Technical Report Documentation Page

1. Report No P564	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Material Selection and Design Consideration for Moisture Damage of Asphalt Pavement**		5. Report Date December 14, 2006 6. Performing Organization Code
7. Author/s **Yong-Rak Kim and Jamilla Emi Sudo Lutif**		8. Performing Organization Report No. P564
9. Performing Organization Name and Address University of Nebraska-Lincoln (Department of Civil Engineering) W351 NH, PO Box 880531, Lincoln, NE 68588		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 26-1118-0065-001
12. Sponsoring Organization Name and Address Nebraska Department of Roads (NDOR) 1400 Highway 2, PO Box 94759, Lincoln, NE 68509		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Moisture damage is a primary mode of distress occurring in Nebraska hot mix asphalt (HMA) pavements. The use of hydrated lime has been recommended for Nebraska HMA pavements to mitigate moisture-related damage. There are several techniques of introducing hydrated lime into HMA mixtures, but the effects of hydrated lime in terms of its physical/chemical and/or mechanical mechanisms on moisture damage resistance to HMA pavements have not been fully understood. Somewhat arbitrarily one percent of lime addition by total weight of dry aggregates in a mix has been applied. Research is needed to better understand moisture damage mechanisms and to evaluate the effects of additives including hydrated lime as moisture damage resisting agents. To this end, various performance testing such as asphalt pavement analyzer (APA) testing under water, Hamburg testing under water, and AASHTO T-283 tensile strength ratio evaluation with different freeze-thaw cycles, and some fundamental property measurements of mix components based on dynamic shear rheometer (DSR) testing, micromechanical fracture-damage testing, and surface energy testing of asphalt mastics and aggregates were conducted. Testing data and analyses demonstrated that hydrated lime contributed to moisture damage resistance due to synergistic effects of mastic stiffening and advanced bonding characteristics at mastic-aggregate interfaces. However, a well-controlled lime treatment to maximize distribution and dispersion of lime particles onto aggregate surfaces would be required. In addition to the clear effects of hydrated lime, mineral filler in the HMA mix demonstrated its damage-resisting effects in an early stage of moisture damage due to substantial stiffening effects from filler addition. Fundamental characteristics of mix components measured in this study were closely related to macroscopic performance behavior of asphalt concrete samples, which infers that the testing-analysis protocol based on the mix components can be a basis for potential specification-type technique for evaluating (and/or predicting) moisture damage of HMA mixtures and pavements.

17. Key Words Moisture Damage, Superpave, Hot Mix Asphalt (HMA), Hydrated Lime	18. Distribution Statement		
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. Of Pages 68	22. Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

FIGURE Page

LIST OF TABLES

CHAPTER 1
INTRODUCTION

Moisture damage is a primary mode of distress in hot mix asphalt (HMA). Commonly known as stripping, this damage accelerates structural degradation of the mixtures in conjunction with cracking and plastic deformation. As illustrated in Figure 1.1, moisture typically reduces stiffness of binder and/or mastic through moisture diffusion and degrades the adhesive bonding between the binder/mastic and aggregate particles. Therefore, a loss of HMA internal strength results in premature distresses such as rutting, raveling, and fatigue cracking.

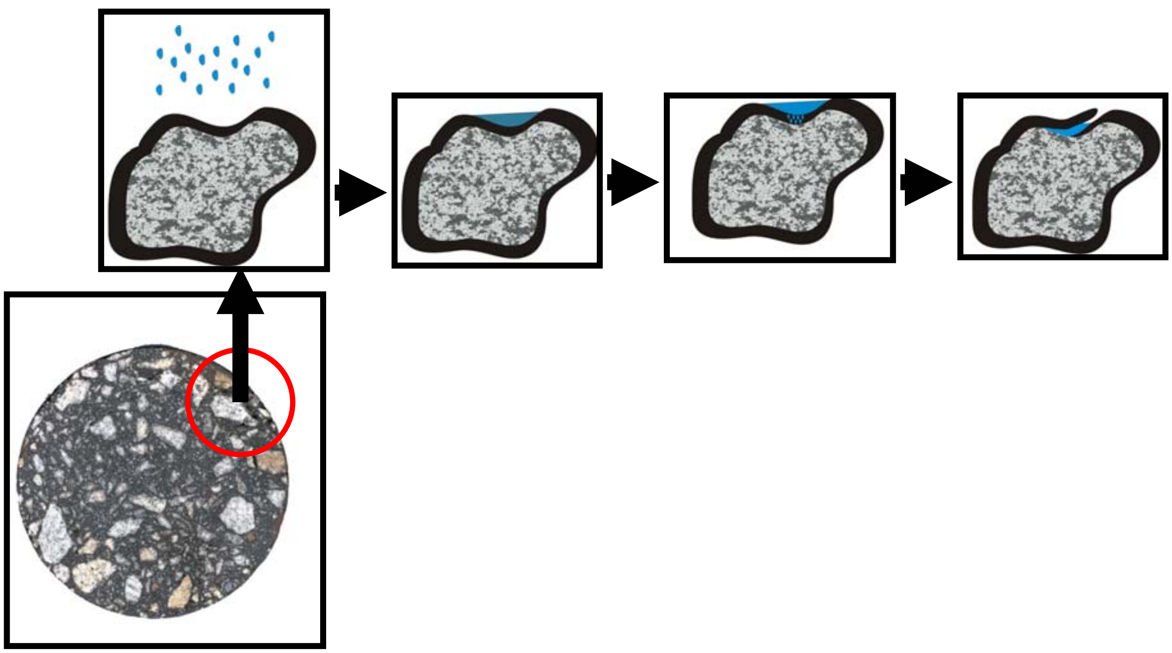


Figure 1.1 Illustration of Moisture Damage Mechanisms

Moisture damage mechanisms are complex, and attempts have been made to simplify them by categorizing them. Still an identification of the fracture mechanisms of asphalt-aggregate systems in the presence of water is difficult, and a synergistic interaction of mechanisms often remains the best explanation of the moisture damage process. A promising approach to assess moisture damage potential is to identify fundamental material properties that affect and control moisture damage and then develop reasonable and efficient testing methods to determine better materials (including anti-stripping agents) and design considerations for resisting moisture-associated damage.

A number of testing methods have been developed to predict and evaluate moisture susceptibility of asphalt mixtures. A standard method, "Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage" in AASHTO T-283 has been developed from the National Cooperative Highway Research Program (NCHRP 4-08 and NCHRP 10-17) projects and widely-used to assess moisture susceptibility of Superpave HMA mixtures by simply comparing indirect tensile strength of HMA samples with and without freeze-thaw (F-T) moisture conditioning. Investigations in rutting performance associated with moisture damage have also been adopted by conducting two popular testing methods of asphalt concrete samples: Hamburg wheel-tracking test and asphalt pavement analyzer (APA) test under water. However, those tests performed in the laboratory using asphalt concrete samples applied a fixed load at a fixed temperature, making it impracticable to predict moisture damage of mixtures under traffic loads and different environmental conditions (Epps *et al.* 2000). Furthermore, the tests (AASHTO T-283, Hamburg, and APA) are somewhat costly, time-consuming and are limited in validating detail damage mechanisms of HMA mixtures due to moisture attack. Testing protocols that are simpler but more reliable and fundamental need to be developed for advanced estimation and prediction of moisture-related damage.

In addition to the need of simple-reliable-fundamental testing protocols to better estimate moisture damage, evaluation of many different types of additives/modifiers and their appropriate application methods to maximize moisture damage resistance of HMA mixtures has been an important issue resulting in many studies. One of well-known anti-stripping additives is hydrated lime. Hydrated lime provides better adhesive compatibility between aggregate and asphalt mastic. Thus, the use of hydrated lime may increase bonding characteristics between aggregate and asphalt. Furthermore, it has also been demonstrated that hydrated lime significantly changes rheological properties of asphalt systems. Many experimental results have shown that adding hydrated lime to the asphalt mixtures significantly improves moisture-damage resistance especially when subjected to the wetting-drying treatment (Fwa and Ong 1994, McCann and Sebaaly 2003, and many more). Based on these facts, one-percent hydrated lime by weight of total dry aggregates in a mix is currently required for Superpave mixes used in Nebraska pavements. However, it has not been clearly understood yet how hydrated lime contributes to moisture-damage resisting mechanisms, and what treating method of hydrated lime into HMA is more effective to mitigate moisture damage and to provide better HMA performance. Table 1.1 demonstrates that there are several methods for adding hydrated lime to asphalt. Each state has developed specifications and procedures that are tailored to its local materials available and the capabilities of construction firms and equipment.

Table 1.1 Methods of Adding Hydrated Lime (Little and Epps 2001)

State	**Method of Adding Hydrated Lime to Asphalt**				
	In Drum	**Dry Lime to Dry Aggregate**	**Dry Lime to Wet Aggregate**	**Lime Slurry to Aggregate**	**Is Lime-Treated Aggregate Marinated**
Arizona			X		No
California				X	Required
Colorado			X	X	Optional
Georgia	X	X			No
Mississippi			X		No
Nevada			X		Required
Oregon			X		Optional
South Carolina			X		No
Texas	X		X	X	No
Utah				X	Optional

1.1. RESEARCH OBJECTIVES

There is a pressing need for a research effort on the subject of moisture sensitivity of asphalt mixtures used in Nebraska. In particular, the study should be focused on developments of reasonable guidelines and testing protocols for selecting better materials combinations that can sufficiently mitigate moisture-related damage. To this end, currently- and widely-used testing methods such as AASHTO T-283 testing method, Hamburg testing, and APA testing under water should be estimated.

In addition to the evaluation of traditional moisture sensitivity testing methods, this study will also take into account the effects of fundamental material properties on moisture damage-related pavement performance. Measurements of fundamental surface energy properties and material characteristics of asphalt binder/mastic and aggregates used in Nebraska will provide an appropriate guideline for selecting better asphalt-aggregate combinations that are more resistant to moisture damage. The effects of hydrated lime as an anti-stripping agent will also be estimated in this study. Furthermore, optimum application of hydrated lime to maximize the moisture-damage resistance will be estimated. Quantitative evaluation to justify which method in lime application provides better performance is necessary.

1.2. RESEARCH SCOPE

To accomplish the objectives, this study has been performed with three phases. Phase 1 consists of literature review, material selection, and volumetric mix design of four SP2-type Superpave mixes used in this study. Phase 2 consists of fabrication of compacted asphalt concrete samples and mechanical testing of the asphalt concrete samples using three traditional performance evaluation techniques (AASHTO T-283, Hamburg, and APA testing). In phase 3, property characterization of mixture constituents are performed using dynamic shear rheometer (DSR), micromechanical fracture-damage testing device and surface energy measuring devices. Based on the performance evaluation and fundamental properties of mixture constituents, the effect of hydrated lime and application methods incorporated with fundamental moisture-damage mechanisms are compared and summarized in the final report including meaningful findings and recommended future work.

1.3. ORGANIZATION OF THE REPORT

This report is composed of five chapters. Following this introduction, Chapter 2 presents background information associated with moisture-damage mechanisms and related testing-analysis methods including recent advancements. In Chapter 3, detailed descriptions of material selection and research methodology employed for this study are presented. Chapter 4 shows laboratory test results such as mix design results of all SP2 mixes, bulk performance testing results from AASHTO T-283, Hamburg, and APA testing, and properties of mixture constituents based on DSR, fracture-damage testing, and surface energy measurements. Laboratory testing results are also discussed in this chapter. Finally, Chapter 5 provides a summary of findings and conclusions of this study. Recommended future research and implementation plans for the Nebraska Department of Roads (NDOR) are also presented in the chapter.

CHAPTER 2
BACKGROUND

Moisture-related damage is a major distress in the U.S. asphalt pavements. The reduction of the adhesion between asphalt and aggregates in the presence of water and the deterioration of the asphalt due to cohesive failure within the asphalt binder itself has been known as two primary driving mechanisms of moisture damage since the 1920s (Solaimanian *et al.* 2003). In 1991, National Cooperative Highway Research Program (NCHRP) conducted a survey to evaluate the impacts of moisture damage in U.S. pavements. The study demonstrated that 70 percent of U.S. Department of Transportation (DOT) presented premature rutting, raveling and wear in their pavements due to moisture damage (Hicks 1991). Due to the great number of U.S. pavements under significant moisture damage, attempts have been made to identify the moisture damage mechanisms and to develop test procedures that could estimate the moisture susceptibility of asphalt mixtures. Furthermore, many different types of additives have been applied to the asphalt mixtures to minimize moisture-related damage. Hydrated lime is the one additive that has shown its unique effects on moisture damage mitigation. Therefore, many state highway agencies have employed and/or required the use of hydrated lime in HMA pavements.

2.1. MOISTURE DAMAGE MECHANISMS ON ASPHALT PAVEMENTS

The performance of asphalt pavements is related to cohesive and adhesive bonding within the asphalt-aggregate system. The loss of cohesion (strength) and stiffness of the asphalt film, and the failure of the adhesive bond between aggregate and asphalt in conjunction with the degradation or fracture of the aggregate were identified as the main mechanisms of moisture damage in asphalt pavements (Terrel and Al-Swailmi 1994). The negative effects of moisture damage on material properties of asphalt mixtures were evaluated by Kim *et al.* (2004). They successfully used the dynamic mechanical analysis (DMA) technique to evaluate fundamental property characteristics of asphalt binders and mastics by measuring fundamental viscoelastic properties. Cylindrical DMA specimens were fabricated using SHRP-classified binders and Ottawa sand to perform various dynamic tests in both wet and dry conditions and determine viscoelastic stiffness of specimens. Testing results clearly demonstrated a significant reduction in the dynamic shear moduli (stiffness) due to the presence of moisture, which might be due to the moisture penetration into mastic or into the mastic-sand interface.

The mechanisms that govern the adhesive failure in the asphalt-aggregate system are even more complex, since the adhesion between two distinct phases is related to mechanical and chemical reactions, molecular attractions, and interfacial energy theory, as mentioned by Mohamed (1993). Several attempts have been made to explain the loss of adhesive bonding between the asphalt film and the aggregate in the presence of water. The differences in physico-chemical properties at the surface of the combined materials used in HMA mixtures are attributed as important factors regarding the adhesive failure of the asphalt-aggregate system. Surface free energy of asphalt binders and aggregates is such an important physico-chemical property. In 2003, Cheng *et al.* proposed an adhesion failure model to analyze the adhesive fracture in the asphalt-aggregate interface in the presence of water. They hypothesized that the adhesive failure was clearly related to the surface energy of the asphalt-aggregate system. They calculated the work of adhesion between the asphalt and the aggregates based on the surface free energy theory, and then using the adhesion failure model, they identified the moisture damage potential of asphalt mixtures. To verify the validity of the model, a comparison between the results from the model and the results from repeated-load permanent deformation tests on asphalt mixtures either in dry or wet conditions were done. Test results validated the adhesion failure model and also showed that, for the same asphalt, the granite mixtures are more vulnerable to moisture damage than the limestone mixtures.

