime is currently the most commonly used treatment for aggregates. Portland cement was used by a number of states (for example, Arizona and Nevada); however, most public agencies no longer use portland cement. Fly ash, flue dust, and polymers are infrequently used currently. The properties of the fly ash and flue dust must be determined to establish if these materials are suitable for use in hot-mix asphalt as antistrip agents. A limited amount of research and field installations have been performed with polymer additions to aggregates.

The physicochemical properties of these types of antistrip agents that are added to the aggregates are discussed elsewhere in these conference proceedings. The physicochemical interaction between these types of antistrip agents and the asphalt binder and aggregate is also discussed elsewhere in these conference proceedings.

Currently, most public agencies use either a liquid antistrip agent and add the liquid to the asphalt binder or use hydrated lime and add the lime to the aggregate. Because these materials are most commonly used, the majority of this synthesis of information will be directed toward the use of liquid antistrip agents added to asphalt binders and the use of hydrated lime added to aggregate before the introduction of the asphalt binder.

LABORATORY TEST METHODS

Laboratory tests are commonly used to determine the effectiveness of different types of antistrip treatments. A brief review of test methods frequently used by public agencies is provided. These test methods are further defined and compared in other papers presented at this conference. The effectiveness of various types of antistrip treatments is determined by the use of these tests described later in this synthesis of information.

A number of test methods have been developed to determine the moisture sensitivity of hot-mix asphalt mixtures. Most of the tests developed are suggested for use during the mixture design process and not for quality control or quality assurance testing. For the most part, extensive data are not available that allow for a good correlation to be established between the laboratory test and field performance.

Laboratory tests to evaluate water sensitivity can be grouped into three categories:

1. Loose mixtures,
2. Representative mixtures, and
3. Compacted mixtures.

Tests that can be placed into each of these categories, and which are subsequently used in this synthesis, are presented below.

Loose Mixture Tests

A variety of loose mixture tests have been developed and continue to be used by some public agencies. Soaking and boiling tests on loose mixtures of asphalt binders and aggregates were used by a number of states in the 1950s and 1960s. The length of soaking, temperature, and method of evaluating the degree of bond loss vary among the techniques used.

The Texas DOT boiling test and ASTM D3625 are examples of these types of tests. In the Texas test, the hot-mix asphalt is soaked and boiled for 10 min. Water sensitivity of the hot-mix asphalt is judged by visually determining the amount of bond loss between the asphalt binder and the aggregate. Samples of mixtures or photographs of mixtures with different percentages of bond loss have been used to assist in the determination of the percent bond loss of the sample.

Representative Mixture Test

The freeze–thaw pedestal test developed at Western Research Institute on the University of Wyoming campus, and further developed at the University of Texas, selects a portion of the fine, one-sized aggregate for testing. The aggregate is coated with asphalt, compacted, placed on a pedestal, and subjected to alternating freeze–thaw cycles until fracture is observed.

The selected fine aggregate fraction and asphalt binder are compacted into a 1.5-in. diameter by ¾-in. sample and immersed in water and alternately frozen and thawed until failure occurs. Research was reported in the 1980s using this test technique to evaluate the effectiveness of various antistrip agents.

Compacted Mixtures

The immersion–compression (ASTM D1075), Chevron, Tunnicliff-Root, and the Lottman tests are examples of compacted mixture tests. All of these tests use the project asphalt binder and the project aggregate. The materials are mixed and compacted for testing. The immersion–compression test has been used extensively by several state DOTs, the U.S. Army Corps of Engineers, and the Federal Aviation Administration. Arizona DOT has modified the test method so that the air voids of the compacted mixture are in the range of 6% to 8%, rather than a typical value of 3% to 5%.

Chevron Asphalt developed a test in the 1960s using compacted hot-mix asphalt. The compacted hot-mix asphalt was subjected to water saturation by vacuum, and the resilient modulus was measured before and after the introduction of water. Lottman and coworkers at the University of Idaho further developed the test method and added freeze–thaw cycles (*2*, *3*) to the test procedure. The developed test procedure was standardized as AASHTO T283, and the freeze–thaw cycles reduced to one.

Tunnicliff and Root (*4*) performed research using similar techniques for NCHRP. Their research resulted in the development of ASTM D4867, which is similar to the Lottman test without the freeze–thaw cycle required. Tensile strength of conditioned and unconditioned samples is measured by the indirect tension test procedure. Tensile strength ratios (TSRs) are often reported for the mixtures tested.

Nevada DOT made further improvements in the Lottman test procedure and tested for both resilient modulus and indirect tensile strength. In addition to testing for TSR, Nevada specifies a minimum dry tensile strength.

The SHRP research program developed a test method that is capable of applying a repeated load while introducing moisture into the sample. The temperature can be cycled to produce freeze–thaw conditions. Texas DOT and the University of Texas at El Paso have continued to perform some developmental work on the test procedure.

Wheel-tracking tests such as the Hamburg and the Purdue University laboratory rut tester are examples of tests used in the United States in the 1990s to today. Laboratory or field compacted samples are subjected to repeated wheel loading in the presence of water, and rut depths are measured.

The immersion–compression, Chevron, Lottman, Tunnicliff and Root, Nevada DOT, and SHRP tests, and the rutting types of tests are all examples of water sensitivity tests performed on compacted mixtures produced from asphalt binders and aggregates used on the paving projects. Those tests that compact samples to relatively high air void contents (6% to 8%), subject the samples to high levels of water saturation, and perform freeze–thaw cycles are the most severe indicators of water sensitivity in hot-mix asphalt. Additional details on these and other test methods can be found in these conference proceedings.

TREATMENTS ADDED TO THE ASPHALT BINDERS

As discussed, liquid antistrip additives have been used effectively and extensively in the United States to reduce the moisture sensitivity of hot-mix asphalt materials. Liquid antistrip agents can affect the engineering properties of the asphalt binder and the engineering properties of the hot-mix asphalt mixture. The effectiveness of the liquid antistrip on the water sensitivity of the hot-mix asphalt mixture depends on the physicochemical properties of the asphalt binder and the aggregate, as well as on the amount of liquid antistrip agent used. Liquid antistrip materials can be added to the asphalt binder at a number of locations and by various methods. The long-term effectiveness of antistrip agents is demonstrated by Tunnicliff and Root (*5*). A summary of information on asphalt binder properties, hot-mix asphalt mixture properties, and construction operations associated with the use of liquid antistrip agents is presented below.

Asphalt Binder Properties

The properties of the combined asphalt binder and liquid antistrip agent depend on the chemistry of the asphalt binder, the chemistry of the liquid antistrip, the concentration level of the liquid antistrip, and the types of carrier or dispersant used with the liquid antistrip, among other factors. The combined binder properties can also depend on the time and temperature of storage of the asphalt binder–liquid antistrip material.

Some of the low-performance liquid antistrip agents use oil-type carriers or dispersants, which can change the physical properties of the asphalt binders. High-performance liquid antistrip agents contain very little dispersants. In the early and middle 1980s, diesel oil was used as a dispersant, a practice long since discarded even in low-performance liquid agents. However, some early testing of liquid antistrip agents was performed with additives containing diesel oil. Table 1 shows the magnitude of the viscosity change at 140°F resulting from the addition of a liquid antistrip on three different asphalt binders. The magnitude of the viscosity change depends on the type of additive, concentration of the additive, and type and source of asphalt binder (*6*).

The degree of aging of an asphalt binder may also be altered by the presence of liquid antistrip agents, as shown in Table 2 (*6*). The viscosity at 140° F of the aged asphalts with liquid antistrip may be lower than that of the control asphalt binder, but the ratio of its viscosity increase (treated sample viscosity after aging to viscosity of treated sample before aging) may be larger. A laboratory aging test was performed to generate the data shown in Table 2.

The penetration of the asphalt cement can also be affected by the presence of a liquid antistrip agent. The magnitude of the penetration change depends on the type of additive, additive concentration, and type and source of the asphalt binder, as shown in Figure 1 (*7*). Figure 2 shows the change in penetration of aged asphalt binders with various concentrations of liquid antistrip agents. Changes in penetration (ratio basis) are shown for three types of asphalt binders and four concentrations of liquid antistrip agents (*8*).

The effect of a liquid antistrip agent's concentration on viscosity is shown in Figure 3 (*7*). The amount of change depends on the asphalt cement type and source. A 30% change in viscosity at 140°F is possible at 1% concentrations of liquid antistrip. Figure 4 shows that the viscosities of treated asphalt binders are reduced in comparison with the aged properties of the original asphalt binders (*7*).

Some Superpave binder testing has been performed on asphalt binders containing various high-performance liquid antistripping agents. Figure 5 shows the changes associated with the parameter G* sin delta ("Adhesion Promoters," Technical Bulletin, Akzo Nobel). Additional G* sin delta data for a variety of asphalt binders and dosage amounts are shown in Figures 6 to 10 (*9*).

In addition, when high-performance liquids are used, they may exhibit little or no change when measured for SHRP asphalt binder properties, as shown in Table 3 (*10*). It should be noted that for the high-performance liquid Agent A, Source B binder would require the addition of 10% of the additive to create a drastic change in the G* sin delta parameter binder property.

The G* sin delta parameter used in Superpave binder specifications is reported to be an indication of fatigue resistance of the binder. Currently, the upper specification limit is 5,000 kPa. Considerable discussion is occurring in the technical community relative to the validity of this parameter for fatigue.

Hot-Mix Asphalt Properties

A South Carolina Department of Highways research program determined the indirect tensile strength of samples subjected to the Tunnicliff–Root test, without freeze thaw cycle (ASTM D3625) (*11*). Figures 11 to 13 show the indirect tensile strengths before and after exposure to water for aggregates from Sources A, B and C. Comparisons are made with control samples (without antistrip treatment) and for samples of hot-mix asphalt made with liquids and lime as antistrip additives.

The South Carolina Department of Highways also conducted studies to investigate the effect of sample storage time on water sensitivity test results (*11*). Figures 14 to 17 show the effect of sample storage time on the moisture-conditioned properties of mixtures subjected to the Tunnicliff Root procedure. Test results from three aggregate sources are shown on these figures for samples stored 24 h and 60 days before testing. The codes used to identify the types of antistrip additives are provided as follows:

0—control (no antistrip additive);
1—liquid antistrip;
2—hydrated lime;
3—liquid antistrip; and
4—liquid antistrips.

Storage times of 60 days increased the dry tensile strength while only slightly altering the tensile strength after the samples had been exposed to a water sensitivity test.

Boil tests performed in South Carolina are shown in Figure 18 (*11*). Three aggregates were used. Results from control samples as well as samples treated with a liquid antistrip and hydrated lime are shown.

Results of the Lottman tests (AASHTO T283 with a freeze–thaw cycle) are shown in Figures 19 to 26 for aggregate samples obtained from California, Florida, Georgia, Mississippi, Missouri, South Carolina, and Utah (*12*). These results were obtained on asphalt binders treated with different dosage levels of amidoamine, polyamine, and lime antistrip agents. In general, it appears that the optimum liquid additive dosage ranged from 0.5% to 0.75% by weight of the binder, whereas the TSR values ranged from 0.95 to 1.05. Hydrated lime was applied at a rate of 1.0% on the basis of the weight of the aggregate. It should be noted that the values for the liquid antistrip agents mirrored the hydrated lime values of TSR.

Texas DOT reported on a study containing several aggregates obtained near the Houston area. Table 4 contains a summary of the results of this study, which used different types of liquid antistrip agents. The results obtained from AASHTO T283 tests indicate that the specification limits of 70% retained strengths could be obtained with various percentages of liquid antistrip agents (*13*).

Figure 27 (*14*) illustrates the relative improvement that may be obtained in the Hamburg rut depth test with the use of various liquid agents. Three different aggregate sources, three binder sources (all modified binders) ranging from PG70-22 to PG76-22, and four liquid agents were used in the study. A rut depth of 12.5 mm for a surface layer is considered unsatisfactory. It can be seen that Liquids A and B performed well.

A Colorado study (*15*) provides TSR data after AASHTO T283 conditioning on hot-mix asphalt mixtures from 20 different projects (Figure 28). The effectiveness of the liquid antistrip materials used on these projects as measured by the TSR value is shown, with one of the conclusions being that "neither lime nor anti-stripping agents are a panacea for moisture damage."

In 1995, Maupin (*16*) reported that considerable stripping was evident in field cores from Virginia projects 3 to 4 years old that contain liquid antistripping agents. One of the conclusions of this study was that hydrated lime appeared to perform better than liquid antistrip agents. Owing to the concerns raised by these findings, another field study was initiated on projects placed in 1991 and 1992 after more stringent specifications were introduced for liquid antistrip agents.

Maupin (*17*) reported in 1997 that the results of this latter study did not validate the previous study conclusion relative to the behavior of liquid antistrip agents and hydrated lime. One conclusion from the 1997 study indicated that hydrated lime and chemical antistrip additives performed at an equal level. It was believed that chemical additive suppliers improved their product to meet specification.

TSR data for 12 Virginia projects are shown in Figure 29 ("Tensile Strength Ratio—Virginia," provided by Akzo Nobel), and with only one exception, the TSR values for liquid antistrip agents and hydrated lime appeared to coincide.

A field evaluation study by Tunnicliff and Root concerning antistripping additives in asphaltic concrete mixtures is presented in *NCHRP Report 373* (*5*). Nineteen test sections were constructed in eight states with and without antistripping additives. Tunnicliff and Root concluded that during the 6- to 8-year study, eight of the nine additives performed satisfactorily, and ASTM Method D4867 correctly predicted the performance of 16 of the 19 experimental sections.

Indirect tensile stiffness modulus values for a base course treated with various dosages of liquid antistrip agent are shown in Figure 30 (*Adhesion Promoters*, Technical Bulletin, Akzo Nobel). Limited data are presented for various soak times, ranging from 0 to 30 days, and they show a much improved modulus with the use of a high-quality liquid.

Several types of liquid antistripping agents, hydrated lime, and a combination of hydrated lime and liquid antistrip agent were used in a Louisiana laboratory and field evaluation study (*18*). The project was constructed in fall 1990, and to date little distress is evident other than some longitudinal cracking in one area. Boil, Ross count, and an AASHTO T283 type of test with 10 multiple freeze–thaw cycles were conducted on project plant run mix. Results of these tests are shown in Figures 31 to 36. The dosage rate for all of the liquids was 0.8%, based on the weight of the asphalt binder, and the rate for hydrated lime was 1.4%, based on the weight of the aggregate. In addition, one test section contained a combination of hydrated lime at 1.4% and a liquid at 0.8%.

In summary, the boil test (Figure 31) does not show a substantial difference between additives; however, when conducting AASHTO T283 with multiples of 1, 3, 5, and 10 freeze–thaw cycles, differences occur with the use of various additives (Figure 33). With the addition of multiple conditioning cycles (Figure 33), a reduction of tensile strength values is noted. Figures 32 and 34 depict the loss of TSR with regard to an increase in air voids and a decrease in wet tensile strength with freeze–thaw cycles. It should be noted that the high-performance Liquid A generally outperformed the other additives in the laboratory phase.

Results from the freeze–thaw pedestal test conducted on an aggregate treated with different types of liquid antistrip agents are shown in Figure 37 (*19*). The number of freeze–thaw cycles to failure is shown. Comparisons with a control sample, hydrated lime, pyridine, and multiple chemical additives added at an unusually low dosage rate of 0.25% are shown in this laboratory study.

Construction Operations

Liquid antistrip agents can be added at the contractor's hot-mix asphalt production facility. The liquid antistrip agent is typically added to the asphalt binder by means of an in-line injection system just before the asphalt binder's entering the drum dryer or batch mixer. The liquid antistrip agent can also be added to the asphalt binder storage tank and circulated before use.

Cost-Effectiveness

The material cost of liquid antistrip agents typically ranges from $0.45 to $0.75 per pound of liquid antistrip. This equates to a cost of $6.75 to $11.25 per ton of asphalt binder for a treatment concentration of 0.75%. Thus, the typical increase in the cost per ton of hot-mix asphalt concrete is from $0.30 to $0.70 for the liquid antistrip agent. The cost for in-line blending equipment installed at the contractor's plant ranges from $10,000 to $25,000. Typically, the in-line blending equipment is amortized over a 5-year period. The total price increase in using a liquid antistrip agent is typically in the range of $0.50 to $0.81 per ton of hot-mix asphalt.

TREATMENTS ADDED TO THE AGGREGATES

As described previously, several treatments have been added to aggregates in an attempt to alter the moisture sensitivity of hot-mix asphalt. Hydrated lime, portland cement, fly ash, flue dust, and polymers are among the materials used. Hydrated lime is currently the most popular treatment used on aggregates, and most of the discussion will center on its use in hot-mix asphalt.

Before a discussion of lime, some of the available information on the use of the other additives will be presented. This limited review includes information on portland cement, flue dust, and polymers.

Two research projects conducted in Nevada provide limited information on the effectiveness of portland cement, fly ash, and lime (*20*, *21*). Figures 38 to 40 illustrate the effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate. The use of portland cement and lime together was not as effective as the use of relatively high percentages of hydrated lime alone on this aggregate. Figure 41 presents research results from a Nevada DOT study, which evaluated mixtures in the laboratory as well as placed sections in the field in a climate subjected to numerous freeze–thaw cycles (*20*, *21*).

Figure 42 illustrates the relative effectiveness of portland cement and hydrated lime based on available data in 1991 (*22*). Lime in general has proven to be a more effective antistrip additive than portland cement over a wide range of aggregate and asphalt binder types.

Polymeric Aggregate Treatment

The use of a polymeric aggregate treatment system provides a protective barrier on the aggregate, which repels water and waterproofs the aggregate while providing an improved bonding with the asphalt. When properly applied, the polymeric aggregate treatment will turn a hydrophilic aggregate into a hydrophobic aggregate, increasing the water resistance of the hot-mix asphalt.

One of the additional benefits observed by using polymeric aggregate in this system of treatment is that the amount of asphalt required in the mixture may be lowered, resulting in cost savings for the hot-mix contractor (*23*, *24*). As the polymer coats the porous aggregate, less asphalt is needed to fully coat the surface.

Western Research Institute conducted a study on the effect of antistrip treatments on asphalt–aggregate systems (*25*). In this study, an environmental scanning electron microscope (ESEM) was used to observe how the asphalt–aggregate interface changes with sequential freeze–thaw cycling under water and to evaluate the effectiveness of antistrip additives. The untreated control samples displayed separation at the asphalt–aggregate interface after only one freeze–thaw cycle. Amine-treated asphalt samples and lime-treated aggregates showed varying degrees of separation after freeze–thaw cycles, whereas the polymeric aggregate–treated samples showed no separation after 10 freeze–thaw cycles.

Asphalt Binder Properties

While the polymeric aggregate treatment is added to the aggregate, there is an interaction at the interface between the aggregate coating and the asphalt. This interaction results in an improved mechanical and chemical bond. The polymer used is specially selected to have compatibility with the asphalt and to enhance the aggregate-coating-asphalt bonding.

Hot-Mix Asphalt Properties

A Florida study investigated various amounts of SBR latex and lime (*26*). The solids concentration of polymer ranged from 0.05% to 0.1%, whereas 1% to 1.5% of lime was used. The amount of amine used was based on the percent asphalt (0.5%). Samples were prepared according to the supplier's recommended procedures. Ratios of the conditioned treated mixtures over the unconditioned untreated mixtures were calculated. SBR-treated mixtures displayed the highest TSR of the various treatments. As more SBR was added, the TSR increased, suggesting that with this aggregate there is a concentration dependency (see Figure 43). The SBR-treated samples show a somewhat higher wet tensile strength than do the samples treated with other antistripping agents and the untreated samples (see Figure 44).

In a Texas study (*27*), aggregates from different regions of Texas were evaluated and both the TSR and Texas boil test were performed. Aggregates from four different districts in Texas were selected and used to evaluate the effectiveness of SBR and lime in preventing moisture damage. The polymer treatment system reduced the percent uncoated aggregate for all the mixtures tested. In Texas, a minimum TSR of 80% is required. None of the aggregates passed the AASHTO T283 test untreated, which means they are all highly moisture sensitive mixtures. The lime treatment worked better with the aggregate from the Pharr District than the SBR treatment did. Because the aggregates are made up of a variety of minerals, the chemical composition and texture of the surface are important variables in the performance of SBR. With the use of the SBR, the aggregates from Atlanta, Amarillo, and El Paso all passed the TSR requirement (see Figure 45). For the Atlanta District, the 0.1% polymer treatment produced much higher dry and wet tensile strengths than did the lime, again indicating an enhancement of the mixture strength (see Figure 46).

Aggregates from two locations in Nevada were also studied (*23*). In both cases, the highest level of SBR performed as well as or better than the lime-treated mixtures (Figures 47 and 48). The SBR-treated samples also showed higher dry and wet tensile strength when compared with no additive and lime. On the basis of these results, SBR treatment is an excellent replacement ASA for lime with these aggregates.

A reduction in the optimum asphalt binder content can be associated with polymer treatment. When the polymer aggregate treatment was used with two marginal aggregates, reductions in binder contents of 0.85% to 0.40% were noted.

Aggregates from four locations in Colorado were studied (*24*). The study was performed to investigate the effectiveness of the polymer aggregate treatment system on four aggregate sources.

The results of the study suggest that the polymer aggregate treatment process should be an acceptable alternative to hydrated lime. Generally, with the polymer aggregate treatment process, the optimum oil contents are lower, and the Lottman TSR values are still acceptable (Figures 49 to 53). This study's results are site specific (Figures 49 to 53). Other sources of aggregate, even though they may be similar, need to be evaluated individually.

Construction Operations

SBR latex concentrate is delivered to the job site and must be diluted to 15% solids before use. This is accomplished automatically when using an approved application unit. The latex is then applied to the aggregate stream. Approved application units have two pumps that proportion the latex and water at the correct ratio. The pumps discharge through a line to the aggregate feed belt. A valve is provided in the combined discharge line to permit sampling of the final blend.

At the hot-mix plant, the latex should be applied to the aggregate stream just before entry into the dryer drum. Very little mechanical agitation of the aggregate is required to properly disperse the SBR latex emulsion, owing to the osmotic characteristic of the SBR latex. Simple devices may be used to introduce mechanical agitation on the belt and disperse the polymer on the aggregate before it enters the heated drum, if desired. The application system is nontoxic, nonflammable, noncorrosive, and easy to clean.

Cost-Effectiveness of Polymeric Aggregate Treatment

The material cost of polymeric aggregate treatment depends on the concentration needed to achieve the desired results. Generally, a range of 0.5 to 1.5 lb solid polymer per ton of aggregate is evaluated to determine the optimum rate, with 1.0 lb being typical. The cost for the application system installed at the contractor's plant ranges from $10,000 to $18,000, depending on the degree of automation required. The material cost increase using the polymeric treatment system varies, depending on the usage rate and pricing of the SBR latex.

Lime Treatments

Hydrated lime [$Ca(OH)_2$] is a fine, highly alkaline inorganic powder that has many industrial and environmental applications throughout the world. It first appeared in about 1910 as an asphalt stiffener in a proprietary product. Lime disappeared for a few decades, was used in the 1950s and 1960s in the Southwest, and began to reappear nationally during the search for solutions to the moisture sensitivity problems that arose in the 1970s. Researchers observed that the addition of hydrated lime to asphalt mixtures improved the adhesive bond between the aggregate and bitumen, substantially reducing the occurrence of stripping. Further research identified chemical reactions that occurred between lime and many bitumens that reduced their affinity for water, in turn reducing the mixtures' tendencies to strip. In addition, when aggregates are coated with clays, hydrated lime can react pozzolanically to remove those deleterious materials that would otherwise damage the mixture. States in those regions where stripping was most prevalent began to add hydrated lime to their mixtures, and word of its benefits spread through the Southeastern states and the Intermountain West.

The decades since hydrated lime was first identified as an antistripping additive have produced dozens of research papers and thousands of field projects expanding the general knowledge of its mechanisms for mitigating moisture damage. In the 1970s, research performed by Plancher et al. (*28*) at the Western Research Institute demonstrated that hydrated lime reacted with carboxylic acid and 2-quinolene groups in asphalts to form insoluble products that were no longer sensitive to moisture. One result of those reactions was an improvement in the cohesive strength of the binder, which was better able to resist the absorption of water. In addition, Petersen asserted that the reactions facilitated strong bonding between asphalt basic nitrogen groups and the aggregate surface. That initial work has been built on by additional studies at Western Research Institute highlighting other contributions that hydrated lime makes to asphalt mixtures—contributions that synergistically reduce the mixtures' susceptibility to moisture.

In addition to chemically reacting with many commonly used bitumens, hydrated lime alters the surface chemistry of aggregates that are susceptible to moisture. For many years, it was hypothesized that the highly alkaline hydrated lime coated the surface of acidic aggregates, facilitating the development of strong bonds between the aggregates and acidic bitumens. With the development of new analytical tools and a deeper understanding of micromechanics, that hypothesis is being more thoroughly investigated by Lytton, Little, and others who are studying the surface energies of bitumens and aggregates. Their work suggests that a hydrated lime wash may alter the surface energy of aggregates, enabling them to bond more strongly with bitumens to withstand the intrusion of water. Further investigations are under way to quantify the extent of that improvement over a broad array of aggregates.

