National Lime Association

LIME

The Versatile Chemical

Comparison of Lime and Liquid Additives on the Moisture Damage of Hot Mix Asphalt Mixtures

Peter E. Sebaaly, Ph.D., P.E.
Pavement Specialist
Reno, Nevada
USA

Prepared for the National Lime Association

April 2007

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Comparison of Lime and Liquid Additives on the Moisture Damage of Hot Mix Asphalt Mixtures

SUMMARY

This report summarizes research and development studies that were conducted within the past 20 years to compare hydrated lime and liquid antistrip additives on the moisture damage of hot mix asphalt (HMA) mixtures. A total of ten studies have been summarized in terms of their objective, materials used, experimental program, and the correlations of the measured properties to the long-term performance of HMA pavements. In most cases the correlations to the long-term performance have been estimated through mechanistic analyses of the HMA pavement using the engineering properties of the HMA mixtures that have been measured in the actual research studies. This report extends the applications of the research data from the experimental programs through the prediction of the long-term performance using up-to-date and sound pavement engineering principles.

Moisture damage of HMA pavements is not a distress by itself but represents a conditioning process after which several distresses may occur individually or simultaneously. The moisture first inflicts damage on the HMA mix by destroying the bond between the aggregate and the asphalt binder or by destroying the internal cohesive strength of the binder. Both actions create a weaker HMA mix that is unable to resist the stresses imposed by the combined effects of traffic loads and environment. As moisture damage reduces the internal strength of the HMA mix, the stresses generated by traffic loads increase significantly and lead to fatigue cracking or rutting of the HMA layer. In the case of environmental stresses, a weaker HMA mix is unable to resist the thermal stresses leading to transverse cracking and aging stresses that create block cracking of the HMA layer.

The report presents a discussion on the mechanical behavior of HMA pavements under traffic loads and environmental stresses, including the nature of the strains (i.e. responses) generated by the two types of stresses and the fundamental engineering properties of the HMA mix that play major roles in resisting these strains. The report also presents detailed discussions of the various tests used to establish the fundamental engineering properties of the HMA mixtures.

The ten summarized studies are divided into two major groups: the three that used the Hamburg wheel tracking device, and the seven that measured engineering properties of the HMA mixtures. The Hamburg device can only compare the relative performance of the HMA mixtures based on empirical indicators that are generated during the conduct of the test. However measuring the fundamental engineering properties of the HMA mixtures enables the determination of the mechanical responses of the HMA pavement which can be used to estimate its long-term performance.

The studies using the Hamburg wheel tracking device were conducted in Colorado, Texas, and Louisiana. The objective of the Hamburg test is to assess the ability of the HMA mix to withstand 20,000 repetitions of the loaded wheel without experiencing severe rutting. As the HMA mix is loaded with the steel wheel, it goes through the creep region and the stripping region. The creep region is where the rutting per wheel

pass is very low, and the stripping region is where the rutting per wheel pass increases significantly. The separation point between the two regions is the stripping inflection point. The higher the inflection point the more resistant the HMA mixture to moisture damage. HMA mixtures that do not experience the occurrence of the inflection point during the Hamburg test are classified as having excellent resistance to moisture damage. The Colorado study showed that lime consistently improved the resistance of the HMA mixtures to moisture damage, while using liquid additives may or may not lead to favorable performance. The Texas study indicated that the lime-treated HMA mixtures are expected to exhibit minor rutting and never experience severe moisture damage that leads to stripping problems. The lime-treated mixtures in the Texas study never reached the stripping inflection point while the liquid-treated mixtures experienced severe rutting. The Louisiana research showed that treating the mixtures with hydrated lime would significantly improve their resistance to moisture damage.

Seven research studies that measured engineering properties of HMA mixtures were reviewed from Texas, Nevada, North Carolina, South Dakota, California, and Idaho. The two Texas studies used the tensile strength property to evaluate the effectiveness of lime and liquid antistrip additives in reducing the moisture damage of HMA mixtures. Both studies showed that lime is consistently and significantly effective in reducing the moisture of HMA mixtures from the various parts of Texas. The Nevada study used both the tensile strength and the resilient modulus properties to evaluate the impact of lime and liquids on the moisture damage of an HMA mixture from Nevada and one mixture from California. The conclusions of the mechanistic analysis that was conducted using the data generated from this research confirmed that lime treatment of the Nevada and California mixtures leads to superior performing HMA pavements at both the un-damaged and moisture-damaged conditions.

The North Carolina study evaluated the shear strength of the lime and liquid-treated mixtures. This study showed that lime treatment of the North Carolina aggregates resulted in consistent improvements of the shear strength at the un-conditioned and moisture-conditioned stages leading to less potential for shear failures of the HMA mixtures under traffic loads. The South Dakota study evaluated the resilient modulus properties of lime- and liquid-treated HMA mixtures under multiple freeze-thaw cycling. This study showed that while the lime-treated mixtures retain good level of resilient modulus after 18 cycles of freeze-thaw, the un-treated and liquid-treated mixtures loose almost 100% of their initial un-conditioned modulus within 6-9 freeze-cycles. This study also showed significant increase in the rutting resistance coupled with the increase in the moisture-conditioned tensile strength property of the lime-treated HMA mixtures will lead to HMA pavements that are highly resistant to rutting, fatigue, and thermal cracking.

The California study showed that the lime-treated mixture provided higher tensile strength and fatigue resistance at the dry stage and maintained these higher properties throughout the entire moisture conditioning process of 0, 4, 8, and 12 months. This indicates that the lime-treated mix will start with a better performing HMA pavement and maintains its superior performance through the long-term field conditioning process leading to a significantly better life cycle cost-benefit ratio than the control and liquid-treated mixtures. The Idaho study showed that the potential increase in rutting as a function of multiple freeze-thaw cycling of the liquid-treated mix is significantly higher than that of the lime-treated mix. Additionally, the liquid-treated HMA deteriorated at a higher rate than the lime-treated mix. The study showed that overall, the lime mix is more stable, less susceptible to rutting, and less susceptible to moisture damage while having similar resistance to fatigue cracking as compared to the liquid mix.

Over the past 20 years, several studies across the US testing lime and liquid additives to HMA were conducted. This report summarizes 10 of such studies where the findings include:

- Lime-treated HMA shows minor rutting compared with liquid additives.
- Lime treatment improved the resistance of HMA to moisture damage.
- Lime-treated HMA was less affected by freeze thaw cycles than liquid additive-treated HMA.
- Lime treatment leads to superior performing HMA pavements in both un-damaged and moisture-damaged conditions.
- Lime-treated HMA pavement shows significantly better life cycle cost-benefit ratio than the un-treated mixtures.
- The lime-treated HMA was more stable and less susceptible to rutting and moisture damage than liquid additives under field conditions.

INTRODUCTION

Since the early 1900s, asphalt has been used as a binder in the construction of hot mix asphalt (HMA) pavements. To date, the United States has almost 2 million miles of asphalt paved roads. Although pavements are thought to be impervious, moisture-induced damage continues to be a detriment to the longevity of the nation's HMA pavements. Through research, engineers and scientists have made great advances in understanding the problem; however, pavements still succumb to early failure from infiltration of moisture.

HMA is a composite material comprised of two major ingredients, aggregate and asphalt. The aggregate is usually obtained from quarry sites and is produced from the crushing of mined rock or gravel. Through the crushing operation, the fractured aggregate takes on a variety of shapes and sizes. The asphalt binder is a petroleum product, sometimes occurring naturally but usually the by-product of refining crude oil. Because the viscosity of the asphalt binder is quite high at normal temperatures, the material has to be heated for proper mixing with the aggregate. The function of the binder is to completely coat the aggregate creating a stable mixture of aggregate and asphalt which resists the imposed stresses induced by the highway traffic and environment.

Once in service, HMA pavements are subjected to changing environmental conditions and traffic wheel loads. The environment plays an important role in conditioning the pavement due to the presence of moisture, the fluctuations in temperature, and aging of HMA mixtures. Combined with the imposed stresses from the repeated traffic loads, a physical separation between the asphalt binder and aggregate may begin to occur. As the binder is displaced, moisture moves in to capture the aggregate's surface. This phenomenon is referred to as "stripping".

The performance of an HMA mixture is primarily measured in terms of its resistance to rutting, fatigue, low temperature cracking, and raveling. The resistance of HMA to these distresses can to some degree be evaluated using performance tests and the measurement of its susceptibility to moisture and temperature. The resistance of HMA to moisture damage is very critical to its long-term performance. Moisture damage manifests itself as a reduction in the overall strength or stiffness of the mixture. Therefore, if an HMA mixture is susceptible to moisture damage, it could eventually fail in any of the four failure modes i.e. rutting, fatigue, low temperature cracking, and raveling.

To attack the problem of moisture damage, many states and other agencies have resorted to specifying antistripping additives in an attempt to increase adhesion at the aggregate-asphalt interface. The primary goal of an antistrip additive is to eliminate the moisture sensitivity of the HMA mixture through improving the bond between the asphalt binder and the aggregate. This binder-aggregate bond is a fundamental property of the HMA mixture which can not be evaluated through testing of the individual components (i.e. binder or aggregate). Another major consideration when evaluating an antistrip additive is its ability to maintain good HMA properties. In other words, the additive must not eliminate the moisture sensitivity problem at the expense of other desirable mixture properties. For example, a successful antistrip additive would maintain the flexibility of the HMA mixture at low and intermediate temperatures and its stability at high temperatures.

Antistrip additives can be categorized into two major groups: liquid and lime. Liquid antistripping additives are chemical surfactants that reduce the aggregate's surface tension promoting better surface coverage. The asphalt is used as a carrier of these liquid additives. However, with this method, only a portion of the introduced liquid ever makes contact with the aggregate's surface. Hydrated lime is an additive to the aggregates that can be applied either in a dry or slurry states. Hydrated lime tends to change the surface chemistry or molecular polarity of the aggregate surface. The result is a stronger adhesion at the interface between the aggregate and asphalt binder.

I. MECHANICAL BEHAVIOR OF HMA PAVEMENTS

The first step in effectively assessing the impact of additives on the performance of HMA pavements is to understand the mechanical response of these pavements under traffic loads. Figure 1 shows an HMA pavement subjected to a traffic wheel load. Typically the wheel load is moving at a certain speed in the direction of traffic. The tire transfers the load to the HMA pavement in the form of vertical and horizontal stresses at the tire-pavement interface. As the stresses dissipate through the various layers, they generate shear strains (γ) near the tire-pavement interface (i.e. within the top 2" of the HMA layer), tensile strains (ε_t) at the bottom of the HMA layer, and vertical strains (ε_v) throughout the various layers.

The shear and compressive strains within the HMA layer are responsible for the formation of permanent deformation within the HMA layer. The vertical strains in the base and subgrade layers are responsible for the formation of permanent deformation within each of these layers. The sum of the permanent deformations from the HMA, base, and subgrade layers represents the total rutting at the surface of the HMA pavement. The tensile strain at the bottom of the HMA layer is responsible for the fatigue cracking of the HMA layer that quickly propagate to the surface of the HMA pavement. The magnitudes of the shear, compressive, and tensile strains are significantly impacted by the magnitude of the applied stresses at the tire-pavement interface, and the engineering properties and thickness of the various layers.

The magnitude of the applied stresses at the tire-pavement interface is a function of the wheel load, tire inflation pressure, and tire type. The thicknesses of the various layers are determined through the structural design process.

The engineering properties of the base and subgrade layers are influenced by the type of these layers (i.e. granular or fine), their density, and their relative moisture content. The impact of the moisture content of these layers on their engineering properties is not the subject of this report, and therefore, will not be discussed.

The engineering properties of the HMA layer play a major role in its resistance to rutting, fatigue, and thermal cracking. The engineering properties of the HMA layer include the following:

- Modulus
- Tensile Strength
- Shear strength
- Resistance to rutting
- Resistance to fatigue
- Resistance to thermal cracking

The higher the engineering properties of the HMA layer the higher its resistance to rutting, fatigue, and thermal cracking. Moisture damage of the HMA layer significantly reduces all of the above listed engineering properties. The following presents a discussion of the engineering properties of HMA mixtures that control their performance and that are impacted by moisture damage.

MODULUS

The modulus of HMA mixtures is defined as the relationship between the applied stress and the resulting strain. For a constant level of the applied stress, the higher the modulus the lower the resulting strain. There are two types of modulus that are typically measured on HMA mixtures: resilient modulus and dynamic modulus. The resilient modulus is used in the 1993 American Association of State Highway & Transportation Officials (AASHTO) Design Guide for Pavement Structures and the dynamic modulus is used in the newly developed AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG).

Resilient Modulus of HMA Mixtures

The 1993 AASHTO design guide uses the resilient modulus (Mr) property of the HMA mixture to determine the required thickness of the HMA layer for a given traffic load, base course, and subgrade conditions. The Mr is measured using the repeated-load indirect tension test. Figure 2 shows the resilient modulus test schematics along with the formula used to calculate the Mr from the measured deflections and load. The test is conducted by applying a compressive load with a haversine waveform (loading = 0.1 sec and rest = 0.9 sec) on the vertical diametral plane of a cylindrical specimen.

Dynamic Modulus of HMA Mixtures

The AASHTO MEPDG uses the dynamic modulus (E*) master curve to evaluate the structural response of the HMA pavement under various combinations of traffic loads, speed, and environmental conditions. Based on the calculated structural responses of the pavement, the thicknesses of the various layers are designed. The E* property of an HMA mix is evaluated under various combinations of loading frequency and temperature. Using the visco-elastic behavior of an HMA mixture (i.e. interchangeability of the effect of loading rate and temperature) the master curve can be used to identify the appropriate E* for any combination of pavement temperature and traffic speed. Figure 3 shows the components and testing conditions of the dynamic modulus test along with a typical master curve for an HMA mix.

Both the Mr and E* property provide an indication on the general quality of the HMA mixture. The higher the Mr or E* property of the HMA mix, without becoming brittle, the lower the generated strains under a given traffic load leading to a longer service life of the pavement. Therefore, any additive (i.e. liquid or lime) that generates higher Mr or E* property of the HMA mix at the dry and moisture conditioned stages will improve the long-term performance of the HMA pavement.

TENSILE STRENGTH

The tensile strength of the HMA mix is generated by the cohesive strength of the asphalt binder and the bond strength at the binder-aggregate interface. Figure 4 shows the indirect tensile strength test where a static load is increasingly applied at a rate of 2.0"/minute to the HMA sample until failure. The tensile strength is calculated from the maximum load that the sample can take prior to cracking.

The higher the tensile strength of the mix the better its resistance to fatigue and thermal cracking will be. Therefore, any additive (i.e. liquid or lime) that generates a higher tensile strength of the HMA mix at the dry and moisture conditioned stages will improve the long-term performance of the HMA pavement.

SHEAR STRENGTH

The shear strength of the HMA mix is generated by the cohesive strength of the asphalt binder, the bond strength at the binder-aggregate interface, and the interlocking among the aggregate particles. Figure 5 shows the triaxial test where a constant confining stress is applied and a vertical stress is increased until the sample fails. The shear strength of the HMA mixtures is defined as:

$$S = C + \sigma \tan(\phi) \tag{1}$$

The S represents the shear strength of the HMA under a given vertical stress (σ). The C and ϕ are shear properties of the HMA mix determined from multiple triaxial tests as shown in Figure 5.

As shown in Figure 1 the HMA mix is subjected to high shear strains near the pavement surface. The higher the shear strength (S) of the HMA mix the more resistant it will be to permanent deformations caused by the developed shear strains. Therefore, any additive (i.e. liquid or lime) that generates higher shear strength of the HMA mix at the dry and moisture conditioned stages will improve the long-term performance of the HMA pavement.

RESISTANCE TO RUTTING

The resistance of HMA mixtures to permanent deformation can be measured either through an engineering test such as the repeated load triaxial test or an empirical test such as the Hamburg wheel tracking device. An engineering test measures engineering properties that can be incorporated into an engineering analysis. An empirical test measures a qualitative indicator that can only be used to compare multiple mixtures. The following presents a brief description of both tests.

The Repeated Load Triaxial Test

The resistance of HMA mixtures to permanent deformation can be evaluated under the repeated load triaxial (RLT) test. The RLT test consists of testing 4 inches x 6 inches cylindrical sample under triaxial state of stresses. Under a given confining pressure, a repeated haversine deviator stress is applied for 0.1 second followed by a 0.6 second rest period while keeping the confining pressure constant. Figure 6 shows the components of the RLT test and a typical response. The axial deformation of the sample is measured over the middle 4.0 inches of the sample by two linear variable differential transformers (LVDTs) placed 180 degrees apart. The LVDTs measure both the resilient and permanent deformations. The axial permanent strain is calculated as the ratio of the permanent deformation over the 4.0 inches gauge length. The RLT test is conducted under multiple temperatures to simulate field conditions of the projects. Using the RLT data, a relationship between the permanent strain and the resilient strain is developed as follows:

$$\varepsilon_p/\varepsilon_r = aN^bT^c \qquad (2)$$

Where: ε_p = Permanent strain within the HMA layer (in/in)

ε_r = Elastic strain within the HMA layer (in/in)

N = Number of load repetitions

T = Temperature of the HMA layer (°F)

a, b, and c = constants determined from the RLT test

Using the relationship in equation 2, the permanent strain within the HMA layer caused by the repetitions of an elastic strain can be estimated and used to estimate the rut depth generated by the HMA layer using the following relationship.

$$RD_{HMA} = \varepsilon_p \text{ x } H_{HMA} \qquad (3)$$

Where: RD_{HMA} = Rutting generated in the HMA layer (in)

H_{HMA} = Thickness of the HMA layer (in)

In order to use the relationship in equation 3 to determine the rut depth generated in the HMA layer, the constants a, b, and c in equation 2 must be determined through the RLT test. In the absence of actual RLT data, the design engineer can use the nationally calibrated relationship that is included in the AASHTO MEPDG.

$$\varepsilon_p/\varepsilon_r = (1.781\text{x}10^{-4})(N)^{0.4262}(T)^{2.028} \qquad (4)$$

The RLT measures the response of the HMA mixture under repeated loads. Each load repetition generates an elastic strain (ε_r) and a permanent strain (ε_p). Higher permanent strains lead to higher rutting in the HMA mix. Therefore, any additive (i.e. liquid or lime) that generates a lower permanent strain in the HMA mix at the dry and moisture conditioned stages will improve the long-term performance of the HMA pavement.

The Hamburg Wheel Tracking Device

The Hamburg wheel tracking device (HWTD) applies repetitive loads through a loaded steel wheel while the HMA mixture is submerged in water. Figure 7 shows the schematics of the Hamburg and a typical rut depth curve for an HMA mix. A sample is typically 10.2 in. wide, 12.6 in. long and 1.6 in. deep. The samples are submerged under water at a temperature between 25 – 70ºC. Typically, the test is conducted at a temperature of 50ºC. A steel wheel, 1.85 inches wide, loads the samples with 158 pounds. A pair of samples is tested simultaneously. The wheel makes 50 passes over each sample per minute. The velocity of the wheel is 1.1 ft/sec in the center of the sample. Each sample is loaded for 20,000 passes or until 20 mm of deformation occurs.

The results of the HWTD (Figure 7) include four components: creep slope, stripping inflection point, stripping slope, and total rut depth or the number of passes to a specific rut depth. The creep slope represents the slope of the permanent deformation in the linear region (number of passes to produce a 1 mm rut depth in the linear region). The stripping inflection point represents the number of passes after which the HMA mix starts exhibiting significant permanent deformation due to moisture damage. The stripping slope is the slope of the permanent deformation in the non-linear region caused by moisture damage (number of passes to produce a 1 mm rut depth in the non-linear region). The total rut depth is the maximum permanent deformation measured under the 20,000 passes. The number of passes to a specific rut depth can represent the number of passes to 10 or 20 mm rut depth. The ideal situation is to eliminate the occurrence of the non-linear region. Therefore, any additive (i.e. liquid or lime) that would allow the HMA mix to complete the 20,000 passes without the occurrence of the stripping inflection point would lead to improved long-term performance of the HMA pavement.

RESISTANCE TO FATIGUE

The resistance of HMA mixtures to fatigue cracking is evaluated using the flexural beam fatigue test, "AASHTO T321-03: Determining the Fatigue Life of Compacted Hot-Mix Asphalt Subjected to Repeated Flexural Bending". The 2.5 x 2.0 x 15 in. beam specimen is subjected to a 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the center portion of the specimen. Constant strain tests are conducted at different strain levels; using a repeated haversine load at a frequency of 10 Hz. Initial flexural stiffness is measured at the 50th load cycle. Fatigue life or failure is defined as the number of cycles corresponding to a 50% reduction in the initial stiffness. The following model is typically used to characterize the fatigue behavior of the HMA mixture:

$$N_f = k_1 \, [1/\varepsilon_t]^{k}2[1/E]^{k}3 \qquad (5)$$

Where: N_f is the fatigue life (number of load repetitions to fatigue damage), ε_t is the applied tensile strain, E is the modulus of the HMA layer, and k_1, k_2, k_3 are experimentally determined coefficients from the fatigue test. Figure 8 shows the schematics of flexural beam fatigue and typical fatigue curve for an HMA mix. The temperature of the fatigue test can be varied to simulate the representative field conditions of the project.