In addition to the two primary driving mechanisms (i.e. cohesive failure of asphalt films and adhesive failure of asphalt-aggregate interfaces), some other phenomena such as displacement, detachment, and build-up pore pressure are some of the effects of a moisture-attacked pavement that lead to adhesive and cohesive failure of the asphalt pavements (Lytton *et al.* 2005). Displacement involves debonding of the asphalt film from the aggregate surface through a break in the asphalt film. The break in the asphalt film is due to several reasons, including incomplete coating of the aggregate surface, traffic load, and freeze-thaw (F-T) cycles that stresses the pavement. Detachment results from the penetration of the water between the aggregate-binder systems without actually breaking the asphalt film. The pore pressure build-up occurs when the pavement is in saturated condition due to moisture attack. With the build-up of pore pressure, the microcracks start to grow and eventually rupture the asphalt film.

2.2. TEST METHODS TO ASSESS MOISTURE SUSCEPTIBILITY

A number of qualitative and quantitative test methods had been developed to predict and evaluate moisture susceptibility of asphalt mixtures. Qualitative tests are based on subjective evaluation of the stripping potential of hot mix asphalt (HMA) mixtures, while quantitative tests provide a specific value such as strength before and after moisture conditioning. Solaimanian *et al.* (2003) described each of the test procedures developed to identify moisture susceptibility of HMA mixtures. Basically, the tests can be divided into two categories: (1) tests on compacted mixtures, and (2) tests on loose mixtures. Tables 2.1 and 2.2 summarize the moisture sensitivity tests on compacted and loose mixtures, respectively.

Many researchers have used those test protocols to verify the moisture damage potential in HMA mixtures. The Superpave system adopted the standard test method AASHTO T-283 as a required test to verify the moisture sensitivity of the HMA mixture designed. This test procedure is also known as a modified Lottman test procedure since it was developed based on work done by Lottman (1978), and further modified through the work of Tunnicliff and Root (1982). More details about this test procedure are given in Chapter 3.

Table 2.1 Moisture Sensitivity Tests on Compacted Mixtures (Solaimanian *et al.* 2003)

Test	ASTM	AASHTO	Other
Moisture vapor susceptibility			California Test 307
			Developed in late 1940s
Immersion–compression	D1075	T165	ASTM STP 252 (Goode, 1959)
Marshal immersion			Stuart 1986
Freeze–thaw pedestal test			Kennedy et al. 1982
Original Lottman indirect tension			NCHRP Report 246 (Lottman, 1982); Transportation Research Record 515 (1974)
Modified Lottman indirect tension	T 283		NCHRP Report 274 (Tunnicliff and Root, 1984), Tex 531-C
Tunnicliff–Root	D 4867		NCHRP Report 274 (Tunnicliff and Root, 1984)
ECS with resilient modulus			SHRP-A-403 (Al-Swailmi and Terrel, 1994)
Hamburg wheel tracking			1993 Tex-242-F
Asphalt pavement analyzer			ECS/SPT NCHRP 9-34 2002-03
Multiple freeze–thaw			

Table 2.2 Moisture Sensitivity Tests on Loose Mixtures (Solaimanian *et al.* 2003)

Test	ASTM	AASHTO	Other
Methylene blue			Technical Bulletin 145, International Slurry Seal Association
Film stripping			(California Test 302)
Static immersion	D1664*	T182	
Dynamic immersion			
Chemical immersion			Standard Method TMH1 (Road Research Laboratory, 1986, England)
Surface reaction			Ford et al. (1974)
Quick bottle			Virginia Highway and Transportation Research Council (Maupin, 1980)
Boiling	D3625		Tex 530-C Kennedy et al. 1984
Rolling bottle			Isacsson and Jorgensen, Sweden, 1987
Net adsorption			SHRP A-341 (Curtis *et al.*, 1993)
Surface energy			Thelen 1958, HRB Bulletin 192
			Cheng *et al.*, AAPT 2002
Pneumatic pull-off			Youtcheff and Aurilio (1997)

* No longer available as ASTM standard.

Laboratory wheel tracking devices such as the asphalt pavement analyzer (APA) and the Hamburg wheel-tracking device (HWTD) are very widely used in U.S. Those equipments are capable of measuring rutting potential of asphalt mixtures incorporated with moisture damage by applying dynamic cyclic loads simulating field traffics on the compacted asphalt concrete samples under water. Cooley *et al.* (2000) conducted a comprehensive review on U.S. loaded wheel testers and found that results obtained from the wheel tracking devices correlated reasonably well to actual field performance when the in-service loading and environmental conditions of that location were reasonably considered. They also concluded that wheel tracking devices, when properly correlated to specific site's traffic and environmental conditions, have the potential to help the user determine pass/fail of the mixture, even if the ability of the wheel tracking devices to adequately predict the magnitude of the rutting for a particular pavement has not been fully validated at this time.

Aschenbrener *et al.* (1995) performed a post-mortem study in 20 pavements that had shown significant performance degradation related to moisture damage. For the study, four tests were conducted: traditional AASHTO T-283, ASTM D-3625 (boiling water test), testing with the environmental condition system (ECS), and the Hamburg testing. All mixtures were treated with anti-stripping agents. They observed that instantaneous failures were generally related with the combination of high temperature, high moisture level, and high traffic instead of freezing conditions. The authors tried to reproduce mixtures used in the 20 pavements and then evaluated the reliability of the moisture sensitivity tests based on the known field performance. From AASHTO T-283, the prediction of failure due to moisture was successfully achieved for mixtures that lasted less than two years in the actual field (6 out of 8). On the other hand, for pavements with high maintenance, this test could not identify their moisture susceptibility. From Hamburg results, they also concluded that test conditions are very severe since four of the seven acceptable sites investigated did not pass the Hamburg failure criteria.

Although those tests performed in laboratory have been extensively used by agencies and researchers, it is important to note that they have been calibrated and implemented on a local basis (a region within a state). No test has been successfully calibrated and implemented across a wide spectrum of conditions. Testing protocols that are somewhat simpler but more reliable and fundamental need to be developed for advanced estimation and prediction of moisture-related damage.

2.3. EFFECTS OF HYDRATED LIME AS AN ANTI-STRIPPING AGENT

Laboratory investigations and field performance evaluations have shown positive effects of hydrated lime in HMA mixtures. According to a study by Hicks (1991), along with amines and portland cement, hydrated lime was generally more effective than polymers in preventing moisture damage. Furthermore, as shown in Figure 2.1, the effectiveness of lime is quite consistent (small standard deviation) compared to other additives such as the amines. The effectiveness of the amines ranges widely, which indicates highly dependent effectiveness on the asphalt-aggregate combinations. Sufficient literature strongly supports the use of hydrated lime to control moisture sensitivity of asphalt mixtures and also to induce other benefits due to lime addition such as stiffening the asphalt binder and HMA, improvements in the resistance to fracture growth at low temperatures, and favorable oxidation kinetics and interactions with products of oxidation to reduce deleterious effects by aging (Aschenbrener 1995, Little and Epps 2001, McCann and Sebaaly 2003).

Ping (1993) conducted a laboratory investigation to monitor effectiveness of lime to protect HMA mixtures from moisture damage. He used lime in slurry form with one percent of lime by weight of total aggregates and conducted AASHTO T-283 testing to obtain tensile strengths from either wet or dry samples. The hydrated lime showed positive effects by enhancing tensile strength ratio of mixtures.

More recently, Huang *et al.* (2005) investigated the impact of lime addition in the moisture resistance of HMA by directly adding lime in the binder (or mastic) prior to mixture preparation. They used two mineralogically-different aggregates, granite with silica and limestone with high concentration of calcium. With two chemically different aggregate surfaces, the authors were expecting different reactions with polar components of the asphalt, resulting in different moisture resistant behavior. Based on the indirect tensile strength results, they found out that lime treatment of the asphalt prior to mixing produced a stronger mixture.

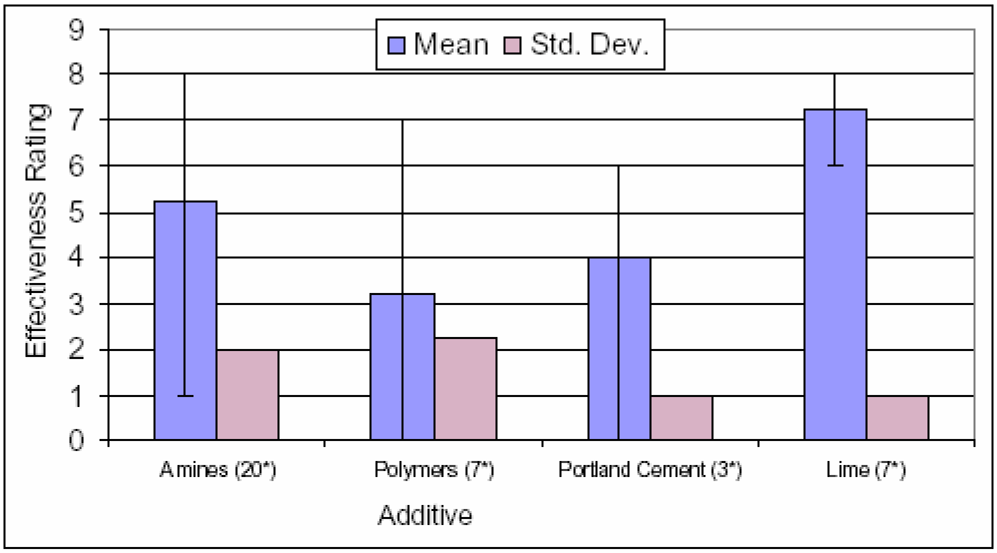


Figure 2.1 Effectiveness Rating of Additives (Hicks 1991)

Another seminal study on this subject was done by McCann and Sebaaly (2003). They evaluated the mechanical properties of lime-treated mixtures before and after multiple cycles of freeze-thaw. They also evaluated the effectiveness of lime treatment by varying the method of lime addition: dry lime into moistened aggregates and lime slurry to dry aggregates, with either a 48-hour marination or no marination process. McCann and Sebaaly (2003) measured resilient modulus, tensile strength, and simple shear strain of each mixture. Based on testing results and statistical analyses, they presented the following findings: 1) the addition of lime reduced the moisture-related rutting potential; 2) the method of lime addition did not significantly affect moisture sensitivity of the mixtures; and 3) the resilient modulus showed to be the best indicator to evaluate mixture's moisture susceptibility specifically for specimens that show minimal differences between unconditioned and conditioned tensile strength.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter describes materials used in this research (aggregates, hydrated lime, and asphalt binder). It also illustrates mix design methods to obtain four Superpave mixes (named B0, B1, B2 and B3) satisfying NDOR (Nebraska Department of Roads) SP2 mix design specifications. At the end of this chapter, a brief description of three asphalt concrete performance tests, APA (asphalt pavement analyzer) testing, Hamburg testing, and AASHTO T-283 testing, performed to evaluate macroscopic moisture-related sensitivity of mixes and three fundamental material constituent tests, DSR (dynamic shear rheometer) testing, micromechanical fracture-damage testing, and surface energy measurements to further investigate material-specific moisture damage mechanisms in the mixes.

3.1. MATERIAL SELECTION

To accomplish more realistic simulation of hot mix asphalt (HMA) mixtures paved in Nebraska, the most widely used local paving materials (aggregates and asphalt binder) were selected for fabricating laboratory samples. Since hydrated lime has been recommended by NDOR to reduce moisture damage of pavements, this project employed hydrated lime and investigated its effects as an anti-stripping agent in part of the studied mixtures.

3.1.1 Aggregates

Total of six local aggregates (5/8-in. limestone, 1/4-in. limestone, several crushed gravels (such as 2A, 3ACR, and 47B), and screenings) were used in this project. 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.

As can be seen, each aggregate demonstrates very different characteristics, so that a wide range of aggregate blends meeting target specific gravity and angularity can be obtained via appropriate aggregate mixing.

Table 3.1 Fundamental Properties of Aggregates

	Aggregate Property						
	Fine Aggregate			Coarse Aggregate			
Aggregate	G_{sb}	**Absorption Capacity (%)**	**FAA (%)**	G_{sb}	**Absorption Capacity (%)**	**CAA (%)**	**Sand Equivalency (%)**
2A	2.580	0.76	37.6	2.589	0.68	28	100.0
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	26.0
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	84.0
47B	2.605	0.49	37.3	2.594	0.65	35	98.0

3.1.2 Asphalt binder

The asphalt binder used in this study is a Superpave performance-graded binder PG 64-22, which has been mostly used for low volume local roads in Nebraska. The asphalt was provided from KOCH Materials Company, located in Omaha. Table 3.2 presents fundamental properties of the binder by performing dynamic shear rheometer (DSR) tests and bending beam rheometer (BBR) tests that have been 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 64-22.

Table 3.2 Properties of Asphalt Binder PG 64-22

Test	**Temperature (°C)**	**Test Result**	**Required Value**
Unaged DSR, G*/sinδ (kPa)	64	1.48	Min. 1.00
RTFO - Aged DSR, G*/sinδ (kPa)	64	3.499	Min. 2.20
PAV - Aged DSR, G*sinδ (kPa)	25	4,576	Max. 5,000
PAV - Aged BBR, Stiffness(MPa)	-12	203.97	Max. 300
PAV - Aged BBR, m-value	-12	0.312	Min. 0.30

3.1.3 Hydrated lime

The use of hydrated lime has been recommended in many states including Nebraska where HMA pavements are susceptible to moisture-related stripping. Hydrated lime has been known as a promising potential material to reduce moisture damage of pavements due to its unique physical/chemical/mechanical characteristics. Regardless of clear impacts of hydrated lime on moisture damage mitigation, it has not been fully understood yet how hydrated lime resists moisture damage, and which treating method of mixing hydrated lime into HMA provides better performance. This study used hydrated lime in two different forms, dry and slurry, to investigate the effects of hydrated lime depending on its type and application method (e.g. dry lime to wet aggregates or lime slurry to wet aggregates). 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. MIX DESIGN METHOD

As mentioned, four SP2 mixes (B0, B1, B2 and B3) were designed to conduct HMA performance tests: APA, Hamburg, and AASHTO T-283. Each mix was designed with the same blend of aggregates in order to keep constant overall aggregate angularities (both CAA and FAA) and mineralogical characteristics. The only variable to differentiate mixes was the additive, marked as **X** in Figure 3.1 in the mix.

