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FINAL REPORT

Research on Fatigue of Asphalt Mixtures and Pavements in Nebraska

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16. Abstract

Hydrated lime has been recognized by the asphalt research community as a material capable to enhance various asphalt mixture properties and performance. In an attempt to mitigate moisture related damage, the Nebraska Department of Roads (NDOR) requires the use of 1.0% additional hydrated lime in the design of hot-mix asphalt (HMA) mixtures to be used in the roadways of the state. The 1.0% lime addition to pre-moistened aggregate may not be the best scenario to maximize pavement performance when pavement distresses such as fatigue cracking, rutting, and moisture damage are considered all together. Thus, it is necessary to investigate an appropriate amount of hydrated lime that would result in the most resistant mixture to various kinds of distresses when hydrated lime is specifically mixed with local asphalt paving materials in Nebraska. The current research project evaluated the stiffness (in the form of the dynamic modulus) and performance (permanent deformation and fatigue damage in both controlled-force and controlled-displacement modes) of mixtures with identical job mix formula and different only on the amount of additional hydrated lime (0.5%, 1.0%, 1.5%, 2.0% and 3.0%). Required testing facilities and devices were installed (or developed at the University of Nebraska (UNL) Geomaterials Laboratory) to allow this project to be conducted. Two testing modes were used: Indirect Tensile (IDT) and Uniaxial Tensile tests. The test results generally showed that the increasing trend of resistance to fatigue damage in controlled-force mode as more hydrated lime was added to the mixtures, which was not observed from the controlled-displacement fatigue tests. The number of cycles to failure reached its maximum value for the 1.5% additional hydrated lime case when the specimens were subjected to the controlled-displacement fatigue testing mode. Extra lime resulted in worse performance. The resistance of the mixtures to the permanent deformations was generally enhanced as more hydrated lime was added, but it seemed to have stabilized after the use of 2.0% hydrated lime. The findings from this project can be strengthened with more data and additional work. Suggested follow-up studies conclude this report.

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CHAPTER 1
INTRODUCTION

Hydrated lime has long been recognized as a highly beneficial component of hot-mix asphalt (HMA) mixtures, based on its ability to reduce moisture sensitivity and stripping. Subsequent research and experience have also demonstrated that the benefits of hydrated lime are much broader, and include:

- Increased mix stiffness and reduced rutting,
- Reduced oxidation and age-hardening effects, and
- Improved low-temperature cracking resistance.

Due to multifunctional effects of hydrated lime, many states including Nebraska have used and/or are currently using hydrated lime to promote pavement performance and to save life cycle cost. The state of Nebraska specified that one percent of hydrated lime by weight of virgin aggregate typically needs to be added to all pre-moistened aggregate in asphalt concrete mixtures.

Hydrated lime in asphalt mixtures can reduce pavement rut-depth due to its distinct stiffening effects and moisture-associated damage by improving the aggregate-asphalt bonding. Aside, several experimental studies have shown that hydrated lime can also reduce asphalt cracking to some extent, because the initial microcracks can be intercepted and deflected by tiny, active lime particles. In fact, the second author has demonstrated fatigue crack resistant characteristics of lime-treated asphalt mixtures using cylindrical sand-asphalt samples and dynamic mechanical testing protocol that he developed.

However, the effects of hydrated lime as a crack resister need to be investigated with more care, since stiffer asphalt mixes are generally more susceptible to cracking. It is obvious that the effects of hydrated lime on fatigue damage due to cracking depend on many factors: amount of lime treated, treating method of lime, properties of mixture constituents such as aggregates and asphalt binder, and many more. One percent lime addition to pre-moistened aggregate, that is a currently employed approach in Nebraska, may not be the best scenario to maximize pavement performance when pavement distresses such as fatigue cracking, rutting, and moisture damage are considered all together. Appropriate use of hydrated lime with local asphalt paving materials in Nebraska needs to be determined scientifically, not arbitrarily.

1.1. RESEARCH OBJECTIVES

The primary objective of this research is to find out an optimum treatment of hydrated lime for HMA mixtures used in Nebraska pavements by primarily performing fatigue tests in conjunction with tests for rut-performance of asphalt mixtures. Furthermore, this study also includes the development of a mechanical testing system that can be used to perform various performance-related tests of asphalt mixtures. Research outcomes are expected to be fundamental bases for improving asphalt pavement design in Nebraska.

1.2. RESEARCH SCOPE

To accomplish the objectives, this study has been performed in two phases. Phase 1 consists of literature review, material selection, and volumetric mixture design of five *SP4 Special* HMA mixtures with different application rates of hydrated lime. Phase 2 consists of the fabrication of compacted asphalt concrete specimens and mechanical property-performance tests (dynamic moduli of mixtures, fatigue tests, and permanent deformation tests) of the asphalt concrete specimens. Based on the property-performance test results, the effect of hydrated lime on mechanical performance behavior of mixtures is summarized in the final report with meaningful findings and recommended future work.

1.3. ORGANIZATION OF THE REPORT

This report is composed of six chapters. Following this introduction, Chapter 2 summarizes reviews of literature of the effects of hydrated lime on HMA mixture performance. In Chapter 3, detailed descriptions of material selection and HMA volumetric mixture design methods employed for this study are presented. Chapter 4 describes the testing facility that was developed and the test methods employed in this study. Test methods include (1) the indirect tensile (IDT) tests used to investigate undamaged viscoelastic stiffness in the form of the dynamic modulus, force-controlled fatigue damage performance, and permanent deformation resistance of HMA specimens; and (2) the uniaxial tensile tests of HMA cylindrical specimens used to perform displacement-controlled fatigue tests. Chapter 5 presents the laboratory test results and the corresponding analyses of test data. Finally, Chapter 6 provides a summary of the findings and conclusions of this study. Recommended future research and implementation plans to the Nebraska Department of Roads (NDOR) are also presented in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

2.1. EFFECTS OF HYDRATED LIME ON PAVEMENT PERPORMANCE

Hydrated lime has been used as a mineral filler and an anti-stripping agent in HMA mixtures by many agencies across North America, including NDOR. Besides working as an anti-stripping agent, hydrated lime has also been recognized to improve the properties and performance of asphalt mixtures.

The mechanisms and reactions occurring in the hydrated-lime-modified HMA mixtures are not fully understood (Bari and Witczak, 2005). Nevertheless, it is known that hydrated lime forms insoluble salts with the highly polar molecules of the asphalt; this could decrease reactions with other mixture constituents to form water-soluble soaps that might promote stripping. Hydrated lime also improves the aggregate-asphalt bonding. The long-term oxidative aging potential of HMA can be reduced by the addition of hydrated lime. It can then be inferred that hydrated lime can reduce the viscosity-building polar components in the binder. Mixture segregation can be reduced by the use of hydrated lime because the finer particles of this material increase the binder film thickness and improve the binder cohesion, which leads to increased adhesion between aggregates and binder.

Bari and Witczak (2005) also reported that hydrated lime increases the indirect tensile strength and resilient modulus of mixtures. Moreover, the slope of HMA fatigue curves increases with the addition of hydrated lime, which means that these mixtures support more loading cycles before failure. Rutting performance also improves because of the use of hydrated lime.

The National Lime Association (2006) has justified the improvement in fatigue performance of asphalt mixtures by the addition of hydrated lime with the following argument: “The greater improvement in fatigue life due to the addition of hydrated lime is a result of the reaction between hydrated lime and the polar molecules in the asphalt cement, which increases the effective volume of the lime particles by surrounding them with large organic chains. Consequently, the lime particles are better able to intercept and deflect microcracks, preventing them from coalescing into large cracks that can cause pavement failure."

Mohammad *et al.* (2000) evaluated engineering properties, permanent deformation characteristics, resilient modulus and fatigue resistance of a typical Louisiana low-volume dense-graded mixture with and without hydrated lime. The effect of hydrated lime on HMA mixtures containing styrene-butadiene modified binder was compared with the effect on the same mixture containing AC-30 asphalt cement. The tests conducted included indirect tensile strength and tensile strain, creep compliance, resilient modulus, fatigue life and the Hamburg loaded-wheel tracking. From the results the authors concluded that mixtures with hydrated lime generally showed an improved performance. Also, the mixtures with hydrated lime and the polymer-modified asphalt binder showed the most improvement, particularly in tests performed at higher temperatures.

Sebaaly *et al.* (2003) conducted a study to assess the effectiveness of lime in reducing moisture sensitivity of the Nevada Department of Transportation's (NDOT) HMA mixtures. They evaluated samples from eight field projects and analyzed data for eight in-service projects. They concluded that lime significantly improved the moisture resistance of HMA mixtures. According to them, lime-treated HMA mixtures were more resistant to multiple freeze-thaw cycles than the untreated mixtures. They also concluded that NDOT was able to maintain a better average Present Serviceability Index (PSI) on pavements built with lime-treated mixtures with less maintenance than pavements with untreated HMA mixtures. Finally, the authors suggested that the use of lime resulted in a 38% average extension in the life of the pavements, and that compares very favorably with the percent increase in the cost of HMA mixtures of 12% due to lime treatment.

Kim *et al.* (2003) investigated the effect of fillers and binders on the fatigue performance of asphalt mixes. For this purpose, the researchers used two binders (AAD-1 and AAM-

1) and two fillers (hydrated lime and limestone) in three different volume fractions (5, 10, and 25% filler/asphalt ratio). To analyze the effects of fillers, the authors used the theory of viscoelasticity, a continuum damage fatigue model, and a rheological particulate composite model. They concluded that the filler type affected the fatigue behavior of asphalt binders and mastics. Fillers also stiffened the binders, and hydrated lime was more effective in stiffening binders than limestone fillers. Another conclusion was that even if the fillers stiffened the binders, they acted in such a way that they provided better resistance to microcracking and thus an increased fatigue life. The better performance observed in the case of hydrated-lime-mixed mastics was interpreted to be an indicator that a mechanism beyond the volume-filling effect occurred. This is also supported by Sebaaly *et al.* (2006). Finally, the researchers concluded that the physicochemical interaction between the binder and the filler was material specific, since the improvement in fatigue life due to hydrated lime was much greater for the AAD-1 mix than for the AAM-1 mix.

Sebaaly (2006) updated a work from Little and Epps (2001), where the advantages of hydrated lime in HMA mixtures were analyzed. They suggested that the ability of hydrated lime to improve the resistance of HMA mixtures to moisture damage, oxidative aging, mechanical properties, and fatigue and rutting performances results in approximate savings of $20 per ton of HMA. They also analyzed field data and concluded that hydrated lime increased the average pavement life by approximately 38%.

Little and Petersen (2005) conducted a study to identify the unique effects of hydrated lime on the performance-related properties of asphalt cements. They concluded that if hydrated lime reacted as active filler with a binder, as shown by Kim *et al*. (2003) to occur for AAD-1 binders but not for AAM-1 binders, then the hydrated lime provided a high-temperature filler effect that was greater than that predicted by models that did not account for physical interactions between materials. However, it was shown that the effect of hydrated lime decreased as the temperature was lowered. For very low temperatures, such as -20°C, the authors suggested that the stiffening provided by the use of hydrated lime was similar to that provided by any other filler. They also concluded that the addition of hydrated lime toughened the mastics, which accounted for a higher resistance to fracture and crack propagation. Another finding was that hydrated lime was much more effective in extending fatigue life and in improving low-temperature cracking than the limestone-type filler. Finally, they concluded that hydrated lime was more effective than limestone and that this effectiveness was bitumen dependent.