Hydrated lime helps to mitigate moisture sensitivity of asphalt mixes in mechanical ways as well as chemical. Lesueur and Little (*29*) demonstrated that hydrated lime significantly increases $G^*/\sin\delta$ without significantly increasing the brittleness of the binder. As an extremely fine, active filler (characteristically 50% smaller than 10 μm), the hydrated lime helps to stiffen the mixture, often increasing the PG rating of the binder by a full grade with the addition of only 1% lime by weight of the aggregate (*30*). By stiffening the mix, the lime increases its resistance to rutting and fatigue cracking, reducing the ability of water to enter the system.

For many bitumens, hydrated lime also reduces the rate of oxidative aging, which extends the resiliency of the mix, in turn reducing the incidence of cracking, which also provides pathways for water to enter the pavement. This reduction in the rate of aging is a function of the reactions between the calcium hydroxide and polar acids in the bitumens that react with the environment, forming brittle compounds. In other words, when hydrated lime reacts chemically with bitumens, it often both eliminates components that facilitate the progression of water through the mix and removes compounds that contribute to oxidative aging.

The addition of hydrated lime to asphalt mixtures commonly results in a complex array of interactions that all contribute to a reduction in moisture sensitivity. The lime reacts chemically with both bitumen and aggregate to remove undesirable chemical compounds on the one hand, and to improve the surface energy and acidity balance on the other. At the same time, the dispersion of fine hydrated lime particles throughout the mastic helps to stiffen the mix, making it more resistant to mechanical failures from rutting and fatigue cracking. The contributions are synergistic, as is appropriate in a complex system such as asphalt cement, contributing interactively to the mitigation of moisture sensitivity in the mixtures.

Asphalt Binder Properties

Laboratory and field research has indicated that benefits of using lime in hot-mix asphalt are not restricted to improving the resistance to water sensitivity. Lime also acts as a mineral filler, can reduce the plastic index if clays are present, and can reduce oxidation of the asphalt binder.

Figures 54 to 56 illustrate the mineral filler effect on asphalt binders. The addition of lime increases the viscosity (see Figure 54) (*9)*, the stiffness of the binder as measured by the rutting parameter ($G^*/\sin \delta$) in the Superpave binder specification (Figure 55) (*31*), and the stiffness of the binder as measured by the fatigue parameter (G* sin delta) in the Superpave binder specification (Figure 56) (*9*). Increases in viscosity with the addition of lime to asphalt binders have been documented elsewhere.

Lime is a well-known stabilizer for clay soils. The lime changes the physicochemical properties of the clay minerals and reduces the plastic limit as well as changing the structure of the clay mineral. Lime is effective in reducing the plastic index of marginal quality granular base courses as well as reducing the plastic index of clays present in some aggregates used for the production of hot-mix asphalt.

Petersen et al. (*32*) investigated the effect of lime on the hardening properties of asphalt binders. Several asphalt binders were used in the study, as were several lime contents. A number of physical properties of the asphalt binders were tested before and after a laboratory aging test. Figure 57 illustrates the reduction in aging resulting from the presence of lime in the asphalt binders.

Jones (*33*) conducted research on Utah pavements that indicated that hardening of the asphalt binder can be reduced by the use of lime in hot-mix asphalt (Figure 58).

Hot-Mix Asphalt Properties

Lime is available in several forms, including high-calcium quick lime, dolomitic quick lime, high-calcium hydrated lime, normal hydrated dolomitic quick lime, and pressure hydrated dolomitic quick lime. High-calcium hydrated lime is by far the most commonly used lime in the United States. Figure 59 (internal data set, Materials and Test Division, Nevada DOT, 1998) and Figure 60 (*34*) indicate the resilient modulus before and after the addition of various types of lime. The hydrated limes used in the study offered the most improvement to moisture sensitivity. The hot-mix asphalt mixture, which used quick lime, did not have a measurable resilient modulus after exposure to water and a freeze–thaw cycle.

Figures 61 and 62 (*35*) indicate that the addition of hydrated lime to a hot-mix asphalt will increase the stiffness of the mixture. Comparison of resilient modulus values at 0%, 1%, and

2% lime indicate that the stiffness is increased on the dry or unconditioned mixtures with the addition of lime (mineral filler effect). Similar trends in the data are noted when tensile strength values are measured. It should also be noted that the conditioned or wet resilient modulus and tensile strength values will also increase with the addition of hydrated lime (improvement in moisture sensitivity of the mixtures).

Research conducted at Oregon State University (*36*) indicates that the permanent deformation or rutting characteristics of hot-mix asphalt will improve in both the dry and wet conditioned states with the addition of lime. Figure 63 indicates the benefit of using hydrated lime to prevent rutting. Data in Figure 64 (*30*) summarize a Texas rutting study on rut depth. The Hamburg wheel-tracking device was used to predict the rutting behavior of hot-mix asphalt mixtures treated with different types of antistrip agents.

Figure 65 (*36*), based on Oregon State University data, also indicates an improvement in fatigue life with the addition of hydrated lime in both the dry and wet conditioned state. Figure 66 (*37*) also indicates that rutting can be reduced by the addition of lime to hot-mix asphalt.

Research has indicated that the amount of hydrated lime needed to improve the moisture sensitivity of a hot-mix asphalt is of the order of 1% to 2% by dry weight of aggregate. Some mixture may require lime contents as high as 2.5% to achieve the desired results (*35*). The amount of lime in a hot mix to reduce oxidative hardening is below 0.5% by dry weight of aggregate.

Asphalt binder contents in hydrated lime–treated hot-mix asphalt often increase slightly (0.1% to 0.3% by dry weight of aggregate) (*35*). Some hot-mix asphalt mixtures may require less asphalt binder with the addition of lime or remain unchanged as compared with mixtures without lime addition.

Construction Operations

Several methods are commonly used to introduce hydrated lime into the asphalt mixture, each of them producing beneficial attributes for moisture sensitivity mitigation. On the basis of the observations earlier in this paper, it might be surmised that each of the methods of addition optimizes different contributions to the rheological and physical attributes of the mixture, but little research has been done to quantify those differences. Suffice it to say that asphalt mixtures benefit from the addition of hydrated lime, no matter how it is introduced into the mix. Following are descriptions of the addition methods most commonly used throughout the country.

Dry Lime on Dry Aggregate This method of adding hydrated lime is arguably the simplest, requiring only the addition of a storage silo and a metering system to an existing asphalt plant. The lime is metered onto the belt or auger that transports the fines into the mixing drum and is added along with the fines. Because some of the fines are usually drawn from the baghouse, any lime that is lost from the mix is recycled through that system. The fines are usually added to the mix immediately before the introduction of the binder. Consequently, the hydrated lime is distributed throughout the binder, some of it coming into direct contact with the aggregate while another fraction is available to react with the bitumen performing as a chemically active filler in the mastic. Because of the small investment required to add dry hydrated lime into the mix, the cost of this method is nominal, generally amounting to approximately $1.00 per ton of hot mix.

Dry Lime on Damp Aggregate A second common method for adding hydrated lime to asphalt mixes is to apply the dry lime to damp aggregate, generally from 1% to 3% above the saturated surface dry condition. The aggregate is then run through a pug mill to mix the lime and the aggregate together, ensuring that the aggregate is coated with lime. The lime/aggregate composite is then either fed directly into the plant (most common) or allowed to marinate in stockpile to allow time for the lime to react with clay or other coatings and contaminants that are present in the aggregate. The dry lime/damp aggregate method has the benefit of visually coating the aggregate before its introduction into the drum or batch mixer, while at the same time providing some free hydrated lime particles to migrate throughout the mastic. Because of the addition of a pug mill to the plant setup, and the addition of free water that must be dried off in the mixing process, this method is more expensive than the dry process, generally costing about $1.50 to $2.00 per ton of mix.

Lime Slurry on Dry Aggregate The addition of hydrated lime slurry to the aggregate arguably provides the best aggregate coating of all the methods, but it presents several challenges to hot-mix producers. The slurried lime is metered onto the aggregates, sometimes using different application rates, depending on the size fraction, and it is run through a pug mill to ensure thorough coating. After mixing in the pug mill, the aggregate is either fed directly into the plant or stockpiled and marinated for some period of time to allow the lime to react with the surface of the stone or any coatings or contaminants in the aggregate. Although this method of hydrated lime addition clearly provides the best aggregate coverage, it presents some problems to users, because the aggregates may contain substantial amounts of water that must be dried off during the mixing. In addition, when the aggregates are stockpiled for marination, yard space is needed, and additional material handling is required. This application method requires equipment for making the lime slurry and metering it onto the aggregate. Consequently, it is the most expensive method for adding lime to the asphalt mixture, often costing about $3.00 to $4.00 per ton to implement.

Figure 60 (*34*) and Figures 67 to 72 provide some laboratory and field evidence of the benefits obtained by adding lime, through the various methods presented as follows. Some data indicate that lime slurry applications are better than the use of dry lime on damp aggregate and dry lime on dry aggregate [see Figure 60 (*34*) and Figure 69 (*38*)], whereas other data, depending on the aggregate, indicate that nearly equal benefits can be obtained by any of the common methods used today (see Figure 69) (*38*).

Marination after the treatment with lime is frequently used in a number of Western states. Figures 67 and 68 (*39*), Figures 70 and 71 (*40*), and Figure 72 (*41*) indicate that some benefit can be obtained from the stockpiling or marination method. The benefits obtained by the use of marination depend on the aggregate, according to some information collected in Nevada.

Figure 73 indicates that treatment of only a fraction of the total aggregate used in a hot-mix asphalt can be effective in improving the moisture sensitivity of the mixture (*42*). Additional studies are needed with a wider range of aggregate types.

Figure 72 (*41*) and Figure 74 (R. E. Graves, "Lime in Sand for Hot-mix Asphalt: Test Project Summary," internal memorandum, Chemical Lime Group, Dec. 1992) indicate that lime-treated aggregates can be stockpiled for periods in excess of 60 days. The length of time allowed for stockpiling of treated aggregates remains an issue in several states.

Cost-Effectiveness of Hydrated Lime

As for any product that has been used successfully for decades, considerable anecdotal evidence exists attesting to the long-term benefits of adding hydrated lime to hot-mix asphalt. In the past

2 years, both the state of Nevada and the National Lime Association (NLA) have quantified the cost-effectiveness of using hydrated lime. A study performed by the University of Nevada–Reno for Nevada DOT (*43*, *44*) compared equivalent sections of lime-treated and nontreated highways that had been constructed between 1987 and 1994. Laboratory tests of field cores and data from the state's pavement maintenance system were both used in the analysis, which concluded that the addition of hydrated lime increased the expected pavement life by an average of 3 years. The 38% increase in life compared favorably with the 12% increase in the original cost of the lime-treated hot-mix asphalt.

In addition, in 2001, NLA commissioned a national study of the cost-effectiveness of hydrated lime, along with the development of a life-cycle cost analysis modeling tool that engineers could use to compare pavement alternatives (*45*). That effort, which included participation from 10 state DOTs and 10 paving contractors (Figure 75) (*45*), concluded that hydrated lime can save from 9% to 20% of a pavement's cost over the course of its life cycle. The actual saving depends on the strategies and activities selected by the agency, of course. The NLA model is based on the widely used FHWA model and is available for free.

SUMMARY

As the composition and quality of asphalt binders and aggregates continue to change and as the demands being placed on hot-mix asphalt pavements continue to increase, it is likely that more and more asphalt mixtures will require the addition of treatments to mitigate moisture sensitivity. Moisture sensitivity problems in hot-mix asphalt mixtures are related to one or more of the following:

- Properties of the asphalt binder,
- Properties of the aggregate,
- Design and characteristics of the hot-mix asphalt,
- Climate,
- Traffic,
- Construction practices, and
- Pavement design considerations.

A variety of treatments are available to improve the water sensitivity of particular hot-mix asphalt. These treatments can be conveniently grouped into those that are added or applied to the asphalt binder and those that are applied to the aggregate. Although the treatments are typically applied to only the asphalt binder or aggregate, their physicochemical effect is on both the asphalt binder and the aggregate.

A variety of chemicals are being incorporated into asphalt binder to reduce the moisture sensitivity of hot-mix asphalt mixtures. The majority of these chemicals presently used are alkyl amines and are sold under a variety of brand names. These types of chemicals are generally referred to as liquid antistrip agents or adhesion agents. Liquid antistrip agents are typically added to the asphalt binders at the contractor's hot-mix asphalt plant or at the refinery.

Hydrated lime, portland cement, fly ash, flue dust, and polymers have been added to aggregates to provide resistance to moisture in hot-mix asphalt mixtures. Of the products identified previously, hydrated lime is the most common addition to aggregates. Typically, hydrated lime is added to the aggregate and mixed before the introduction of the asphalt binder into the hot-mix asphalt mixing plant.

Liquid antistrip agents and hydrated lime are presently the most common types of antistrip agents used in the United States. The information contained in this report illustrates the behavior of these two types of antistrip agents on asphalt binder properties as well as on hot-mix asphalt mixtures.

Results obtained on laboratory-prepared samples and testing in the laboratory indicate that both liquid antistrip agents and hydrated lime can improve the moisture sensitivity of hot-mix asphalt. In addition, these antistrip agents can influence the behavior of hot-mix asphalt mixtures and thus pavement behavior relative to rutting, fatigue, raveling, and so forth. The magnitude of improvement offered by these antistrip chemicals as illustrated by laboratory tests depends on the laboratory test method used to evaluate moisture sensitivity as well as the asphalt binder source, aggregate type, antistrip concentration, and other aspects.

Few research reports are available that define the behavior of antistrip agents on field-produced mixtures and define the performance of pavements with and without antistrip agents. Thus, life-cycle cost information associated with the use of these antistrip chemicals is limited.

Research continues to improve the understanding of asphalt binders and aggregates and to develop fundamental tests that will enable engineers to confidently evaluate and predict the performance of hot-mix asphalt and pavements. Research to improve available antistrip agents is also under way. The growing understanding of the basic science and fundamental engineering principals, including surface energy and fracture mechanics, will allow the development of improved methodologies to reduce moisture sensitivity.

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TABLE 1 Viscosity Change in Different Asphalt Binders as a Result of Addition of an Antistrip Agent

Liquid Antistrip Additives
Original Asphalt Viscosity, 140° F

Asphalt	Control	Additive A	Additive B
A	1980	1760	1810
B	2250	2060	2070
C	1430	1300	1340

Source: Anderson et al. (*6*).

TABLE 2 Viscosity Change in Different Aged Asphalt Binders as a Result of Addition of an Antistrip Agent

Liquid Antistrip Additives
Aged Asphalt Viscosity, 140°F

Asphalt	Control	Additive A	Additive B
A	3680 (1.28)	3570 (1.41)	3220 (1.54)
B	5770 (1.31)	5160 (1.43)	4620 (1.52)
C	4070 (1.23)	3660 (1.39)	3390 (1.49)

Source: Anderson et al. (*6*).

TABLE 3 G*Sin(delta) Values for Binders with Various Liquid Antistrips

Binder Source	Liquid Antistrip Agent	Additive, %	Test Temp, °C	G*/sin d kPa
A	None	----	64	1.35
A	A	1.0	64	1.36
B	None	---	64	1.44
B	A	1.0	64	1.34
B	A	10.0	64	0.38
B	B	1.0	64	1.17

Source: PaveTex Engineering and Testing, Inc. (*10*).

TABLE 4 Texas DOT Liquid Antistrip Study

Type of Mixture	Liquid Additive, Percent			
	0	0.5	1.0	1.5
Surface	5* (21)**	74 (23)	63 (30)	
Leveling	17 (24)	100 (7)	68 (15)	
Base	13 (8)	71 (7)	67 (15)	29 (7)

Source: Ho (*13*).
* Percentage of projects passing 0.70 TSR requirement for AASHTO T283 (with freeze–thaw).
** Number of samples.

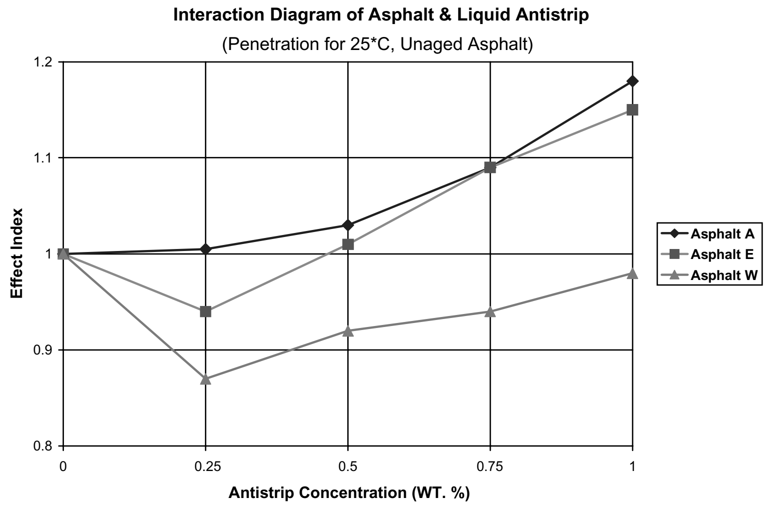

FIGURE 1 Penetration of asphalt binders as a function of antistrip agent concentration (*7*).

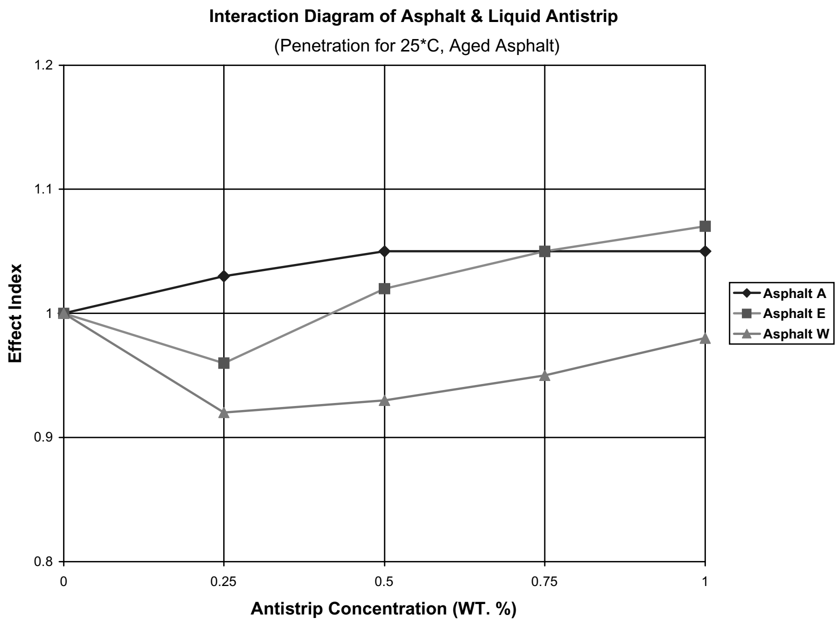

FIGURE 2 Penetration of aged asphalt binders as a function of antistrip agent concentration (*8*).

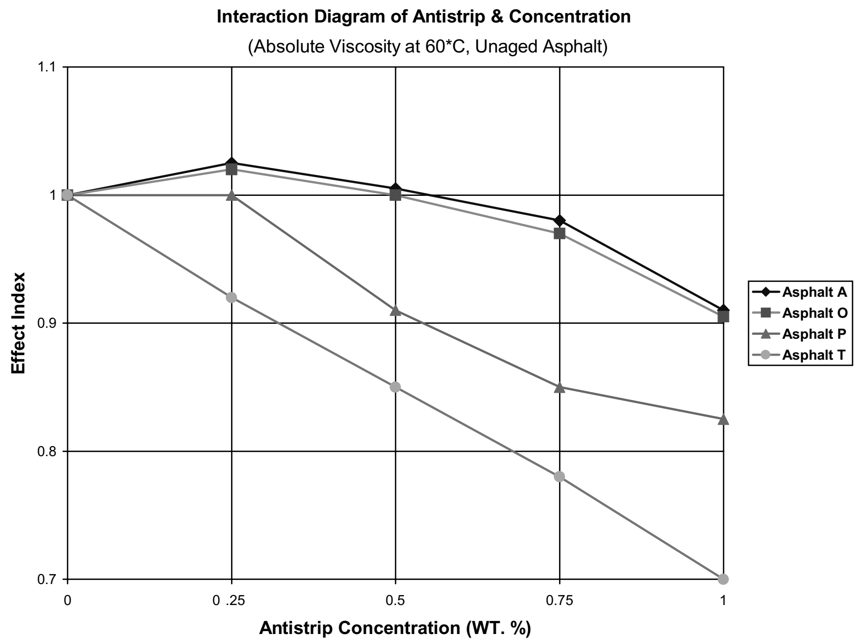

FIGURE 3 Absolute viscosity of asphalt binders as a function of antistrip agent concentration (*7*).

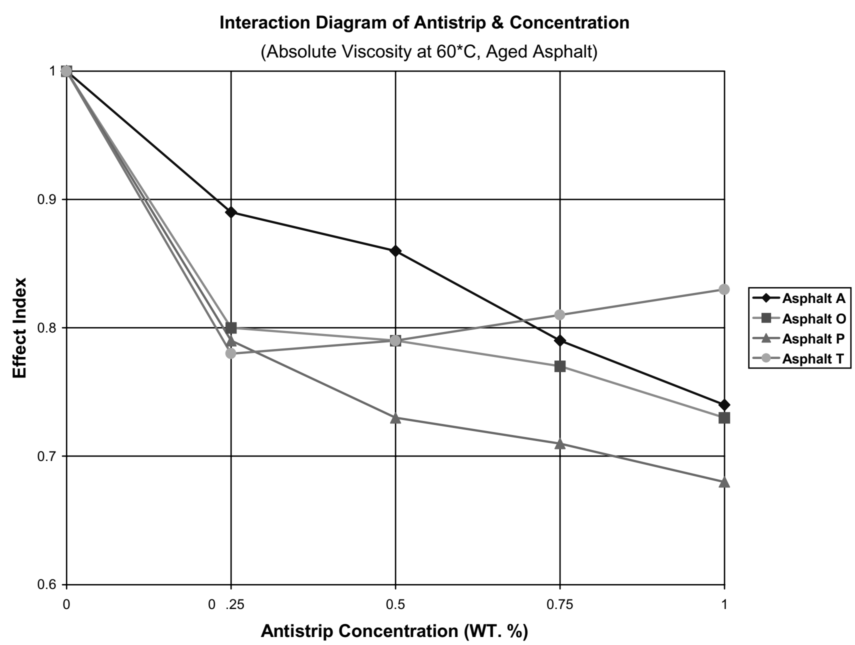

FIGURE 4 Absolute viscosity of aged asphalt binders as a function of antistrip agent concentration (*7*).

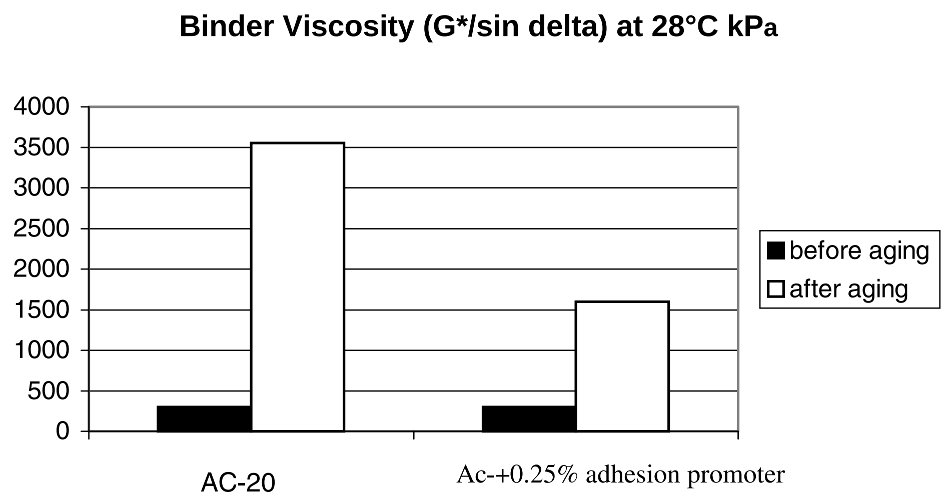

FIGURE 5 Binder stiffness and aging after PAV ("Adhesion Promoters," Akzo Nobel).

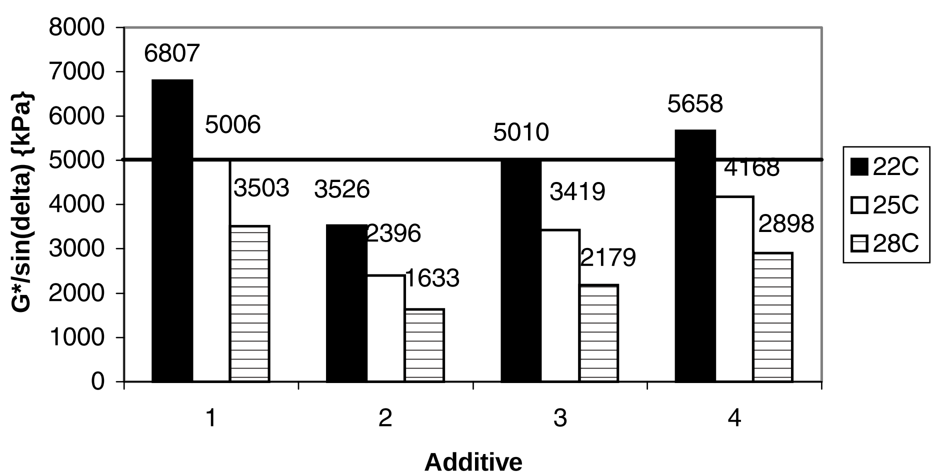

FIGURE 6 Effect of various additives on fatigue cracking West Texas sour crude (*9*).