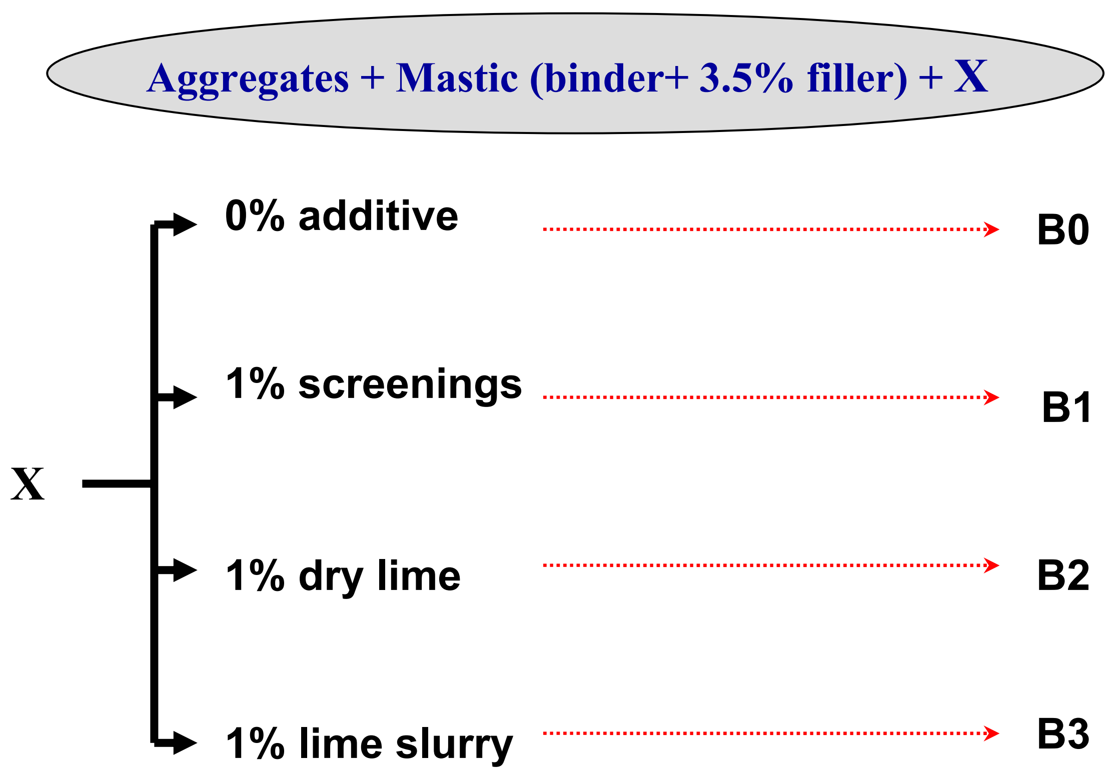


Figure 3.1 SP2 Mixes Designed (B0, B1, B2 and B3)

The mix, B0 is a control mix where no additive is in the mix. Figure 3.2 presents an overall gradation of aggregate blends targeted to form the mix B0. As shown in the figure, the mix satisfies Superpave control points and is located below restricted zone.

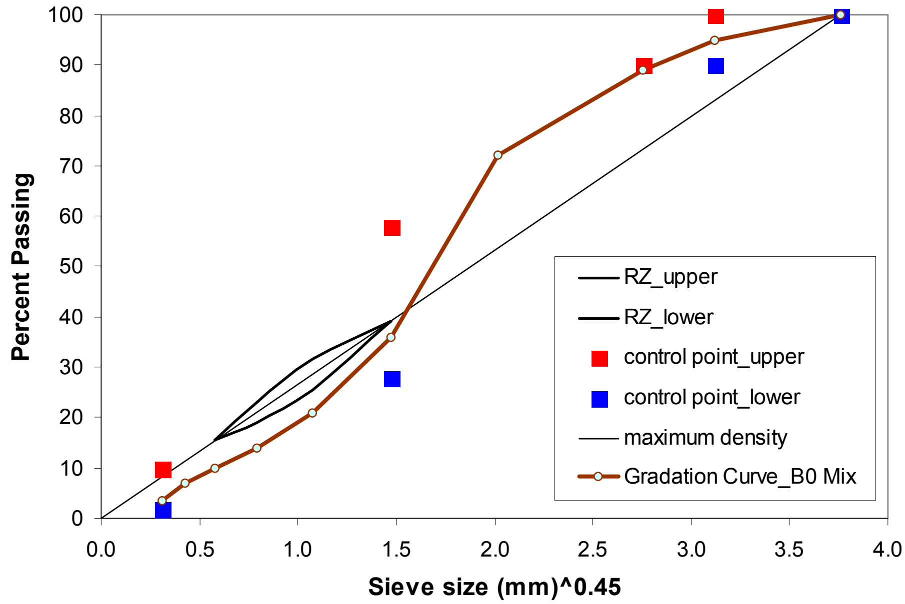


Figure 3.2 Aggregates Gradation Curve of the Mix B0 (Reference Mix)

One percent filler of screenings by total weight of aggregates was added to B0 to design the mix, B1. Any change in laboratory performance testing data from B0 to B1 will explain the effect of additional filler (one percent screenings) in a mix on moisture-related damage such as rutting and stripping. Additional fillers generally stiffen the binder resulting in more rut-resistant HMA mixes.

In order to investigate effects of hydrated lime as an anti-stripping agent, two different mixes, B2 and B3 were designed. As shown in Figure 3.1, one percent of lime in dry form was treated to B2 and in slurry form to B3, respectively. Comparing mix performance testing results from B2 (or B3) with the mix B0 will reveal any benefits obtained from lime addition, and performance variations between B2 (or B3) and B1 will show effects by replacing mineral fillers (such as screenings) with lime. Furthermore, the effectiveness dependent on treating method of hydrated lime into HMA can also be evaluated by simply comparing two mixes, B2 and B3.

Each mix was then designed by following the elaborated steps described in Figure 3.3. As shown in Figure 3.3, one fine aggregate, screenings passing No. 16 sieve was washed and dried before blending with other aggregates because the screenings through dry sieving contained too much 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.

For the lime-treated mixtures, aggregate blends were moisturized before lime was added to the mix. The mix B2 refers to a process of adding 3.0% water, by weight of total aggregates, to dry aggregates and distributing the moisture by mixing. Dry hydrated lime at a rate of 1.0%, by total dry weight of aggregate, was then mixed with the wet aggregates for 10 minutes to produce evenly-distributed lime-water films on aggregate surfaces. The lime-treated aggregates were then oven dried for 2 hours to eliminate all water before the addition of asphalt binder. The 1.0% hydrated lime by weight of total dry aggregates is currently the required amount of lime for Superpave mixes used in Nebraska pavements.

As noted, one of the primary objectives of this project is to evaluate application methods of hydrated lime into HMA mixtures. To meet this goal, two mixes, B2 and B3, were introduced and compared. For better comparisons, the amount of hydrated lime and the water in those two mixes (B2 and B3) should be controlled so that the effect of lime-treatment process on HMA moisture-related performance can be revealed in a more appropriate way. In an attempt to know proportional characteristics, lime slurry was oven-dried and weighed before and after drying. Several repetitions of this process yielded 0.385 lime/water ratio in slurry. Consequently, 1.2% water was necessary for the B3 mix to match with 3.0% water in the B2 mix. The amount of lime slurry added to wet aggregates in B3 mixes was set to result in 1.0% of dry lime by total weight of aggregates after being oven dried.

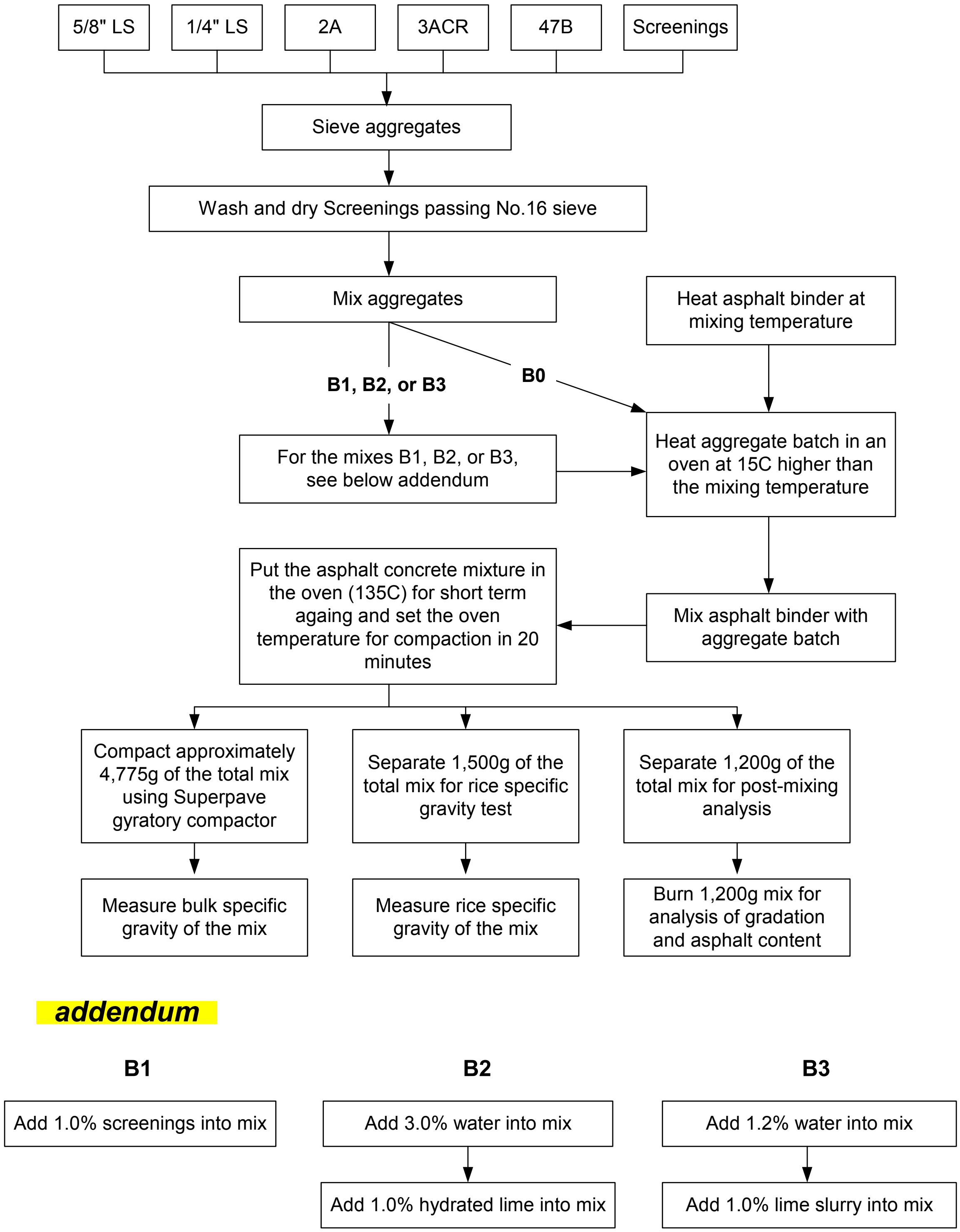


Figure 3.3 Mix Design Procedure

All the mixes for this project are SP2 type, a low quality weak mix used mostly for low volume local road pavements. The compaction effort used for the SP2 mix is the one for a traffic volume around 0.3 to 1 million equivalent single axle loads (ESALs). Table 3.4 summarizes NDOR specification requirements of aggregate properties, volumetric mix design parameters, and laboratory compaction effort for the SP2 mix. Compaction effort was estimated based on average value of high air temperature in Omaha, Nebraska: 98ºF (36.67ºC).

Table 3.4 Required Volumetric Parameters and Aggregate Properties for SP2 Mix

	NDOR Specification (SP2 Mix)
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	> 65
FAA (%): fine aggregate angularity	> 43
SE (%): sand equivalency	> 40
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 - 78
$\%P_b$: asphalt content	-
D/B (ratio): dust-binder ratio	0.7 - 1.7

All four mixes designed in asphalt/concrete laboratory at the University of Nebraska-Lincoln (UNL) were submitted to NDOR asphalt/aggregate laboratories for validation of aggregate properties (i.e. Superpave consensus properties of aggregates) and volumetric mix design parameters. UNL design values and NDOR validations are presented and compared in following chapter, Chapter 4 Testing Results and Discussion.

3.3. PERFORMANCE EVALUATION OF ASPHALT CONCRETE MIXES

Three most popular performance tests associated with evaluation of HMA moisture damage and susceptibility were conducted in this project: AASHTO T-283 (“Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage"), APA testing of compacted asphalt concrete samples under water, and Hamburg testing of compacted asphalt concrete samples under water.

3.3.1 AASHTO T-283

The evaluation of moisture sensitivity of asphalt concrete samples has been widely accomplished using a standard method, AASHTO T-283. This test procedure was elaborated based on a study by Lottman (1978) and posterior work developed by Tunnicliff and Root (1982). Studies by Witczak *et al.* (2002), McCann and Sebaaly (2003), and many more have employed this technique for assessing moisture sensitivity of various mixtures and materials due to its simplicity, even if this laboratory evaluation has a relatively low correlation with actual performance in field.

As demonstrated in Figure 3.4, the AASHTO T-283 testing applies a compressive load to a cylindrical specimen through two diametrically opposed, arc-shaped rigid platens to induce tensile stress along the diametral vertical axis of the test specimen.

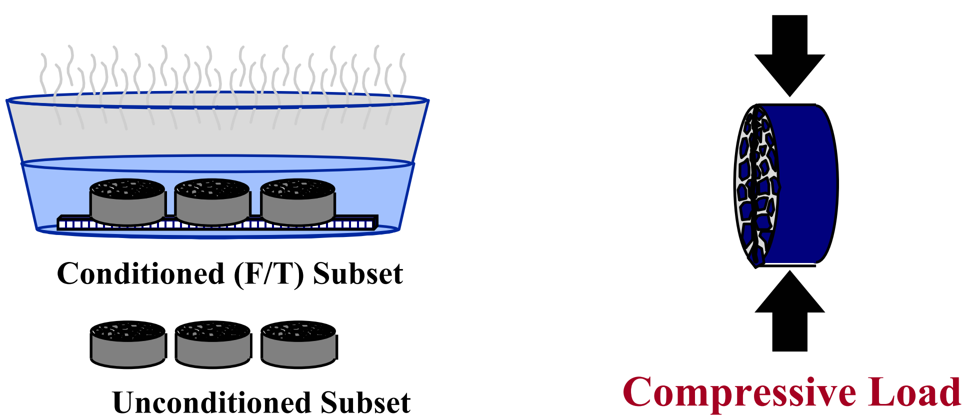


Figure 3.4 Schematic View of AASHTO T-283 Testing

A series of splitting tensile strength tests are conducted at a constant strain rate of 2 in. per minute vertically until vertical cracks appear and sample fails. A peak compressive load (in Figure 3.5) is recorded and used to calculate tensile strength of the sample using the following equation:

$$TS = \frac{2 \cdot P}{\pi \cdot t \cdot D} \qquad [3.1]$$

where TS = tensile strength (psi),

P = peak compressive load (lb),

t = specimen thickness (in), and

D = specimen diameter (in).

Three subsets of specimens are fabricated and tested, with two subsets subject to partial vacuum saturation followed by one freeze-thaw (F-T) cycle and six F-T cycles, respectively prior to be tested. Third subset is tested without conditioning process. Numerical index of resistance of asphalt mixtures to water is expressed as the ratio of the average tensile strength of the dry specimens to the average tensile strength of the conditioned specimens.