Bari and Witczak (2005) stated that the effects of hydrated lime on the dynamic modulus of HMA mixtures have rarely been evaluated. The authors mentioned that this evaluation was important since the dynamic modulus is the design stiffness parameter at all three levels of hierarchical input for the HMA characterization of the new Mechanistic-Empirical Pavement Design Guide (MEPDG). In their studies, the authors used four different binders, different hydrated lime contents and mixtures from varying locations, such as Two Guns, Maryland Department of Transportation, WesTrack, Bidahouchi and the Salt River base. The general trend for all the mixtures was an increase in stiffness with the addition of hydrated lime. However, for the Two Guns mixtures, 2.0% of hydrated lime addition produced less stiff mixtures than the 1.0% addition case. As an average, the rank of improvement in the stiffness for the different contents analyzed from worst to best was: 2.0%, 1.0% and 1.5%, 3.0%, and 2.5%. This rank was based on the average of ratios between the stiffness of the mixtures with and without hydrated lime. The respective average ratios were of 1.17, 1.21 and 1.21, 1.28, and 1.50. Finally, the authors quantified the amount of hydrated lime that interacted with the binders to increase their stiffness. For 1.0% addition, the percent interacting with the binder was about 2.8%. For the 2.0% case, this number jumped to 3.3%. They concluded that the variation in these values reflected the complex interaction of hydrated lime with binder type and quality and aggregate characteristics and gradation.

2.2. VISCOELASTIC PROPERTIES OF ASPHALT MATERIALS

Smith (2004) defined viscoelastic material as “one that can both store and dissipate mechanical energy in response to deformation by a mechanical stress. The storage ability is referred to as elasticity and the dissipative losses are due to viscous effects.” According to the author, an elastic material is the one that responds instantaneously to the solicitations, whereas viscous effects act to delay the response to a time-varying stress or strain. This delay is called "phase angle" or "time lag." A phase angle (ϕ) of 90° represents a perfect viscous behavior, whereas the 0° time lag characterizes an elastic material. Viscoelastic materials have phase angles between 0° and 90°. This means that when they are loaded, parts of the deformation are recoverable or elastic, and the remaining parts are irrecoverable or viscous.

According to Kim *et al.* (2002), the viscoelastic properties that should be obtained when modeling asphalt mixtures are creep compliance, relaxation modulus, or complex modulus (from which the phase angle and dynamic modulus are determined). The authors stated that the creep compliance and the complex modulus can be easily obtained from testing, whereas the relaxation modulus cannot be easily obtained from testing, because of the high initial load caused by a step displacement input. However, the authors suggested that these three material properties were related, and they showed procedures to obtain the relaxation modulus from either the creep compliance or the complex modulus.

The asphalt resistance to deformation when subjected to a repeated sinusoidal load is represented by the complex modulus (E^*). This modulus is expressed by a complex number composed of a real and an imaginary part. The real part is related to the so-called storage or elastic modulus (E'), whereas the imaginary part represents the loss or viscous modulus (E''). The dynamic modulus can be obtained from the storage and loss modulus by using Equation 2.1.

$$\left|E^*\right| = \sqrt{(E')^2 + (E'')^2} \tag{2.1}$$

where E' and E'' can be obtained from $\left|E^*\right|$ and ϕ by using the following relationships:

$$E' = \left|E^*\right| \cos\phi \tag{2.2}$$

$$E'' = \left|E^*\right| \sin\phi \tag{2.3}$$

The other two viscoelastic characteristics, stress relaxation and creep, were defined by Smith (2004) as follows: stress relaxation is the phenomenon of decay occurring over the time of induced stresses in a body when a strain is applied and then maintained constant (step function). Whereas creep is the increase in the strain deformation over time when stresses are applied as a step function to a body and may be defined as the time-dependent part of strain due to an applied stress. Creep compliance is the time-dependent strain divided by the applied stress (AASHTO T322). Relaxation modulus is the stress per unit of applied strain (Findley *et al.*, 1976).

Kim *et al*. (2004) suggested that the dynamic modulus is the most important HMA property to be characterized. The dynamic modulus represents the temperature- and frequency-dependent (and thus time-dependent) stiffness characteristics of the material. Contrary to the Simple Performance Test (SPT) protocol (Witczak *et al.*, 2002) where uniaxial-triaxial compressive testing to a HMA cylindrical test specimen was proposed to characterize the dynamic modulus, the authors claimed the indirect tensile (IDT) testing mode to be more appropriate. This was due to the limitation in size of the in-situ cored samples. The uniaxial-triaxial compressive testing mode requires a long specimen (generally 150 mm tall) for testing. This is not practical considering a typical asphalt layer thickness. However, more care must be taken when deriving the viscoelastic material properties under the IDT testing mode because of the biaxial stress-strain state that occurs in an IDT specimen. The modulus of the material cannot be obtained by simply dividing the horizontal stress by the horizontal strain. Instead, the modulus is associated with the ratio between the biaxial stress and the horizontal strain.

Considering linear viscoelasticity theory and the biaxial stress-strain state developed in an IDT specimen, Kim *et al*. (2004) derived an analytical solution for the dynamic modulus and presented the following expression:

$$|E^*| = 2\frac{P_o}{\pi a d}\frac{\beta_1\gamma_2 - \beta_2\gamma_1}{\gamma_2 V_o - \beta_2 U_o} \qquad (2.4)$$

where P_o = amplitude of the sinusoidal load applied,

a = loading strip width,

d = specimen thickness,

U_o = constant amplitude of horizontal displacements,

V_o = constant amplitude of vertical displacements, and

$\beta_1, \beta_2, \gamma_1, \gamma_2$ = coefficients related to the specimen diameter and gauge lengths.

The calculated values for several combinations of specimen diameter and gauge lengths are given in Table 2.1 (Kim *et al.*, 2004). The authors validated the accuracy of their solution with experimental data from both uniaxial and IDT tests.

Table 2.1. Coefficients for Dynamic Modulus Determined from IDT Testing

Specimen Diameter (mm)	Gauge Length (mm)	β_1	β_2	γ_1	γ_2
101.6	25.4	-0.0098	-0.0031	0.0029	0.0091
101.6	38.1	-0.0153	-0.0047	0.0040	0.0128
101.6	50.8	-0.0215	-0.0062	0.0047	0.0157
152.4	25.4	-0.0065	-0.0021	0.0020	0.0062
152.4	38.1	-0.0099	-0.0032	0.0029	0.0091
152.4	50.8	-0.0134	-0.0042	0.0037	0.0116

Kim *et al*. (2004) also suggested that the reduction in the number of testing temperatures recommended by AASHTO TP62 (2003) to be three instead of five, could be compensated for by adding two more testing frequencies. With that modification, the time required to conduct the necessary experiments to create a master curve would drop from 11 or 12 hours to less than 8 hours. The suggested testing temperatures and frequencies were, respectively, -10°C, 10°C and 35°C and 0.01Hz, 0.05Hz, 0.1Hz, 0.5Hz, 1Hz, 5Hz, 10Hz and 25Hz. The number of cycles of loading suggested for each testing frequency is shown in Table 2.2.

Table 2.2. Frequencies and Number of Cycles of IDT Dynamic Modulus Tests

Frequency (Hz)	Cycles
25	200
10	200
5	100
1	20
0.5	15
0.1	15
0.05	15
0.01	15

Since the stiffness of asphalt is time dependent, Anderson *et al.* (1994) suggested that such a material be classified as a rheological material. The word is derived from the Greek “rheo” which translates literally as “to flow.” In addition, asphalt is also temperature dependent. Therefore, loading rate and temperature variations should be taken into account when characterizing the flow properties of asphaltic materials.

The time-temperature dependency in materials such as asphalt can be classified as thermo-rheologically simple, because they exhibit similar behavior at fast loading rates and cold temperatures and at slow loading rates and warm temperatures. This time-temperature dependency can be represented by a single parameter called reduced time, ξ, through the time-temperature superposition principle. This principle is a powerful tool to predict material behavior over a range of loading times that are much wider than the range of testing times. Lundström and Isacsson (2004) and Kim *et al.* (2002) expressed the reduced time as shown in Equation 2.5.

$$\xi = \frac{t}{a_T} \tag{2.5}$$

where t = physical time (duration of test), and

a_T = time-temperature shift factor.

Kim *et al.* (2002) also suggested that, since the complex modulus is described as a function of frequency (*f*), a new parameter called reduced frequency, ζ should be used. Equation 2.6 represents the reduced frequency as a function of a_T.

$$\zeta = f \times a_T \tag{2.6}$$

The shift factor can be determined from any of the linear viscoelastic tests and should be the same for all the viscoelastic material properties, including creep compliance, relaxation modulus, and complex modulus. A more detailed discussion will appear later in the section in Testing Facilities and Methods.

2.3. FATIGUE AND RUTTING DISTRESSES

There are several factors and mechanisms that cause failure of asphalt concrete structures. Figure 2.1 shows a section of pavement in the west part of Lincoln, Nebraska with severe damage.

Figure 2.1. Distresses of a Low Traffic Pavement in Lincoln, Nebraska

Among the documented distresses in asphalt concrete layers, the most common distresses that control pavement structural design are fatigue cracking and rutting. Following is a brief description of each distress.

2.3.1 Fatigue or alligator cracking

Fatigue cracking occurs due to an inadequate structural support for the given loading, which can be caused by: the decrease in pavement-load-supporting characteristics due to loss of base, subbase or subgrade support resulting from poor drainage or stripping at the bottom of the HMA layer; the level of load that exceeds the level anticipated by the design; inadequate structural design; and poor construction procedures such as inadequate compaction. Brown *et al*. (2001) demonstrated that for thin pavements, fatigue cracking started at the bottom of the HMA due to high tensile strains and migrated upward toward the surface; whereas for thick pavements, cracks started on the HMA surface due to tensile strains at the surface and migrated downward. If not properly repaired with time, this distress allows moisture to infiltrate and leads to problems arising from moisture damage. Figure 2.2 illustrates a fatigue failure of a pavement section in Lincoln, Nebraska. Potholes, which are shown in Figure 2.3, are physically separated pieces of HMA dislodged from the pavement by the action of traffic and from fatigue cracking.

Figure 2.2. Fatigue-Damaged Pavement in Lincoln, Nebraska

Figure 2.3. Pothole Created as a Result of Severe Fatigue Damage

Huang (2004) stated that there are two types of controlled loading that can be applied in fatigue tests: controlled-stress (or force) and controlled-strain (or displacement). In the controlled-stress tests, the stress remains constant and the strain increases with the number of repetitions. On the other hand, in the controlled-strain tests, the strains are held constant and the stress decreases with the cyclic strain application. Ghuzlan and Carpenter (2000) refer to Monismith and Salam (1973) to suggest that controlled-stress loading represented the behavior of thick pavements where the HMA layer was approximately more than six inches thick. The controlled-strain loading mode was applicable to thin pavements, which are HMA layers less than two inches thick.

According to Ghuzlan and Carpenter (2000), the fatigue life obtained using controlled-stress testing was shorter than the fatigue life obtained from the controlled-strain testing. Damage was done faster in the controlled-stress testing than controlled-strain testing, because the same stress was used during the test, whereas it decreased during controlled-strain testing. In their work, the authors used the concept of energy dissipation to define a unified failure criterion for both controlled-stress and controlled-strain testing modes. According to the authors, dissipated energy examined as a change between two load cycles provided a more fundamentally correct indication of damage occurring between load cycles than cumulative dissipated energy. They proposed that the ratio in the dissipated energy between cycles and the total dissipated energy to sample failure provided a consistent failure indicator that appeared to be independent of the mode of loading.