In order to use the relationship in equation 5 to determine the fatigue life of the HMA pavement, the constants k_1, k_2, and k_3 must be determined through the flexural beam fatigue test. In the absence of actual fatigue test data, the design engineer can use the nationally calibrated relationship that is included in the AASHTO Mechanistic-Empirical Pavement Design Guide.

$$N_f = 0.00432 * C * k_1 \, (1/\varepsilon_t)^{3.9492} (1/E)^{1.281} \qquad (6)$$

$$C = 10^{M}$$

$$M = 4.84[(V_b/(V_a+V_b))-0.69]$$

$k_1 = 1/[0.000398 + (0.003602/1+e^{(11.02-3.49h}ac^{)}]$

Where: ε_t = Tensile strain at the bottom of the HMA layer (in/in)

E = Modulus of the HMA mix (psi)

V_a = Effective binder content (%)

V_b = Air-voids (%)

h_{ac} = Thickness of the HMA layer (in)

The fatigue relationship for an HMA mix inversely relates the number of loads to failure with the tensile strain and the modulus of the HMA layer. This indicates that the lower the tensile strain the higher the number of load repetitions to failure. Figure 1 shows that a tensile strain at the bottom of the HMA layer is generated every-time a load passes over the pavement. According to the fatigue relationship, the lower the generated tensile strain the higher the number of load repetitions the pavement can withstand prior to fatigue cracking. The magnitude of the tensile strain is a function of the thicknesses of the various layers and the modulus of the HMA mix. For a given pavement structure, the higher the modulus of the HMA mix the lower the tensile strain at the bottom of the HMA layer. But at the same time, a higher modulus tends to lower the number of load repetitions to failure according to equations 5 and 6. Therefore, equation 6 is not recommended to be used for comparing the fatigue performance of two HMA mixtures. In cases where there is a need to compare two HMA mixtures such as untreated and treated mixtures, it is highly recommended that the fatigue relationship of each mix is developed and then the two mixtures are compared using their corresponding relationships.

Figure 9 shows fatigue relationships for two HMA mixtures. The fatigue relationship of mix A is better than the fatigue relationship of mix B. This can be observed by a looking at a constant strain level of 500 microns; mix A will survive 130,000 repetitions of this strain level while mix B will only survive 40,000 repetitions. Therefore, the most ideal additive (i.e. liquid or lime) is the one that improves the fatigue relationship of the mix at the dry and moisture conditioned stages.

RESISTANCE TO THERMAL CRACKING

HMA pavements contract as they are subjected to a reduction in their temperature. As the pavement contracts, it subjects the HMA layer to internal tensile stresses. Once the internal tensile stresses exceed the tensile strength of the HMA mix, a thermal crack will occur. In the field, thermal cracks are in the form of transverse cracks that run straight across the pavement.

Measuring the resistance of the HMA mixture to thermal cracking is usually done through the Thermal Stress Restrained Specimen Test (TSRST) (AASHTO TP10-93). The test cools down a 2 in. x 2 in. x 10 in. beam specimen at a rate of 10°C/hour while restraining it from contracting. While the beam is being cooled down, tensile stresses are generated due to the ends being restrained. The HMA mixture would fracture as the internally generated stress exceeds its tensile strength. The temperature at which fracture occurs is referred to as “fracture temperature” and represents the field temperature under which the pavement will experience thermal cracking. Figure 10 shows the schematics of the TSRST.

MOISTURE CONDITIONING

Moisture conditioning is an important step in the evaluation of moisture damage of HMA mixtures. Most research activities that evaluate the moisture damage of HMA mixtures rely on comparing the various properties of the mix before and after moisture conditioning. The properties prior to moisture conditioning are typically referred to as "dry" or "unconditioned" while the properties after moisture conditioning are typically referred to as "wet" or "conditioned".

The most commonly used moisture conditioning process is the one recommended by AASHTO T-283-03 test method entitled: "Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage." The moisture conditioning process consists of compacting HMA samples at air-voids between 6.5 and 7.5%, saturating half of the samples to a level between 70 and 80%, then subjecting the saturated samples to a freeze-thaw cycle consisting of freezing at 0oF for 16 hours followed by 24 hours thawing at 140oF and 2 hours at 77oF. It should be noted that versions of the AASHTO T-283 test prior to 2003 included the freeze cycle (i.e. freezing at 0oF for 16 hours) as an optional step. As a result, some research studies report the use of AASHTO T-283 but the actual evaluation may not include the freeze-thaw cycle. Therefore, it is very important to identify the exact procedure that was followed during the conduct of the research.

In some cases a destructive test (e.g. a test that destroys the sample) is used to evaluate the properties of the HMA mixtures such as the tensile strength test while in other cases a nondestructive test (e.g. a test that does not destroy the sample) such as the Mr is used. If a destructive test is used, the unconditioned and conditioned properties will have to be measured on two different sets of samples having very close air-voids. If a nondestructive test is used, the unconditioned and conditioned properties are measured on the same set of samples.

II. IMPACT OF ADDITIVES ON THE MOISTURE DAMAGE OF HMA MIXTURES

This part of the report summarizes several studies that evaluated the impact of lime and liquid antistrip additives on the moisture damage of HMA mixtures. The documented studies have used various combinations of the tests that were described in the previous section. Some of the studies evaluated laboratory mixtures while others evaluated field mixtures or a combination of the two types. Each study is identified by its title and the principal investigators while complete references are listed at the end of the report.

The goal of this documentation is to identify the objectives of each study, describe the experimental program used, and to present the findings and recommendations that resulted from each study and how they can be implemented into pavement engineering. A total of ten research studies are summarized in this report. The studies are grouped into two categories: studies that used the Hamburg wheel tracking device, and studies that used other mechanical tests.

A. STUDIES THAT USED THE HAMBURG WHEEL TRACKING DEVICE

This section documents three research studies that used the Hamburg wheel tracking device to evaluate the impact of lime and liquid additives on the moisture damage of HMA mixtures. It should be recognized that the HWTD is an empirical test that does not generate any engineering properties. The four components of the HWTD are: the creep slope, the stripping inflection point, the stripping slope, and total rut depth or number of passes to a specific rut depth. As previously discussed, the ideal situation is to eliminate the occurrence of the stripping region where the mix will not reach the stripping inflection point during the HWTD test.

All four components of the HWTD test are empirical measures and they can only be used to compare the performance of one HMA mix relative to another mix. For example, if an additive eliminates the occurrence of the stripping region, it will compare favorably against another additive that experiences a stripping inflection point during the HWTD test. Some agencies have established a failure criterion for the HWTD test, such as a maximum total rut depth of 10 mm under 20,000 passes. Again, such a criterion can be used to assess the effectiveness of the additives.

Influence of Compaction Temperature and Antistripping Treatment

T. Aschenbrener and N. Far, Colorado DOT

This study was conducted by the Colorado DOT in 1994 to evaluate the performance of several HMA mixtures in the Hamburg wheel tracking device [Aschenbrener and Far (1994)]. A total of four types of HMA mixtures were evaluated. The same AC-20 asphalt binder was used with the four different aggregate sources. Each mix type had a control, a lime-treated, and four liquid-treated mixtures as shown in Table 1. The hydrated lime was used at 1% by dry weight of aggregate and the liquid additives were added at 0.5% by weight of binder.

All mix designs were conducted using the Texas Gyratory compactor. Optimum binder contents were selected at air-voids of 4% and minimum voids in mineral aggregates (VMA) of 13.0%. The optimum binder contents were established for the lime-treated mixtures from each mix type and were used for all other mixtures. Using the optimum binder content established for the lime-treated mixtures for the other mixtures may be considered a limitation of this study. Table 2 summarizes the optimum binder contents used this Colorado DOT study.

All HWTD samples were compacted using the kneading compactor to air-voids of 6.5 +/-1.5% and were tested at 45°C (113°F). The Colorado DOT uses an HWTD criterion of 10 mm maximum rut depth under 20,000 repetitions. Table 3 summarizes the HWTD data for all the mixtures evaluated in this study.

Findings: In general both the lime and liquid additives improved the behavior of the HMA mixtures in the HWTD as compared to the control mixtures. The HWTD data summarized in Table 3 indicate that the hydrated lime was highly effective in reducing the rut depth in the HWTD for all mixtures while the liquid additives worked well with some mixtures, but it did not significantly improve the performance of others.

Applications: The practical applications that can be derived from this Colorado study would be that using hydrated lime with any of Colorado's HMA mixtures would significantly improve their performance in the HWTD test. On the other hand, using liquid additives may or may not lead to a favorable performance in the HWTD test, depending on the specific conditions of the HMA mix and properties of the liquid additive. Recognizing how variable aggregate sources can be during actual production, the use of lime would offer a consistent and reliable technology to combat moisture damage of Colorado's HMA mixtures.

Moisture Susceptibility of Hot-Mix Asphalt

R. Izzo and M. Tahmoressi, Texas DOT

In 1999, the Texas DOT used the HWTD to evaluate the moisture damage of HMA mixtures treated with hydrated lime and liquid additives [Izzo and Tahmoressi (1999)]. A total of six types of HMA mixtures were evaluated. The same AC-20 asphalt binder was used with the six different aggregate sources. Each mix type had a control, lime-treated, and liquid-treated mixtures. The optimum binder contents of the various mixtures were established on the un-treated mixtures following the TxDOT mix design method for HMA mixtures and are summarized in Table 4.

All of the HWTD samples were compacted in the Superpave gyratory compactor (SGC) into 6.0 inches diameter cylinders at air-voids of 7+/-1%. Two 6.0 inches cylinders are then fitted side-by-side and loaded with the HWTD wheel. The HWTD tests were conducted at 40°C and 50°C temperatures. Based on the measured HWTD data from the various mixtures, the researchers concluded that the 50°C data are not highly reliable due to its proximity to the softening point of the AC-20 binder. Therefore, the 40°C test data were used in the final analysis.

Table 5 summarizes the HWTD data for the various mixtures in terms of the number of passes to 20 mm: rut depth (Nf), creep slope, stripping slope, and stripping inflection point (SIP). The creep and stripping slopes are defined as the number of passes to generate 1 mm rut depth in the creep and stripping regions, respectively. Therefore, the higher the slopes the more resistant the HMA mix will be to moisture damage. The SIP is defined as the number passes at which the stripping region begins. Again the higher the SIP the more resistant the HMA mix will be to moisture damage.

Findings: Ideally in HWTD testing the stripping region is eliminated. The data in Table 5 show that all six TxDOT HMA mixtures that were treated with lime did not go into the stripping region, while the control and liquid-treated mixtures went into the stripping region, except for the gravel mix. In addition, the lime-treated mixtures exhibit significantly higher creep slopes than both the control and liquid-treated mixtures indicating that the lime will significantly reduce the early rutting of the mixtures. In the case of Nf, the majority of the mixtures resulted in Nf higher than 20,000 passes indicating that the 20 mm rut depth criterion adopted by the researchers for the selection of Nf is highly un-conservative.

The impact of liquid additives on the performance of the HMA mixtures in the HWTD was mixed. In the cases of the gravel and gravel with limestone screenings mixtures, the liquid additive resulted in a weaker mixture as indicated by the lower creep slope of the liquid-treated mixtures as compared to the control. In the other mixtures, the improvements achieved by the liquid additive were marginal.

Applications: The results of the TxDOT HWTD study resulted in a clear conclusion that lime treatment of Texas HMA mixtures will prevent their moisture damage. Lime-treated Texas HMA mixtures are expected to exhibit minor rutting and never experience severe moisture damage that leads to stripping problems. On the other hand, the same Texas HMA mixtures treated with liquid additives have a high tendency to experience severe rutting and severe moisture damage leading to stripping failures.

Superpave Mixtures Containing Hydrated Lime

L. Mohammad, Louisiana DOT

This study was conducted by researchers at the Louisiana Transportation Research Center (LTRC) in 2006 [Mohammad (2006)]. The overall study had several objectives; however, the objective that is applicable to this report assessed the performance of HMA mixtures with PG70-22 binder treated with hydrated lime against the performance of HMA mixtures with a PG76-22 binder. Two types of lime treatments were applied to the mixtures with the PG70-22 binder: a) the hydrated lime was applied to wet aggregates and b) the hydrated lime was injected into the drum. Both lime-treated mixtures included 1.5% lime by dry weight of aggregate.

All HMA mixtures were made from siliceous limestone aggregates with 19.0 mm nominal maximum size. The following mixtures were designed using the Superpave Volumetric Mix Design method:

- M76CO: HMA mixture with a PG76-22 binder without lime

- M70LS: HMA mixture with a PG70-22 binder with lime added to wet aggregates

- M70LM: HMA mixture with a PG70-22 binder with lime injected into the drum

Table 6 summarizes the mix design data for the three HMA mixtures. Table 7 summarizes the performances of the three HMA mixtures in the HWTD. All lab samples were compacted to air-voids of 7+/-0.5%.

Findings: The evaluation of the three Louisiana HMA mixtures in the HWTD indicated that lime treatment of an HMA mixture made with a PG70-22 binder would result in the same performance as an HMA mixture made with a PG76-22 binder. This finding holds true whether the hydrated lime is added to wet aggregate or it is injected into the drum.

Applications: The findings of this study should not be over implemented. Even though the study showed that a PG70-22 binder treated with hydrated lime would produce similar performance to a PG76-22 binder, it is not recommended that a PG70-22 binder be specified in places where a PG76-22 binder is required. The HWTD test evaluates one aspect of the overall performance of the HMA mixture, and relying on this evaluation alone may jeopardize the overall long-term performance of the HMA mix. The improved performance achieved by the lime treatment should be used as an additional assurance for successful long-term field performance.

B. STUDIES THAT MEASURED ENGINEERING PROPERTIES OF HMA MIXTURES

This section of the report presents seven research studies that measured engineering properties of HMA mixtures to assess the effectiveness of lime and liquid additives in reducing moisture damage of HMA mixtures. The main advantage of measuring engineering properties is that they can be directly used to evaluate the mechanical behavior of HMA pavements. For example, the measured modulus of the untreated and treated HMA mixtures can be used in a mechanistic analysis to compare the strain responses of the HMA pavement (as shown in Figure 1). Based on the calculated strain responses, the long-term performance of the untreated and treated HMA pavements can be estimated and compared.

Effectiveness of Antistripping Additives to Protect Against Moisture Damage

T. Kennedy and W. Ping, University of Texas

This research project executed an extensive program that evaluated the impact of lime and liquid additives on the moisture damage of HMA mixtures from eight Texas districts [Kennedy and Ping (1991)]. Lime treatments of the laboratory prepared HMA mixtures were applied in the form of lime slurry. The types of liquid additives varied among the various districts to simulate the actual field practice. Table 8 summarizes the dosages of the lime and liquid additives along with the optimum binder contents of the various mixtures. Two types of evaluations were conducted: tensile strength ratio after a single freeze-thaw cycle and tensile strength ratios after multiple freeze-thaw cycles.

The tensile strength ratio (TSR) is defined as the ratio of the average tensile strength for the conditioned samples over the average tensile strength of the unconditioned samples times 100. The moisture conditioning process for the single freeze-thaw cycle followed the AASHTO T-283 procedure described earlier. The research program evaluated the TSR properties for laboratory-prepared and field-produced mixtures from all eight districts. The evaluation of the TSR data of the field produced mixtures showed very inconsistent trends and erratic behavior. It seems that some serious difficulties were encountered in producing consistent field mixtures from the various treatment alternatives.

Based on these observations and in the absence of any documented rational for such data irregularities from the researchers, it was decided to only include the TSR properties after a single freeze-thaw cycle on the laboratory produced mixtures as summarized in Table 9. It should be noted that the higher the TSR the lower the moisture damage of the mixture will be. A TSR value above 100 indicates that the moisture conditioned tensile strength of the mix is higher than its corresponding unconditioned strength. Such a phenomenon usually occurs with some lime-treated HMA mixtures.

In the second part of the research, the TSR properties of the laboratory mixtures were measured at multiple freeze-thaw cycles of: 1, 3, 5, 7, and 9. The samples were compacted to 7+/-1% air-voids and saturated to 60-80%. The freeze-thaw cycling was achieved by submerging the saturated samples in water and placing them in a freeze-thaw chamber with the following cycle: 14.5 hours at 0ºF, 23.5 hours at 140ºF, and 8.5 hours at 80ºF. The samples were tested for their tensile strength at the various freeze-thaw cycles. Figure 11 summarizes the TSR properties as a function multiple freeze-thaw cycles for the various mixtures.

Findings: The TSR properties of the laboratory mixtures indicate that lime treatment is consistently highly effective in reducing moisture damage of the Texas HMA mixtures from all eight districts. The TSR values of the lime-treated mixtures are significantly higher than the TSR values for all liquid additives from all eight districts. Some liquid additives provided only marginal improvement of the TSR as compared to the control mix. The great majority of the liquid-treated mixtures will not pass the commonly-used TSR criterion of 70-80%.

The multiple freeze-thaw data show that the lime-treated mixtures started with a higher TSR after cycle 1 and maintained higher TSR properties over the entire nine cycles except for District 1 where the lime-treated mixtures did as well as other liquid additives. It should be noted that the mixtures from Districts 1 and 19 exhibit TSR values above the 70% for the control mix.

Applications: The combination of the HMA mixtures from eight districts and the wide range of liquid additives that were evaluated in this research provide a significant platform for effective recommendations concerning the issue of moisture damage of Texas HMA mixtures. The TSR properties at multiple freeze-thaw cycles indicate that lime treatment of the HMA mixtures would result in superior mixtures that are capable of resisting moisture damage. The results of the multiple freeze-thaw experiment clearly show that lime treatment improves the long-term tensile strength of the HMA mixtures. HMA mixtures with higher retained tensile strength property (i.e. higher TSR) would provide higher resistance to fatigue, block cracking, and thermal cracking which will ultimately lead to improved long-term performance of HMA pavements.

New Generation of Antistripping Additives

K. Pickering, P.E. Sebaaly, M. Stroup Gardner, and J. Epps, University of Nevada

This research study was conducted in 1992 by researchers at the University of Nevada, Reno [Pickering et al (1992)]. The objective of the research was to compare the effectiveness of lime and two liquid additives in reducing the moisture damage of two HMA mixtures: one from Nevada and one from California. The research program measured the resilient modulus and tensile strength properties of the HMA mixtures before and after moisture conditioning. The moisture conditioning process followed the procedure described in AASHTO T-283 with a single freeze-thaw cycle.

A single source of hydrated lime at 1 and 2 percents by dry weight of aggregate was used in the form of dry lime added to wet aggregates. Two liquid additives were blended directly into the binder at 0.5, 1, and 2 percents by weight of binder were used. Liquid I was manufactured by Exxon Chemical and Liquid II was manufactured by Unichem International. An AR-4000 asphalt binder was used to prepare all mixtures. Aggregates were obtained from two sources located in northern Nevada and northern California. The northern Nevada aggregate is a river deposit gravel and the northern California aggregate came from a limestone quarry. The Hveem mix design method was used to identify the optimum binder contents for all the HMA mixtures.

Resilient Modulus Properties

The resilient modulus (Mr) properties were used to evaluate the moisture damage of the HMA mixtures for two reasons: 1) the Mr test is a nondestructive test that can be conducted on the same samples before and after moisture conditioning and 2) the Mr is an engineering property that can be used to estimate the response of HMA pavements under traffic loads.

Figures 12 and 13 summarize the Mr properties of the unconditioned and moisture-conditioned HMA mixtures from the two aggregates sources. The data show that the Mr after moisture conditioning is significantly improved with the addition of lime in any amount for both aggregate sources. In addition, for both sources, the ratios of conditioned to unconditioned Mr values are at least 70% for all percentages of lime.

In the case of the liquid I additive, the Mr data show that the 1% concentration level has significantly increased the unconditioned modulus of the mixtures with both types of aggregates. However, after moisture conditioning there is retention of only 30 and 20% for the Nevada and California mixtures, respectively. Although the liquid I additive improved the moisture conditioned Mr at the 2% concentration for the California aggregate, its actual values is still significantly lower than the lime-treated mixture.

In the case of the liquid II additive, the Mr data show that the 0.5% concentration resulted with the highest unconditioned Mr property while the highest conditioned Mr property occurred at the 2% concentration for both mixtures. The unconditioned and conditioned Mr properties of HMA mixtures treated with the liquid II additive are significantly lower than the Mr properties of the lime-treated mixtures.

Tensile Strength Properties

The tensile strength (TS) property of an HMA mix gives an indication on the overall strength of the mix and its resistance to cracking. In addition, the tensile strength ratio is a commonly used indicator on the moisture damage potential of HMA mixtures.

Figures 14 and 15 show the unconditioned and moisture conditioned TS properties of the two HMA mixtures. The data show that the unconditioned and conditioned TS are significantly improved with the addition of lime in any amount for both aggregates. All of the TSR values of the lime-treated mixtures are well above 80%.

In general, the unconditioned and conditioned TS properties of the HMA mixtures treated with both liquid I and II additives are significantly lower than the TS properties of the lime-treated mixtures. Liquid I at first showed some promising unconditioned TS at the 2% concentration, but after conditioning relatively poor retained TS are achieved. The same observation holds true for liquid II where at 0.5 and 1% concentrations the unconditioned TS properties are improved but the corresponding conditioned TS properties are significantly lower than the lime-treated mixtures.

Findings: The resilient modulus and tensile strength data indicate that the lime treatment of the two aggregate sources resulted in significant improvements of the unconditioned and moisture conditioned properties. In the case of the liquid I and II additives, the improvements in the Mr and TS properties were insignificant and inconsistent. In most cases the liquid additives would show an improvement in the unconditioned property but they would not maintain the improvement after moisture conditioning and vise versa. This leads to the conclusion that it would be impossible to optimize both the unconditioned and conditioned properties of HMA mixtures treated with both liquid I and II. It should be noted that an effective additive must improve both the unconditioned and moisture conditioned properties in order to insure good long-term performance.

Applications: The tensile strength data generated from this study show that lime-treated HMA mixtures would exhibit significantly higher unconditioned and moisture conditioned TS properties than HMA mixtures treated with the two liquid additives. This indicates that HMA pavements constructed with lime-treated HMA mixtures would have better long-term resistance to fatigue and thermal cracking than HMA pavements constructed with HMA mixtures treated with the two liquid additives.