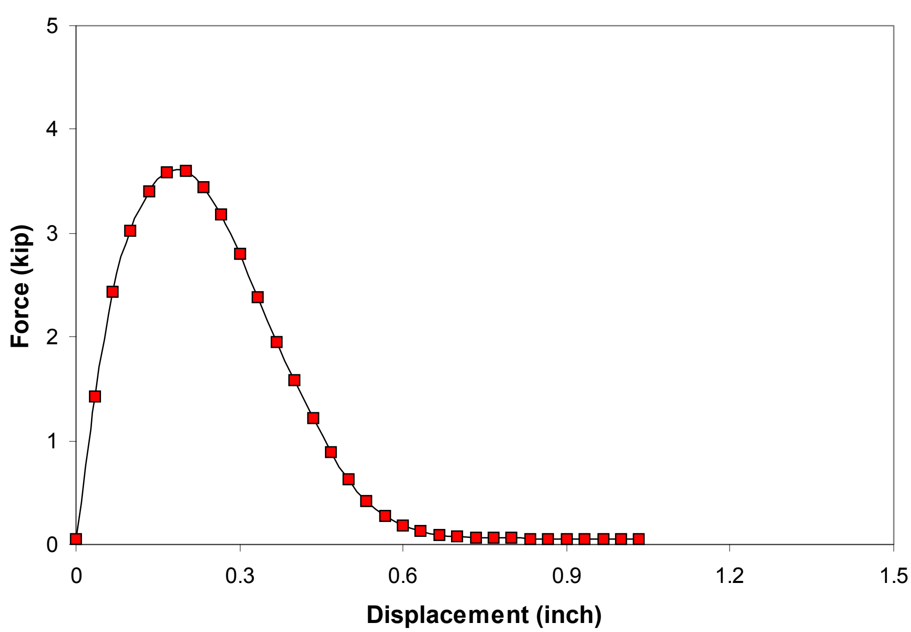


Figure 3.5 Typical AASHTO T-283 Testing Result

3.3.2 Asphalt pavement analyzer (APA) testing under water

Rutting susceptibility and moisture resistance of asphalt concrete samples can be evaluated using the asphalt pavement analyzer (APA) shown in Figure 3.6. The APA is an automated, new generation of Georgia Load Wheel Tester (GLWT) used to evaluate rutting, fatigue, and moisture resistance of asphalt concrete mixtures. During the APA test, the rutting susceptibility of compacted specimens is tested by applying repetitive linear loads through three pressurized hoses via wheels to simulate trafficking. Even though it has been reported that APA testing results are not very well matched with actual field performance, APA testing is relatively simple to do and produces rutting potential of mixes by simply measuring sample rut depth. To evaluate moisture damage and susceptibility, asphalt concrete samples from each mix are maintained under water at the desired temperature during the test, and submerged deformations are measured with an electronic dial indicator. Due to its simplicity and popularity, the APA was employed in this project to estimate effects of additives and application methods of hydrated lime on moisture-related rut damage of HMA mixes. Testing results are presented and discussed in Chapter 4.

Figure 3.6 APA Testing Machine

3.3.3 Hamburg testing

The Hamburg wheel-tracking was originally developed in the city of Hamburg, Germany by Helmut-Wind in the 1970's, based on a similar British device that used a rubber tire. By measuring rut depth and the number of passes to failure, the test evaluates premature failure susceptibility of asphalt concrete mixtures due to weakness of asphalt-aggregate structures, inadequate asphalt binder stiffness, inadequate adhesion between asphalt and aggregate, and moisture damage.

A repetitive load is applied over a pair of specimen simultaneously by a steel wheel with a diameter of 8 in. and width of 1.85 in. The linear variable differential transducers (LVDTs) measure the specimen's rut depth induced by the wheel trafficking. The specimens are cored in order to fit the testing mold, as shown in Figure 3.7. They are conditioned at the testing temperature for a minimum of 30 min. A water bath controls the temperature. Figure 3.8 shows a typical Hamburg wheel-tracking device.

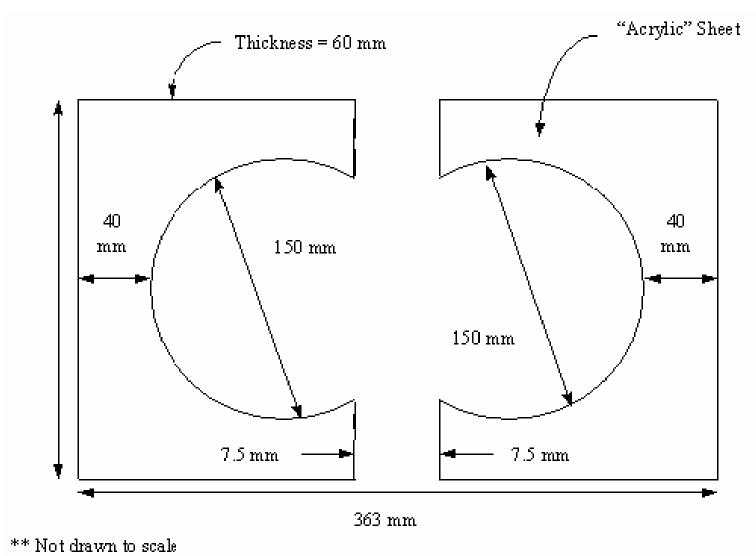
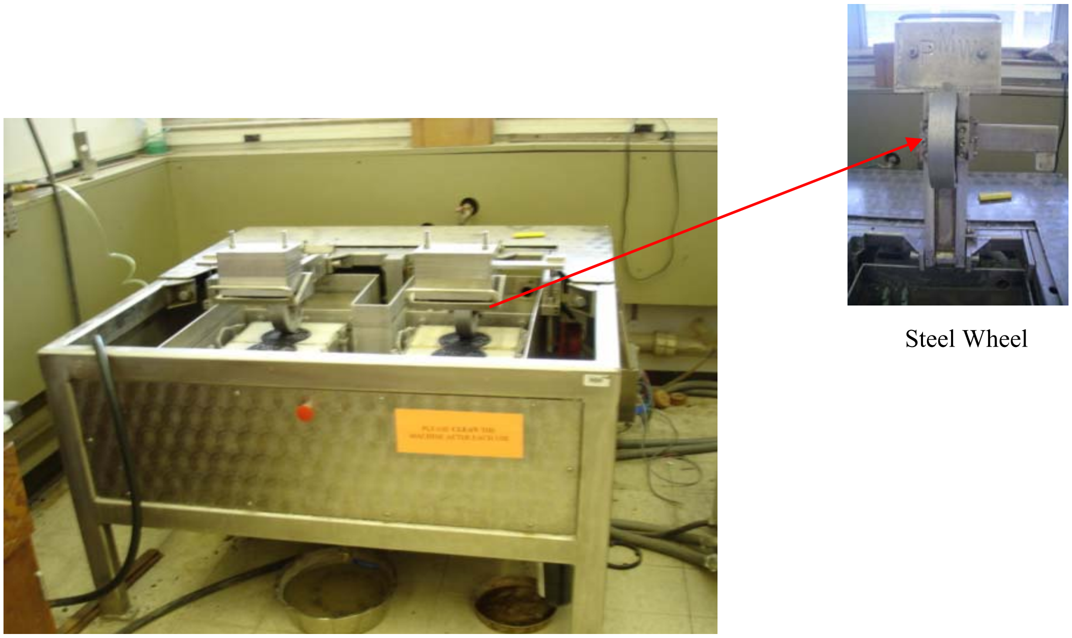


Figure 3.7 Hamburg Testing Mold



Steel Wheel

Figure 3.8 Hamburg Wheel-Tracking Device

Hamburg testing results can be plotted with a curve (rut depth vs. number of passes) as shown in Figure 3.9. Hines (1991) defined the creep slope, stripping slope, and stripping inflection point. As stated by Aschenbrener (1995), the creep slope relates to rutting from plastic deformation. It is the inverse of the rate of deformation in the linear region of the deformation curve after post-compaction effects have ended and before the onset of stripping. The stripping slope is the inverse of rate of deformation in the linear region of deformation curve after stripping begins until the end of the test. The stripping slope is related to the severity of moisture damage. The stripping point is the number of passes at the intersection of the creep slope and the stripping slope. It is related to the resistance of HMA mixtures to moisture damage.

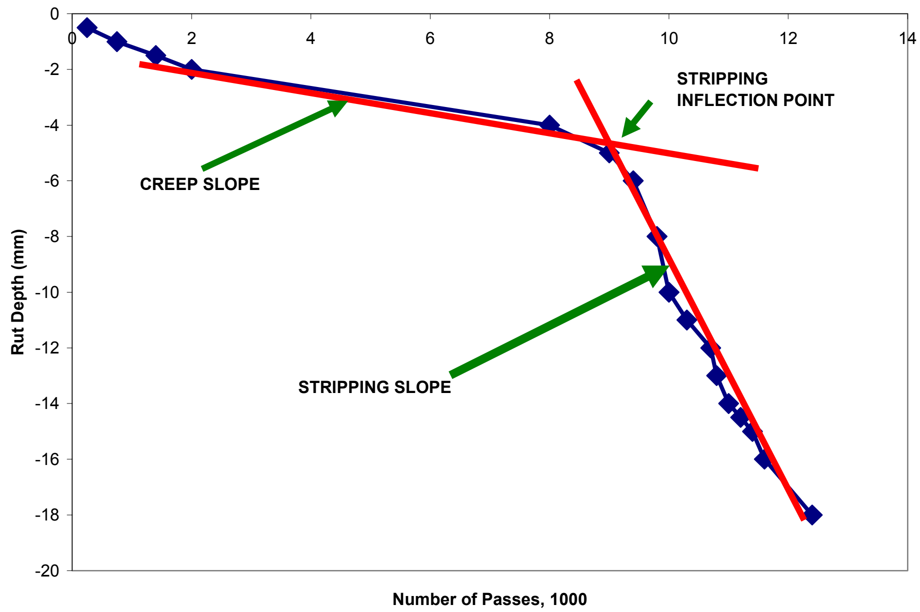


Figure 3.9 Typical Hamburg Testing Results

3.4. PROPERTY EVALUATION OF MIX CONSTITUENTS

Many studies have demonstrated that moisture typically reduces the mastic stiffness and degrades the adhesive bonding between the mastic and aggregate particles. Fundamental material properties are key controlling factors related to moisture damage. Thus, this research project evaluated the fundamental properties of the mixture constituents (asphalt mastic and aggregates) by performing dynamic shear rheometer (DSR) testing of binder/mastics, micromechanical fracture-damage testing of binder/mastics, and surface energy measurements of mastics and aggregates to further evaluate, respectively, stiffness of binder/mastics, strength of binder/mastics, and bonding potential of mastics-aggregates of each mix (B0, B1, B2, and B3) considered in this project. Measurements of fundamental properties and material characteristics of mix components will provide an appropriate tool to identify moisture damage mechanisms, to evaluate effects of additives and treating methods in a more detailed view, and to select better asphalt-aggregate combinations that are more resistant to moisture damage based on better understanding.

3.4.1 Dynamic shear rheometer (DSR) testing

The DSR is one of the primary equipment that has been used to identify Superpave performance grade and to characterize viscoelastic properties of asphalt binder mostly at intermediate and high service temperatures. Since this project investigates the effects of additives (e.g. additional mineral filler or hydrated lime) on moisture-related rut damage of HMA mixtures, the use of the DSR by simply measuring complex shear moduli of asphalt mastics extracted from each HMA mix will produce insights that can evaluate stiffness of mastics and the role of mastic stiffness to moisture damage susceptibility.

As shown in Figure 3.10, a dynamic torsional shear stress at the desired temperature is applied to obtain two fundamental viscoelastic properties: dynamic shear modulus $|G^*|$, representing stiffness of sample and the phase angle δ that represents the relative amount of recoverable and non-recoverable deformation.

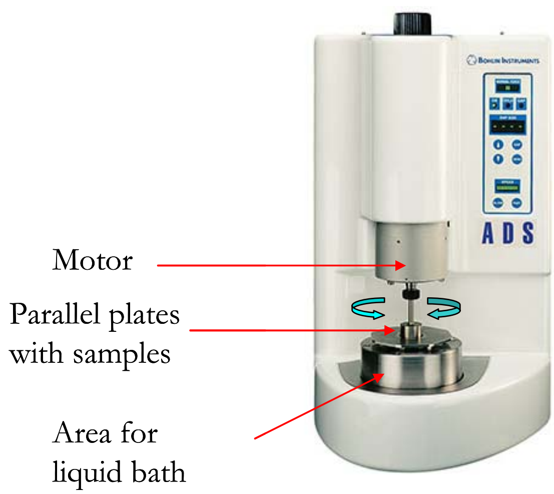


Figure 3.10 Dynamic Shear Rheometer

3.4.2 Micromechanical fracture-damage testing

Moisture damage accelerates structural degradation of HMA mixtures in conjunction with fracture and plastic flow, because moisture typically reduces stiffness and strength of mastic through diffusion. Damage-associated properties of asphalt mastics need to be identified in an appropriate way for better understanding of damage processes involved and physical/mechanical effects of additives (such as mineral fillers or hydrated lime) on HMA moisture damage resistance, however accurate characterization and evaluation of damage of mastics is challenging because asphalt mastics typically demonstrate significant level of nonlinearity and inelasticity when they are subjected to damage.

A testing method for the better understanding of damage characteristics of asphalt mastic samples should be one that can appropriately identify the complex nonlinear-inelastic damage growth of mastics and concurrently is easy to perform and produces repeatable testing results. This study employed a micromechanical fracture-damage testing device developed by the PI and his research team at the University of Nebraska-Lincoln (Freitas *et al.* 2006).

As illustrated in Figure 3.11, the micromechanical fracture-damage testing device is composed of three main parts: (i) control system; (ii) motion system; and (iii) data acquisition system. A stepping motor connected to a gear box generates a torque to side screws that drive the translation stages in opposite directions. A load cell reads the real-time resisting force during the test and sends the electric signals to a data acquisition system where these signals are translated into engineering values (e.g. time, displacement, and resisting force). The test can be performed under a displacement-controlled static or cyclic mode. Asphalt mastics are fabricated in a form of thin film between two metal plates (shown in Figure 3.12), and opening or shearing movement between two plates is induced to evaluate progressive damage-dependent mechanical properties of mastic samples.

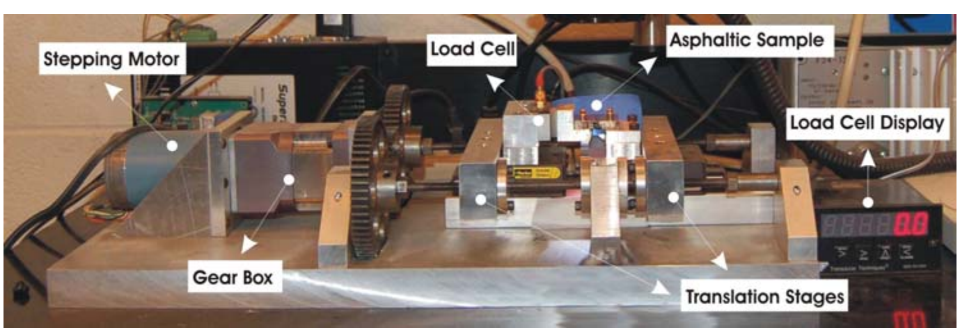


Figure 3.11 Fracture-Damage Testing Device Set-up (Freitas *et al.* 2006)

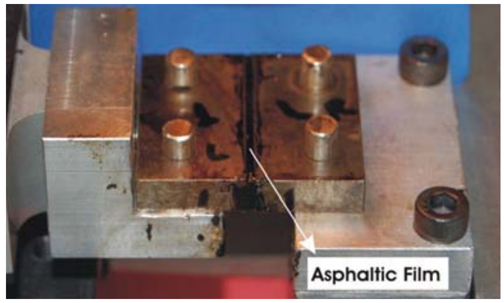


Figure 3.12 Asphalt Film Sample for Testing (Freitas *et al.* 2006)

The micromechanical fracture-damage testing system has shown a great success. Figure 3.13 presents the force versus time curves for a set of five replicates (neat asphalt binder PG 64-22) at the same opening displacement rate (0.00027 m/s) and at a testing temperature of 24ºC. Figure 3.13 demonstrates that the testing is highly replicable. No large discrepancies among the samples were observed. For this project, fracture-damage characteristics of mastic samples from each different mix can be compared by simply monitoring the peak value of the curve, representing strength of the mastic, and/or the area under the force-time curve that represents total dissipated energy to failure.