Tangella *et al*. (1990) reviewed the main factors affecting the fatigue performance of dense-graded HMA mixtures. They also reviewed various available fatigue test methods, addressed the advantages and disadvantages of these methods and ranked them in order of preference. The test methods evaluated were: simple flexural test, supported flexure test, direct axial test, indirect tensile (IDT) test, fracture mechanics test, and wheel-tracking test. The flexural test was ranked as the best. Even though the IDT test resulted in a complex biaxial stress state and underestimated fatigue life, it was ranked second because it was simple and used the same equipment as the other tests.

2.3.2. Permanent Deformation or Rutting

Rutting represents surface depressions as shown in Figure 2.4. Possible causes of rutting include: insufficient compaction effort during construction, which results in increasing densification of the mix under traffic loads; inadequate pavement structure, which causes rutting in the subgrade; and improper mix design due to too many rounded aggregates, excessive asphalt content, or insufficient air voids, which causes rutting in the HMA.

Figure 2.4. Permanent Deformation (Rutting)

Kandhal and Mallick (2001) found that stiffer binder courses with larger aggregates generally had less rutting potential compared with more flexible courses with finer aggregates and higher asphalt contents.

Witczak *et al*. (2002) conducted a study on the different available testing procedures for characterization of HMA performance related to rutting, fatigue cracking, and low-temperature cracking. The final product of their study consisted of five test methods called simple performance tests (SPT), and three of them are related to characterization of rutting performance of HMA mixtures:

- Test method for dynamic modulus of asphalt-concrete mixtures for permanent deformation,
- Test method for repeated load testing of asphalt-concrete mixtures in uniaxial compression (flow number test), and
- Test method for static creep and flow time of asphalt-concrete mixtures in compression (flow time test).

CHAPTER 3
MATERIALS AND MIXTURE DESIGN

This chapter describes materials and mixture design methods used to obtain five HMA mixtures satisfying NDOR *SP4 Special* mixture design specifications. Each mixture was designed with the same blend of aggregates in order to keep constant overall aggregate angularities and mineralogical characteristics. The only variable in the mixtures was the amount of hydrated lime, which ranged from 0.5% to 3.0%.

3.1. MATERIALS SELECTION

To accomplish the most realistic simulation of HMA mixtures paved in Nebraska, common local aggregates and asphalt binder were selected for fabricating laboratory samples.

3.1.1. Aggregates

A total of six local aggregates were used in this project. These were 5/8-inch Limestone (5/8" LS), 1/4-inch Limestone (1/4" LS), Screenings, and several crushed gravels: 2A, 3ACR, and 47B. These aggregates were selected because they are most widely used by Nebraska pavement contractors. Table 3.1 illustrates laboratory-measured physical properties such as bulk specific gravity (G_{sb}) and absorption capacity of each aggregate. In addition, important Superpave aggregate consensus properties, coarse aggregate angularity (CAA), fine aggregate angularity (FAA), and sand equivalency (SE) are also presented in the table. Each aggregate demonstrates very different characteristics, so a wide range of aggregate blends meeting the target specific gravity and angularity can be obtained.

Table 3.1. Fundamental Properties of Aggregates

Aggregate	*Aggregate Property*						
	Fine Aggregate			*Coarse Aggregate*			
	G_{sb}	*Absorption Capacity (%)*	*FAA (%)*	G_{sb}	*Absorption Capacity (%)*	*CAA (%)*	*Sand Equivalency (%)*
2A	2.58	0.76	37.6	2.589	0.68	28	100
1/4" LS	N/A	N/A	N/A	2.607	1.54	100	N/A
Screening	2.478	3.66	46.7	N/A	N/A	N/A	26
5/8" LS	N/A	N/A	N/A	2.624	1.25	100	N/A
3ACR	2.556	1.13	43.7	2.588	0.75	70	84
47B	2.605	0.49	37.3	2.594	0.65	35	98

3.1.2. Asphalt binder

The asphalt binder used in this study was a Superpave performance-graded binder, PG 64-28, which has been mostly used for the *SP4 Special* mixture in Nebraska. The asphalt was provided from Jebro Inc. Table 3.2 presents fundamental properties of the binder obtained from Dynamic Shear Rheometer (DSR) tests and Bending Beam Rheometer (BBR) tests. These tests are designated in the Superpave binder specification to identify performance grade and viscoelastic properties of asphalt binder. Testing results clearly demonstrate that performance grade of the binder is 64-28.

Table 3.2. Properties of Asphalt Binder PG 64-28

Test	*Temperature (°C)*	*Test Result*	*Required Value*
Unaged DSR, $G^*/\sin\delta$ (kPa)	64	1.21	Min. 1.00
RTFO - Aged DSR, $G^*/\sin\delta$ (kPa)	64	3.01	Min. 2.20
PAV - Aged DSR, $G^*\sin\delta$ (kPa)	19	2,111	Max. 5,000
PAV - Aged BBR, Stiffness (MPa)	-18	181	Max. 300
PAV - Aged BBR, *m*-value	-18	0.32	Min. 0.30

3.1.3. Hydrated lime

Hydrated lime was obtained from Mississippi Lime Company located at Sainte Genevieve, Missouri. Basic chemical and physical properties of hydrated lime used for this study are presented in Table 3.3.

Table 3.3. Physical and Chemical Properties of Hydrated Lime

Physical Properties	
Specific Gravity	2.343
Dry Brightness, G.E.	92.0
Median Particle Size - Sedigraph	2 micron
pH	12.4
BET Surface Area	22 m2/g
-100 Mesh (150 µm)	100.0%
-200 Mesh (75 µm)	99.0%
-325 Mesh (45 µm)	94.0%
Apparent Dry Bulk Density - Loose	22lbs./ft^3
Apparent Dry Bulk Density - Packed	35lbs./ft^3
Chemical Properties	
$Ca(OH)_2$ - Total	98.00%
$Ca(OH)_2$ - Available	96.80%
CO_2	0.50%
H_2O	0.70%
$CaSO_4$	0.10%
Sulfur - Equivalent	0.024%
Crystalline Silica	<0.1%
SiO_2	0.50%
Al_2O_3	0.20%
Fe_2O_3	0.06%
MgO	0.40%
P_2O_5	0.010%
MnO	0.0025%

3.2. MIXTURE DESIGN METHOD

As mentioned previously, five *SP4 Special* mixtures (F05, F10, F15, F20, and F30) were designed for this study. Each mixture was designed with the same blend of aggregates in order to keep aggregate angularities and mineralogical characteristics constant. The only variable in the mixtures was the amount of hydrated lime, marked as **X** in Figure 3.1.

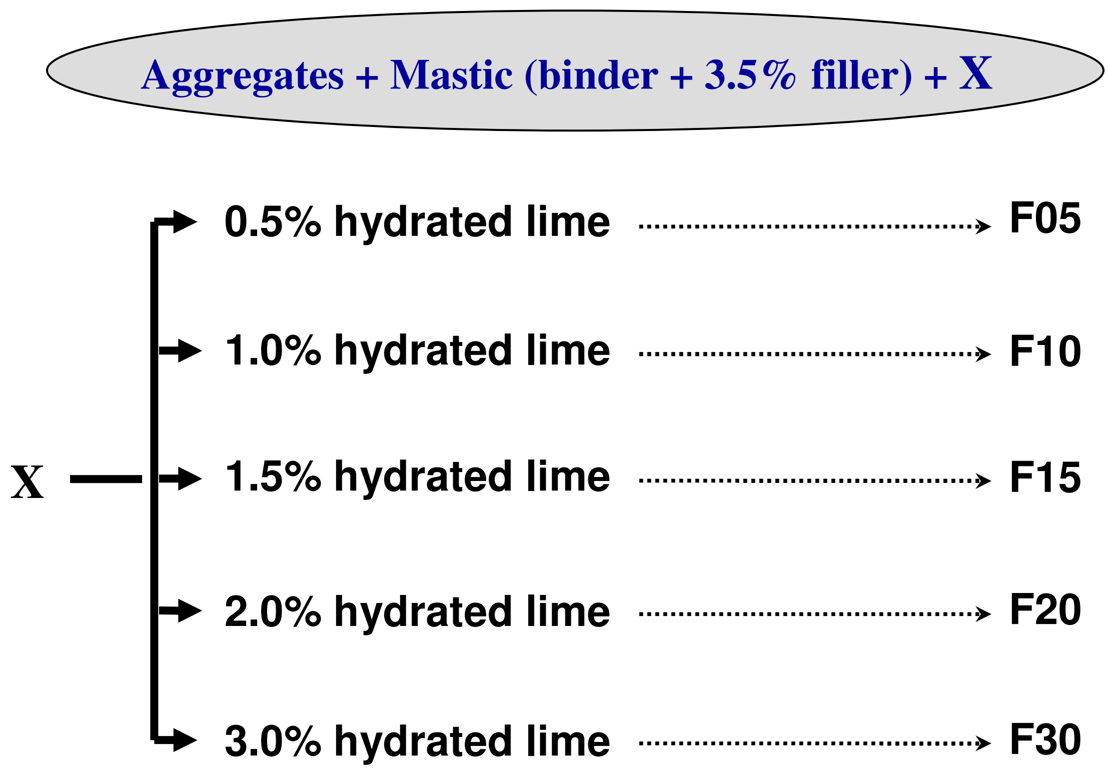

Figure 3.1. The Five SP4 Special Mixtures Designed for This Study

Figure 3.2 presents the gradation of aggregate blends without hydrated lime. As shown in the figure, the mixture satisfies Superpave control points and is located below the restricted zone (RZ).

Each mixture was then designed by following the elaborated steps described in Figure 3.3. As shown in Figure 3.3, Screenings passing No. 16 sieve were washed and dried before blending with other aggregates to eliminate extra dust (Kim *et al.*, 2006). Uncontrolled dust content significantly affects HMA volumetric properties such as voids in mineral aggregates (VMA) and dust/binder (D/B) ratio. Many problematic mixtures are associated with inappropriate dust control. In an attempt to minimize problems associated with dust, a rigorous control of dust content was conducted.