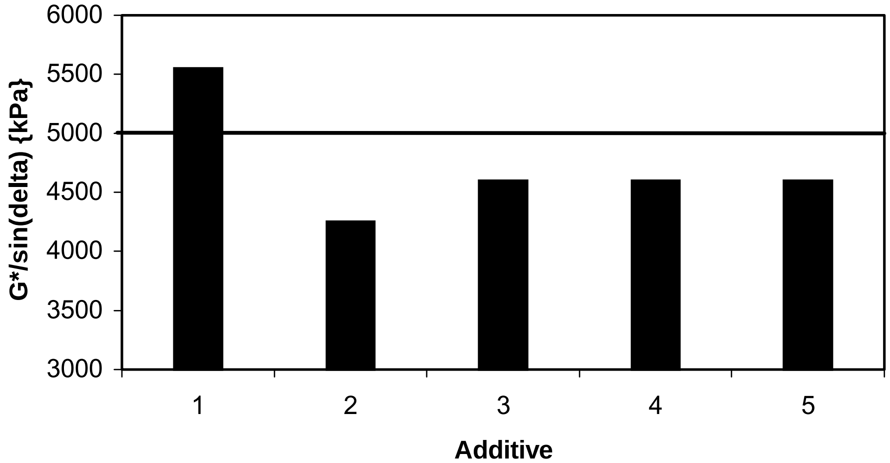

FIGURE 7 Effect of LAS on fatigue cracking of AC-20 (*9*).

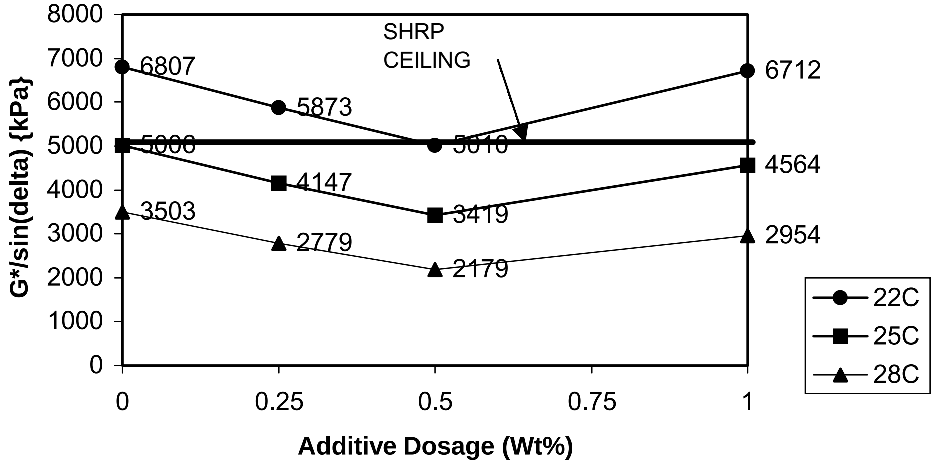

FIGURE 8 Effect of dosage of an antistrip additive on fatigue cracking West Texas sour crude (*9*).

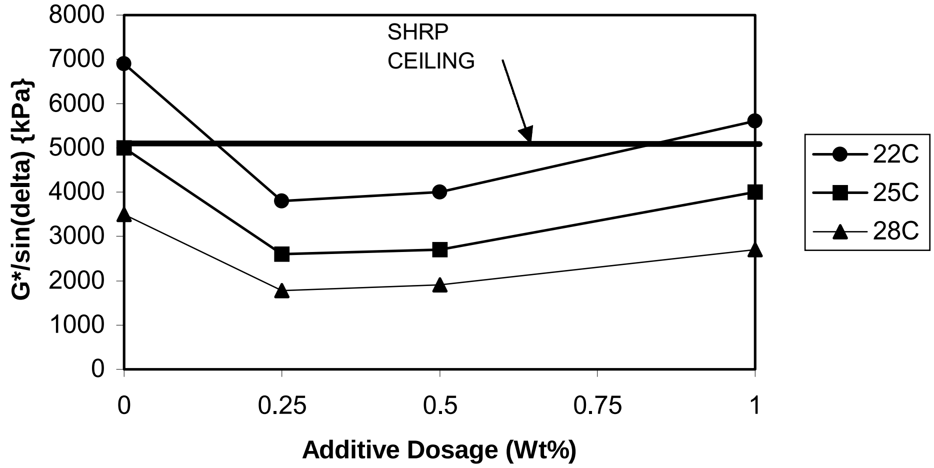

FIGURE 9 Effect of dosage of an antistrip additive on fatigue cracking West Texas sour crude (*9*).

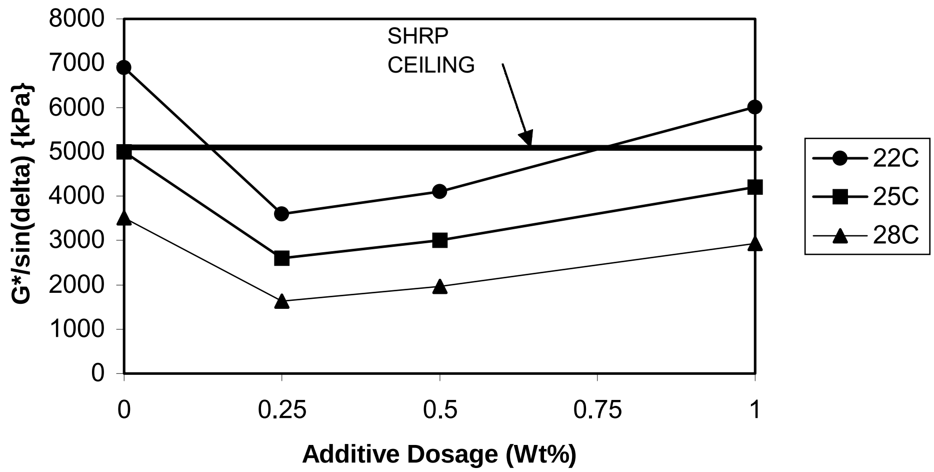

FIGURE 10 Effect of dosage of an antistrip additive on fatigue cracking West Texas sour crude (*9*).

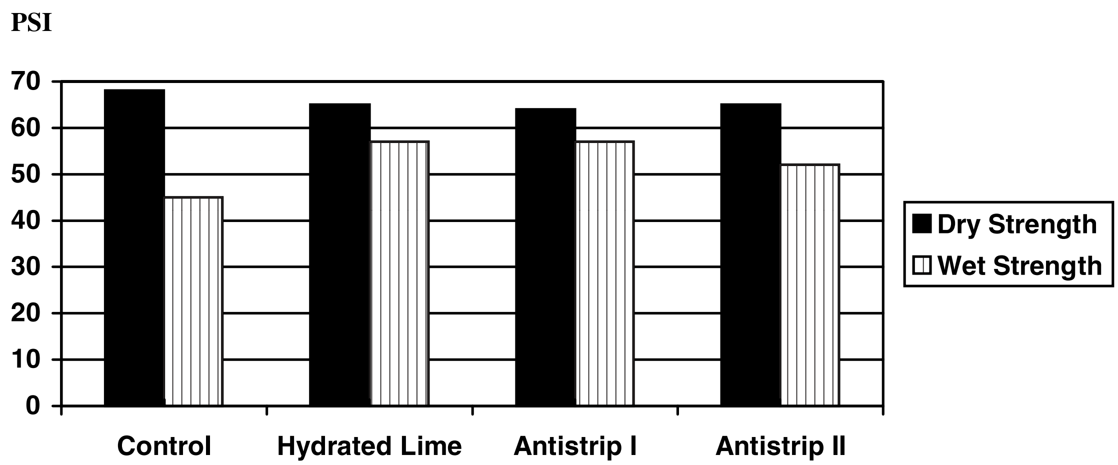

FIGURE 11 Indirect tensile strength of Aggregate A as a function of antistrip before and after exposure to water (*11*).

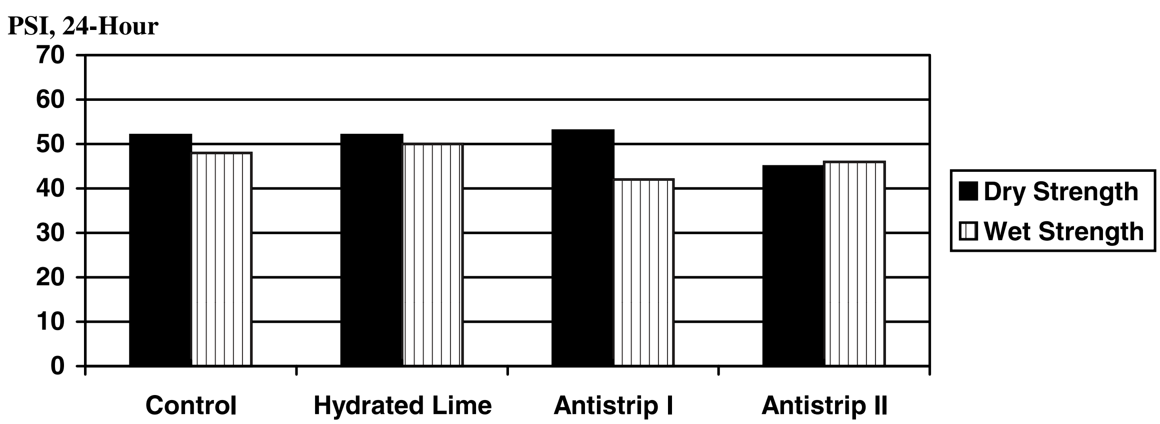

FIGURE 12 Indirect tensile strength of Aggregate B as a function of antistrip before and after exposure to water (*11*).

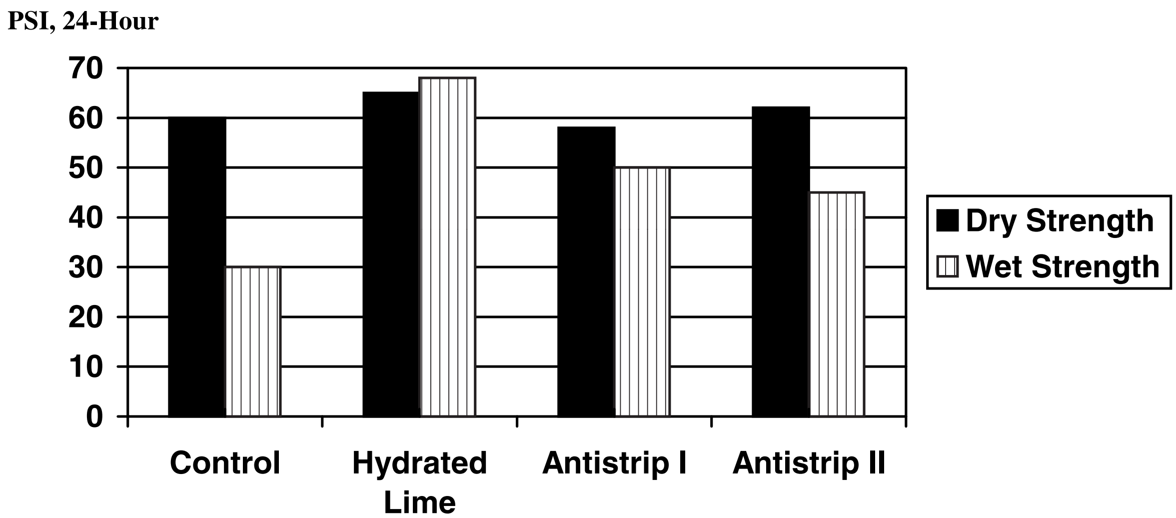

FIGURE 13 Indirect tensile strength of Aggregate C as a function of antistrip before and after exposure to water (*11*).

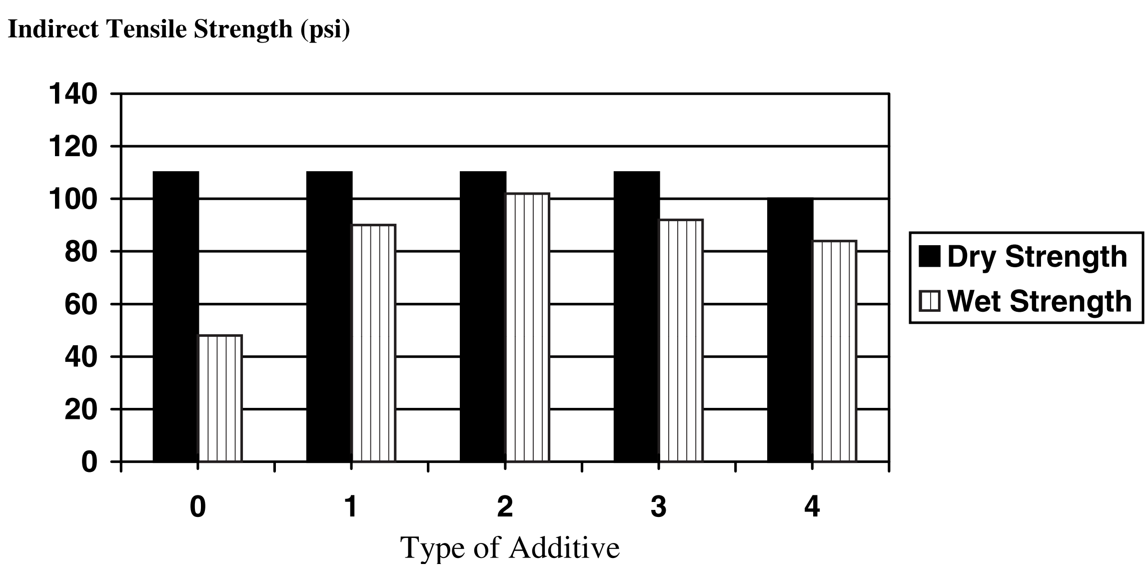

FIGURE 14 Indirect tensile strength as a function of antistrip before and after 24 h of moisture conditioning (*11*).

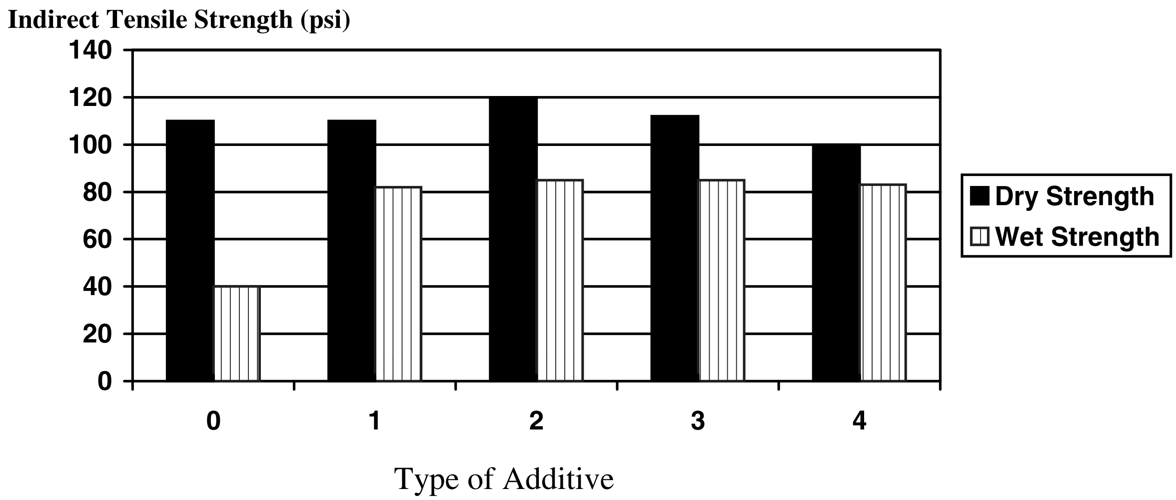

FIGURE 15 Indirect tensile strength as a function of antistrip before and after 24 h of moisture conditioning (*11*).

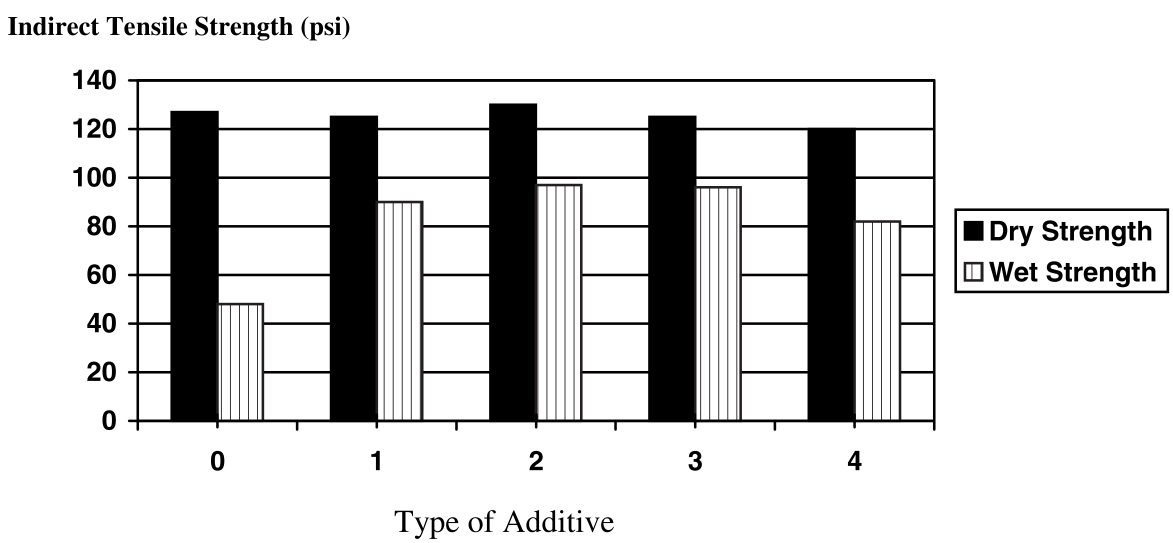

FIGURE 16 Indirect tensile strength as a function of antistrip before and after 60 days of moisture conditioning (*11*).

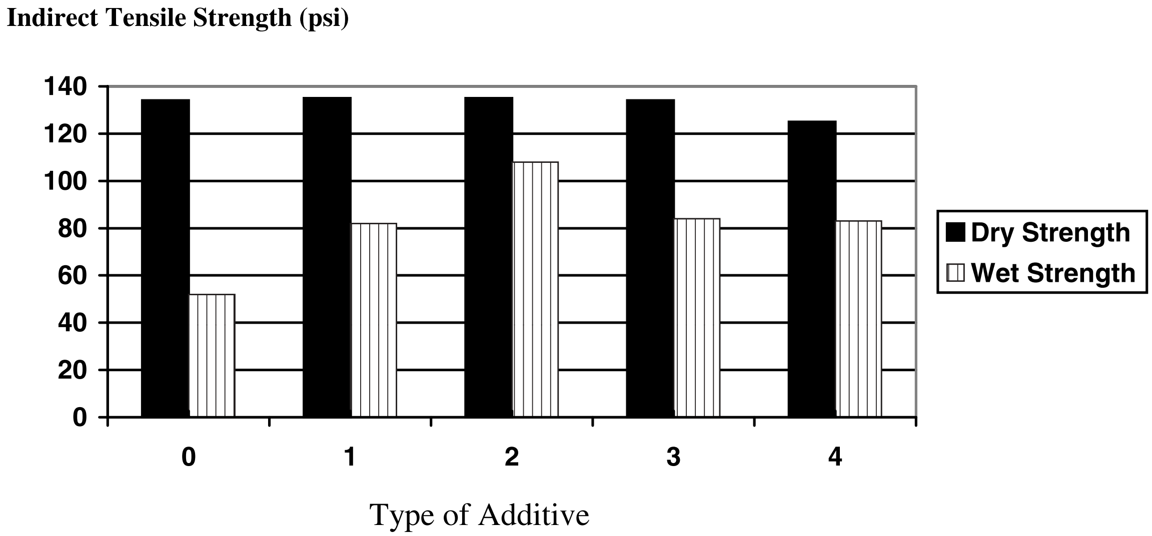

FIGURE 17 Indirect tensile strength as a function of antistrip before and after 60 days of moisture conditioning (*11*).

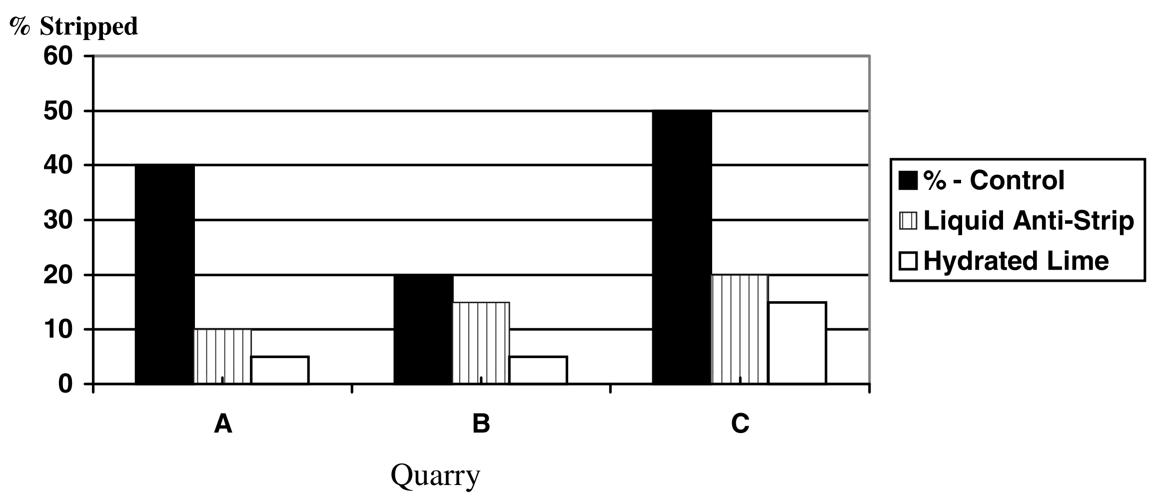

FIGURE 18 Boil test results as a function of antistrip agent and quarry (*11*).

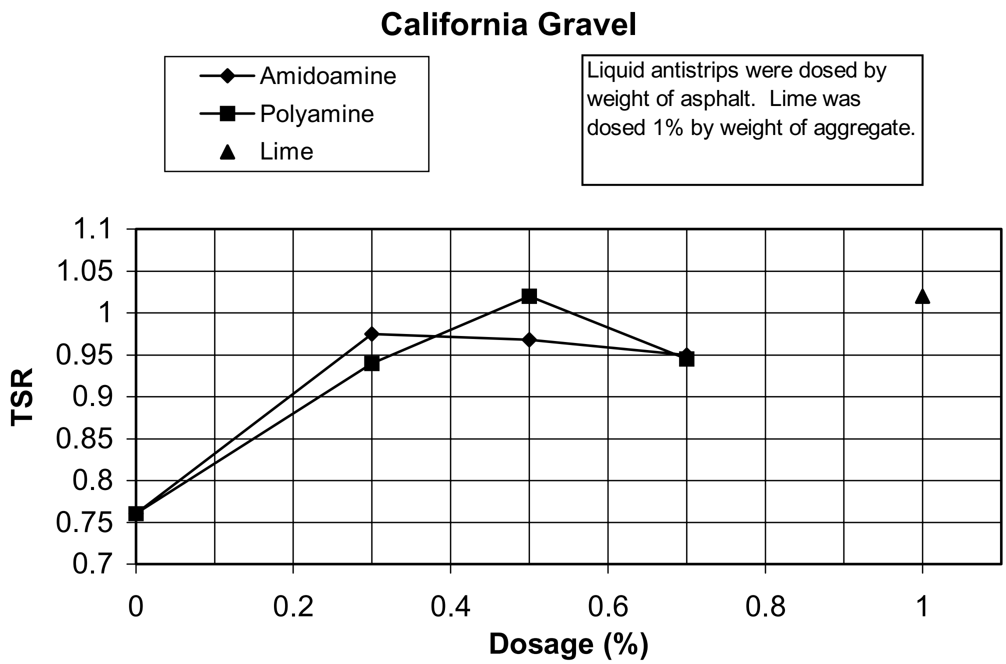

FIGURE 19 Results of Lottman tests for aggregates treated with different antistrip agents in California (*12*).