The resilient modulus data generated from this study show that the lime-treated HMA mixtures would exhibit significantly higher unconditioned and moisture conditioned Mr properties than HMA mixtures treated with the two liquid additives. This indicates that HMA pavements constructed with lime-treated HMA mixtures would have better overall long-term performance than HMA pavements constructed with HMA mixtures treated with the two liquid additives.

In addition to the general comparisons of the mixtures properties, the Mr properties can be used to conduct comparative mechanistic analyses of HMA pavements constructed with untreated, lime-treated, and liquid-treated mixtures. Figure 16 shows the HMA pavement structure that was used to conduct the comparative mechanistic analyses. The base and subgrade layers were assigned fixed properties while the properties of the HMA layer will be varied to represent lime-treated and liquid-treated HMA mixtures at the unconditioned and conditioned stages. The Mr properties of the un-damaged and moisture-damaged pavements were obtained from Figures 12 and 13.

The mechanistic analysis consists of comparing the relative rutting performance of the various mixtures using the relationship presented in equation 4. Every-time the Mr of the HMA layer is changed to represent an un-damaged or a moisture-damaged pavement, a new pavement structure is created and analyzed. For each of the pavements, the multi-layer elastic solution is used to calculate the elastic compressive strain (εr) at the middle of the HMA layer under an 18,000 single axle load. A 0.5" rut depth limit and the thickness of the HMA layer of 6.0" are used in equation 3 to calculate the required permanent strain ($\varepsilon p = 0.0833$). The calculated εr (summarized in Table 10) for each pavement and the calculated εp are then used in equation 4 to determine the number of load repetitions to 0.5" rut depth. It should be noted that since the ratios of the number of load repetitions are used in the analysis, the temperature term in equation 4 drops-out.

Table 10 summarizes the calculated elastic compressive strains for the various pavements and the corresponding ratios of the number of load repetitions to 0.5" rut depth from the HMA layer. The ratio of 1.0 for the untreated HMA pavement at the un-damaged stage indicates that the ratios of all other pavements are estimated relative to this pavement condition. A review of the data in Table 10 leads to the following conclusions:

- The untreated HMA mixtures retained only 10% of their rutting resistance when subjected to moisture damage for both the Nevada and California mixtures.

- The lime-treated HMA mixtures improved the rutting resistance of the un-damaged HMA pavements for both the Nevada and California mixtures. In the case of moisture-damaged pavements, the lime-treated HMA mixtures maintained 60% of the rutting resistance of the Nevada mixture while it improved the rutting resistance of the California mixture by 80%.

- The liquid I-treated HMA mixtures improved the rutting resistance of the un-damaged HMA pavements for both the Nevada and California mixtures. In the case of moisture-damaged pavements, the liquid I-treated HMA mixtures only maintained 10 and 30% of the rutting resistance of the Nevada and California mixtures, respectively.

- The liquid II-treated HMA mixtures reduced the rutting resistance of the un-damaged HMA pavements for the Nevada mixture by 10% while it improved the rutting resistance of the un-damaged pavements for the California mixture by 20%. In the case of moisture-damaged pavements, the liquid II-treated HMA mixtures only maintained 30% of the rutting resistance of the Nevada and California mixtures.

The conclusions from the mechanistic analysis confirm that the lime treatment of the Nevada and California mixtures that were evaluated in this study leads to superior performing HMA pavements at both the un-damaged and moisture-damaged conditions.

Methods of Adding Lime to Hot Mix

M. Tahmoressi and M. Mikhail, Texas DOT

This study was conducted in two parts: Part I evaluated the different methods of adding lime to HMA mixtures and Part II compared different antistripping additives [Tahmoressi and Mikhail (1999)]. This report summarizes Part II of the study.

Two TxDOT HMA mixtures were treated with lime and three different liquid additives referred to as: A, B, and C. Mix 1 was a type C crushed gravel that contains substantial amounts of limestone screenings (38%). Mix 2 was a type C mix which used the same aggregate as Mix 1 but with minor amount of limestone screenings (5%). The same asphalt binder graded as PG64-22 was used for both mixtures at optimum binder contents of 4.6 and 5.3% for Mix 1 and Mix 2, respectively. The lime was added to wet aggregates at the content of 1% by dry weight of aggregate. The liquid additives were blended into the binder according to the recommendations of the manufacturers. The moisture conditioning was similar to the AASHTO T-283 process with one freeze-thaw cycle. The tensile strength property was used to assess the moisture damage of the HMA mixtures. Table 11 summarizes the moisture conditioned tensile strength and the tensile strength ratio of the various mixtures.

Findings: The data in Table 11 indicate that the use of both lime and liquid additives significantly improved the moisture-conditioned tensile strength property and the tensile strength ratio of the two Texas HMA mixtures that were evaluated in this research. However, the lime treatment of Mix 1 provided significantly higher moisture-conditioned tensile strength than the liquid additives.

Applications: The reporting of the moisture-conditioned tensile strength along with the tensile strength ratio is a very effective way to prove the impact of the additives instead of the customary process of only reporting the ratio. The moisture-conditioned tensile strength represents the property that is retained in the mix after the moisture damage has occurred. The results of this research study showed that lime treatment of Texas aggregates is a very reliable method for significantly improving their resistance to moisture damage. Since the tensile strength is directly related to the resistance of HMA mixtures to fatigue and thermal cracking, the lime-treated HMA mixtures are expected to lead to better long-term performance of HMA pavements.

Moisture Susceptibility of Asphalt Mixtures

P. Khosla, B. Birdsall, and S. Kawaguchi, North Carolina State University

This study evaluated the impact of additives on the shear strength of three North Carolina HMA mixtures [Khosla et al (2000)]. The three mixtures included three different 100% crushed-stone aggregates found in North Carolina: marine limestone with good resistance to moisture damage, a slate aggregate with moderate resistance to moisture damage, and a granite gneiss with poor resistance to moisture damage. All three mixtures were designed with the Superpave Volumetric Mix Design method as a 9.5-mm nominal maximum size mix. The same asphalt binder of PG64-22 was used for all three mixtures.

The three additives included: hydrated lime, liquid amine, and liquid phosphate ester. Moisture conditioning of the mixtures was achieved following the AASHTO T-283 test method at 65% saturation but without the freeze-thaw cycle. All samples were compacted to 7+/-0.5% air-voids. A triaxial test was used to evaluate the shear strength (as defined in equation 1 and Figure 5) of the unconditioned and moisture-conditioned samples. The cohesion value, C, is affected by the aggregate-asphalt bonding of the mixture, and the friction angle, ϕ, is related to the internal friction of the mix. It is believed that moisture damage of the HMA mix should impact the C value, while the ϕ remains unchanged. Table 12 summarizes the shear strength properties of the three HMA mixtures at the unconditioned and moisture-conditioned stages.

Findings: The shear strength data measured on the three HMA mixtures confirmed the belief that the C value is impacted by moisture damage of the mix while the ϕ is not impacted by moisture damage. This is shown by the ratios of the C ranging from the 38 to 97% while the ratios of the ϕ's are all above 90%. The C values coincided well with the historical performance of the mixtures. The marine limestone mix was defined as having the best resistance to moisture damage (showed the highest C value of the un-treated mix), followed by the slate and granite gneiss mixes.

The lime treatment of the three North Carolina aggregates showed a consistent increase in the un-conditioned and moisture-conditioned C values for all three mixtures. The effectiveness of the liquid additives depended on the type of mixture. In the case of the slate, the amine additive was effective while in the case of the granite gneiss, the phosphate ester was effective. This leads to the conclusion that hydrated lime is very consistent in improving the shear resistance of the North Carolina HMA mixtures. On the other hand, a unique liquid additive must be defined for each mix in order to achieve improvements in the resistance to moisture damage.

Applications: The significance of the improvements in the shear strength of the HMA mix can be realized by looking at the responses of HMA pavements under traffic loads depicted in Figure 1. The shear strains (γ) generated near the tire-pavement interface must be resisted by the shear strength of the HMA mix, otherwise a shear failure of the HMA mix will occur and severe rutting in the HMA layer will develop. The relationship shown in equation 1 indicates that the shear strength of an HMA under a constant vertical stress is controlled by the C and ϕ values of the mix. The higher the C and ϕ values the higher the developed shear strength of the HMA mix and the less likelihood for a shear failure. Therefore, as this study showed, lime treatment of the North Carolina aggregates resulted in consistent improvements of the C values at the un-conditioned and moisture-conditioned stages leading to less potential for shear failures of the HMA mixtures under traffic loads. It should be noted that the major source of rutting in the Westrack experiment was the shear failure of the HMA mix within the top 3 inches of the HMA layer.

Antistrip Additives for Bituminous Mixtures

P.E. Sebaaly, P. Tohme, Edgard Hitti, Kaci Stansbury, and J. Epps, University of Nevada

This research study was conducted by the researchers at the University of Nevada, Reno for the South Dakota Department of Transportation [Sebaaly et al (2003)]. The overall objective of this research project was to evaluate the effectiveness of antistripping additives in reducing the moisture damage of HMA mixtures using laboratory tests and field performance. The research evaluated the effectiveness of lime and other antistripping additives in reducing the moisture damage of HMA mixtures in South Dakota.

Two projects were constructed to evaluate the field performance of various antistrip additives. The first project was constructed August 28-31, 2000, on SD-314 in Yankton, SD (south-eastern) and the second project was constructed on October 2-10, 2000, on US-14 in Wall, SD (south-western). Each project included the following six test sections:

- Section 1: Control no additive
- Section 2: Lime on wet aggregates (4% above saturated-surface-dry (SSD))
- Section 3: Lime on wet aggregates (4% above SSD)
- Section 4: Lime on aggregate at in situ moisture content
- Section 5: Ultrapave (UP5000) additive on aggregate at in situ moisture
- Section 6: Liquid antistrip additive blended into the binder

The aggregates used on the SD-314 project were a blend of quartzite and gravel. The same gradation was used for all six sections. The asphalt binder was a PG64-22 un-modified. The mix designs for all six sections were developed by a consultant following the Marshall mix design method (AASHTO T-245) at 50 blows and called for an optimum binder content of 6.0 % by weight of total mix with air voids of 4.4% and VMA of 15.3 %. For sections 2, 3, and 4, the lime was added at a rate of 0.75% by dry weight of aggregate. For section 5 the UP 5000 was added at a rate of 454 g/ton of aggregate. For section 6, the liquid antistrip was blended into the binder at the terminal.

The aggregates used on the US-14 project were a blend of limestone and gravel. The same gradation was used for all six sections. The asphalt binder was a polymer-modified PG64-28. The mix designs for all six sections were developed by the same consultant as for the SD-314 sections following the Marshall mix design method (AASHTO T-245) at 50 blows and called for an optimum binder content of 5.9% by weight of total mix with air voids of 4.4% and VMA of 15.0 %. The lime, UP5000 and liquid antistrip were added with the same process used on the SD-314 sections.

The binder contents of the field mixtures were measured using the laboratory extraction technique as specified in AASHTO T-164. Table 13 summarizes the measured binder contents of the various field mixtures on SD-314 and US-14. The data indicate that the in-place binder contents are within normal construction variability (+/-0.5%) which are not expected to greatly influence the long-term performance of the various mixtures.

Loose mixtures were sampled from the top lift near the middle of each section and compacted in the laboratory to create field mixed-laboratory compacted (FMLC) samples. The FMLC samples were compacted using the Marshall hammer to air-voids between 6 and 8%. The tensile strength of the FMLC samples were evaluated under one freeze-thaw cycle and the resilient modulus of the FMLC samples were evaluated under multiple freeze-thaw cycles. Figures 17 through 20 show the tensile strength and resilient modulus properties of the mixtures from the various sections of the South Dakota projects.

Findings: The resilient modulus and tensile strength properties of the field mixed-laboratory compacted samples measured at both the unconditioned and conditioned stages indicated that the mixtures treated with hydrated lime on both projects (SD-314 and US-14) have better moisture resistance than the control, UP5000 and liquid antistrip mixtures. The superior performance of the mixtures treated with hydrated lime was shown by higher retained strength after the moisture conditioning process. In general, the control, UP5000 and the liquid antistrip mixtures generated unconditioned strength properties which are similar to the mixtures treated with hydrated lime. However, when these mixtures were moisture conditioned, their strength fell significantly below the conditioned properties of the mixtures treated with hydrated lime. The multiple freeze-thaw experiment showed that the mixtures treated with hydrated lime performed significantly better than the control, UP5000 and the liquid antistrip mixtures at both locations. It was recommended that any new antistripping product should be evaluated using the multiple freeze-thaw process prior to acceptance for field applications.

Applications: The resilient modulus properties after multiple freeze-thaw cycles are shown in Figures 19 and 20. The control, UP5000 and the liquid antistrip sections loose almost 100% of their initial un-conditioned modulus within 6 and 9 freeze-thaw cycles for the US-14 and SD-314 projects, respectively. If it is assumed that HMA pavements in South Dakota are subjected to multiple freeze-thaw conditions in 4 month out of the year, and the sixth freeze-thaw cycle represents the damaged modulus, then the weighted resilient modulus of the year for each section can be evaluated as follows:

$$Mr_{(weighted)} = 0.70(Mr_{un\text{-}conditioned}) + 0.30(Mr_{conditioned\ after\ sixth\ cycle}) \quad (7)$$

For sections on SD-314, the following weighted Mr properties are obtained:

Section	$Mr_{(weighted)}$ at 77°F, psi
Control	375,000
Lime on Wet Agg-1	495,000
Lime on Wet Agg-2	485,000

Lime on SSD Agg	535,000
UP5000	420,000
Liquid Antistrip	455,000

For sections on US-14, the following weighted Mr properties are obtained:

Section	$Mr_{(weighted)}$ at 77°F, psi
Control	265,000
Lime on Wet Agg-1	345,000
Lime on Wet Agg-2	350,000
Lime on SSD Agg	330,000
UP5000	310,000
Liquid Antistrip	320,000

Using the weighted modulus properties, a mechanistic analysis similar to the one conducted for the Pickering, et al study, can be conducted. The weighted Mr properties are used to conduct comparative mechanistic analyses of HMA pavements constructed with untreated, lime-treated, UP5000-treated, and liquid-treated mixtures. The pavement shown in Figure 16 will be used, with the exception that the modulus properties of the HMA layer will come from the weighted moduli values shown above. Since all three lime-treated sections resulted in close values of the weighted Mr property, only one lime-treated section will be analyzed from each project using the average property of the three sections. The base and subgrade layers were assigned fixed properties while the properties of the HMA layer were varied to represent lime-treated, UP5000, and liquid-treated HMA mixtures.

The mechanistic analysis consists of comparing the relative rutting performance of the various mixtures using the relationship presented in equation 4. For each of the pavements, the multi-layer elastic solution is used to calculate the elastic compressive strain (ε_r) at the middle of the HMA layer under an 18,000 single axle load. A 0.5" rut depth limit and the thickness of the HMA layer of 6.0" are used in equation 3 to calculate the required permanent strain (ε_p= 0.0833). The calculated ε_r (summarized in Table 14) for each pavement and the calculated ε_p are then used in equation 4 to determine the number of load repetitions to 0.5" rut depth. It should be noted that since the ratios of the number of load repetitions are used in the analysis, the temperature term in equation 4 drops-out.

Table 14 summarizes the calculated elastic compressive strains for the various pavements and the corresponding ratios of the number of load repetitions to 0.5" rut depth form the HMA layer. The ratio of 1.0 for the untreated HMA pavement indicates that the ratios of all other pavements are estimated relative to this pavement. A review of the data in Table 14 indicates that the lime treatment of South Dakota HMA mixtures results in 100% increase in their rutting resistance, while the UP5000 results in 30% increase and the liquid antistrip results in 60% increase.

The significant increase in the rutting resistance coupled with the increase in the conditioned tensile strength property of the lime-treated HMA mixtures will lead to HMA pavements that are highly resistant to rutting, fatigue, and thermal cracking. With the improved performance properties of the lime-treated HMA mixtures, the expected long-term performance of the lime-treated pavements in South Dakota will be superior to the UP5000 and Liquid-treated HMA pavements.

Long-Term Effectiveness of Antistripping Additives

Q. Lu and J. Harvey, University of California

This research study evaluated the resistance to moisture damage of an HMA mix manufactured with a California aggregate that is known to have poor compatibility with asphalt binder [Lu and Harvey (2006)]. The aggregate source was granite and the binder was an AR-4000 that also graded as a PG64-16. The evaluated mixtures included the following: control, lime-treated, liquid A-, and liquid B-treated mixtures. The hydrated lime was added to the damped aggregate at the rate of 1.4% by dry weight of aggregate. The liquids were added into the binder at the rate of 0.75% by weight of binder. The Hveem mix design method was used which recommended an optimum binder content of 5.0% by dry weight of aggregate for all mixtures.

The research study conducted two experiments: one experiment evaluated the tensile strength properties of the mixtures and another experiment evaluated the fatigue resistance of the mixtures. Both experiments compared the properties of the various mixtures at the un-conditioned and moisture-conditioned stages.

The tensile strength experiment evaluated the control, lime-treated and liquid A-treated mixtures. The mixtures were evaluated at three stages:

I. un-conditioned,

II. conditioned in 100% humidity, and

III. conditioned in 100% humidity followed by one freeze-thaw cycle.

The samples that were subjected to moisture conditionings (II and III) were tested after 0, 4, 8, and 12 months. The samples that were subjected to moisture conditioning (III) were tested after being subjected to 0, 4, 8, and 12 months in the 100% humidity room and followed by the freeze-thaw cycle for each of the four time periods. All the samples that were subjected to moisture conditionings (II and III) were partially saturated to 70-80% prior to the moisture conditioning process. It should be noted that a conditioning period of “0” means that the samples were tested immediately after saturation while the “dry” condition means that the samples were tested without any saturation. Figures 21 and 22 show the tensile strength properties and the tensile strength ratios of the various mixtures. The tensile strength ratio represents the ratio of the tensile strength after the various conditioning periods over the tensile strength at the dry condition. The 25C notation on the figures indicates that the samples were tested following moisture conditioning (II) and the CTM notation indicates that the samples were tested following moisture conditioning (III).

The fatigue resistances of the HMA mixtures were evaluated using the flexural beam fatigue test (AASHTO T321-03) at a single strain level of 400 microns. This part of the research evaluated four HMA mixtures: control, lime-treated, liquid A-treated, and liquid B-treated mixtures subjected to one moisture conditioning process. The moisture conditioning process used in this part of the research consisted of the 100% humidity without the freeze-thaw cycle (i.e. conditioning stage II).

The impact of moisture damage on the fatigue resistances of the various mixtures was evaluated in terms of its impact on the initial stiffness and the fatigue life. The initial stiffness is defined as the stiffness of the HMA mix after 50 cycles of the 400 microns bending strain. The fatigue life is defined as the number of strain cycles necessary to reduce the initial stiffness by 50%. In other words the constant strain level of 400 microns is applied to the beams from the various HMA mixtures. After 50 cycles the measured stiffness of the beam is referred to as the "initial stiffness." The test continues to monitor the stiffness of the beam under the repeated strain of 400 microns. Once the stiffness of the beam reaches the 50% level of its initial stiffness, then the number of cycles is identified as the "fatigue life" of the mix.

It should be noted that a conditioning period of "0" means that the samples were tested immediately after saturation while the "dry" condition means that the samples were tested without any saturation. Figures 23 and 24 show the initial stiffness and fatigue life properties of the various mixtures. The initial stiffness and fatigue life ratios represent the ratios of the two properties after the various conditioning periods over their values at the dry condition.

Findings: The tensile strength properties of the evaluated mixture showed that hydrated lime improves the tensile values at both the un-conditioned and moisture-conditioned stages. Figure 21 shows that the un-conditioned (i.e. dry) tensile strength properties of the control, lime-treated and liquid A-treated mixtures were all the same. However, after the moisture conditioning, the tensile strength properties of the mixtures were significantly reduced, except for the lime-treated mixture. Figure 22 shows that the tensile ratios of the lime-treated mixture are significantly higher than the control and liquid A-treated mixtures. This indicates that the lime-treated mixture maintained higher tensile strength properties at both the un-conditioned and moisture-conditioned stages.

The fatigue properties shown in Figure 23 indicate that the lime-treated mixture started with higher initial stiffness than the control and the two liquid-treated mixtures and maintained higher initial stiffness after moisture damage. Similarly, the fatigue properties shown in Figure 24 indicate that the lime-treated mixture started with higher fatigue life than the control, and the two liquid-treated mixtures and maintained higher fatigue life after moisture damage. In fact the fatigue life data in Figure 24 show that the lime-treated mixture had better fatigue life after moisture conditioning than before moisture conditioning. This is a unique behavior that has been reported in other lime-treated mixtures around the country.

Applications: This research effort evaluated the impact of long-term moisture damage on the tensile strength and fatigue properties of a California mixture treated with lime and two liquid antistrip additives. The unique findings of this research effort is that it showed that the lime-treated mixture provided higher tensile strength and fatigue resistance at the dry stage and maintained these higher properties throughout the entire moisture conditioning process of 0, 4, 8, and 12 months. This indicates that the lime-treated mix will start with a better performing HMA pavement and maintains its superior performance through the long-term field conditioning process leading to a significantly better life cycle cost-benefit ratio than the control and liquid-treated mixtures.

All the data generated from this research showed that this California aggregate source would generate a poor HMA mix if left un-treated. However, treating this mix with either liquid A or B showed some improvements which were not sustained under long-term moisture conditioning and would not optimize the long-term performance of this mixture. Both the tensile strength and fatigue resistance data showed that treating this California HMA mix with hydrated lime would result in the most optimum long-term performance of the HMA pavement.