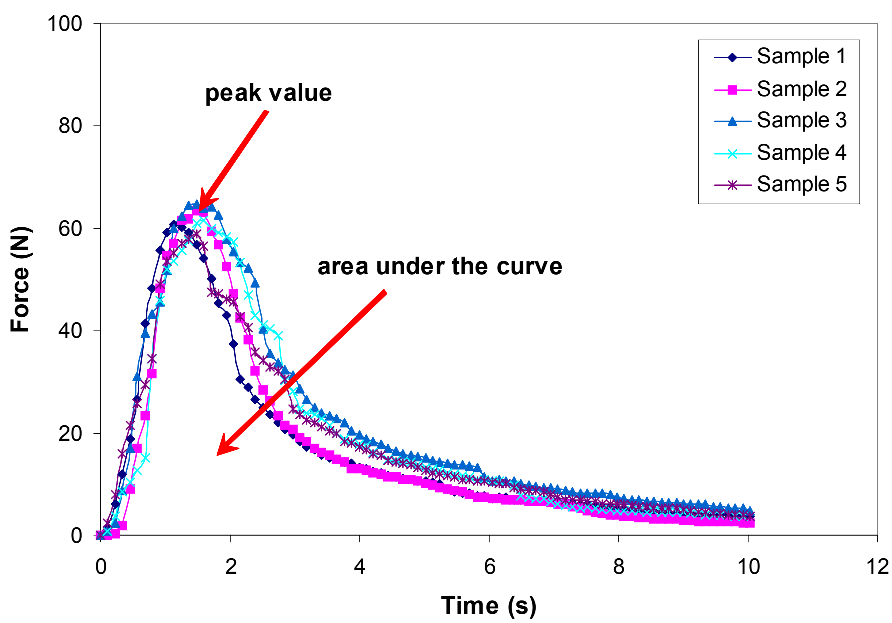


Figure 3.13 Testing Results of Five Asphalt Binder Replicates

3.4.3 Surface free energy measurements

Several mechanisms govern the degradation of the adhesive bond between the asphalt mastic and the aggregate in the presence of water. These mechanisms can be largely attributed to different physico-chemical properties at the surfaces of these materials. Evidence from the literature suggests that important thermodynamic parameters that are correlated to moisture damage of HMA mixtures can be derived by measuring the surface free energy of the asphalt binders/mastics and aggregates (Bhasin *et al.* 2006, Cheng 2002).

In this research the surface free energy components of asphalt mastic for each mix (e.g. B0, B1, B2, and B3) were determined by measuring the dynamic contact angles of different probe liquids with the Wilhelmy plate device as shown in Figure 3.14. The surface free energy components of aggregates were also determined by using the universal sorption device (USD) illustrated in Figure 3.15. The methodology used for these tests follows the procedure outlined in Hefer *et al.* (2006) and Bhasin and Little (2006).

Figure 3.14 Wilhelmy Plate Testing Device

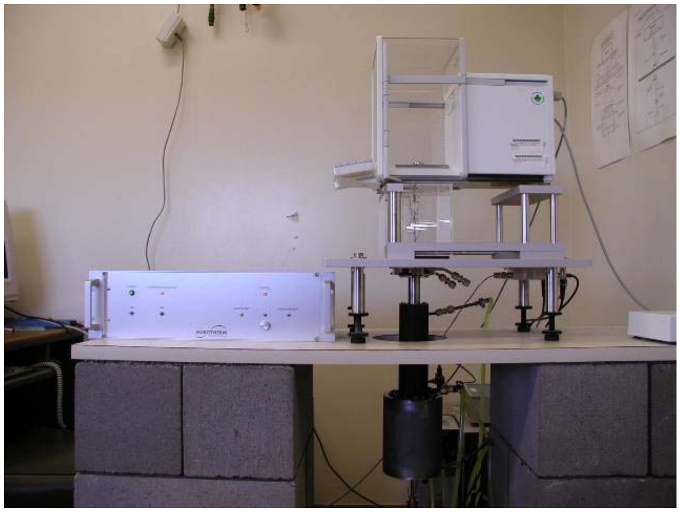


Figure 3.15 Universal Sorption Device (USD)

The acid-base theory can be used to determine the surface energy components of an arbitrary material. According to this theory, the total surface free energy of a material, γ^{total}, consists of three different components as follows:

$$\gamma^{total} = \gamma^{LW} + 2\sqrt{\gamma^{+}\gamma^{-}} \quad [3.2]$$

where, γ^{LW} = Lifshitz - van der Waals component,

γ^{+} = Lewis acid component, and

γ^{-} = Lewis base component.

Then, the work of cohesion, adhesion, and debonding can be calculated from the three surface free energy components of the asphalt mastic, aggregate, and water using the following equations:

$$W_{AM} = 2\sqrt{\gamma_A^{LW}\gamma_M^{LW}} + 2\sqrt{\gamma_A^{+}\gamma_M^{-}} + 2\sqrt{\gamma_A^{-}\gamma_M^{+}} \quad [3.3]$$

$$W_{MM} = 2\gamma_M^{LW} + 4\sqrt{\gamma_M^{+}\gamma_M^{-}} \quad [3.4]$$

$$W_{AMW}^{wet} = \gamma_{AW} + \gamma_{MW} - \gamma_{AM} \quad [3.5]$$

where W_{MM} = work of cohesion of the asphalt mastic,

W_{AM} = work of adhesion between the asphalt mastic and the aggregate, and

W_{AMW}^{wet} = work of debonding between mastic-aggregate in the presence of water.

The subscripts '*A*' and '*M*' refer to the aggregate and asphalt mastic. Subscripts '*AW*', '*MW*', and '*AM*' refer to the aggregate and water, asphalt mastic and water, and asphalt mastic and aggregate interfaces, respectively, and γ_{ij} is the interfacial energy between any two materials, '*i*' and '*j*' that is derived from their respective surface free energy components as follows:

$$\gamma_{ij} = \gamma_i + \gamma_j - 2\sqrt{\gamma_i^{LW}\gamma_j^{LW}} - 2\sqrt{\gamma_i^{+}\gamma_j^{-}} - 2\sqrt{\gamma_i^{-}\gamma_j^{+}} \qquad [3.6]$$

Substituting equation [3.6] into [3.5] and rearranging yields

$$\begin{aligned} W_{AMW}^{wet} &= 2\gamma_w^{LW} + 2\sqrt{\gamma_M^{LW}\gamma_A^{LW}} - 2\sqrt{\gamma_M^{LW}\gamma_W^{LW}} - 2\sqrt{\gamma_A^{LW}\gamma_W^{LW}} + \\ &4\sqrt{\gamma_W^{+}\gamma_W^{-}} - 2\sqrt{\gamma_W^{+}}\left(\sqrt{\gamma_M^{-}} + \sqrt{\gamma_A^{-}}\right) - 2\sqrt{\gamma_W^{-}}\left(\sqrt{\gamma_M^{+}} + \sqrt{\gamma_A^{+}}\right) + \\ &2\sqrt{\gamma_M^{+}\gamma_A^{-}} + 2\sqrt{\gamma_M^{-}\gamma_A^{+}} \end{aligned} \qquad [3.7]$$

The work of debonding between asphalt mastic and aggregate in the presence of water, W_{AMW}^{wet} is always a negative value indicating that bond energy between the asphalt mastic and aggregate is released in the presence of moisture or that moisture will replace asphalt mastic at the interface. The potential of water to replace the asphalt mastic bond is directly proportional to the magnitude of this negative value. The more negative the value of W_{AMW}^{wet} is, the greater is the potential for asphalt-aggregate bond loss.

CHAPTER 4
TESTING RESULTS AND DISCUSSION

Superpave mix designs of all four SP2 mixes (B0, B1, B2 and B3) accomplished at UNL were validated from NDOR asphalt/aggregate laboratories. Mix design results from both UNL and NDOR laboratories are presented in this chapter. Laboratory performance testing results from AASHTO T-283, asphalt pavement analyzer (APA), and Hamburg wheel-tracking device are also presented and discussed in detail in this chapter. Based on the performance testing results, a hypothesis is drawn to explain the effects of additives (e.g. mineral fillers, hydrated lime, or lime slurry) on moisture damage mechanisms of asphalt mixtures. Component property testing results from dynamic shear rheometer (DSR), micromechanical fracture-damage testing device, and surface energy measuring systems are then presented to correlate hot mix asphalt (HMA) performance data with component properties and to validate the hypothesis made as well.

4.1. MIX DESIGN RESULTS

Volumetric parameters and aggregate properties of each mix are shown in Table 4.1. All SP2 mixes were designed at UNL, and representative batches of each mix were sent to NDOR laboratories for validation. As can be seen in the table, mix volumetric properties and aggregate characteristics obtained from UNL laboratory matched well with NDOR measurements and met NDOR SP2 mix specifications. Based on NDOR validation study, it can be inferred that UNL mix designs have been conducted successfully.

Table 4.1 Volumetric Mix Properties and Aggregate Properties

	NDOR LIMITS	B0		B1		B2		B3	
		UNL	NDOR	UNL	NDOR	UNL	NDOR	UNL	NDOR
G_{mm}	-	2.426	2.422	2.427	2.424	2.434	2.431	2.435	2.421
G_{sb}	-	2.578	2.578	2.578	2.578	2.578	2.578	2.578	2.578
G_{mb}	-	2.348	2.351	2.361	2.369	2.362	2.372	2.357	2.363
CAA	> 65	76	70	76	70	76	70	76	70
FAA	> 43	43.3	42.9	43.3	42.9	43.3	42.9	43.3	42.9
SE	> 40	-	73	-	73	-	73	-	73
F&E	< 10	-	1	-	1	-	1	-	1
$\%V_a$	4 ± 1	4.5	4.3	4	3.5	4.2	3.7	4.5	3.7
VMA	> 14	15.4	15.1	14.7	14.4	14.4	14.1	14.7	14.7
VFA	65 - 78	70.6	71.74	72.9	75.4	70.8	73.7	69.3	75.1
$\%P_b$	-	5.82	5.62	5.61	5.57	5.4	5.35	5.43	5.71
D/B	0.7 - 1.7	1.08	0.87	1.01	1.04	1.26	1.15	1.15	1.00

4.2. PERFORMANCE TESTING RESULTS OF ASPHALT CONCRETE MIXES

4.2.1 AASHTO T-283 testing results

For each mix, three subsets (3 specimens for each subset) compacted with 7.0% ± 0.5% air voids were tested. First subset was tested in dry condition, second subset was subjected to partial vacuum saturation (degree of saturation of 70 to 80%) followed by one freeze-thaw (F-T) cycle, and third subset was tested with the partial vacuum saturation and six times of F-T cycles. In the field, asphalt mixtures may experience many F-T cycles during service life, which was simulated by introducing the multiple F-T cycling.

Figure 4.1 illustrates representative testing results that demonstrate testing repeatability and a fact that conditioned samples experience severe moisture damage than unconditioned samples and, as expected, the multiple F-T cycling accelerates moisture damage, which results in substantial structural degradation of the HMA samples.

The test results are summarized in Table 4.2. Each tensile strength value reflects the average of three values obtained from testing three specimens (3 specimens per each subset). Tensile strength values in Table 4.2 were then used to calculate tensile strength ratios (TSR) as follows:

$$TSR = \frac{TS_c}{TS_d} \quad [4.1]$$

where TS_c = average tensile strength of the conditioned subset, and

TS_d = average tensile strength of the dry subset

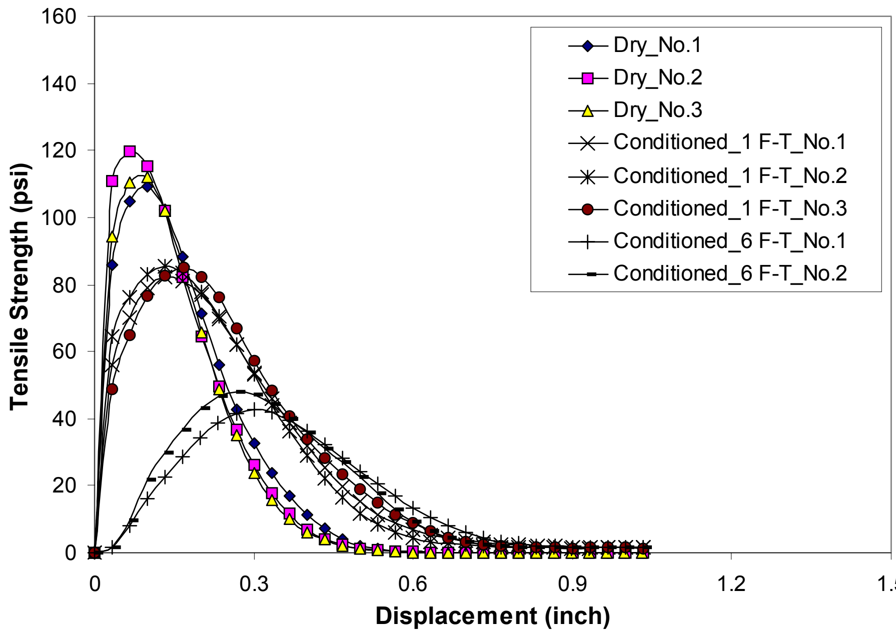


Figure 4.1 AASHTO T-283 Testing Results (B3 Mix)

Table 4.2 Summary of Testing Results (Averaged Tensile Strength)

Mix Type	**Additives**	**Tensile Strength (psi)**		
		Unconditioned	**1 F-T**	**6 F-T**
B0	None	96.70	66.30	10.30
B1	1.0% Screenings	108.34	82.99	11.69
B2	1.0% Dry Lime	112.86	86.82	54.74
B3	1.0% Lime Slurry	113.73	84.15	45.31

Averaged TSR-values of each mix are plotted in Figure 4.2. The figure clearly demonstrates that hydrated lime contributed to an increase in TSR, inferring mitigation of moisture damage due to lime treatment. The effect of lime was even more impressive when the mixes were subjected to multiple F-T cycling. The mixes without lime-treatment, i.e. B0 and B1 experienced severe damage with multiple F-T cycles. Even if it may not be conclusive, the figure also infers that treating dry lime to wet aggregates may produce better efficiency to moisture damage resistance than treating lime slurry onto aggregates. One more thing to be noted from the figure is that additional mineral filler in the mix may play an important role to reduce initial stage of moisture damage, which can be verified from the fact that TSR value of mix B1 (mix with one percent additional filler, screenings) is similar to that of mix B2 and greater than that of mixes B0 and B3 when mixtures were under one F-T cycle. The increase in stiffness due to filler addition typically makes HMA mixtures more damage-resistant.