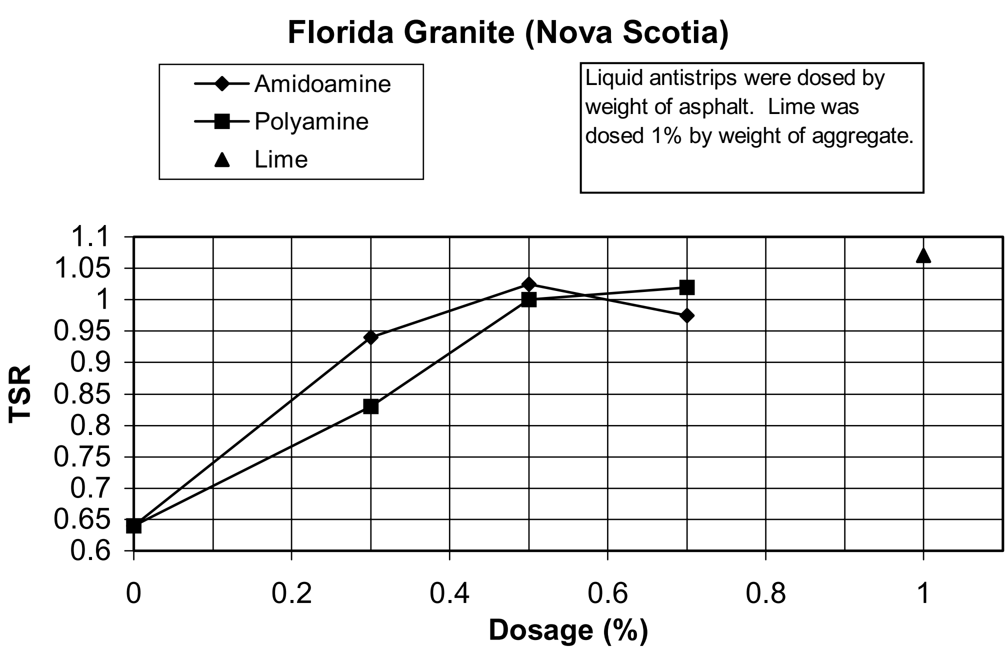

FIGURE 20 Results of Lottman tests for aggregates treated with different antistrip agents in Florida (*12*).

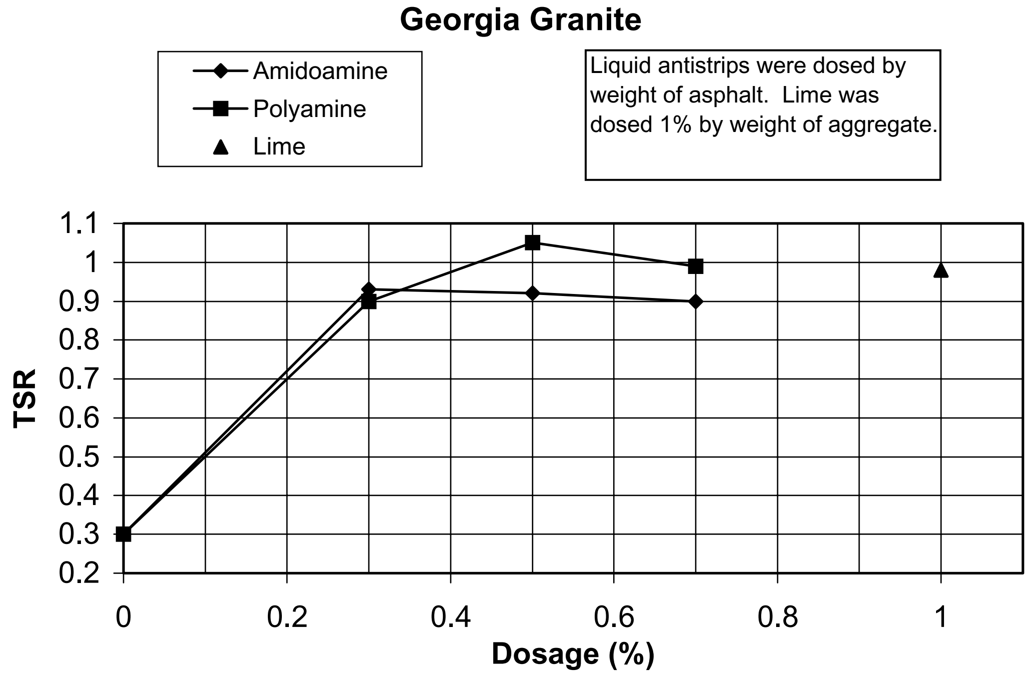

FIGURE 21 Results of Lottman tests for aggregates treated with different antistrip agents in Georgia (*12*).

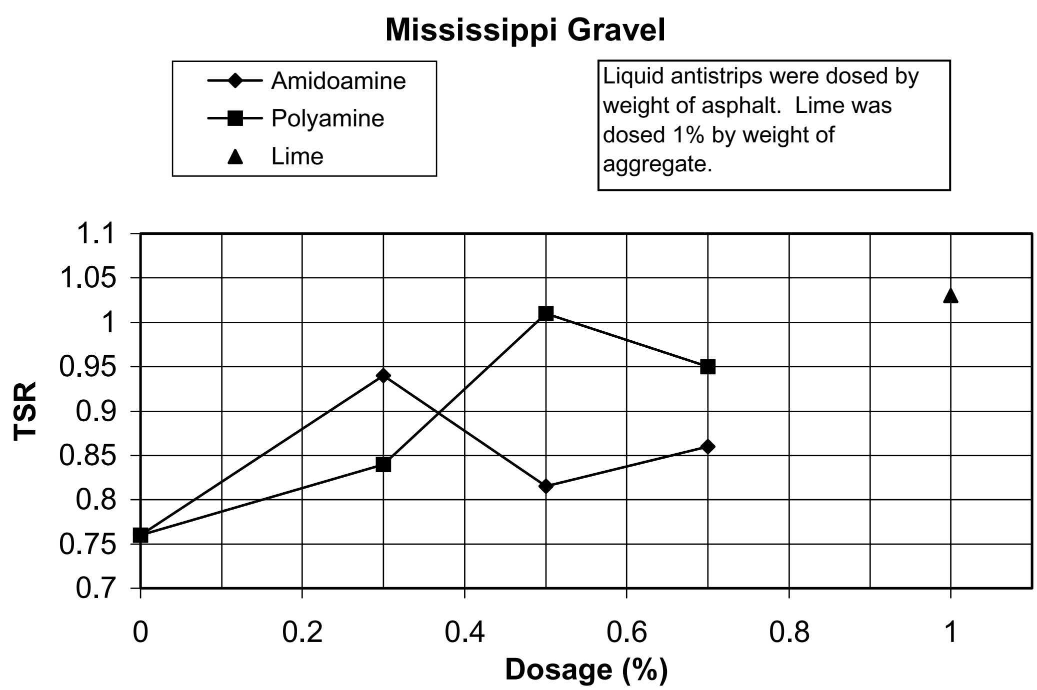

FIGURE 22 Results of Lottman tests for aggregates treated with different antistrip agents in Mississippi (gravel) (*12*).

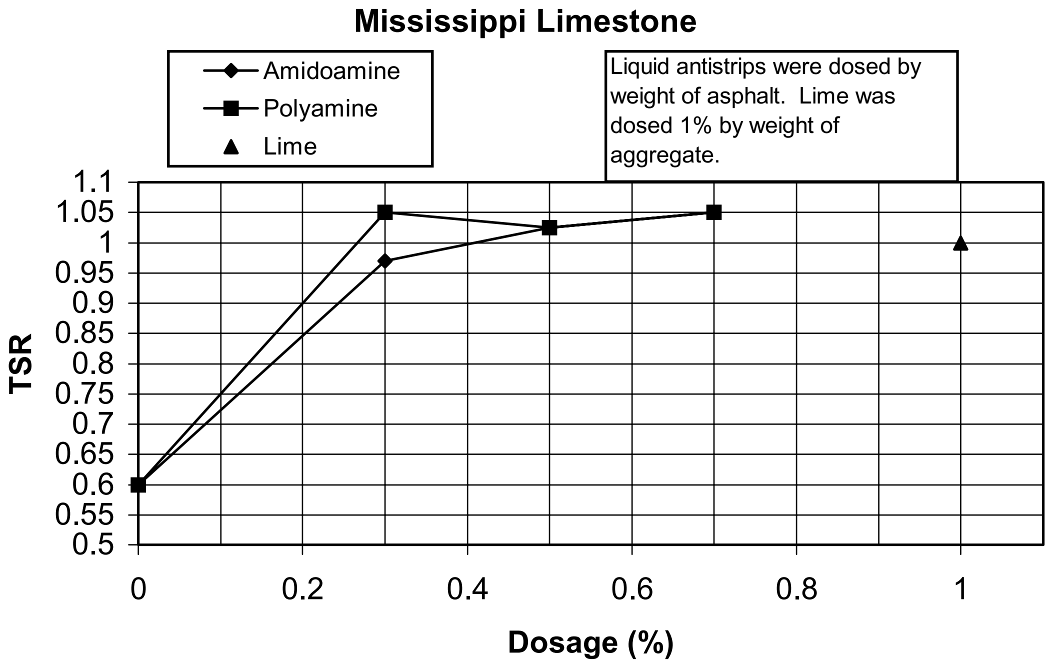

FIGURE 23 Results of Lottman tests for aggregates treated with different antistrip agents in Mississippi (limestone) (*12*).

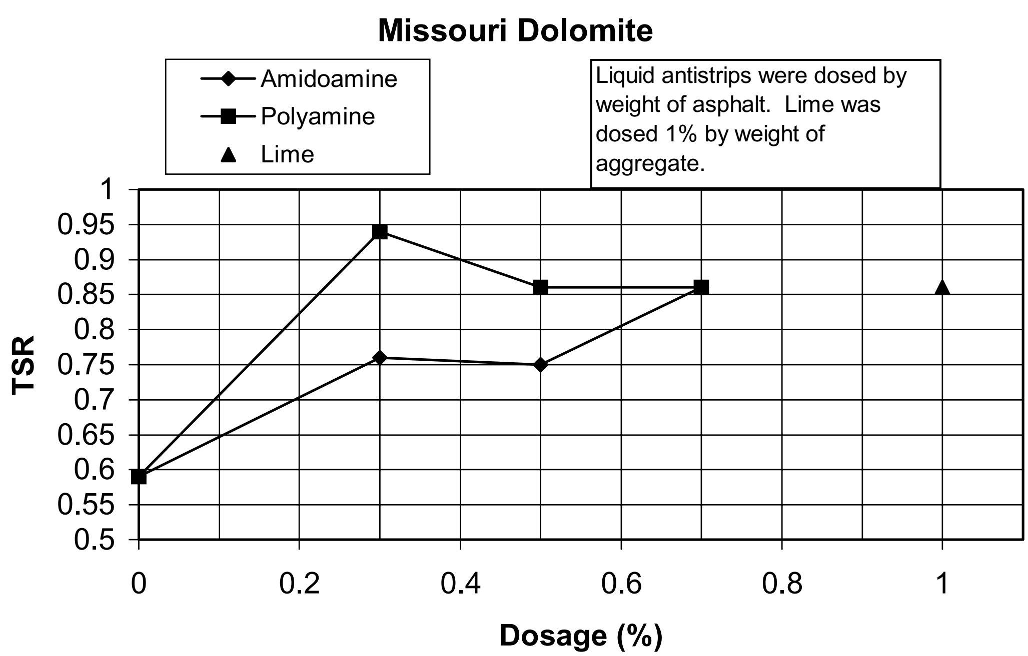

FIGURE 24 Results of Lottman tests for aggregates treated with different antistrip agents in Missouri (*12*).

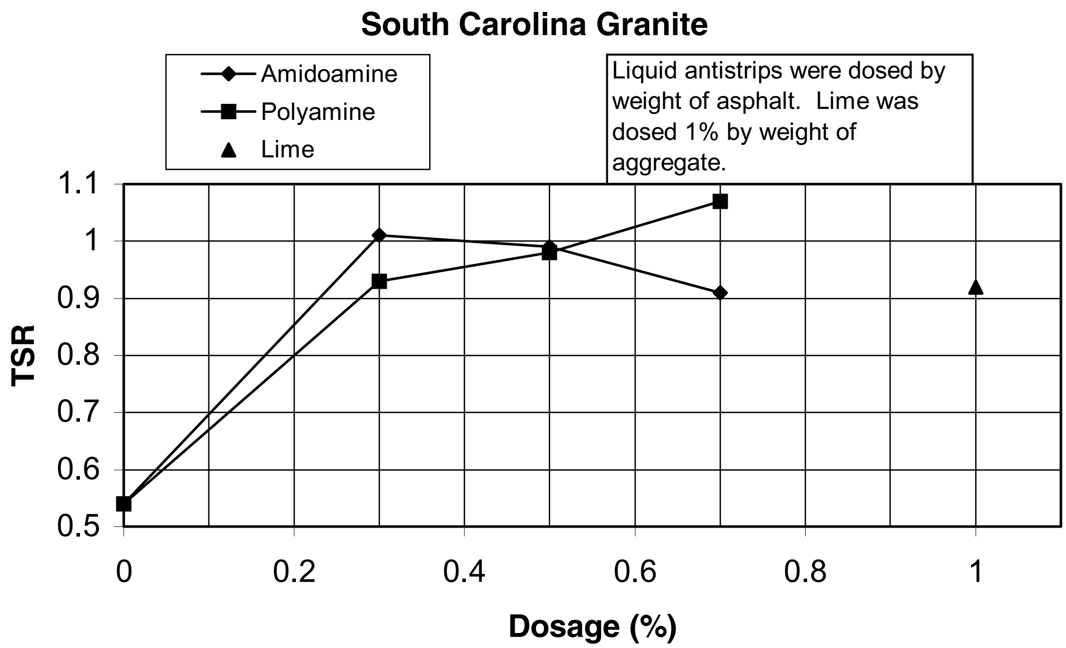

FIGURE 25 Results of Lottman tests for aggregates treated with different antistrip agents in South Carolina (*12*).

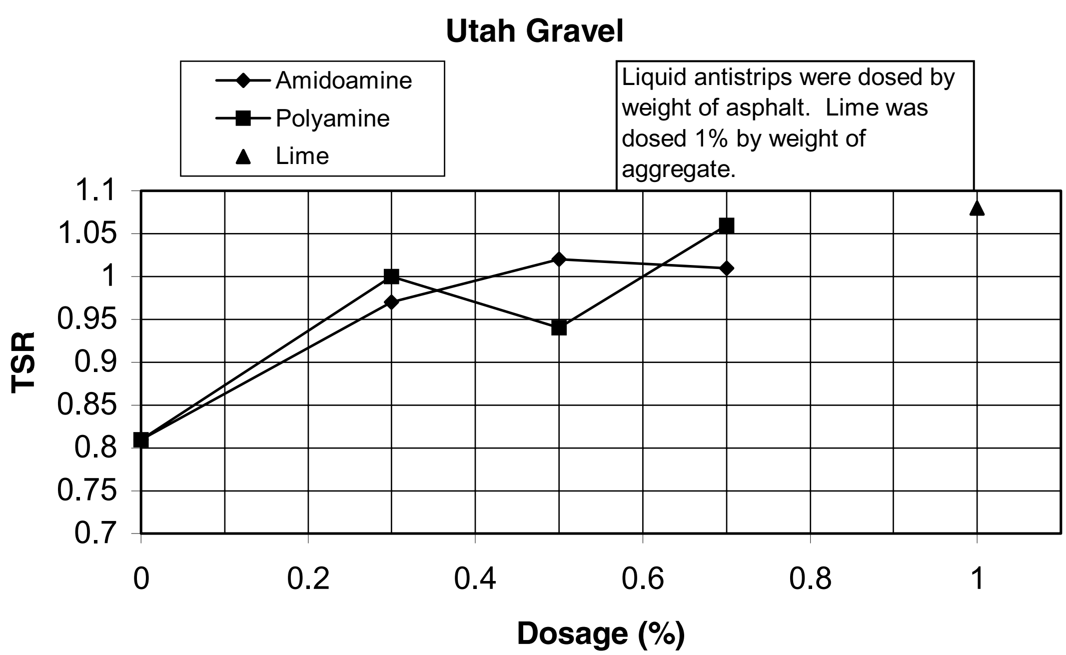

FIGURE 26 Results of Lottman tests for aggregates treated with different antistrip agents in Utah (*12*).

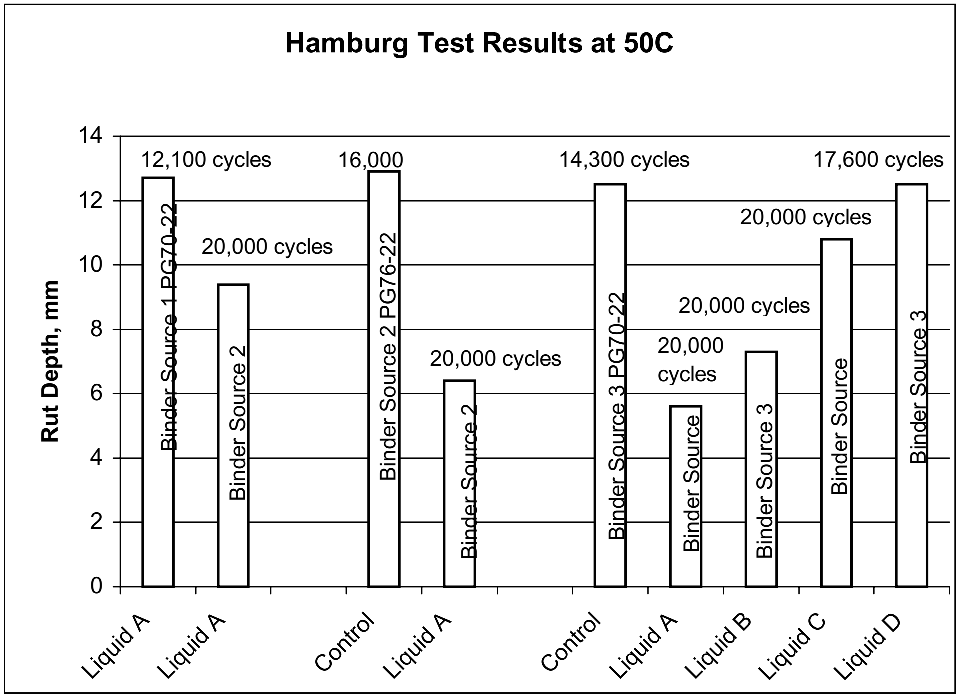

FIGURE 27 Hamburg rut test results for mixtures using various liquid antistrips and asphalt binders (*14*).

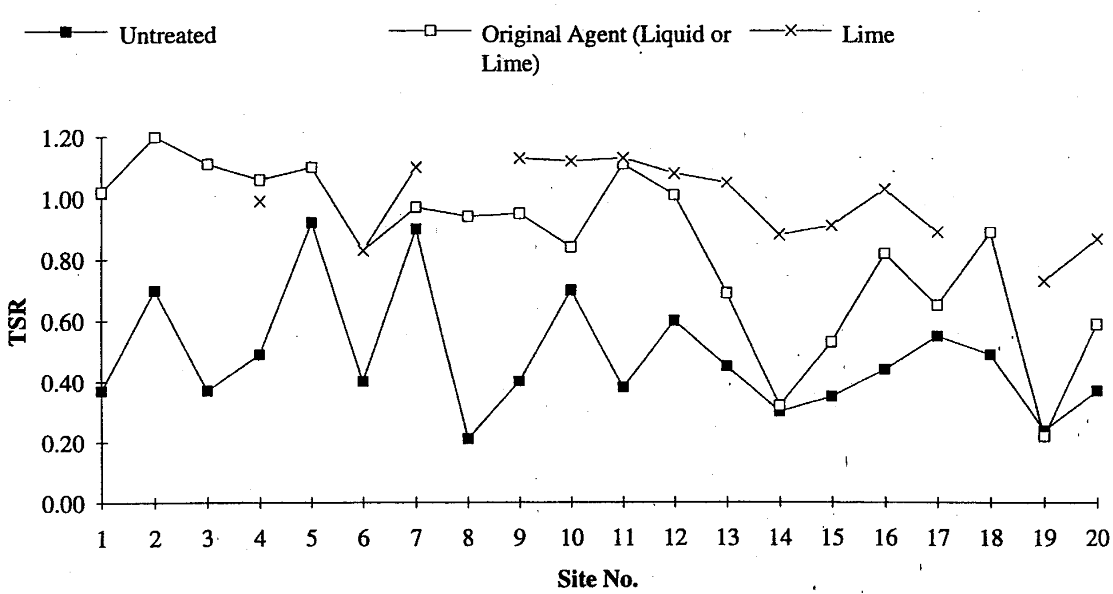

FIGURE 28 Effect of liquid antistrip on tensile strength ratio for various projects in Colorado (*15*).

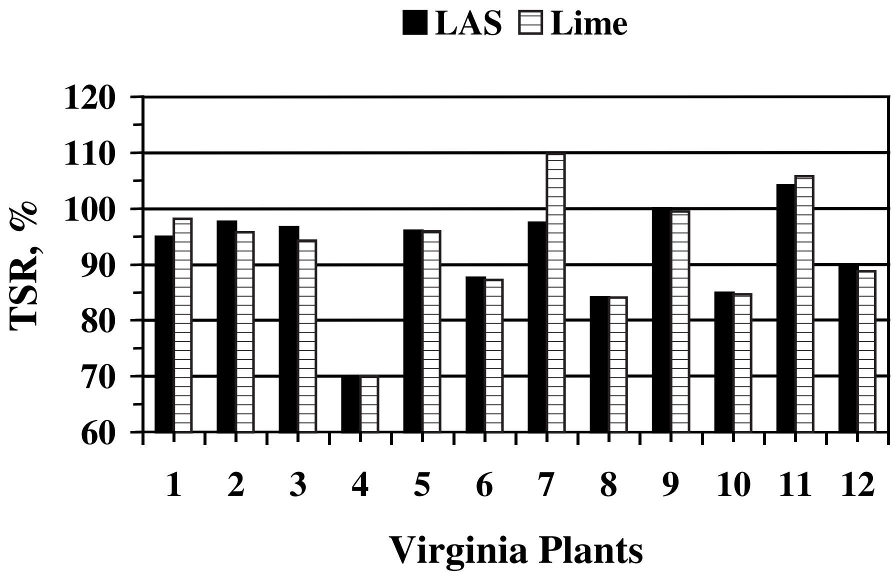

FIGURE 29 Comparison of tensile strength ratios for various projects in Virginia using liquid antistrip agents and lime ("Tensile Strength Ratio—Virginia," provided by Akzo Nobel).

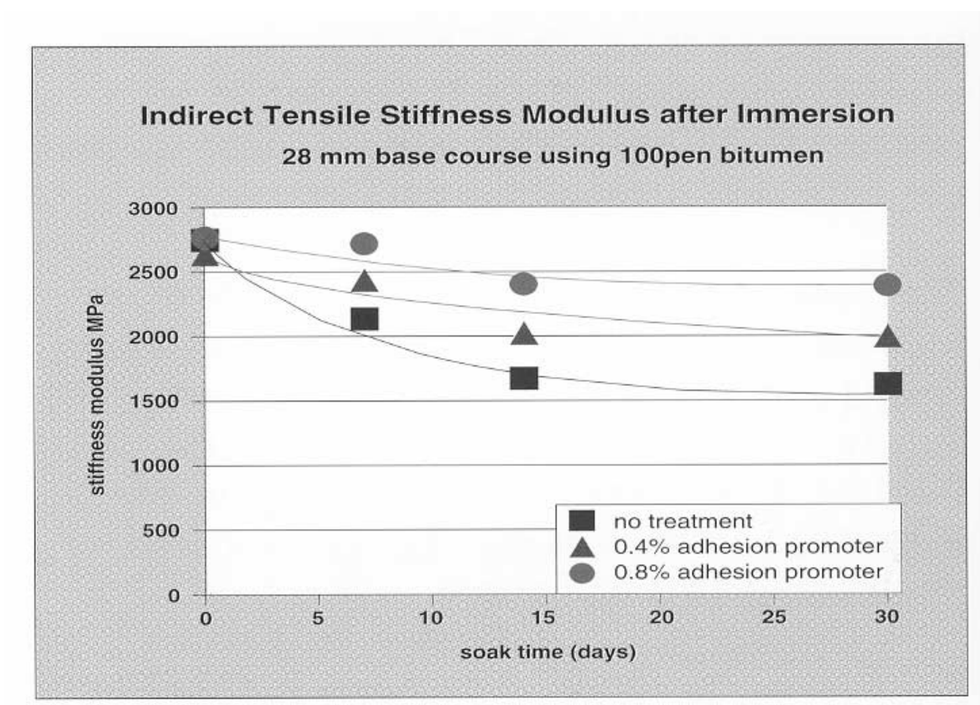

FIGURE 30 Indirect tensile stiffness modulus values for a base course treated with various dosages of liquid antistrip (*Adhesion Promoters*, technical bulletin, Akzo Nobel).

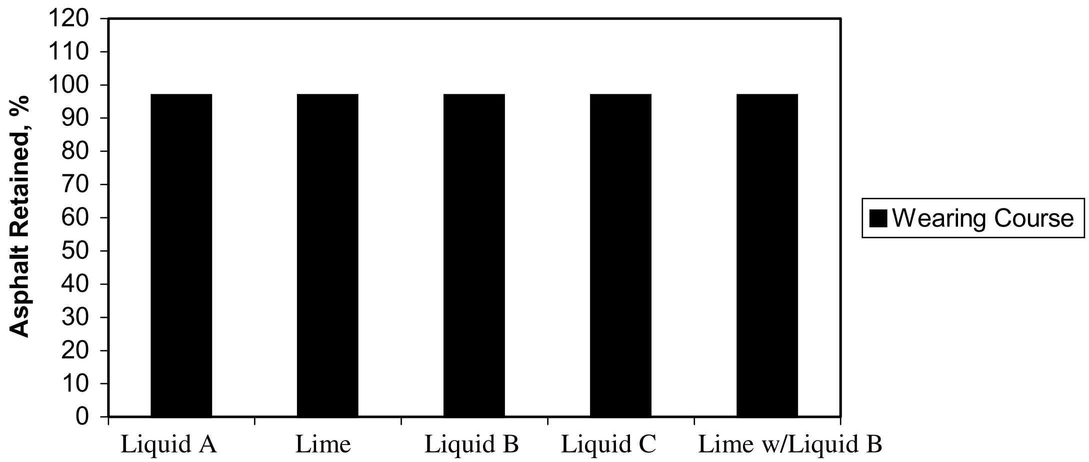

FIGURE 31 Louisiana boil test results using various antistrip agents in mixtures in Louisiana (*18*).