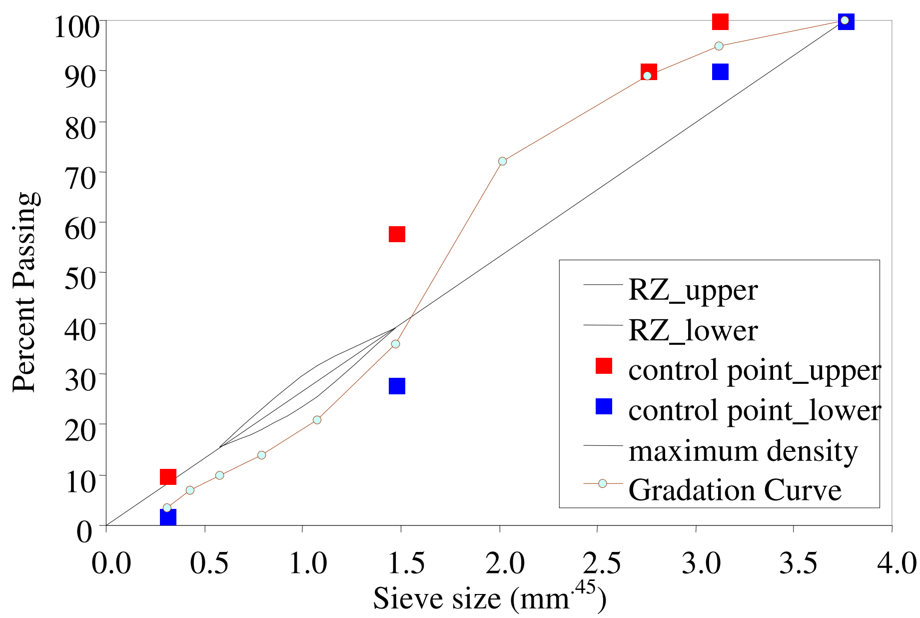

Figure 3.2. Aggregate Gradation Curve without Hydrated Lime

For the lime treatment, dry aggregate blends were moisturized with an addition of 3.0% water by weight of total aggregates. Dry hydrated lime at a different rate (from 0.5% to 3.0%) by total dry weight of aggregate was then mixed with the wet aggregates for 10 minutes to produce evenly distributed lime-water films on the aggregate surfaces. The lime-treated aggregates were then oven dried for four hours to eliminate all water before the addition of the asphalt binder.

All the mixtures for this project were *SP4 Special* mixture used mostly for low volume local road pavements. The compaction effort used for the *SP4 Special* mixture was for a traffic volume around 0.3 to 1.0 million equivalent single axle loads (ESALs). Table 3.4 summarizes NDOR specification requirements of aggregate properties, volumetric mixture design parameters, and laboratory compaction effort for the *SP4 Special* mixture. Compaction effort was estimated based on the average value of high air temperature in Omaha, Nebraska: 98ºF (36.67ºC).

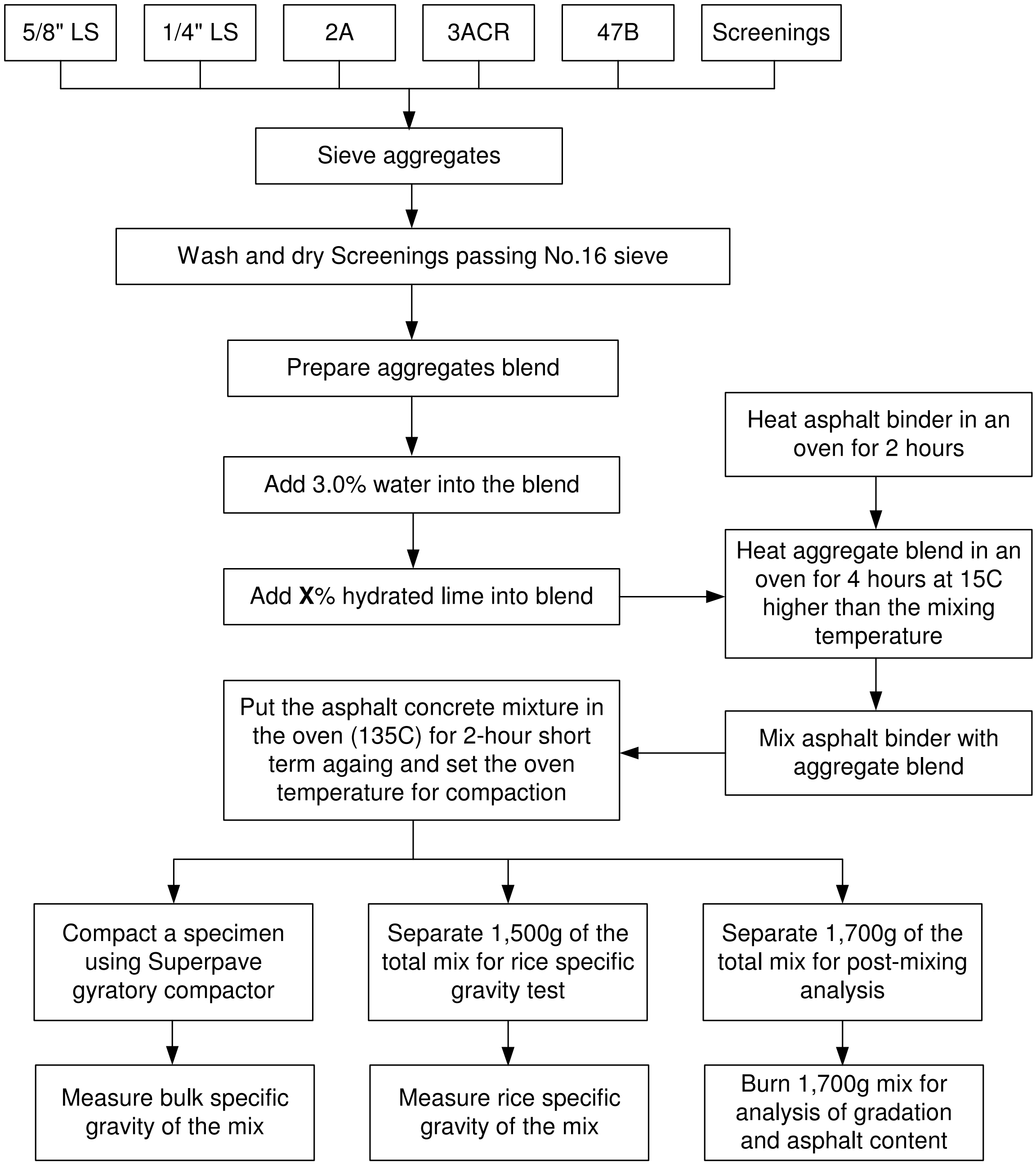

Figure 3.3. Mixture Design Procedure

Table 3.4. Required Volumetric Parameters and Aggregate Properties for SP4 Special

	NDOR Specification (SP4 Special Mixture)
Compaction Effort	
N_{ini}: the number of gyration at initial	7
N_{des}: the number of gyration at design	76
N_{max}: the number of gyration at maximum	117
Aggregate Properties	
CAA (%): coarse aggregate angularity	> 85/80
FAA (%): fine aggregate angularity	> 45
SE (%): sand equivalency	> 45
F&E (%): flat and elongated aggregates	< 10
Volumetric Parameters	
$\%V_a$: air voids	4 ± 1
%VMA: voids in mineral aggregates	> 14
%VFA: voids filled with asphalt	65 - 75
$\%P_b$: asphalt content	-
D/B (ratio): dust-binder ratio	0.7 - 1.7

All five mixtures designed in the Geomaterials Laboratory at the University of Nebraska-Lincoln (UNL) were submitted to NDOR laboratories for validation of aggregate properties and volumetric mixture design parameters. UNL design values and NDOR validations are presented and compared in Table 3.5. As can be seen in the table, mixture volumetric properties and aggregate characteristics obtained in the UNL laboratory matched well with NDOR measurements and met NDOR *SP4 Special* volumetric mixture design specifications. Based on the NDOR validation study, it can be inferred that UNL mixture designs were conducted successfully.

Table 3.5. Volumetric Mixture Properties and Aggregate Properties

	NDOR LIMITS	F05		F10		F15		F20		F30	
		UNL	NDOR	UNL	NDOR	UNL	NDOR	UNL	NDOR	UNL	NDOR
G_{mm}	-	2.428	2.421	2.418	2.431	2.431	2.437	2.431	2.438	2.439	2.428
G_{sb}	-	2.577	2.577	2.577	2.577	2.577	2.577	2.577	2.577	2.577	2.577
G_{mb}	-	2.328	2.334	2.323	2.339	2.336	2.344	2.334	2.347	2.340	2.336
$\%V_a$	4 ± 1	4.1	3.6	3.9	3.8	3.9	3.8	4.0	3.8	4.1	3.8
VMA	> 14	15.1	14.9	15.0	14.5	14.3	14.0	14.2	13.7	13.9	14.0
VFA	65 - 78	72.9	75.9	73.9	73.9	72.7	72.9	71.9	72.6	70.7	73.2
$\%P_b$	-	6.00	5.99	5.75	5.71	5.50	5.46	5.25	5.17	5.15	5.03
D/B	0.7-1.7	0.93	0.95	1.21	1.14	1.40	1.30	1.48	1.45	1.47	1.47

CHAPTER 4
TESTING FACILITIES AND METHODS

One of the major accomplishments of this study was the development of a new mechanical testing facility for HMA samples. The UNL research team installed the UTM-25kN (Universal Testing Machine with a 25kN load cell) mechanical testing system in the Geomaterials Laboratory for various mechanical tests of asphalt mixtures. This chapter briefly describes the mechanical testing system that was installed and the corresponding test methods that were used to evaluate the effects of hydrated lime on the performance and properties of HMA mixtures. Supporting theoretical background of each test method is also introduced in this chapter for better understanding and interpretation of test data, which are presented in Chapter 5.

4.1. TESTING FACILITIES: IDT TEST AND UNIAXIAL TENSILE TEST

4.1.1. IDT test

The indirect tensile (IDT) testing mode was chosen to characterize the mixtures from their dynamic modulus, fatigue lives under controlled-force conditions, and permanent deformation potential. The procedures described follow those suggested by Kim *et al.* (2004).

The Superpave Gyratory Compactor (SGC) compacted samples of 150mm diameter and approximately 115mm height with 4,775g of mixture. The samples were then cored to produce specimens with 100mm diameters. Figure 4.1 shows the coring process and a cored specimen from the SGC-compacted HMA mixture.

Figure 4.1. Coring the SGC Compacted HMA Mixture

Each cored specimen was then cut to produce two IDT specimens 38mm high. Figure 4.2 shows the cutting process, and Figure 4.3 shows the IDT specimens with gauge points attached. This coring and cutting process was employed to reduce the variation in the distribution of air voids in the sample and to obtain smooth surfaces which provided better bonding between the gauge points and the specimen surface.

Figure 4.2. Cutting Process of the Cored HMA Sample

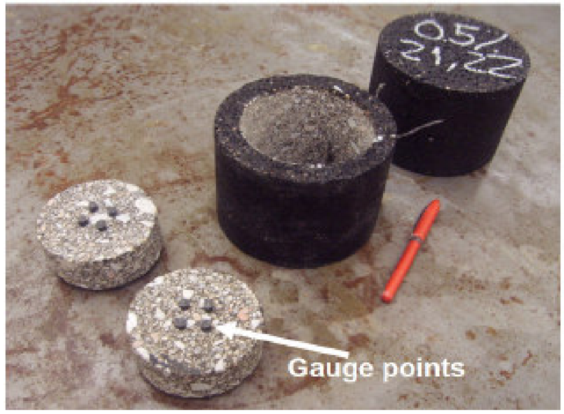

Figure 4.3. IDT Specimens from the Coring-Cutting Process

The gauge points were placed as accurate as possible to the desired locations of the specimen to alleviate positioning errors. Towards the end, a gauge point mounting and gluing device, as shown in Figure 4.4, was developed and used. Lateral metallic bars were also used to avoid rotation and translation at the top and bottom plates while gluing the gauge points.