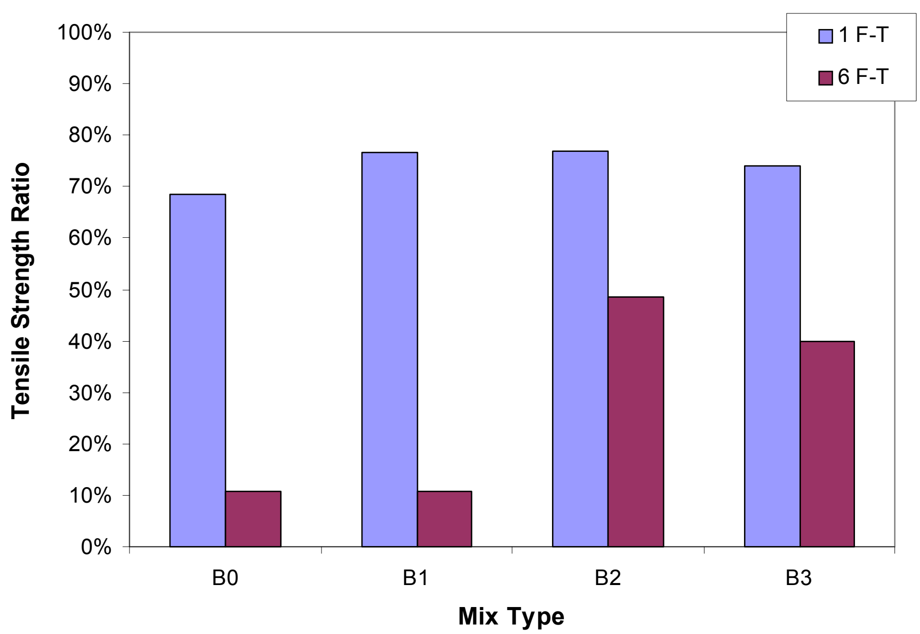


Figure 4.2 Tensile Strength Ratio of Each Mix

4.2.2 APA testing results

The APA testing was conducted on pairs (up to three) at a time using gyratory-compacted asphalt concrete specimens of 75-mm high with 4.0 ± 0.5% air voids. In case that APA specimen demonstrates deeper than 12-mm rut depth before the completion of the 8,000 cycles, the testing was manually stopped to protect APA testing molds and the corresponding number of strokes at the 12-mm rut depth was recorded. Testing was conducted at 64ºC which is the high temperature of the standard Superpave binder performance grade (PG) in this study. In order to evaluate moisture susceptibility, the test was conducted under water. The water temperature was also set at 64ºC. The APA specimens were pre-heated in the APA chamber for 16 hours before testing. The hose pressure and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively.

Table 4.3 presents a summary of APA performance testing results of all mixes. Considering all data, B2 mixes generally performed best, and B0 mixes demonstrated significantly susceptible characteristics to moisture-related rutting: all B0 samples failed before they reached 8,000 cycles. Another fact to be noted from the table is that lime slurry-treated mix, B3 was generally more rut-susceptible than dry lime-treated mix, B2, which has also been observed from the testing, AASHTO T-283. The role of mineral fillers on initial-stage moisture damage resistance due to stiffening effects can also be explained from the table. Rut-resistance of the mix B1 (mix with one percent additional filler, screenings) was similar to that of the mix B2 and better than that of mixes B0 and B3. In an attempt to compare APA rut depths of all tested mixes better, averaged rut depths of each pair of mixes were plotted in Figure 4.3.

Even if B1 mixes showed more rut-resistant behavior than lime slurry-treated mixes, B3, the stripping of asphalt film observed from B1 mixes was more severe than the stripping from B3 mixes, as shown in Figure 4.4. Based on this observation, it can be inferred that hydrated lime enhances asphalt-aggregate interfacial properties by improving bonding characteristics between asphalt and aggregates rather than fully acting as a mineral filler to stiffen binder. Therefore, the mix with additional filler may behave better to initial-level moisture damage that is typically represented by APA rut depths, since the filler-added mix is stiffer than the lime-treated mix.

Table 4.3 Volumetric Parameters and APA Rut Depths of Each Sample

Mix type	Position	Air voids	G_{mb}	Rut depth (mm) @ 8,000 strokes	Rut depth (mm) @ 3,000 strokes
B0	Front 1	4.5	2.320	-	7.20
	Back 1	4.3	2.325	-	8.49
	Front 2	3.8	2.334	-	12.91
	Back 2	3.7	2.336	-	11.43
B1	Front 1	3.5	2.340	7.30	4.05
	Back 1	3.5	2.341	9.01	4.02
	Front 2	3.8	2.334	6.52	4.36
	Back 2	4.0	2.329	8.61	4.50
B2	Front 1	3.7	2.340	5.90	3.75
	Back 1	3.7	2.340	6.01	3.89
	Front 2	3.8	2.337	8.96	4.27
	Back 2	4.1	2.331	7.37	3.59
B3	Front 1	3.9	2.335	14.78	6.04
	Back 1	4.0	2.333	11.54	5.89
	Front 2	3.7	2.329	17.04	7.85
	Back 2	3.5	2.334	12.69	5.58

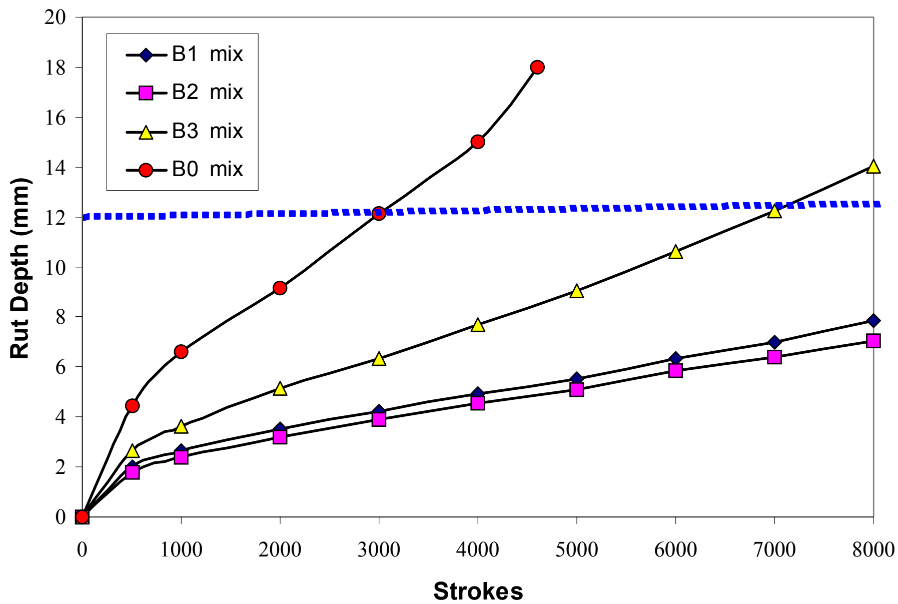


Figure 4.3 Continuous APA Rut Depths of Each Mix

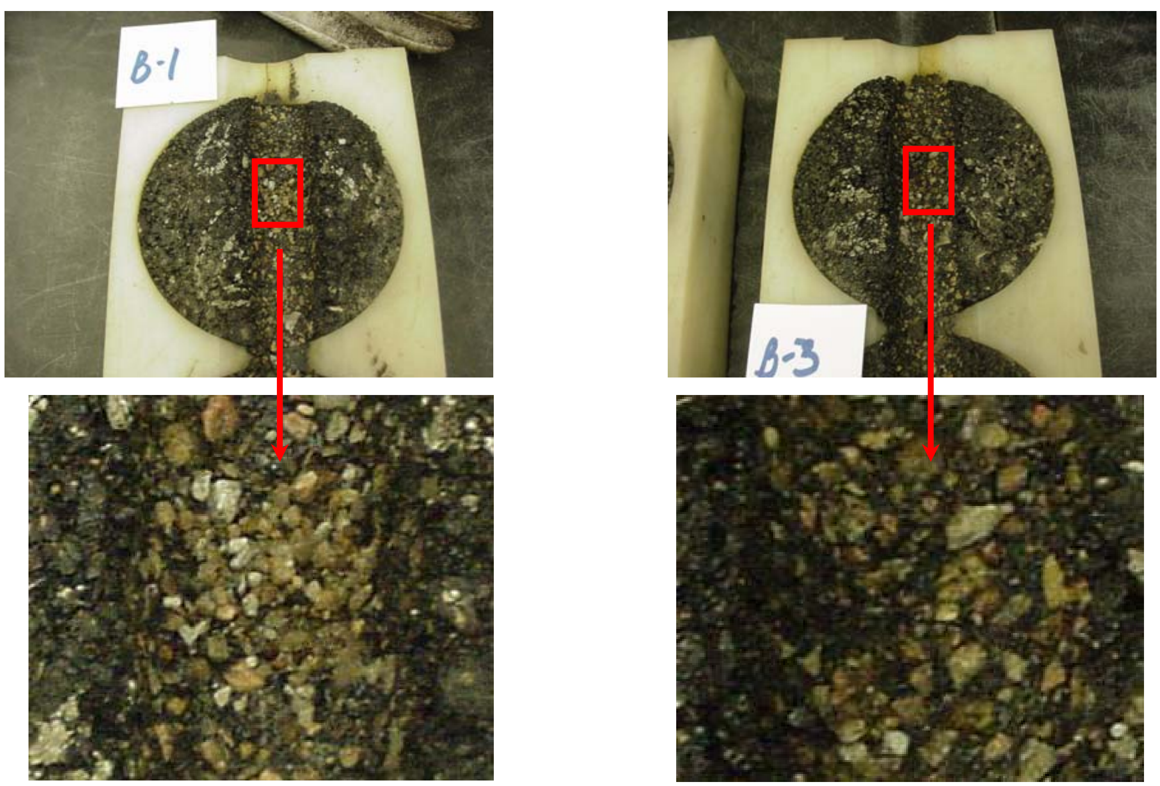


Figure 4.4 Stripping Observed After APA Testing (B1 vs. B3)

4.2.3 Hamburg testing results

Cylindrical specimens were compacted with 7.0% ± 1.0% air voids using a Superpave gyratory compactor, and then the specimens were cut to the required dimensions in order to fit in the molds prior to performing the test. Figure 4.5 shows the specimens after being cut.

Figure 4.5 Hamburg Specimens After Being Cut

The specimens were then submerged in water at 158°F, as shown in Figure 4.6. A pair of steel wheels with a 158 ± 22 lbs passed on top of specimens under water at a constant rate of 50 wheel passes per minute until the specimens failed. The rut depth induced by the wheel trafficking was measured by linear variable differential transducers (LVDTs).

Figure 4.6 Hamburg Specimens under Testing

As mentioned in Chapter 3, the Hamburg testing measures the combined effects of rutting and stripping by rolling steel wheels across the surface of the HMA specimen that is immersed in hot water. Figure 4.7 presents Hamburg testing results of each mixture tested (B1, B2, and B3) for this study. The dry lime-treated mix (B2) performed significantly better than the other mixes. Lime slurry-treated mix (B3) was more rut-susceptible than the mix with one percent additional filler in it (B1), but looking at the stripping points that represent mix potential to debonding, the slurry-treated mix was somewhat better than the mix B1, which is in good agreement with other testing results obtained from APA and AASHTO T-283 testing.

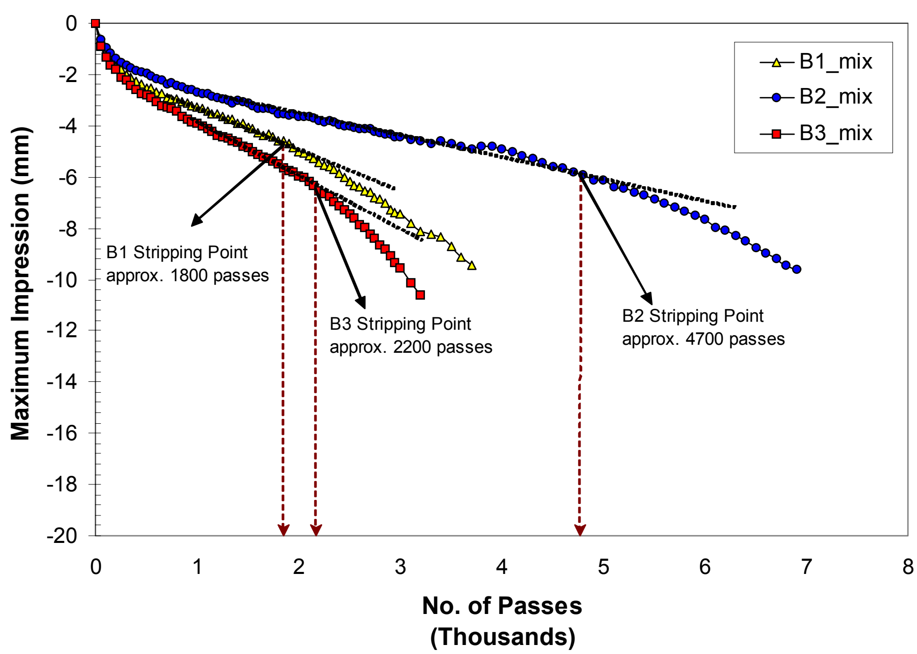


Figure 4.7 Hamburg Testing Results of Each Mix

4.2.4 Preliminary findings from HMA performance testing

Based on testing results from three performance testing of asphalt concrete samples, preliminary findings can be summarized as follows:

- Dry lime-treated mix (B2) was the most moisture-damage resistant. It was generally superior to any mixes tested including the lime slurry-treated mix.
- Lime slurry-treated mix was somewhat more rut-susceptible than the mix with filler addition. However, lime treatment enhanced bonding characteristics at mastic-aggregate interfaces to reduce moisture-related stripping. This was commonly observed from all performance tests conducted.
- Mineral fillers reduced the early stage of moisture damage (such as moisture-related rutting), but the effect of mineral fillers degraded with severe moisture attacks such as multiple freeze-thaw cycles.

4.3. HYPOTHESIS BASED ON PRELIMINARY FINDINGS

Preliminary observations from the asphalt concrete performance testing indicated that dry lime-treated mixtures were always superior to lime slurry-treated mixtures even if they were mixed with the same amount of lime particles and water at the same laboratory processing conditions: time and temperature for mixing and drying. In an attempt to address the question, why the lime slurry-treated mixes was more damage-susceptible than the dry lime-treated mixes, a series of procedure for batching, mixing, and compaction of each mix was investigated carefully, and it was found that introducing dry lime into wet aggregates (such as the mix B2) generally produced more homogeneous mixture with better distributions of lime particles on the aggregates (see Figure 4.8) when compared to the case (mix B3), the addition of lime slurry on the aggregates (Figure 4.9). As mentioned in Chapter 3, the recipe for the lime slurry mix was made in order to yield the exactly same amount of total lime and water added as the ones in the mix B2 (dry lime to moistened aggregates) for better comparisons. Consequently, 1.2% water was added for the B3 mix to match with 3.0% water in the mix B2, since lime slurry already contained 61.5% water in it.