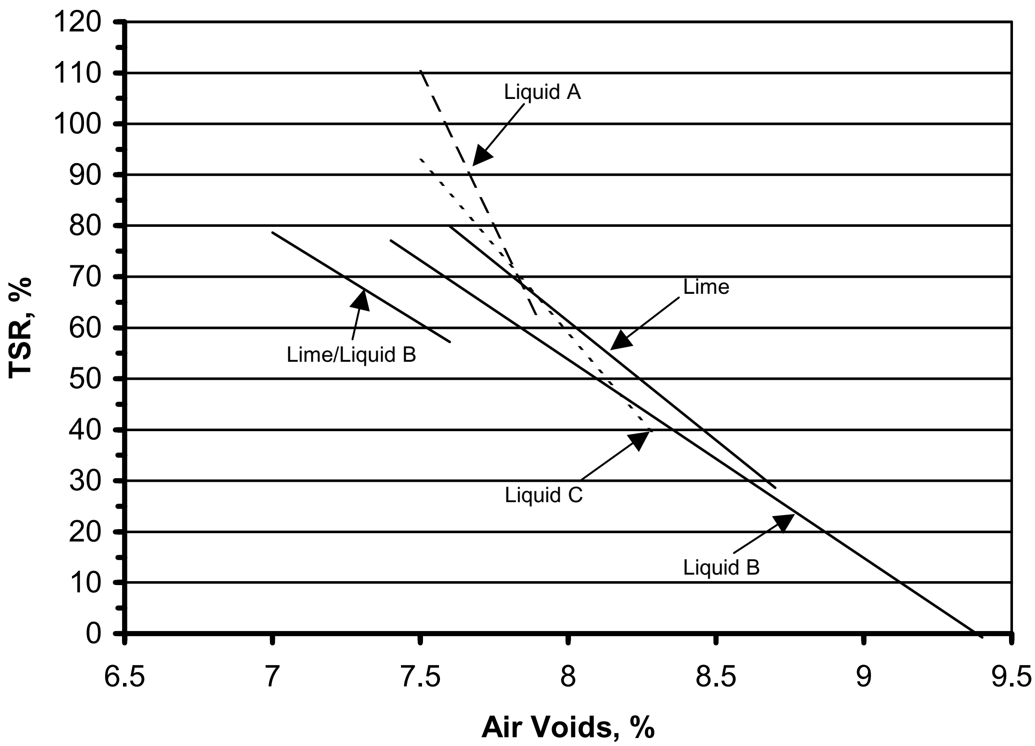

FIGURE 32 Tensile strength ratio test results using various antistrip agents in mixtures in Louisiana (*18*).

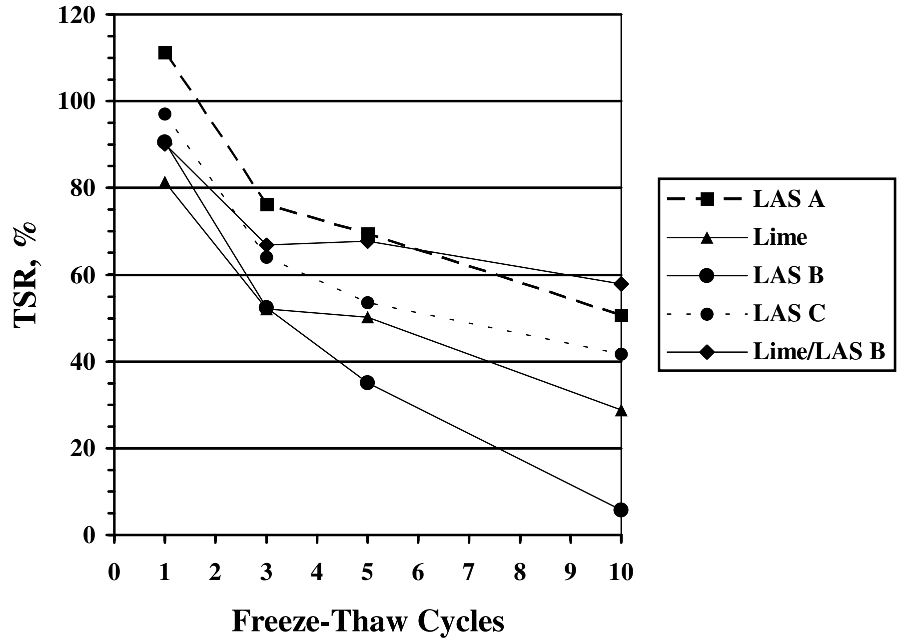

FIGURE 33 Tensile strength ratio test results as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

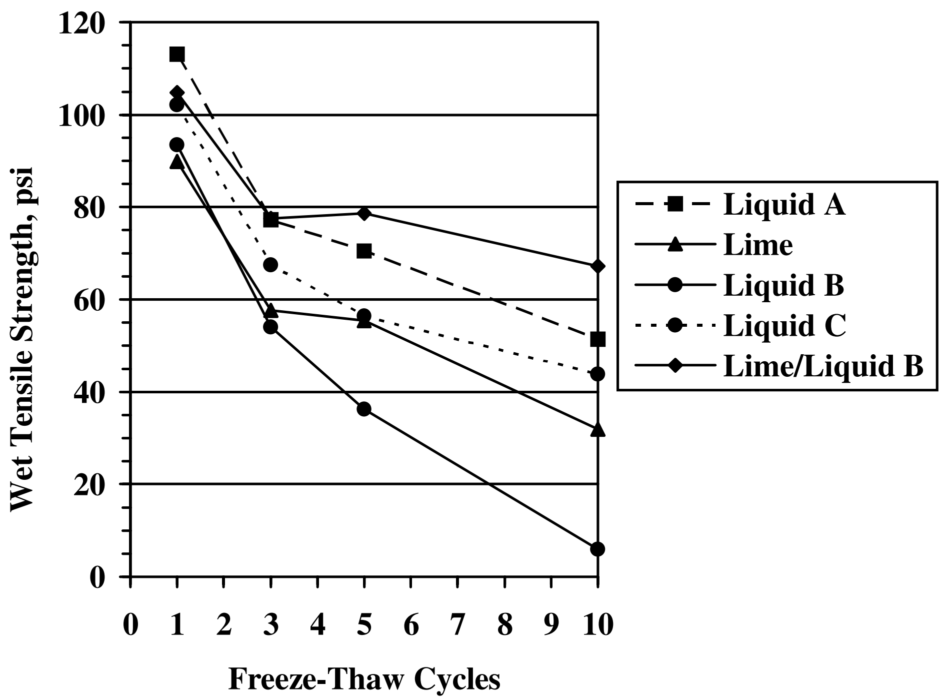

FIGURE 34 Wet tensile strength results as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

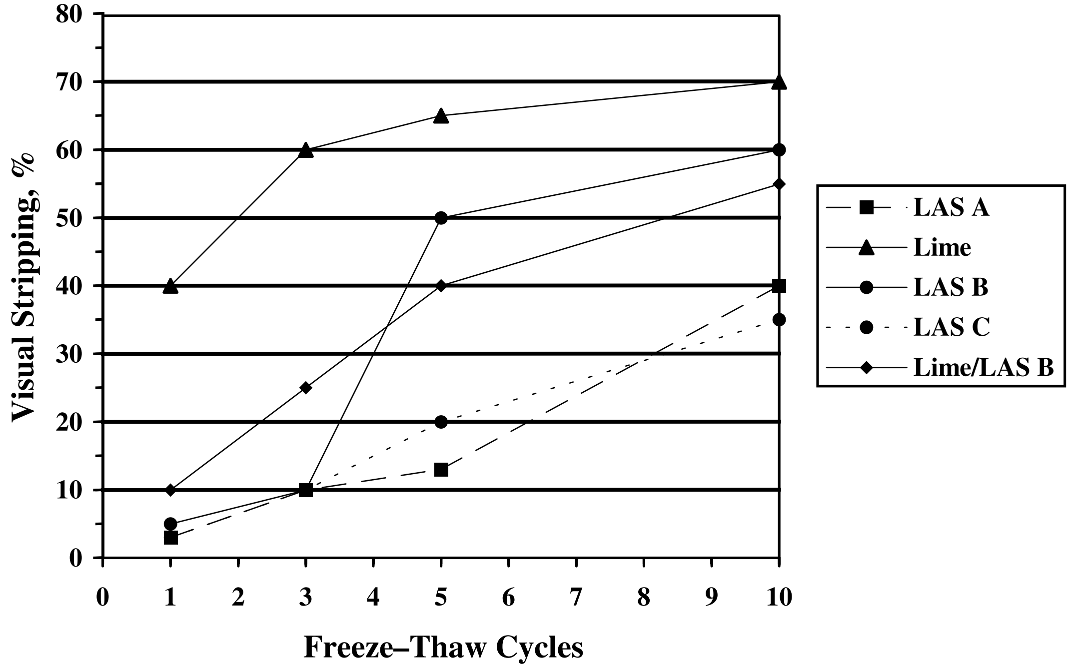

FIGURE 35 Visual stripping percentage as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

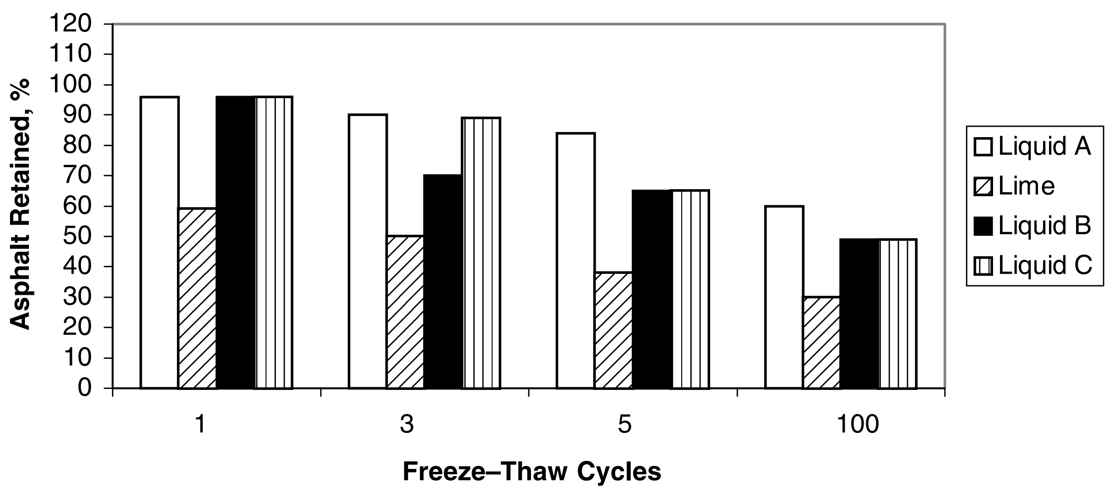

FIGURE 36 Asphalt retained percentage as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

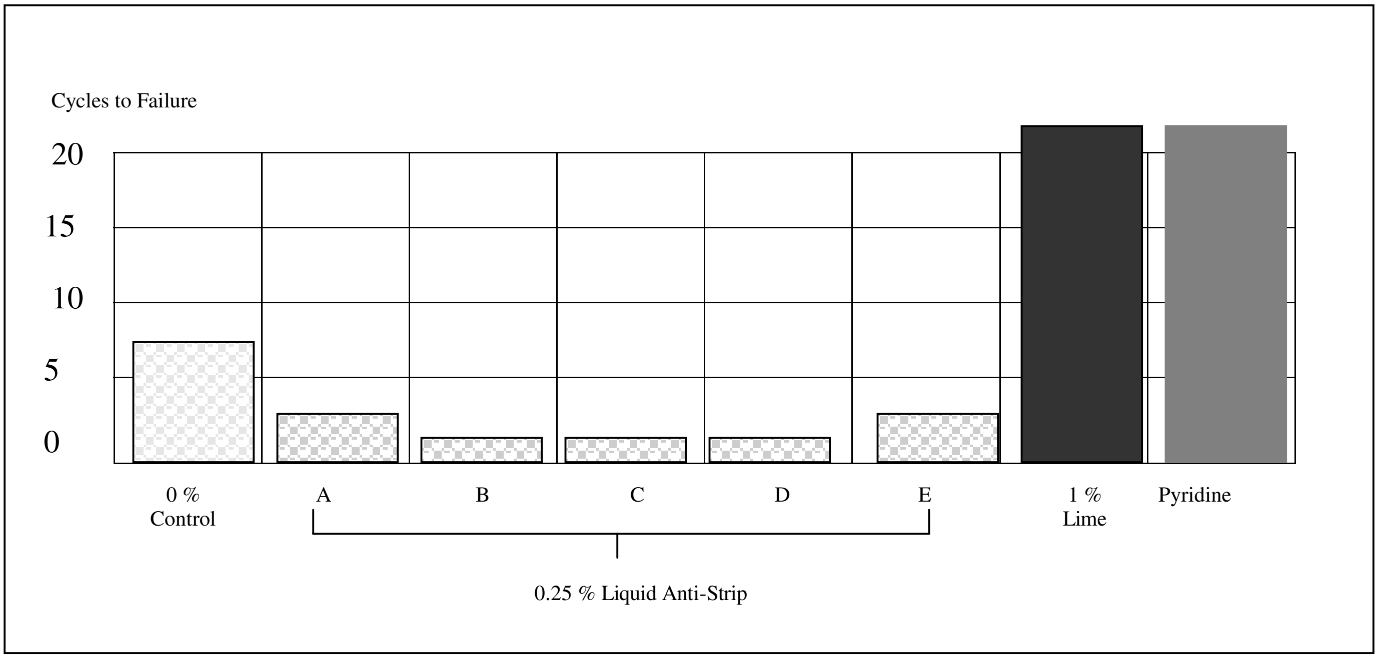

FIGURE 37 Effect of selected modifiers on moisture damage freeze–thaw pedestal test (*19*).

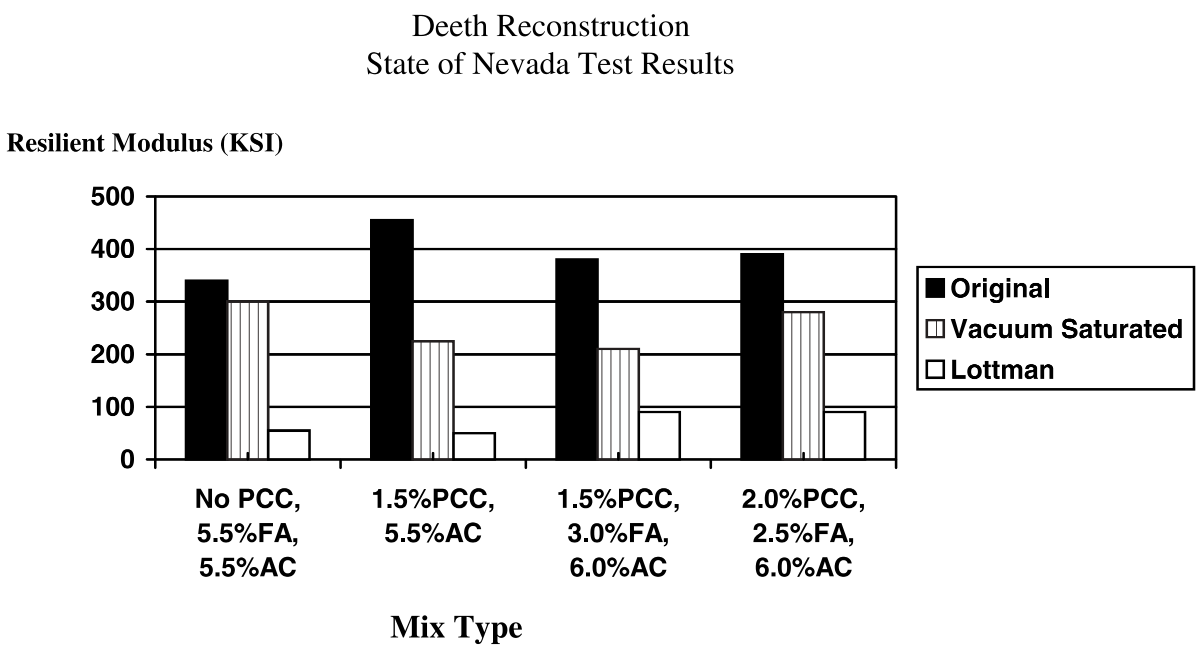

FIGURE 38 Effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate (*20*, *21*).

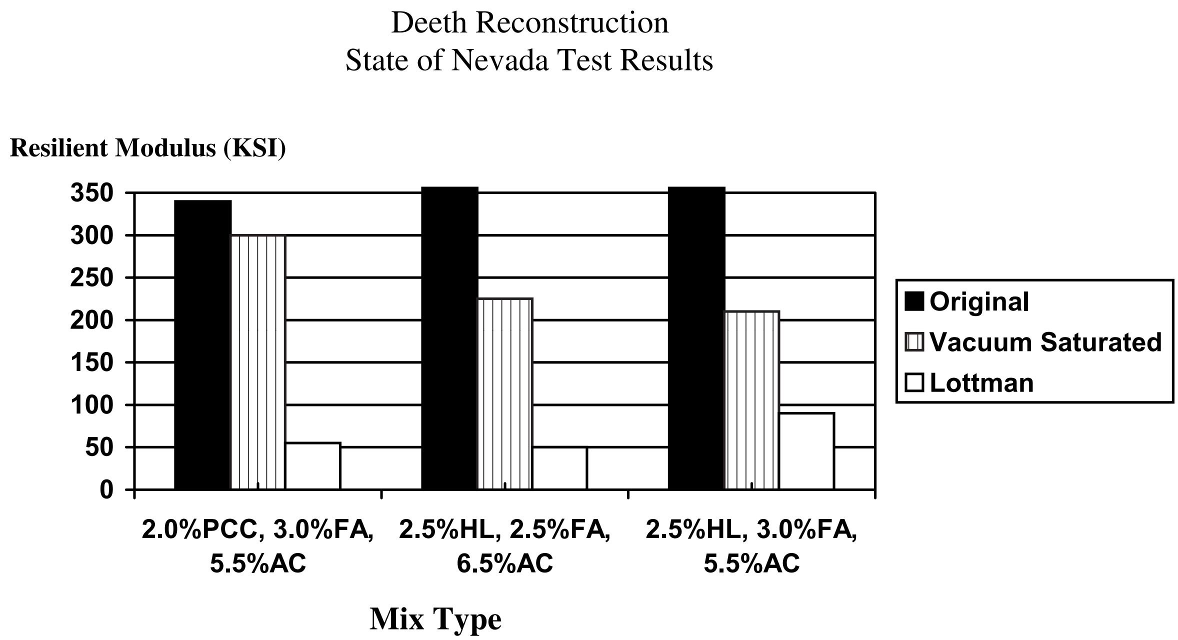

FIGURE 39 Effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate (*20*, *21*).

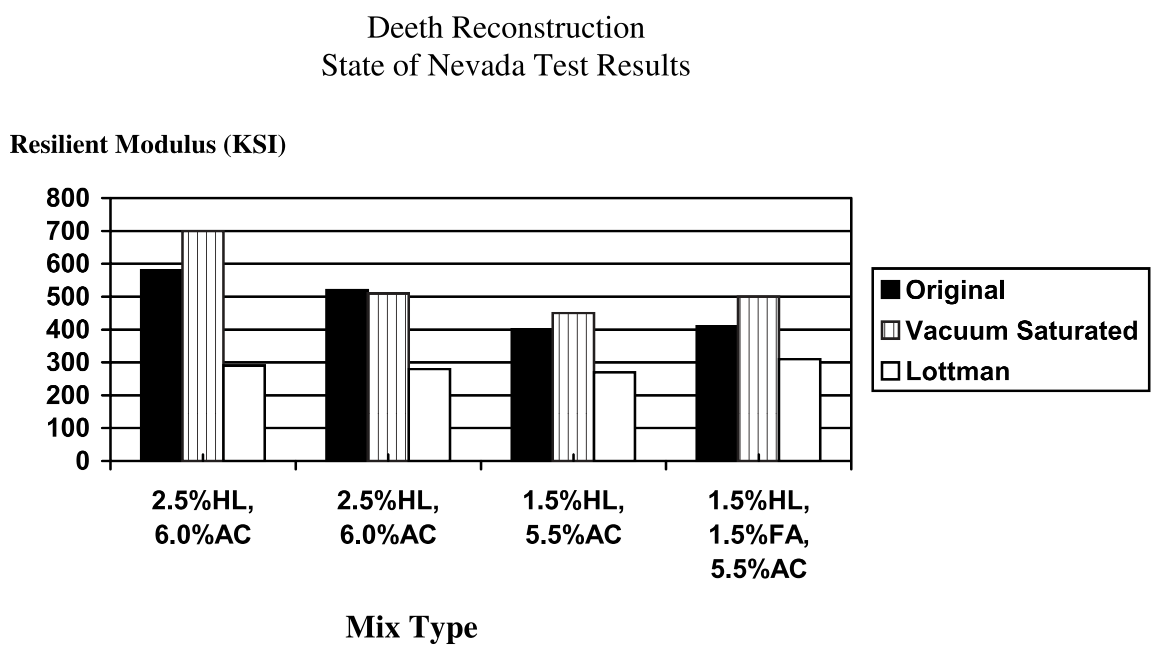

FIGURE 40 Effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate (*20*, *21*).

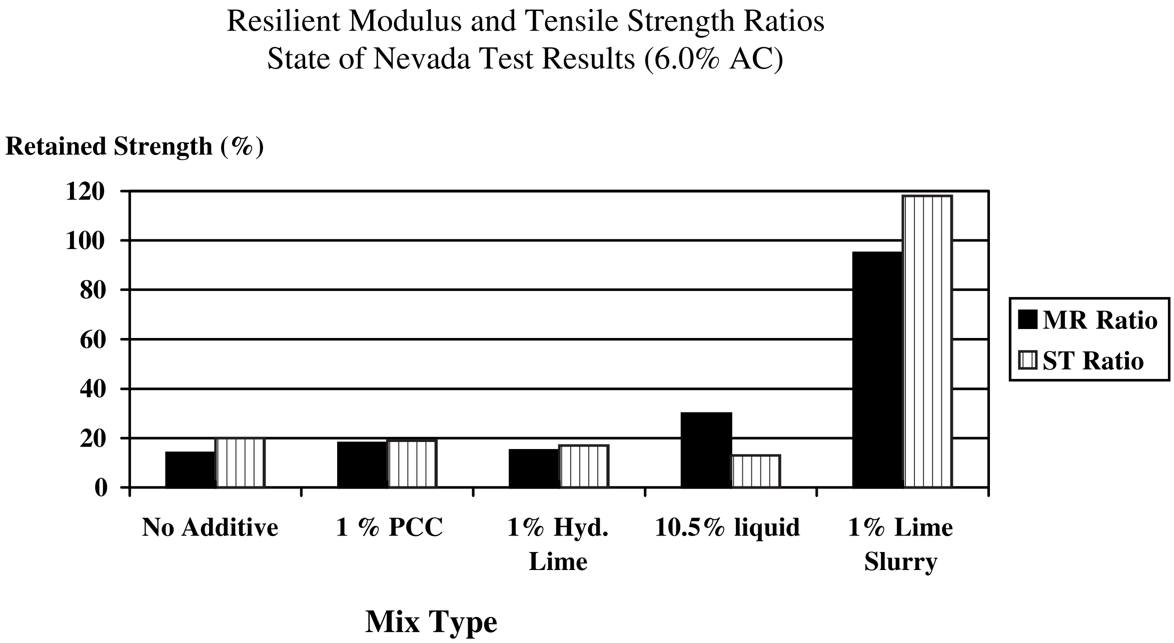

FIGURE 41 Resilient modulus and tensile strength ratios of various mixtures evaluated in Nevada (6.0% AC) (*20*, *21*).