Impact of Lime and Liquid Antistrip on an Idaho Mixture

P.E. Sebaaly, D. Little, E. Hajj, and A. Bhasin, University of Nevada and Texas A&M University

This research effort was sponsored by the Chemcial Lime Company and conducted by researchers at the University of Nevada and Texas A&M University [Sebaaly et al (2006)]. The overall objective of this study was to compare the impact of adding hydrated lime and a liquid antistrip on the performance of a typical Idaho Transportation Department (ITD) HMA mixture supplied from a field trial on Project Number ST-3804(601).

The project is located in Idaho on State Highway 67. The entire project used an HMA mixture treated with a liquid antistrip additive selected by the ITD. The lime-treated HMA mixture was placed between mileposts 8 and 9 in the southbound direction. The liquid antistrip section between mileposts 7 and 8 in the southbound direction was used as a control section for the experiment. The structural design for both sections consisted of 3.0 inches of HMA over 8.0 inches of aggregate base. ITD staff collected cores from both sections along with loose samples of plant-produced mixtures. Throughout this summary the lime section will be labeled as "Lime mix" and the control section will be labeled as "Liquid mix".

The HMA mixtures on SH67 consisted of an ITD 3/4" dense graded mix designed using the Hveem mix design method. The asphalt binder was supplied by the Idaho Asphalt Supply Company and graded as PG58-28. The optimum binder content of the lime mix was 4.90% by total weight of the mix (i.e. 5.25% by dry weight of aggregate). The optimum binder content of the liquid mix was 5.10% by total weight of the mix (i.e. 5.40% by dry weight of aggregate).

The lime was added in the form of dry lime on damp aggregate at a content of 1.0% by dry weight of aggregate. The lime-treated aggregates were marinated for 48 hours prior to mixing. The Unichem (RAA04013) liquid antistrip was blended into the binder at the terminal at a content of 0.5% by weight of binder.

The laboratory evaluation program consisted of the following three tasks:

(a) evaluate the resistance of the mixtures to multiple freeze-thaw cycling,

(b) evaluate the dynamic modulus master curve of the mixtures, and

(c) evaluate the dynamic creep in tension of the mixtures.

The resilient modulus (Mr) property was used to monitor the behavior of the HMA mixtures under the repeated freeze-thaw (F-T) cycling. The Mr property was selected for the following two reasons: 1) Mr is an engineering property of the mixture that has been extensively used in pavement design and analysis applications, and 2) the Mr test is non-destructive, which means the test can be repeated on the same sample after multiple freeze-thaw cycles eliminating the variability associated with the use of different samples at various stages.

The multiple freeze-thaw cycling followed the procedure outlined in AASHTO T-283 at multiple stages. A total of three 4-inch diameter cores were evaluated from each section following the procedure outlined below:

- Measure the dry Mr at 77°F (i.e. 0 F-T cycles).
- Subject the cores to 75 ± 5% saturation.
- Subject the saturated samples to multiple freeze-thaw cycling; where one freeze-thaw cycle consists of freezing at 0°F for 16 hours followed by 24 hours thawing at 140°F and 2 hours at 77°F.
- Subject each core to the required number of freeze-thaw cycles.
- Conduct Mr testing at 77°F after cycles: 3, 6, 9, 12, 18, and 21.
- Take pictures of the cores at various freeze-thaw cycles.

Table 15 and Figure 25 summarize the Mr properties of the two mixtures at various freeze-thaw cycles. Each core was tested until it reached a Mr property close to or below 100 ksi. The Ratio represents the ratio of the Mr property at the various freeze-thaw cycles to the Mr property at the dry condition (0 F-T cycles).

The research also measured the dynamic modulus (E*) master curves of the Liquid and Lime mixtures. The samples for this task were compacted from loose field mixtures to a 6-inch diameter and a 7-inch high using the Superpave Gyratory Compactor (SGC). The samples were then cored and the ends were sawed to achieve final finished samples 4-inch in diameter and 6-inch high. The compaction effort of the SGC was adjusted so that the air voids in the finished samples were 7±0.5%.

Figure 26 shows the dynamic modulus master curve at a reference temperature of 77°F for the Liquid and Lime mixtures. Initially, the E* master curves were measured for both mixtures in the dry stage. After the completion of the multiple F-T testing, it was decided to also measure the E* master curves after multiple F-T cycles. The initial intent was to subject both mixtures to 21 F-T cycles and then measure their E* properties. However, during the F-T cycling of the E* samples, the Liquid mix samples started disintegrating after cycle 9 and became un-testable after cycle 10. Following this occurrence, the multiple F-T cycling of the E* samples was terminated and the Lime mix samples were tested after 10 F-T cycles. The measured E* master curve for the Lime mix after 10 F-T cycles is shown in Figure 26. The E* master curves data can be interpreted as follows: the horizontal axis represents the loading frequency in Hertz (Hz) which is directly related to the time of loading that the HMA mix experiences under traffic loads. Typical highway traffic generates loading frequencies between 20 and 30 Hz while slower traffic generates loading frequencies between 2 and 3 Hz.

The dynamic creep in tension test was conducted to evaluate the fatigue damage potential of the Lime and Liquid mixtures. The tensile stress used in the tensile creep testing was in the form of a sinusoidal wave form with a wavelength of 0.1 seconds followed by a rest or dwell period of 0.9 seconds. Each load cycle is composed of stress application and a rest period. Figure 27 shows the typical applied load form and response from the dynamic creep test. When the data of the dynamic creep in tension are plotted on a log scale, the following relationship is obtained.

$$\log \varepsilon_p = \log a + b \log \mathrm{N} \tag{7}$$

Initially the sample undergoes permanent deformation at an increasing rate for the first few hundred cycles, which is quantified by the intercept parameter "log a". After this initial phase, the rate of accumulated permanent deformation stabilizes and becomes constant and is quantified by the slope parameter "b". While the intercept parameter log a is very sensitive to initial air voids in the sample, the slope parameter b is a more reliable measure of rate of damage in the mixture. Since the tests are performed in direct tension, a smaller value of b indicates a lower rate of damage accumulation and a longer fatigue life.

Samples for the dynamic creep test were compacted to a 4-inch diameter and a 7-inch high using the SGC. The samples were then cored and the ends were sawed to achieve final finished samples 3-inch in diameter and 6-inch high. The compaction effort of the SGC was adjusted so that the air voids in the finished samples were 7±1%. A total of eight samples were prepared for each of the Liquid and Lime field mixtures. While four samples were tested in the dry condition, the rest of the samples were tested after moisture conditioning. The moisture conditioning process consisted of only moisture saturation without any freeze-thaw.

Findings: The data summarized in Table 15 and Figure 25 show that the Liquid mix deteriorated at a significantly faster rate than the Lime mix. The Lime mix started at a higher dry Mr values and maintained good modulus properties over the entire 21 freeze-thaw cycles. After 21 F-T cycles, all of the three cores from the Liquid mix retained Mr properties that are at or below the 100 ksi level which prompted the termination of the testing program. Figure 28 shows the physical conditions of the cores after 22 F-T cycles. It can be seen that the Liquid mix cores fully disintegrated at that stage while the Lime mix cores remained in good condition.

The E* master curve data shown in Figure 26 indicate that in the dry condition the Lime mix exhibits higher dynamic modulus than the Liquid mix under all loading frequencies. Since the E* axis is on a logarithmic scale the minor differences shown on the graph represent significant jumps in the actual value of the E*. For example, at a loading frequency of 20 Hz, the E* is 750 ksi and 580 ksi for the Lime and Liquid mixtures, respectively, indicating a 30% difference. While the Liquid mix samples disintegrated after cycle 9, the Lime mix samples were tested after 10 F-T cycles and their E* master curve is also shown in Figure 26. After 10 F-T cycles, the Lime mix still shows higher E* values than the Liquid mix without F-T cycling at loading frequencies higher than 5 Hz. However, at frequencies below 5 Hz, the Lime mix after 10 F-T cycles showed lower E* values than the Liquid mix without F-T cycling.

The data from the dynamic creep test was fitted by regression to obtain the slope parameter b shown in Equation 7. Table 16 shows that the slope parameter, b, for both the Liquid and Lime mixtures at the dry state are approximately the same indicating similar fatigue characteristics. The slope parameter for the moisture conditioned Lime mix was lower than the slope parameter for the moisture conditioned Liquid mix indicating better fatigue characteristics for the moisture conditioned Lime mix.

Applications: The pavement structure on the SH-67 project consists of 3.0 inches of HMA layer over 8.0 inches of aggregate base. The laboratory testing showed that the dry Mr properties at 77°F of the Liquid and Lime mixtures are 233 and 264 ksi, respectively. Both mixtures can be classified as highly flexible due to their medium level Mr properties at 77°F. The combination of highly flexible HMA mixtures with a thin HMA layer would perform well in resisting fatigue cracking but may not be able to sufficiently resist permanent deformation. Therefore, it was advantageous to assess the relative resistance of the mixtures to permanent deformation and the impact of multiple freeze-thaw cycling on their potential rutting performance.

A comparative mechanistic analysis of the pavement sections on SH-67 was conducted using the measured Mr properties of the Liquid and Lime mixtures and the thickness of the constructed pavement section of 3.0 inches of HMA over 8.0 inches of aggregate base. The objective of the analysis is to compare the rutting performance of the two pavement sections: Liquid and Lime. The properties of the base and subgrade were maintained constant (Mr for base of 50,000 psi and Mr for Subgrade of 15,000 psi) while the property of the HMA layer was changed to represent the Liquid and Lime mixes at various F-T cycles.

The rutting relationship presented in equations 2-4 were used to predict the rutting behaviors of the Liquid and Lime mixes under 0.5 million 18 kips single axle load. The rutting behavior was determined in terms of the percent increase in rutting due to the multiple F-T cycling. Both mixtures were assumed to have good resistance to rutting at the dry stage and the increase in their rutting potential was predicted as the mixtures were subjected to multiple F-T cycles. Table 17 summarizes the results of this analysis.

The use of the rutting resistance of the mixtures at the dry stage as a base level eliminates the need to have a field-calibrated rutting model, since all predictions are made relative to the base level and no absolute rutting values are determined. Given the fact that the Lime mix exhibits a higher Mr property at the dry stage than the Liquid mix the base level analysis is a conservative approach in favor of the Liquid mix.

In summary, the analysis of the multiple freeze-thaw data of the Liquid and Lime mixtures placed on the SH-67 project in Idaho, leads to the following conclusions.

- The lime mix exhibits higher Mr values than the Liquid mix at the dry stage.
- As the mixtures are subjected to multiple F-T cycles, the Lime mix retained higher Mr values than the Liquid mix.
- After 21 F-T cycles, the Lime mix retained 65% of its dry Mr property while the Liquid mix retained only 37% of its dry Mr property.
- The core samples from the Lime mix remained in a good condition after 22 F-T cycles. One of the cores from the Liquid mix disintegrated after 16 F-T cycles and the other two cores disintegrated after 22 F-T cycles.

- The mechanistic analysis to predict the rutting resistance of the mixtures showed that the potential increase in rutting as a function of multiple F-T cycling of the Liquid mix is significantly higher than that of the Lime mix.

In the case of the E* master curves, the data indicate that the Lime mix exhibits higher dynamic modulus than the Liquid mix under all loading frequencies in the dry state, and while the Liquid mix disintegrates after 9 F-T cycles, the Lime mix still maintained an acceptable level of dynamic modulus after 10 F-T cycles under all loading frequencies. In fact, for loading frequencies higher than 5 Hz, the Lime mix following F-T cycling maintained higher moduli than the Liquid mix without F-T cycling. Since the E* property directly impacts the resistance of the HMA mixture to all types of distresses, this increase in the E* property of the lime-treated mixture will translate into better long-term field performance of the lime-treated pavement as compared to the liquid-treated pavement.

The rates of permanent deformation in the dynamic creep test for Lime and Liquid mixtures do not appear to be significantly different. Therefore, the additional strength of the Lime mixture does not contribute to premature fatigue cracking. This finding is consistent with previous findings that have shown lime to be able to stiffen asphalt mixtures while actually reducing micro-crack growth potential and increasing micro-crack healing potential.

In summary, based on the mechanical properties of Lime and Liquid mixtures at the moisture conditioned and unconditioned stages, the researchers concluded that the Lime mix is more stable, less susceptible to rutting, and less susceptible to moisture damage while having similar resistance to fatigue cracking as compared to the Liquid mix.

III. REFERENCES

1. Aschenbrener, T. and Far, N., "Influence of Compaction Temperature and Antistripping Treatment on the Results from the Hamburg Wheel-Tracking Device," Report # CDOT-DTD-R-94-9, Colorado Department of Transportation, July 15, 1994.

2. Izzo, R.P. and Tahmoressi, M., "Use of the Hamburg Wheel-Tracking Device for Evaluating Moisture Susceptibility of Hot-Mix Asphalt," Transportation Research Record 1681, Transportation Research Board, Washington, DC, 1999.

3. Kennedy, T. and Ping, W.V., "An Evaluation of Effectiveness of Antistripping Additives in Protecting Asphalt Mixtures from Moisture Damage," Journal of the Association of Asphalt Paving Technologists, Volume 60, 1991.

4. Khosla, N.P., Birsdall, B.G., and Kawaguchi, S., "Evaluation of Moisture Susceptibility of Asphalt Mixtures, Conventional and New Methods," Transportation Research Record 1728, Transportation Research Board, Washington, DC, 2000.

5. Lu, Q. and Harvey J.T., "Laboratory Evaluation of Long-Term Effectiveness of Antistripping Additives," The 85th Annual Meeting of the Transportation Research Board CD-ROM, Washington DC, 2006.

6. Mohammad, L., "Evaluation of Superpave Mixtures Containing Hydrated Lime," Research Summary from the Louisiana Transportation Research Center, Baton Rouge, LA, 2006.

7. Pickering, K., Sebaaly, P.E., Stroup-Gardiner, M., and Epps, J.A., "Evaluation of New Generation of Antistripping Additives," Transportation Research Record 1342, Transportation Research Board, Washington, DC, 1992.

8. Tahmoressi, M. and Mikhail, M., "Evaluation of Methods of Adding Lime to Hot Mix," Research Report, Texas Department of Transportation, Austin, TX, 1999.

9. Tohme, P., Sebaaly, P.E., Hajj, E.Y., and Johnston, D., "Effectiveness of Antistrip Additives for Bituminous Mixtures," International Journal of Pavements, Volume 3, Number 1-2, January-May, 2004.

10. Sebaaly, P.E., Little, D., Hajj, E.Y., and Bhasin, A., "Impact of Lime and Liquid Antistrip on the Properties of an Idaho Mixture," The 86th Annual Meeting of the Transportation Research Board CD-ROM, Washington DC, January 21-25, 2007.

Table 1. Experimental Program for the Colorado DOT Study using the Hamburg Wheel Tracking Device [Aschenbrener and Far (1994)].

Mix Type	1% Hydrated Lime	Liquid Additive "A"		Liquid Additive "B"	
		Type "1"	Type "2"	Type "1"	Type "2"
Mix 1	X	X	X	X	X
Mix 2	X	X	X	X	X
Mix 3	X	X	X	X	X
Mix 4	X	X	X	X	X

X – Replicate samples tested in the HWTD at 45°C.

Table 2. Optimum Binder Contents used in the Colorado Study [Aschenbrener and Far (1994)].

Mix Type	Optimum Binder Content (%)	Air-Voids at Optimum (%)	VMA at Optimum (%)
Mix 1	5.2	4.0	13.8
Mix 2	5.1	4.0	14.4
Mix 3	5.2	4.0	14.1
Mix 4	5.1	4.0	13.5

Table 3. Rut Depth (mm) under the HWTD for the HMA Mixtures Evaluated in the Colorado Study [Aschenbrener and Far (1994)].

Mix Type	Control	1% Hydrated Lime	Liquid Additive "A"		Liquid Additive "B"	
			Type "1"	Type "1"	Type "1"	Type "2"
Mix 1	17.0	1.4	2.2	3.1	6.3	7.4
Mix 2	>20	2.3	8.1	8.4	5.3	14.6
Mix 3	>20	2.5	13.7	8.5	>20	12.4
Mix 4	8.7	2.3	6.2	4.6	5.0	4.3

Table 4. Optimum Binder Contents used in the Texas Study [Izzo and Tahmoressi (1999)].

Mix Type	Optimum Binder Content (%)
Limestone	5.3
Granite Mountain	4.6
Basalt	4.6
Gravel	5.0
Gravel with limestone screenings	5.3
Gravel with granite screenings	5.5

Table 5. Hamburg Wheel Tracking Device Data of the HMA Mixtures Evaluated in the TxDOT Study at 40ºC [Izzo and Tahmoressi (1999)].

Mix Type	Control				Lime-Treated				Liquid-Treated			
	Nf	Creep Slope	Stripping Slope	SIP	Nf	Creep Slope	Stripping Slope	SIP	Nf	Creep Slope	Stripping Slope	SIP
Limestone	19,519	4,856	459	12,026	>20,000	8,871	NA	NA	>20,000	5,469	777	12,768
Granite Mountain	>20,000	2,979	640	13,310	>20,000	9,919	NA	NA	>20,000	4,780	1,050	12,192
Basalt	14,250	1,926	446	5,456	>20,000	7,026	NA	NA	>20,000	3,626	1,402	9,275
Gravel	>20,000	9,815	NA	NA	>20,000	10,465	NA	NA	>20,000	5,770	NA	NA
Gravel with limestone screenings	10,222	2,082	279	6,010	>20,000	5,252	NA	NA	15,465	1,511	491	9,052
Gravel with granite screenings	5,607	907	163	3,158	>20,000	3,427	NA	NA	13,400	3,471	744	9,565

Table 6. Mix Design Properties of the HMA Mixtures Evaluated in the Louisiana Study [Mohammad (2006)].

Mix Design Property	Mix Type			Specification
	M76CO	M70LS	M70LM	
Optimum Binder Content (%)	4.0	3.6	3.6	
Air-Voids (%)	3.7	3.6	3.6	2.5 – 3.5
VMA (%)	12	12	12	12
VFA (%)	68	69	69	68-78
Film Thickness (microns)	7.9	7.2	7.2	

Table 7. Hamburg Wheel Tracking Device Data of the HMA Mixtures Evaluated in the Louisiana Study
[Mohammad (2006)].

Mix Type	Hamburg Rut Depth under 20,000 Passes (mm)
M76CO	3.5
M70LS	2.5
M70LM	2.8

Table 8. Summary of Binder Contents and Additive Dosage for the various Laboratory Mixtures Tested in the Texas Study [Kennedy and Ping (1991)].

TxDOT District	Additive	Additive Dosage*	Binder Content (%)
17 – River Gravel	Control Lime BA 2000 Perma-Tac	0 1.5 1.0 1.0	4.9
16 – Limestone	Control Lime Aquashield DOW Pavebond LP	0 1.0 0.5 0.41 0.5	4.3
13 – Crushed Gravel	Control Lime BA 2000 Perma-Tac	0 2.0 1.0 1.0	5.0
6 - Fhyolite	Control Lime Pavebond LP Perma-Tac Unichem	0 1.0 1.0 1.0 1.0	6.2
25 – Crushed Gravel	Control Lime Aquashield II Fina-A Perma-Tac Unichem	0 1.0 1.0 1.0 1.0 1.0	
1 – Crushed Sandstone	Control Lime ARR-MAZ DOW Fina-A Indulin AS-1 Pavebond Special Perma-Tac Plus	0 1.5 0.75 0.45 1.0 1.0 1.0 1.0	6.0
19 – Crushed Gravel	Control Lime ARR-MAZ Aquahield BA 2000 Perma-Tac	0 1.0 1.0 0.8 0.5 1.0	5.3
21 – Crushed Gravel	Control Lime APR-MAZ Aquashield II DOW Fina-B Pavebond LP Perma-Tac	0 1.0 1.0 0.41 0.5 0.41 1.0 1.0	5.2

*/ The dosage of hydrated lime is based on dry weight of aggregate and the dosage of liquid additives is based on weight of asphalt binder.

**/ The optimum asphalt binder content is by total weight of mix.

Table 9. Summary of Tensile Strength Ratio Properties for the various Laboratory Mixtures Tested in the Texas Study [Kennedy and Ping (1991)].

TxDOT District	Additive	TSR for Laboratory Mixtures (%)
17 – River Gravel	Control Lime BA 2000 Perma-Tac	51 118 82 82
16 – Limestone	Control Lime Aquashield DOW Pavebond LP	44 74 56 53 60
13 – Crushed Gravel	Control Lime BA 2000 Perma-Tac	43 142 64 61
6 - Fhyolite	Control Lime Pavebond LP Perma-Tac Unichem	20 78 40 49 37
25 – Crushed Gravel	Control Lime Aquashield II Fina-A Perma-Tac Unichem	67 130 119 98 103 92
1 – Crushed Sandstone	Control Lime ARR-MAZ DOW Fina-A Indulin AS-1 Pavebond Special Perma-Tac Plus	74 106 114 70 110 107 121 115
19 – Crushed Gravel	Control Lime ARR-MAZ Aquahield BA 2000 Perma-Tac	112 107 119 125 116 93
21 – Crushed Gravel	Control Lime APR-MAZ Aquashield II DOW Fina-B Pavebond LP Perma-Tac	24 104 52 73 35 45 51 47

Table 10. Summary of the Mechanistic Analyses of Untreated, Lime-treated and Liquid-treated HMA Pavements.

HMA Pavement	Nevada Mixture			
	Un-Damaged		Moisture-Damaged	
	εr (10-6) in/in	Ratio of Number of load repetitions to 0.5" rut depth from the HMA layer*	εr (10-6) in/in	Ratio of Number of load repetitions to 0.5" rut depth from the HMA layer
Untreated	209	1.0	650	0.1
Lime-treated	172	1.6	254	0.6
Liquid I-treated	135	2.8	520	0.1
Liquid II-treated	213	0.9	340	0.3
	California Mixture			
Untreated	227	1.0	698	0.1
Lime-treated	141	3.1	179	1.8
Liquid I-treated	221	1.1	366	0.3
Liquid II-treated	213	1.2	391	0.3

*/ Ratio of the number of load repetitions to 0.5" rut depth from the HMA layer of the various treated pavements over the untreated pavements in the un-damaged stage.