In an attempt to simulate a similar level of mix homogeneity from slurry-treated mix as the mix with dry lime, more water was added in the manufactured lime slurry to result in new lime slurry with 25% of lime particles and 75% water in its composition. As presented in Figure 4.10, the new lime slurry-treated mixture (i.e. mixture with diluted lime slurry) was much more homogeneous with better dispersion of lime particles than the original lime slurry-treated mixture, which may eliminate unfavorable surfaces of some aggregates observed from the original B3 mixes (Figure 4.9).

Figure 4.8 Dry Lime Treated Aggregates (Before and After Oven Dry)

Figure 4.9 Lime Slurry Treated Aggregates (Before and After Oven Dry)

Figure 4.10 Diluted Lime Slurry Treated Aggregates (Before and After Oven Dry)

Taking into account the distribution of lime particles in each mix, the following illustrations (Figure 4.11) were drawn to represent asphalt mastic-aggregate system of each mix tested for this study.

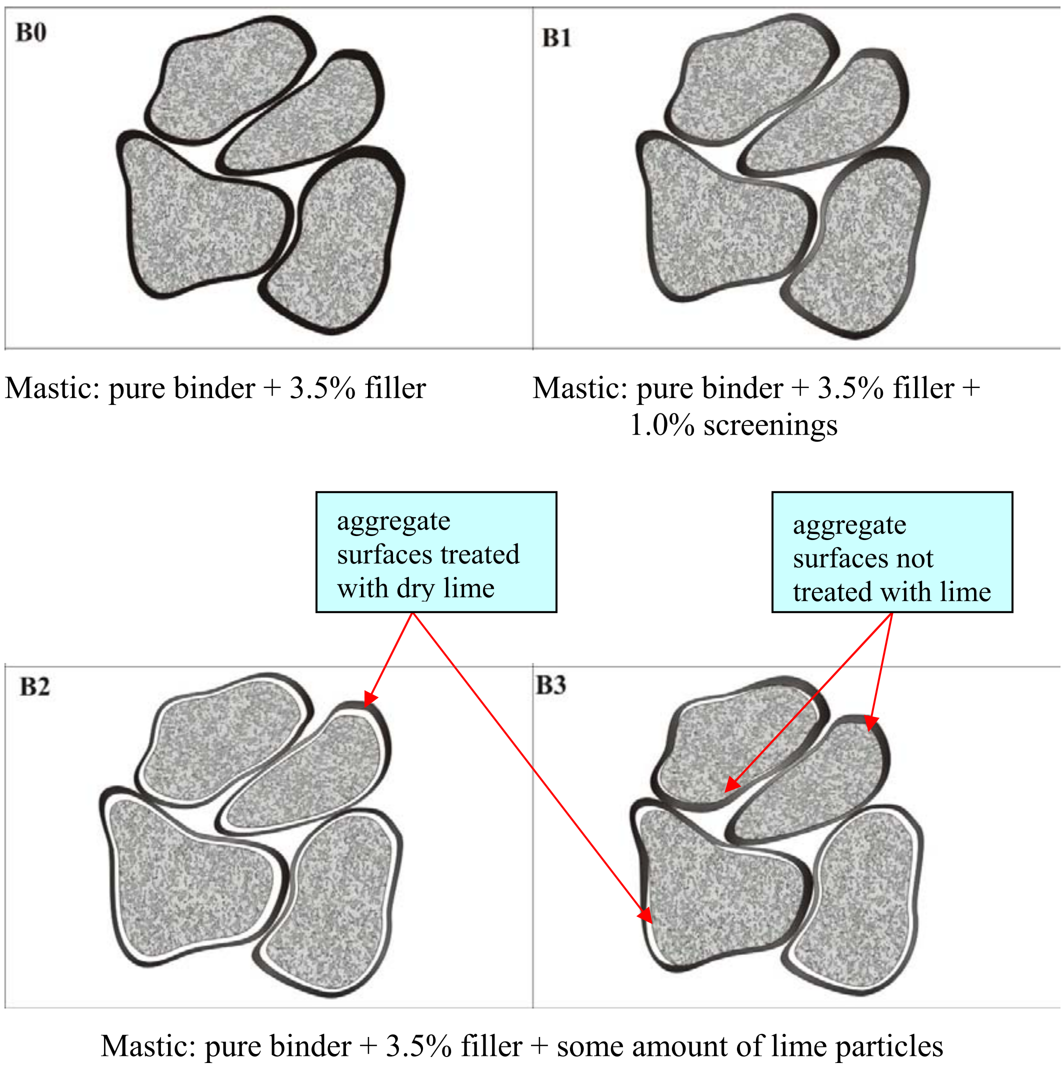


Figure 4.11 Illustrations Representing Mastic-Aggregate System of Each Mix

As shown in the figure, all mixes contained 3.5% filler, and an extra 1.0% additive was added in B1, B2, and B3. Excluding the common factor, 3.5% filler in each mix, simplifies mix characteristics as: aggregates with pure binder for the mix B0, aggregates with mastic filled by 1.0% screenings for the mix B1, aggregates with mastic filled by some amount of lime particles for mixes B2 and B3. The amount of lime that reacted with the binder to form the mastic in mixes B2 and B3 is difficult to know, since it is not trivial to monitor how much lime particles are separated from aggregates and added in the binder to form mastic phase during asphalt-aggregate mixing process. Furthermore, as validated from Figures 4.9 and 4.11, it can be noted that the mix B3 develops partial treatments of lime due to relatively high viscosity of lime slurry with only 1.2% additional water. The introduction of lime slurry needs more care to produce better-performing homogeneous mix. According to a study by Hicks (1991), the use of lime slurry, in fact, is sometimes limited, since only certain aggregates may be treated and be effective with lime slurry. A primary reason for the premature failure observed from the mix B3 compared to the mix B2 is probably due to the unfavorable aggregate surfaces where sufficient lime was not treated.

Based on visual observations illustrated in Figures 4.8 to 4.10 and performance testing results using asphalt concrete samples, one can draw the following tentative hypotheses to address questions such as (1) why was dry lime-treated mix better than lime slurry-treated mix; (2) why was the mineral filler-added mix somewhat more rut-resistible than the lime slurry-treated mix; and (3) why did treatment of hydrated lime reduce stripping of asphalt films.

- Mastic formed in B1 is stronger than mastic in B0, which resulted in a better rutting performance of B1 when compared to B0.
- Mastic formed in B1 is stronger than mastic in B2 or B3, which resulted in a better rut-resistance from B1 when compared to B3.
- Bonding energy at interfaces between mastic and aggregates is improved by lime treatment, which can be explained from better resistance to stripping from the mix B3 than the mix B2.
- Contributions of hydrated lime can be from both binder stiffening effects that mitigate damage by moisture diffusion process and better bonding characteristics of mastic-aggregate systems that reduce failure by stripping.

The hypotheses constructed herein were validated through several key laboratory tests to investigate fundamental properties of mix components and their impacts on moisture damage-related HMA performance. The following sub-sections present testing results and discussion.

4.4. FUNDAMENTAL PROPERTIES OF MIX COMPONENTS

This section presents testing results and findings from the analysis of fundamental properties of mix components by evaluating the stiffness of binder/mastics using the DSR and nonlinear damage properties of binder/mastics using the fracture-damage testing device. Also, the bonding characteristics of aggregates and mastics were investigated through surface free energy measurements. Fundamental component properties are related to performance testing results of asphalt concrete samples to validate the hypothesis made and also to take into account the effects of fundamental material properties on moisture damage-related pavement performance. This effort will eventually provide an appropriate guideline for selecting better asphalt-aggregate combinations that are more resistant to moisture damage.

4.4.1 Dynamic shear rheometer (DSR) testing results

As mentioned, the DSR testing was introduced to mechanically characterize stiffness variations due to additives in each mix. A shear strain of 0.6%, which is low enough not to cause any nonlinear damage, was selected and applied to each 8-mm tall and 2-mm thick DSR sample with increasing loading frequencies from 0.1Hz to 10Hz (so-called frequency sweep testing) at three different temperatures (20°C, 30°C and 40°C). Testing results at temperatures, 20°C and 40°C were then superposed to testing results at 30°C by shifting process to form a long-term frequency-domain linear viscoelastic curve, so-called master curve at the target temperature, 30°C. The master curve is a characteristic curve that represents loading time- or loading frequency-dependent viscoelastic stiffness behavior of each specific binder or mastic.

Figure 4.12 presents the master curves of a neat binder, a filled binder (i.e. mastic with 1.0% screenings), and hydrated lime-treated binders with two different rates, 0.5% and 1.0%. The neat binder and the filled binder with 1.0% screenings was intended to simulate binder/mastic stiffness in the mix B0 and B1, respectively. Simulation of mastic in the mix B2 or B3 is somewhat non-trivial, since in those mixes the amount of hydrated lime that is separated from aggregates and reacts with the binder as a filler or that is adhered to aggregate particles as an anti-strip agent is unknown. Therefore, two arbitrary cases were considered merely for investigating stiffening trends of mastics as the amount of hydrated lime in the mastic varies. The mastic with 0.5% of hydrated lime in the figure indicates that 50% of the lime treated in the mix was separated from aggregates and reacted with the binder to form mastic. The mastic with 1.0% of hydrated lime is the one that total amount of lime treated reacted with the binder to form the mastic. Even if the mastic with 1.0% of hydrated lime is not the case in a real mix, testing data from this case can be incorporated with testing results from the other cases, the mastic with 0.5% of hydrated lime and the neat binder, to characterize stiffening effects due to lime addition.

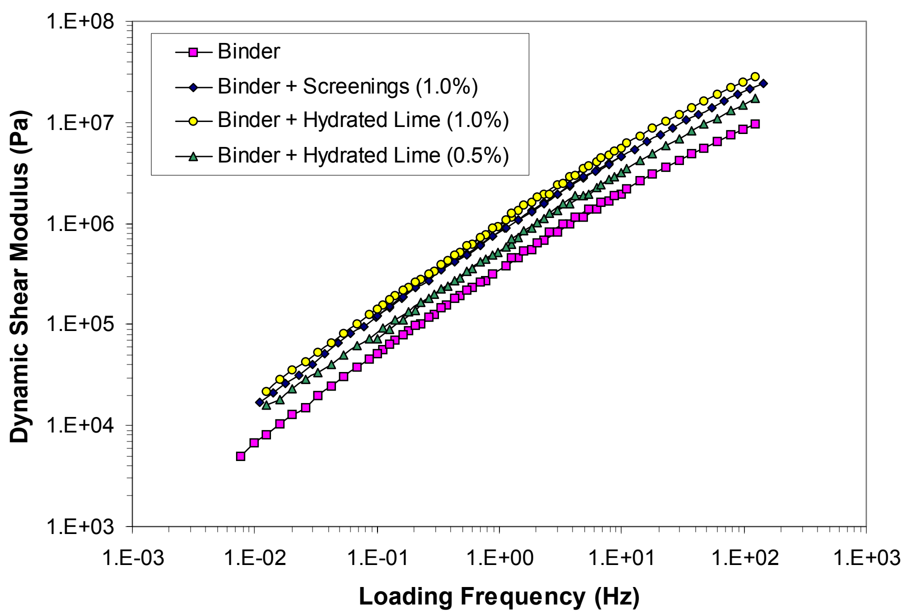


Figure 4.12 Master Curves at 30°C of Each Binder/Mastic

As can be seen from Figure 4.12, both mineral filler (screenings) and hydrated lime clearly contributed to binder stiffening. The position of the master curves demonstrates that hydrated lime mixed mastic is slightly stiffer than filler (screenings) mixed mastic at the same application rate, 1.0% by weight of total dry aggregates, whereas the mastic stiffness in the real mix B1 is expected to be stiffer than the mastic stiffness in the mix B2 or B3, since all lime particles treated in the mix B2 or B3 are not likely separated but more likely adhered to aggregates. Therefore, stiffer mastic in the mix B1 can contribute to somewhat better rut-resistance observed from the mix B1 than the mix B3 to the initial stage of moisture damage.

4.4.2 Fracture-damage testing results

In addition to the undamaged stiffening characteristics through the DSR testing, damage-associated properties of asphalt binder/mastics were evaluated using the fracture-damage testing device. This testing can account for damage-resisting mechanisms induced from additives (hydrated lime or mineral filler) by simply monitoring peak value and/or area inside of the force-time curve resulting from the fracture-damage testing device as illustrated in Chapter 3.

Testing results were very sensitive to the type of materials. Figure 4.13 illustrates force-time curves using the same set of materials (a neat binder PG 64-22, a mastic with 1.0% screenings, and two hydrated lime treated mastics with different application rates, 0.5% and 1.0%) as employed for the DSR testing. All tests were performed at the same loading speed (0.00027 m/s) and at testing temperature, 24^{o}C. Based on the figure, the mastic strength (peak value of the force-time curve), compared to the strength of neat asphalt binder, increased significantly due to additives, and hydrated lime mastics were more fracture-resistant than mastics with mineral filler at the same application rate, 1.0%. However, similar to the DSR testing results, one can expect that the mastic strength of the mix B1 will be most likely similar or greater than the mastic strength of the mixes B2 or B3, because all lime particles treated to aggregates in the mixes B2 or B3 are not probably debonded from aggregates to form the mastic containing 1.0% lime.

Furthermore, based on testing results from the DSR and the fracture-damage testing device, it can also be inferred that substantial contributions to initial stiffness and strength gain from additives can delay stiffness/strength reduction due to moisture diffusion; therefore, the mastic is more resistant to fracture which results in the slow process to failure of adhesive bonding between the mastic and aggregate particles.

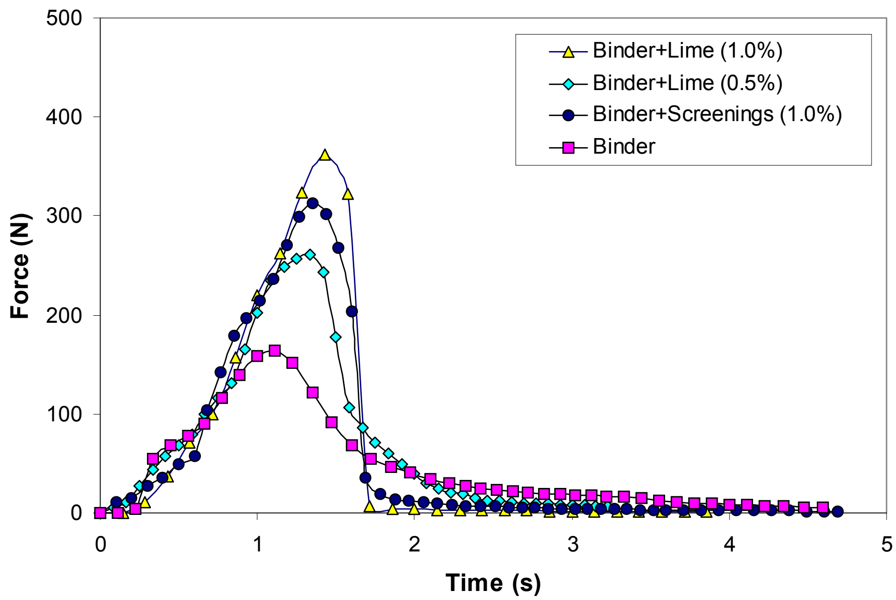


Figure 4.13 Fracture-Damage Testing Results

4.4.3 Surface free energy testing results

As introduced in Chapter 3, surface free energy components of asphalt mastics and aggregates indirectly quantify mastic-aggregate adhesive bonding properties of each mix (B0, B1, B2, and B3) in the presence of water so that one can judge how additives (mineral fillers or hydrated lime) act on mastic-aggregate interfaces to improve adhesive bonding potential.