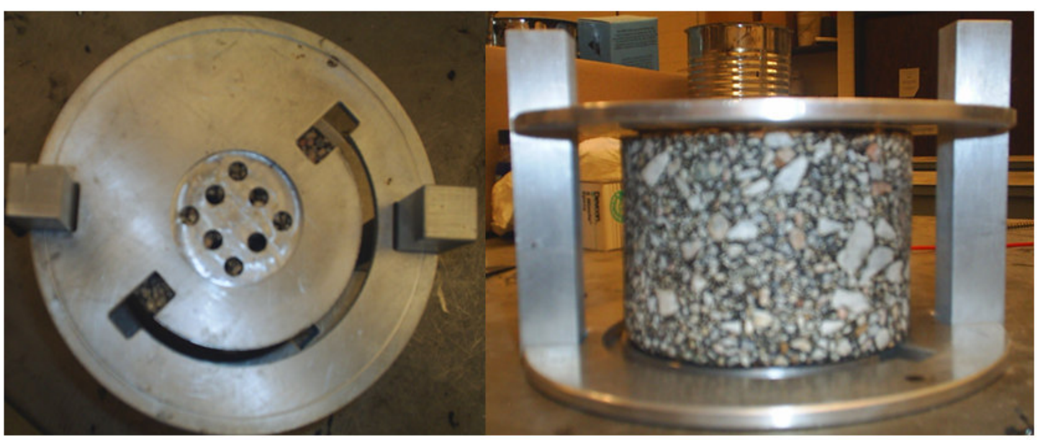

Figure 4.4. Gauge Points Mounting and Gluing Device

The gauge length used to mount the extensometers for measuring displacements was 25.4mm. After gluing the gauge points and attaching the extensometers in both sides of the specimen, the specimen was placed between loading strips that were held together by two cylindrical bars. The specimens were then placed into the environmental chamber of the UTM-25kN for the temperature conditioning required for each test. The range of temperatures that can be controlled by the environmental chamber is between -15°C and 60°C. Figure 4.5 shows the testing setup with the specimen installed.

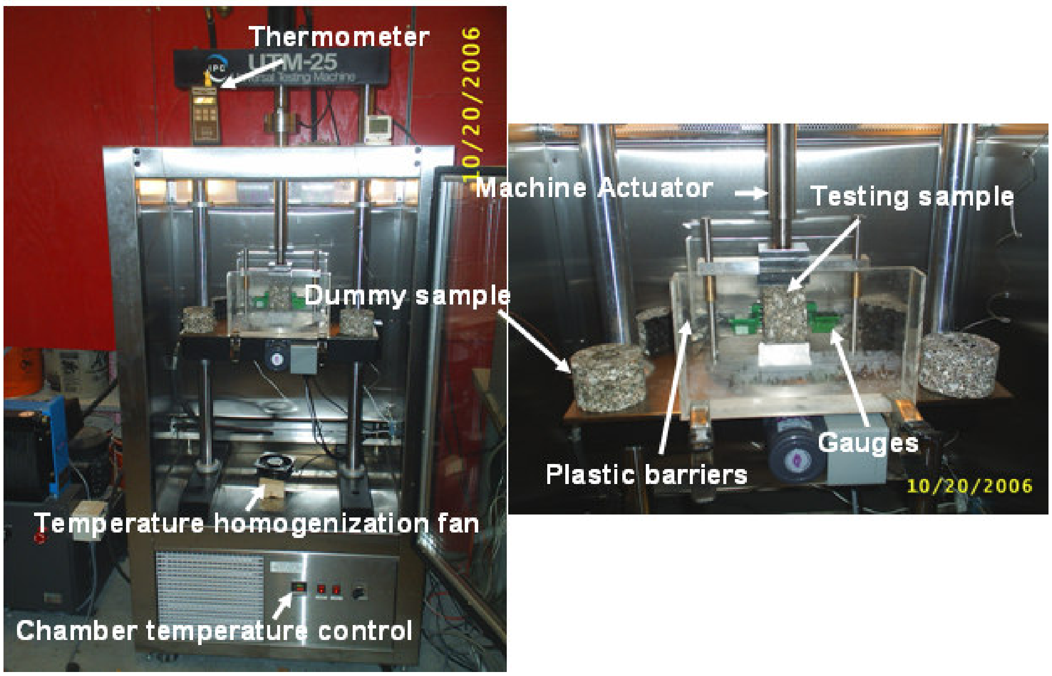

Figure 4.5. IDT Testing Set-up with the Specimen Installed

4.1.2. Uniaxial tensile test

Considering the fact that IDT testing mode was not appropriate for fatigue tests in controlled-displacement mode (Kim and Wen, 2002), the UNL researchers decided to create a uniaxial tensile testing setup that was mounted in the same system, UTM-25kN.

The process of sample fabrication was similar to that described for the IDT tests in the previous section. The SGC compacted samples with 150mm diameter and 125mm tall with 5,200g of material. They were cored using a 3-inch diamond coring bit, and the ends of the cored sample were cut 5mm each end to produce flat and smooth surfaces of the specimen for the uniaxial tensile fatigue tests. The height of 115mm that was employed for this study was shorter than the value recommended by the asphalt research community (Chehab *et al.*, 2000). However, the compactor (Model: Troxler 4140) available was not able to produce samples taller than 125mm. The national NCHRP study (Witczak *et al.*, 2002) recommended 150mm tall specimen after coring-cutting process for general purposes of asphalt concrete characterization.

Plastic steel glue was used to attach the extremities of the HMA specimens to metallic cylindrical platens. Those platens were used to transmit stresses from the machine actuator to the specimens. The device allowed for the correct positioning of the specimen between the metallic platens and is shown in Figure 4.6.

Figure 4.6. Device for the Correct Sample Positioning between Loading Platens

The apparatus developed at UNL for the uniaxial tensile tests can be seen in Figure 4.7. It provides precise alignment of a cylindrical specimen with respect to the loading axis and reduces eccentric stress concentration during tests. Before testing, each specimen was conditioned for at least two hours in the chamber at the target testing temperature.

Figure 4.7. Uniaxial Tensile Testing Apparatus

4.2. TEST METHODS

This section presents test methods that were adopted for the characterization of the dynamic modulus and performance of HMA specimens mixed with varying amount of hydrated lime (0.5% to 3.0%). Determination of the dynamic modulus is very important because the dynamic modulus is the material stiffness property used in the all three levels of hierarchical inputs for the HMA characterization of the new Mechanistic-Empirical Pavement Design Guide (MEPDG). Fatigue and rutting are, together with thermal cracking, the main distresses causing failure to asphalt pavements. Moreover, fatigue tests in controlled-force mode characterize the behavior of pavements with thick HMA layers, whereas fatigue in controlled-displacement tests is considered to represent the behavior of pavements with thin HMA layers. Thus, the fatigue tests were performed in both testing modes: controlled-force and controlled-displacement. In addition, rutting potential of HMA mixtures with different amount of hydrated lime were characterized by conducting the IDT tests at a high temperature condition, 60^{o}C.

4.2.1. Viscoelastic stiffness of HMA mixtures: dynamic modulus

The dynamic modulus of the HMA mixtures was characterized in IDT mode and with Equation 2.4 provided by Kim *et al*. (2004). As discussed in Section 2.2, three temperatures and eight loading frequencies were used. Before the cyclic loads were applied, the specimens were preconditioned with 200 cycles at 25Hz, which was recommended by the NCHRP study (Witczak *et al.*, 2002). The loading levels were carefully adjusted until the sample deformations were between 50 and 75 microstrain which was considered low enough not to cause nonlinear damage in the specimen so that the resulting dynamic modulus represented intact stiffness of the specimen. The amplitudes of the horizontal and vertical deformations for the last five loading cycles were averaged and used in Equation 2.4 to give the dynamic modulus at each testing frequency. The dynamic moduli determined using this approach were plotted against loading frequencies in Figure 4.8.

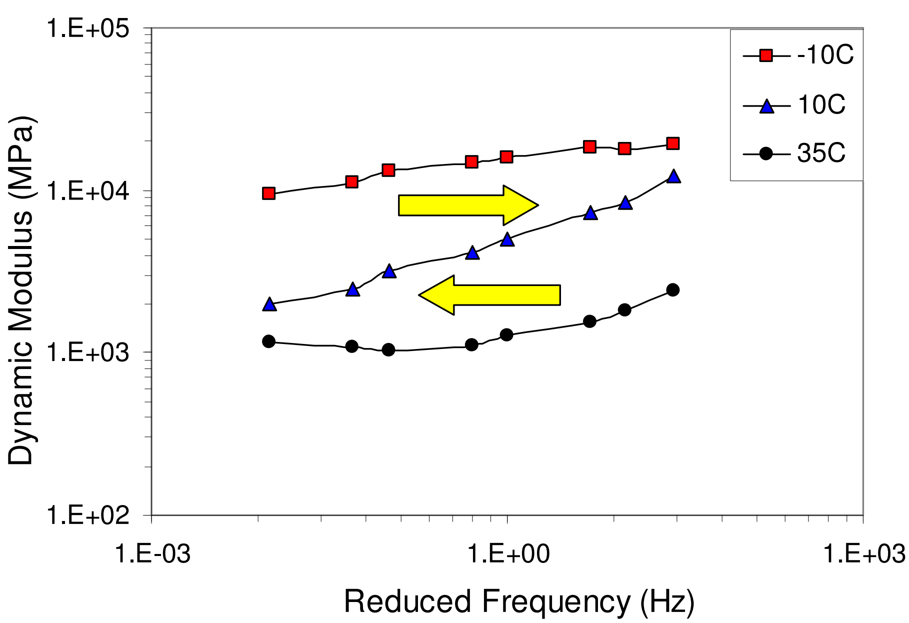

Figure 4.8. Dynamic Modulus in the Testing Frequency Domain

The dynamic moduli for the 24 temperature-frequency combinations were used to construct a master curve by shifting process as illustrated in Figures 4.8 and 4.9. The master curve represents the stiffness of the material in a wide range of loading frequencies (or loading time equivalently). In this attempt, the frequency-temperature superposition concept was applied. This was done by applying shifting factors (a_T) that produced the best matches for the construction of a single master curve at a reference temperature of 10℃. A second order polynomial function, shown in Figure 4.10, was used to obtain the appropriated shifting factor that was used to move the whole master curve in the horizontal direction. This represented the stiffness of the materials at a chosen temperature of 20℃ and is shown in Figure 4.11.