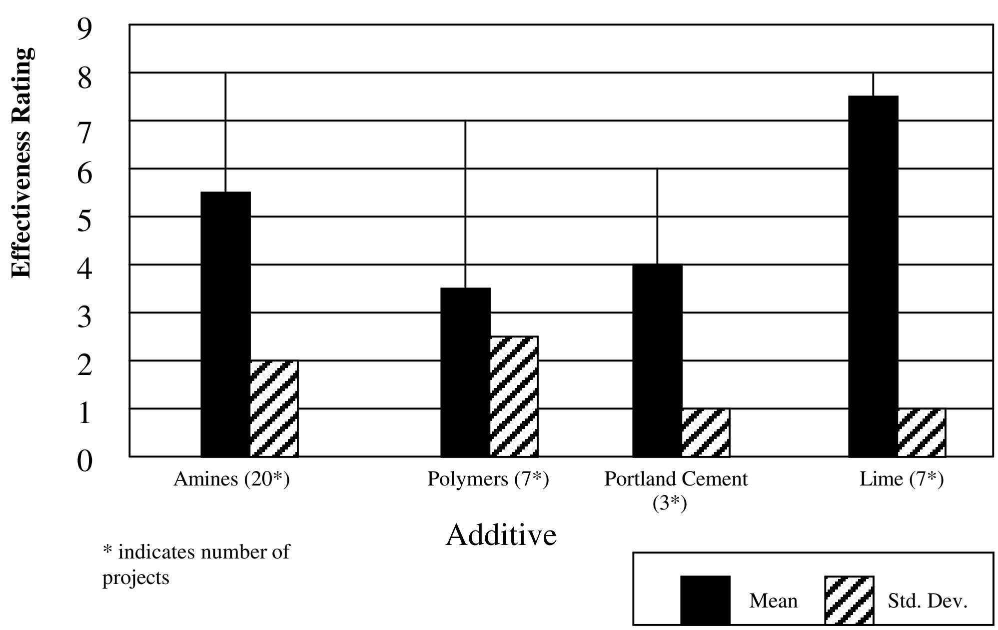

FIGURE 42 Relative effectiveness of additives in eliminating or reducing moisture problem (*22*).

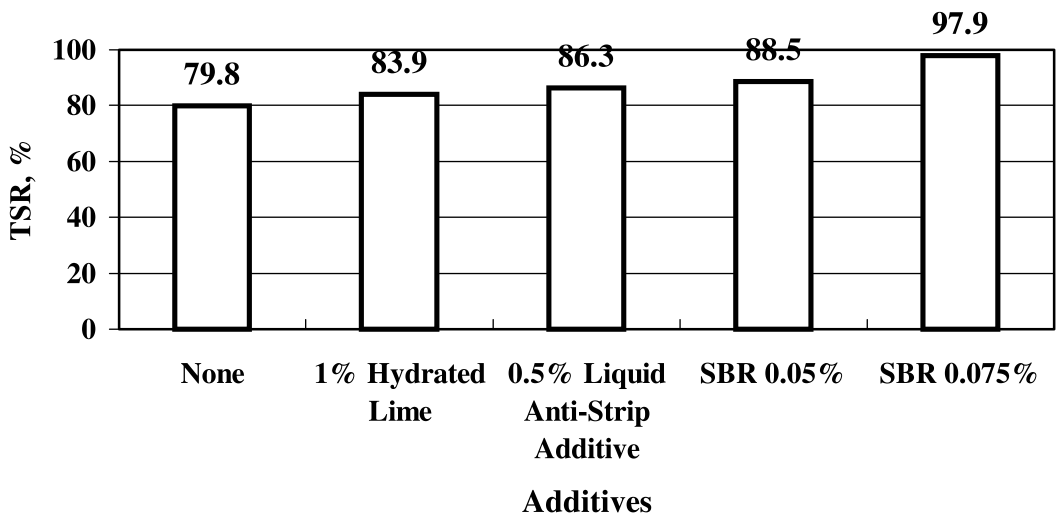

FIGURE 43 Florida study: tensile strength ratios with various antistrip agents with Florida granite (*26*).

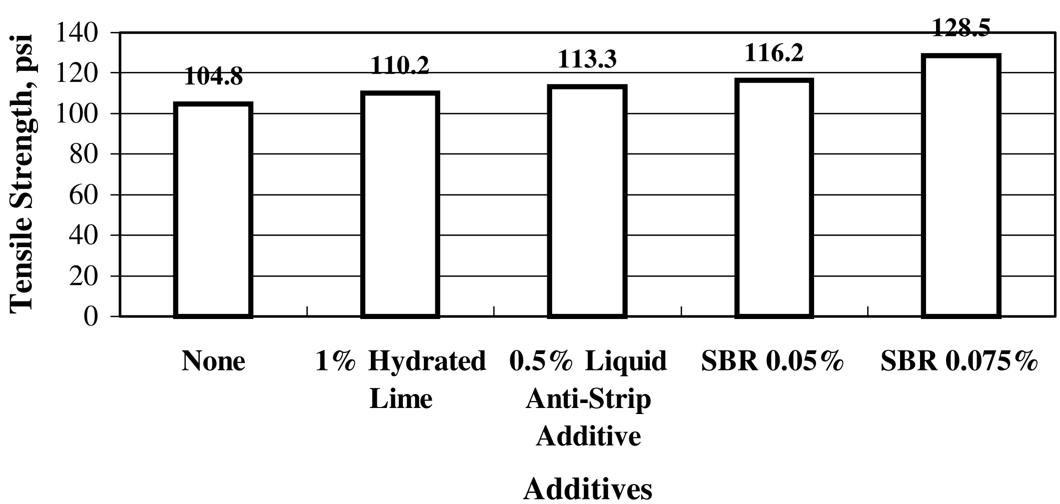

FIGURE 44 Florida study: wet tensile strength with various antistrip agents with Florida granite (*26*).

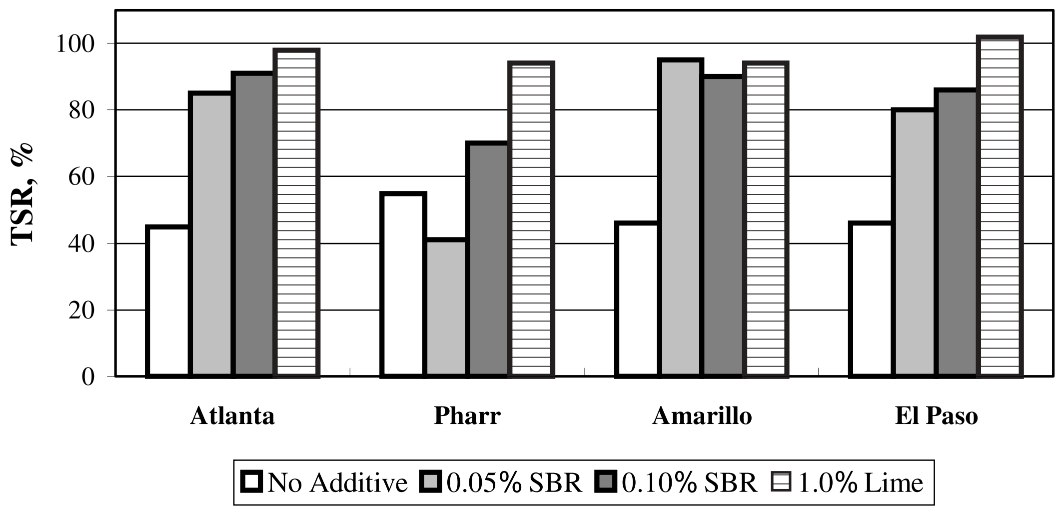

FIGURE 45 Texas study: tensile strength ratios with various antistrip agents with various Texas aggregates (*27*).

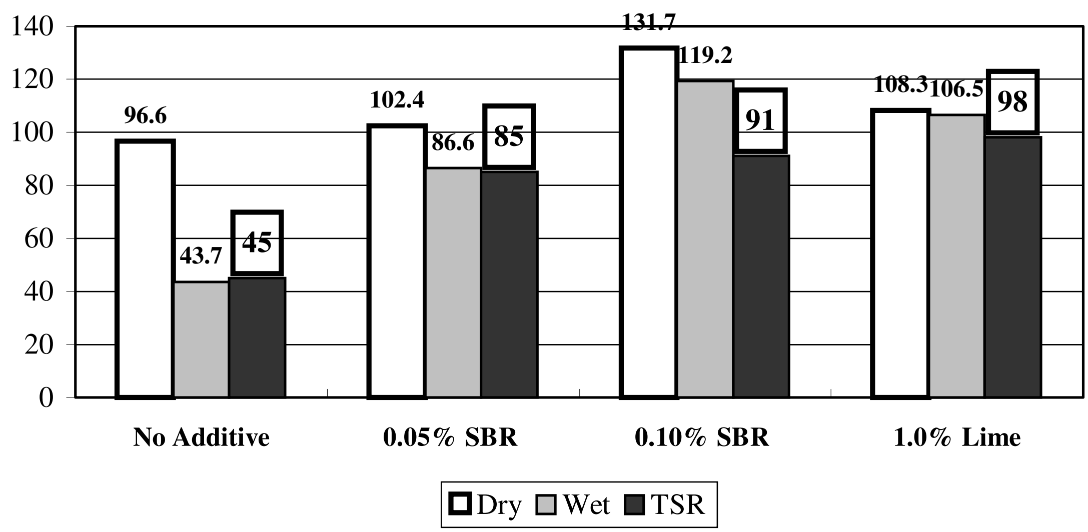

FIGURE 46 Texas study: tensile strength versus tensile strength ratio with various antistrip agents with Atlanta District aggegate (*27*).

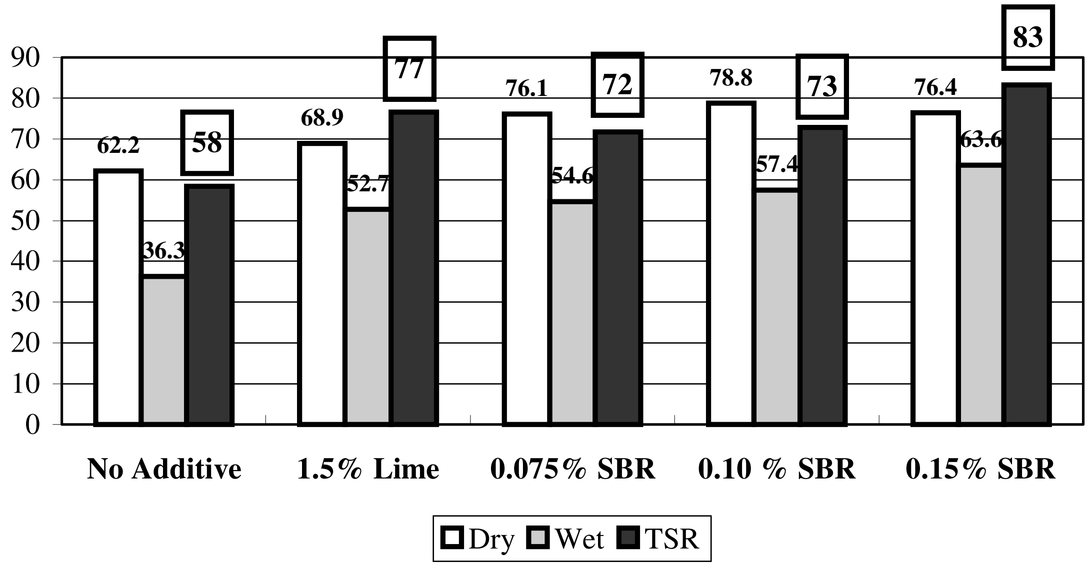

FIGURE 47 Nevada study: tensile strength versus tensile strength ratio with various antistrip agents with Elko aggregate (*23*).

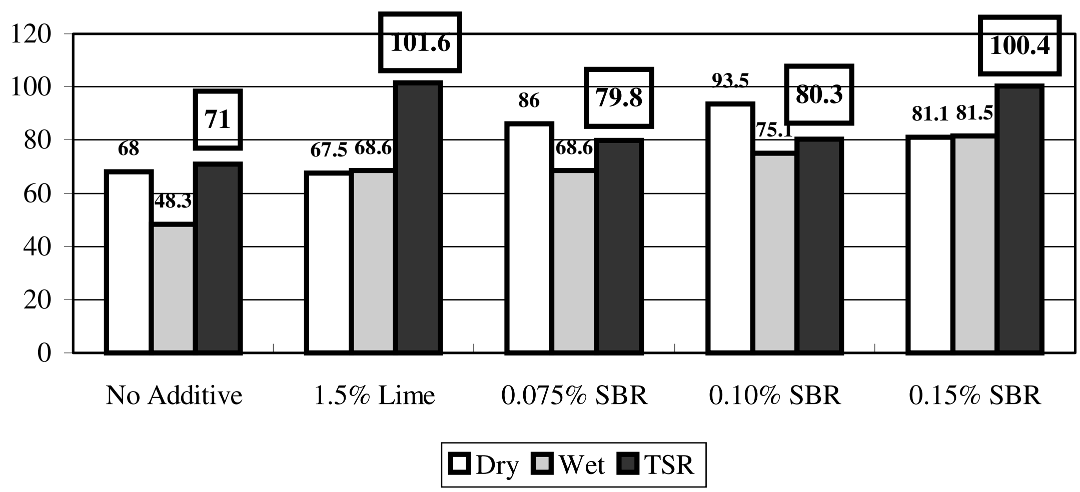

FIGURE 48 Nevada study: tensile strength versus tensile strength ratio with various antistrip agents with Lockwood aggregate (*23*).

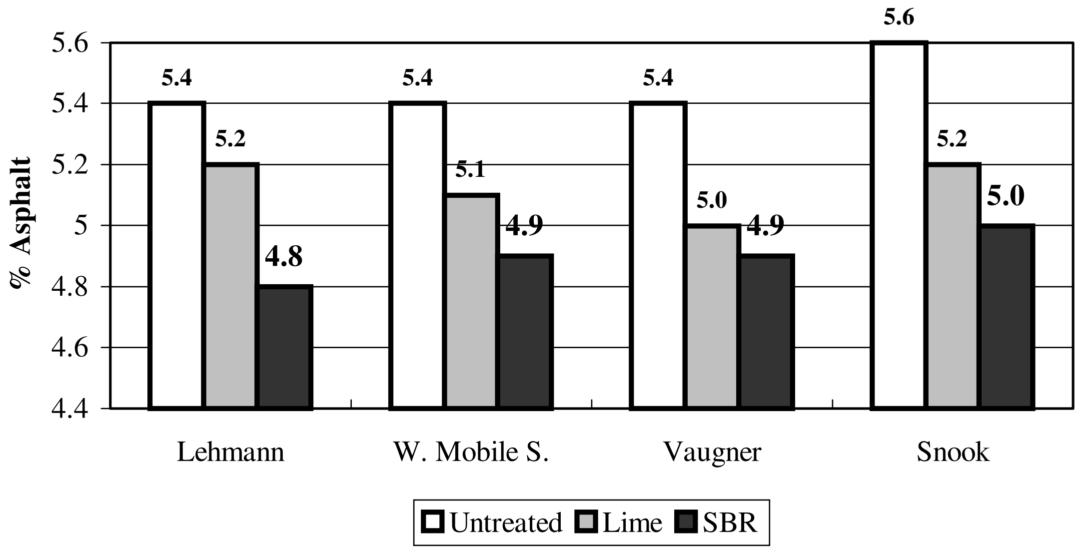

FIGURE 49 Colorado study: optimum oil content with various antistrip agents with Colorado aggregates (*24*).

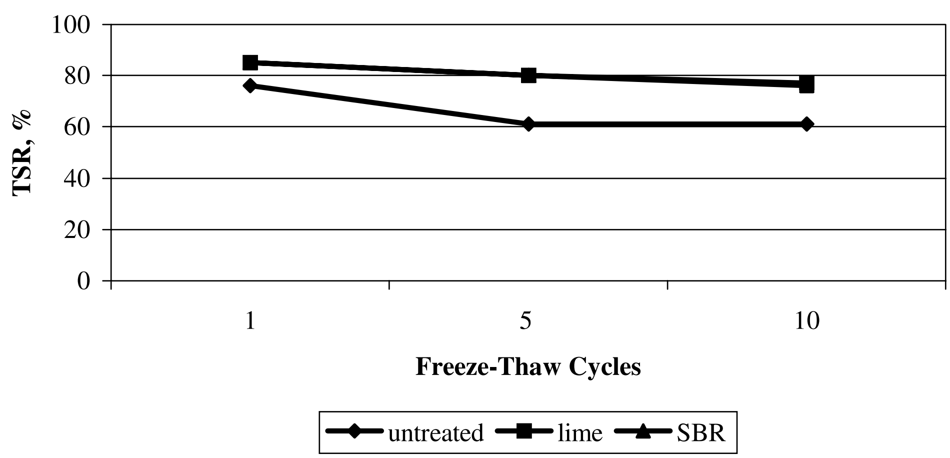

FIGURE 50 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Western Mobile South aggregate (*24*).

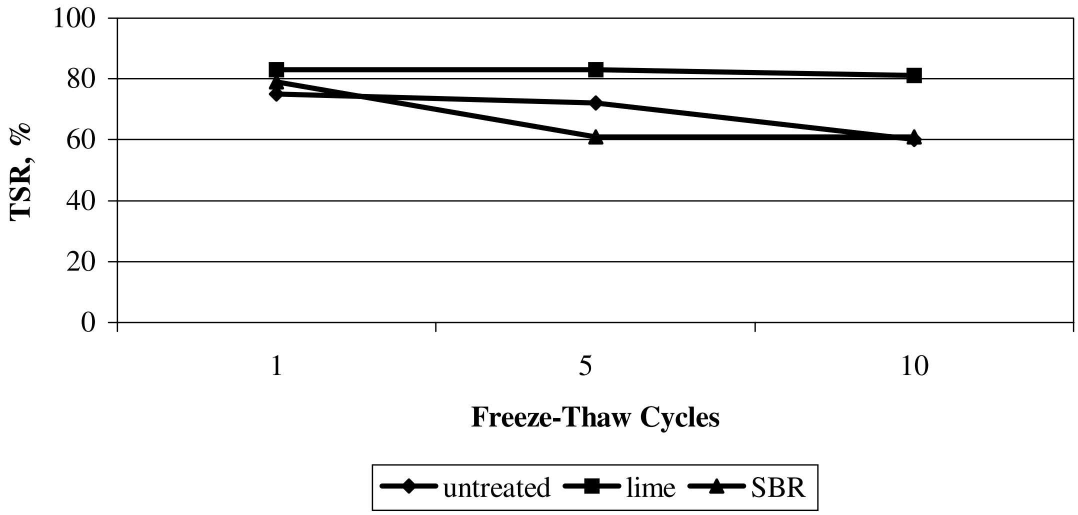

FIGURE 51 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Lehmann aggregate (*24*).

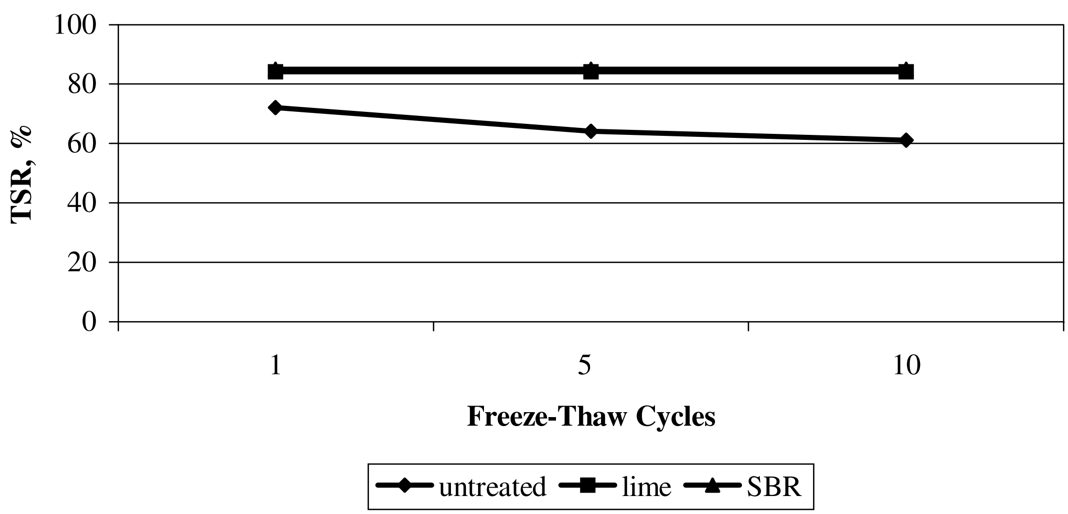

FIGURE 52 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Vaugner aggregate (*24*).

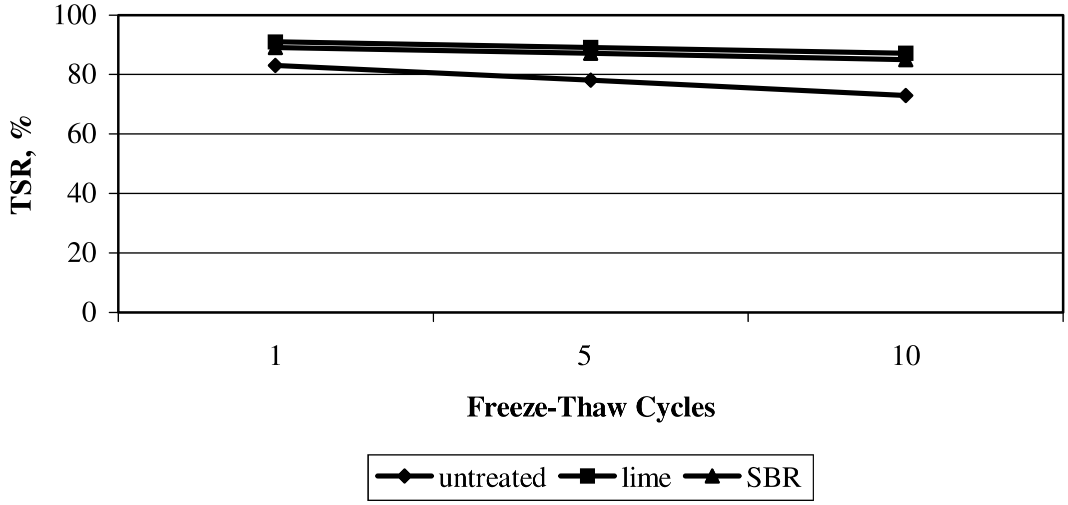

FIGURE 53 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Snook aggregate (*24*).

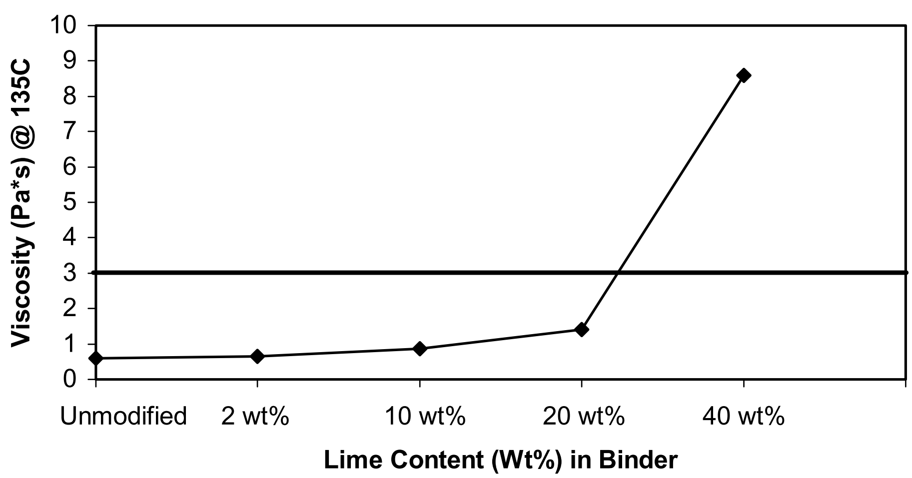

FIGURE 54 Effect of lime dosage on binder viscosity (*9*).

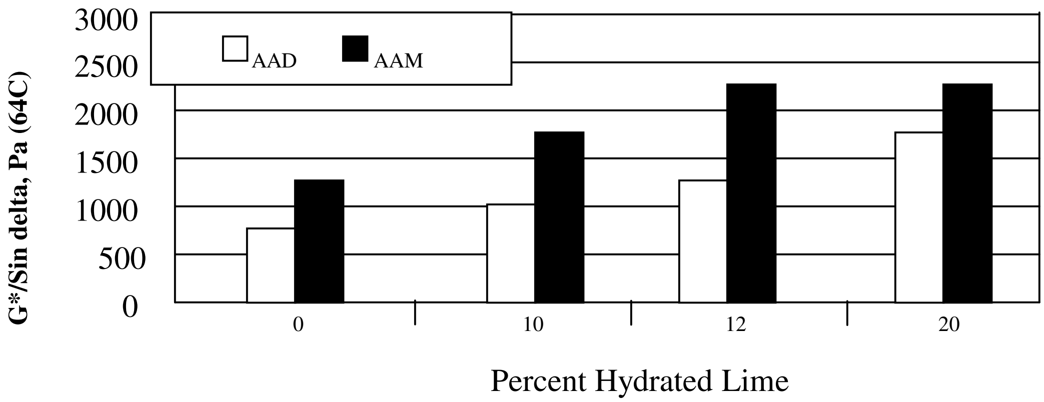

FIGURE 55 Effect of the addition of hydrated lime on asphalt binder rheology, G*/sin(delta) (*31*).