Table 11. Moisture Conditioned Tensile Strength and Tensile Strength Ratios of the HMA Mixtures Evaluated in the TxDOT Study [Tahmoressi and Mikhail (1999)].

Mix Type	HMA Mix 1	
	Conditioned Tensile strength at 77oF, psi	Tensile Strength Ratio (%)
Untreated	48	45
Lime-Treated	114	98
Liquid A-Treated	98	97
Liquid B-Treated	93	91
Liquid C-Treated	94	91
	HMA Mix 2	
Untreated	45	48
Lime-Treated	75	91
Liquid A-Treated	71	97
Liquid B-Treated	68	88
Liquid C-Treated	70	94

Table 12. Shear Strength Properties of the HMA Mixtures Evaluated in the North Carolina Study [Khosla et al (2000)].

Aggregate	Treatment	Condition	Cohesion C, psi	Ratio of C, %	Friction Angle, ϕ, (degrees)	Ratio of ϕ, %
Marine Limestone	None	Unconditioned	3.00	81	57	100
		Conditioned	2.42		57	
	Lime	Unconditioned	7.78	92	59	97
		Conditioned	7.18		57	
	Amine	Unconditioned	3.48	86	54	95
		Conditioned	3.00		51	
	Phosphate	Unconditioned	6.04	87	57	93
		Conditioned	5.24		53	
Slate	None	Unconditioned	2.60	47	55	107
		Conditioned	1.22		59	
	Lime	Unconditioned	4.95	75	55	100
		Conditioned	3.70		55	
	Amine	Unconditioned	10.01	73	52	111
		Conditioned	7.31		58	
	Phosphate	Unconditioned	5.48	77	59	100
		Conditioned	4.21		59	
Granite Gneiss	None	Unconditioned	1.33	38	55	100
		Conditioned	0.50		56	
	Lime	Unconditioned	1.80	97	52	104
		Conditioned	1.74		54	
	Amine	Unconditioned	1.40	90	50	104
		Conditioned	1.26		52	
	Phosphate	Unconditioned	2.44	73	51	102
		Conditioned	1.78		52	

Table 13. Extracted Binder Contents of Field Mixtures from the South Dakota Sections [Sebaaly et al (2003)].

Section Number	Recommended Optimum Binder Content (%)		Extracted Binder Content (%)	
	SD314	US14	SD314	US14
1: Control	6.00	5.90	6.17	6.09
2: Lime on wet aggregates – 1	6.00	5.90	6.16	5.67
3: Lime on wet aggregates – 2	6.00	5.90	6.16	5.67
4: Lime on in situ aggregates	6.00	5.90	5.88	5.55
5: UP5000	6.00	5.90	5.74	6.09
6: Liquid antistrip	6.00	5.90	5.74	6.04

Table 14. Summary of the Mechanistic Analyses of the South Dakota Sections.

HMA Pavement	SD314 Project		US14 Project	
	εr (10-6) in/in	Ratio of Number of load repetitions to 0.5" rut depth from the HMA layer*	εr (10-6) in/in	Ratio of Number of load repetitions to 0.5" rut depth from the HMA layer
Untreated	142	1.0	209	1.0
Lime-treated	103	2.1	157	2.0
UP5000-treated	126	1.3	175	1.5
Liquid-treated	115	1.6	169	1.6

*/ Ratio of the number of load repetitions to 0.5" rut depth from the HMA layer of the various treated pavements over the untreated pavements in the un-damaged stage.

Table 15. Summary of the Mr Properties of the Liquid and Lime Mixtures from the Idaho Project [Sebaaly et al (2206)].

F-T Cycles	Liquid Mix					Lime Mix				
	Mr at 77°F, ksi			Average Mr (ksi)	Ratio* (%)	Mr at 77°F, ksi			Average Mr (ksi)	Ratio* (%)
	Core6	Core9	Core17			Core7	Core8	Core14		
0	192	251	256	233	na	259	266	266	264	na
3	244	251	270	255	100	275	280	248	268	100
6	185	256	242	228	98	278	271	268	272	100
9	122	158	203	161	69	292	245	262	266	100
12	181	148	200	176	76	244	257	228	243	92
18	65	127	127	106	45	165	208	178	184	70
21	NA	69	103	86	37	154	189	172	172	65

*/ Ratio of the Mr property at the various freeze-thaw cycles to the Mr property at the dry condition (0 F-T cycles)

Table 16. The Slope b of Accumulated Damage Curve from Dynamic Creep in Tension of Liquid and Lime Mixtures from the Idaho Project [Sebaaly et al (2006)].

Liquid Mixtures										
	Dry					Moisture Conditioned				
Sample ID	1	2	3	4	Average	5	6	7	8	Average
Air Voids, %	7.1	6.8	6.2	6.6	6.7	6.6	7.3	7.1	7.4	7.1
Slope b	N/A	N/A	0.41	0.55	0.48	0.61	0.67	N/A	N/A	0.64
Lime Mixtures										
	Dry					Moisture Conditioned				
Sample ID	1	2	3	4	Average	5	6	7	8	Average
Air Voids, %	7.0	6.8	6.5	6.7	6.8	6.2	7.3	6.8	6.2	6.6
Slope b	0.43	N/A	N/A	0.50	0.46	N/A	0.63	0.50	N/A	0.57

Table 17. Impact of Multiple Freeze-Thaw Cycling on the Rutting Potential of Liquid and Lime Mixtures from the Idaho Project [Sebaaly et al (2006)].

F-T Cycles	Increase in Potential for Rutting at 0.5 million ESALs (%)	
	Liquid Mix	**Lime Mix**
0	na	na
3	0	0
6	3	0
9	55	0
12	40	10
18	150	55
21	220	65

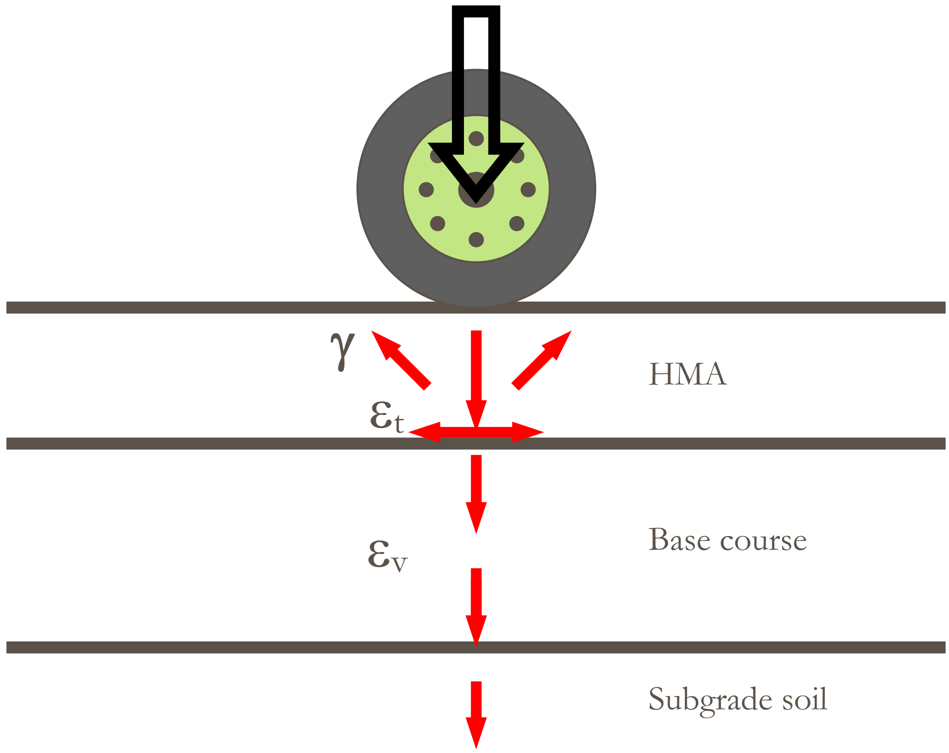
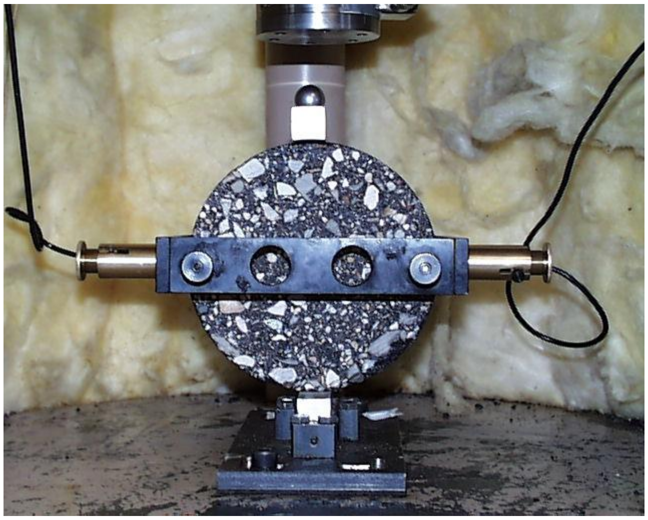
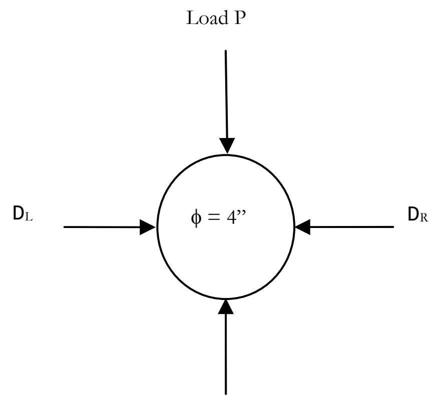


Figure 1. Typical HMA Pavement Subjected to a Traffic Wheel Load.

Resilient Modulus Set-Up





$$M_R = \frac{P(\mu + 0.27)}{t \times \Delta_i}$$

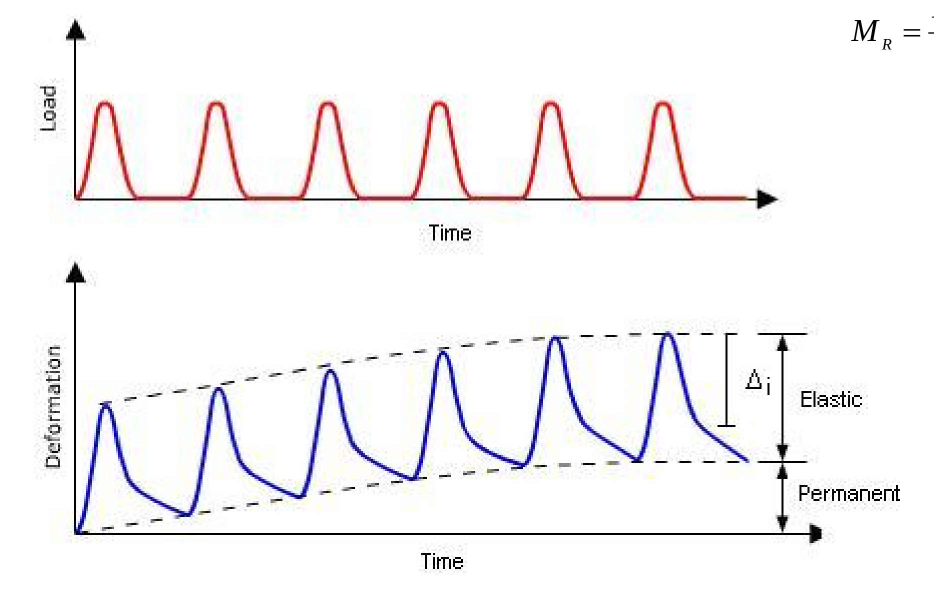
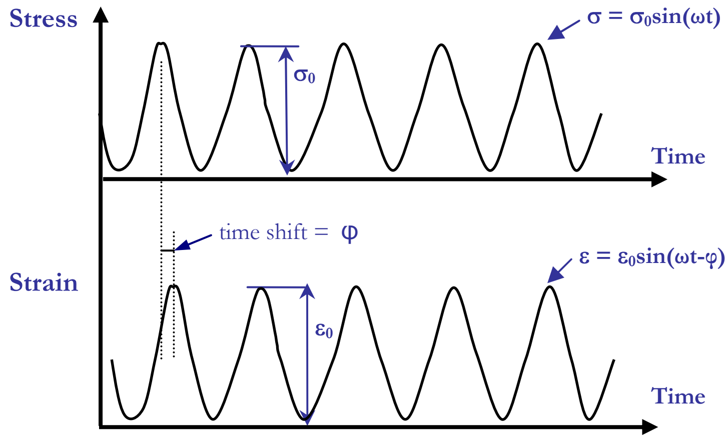


Figure 2. Components of the Resilient Modulus Test for an HMA mix.

Dynamic Modulus Set-Up

Applied Stress & Measured Strain



Dynamic Modulus

$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

Typical E* Master Curve

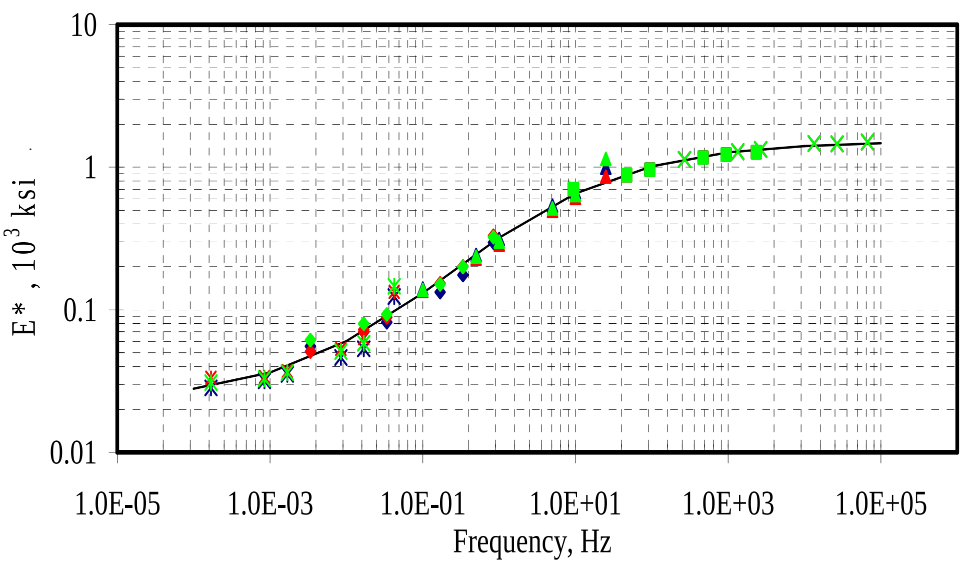


Figure 3. Components of the Dynamic Modulus Test and a Typical E* Master Curve for an HMA mix.

Tensile Strength Test Set-Up

Tensile Strength, St

$$S_t = \frac{2P_{max}}{\pi \times t \times D}$$

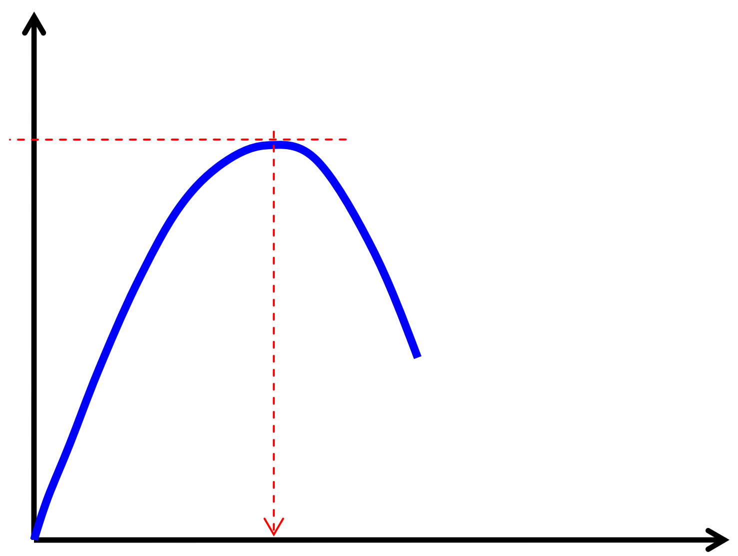


Figure 4. Components of the Indirect Tensile Strength Test for a HMA mix.

Triaxial Compression Strength Test Set-Up

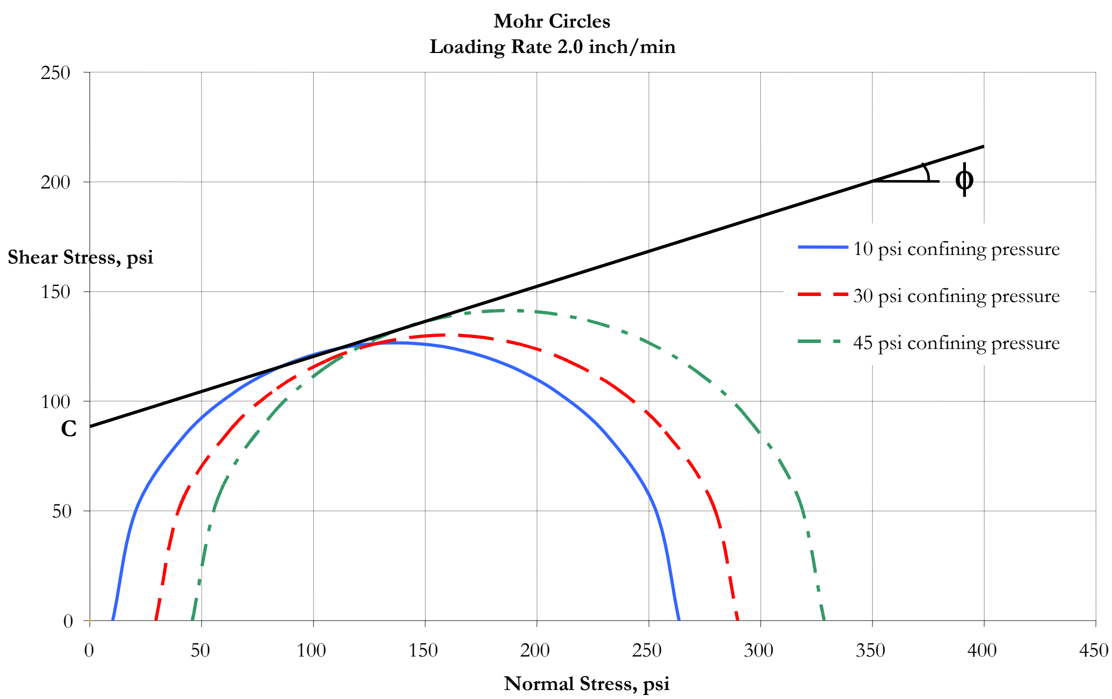


Figure 5. Components of the Triaxial Compression Strength Test and a Typical Mohr-Coulomb failure Envelop for a HMA Mix.

Repeated Load Triaxial Set-Up

Loading and Response

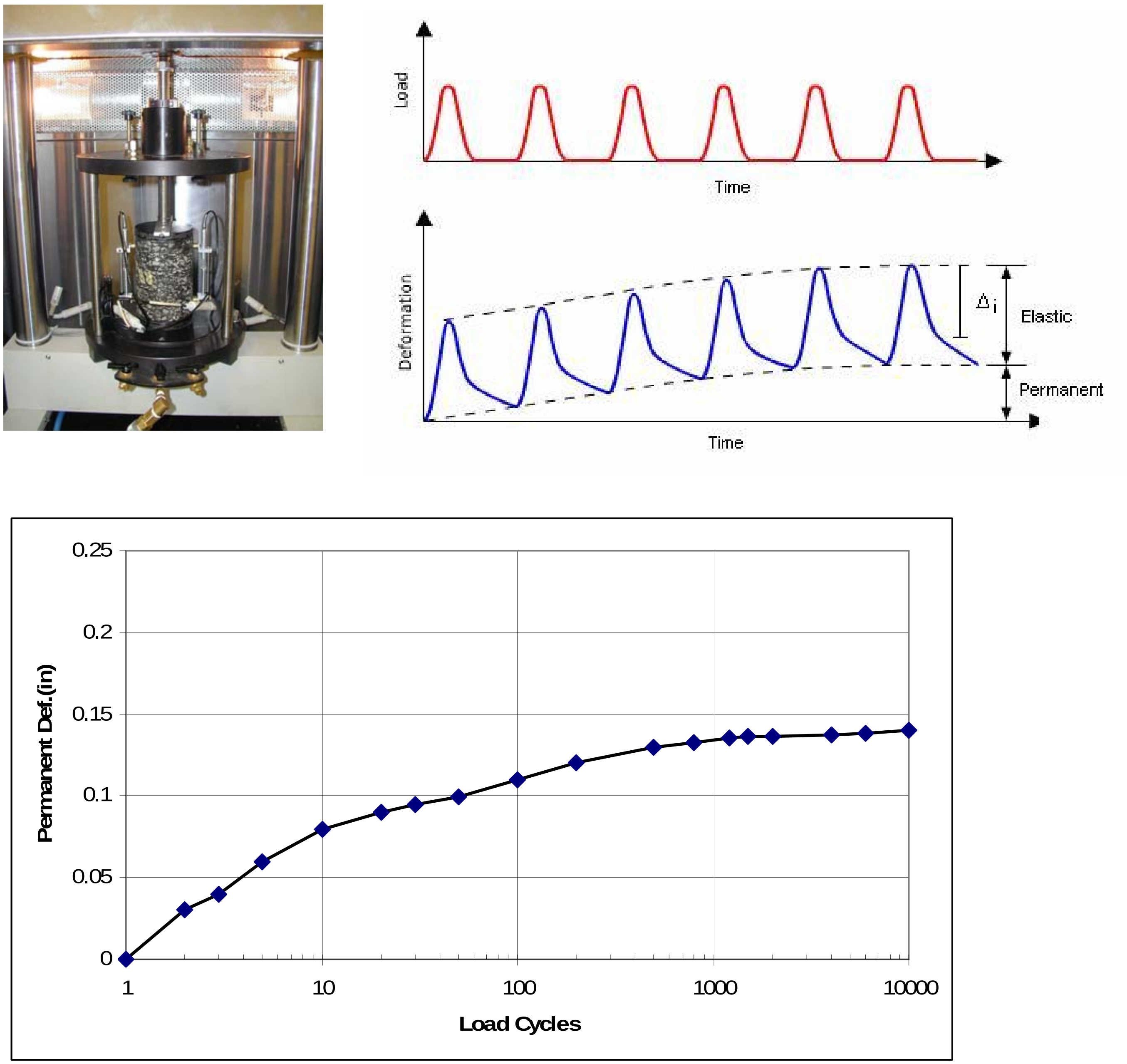


Figure 6. Components of the Repeated Load Triaxial Test and a Typical Permanent Deformation Curve for an HMA Mix.