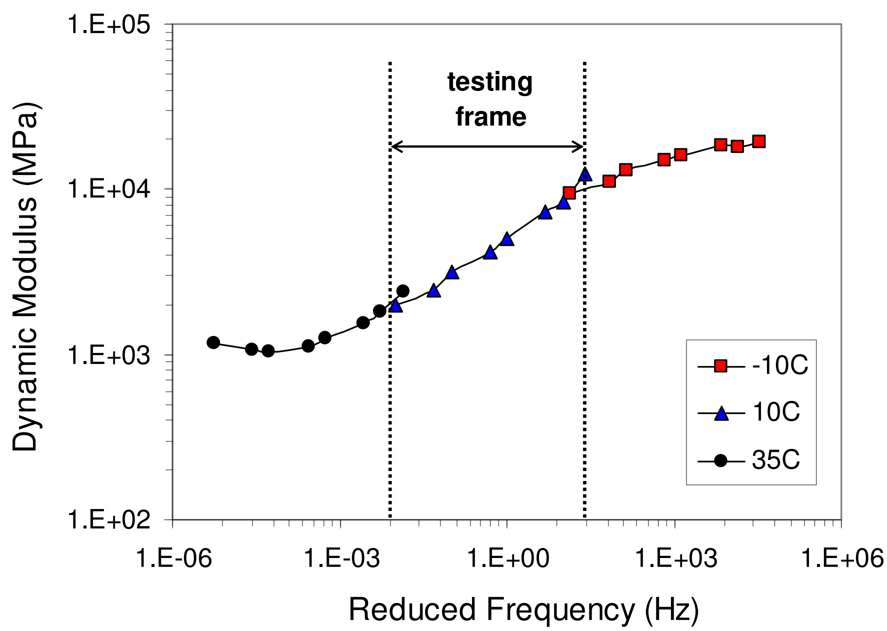

Figure 4.9. Dynamic Modulus Master Curve at 10°C

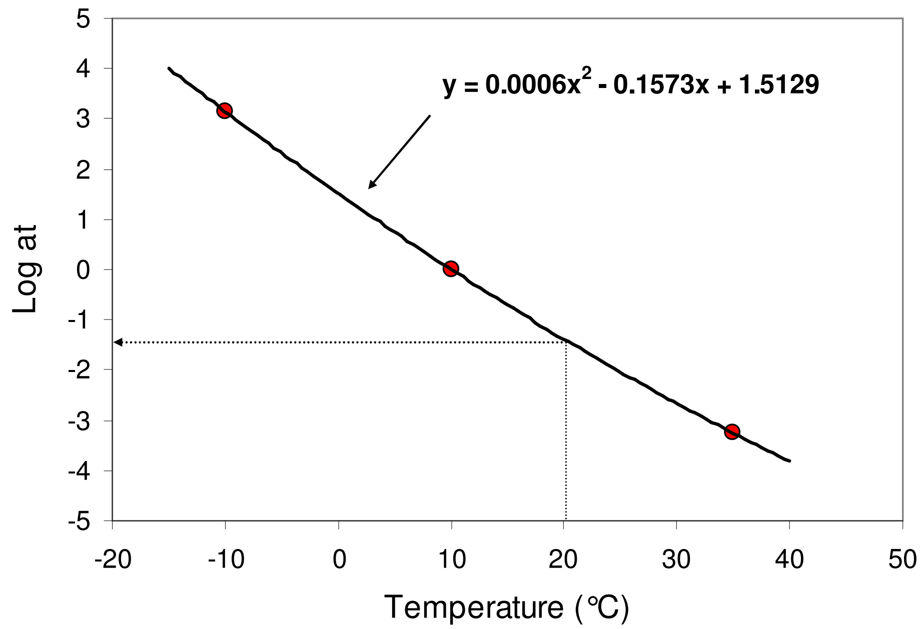

Figure 4.10. Shifting Factors vs. Temperatures (in Log Scale)

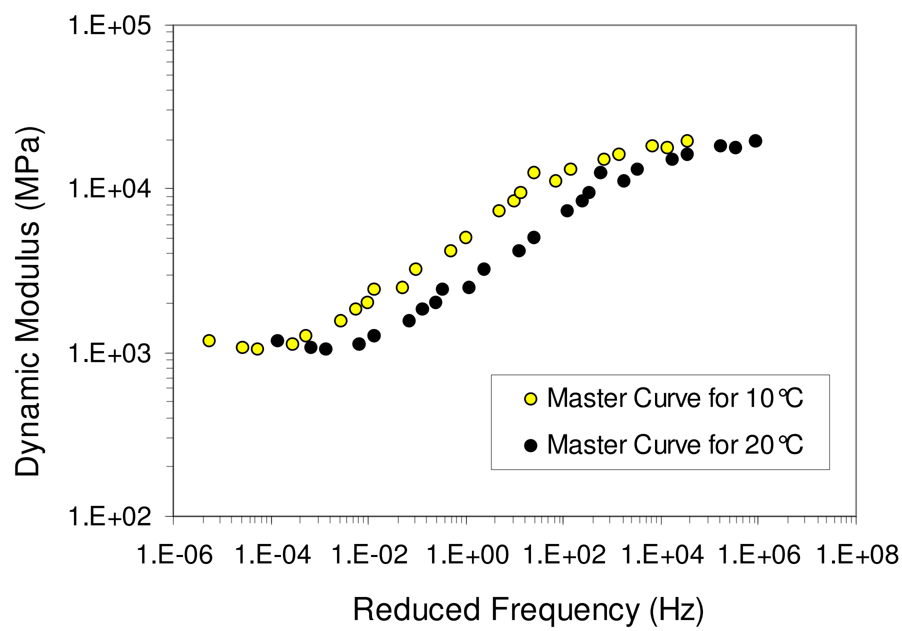

Figure 4.11. Constructing a Master Curve at 20°C by Shifting Process

The master curve was then mathematically modeled by fitting it to a sigmoidal function as expressed by (NCHRP 1-37A, 2004):

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}} \tag{4.1}$$

where t_r = reduced time of loading at reference temperature,

δ = minimum value of $\log|E^*|$,

$\delta + \alpha$ = maximum value of $\log|E^*|$, and

β, γ = parameters describing the shape of the sigmoidal function.

4.2.2. IDT fatigue performance tests: controlled-force mode

Fatigue cracking is a pavement distress that typically occurs at intermediate temperatures. Due to this fact, the testing temperature chosen to characterize the fatigue lives of the mixtures was 20℃. The testing frequency chosen was 10Hz which is approximately equivalent to a vehicle speed of 50mph (Huang, 2004). The horizontal deformation, parallel to the axis of tensile stress, was monitored and used to determine the failure of the specimens. This was based on the concept that fatigue damage generally occurred when high levels of tensile strains at the bottom of the HMA layer created cracks that propagated upward towards the surface (Brown *et al.*, 2001). Failure was considered to occur when the constant rate of increase of the horizontal deformations was replaced by a faster rate of increase of the deformations, as demonstrated in Figure 4.12. After that point, the microcracks present in the specimen were combined into macrocracks and the specimen was broken into two pieces, which is shown in Figure 4.13.

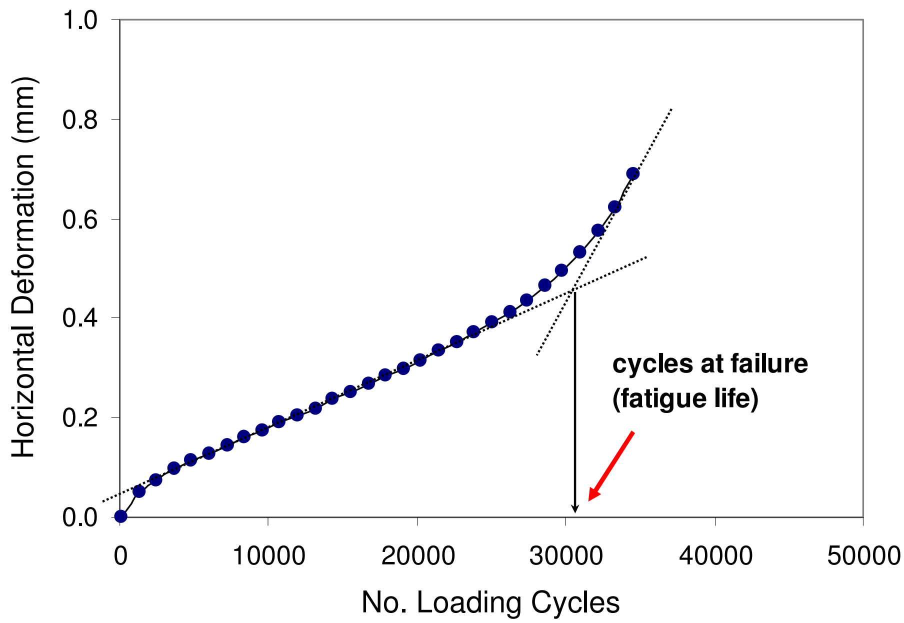

Figure 4.12. Fatigue Failure Criterion for Controlled-Force Fatigue Tests

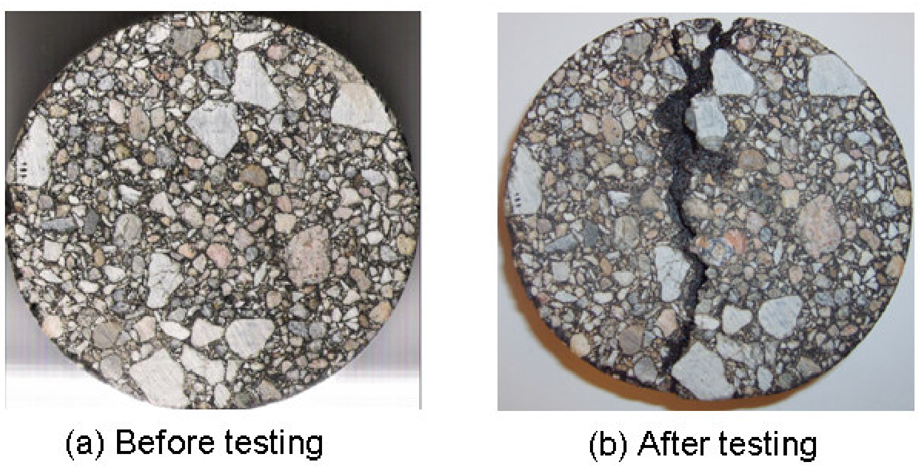

Figure 4.13. IDT Specimen Before and After Fatigue Test

4.2.3. Uniaxial tensile fatigue performance tests: controlled-displacement mode

As previously discussed, fatigue tests in controlled-force mode represent the fatigue behavior of asphalt pavements with thick HMA layers only. For the characterization of the behavior of structures with thin HMA layers, fatigue tests in controlled-displacement mode were conducted by using cylindrical HMA specimens subjected to the uniaxial tensile loading condition.

The testing temperature and frequency for the fatigue tests in controlled-displacement mode was also chosen to be 20℃ and 10Hz, respectively. The amplitude of the applied cyclic deformations was 1,700 microstrain, which was large enough to develop fatigue damage. The failure criterion chosen was based on a study by Kim (2003). He characterized fatigue behavior of various asphalt mixtures and found a transition point in the plot of stiffness versus loading cycles. This transition point occurred between two inflection points and was considered the most reasonable estimate of fatigue failure. Figure 4.14 presents the failure criterion determined by the transition point.

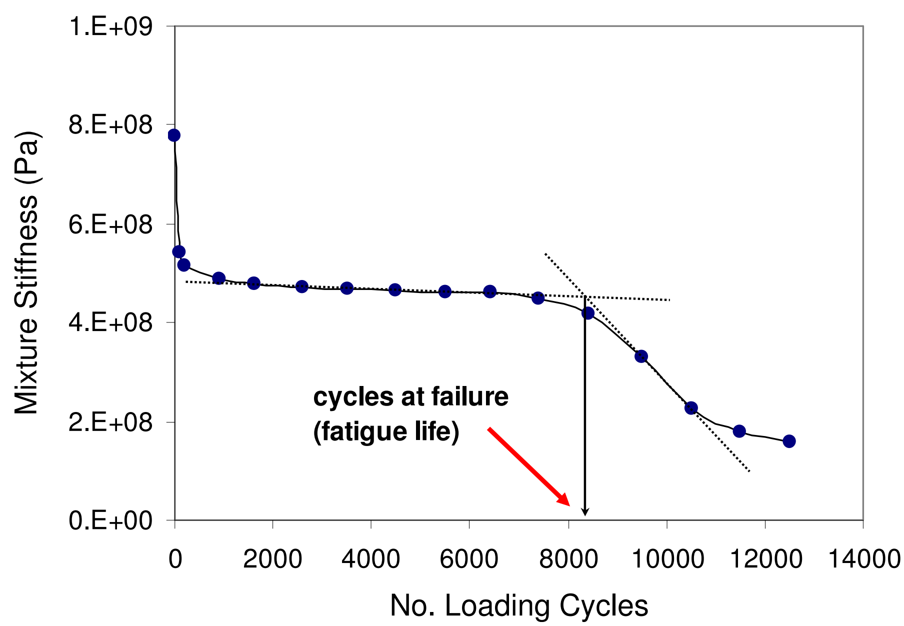

Figure 4.14. Fatigue Failure Criterion for Controlled-Displacement Fatigue Tests

4.2.4. IDT permanent deformation tests

The testing temperature chosen to characterize the resistance of the mixtures to the permanent deformations was 60°C which simulated rutting behavior of HMA mixtures at the high temperatures during summer seasons. A constant load of 0.27kN was applied to the specimens and the vertical displacement of the UTM-25kN actuator was monitored and used to determine the failure of the specimen. The failure point due to plastic flow was determined at the transition stage from secondary creep to tertiary creep as demonstrated in the actuator displacement - time curve shown in Figure 4.15.