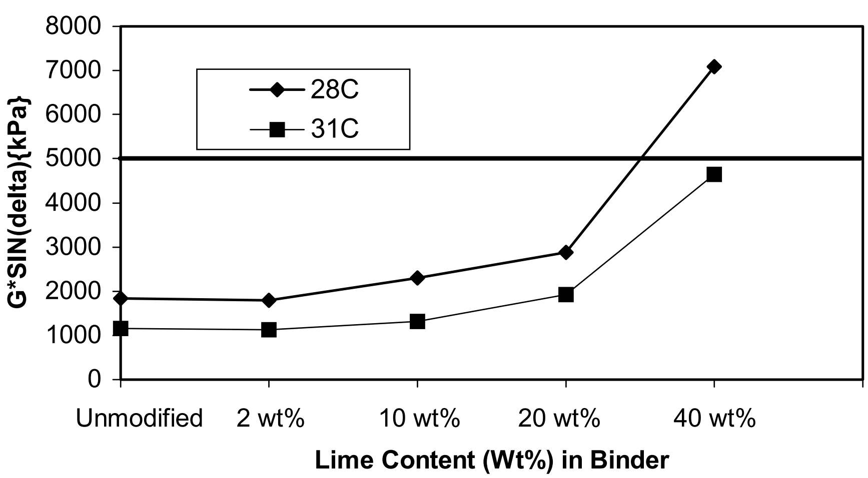

FIGURE 56 Effect of lime dosage on binder viscosity (*9*).

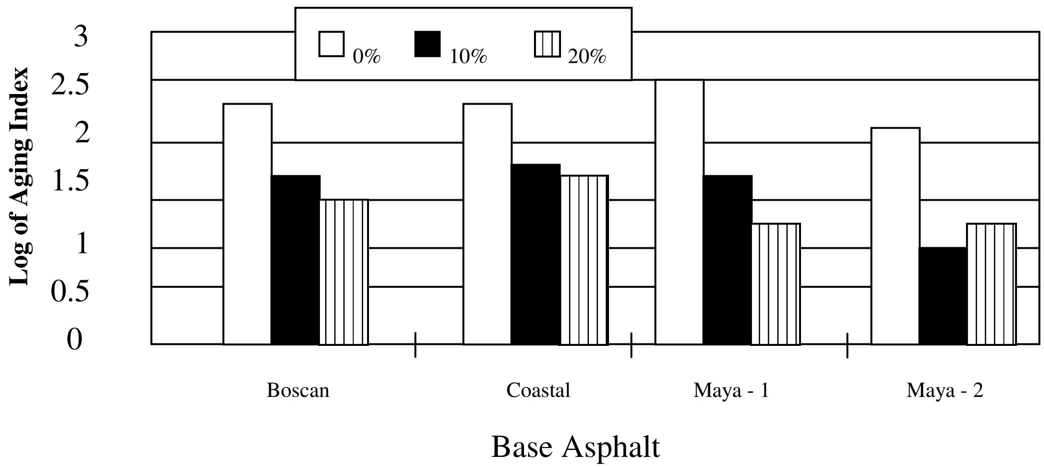

FIGURE 57 Effect of hydrated lime in reducing the aging of asphalt binders (*32*).

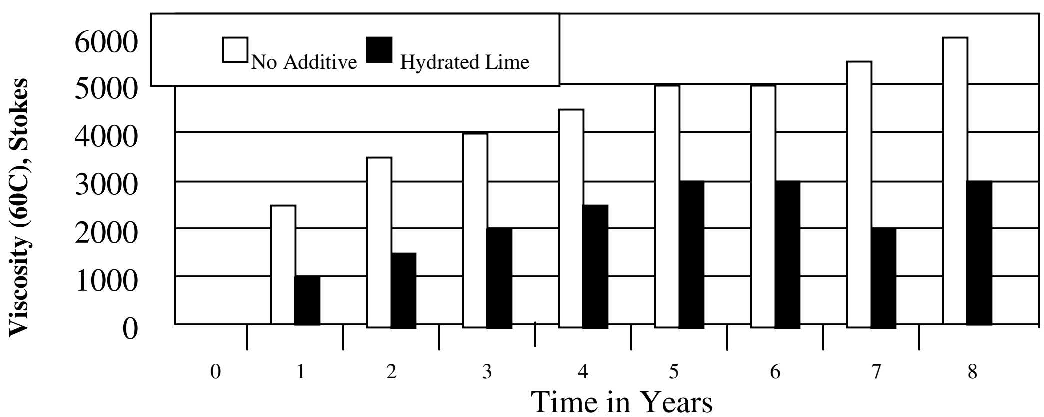

FIGURE 58 Field data demonstrating the effect of hydrated lime on the hardening of asphalt binder based on Utah data (*33*).

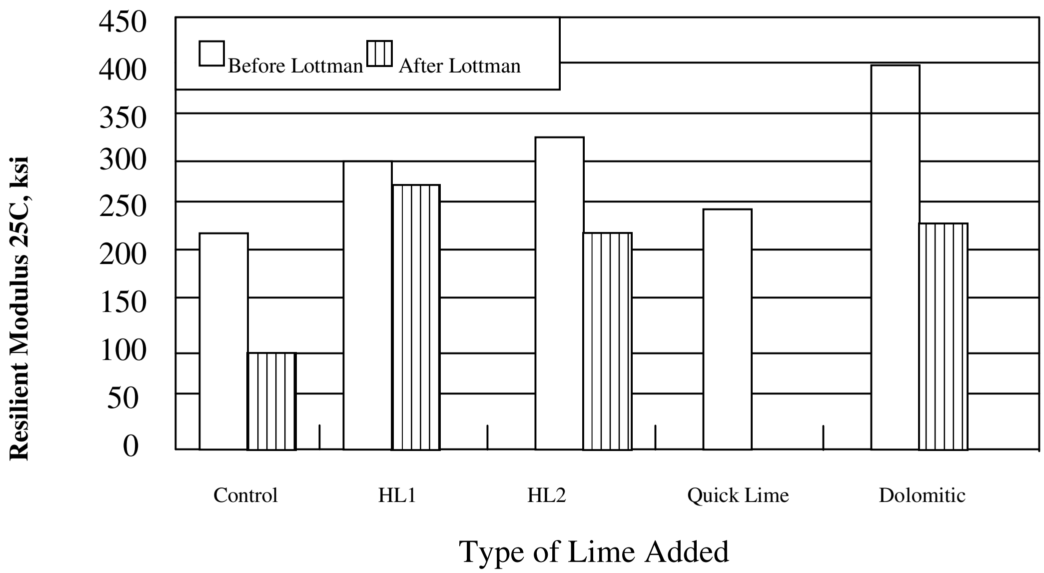

FIGURE 59 Effect of type of lime added to dry aggregate on the resilient modulus (internal data set, Materials and Test Division, Nevada DOT, 1998).

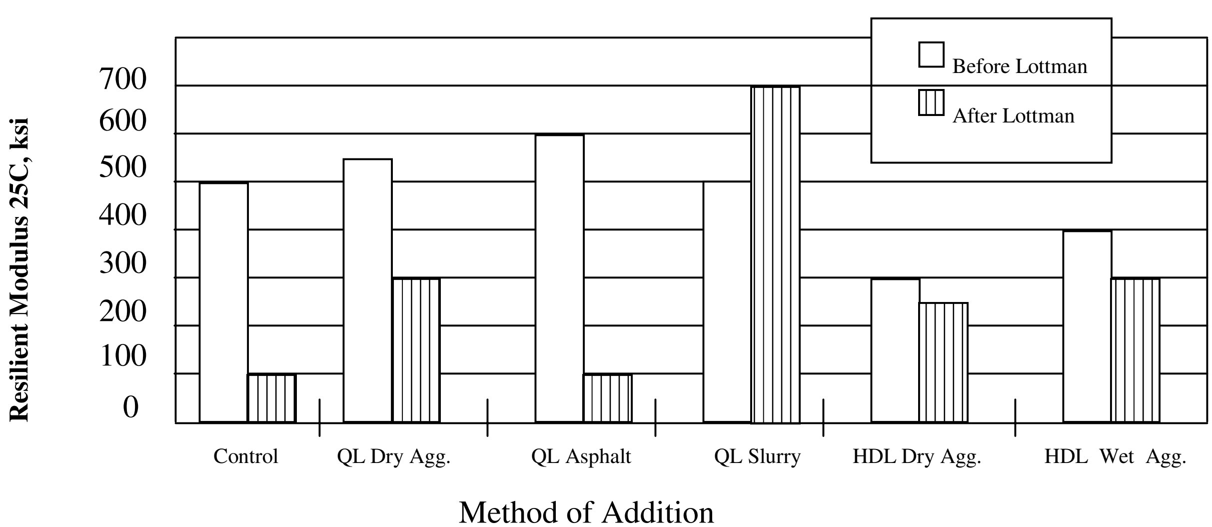

FIGURE 60 Effect of the method of hydrated lime addition on the restrained resilient modulus after Lottman conditioning (*34*).

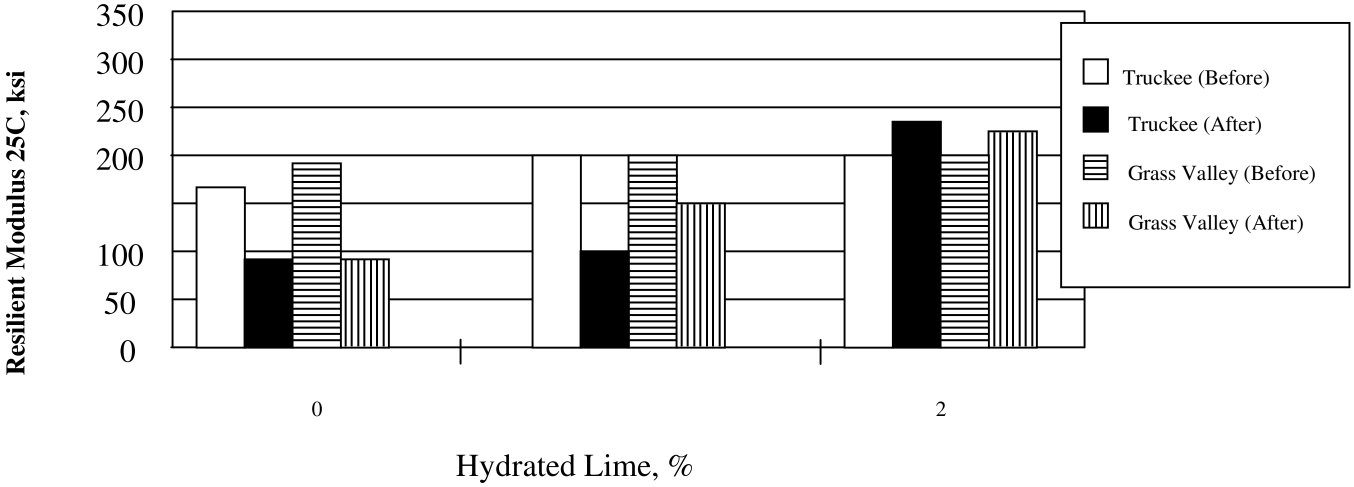

FIGURE 61 Effect of hydrated lime on the resilient moduli before and following Lottman conditioning for Truckee and Grass Valley, California, mixtures (*35*).

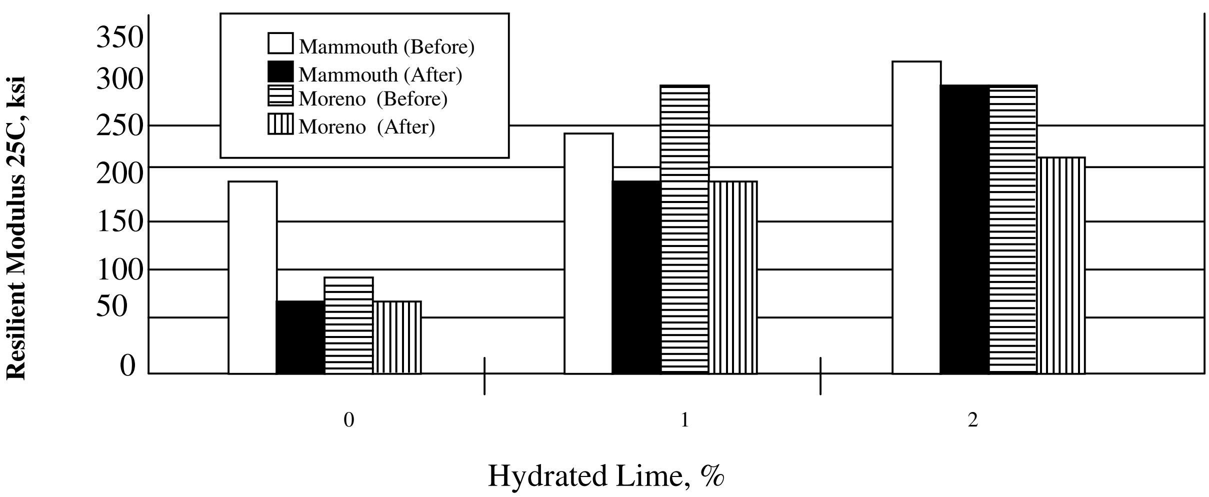

FIGURE 62 Effect of hydrated lime addition on the resilient moduli before and following Lottman conditioning for Mammouth and Moreno, California, mixtures (*35*).

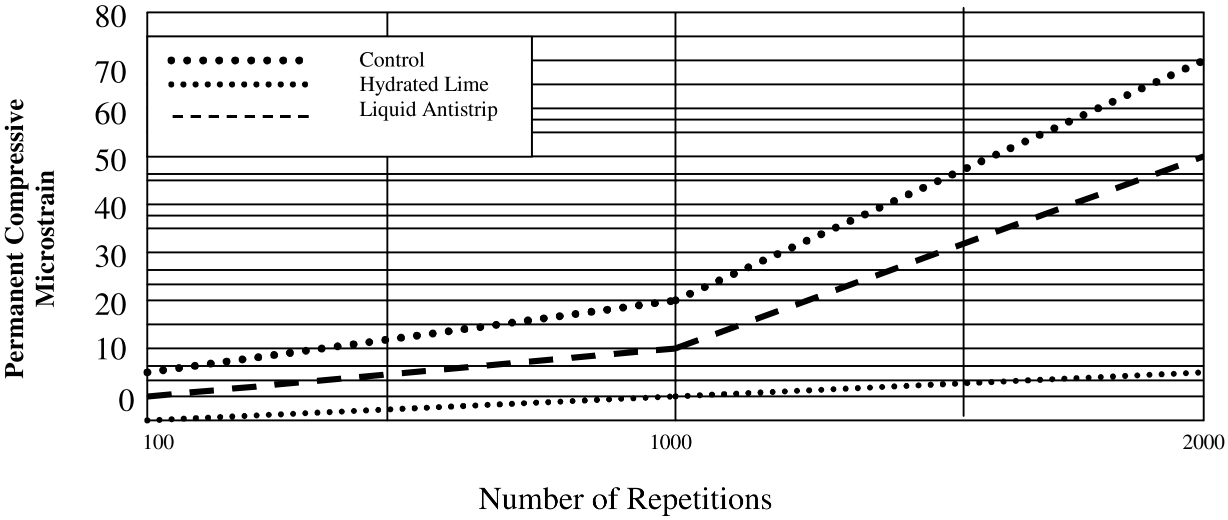

FIGURE 63 Effect of additives (with moisture) on permanent deformation: Oregon Department of Highways field study (*36*).

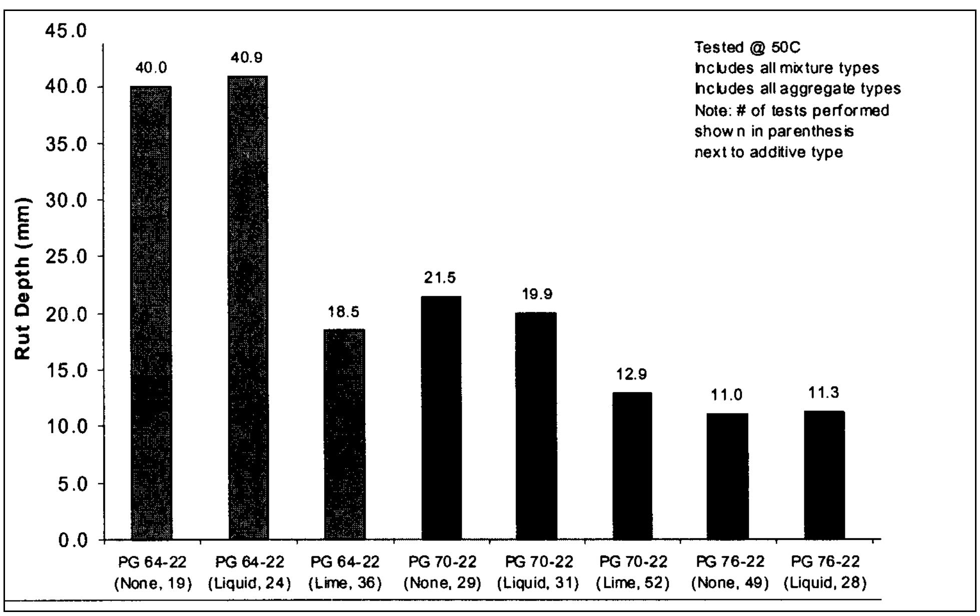

FIGURE 64 Effect of binder grade and additive type (*30*).

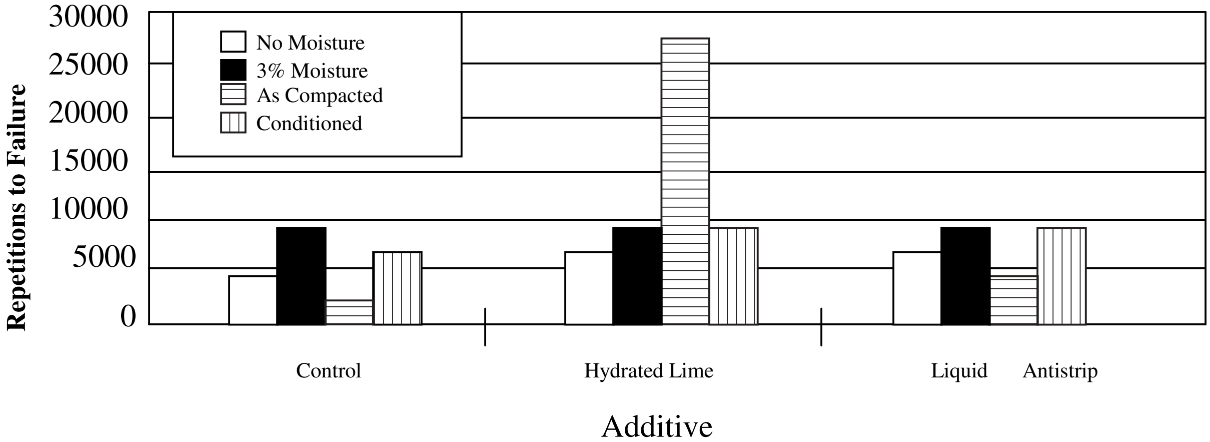

FIGURE 65 Effect of additives on fatigue life: Oregon Department of Highways field study (*36*).

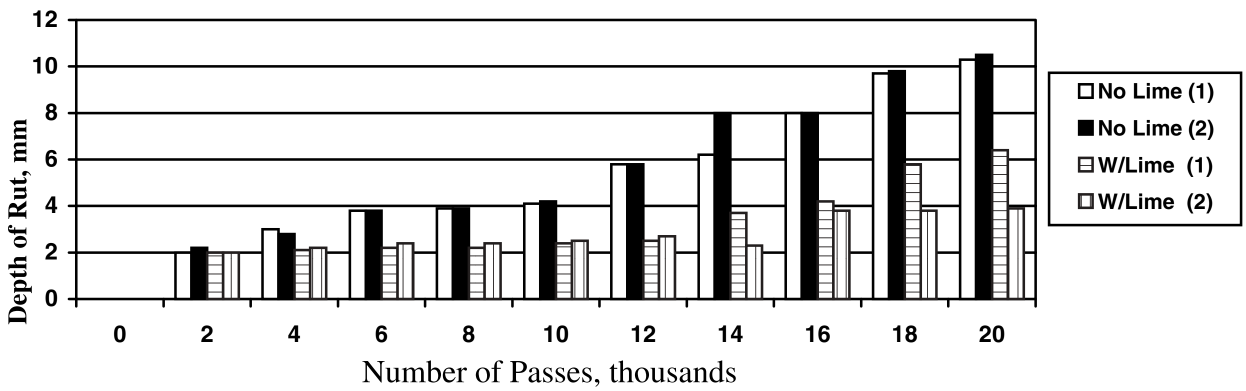

FIGURE 66 Results of rut tracking tests from Wuppertal-Dornap, Germany (*37*).

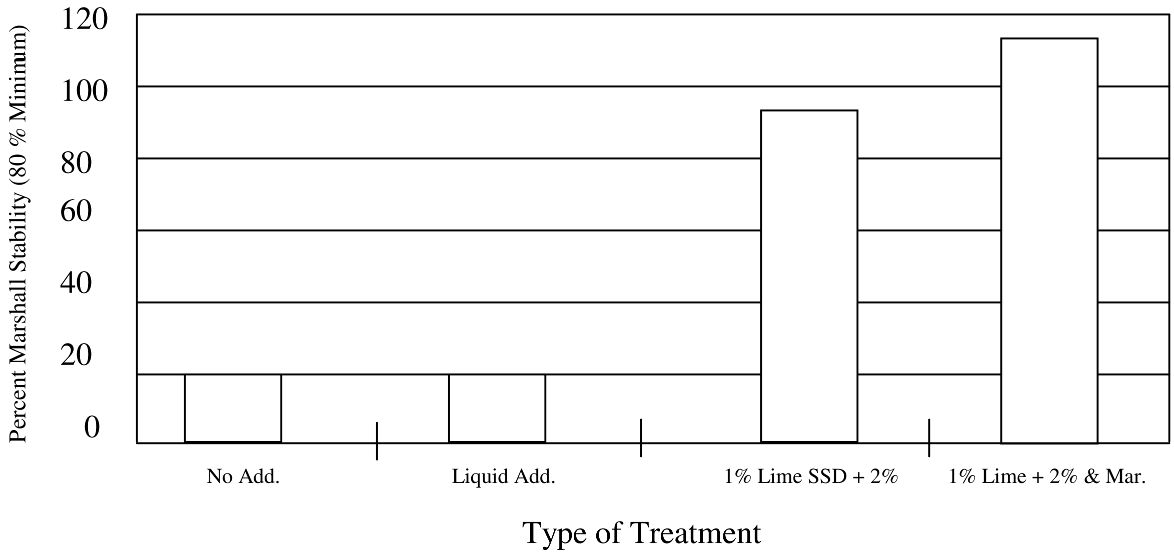

FIGURE 67 Effect of the type of additive and method of addition on the retained tensile strength of materials from SR-50, Millard County Line to Salina, Utah (*39*).

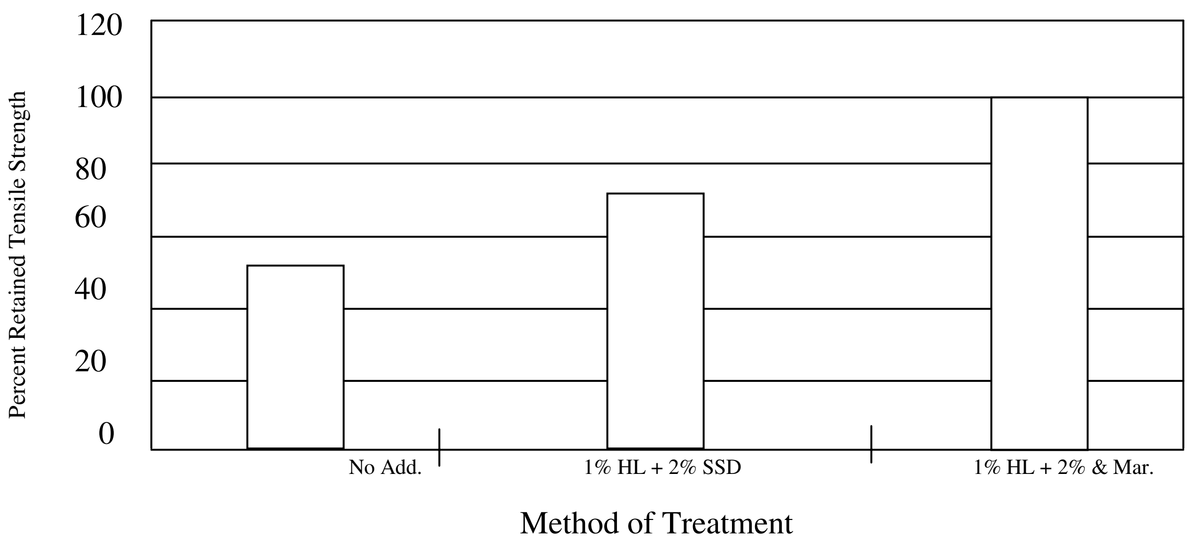

FIGURE 68 Effect of lime addition on tensile strength ratio for materials from I-70 Wetwater to Colorado Line, Utah DOT (*39*).