Hamburg Wheel Tracking Test Set-Up

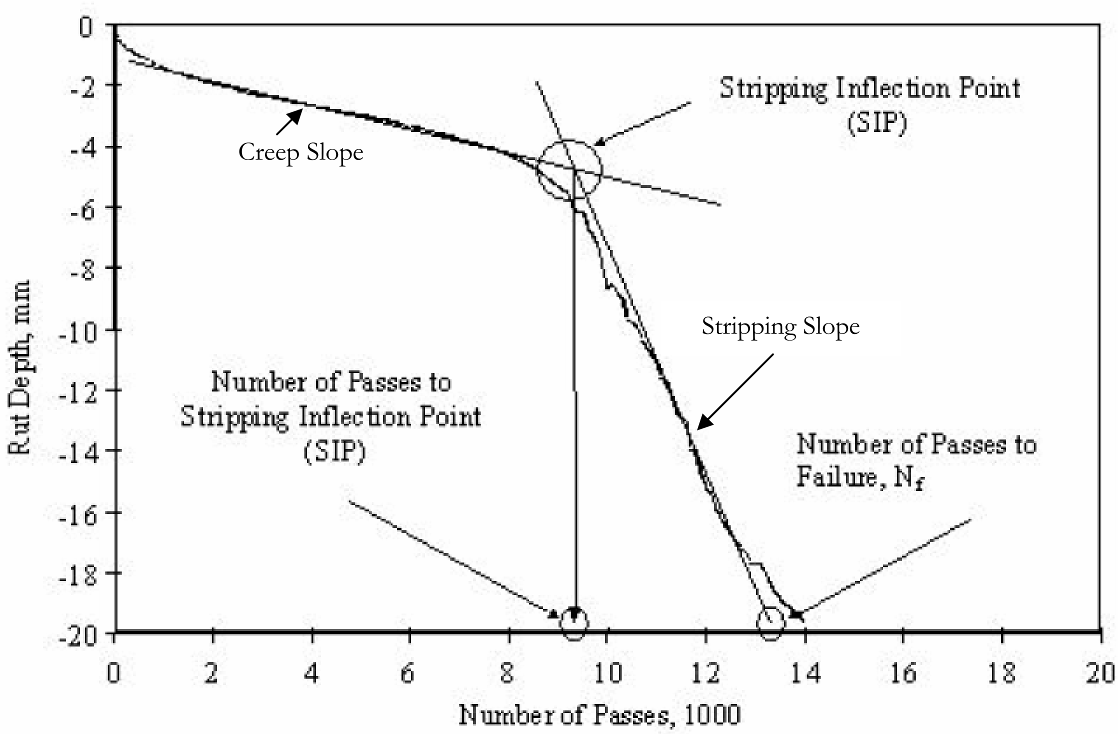
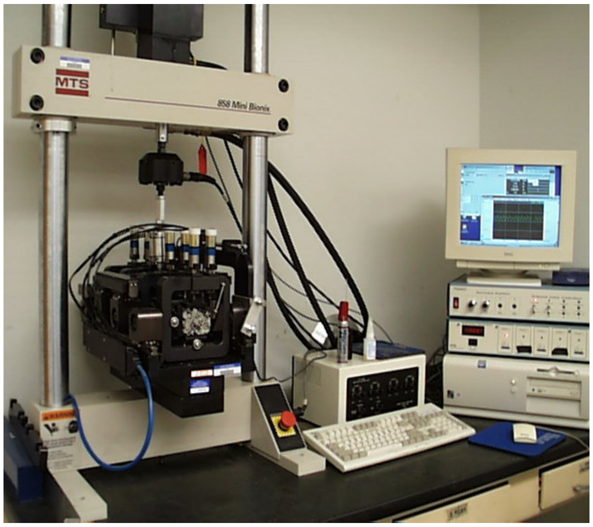
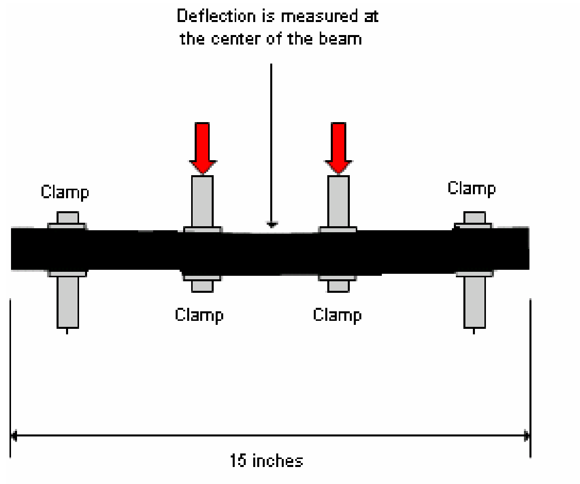


Figure 7. Components of the Hamburg Wheel Tracking Device and a Typical Permanent Deformation Curve for a HMA Mix.

Flexural Beam Fatigue Set-Up





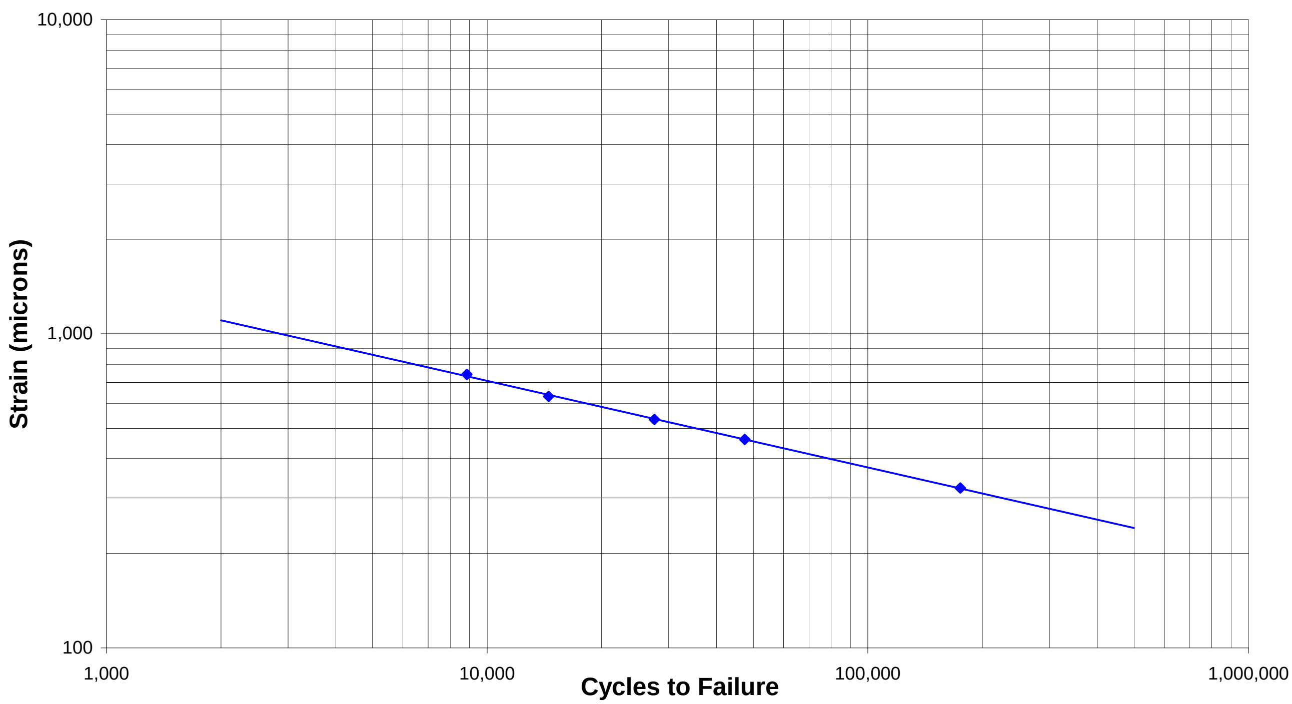


Figure 8. Components of the Beam Fatigue Test and a Typical Fatigue Curve for an HMA Mix.

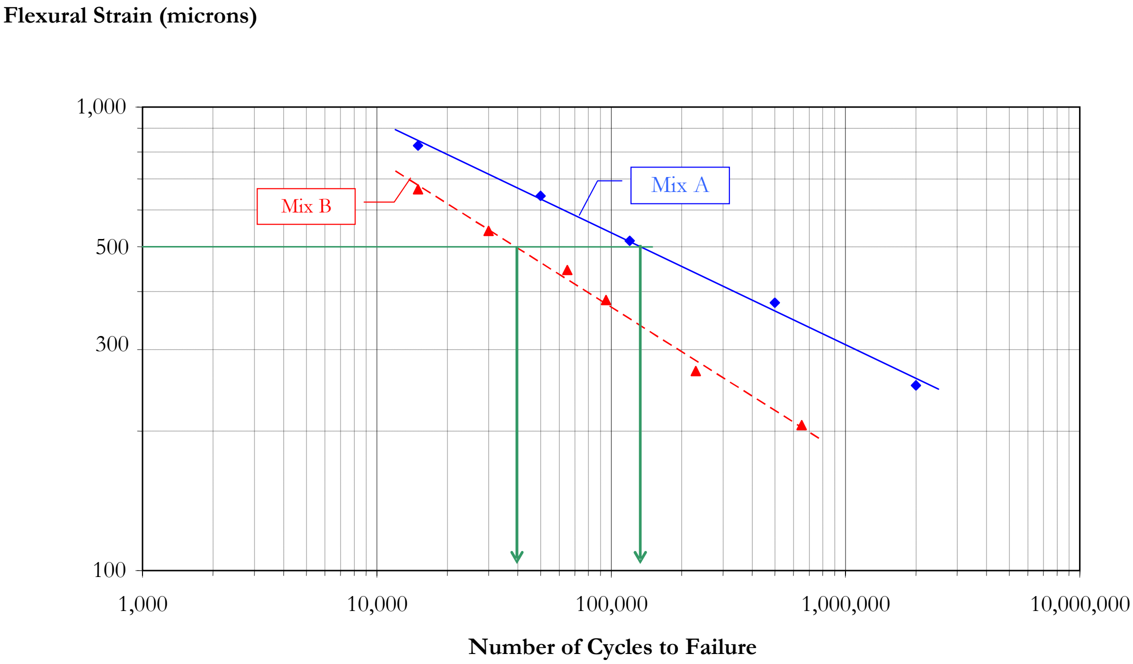


Figure 9. Comparison of Fatigue Relationships for two HMA Mixtures.

TSRST Set-Up

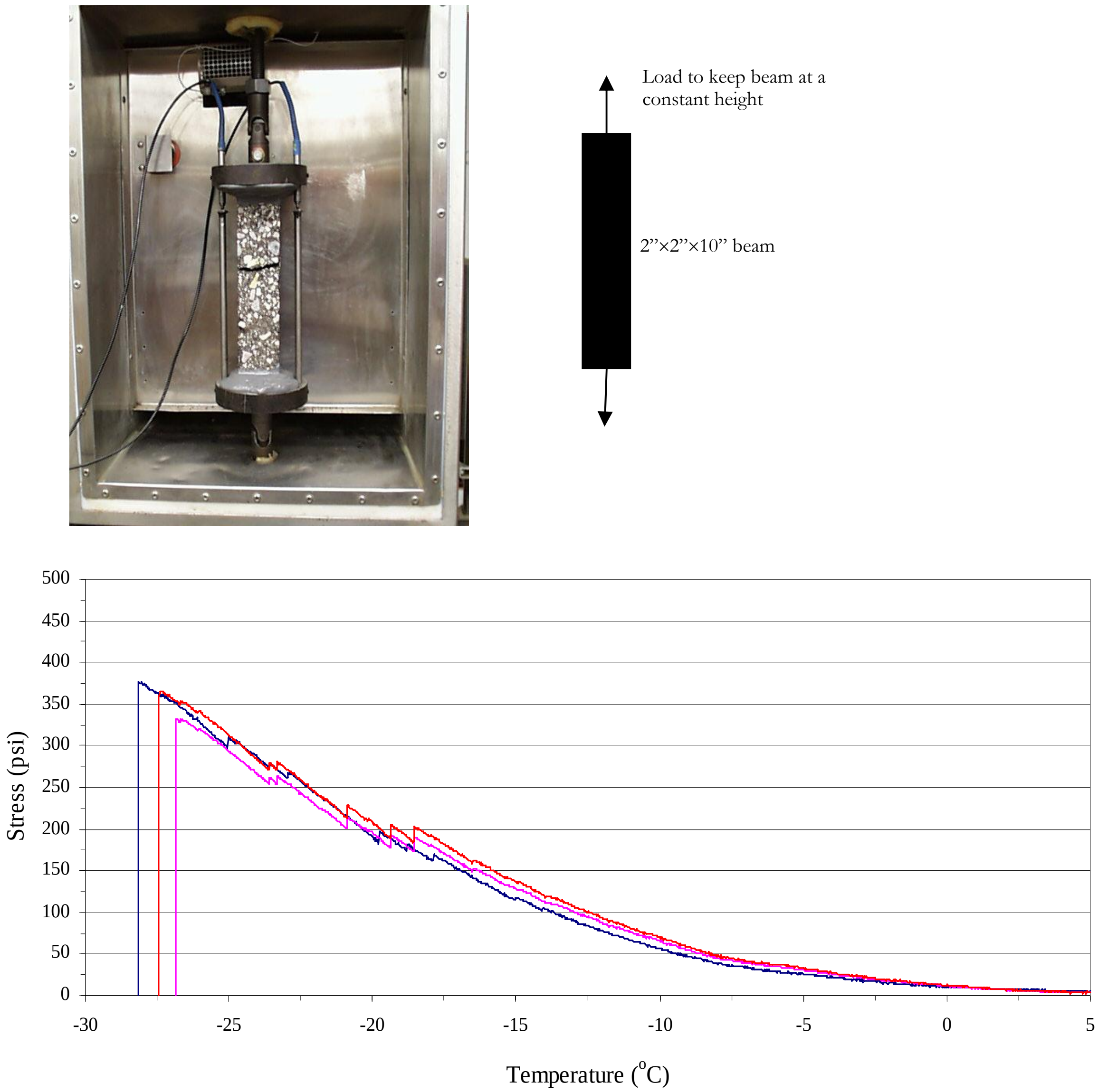


Figure 10. Components of the TSRST Test and Typical Stress-Temperature Curve for an HMA Mix.

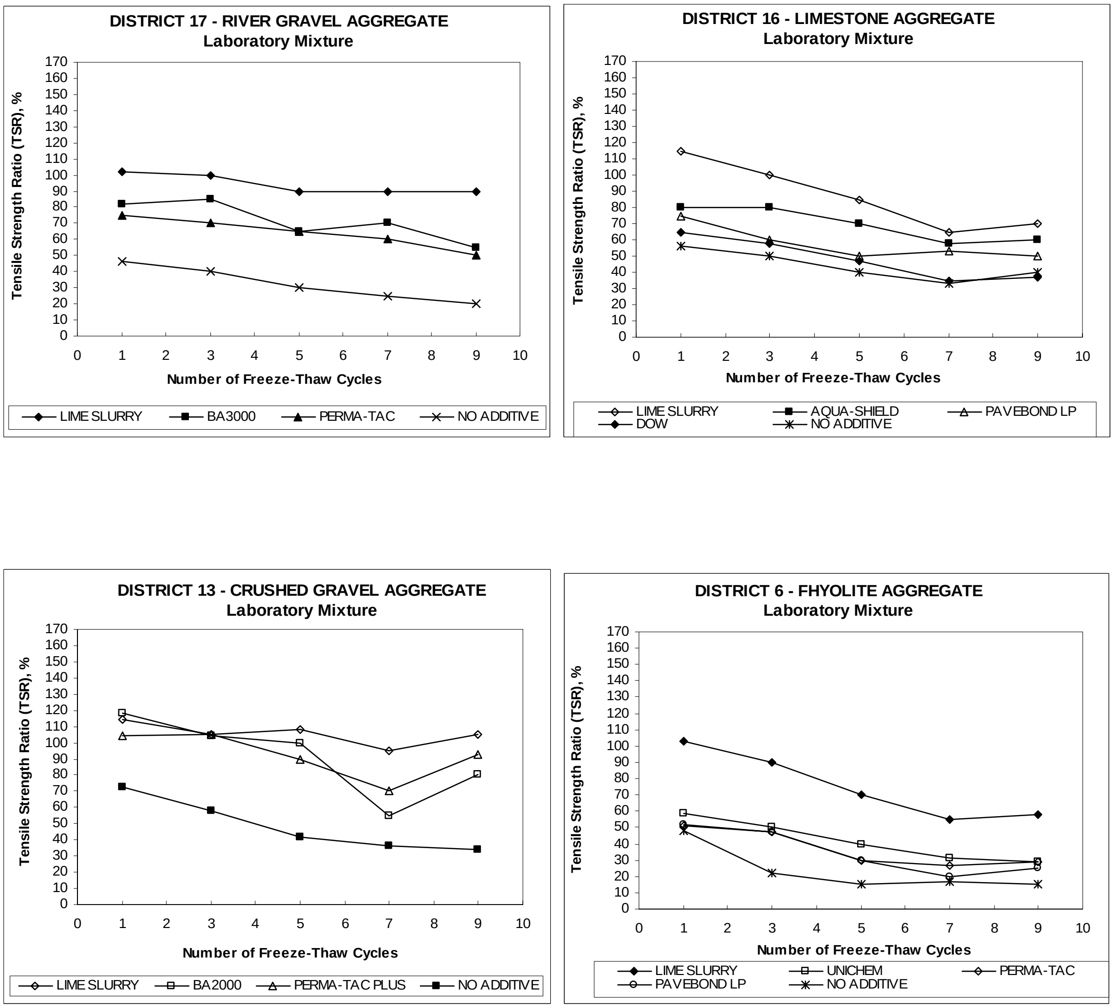


Figure 11. Multiple Freeze-Thaw Cyclic Tests Results for Laboratory Mixtures Comparing Severity of Tests Method on the Ability to Differentiate between Lime and Other Antistrip Additives [Kennedy and Ping (1991)]. (continued on next page)