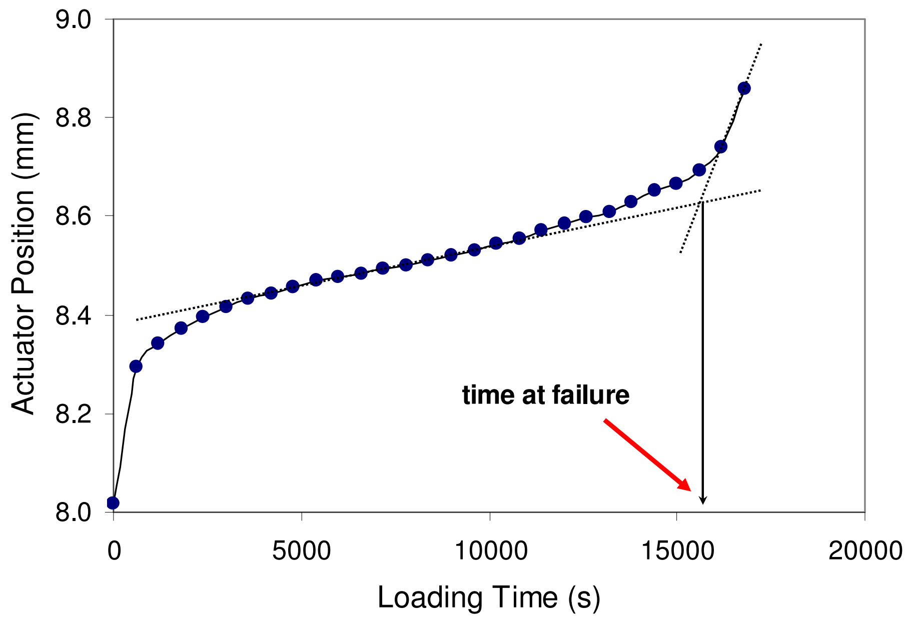

Figure 4.15. Failure Criterion for Permanent Deformation Tests

CHAPTER 5
TEST RESULTS AND DISCUSSION

Laboratory test results are presented and discussed in detail in this chapter. Based on the test results, the effects of hydrated lime on the fundamental properties and damage-associated performance of asphalt mixtures were evaluated. Fatigue performance tests conducted at both controlled-force and controlled-displacement modes were expected to provide more accurate and comprehensive information to judge the crack-resistant characteristics of hydrated lime. In addition, permanent deformation test results were incorporated with the fatigue tests results, which lead to a better understanding of the proper addition rate of hydrated lime in asphalt mixtures. This may maximize pavement performance when both cracking and rutting are considered together.

5.1. DYNAMIC MODULI OF MIXTURES

Table 5.1 shows the coefficients of the sigmoidal function that provided the best fitting to the dynamic modulus testing data for the five mixtures. These values correspond to the stiffness of the mixtures at 20℃. Figure 5.1 shows the dynamic modulus obtained from testing and from using the sigmoidal function (SF) (Equation 4.1).

Table 5.1. Coefficients of Sigmoidal Function

Hydrated Lime Content	Sigmoidal Function Coefficients			
	δ	α	β	γ
0.5%	4.233899	-1.266230	-0.848110	0.703790
1.0%	4.365754	-1.227920	-1.153420	0.652984
1.5%	4.241640	-1.084910	-0.841400	0.717066
2.0%	4.281950	-1.318090	-0.705730	0.661875
3.0%	4.653315	-1.826740	-0.572640	0.372886

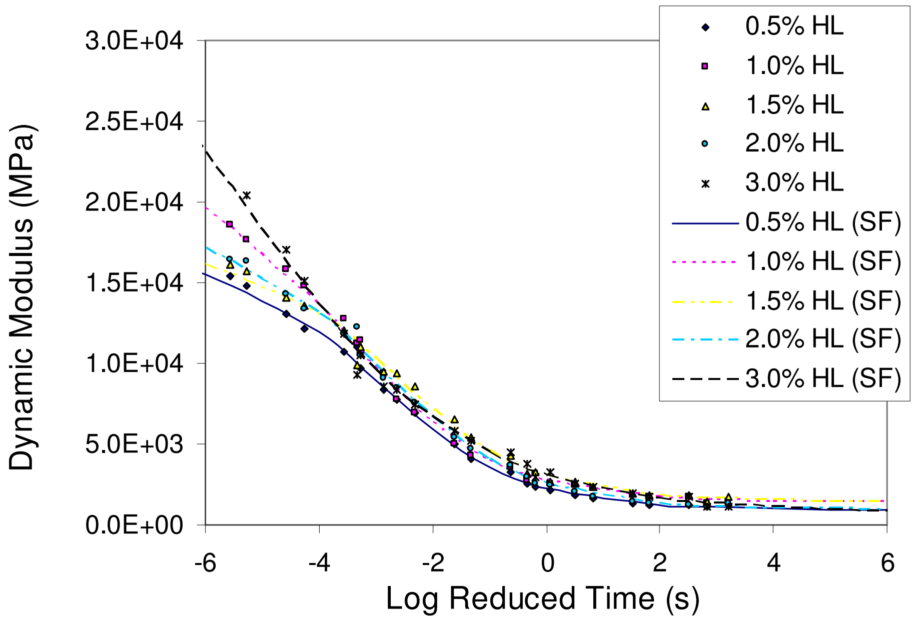

Figure 5.1. Dynamic Modulus of Each Mixture

As mentioned in the previous sections, the loading frequency used in this study to characterize the fatigue lives of the mixtures was 10Hz. It was therefore suggested to observe the dynamic modulus of each mixture at the loading frequency of 10Hz, since the dynamic modulus at 10Hz represented material stiffness of each mixture subjected to fatigue tests at the same loading frequency (10Hz). This was accomplished by simply converting time-domain horizontal axis in Figure 5.1 into frequency-domain axis followed by finding the dynamic modulus at the loading frequency of 10Hz. A common approximation relating the loading time (t) and loading frequency (f) is the following:

$$f = \frac{0.1}{t} \tag{5.1}$$

This approximation originated from an approximate relationship between the viscoelastic relaxation modulus and the real part of the complex modulus as described by Christensen (1982).

$$E(t) \approx E^{'}(\omega)\Big|_{\omega=\frac{2}{\pi}} \qquad (5.2)$$

where $\omega = 2\pi f$. (5.3)

Using the data in Figure 5.1 and Equation 5.1, the dynamic moduli of the five mixtures at 10Hz were plotted and are shown in Figure 5.2. The figure indicates that the mixture with the lowest stiffness contained 0.5% hydrated lime and that the addition of more hydrated lime generally stiffened the mixtures.

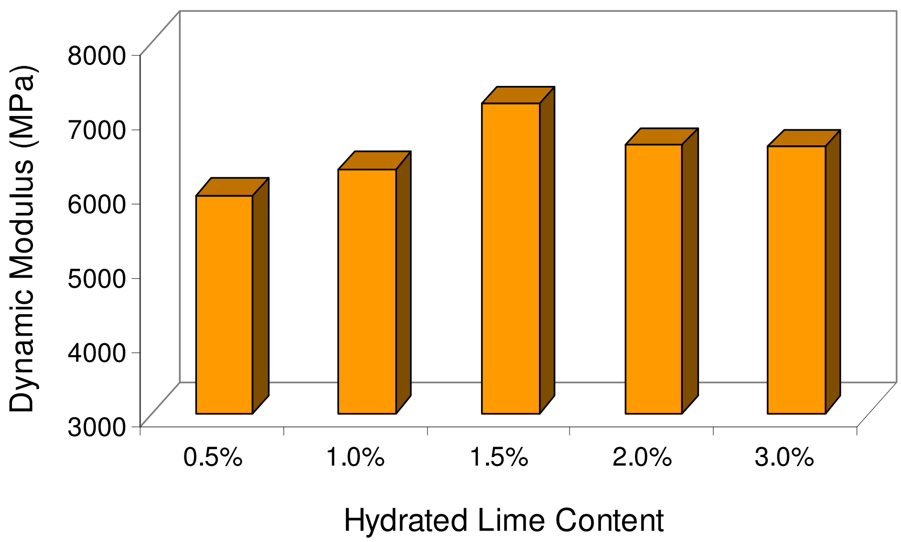

Figure 5.2. Dynamic Moduli of the Mixtures at 10Hz

5.2. IDT FATIGUE TEST RESULTS

Table 5.2 shows the number of cycles to failure for the IDT fatigue tests in controlled-force mode. The data in Table 5.2 were plotted in Figure 5.3. There was an increasing trend in the resistance to fatigue damage as more hydrated lime was added to the mixtures. This was an expected phenomenon since the addition of hydrated lime resulted in stiffer mixtures. Stiffer mixtures typically lasted longer under the controlled-force fatigue testing, which was not true in the case of controlled-displacement fatigue testing. The only mixture that violated the increasing trend of fatigue damage resistance to cyclic loading was the mixture with 2.0% hydrated lime. As observed from Figure 5.2 and Figure 5.3, better performance to fatigue damage from the mixture with 1.5% hydrated lime than other mixtures is in good agreement with the higher stiffness (represented by the dynamic modulus) experienced from the 1.5% hydrated lime mixture. However, additional studies are necessary to support these results and better explain mechanisms related.