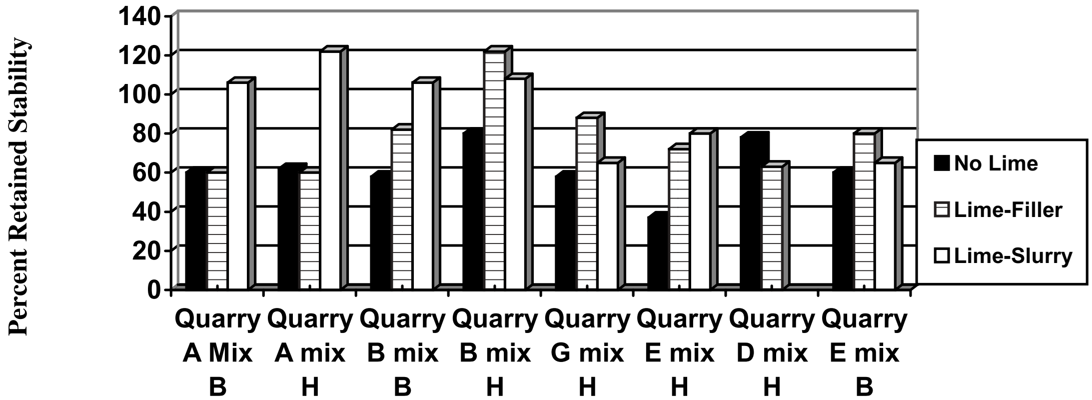

FIGURE 69 Effect of the addition of lime and method of addition on the retained stability for Georgia DOT mixtures (*38*).

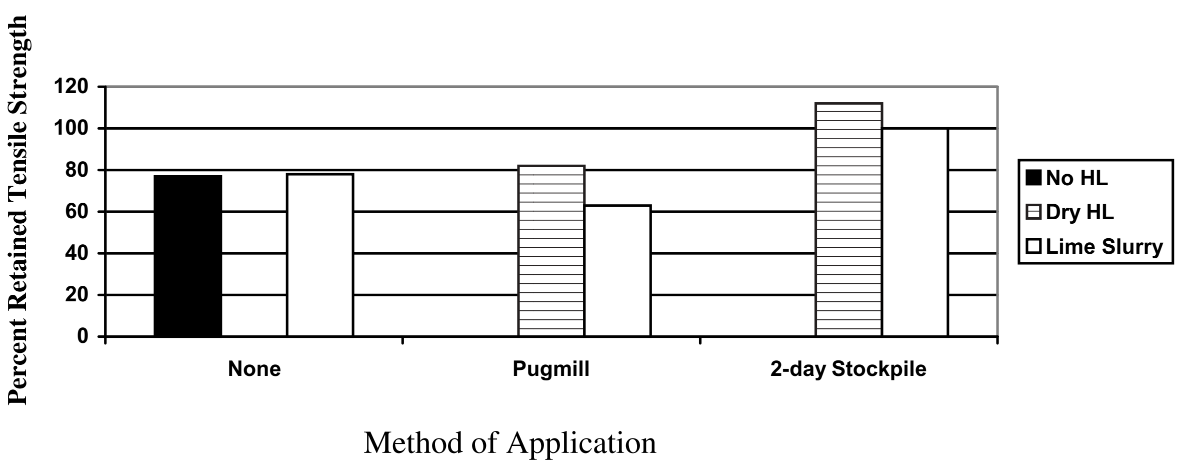

FIGURE 70 Effect of the method of application on retained tensile strengths of batch plant operations in Texas (*40*).

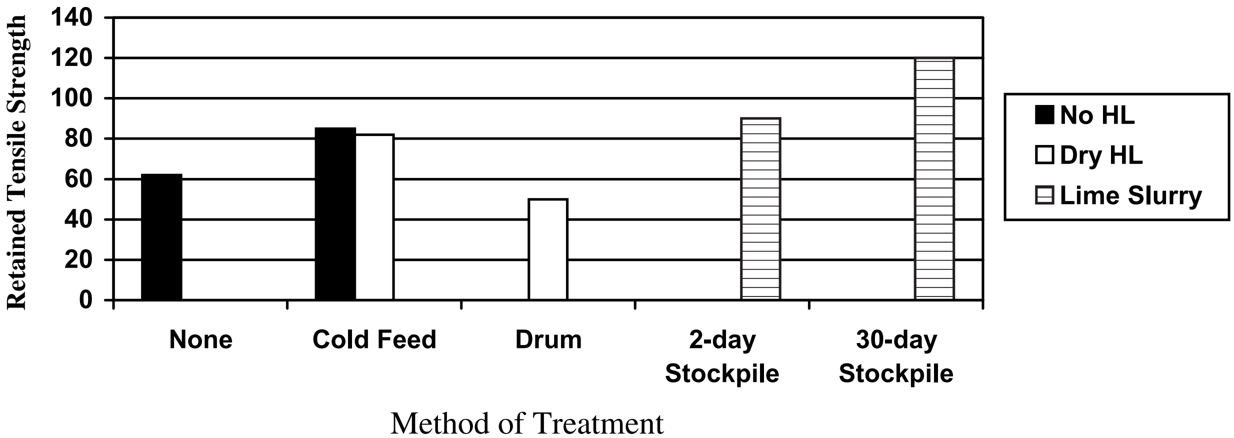

FIGURE 71 Effect of addition of lime to drum plant operations (*40*).

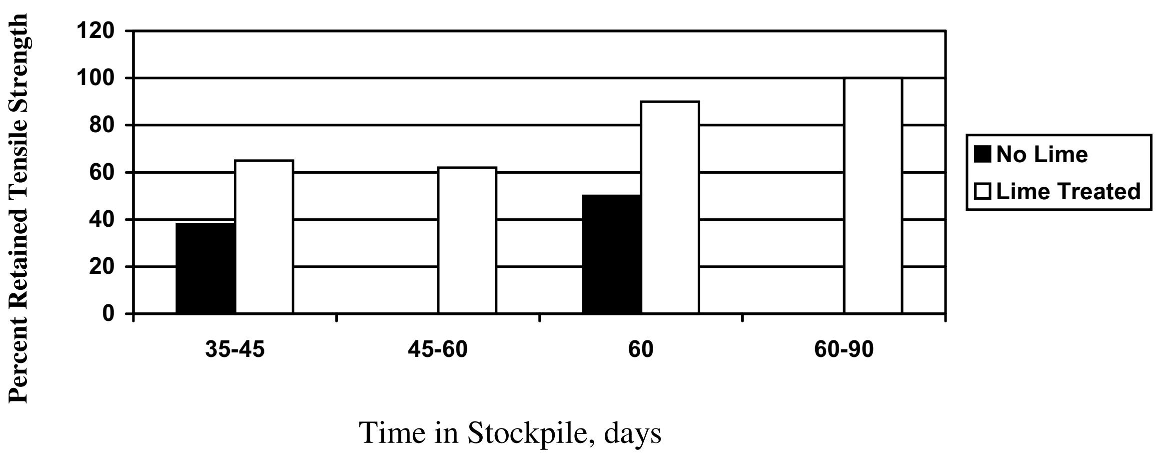

FIGURE 72 Effect of addition of lime to drum plant operations (*41*).

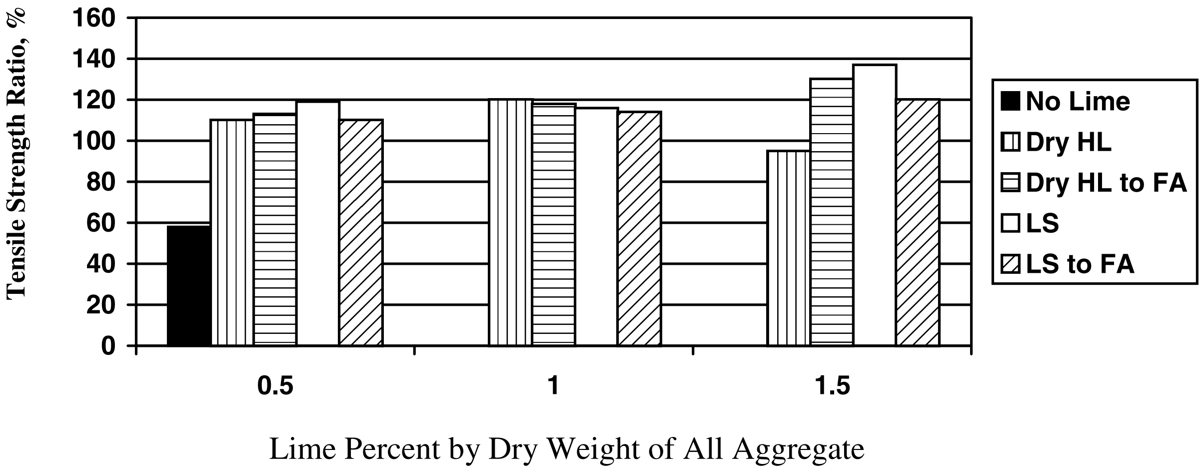

FIGURE 73 Effect of method of lime marination and percent lime added to granite aggregate (*42*).

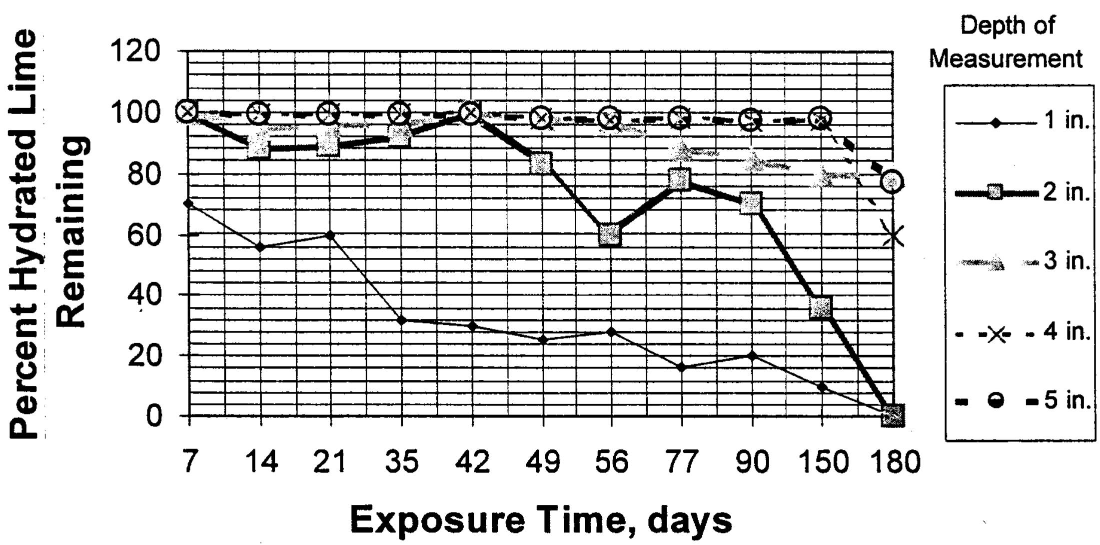

FIGURE 74 Effect of exposure time and stockpile carbonation on the active $Ca(OH)_2$ remaining (E. R. Graves, "Lime in Sand for Hot-Mix Asphalt: Test Project Summary," internal memorandum, Chemical Lime Group, Dec. 1992).

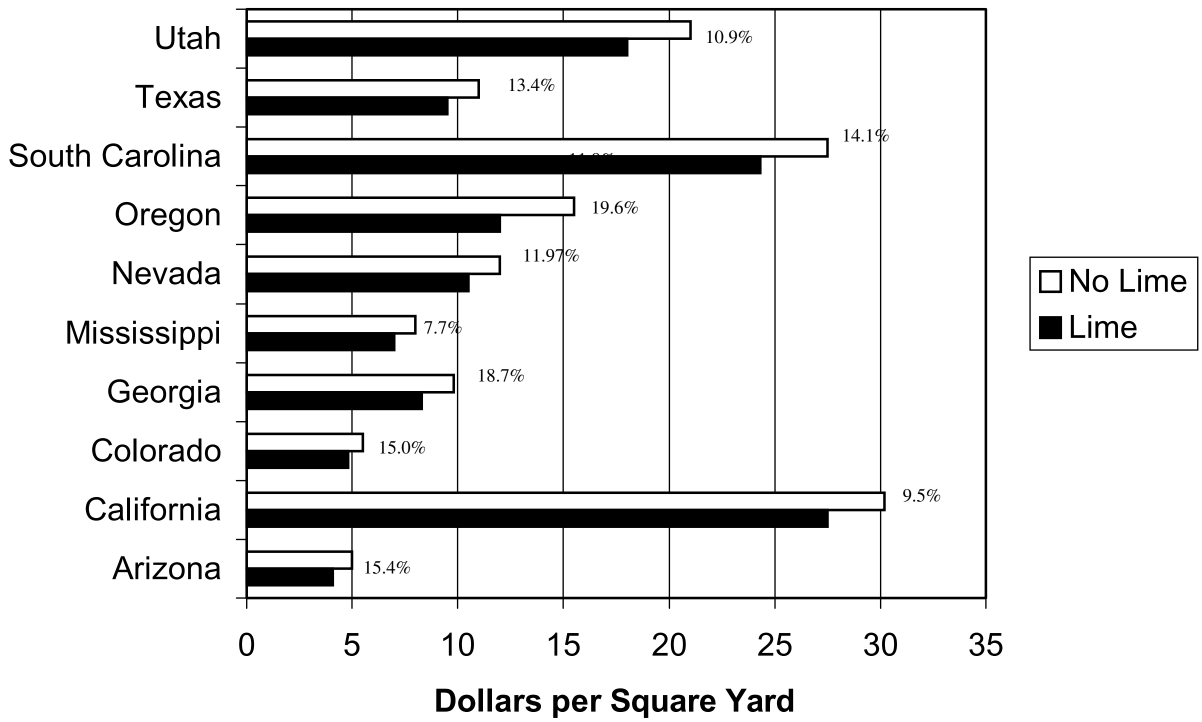

FIGURE 75 Life-cycle cost analysis of using lime for various states (*45*).

TOPIC 4

Questions and Answers

JON EPPS
Granite Construction, Speaker

ERIC BERGER
Chemical Lime, Speaker

JAMES ANAGNOS
Akzo Nobel Asphalt, Speaker

Q1—Pat Lavin, Arr-Maz
What is the purpose of marinating the lime?

A—Eric Berger
Most commonly, it is used to react with the undesirable surface stuff, surface coatings, be they fine particles that it can often carbonate or clay with which it can react pozzolanically. In the case of granitic and other quarried stones, it just seems to provide better performance in some circumstances. The state of Nevada did quite a bit of work on this several years ago, and I think you did quite a bit of it, didn't you, Jon, where they compared by testing behind the paver whether marination of a dry lime on damp aggregate process, not a slurried process, improved the performance? They concluded that yes, indeed, it did. In a later study that Peter Sebaaly did comparing the different application methods, NDOT decided that they'd stick to the marination method that worked best for them. But the study noted that in about 80% of the circumstances, the data indicated it didn't really matter that much whether you marinated or didn't marinate.

Q2—Pat Lavin, Arr-Maz
So the different time frames like 30 days or 3 weeks or 6 weeks are really indifferent?

A—Eric Berger
For how long you could leave it in stockpile?

Q3—Pat Lavin, Arr-Maz
For how long are you supposed to marinate it before you can use it?

A—Eric Berger
Usually that's 24 to 48 hours before you can put it in the plant. That varies by the state that requires marination. In terms of leaving it in the stockpile, there have been a couple of studies done. Dallas Little did one in Mississippi a good number of years ago. Dr. Robin Graves, who's in the audience here, did one probably 10 years ago or so. They discovered that in stockpile, it could remain active; the calcium hydroxide will remain chemically active for months.

A—Jon Epps
Those data are contained in the paper, too, about the stockpile. The carbonation takes place in the stockpile from the outside in and shows the depths of carbonation for various lengths of storage time that Robin Graves did. The other thing I might mention, and Dean can speak up if he wants. The most effective use of the marination process seems to be with those aggregates that contain some clay in them and gave enough time for the ion exchange to take place, which is pretty instantaneous if you can get the clay to the lime and then maybe it will have a pozzolanic reaction. And a little water.

Q4—Larry Santucci, University of California, Berkeley
This is a question for Eric and maybe a question some folks here from Caltrans might ask. On the chart that you showed toward the end of your presentation on cost savings using lime, could you explain why California is spending $30 per square yard while Colorado appears to be spending only $5 per square yard on projects?

A—Eric Berger
I don't even have to bother Gary, the author of that study, with that because I worked for the state of Washington for a decade or 15 years, and the differences depend upon which costs are captured in a state's reconstruction or maintenance activities. Wouldn't you say that that's true and different states report very differently, which is one of the reasons why it is so hard to transfer a PMS program from one state to another? I am sure that is what the cost difference is.

Q5—Larry Santucci
So this is not an apples-to-apples comparison of costs?

A—Eric Berger
It is data generated by each state for each state. But if you wanted to compare South Carolina with Colorado, it probably would be inappropriate because there are guardrails in one and shoulder widening in the other.

Q6—Gayle King, Koch Pavement Solutions
Based upon research by Bishara and Fager at Kansas DOT and reports from Ludo Zanzotto at Calgary, there appear to be serious incompatibilities between certain asphalt modifiers. In particular, one might boost a binder's PG grade with acidic materials while at the same time adding basic components to the mix as antistripping agents. The problem is primarily communication. The binder supplier modifies the PG grade, but the contractor chooses the antistrip solution. In response to problems observed in Oklahoma and elsewhere, Nebraska just published a specification that requires binder suppliers to add liquid amines at their terminal before the binder is graded, so that grade fallback and modifier incompatibility can be avoided. Any thoughts on whether that's an appropriate solution, or are there other ways to avoid compatibility problems?

A—Jon Epps
Is that a question, Gayle, or a statement?

Q7—Gayle King
I'd like to hear what others might suggest as a solution. How should we handle such incompatibility issues?

A—Jon Epps
I'll just start out by saying that some public agencies require sampling the asphalt binder in the feed line to the mixing chamber, and so whatever goes on before that is the contractor's and supplier's responsibility. That forces the issue just like you are suggesting. Jim, do you have a comment? Eric?

A—Eric Berger
My response to that is one test is worth a thousand expert opinions.

A—Jim Anagnos
I think so far we have had this occur several times in the state of Texas with particular suppliers and basically the liquids are added at the contractor's point in that state, at the contractor on site. The thing that he has addressed, the problem at that point, he has changed suppliers of the binder. I'm not saying that is the solution to it, but those are some of the things that have been done. I guess the biggest solution to it would be to have it added at the refinery and allow the folks at the refinery to have that worked in. Sometimes you can add concentrated amounts of amines, particular kinds of amines; it is my understanding that will combat that. You're going to ask me how much that is. I can't answer. I don't know.

Q8—Pat Lavin, Arr-Maz
I think what Gayle is specifically talking about is the state of Kansas has developed a specification where they don't like the idea of using phosphoric acid to bump the grade of their asphalt binders. So what they are doing is they are requiring the asphalt supplier to prequalify their binder with amine antistrip additive as a way to test for the presence of phosphoric acid in the asphalt. What we've found out is it is also crude sensitive. In other words, one supplier will knock it down a grade and another supplier won't.

Q9—Bob Humer, Asphalt Institute
Jon, in one of your slides, there is a polymeric treatment of aggregates and it says 1 pound per ton, which is like 5/100th of a percent. In what form is that and how do you really treat that entire aggregate surface with 1 pound of polymeric materials? Just give me a picture of how this works.

A—Jon Epps
Very carefully, obviously, is the answer to that. Peter, do you want to respond to that? Peter Sebaaly is in the audience and he was the everyday person on that study.

A—Peter Sebaaly, University of Nevada, Reno
Yes, the 1 pound per ton is a true figure. You dilute the material. It is a very thin material and you dilute it with water and very, very, very carefully you mix it in the lab. That's all I can say.

Q10—Bob Humer, Asphalt Institute
Just a comment, Eric. You said that mixing lime with asphalt is still in kind of a trial stage. On reservoirs, such as for drinking water, we like to see a coating of mastic, which is specified as a blend of paving grade asphalt and 70% by weight lime. Sometimes that is a little hard to blend, so they drop off to 60% lime. So we are at pretty high concentrations of blending lime in with asphalt for those mastic coatings. Just that you are aware of that. A good example is the MWD Devil's Canyon Afterbay reservoir near San Bernardino.

A—Eric Berger
One of the problems that we've had, and this is being worked on both here in the U.S. as well as in Europe, is the volume that we can blend in at the time just as you described. Dallas Little and Chemical Lime and the Arizona DOT are sort of struggling their way to a field trial of this very thing. But it certainly would simplify matters for everyone and do a world of good for a lot of bitumens, I think.

Q11—Barry Baughman, Ultrapave
I'd like to address the polymer issue. It is 1 pound of dry polymer per ton of aggregate. Basically, the material is supplied as a latex, which has very small particles and very large surface areas. They are applied on the belt as the aggregate goes down into the drum dryer. During the first few feet in the drum dryer, they get dispersed throughout the aggregate. They form a waterproof coating onto the aggregate. Basically, the aggregate (which is water loving) becomes water repelling. The material we use is also a hydrocarbon polymer; therefore, it has an attraction to the asphalt and improves or enhances the bond to the asphalt. If anyone has any questions, they can see me.

Q12—Ron Sekhon, Caltrans
What is the chemical composition of these liquid antistrips? With lime we have some sort of information how the reaction takes place with the clay particles and so forth. I was interested in knowing how the liquid antistrip works.

A—Jim Anagnos
If you want the chemical composition, you're not going to get that from me because I don't know what it is. You might have to ask the chemists who are involved like companies like Arr-Maz, Akzo Nobel, Unichem, Rohm & Haas. Those chemists might be able to divulge that kind of information. I cannot.

Q13—Jack Van Kirk, Basic Resources, Inc.
One of the things that we're really toiling with in California, we have for many years, is liquids versus lime. There have been a lot of studies done, and I know in the early years certain types of liquids came out that were used and weren't quite as effective. Later on, I guess a new line of liquids came out and one of the things that is very difficult for a lot of us in the audience to do when we look at these studies is you look at the lime folks and they show the lime is great and the liquid is not. You look the other way and you find the liquid is just as good as the lime in different ways. One of the things that would be very helpful to us is to look at some type of study that you showed earlier and I think it indicates that when you use a liquid it makes a big difference in the kind of liquid you use on the type of aggregate you have. So, the question is,

when the lime studies were done, are we looking at apples and oranges? Are we looking at the same types of things that they are looking at today—like you talked about a high-quality liquid as opposed to some of the things that were looked at early on? It is like the white industry versus the black industry when it comes to pavements. It is the same thing for lime versus liquids. If we are going to be able to move forward with this in an equal type of evaluation, we have to be looking at the same types of products in both cases and we all know that lime works very well. The bottom-line question is, is there a difference today with the liquids that are being done that are going to give us the same type of performance as maybe dry lime to wet aggregate or even the lime slurrying in some cases and were they different in some of the cases that were done in the lime industry?

A—Jim Anagnos
I know, for example, for some of the experimental work we did at the University of Texas between 1970 up to 1990 that I was involved with—I know at that time we used an awful lot of liquids that were not very good performers. And I suspect, I don't have absolute data on it, I just know from my own experience that we used additives that were not good performers. I don't know what the studies would have shown back then if you had used a high-performance additive and whether they were available at that time. I can't answer. I don't know. But I have a feeling that a lot of the studies were done with inferior products. For example, in Virginia, I think Bill Maupin looked at a study early on in the early 1990s of some projects that were placed and he found that the liquid did not perform well. So, he raised his specifications, his requirements, and he went back out and looked at projects under the new requirements and found that they were not any different. He could not see any discernible difference between the liquids and the hydrated lime. What I am leading up to is I guess you have to have some sort of testing process to look at these things. This is a very complicated situation. I didn't get to say this earlier, but I don't think that you have an elixir of an additive that can be added to anything and everything and have it accomplish everything under the sun. I don't think that's possible. I don't think you're going to ever find it. I don't know that you're ever going to find a particular test that's going to be 100% positive each time. I say positive, that it will relate to field performance. When you look at field performance you have many other issues involved besides "what kind of additive did you put in," so that's a very hard correlation to make.

A—Jon Epps
Just an observation from reviewing the literature once again, Jack. It's not an answer to your question. The various types of additives that we've talked about today are certainly asphalt binder dependents. It's been said already they're aggregate dependent, their concentration dependent, and they are also test method dependent in terms of how good they show up to be. That's as a minimum that I found out.

Q14—Mike Cook, Caltrans
Two quick questions. We had some discussion about marination of lime-treated aggregate and the maximum marination period allowed. Does environment like rain affect that maximum marination period? My second question is how do we know what a high-quality liquid antistrip is? Is there any ASTM or AASHTO designation or a reference to differentiate between antistrips that perform well and those that perform poorly?

A—Eric Berger
The answer is that I don't remember in Robin Graves' study, but I do remember in the study that Dallas Little did in Mississippi that during the 6 months or so that the material sat in stockpile, it rained at least 8 inches. What happened was that the carbonation, which for those of you who don't know is the retransformation of the calcium hydroxide into calcium carbonate or limestone, proceeded from the outside surface of the stockpile just a couple of inches into the stockpile. The calcium hydroxide was active on the inside of the stockpile. It seems to me Robin's study went at least that long, and did it rain much in that study?

A—Robin Graves
Yes.

A—Eric Berger
He said yes.

A—Jon Epps
And it was for over 120 days, Robin, or something like that?

A—Robin Graves
About 6 months.

A—Jon Epps
Jim, can you answer the next question, which dealt with how do you tell the liquid antistrips that perform well from those that perform poorly?

A—Jim Anagnos
The only way I know to do it is by doing some additional testing. For example, you might use a Hamburg-type test, you might use a PG grading-type SHRP-type test to see what that additive is doing to your neat binder. But I think it all comes down to what you are doing for testing. Is there something in AASHTO or ASTM that this qualifies one as being a "good one or a bad one"? I don't know of any.