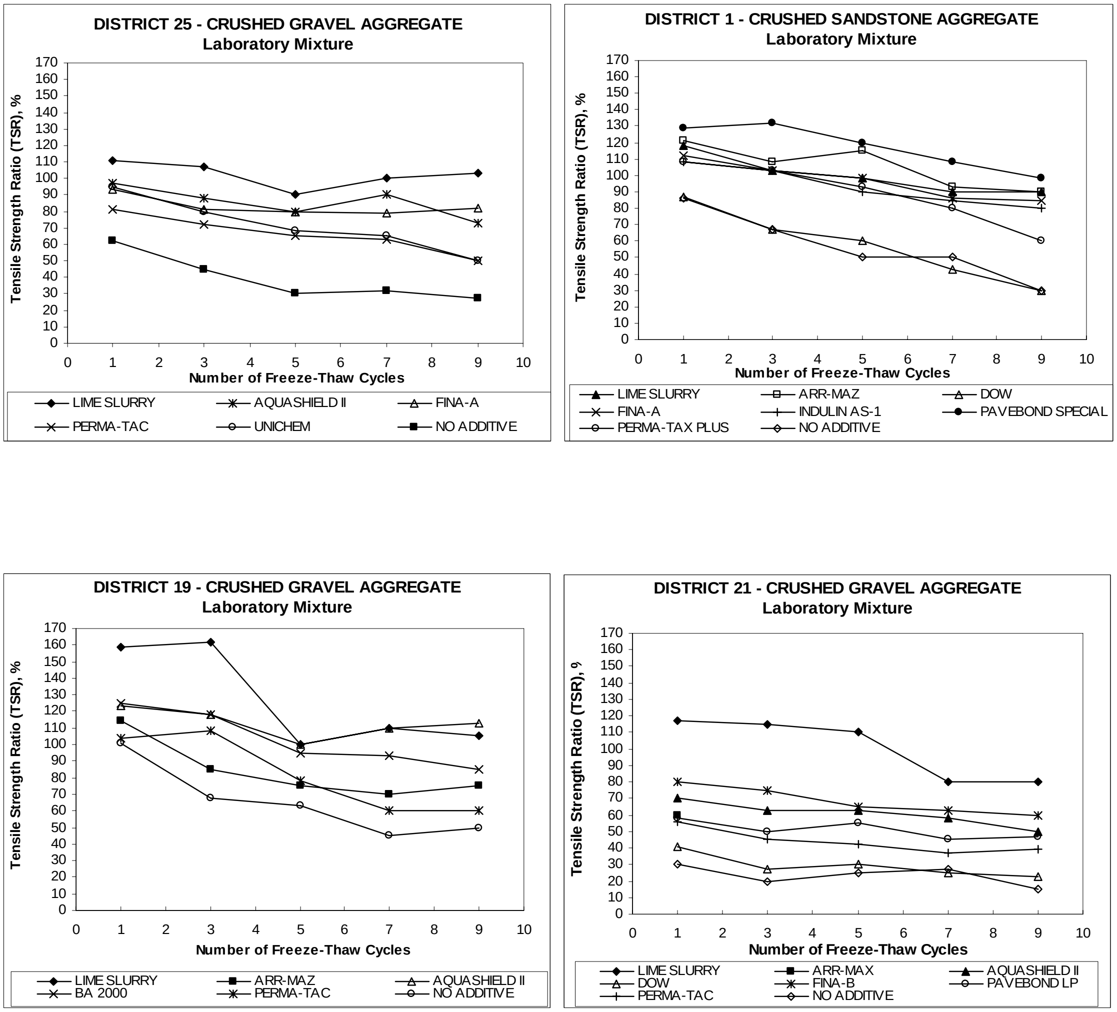
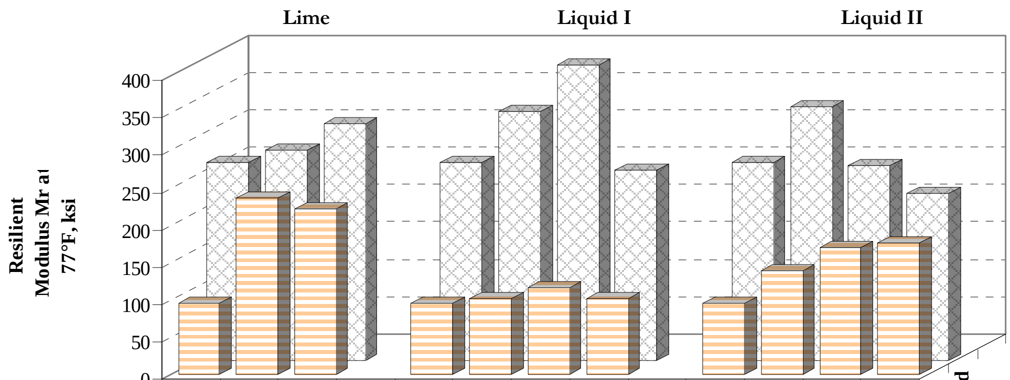


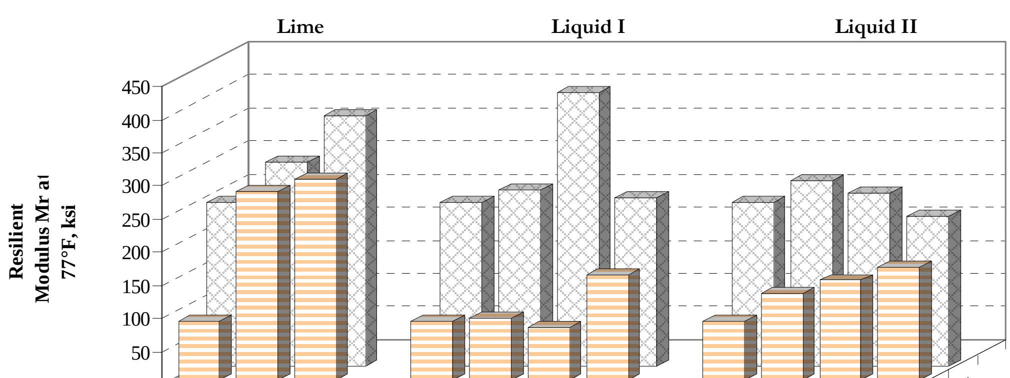
Figure 11. Multiple Freeze-Thaw Cyclic Tests Results for Laboratory Mixtures Comparing Severity of Tests Method on the Ability to Differentiate between Lime and Other Antistrip Additives [Kennedy and Ping (1991)] (continued).



	Lime 0	Lime 1	Lime 2	Liquid I 0	Liquid I 0.5	Liquid I 1	Liquid I 2	Liquid II 0	Liquid II 0.5	Liquid II 1	Liquid II 2
Conditioned	96	236	222	96	102	117	102	96	139	171	176
Unconditoned	264	280	316	264	332	394	253	264	338	260	223
Ratio %	36	84	70	36	31	30	40	36	41	66	79

Percent Additive, %

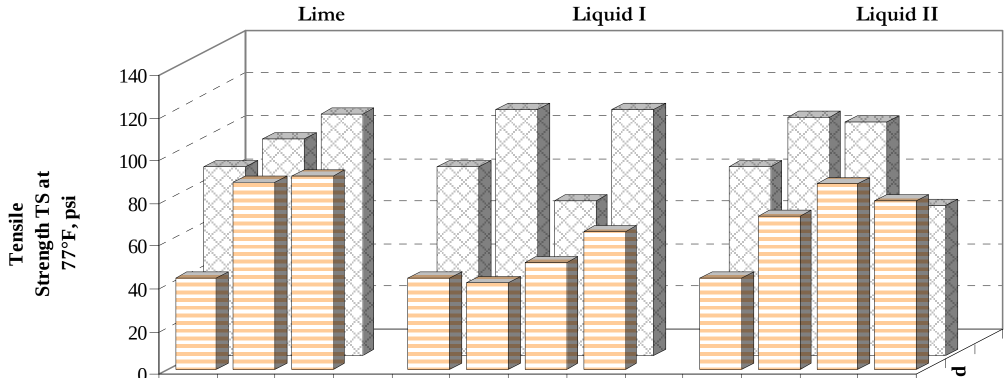
Figure 12. Comparison of Resilient Modulus before and after Moisture Conditioning for the Nevada Aggregate [Pickering at al (1992)].



	Lime 0	Lime 1	Lime 2	Liquid I 0	Liquid I 0.5	Liquid I 1	Liquid I 2	Liquid II 0	Liquid II 0.5	Liquid II 1	Liquid II 2
Conditioned	90	286	304	90	93	79	160	90	131	151	170
Unconditoned	246	307	377	246	264	412	252	246	279	260	225
Ratio %	37	93	81	37	35	19	63	37	47	58	76

Percent Additive, %

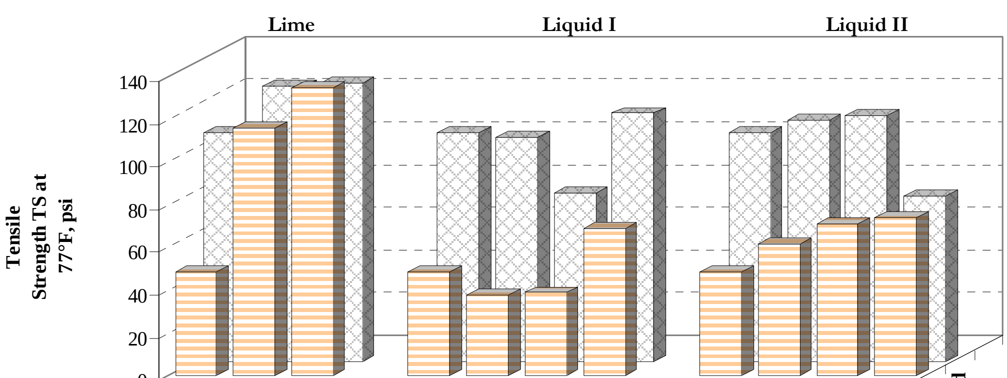
Figure 13. Comparison of Resilient Modulus before and after Moisture Conditioning for the California Aggregate [Pickering at al (1992)].



	Lime			Liquid I				Liquid II			
	0	1	2	0	0.5	1	2	0	0.5	1	2
Conditioned	43	88	91	43	41	50	65	43	72	87	79
Unconditoned	88	101	113	88	115	72	115	88	111	109	70
Ratio %	49	87	81	49	36	69	57	49	65	80	100

Percent Additive, %

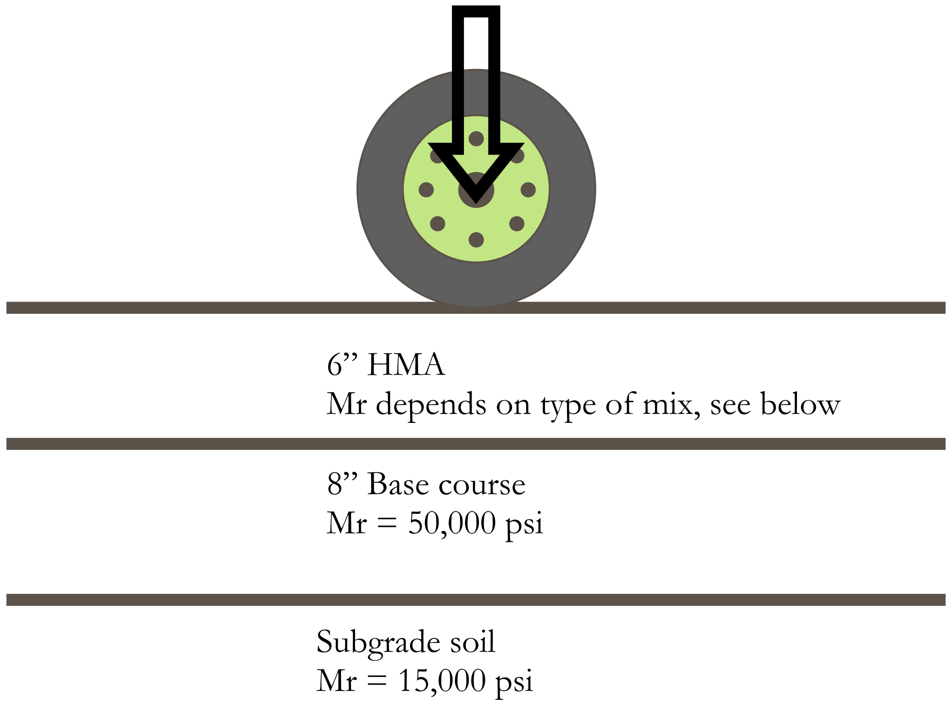
Figure 14. Comparison of Tensile Strength before and after Moisture Conditioning for the Nevada Aggregate
[Pickering at al (1992)].



	Lime			Liquid I				Liquid II			
	0	1	2	0	0.5	1	2	0	0.5	1	2
Conditioned	49	116	135	49	38	39	69	49	62	71	74
Unconditoned	107	129	130	107	105	79	116	107	113	115	77
Ratio %	46	90	100	46	36	49	60	46	55	62	96

Percent Additive, %

Figure 15. Comparison of Tensile Strength before and after Moisture Conditioning for the California Aggregate
[Pickering at al (1992)].



Mix Type	**Mr Property at 77°F, psi**			
	Unconditioned		**Conditioned**	
	Nevada	California	Nevada	California
Un-treated HMA	264,000	246,000	96,000	90,000
Lime-Treated HMA	316,000	377,000	222,000	304,000
Liquid I Treated HMA	394,000	252,000	117,000	160,000
Liquid II Treated HMA	260,000	260,000	171,000	151,000

Figure 16. Pavement Structure and Materials Properties used in the Mechanistic Analyses.

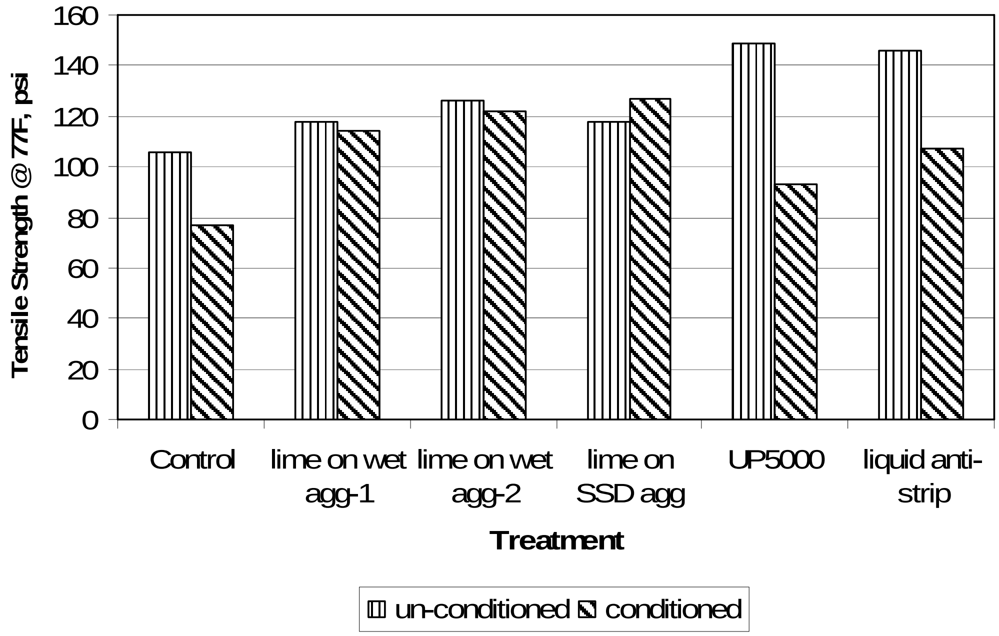


Figure 17. Tensile Strength Properties before and after One Freeze-Thaw Cycle for the South Dakota Section on SD314 [Sebaaly et al (2003)].

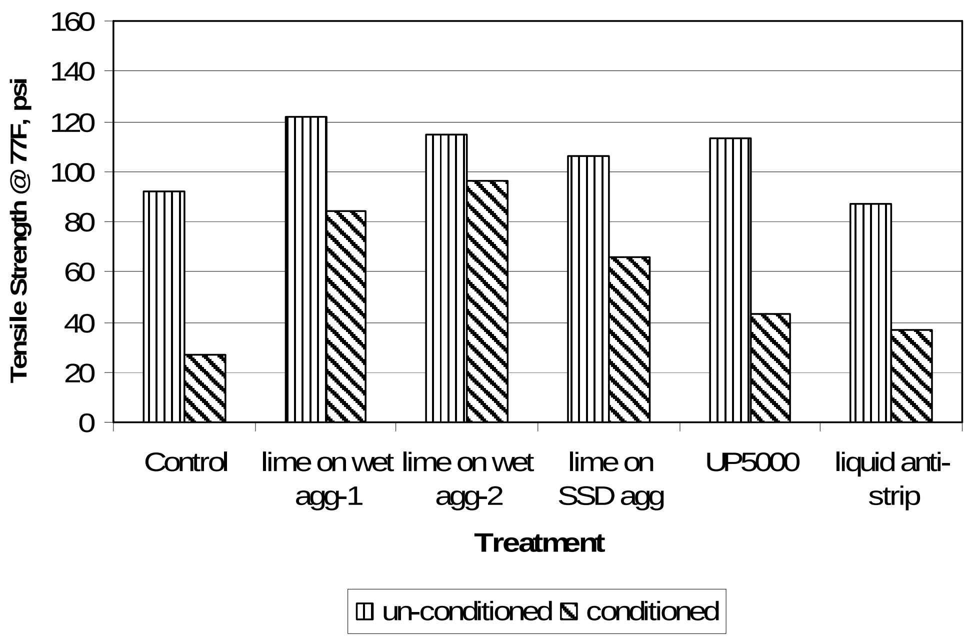


Figure 18. Tensile Strength Properties before and after One Freeze-Thaw Cycle for the South Dakota Sections on US14 [Sebaaly et al (2003)].

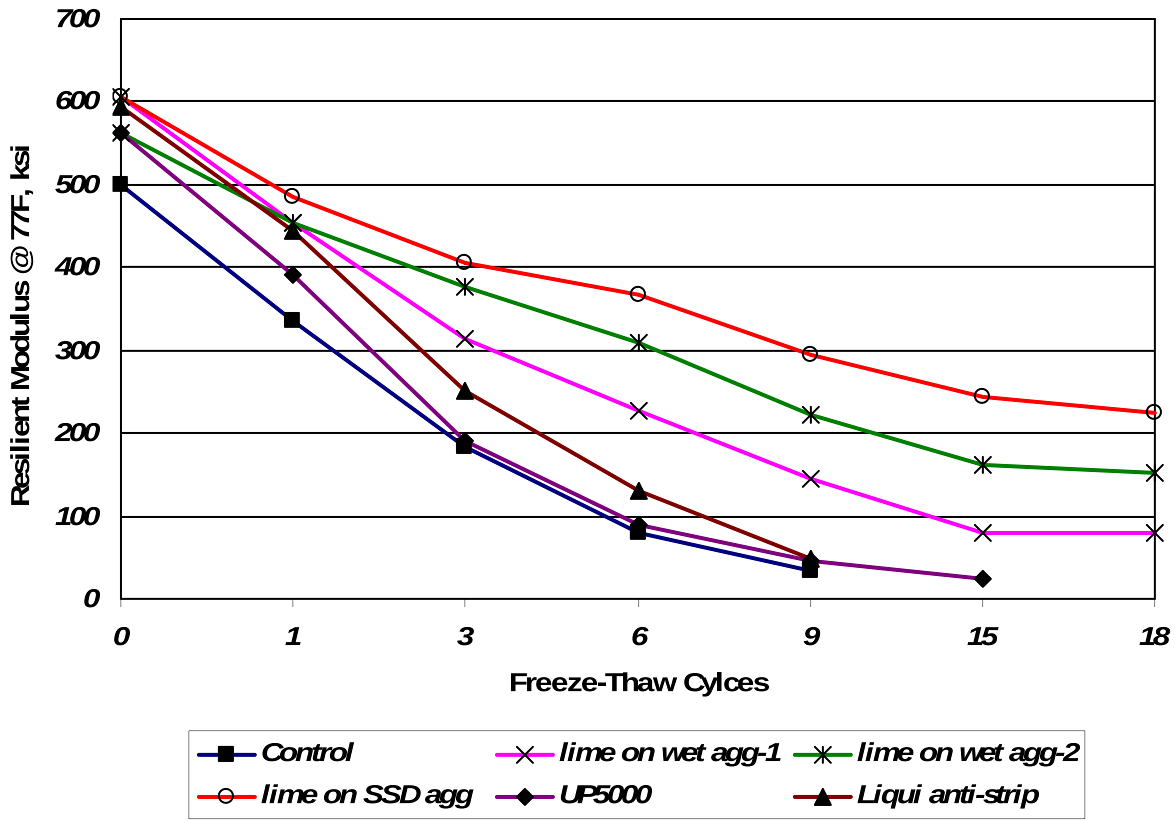


Figure 19. Resilient Modulus Properties after Multiple Freeze-Thaw Cycles for the South Dakota Sections on SD314 [Sebaaly et al (2003)].

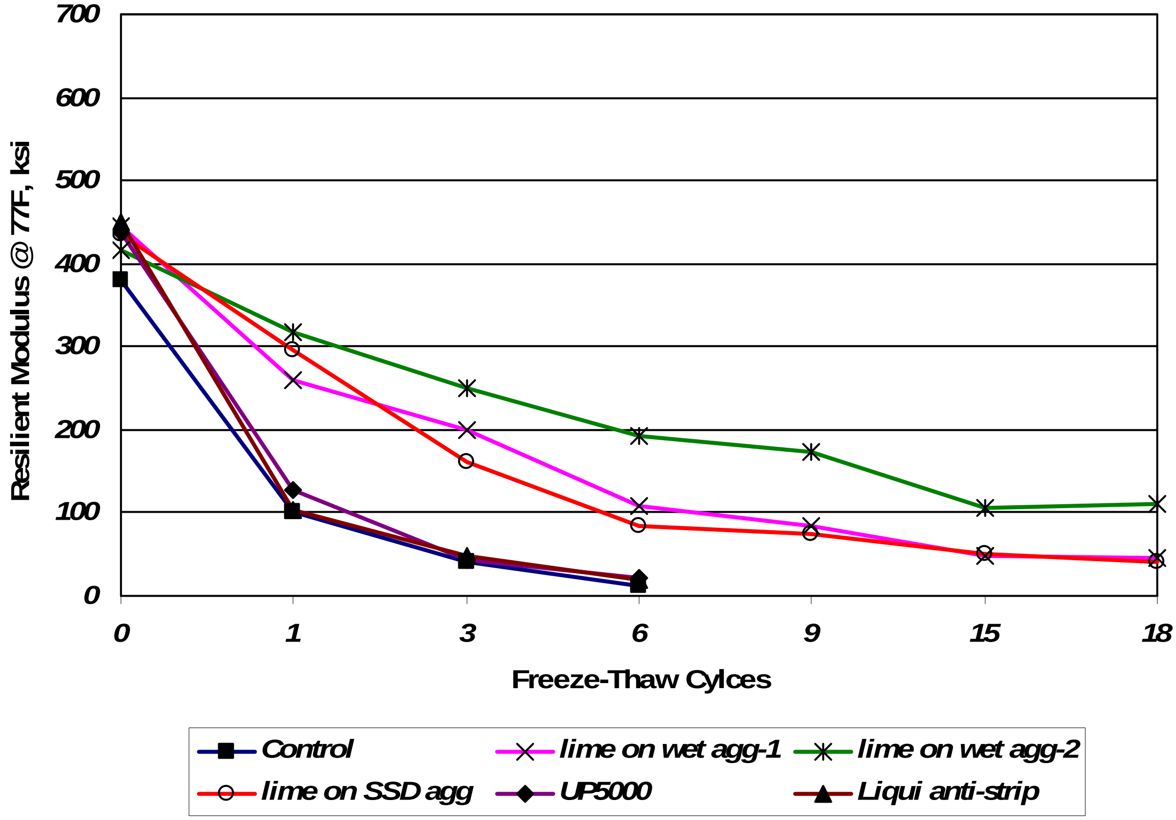


Figure 20. Resilient Modulus Properties after Multiple Freeze-Thaw Cycles for the South Dakota Sections on US14 [Sebaaly et al (2003)].