Table 5.2. Fatigue Lives from the IDT Controlled-Force Fatigue Tests

Hydrated Lime Content	0.5%	1.0%	1.5%	2.0%	3.0%
Cycles to Failure	24000	140000	190000	92000	300000
	20000	55000	320000	112000	355000
	-	115000	-	135000	-
	-	31000	-	80000	-
Cycles to Failure (average)	22000	85250	255000	104750	327500

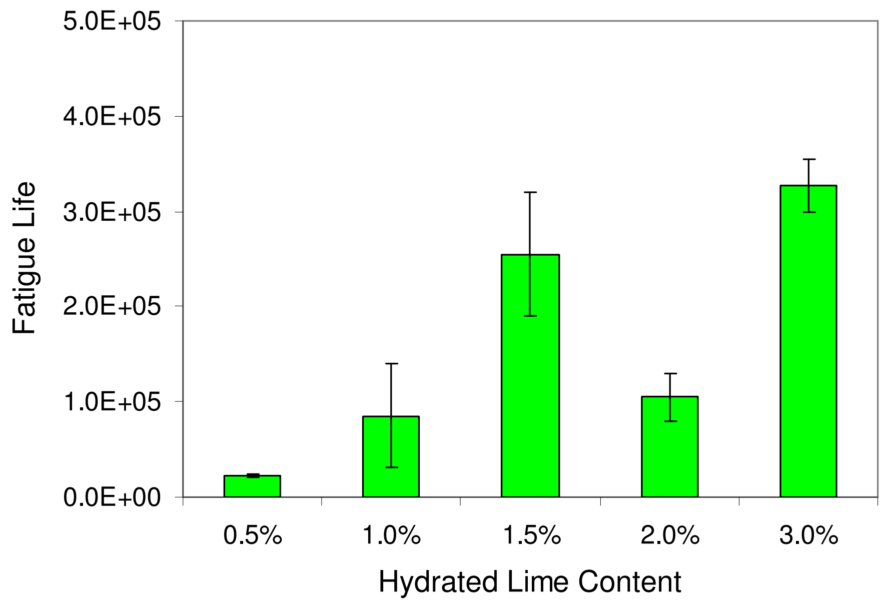

Figure 5.3. Average Fatigue Lives from the IDT Controlled-Force Fatigue Tests

5.3. UNIAXIAL TENSILE FATIGUE TEST RESULTS

For better insight into the effects of hydrated lime on fatigue performance of HMA mixtures, controlled-displacement fatigue tests were also performed. Because of the limitations of IDT testing to the controlled-displacement mode, the uniaxial tensile testing with repeated loading cycles (in controlled-displacement mode) was conducted on cylindrical specimens at 20^{o}C and 10Hz. The results in the form of fatigue life are presented in Table 5.3 and Figure 5.4, where averaged values of fatigue lives of each mixture are plotted.

The controlled-displacement fatigue tests resulted in a different optimality from the previous case of controlled-force tests. The results of the fatigue tests in controlled-displacement mode showed that the best performance was at the 1.5% hydrated lime, and the addition of extra quantities of hydrated lime resulted in mixtures less resistant to the fatigue damage. Several studies, including a study by Kim *et al.* (2003), demonstrated that hydrated lime provided better resistance to microcracking and thus an increased fatigue life under the controlled-displacement testing mode even if mixtures were stiffened due to the addition of hydrated lime. Since stiffer mixtures are generally more susceptible to cracking such as fatigue damage, the better performance observed in the case of hydrated-lime-mixed HMA was interpreted to be an indicator that a mechanism, the physicochemical interaction between the binder and hydrated lime, beyond the volume-filling effect occurred. However, as clearly indicated in Figure 5.4, the contribution of hydrated lime to fatigue damage resistance depended on the amount of hydrated lime.

Table 5.3. Fatigue Lives from the Uniaxial Tensile Fatigue Test

Hydrated Lime Content	0.5%	1.0%	1.5%	2.0%	3.0%
Cycles to Failure	82000 160000	153000 450000	222000 656000	105000 168000	7800 27000
Cycles to Failure (average)	121000	301500	439000	136500	17400

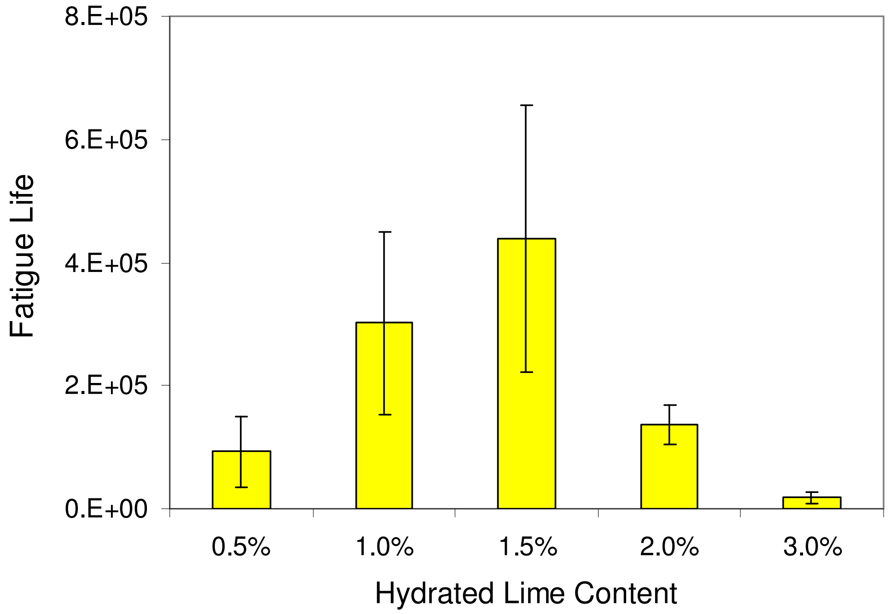

Figure 5.4. Average Fatigue Lives from the Uniaxial Tensile Fatigue Tests

Even though the trends observed in the results in controlled-force and controlled-displacement modes were not the same, both testing modes revealed the high resistance of the mixture with 1.5% additional hydrated lime to the fatigue damage.

5.4. PERMANENT DEFORMATION TEST RESULTS

Table 5.4 and Figure 5.5 show the results obtained from the permanent deformation tests where the constant load (0.27kN) IDT testing mode was used at the testing temperature of 60^{o}C to induce significant plastic flow of the specimens. An increasing trend of resistance to rutting occurred as more hydrated lime was added to the mixtures. From Figure 5.5, it also appears that the addition of more than 2.0% of hydrated lime did not improve the performance, as the time to failure for the 3.0% case was very similar to the time to failure of the 2.0% case.

Table 5.4. Time to Failure from the Permanent Deformation Performance Tests

Hydrated Lime Content	0.5%	1.0%	1.5%	2.0%	3.0%
Time to Failure (s)	380	700	3700	15000	12500
	170	870	2300	8500	8000
Time to Failure (s) (average)	275	785	3000	11750	10250

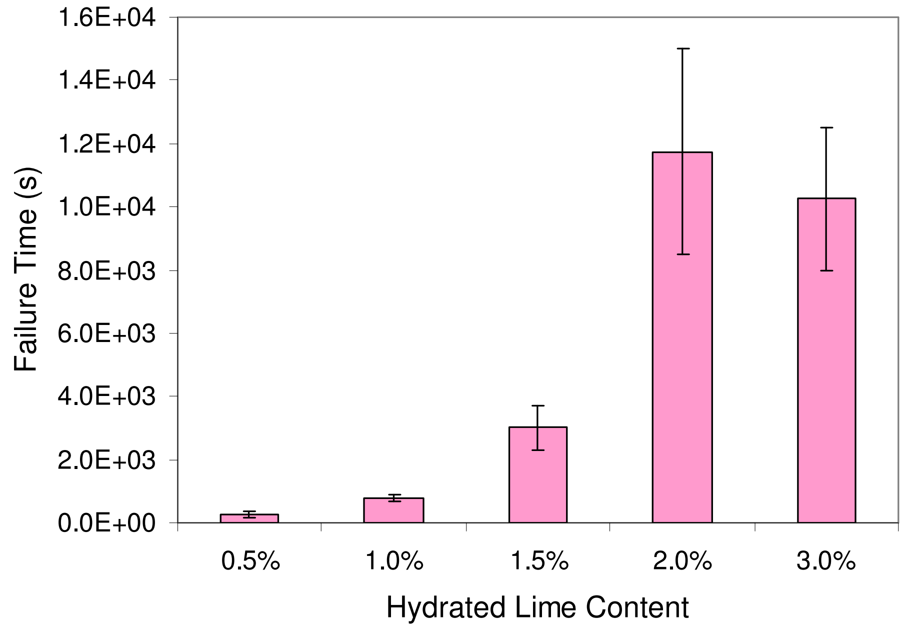

Figure 5.5. Average Time to Failure from the Permanent Deformation Tests

5.5. SUMMARY OF TEST RESULTS AND FURTHER DISCUSSION

As discussed in the previous sections, hydrated lime generally improved the properties and performance of the mixtures. In the stiffness results, it was possible to identify that the addition of hydrated lime stiffened the mixtures, as the 0.5% case had the lowest stiffness among all mixtures. For the fatigue tests in controlled-force mode, there was an increasing trend in resistance to cyclic loading as more hydrated lime was used, even if the better performance to fatigue damage was observed from the mixture with 1.5% hydrated lime addition than the mixture with 2.0% hydrated lime. On the other hand, for the tests of fatigue in controlled-displacement mode, an optimum amount of hydrated lime for the best performance of the mixtures was found to exist at 1.5% hydrated lime. Mixtures with more than 1.5% hydrated lime failed faster than the mixture with 1.5%. This is a clear indication of the positive effects of hydrated lime on fatigue damage resistance by its toughening mechanisms related to physicochemical interactions with binder and mineral aggregates. However, the toughening can be impeded by adding a critical amount of hydrated lime which produces mixtures that are prone to cracking due to material brittleness. The performance tests for permanent deformations showed that the resistance of the mixtures to rutting increased exponentially as more hydrated lime was added. However, for more than 2.0% additional hydrated lime, no additional improvement in performance was observed.

CHAPTER 6
CONCLUDING REMARKS

Performance changes and fundamental material characteristics primarily associated with fatigue cracking damage due to the addition of hydrated lime in different amount in HMA mixtures were studied through various experimental approaches. Based on this study, the following conclusions and suggested follow-up studies were drawn.

5.1. CONCLUSIONS

- The research approach employed herein was successful to accomplish the study objectives.

- Hydrated lime improved the stiffness of the mixtures. The mixture with lowest hydrated lime content (0.5% in this study) was also the one with the lowest stiffness (in the form of dynamic modulus).

- For the tests of fatigue in controlled-force mode, the resistance of the mixtures followed a similar trend to that observed from the results of dynamic modulus. This was expected because, in general, the fatigue lives of stiffer mixtures in controlled-force mode are longer.

- The results for the tests of fatigue in controlled-displacement mode clearly showed the existence of an appropriate amount of hydrated lime. The 1.5% hydrated lime created the most resistant mixture. The addition of extra hydrated lime resulted in mixtures less resistant to the controlled-displacement fatigue damage.

- The resistance of the mixtures to permanent deformations was improved as more hydrated lime was added. However, there was a trend of convergence when more than 2.0% hydrated lime was added.

5.2. RECOMMENDED FURTHER STUDIES

- Test data obtained from this study can be used for mechanical stress analyses to better investigate and understand the effects of hydrated lime which are clearly dependent on the amount of hydrated lime added and the applied fatigue test loading modes: controlled-force versus controlled-displacement. Some mechanical theories such as the nonlinear viscoelastic theory and the continuum damage mechanics approaches can be employed to conduct damage analyses which can lead to better identification of toughening mechanisms of hydrated lime.

- Findings from this study can be strengthened with more laboratory data and field performance observations, if available.

- Because Nebraska is a state that experiences extreme temperatures in the winter, the performance of the mixtures at low temperatures and the resistance of the mixtures to thermal cracking should be evaluated. The effects of hydrated lime on thermal cracking can be associated.

5.3. NDOR IMPLEMENTATION PLAN

The findings of this research project provide support of current NDOR practices and also provide thought provoking material properties as NDOR delves into the implementation of the MEPDG. Current requirements for the use of 1.0% hydrated lime in HMA mixtures for the purpose of mitigating moisture related damage will continue, as virtually all HMA construction is overlaying existing pavements and the concern for "designing for fatigue" is not an immediate concern. Currently other research efforts are ongoing with focus on other material properties for use in the MEPDG. Findings from other research efforts combined with the finding of this research will be valuable during the implementation of the MEPDG.

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