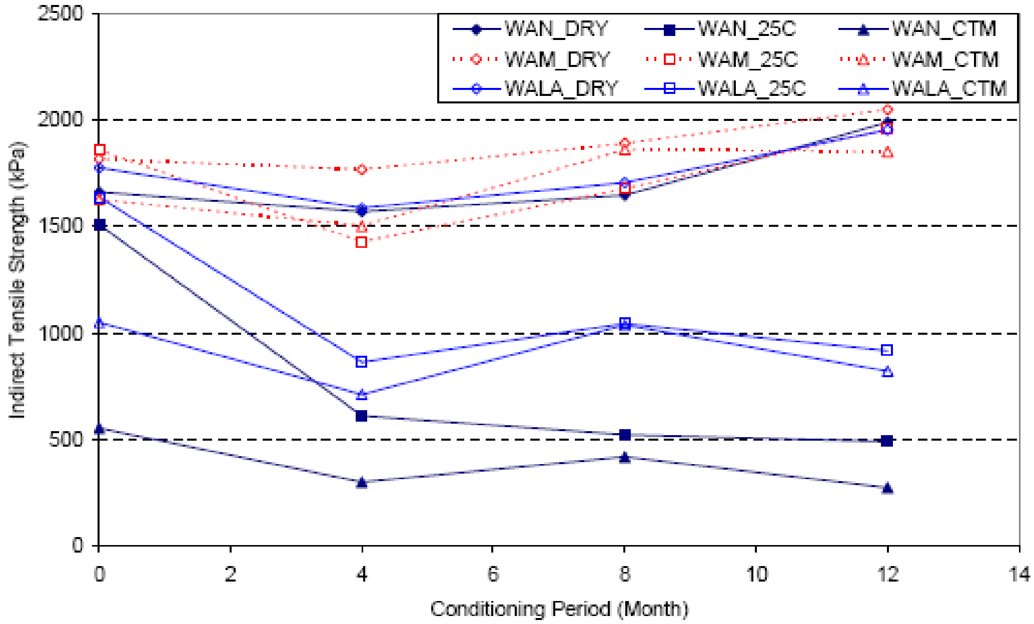


Figure 21. Tensile Strength Properties of the California HMA Mixture without Treatment, Lime-treated, and Liquid-Treated (WAN – control mix, WAM – lime-treated, WALA – liquid A-treated) [Lu and Harvey (2006)].

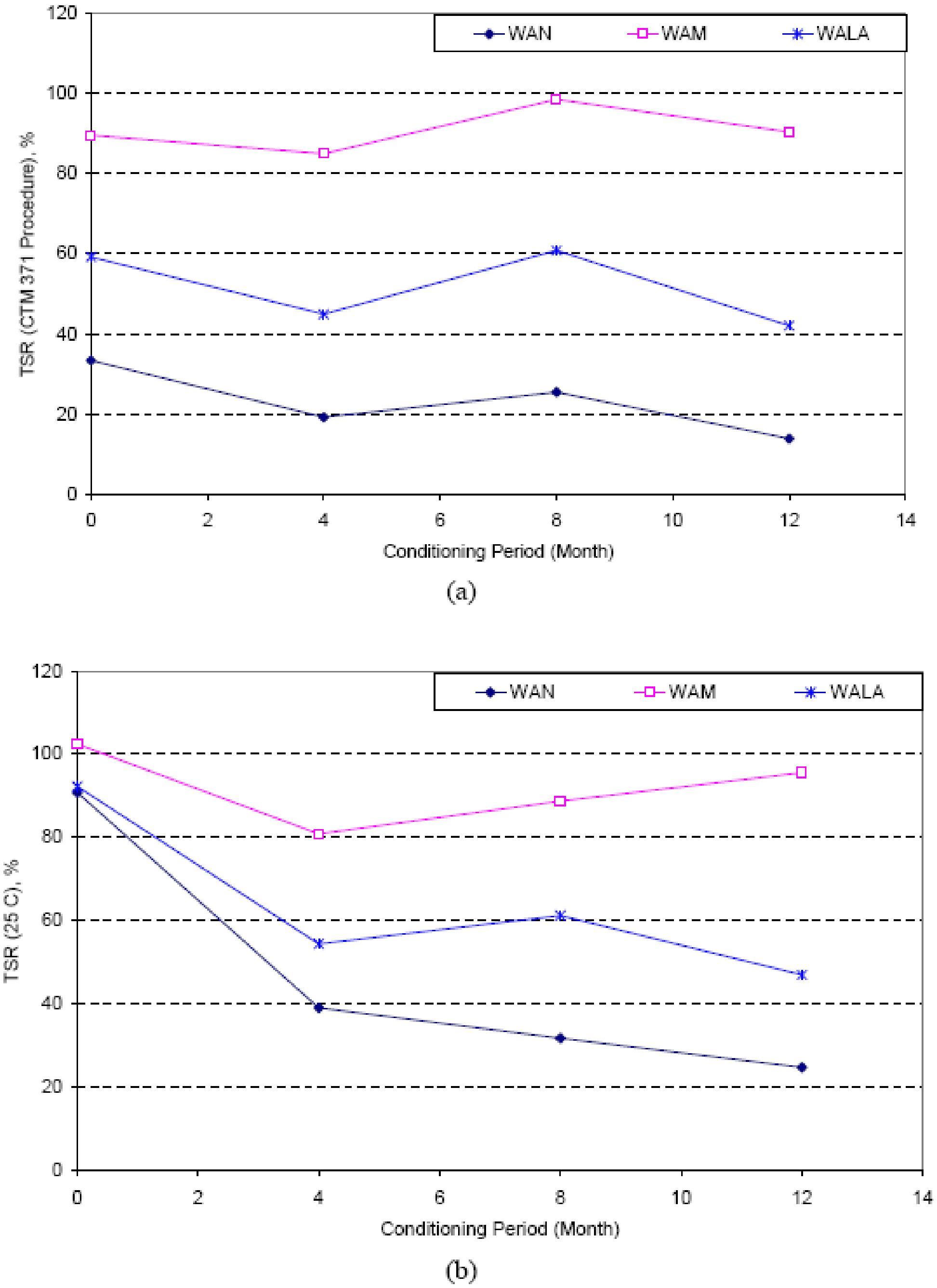


Figure 22. Tensile Strength Ratios of the California HMA Mixture without Treatment, Lime-treated, and Liquid-Treated (a – conditioned in 100% humidity and followed by a freeze-thaw cycle, b – conditioned I 100% humidity) [Lu and Harvey (2006)].

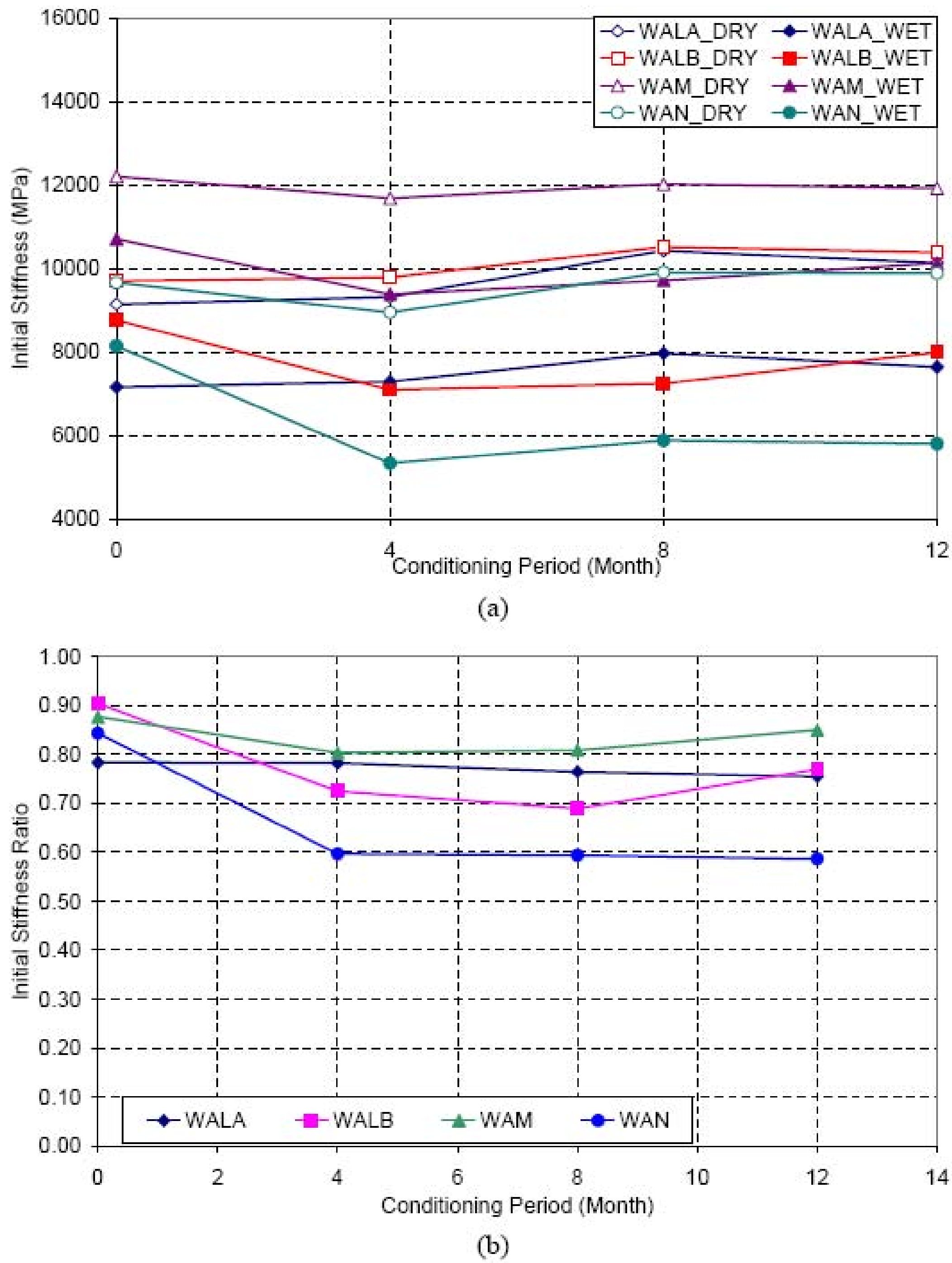
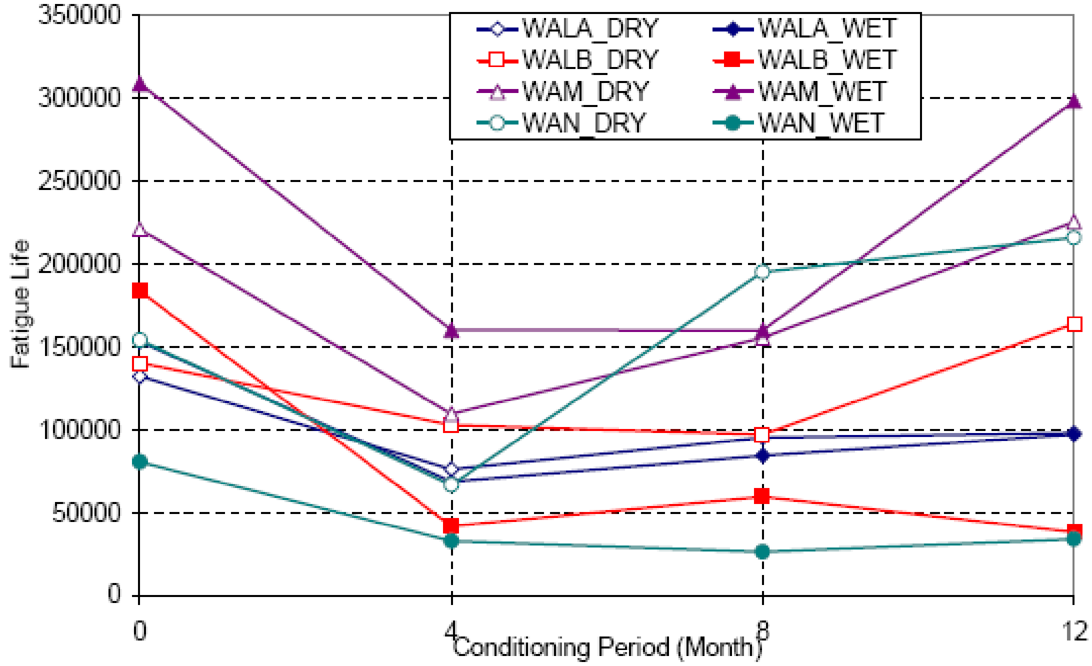
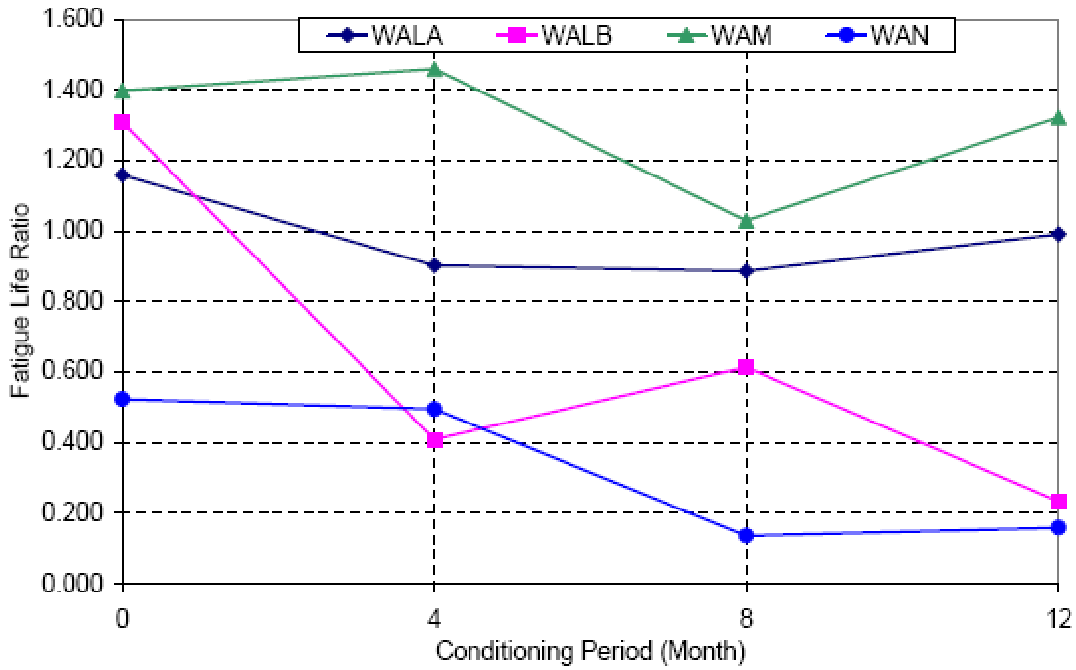


Figure 23. Initial Stiffness of the California HMA Mixture without Treatment, Lime-treated, and Liquid-Treated (WAN – control mix, WAM – lime-treated, WALA – liquid A-treated, WALB – liquid B-treated) [Lu and Harvey (2006)].



(a)



(b)

Figure 24. Fatigue Life of the California HMA Mixture without Treatment, Lime-treated, and Liquid-Treated (WAN – control mix, WAM – lime-treated, WALA – liquid A-treated, WALB – liquid B-treated) [Lu and Harvey (2006)].

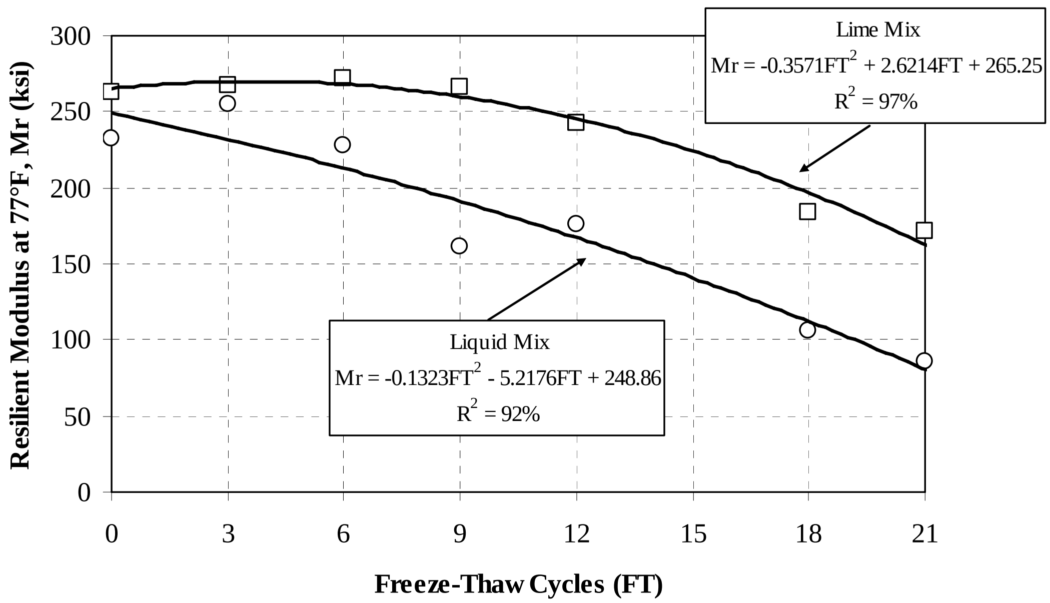


Figure 25. Resilient Modulus Properties at various Freeze-thaw Cycles of the Lime and Liquid Mixtures from the Idaho Project [Sebaaly et al (2006)].

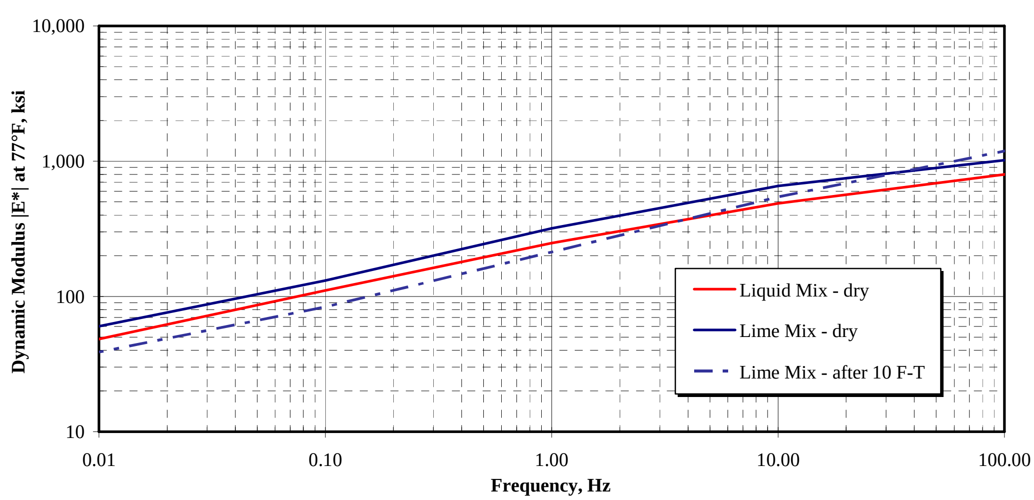


Figure 26. Dynamic Modulus Master Curves of the Lime and Liquid Mixtures from the Idaho Project [Sebaaly et al (2006)].

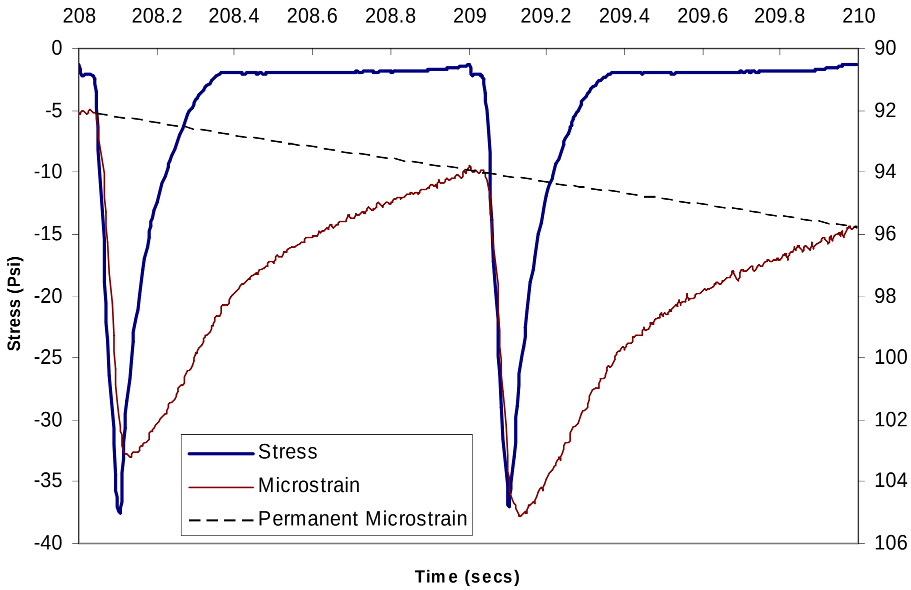


Figure 27. Typical Loading Function and Response from the Dynamic Creep Test that was used on the Idaho Project [Sebaaly et al (2006)].

Liquid Mix - Core 6C
(Failed after 19 Cycles)

Liquid Mix - Core 9C

Liquid Mix - Core 17C

Lime Mix - Core 7L

Lime Mix - Core 8L

Lime Mix - Core 14L

Figure 28. Conditions of the Cores from the Liquid and Lime Sections on the Idaho Project after 22 Freeze-thaw Cycles [Sebaaly et al (2006)].