In order to compare mastic-aggregate bonding potential of each mix in a more appropriate way, three mastics and two representative aggregates were considered and tested using the Wilhelmy plate method and the universal sorption method for mastic surface free energy components and for aggregate surface free energy components, respectively as illustrated in Table 4.4. A detailed discussion to sample preparation and testing procedure can be referred to studies by Hefer *et al.* (2006) and Bhasin and Little (2006), respectively. Each mastic shown in the table was intended to simulate mastic phase of each mix, B0, B1, and B2 (or B3). Instead of using an entire aggregate blend in the real mix, two separate aggregates, (screenings and 3ACR) were tested for this study, because surface properties of the blend are likely to be an average of the surface properties of individual aggregates which is not the true representation of the system. For example, an average surface property of a blend that shows fair performance might be the case with aggregates from two different sources with extremely favorable and extremely unfavorable surface properties in terms of moisture damage. In practice, debonding of asphalt film from the poor performing aggregate will occur much sooner so that the entire mixture will be moisture-susceptible. Therefore it is important to examine the surface properties of each aggregate independently as opposed to the surface properties of the entire blend. This project selected two aggregates (screenings and 3ACR), since they are representative aggregates that were used dominantly to design each mix for this study.

Table 4.4 Matrix of Materials for Surface Free Energy Measurements

Mastics for Wilhelmy plate method	**Aggregates for USD**	
Mastic (simulating the mix B0)	Screenings	3ACR
Mastic (simulating the mix B1)		
Mastic (simulating the mix B2 or B3)		

Table 4.5 summarizes surface free energy components (Lifshitz - van der Waals component, Lewis acid component, and Lewis base component) and a total surface free energy of three mastics and two aggregates tested for this study. Surface free energy properties of water are also presented in the table, since they are necessary to calculate the work of debonding at interfaces between mastic and aggregate in the presence of moisture of each mix.

Table 4.5 Surface Free Energy Properties of the Asphalt Mastics and Aggregates

Material	Total surface free energy and components (ergs/cm^2)			
	Total (γ^{Total})	**LW** (γ^{LW})	**Acid** (γ^{+})	**Base** (γ^{-})
Mastic (B0)	22.1	22.0	0.01	0.28
Mastic (B1)	19.1	18.8	0.04	0.40
Mastic (B2 or B3)	18.3	17.8	0.09	0.70
Aggregate (screenings)	107.9	51.8	1.8	430.6
Aggregate (3ACR)	86.4	54.8	1.3	187.1

Note: LW is the Lifshitz-van der Waals component of surface free energy

The surface free energy properties of each material were then used to compute four different thermodynamic parameters that can be used to assess moisture sensitivity of each asphalt-aggregate system. These four parameters are enumerated as follows (Bhasin *et al.* 2007, Little and Bhasin 2006):

$$ER_1 = \left| \frac{W_{AM}}{W_{AMW}^{wet}} \right| \quad [4.2]$$

$$ER_2 = \left| \frac{W_{AM} - W_{MM}}{W_{AMW}^{wet}} \right| \quad [4.3]$$

$$ER_1 * SSA = \left| \frac{W_{AM}}{W_{AMW}^{wet}} \right| * SSA \quad [4.4]$$

$$ER_2 * SSA = \left| \frac{W_{AM} - W_{MM}}{W_{AMW}^{wet}} \right| * SSA \quad [4.5]$$

As noted earlier in Chapter 3, W_{MM} is the work of cohesion of the asphalt mastic, W_{AM} is the work of adhesion between the asphalt mastic and the aggregate, and W_{AMW}^{wet} is the work of debonding (which is typically negative) that represents the magnitude of thermodynamic potential that drives moisture damage. The specific surface area of the aggregate, *SSA* is determined as an automatic part of the test and analysis procedure. The work of cohesion, adhesion and debonding can be calculated from the three surface free energy components of the asphalt mastic, aggregate, and water using equations presented in Chapter 3 (see equations [3.3], [3.4], and [3.7]).

Each energy parameter, ER_1, ER_2, $ER_1 * SSA$, and $ER_2 * SSA$ is an independent measure of the moisture sensitivity of the asphalt materials used in the mixture. A combination of asphalt mastic and aggregate that yields a higher value of these parameters typically indicates better resistance to moisture damage. An important difference between the parameters ER_1 (or $ER_1 * SSA$) and ER_2 (or $ER_2 * SSA$) is that the former accounts for adhesion and reduction in free energy due to debonding by water, whereas the latter accounts for wettability and reduction in free energy due to debonding by water. Wettability is the ability of the asphalt mastic to coat the surface of aggregates. Since the parameters ER_2 and $ER_2 * SSA$ account for the wettability of the aggregate by the asphalt mastic, they provide a better assessment of the moisture sensitivity of materials (Bhasin *et al.* 2007). Also, the energy terms that include the specific surface area of the aggregate (SSA) are generally more useful to evaluate the effect of aggregate while comparing two systems with different aggregate types.

As presented in Figures 4.14 to 4.17, with the exception of aggregate 3ACR assessed using parameters ER_1 and $ER_1 * SSA$, the energy parameters indicated that the mix B2 or B3 (with hydrated lime treatment) was better resistant to moisture damage as compared to the mixes B0 and B1 (mixes without hydrated lime). For the aggregate 3ACR a reduction in the magnitude of ER_1 and $ER_1 * SSA$ indicates that there might be a reduction in the work of adhesion due to the addition of hydrated lime. However, this effect is ultimately compensated by the increased wettability of the aggregate resulting in a better resistance to moisture damage as indicated by parameters ER_2 and $ER_2 * SSA$. Consistent trends were observed from the parameters ER_2 and $ER_2 * SSA$ for both screenings and 3ACR.

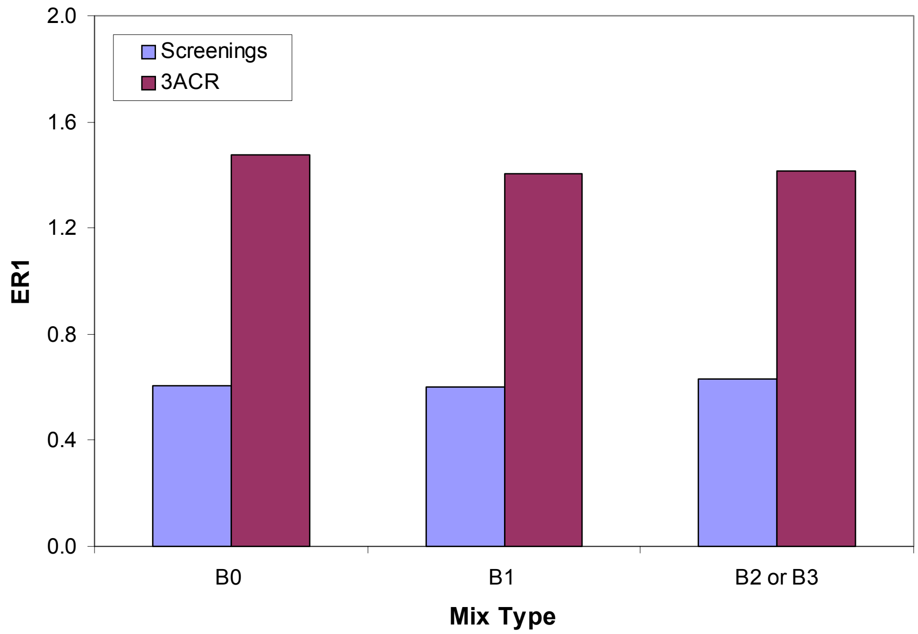


Figure 4.14 Comparison of Energy Parameter ER1 for the Two Aggregates

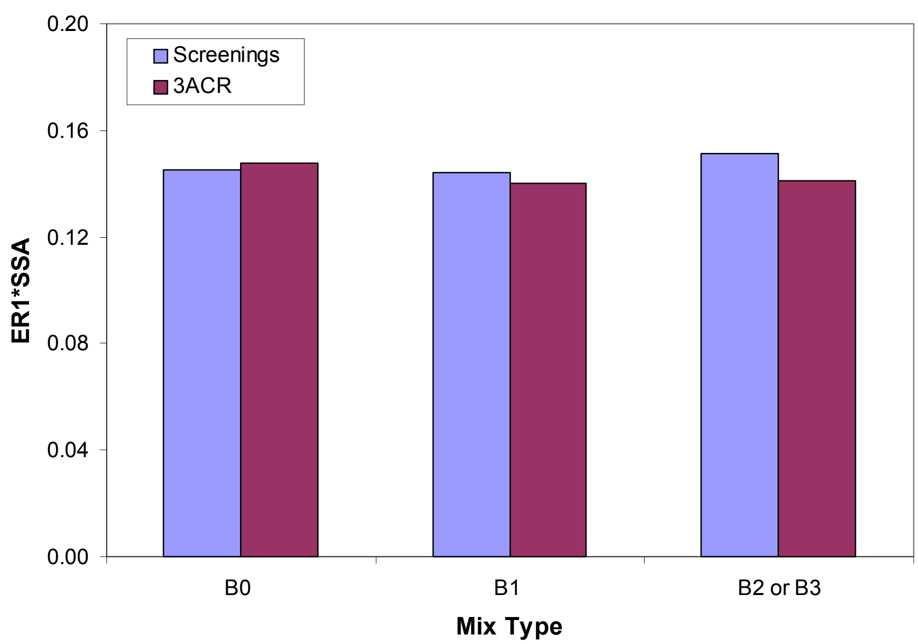


Figure 4.15 Comparison of Energy Parameter ER1*SSA for the Two Aggregates

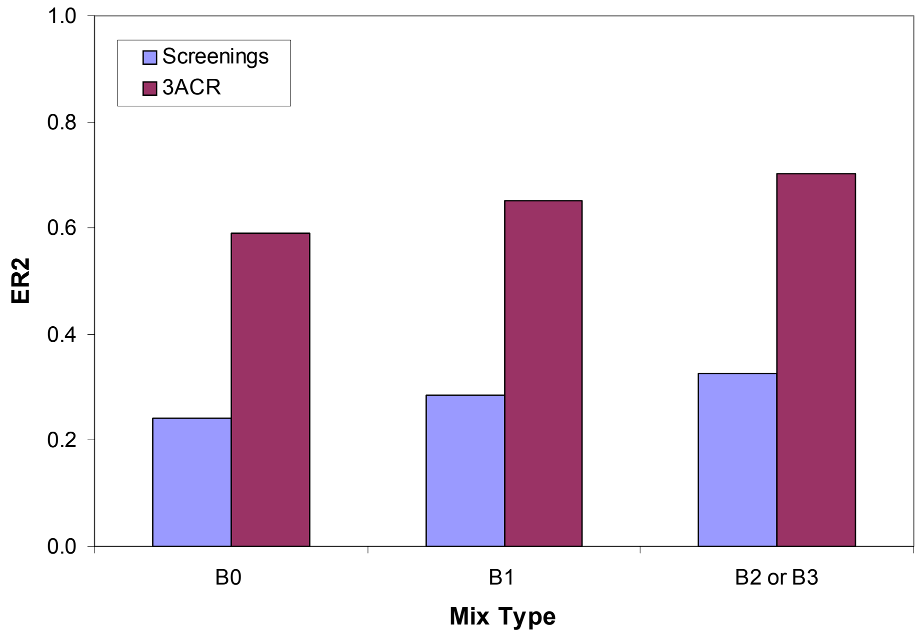


Figure 4.16 Comparison of Energy Parameter ER2 for the Two Aggregates

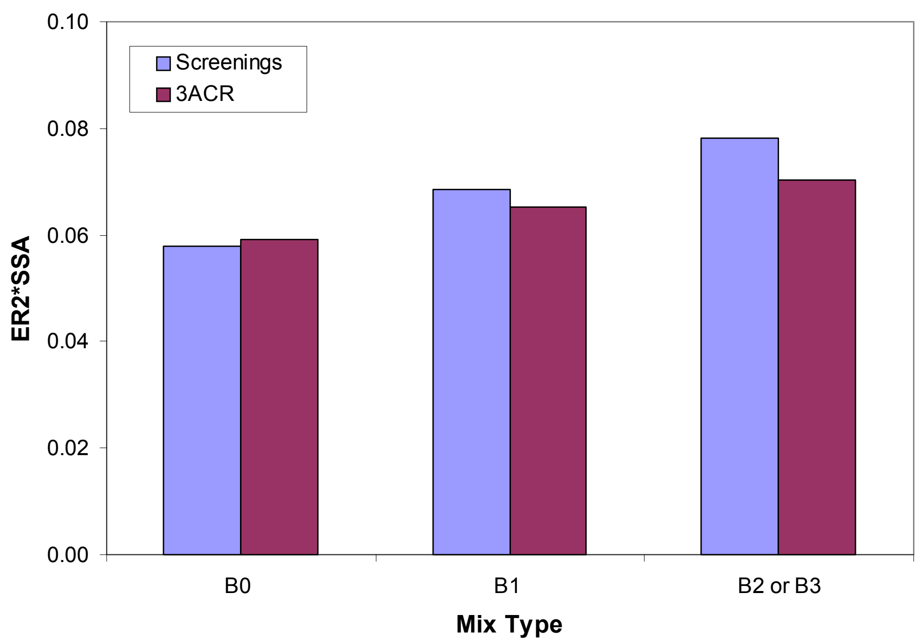


Figure 4.17 Comparison of Energy Parameter ER2*SSA for the Two Aggregates

Even if it is premature to generalize findings with limited surface energy data presented in this report, the effect of hydrated lime to resist moisture damage based on its unique impacts on better bonding between asphalt and aggregates can be validated. Hydrated lime improves moisture-related performance of HMA mixtures from its synergistic effects: stiffening of binder to resist damage by moisture diffusion and better bonding at asphalt-aggregate interfaces to resist damage by stripping.

4.5. SUMMARY OF TESTING RESULTS AND FURTHER DISCUSSION

Table 4.6 summarizes each testing by specifying its related HMA performance or properties and the rank of mixtures observed from each testing. The rutting performance rank investigated from the APA and Hamburg testing agreed well with the rank of tensile strength ratio with one F-T cycle, which is related to the fact that stiffer mastic in the mix B1 plays an important role to resist early-stage moisture damage mostly due to moisture diffusion into mastic. Mastic properties measured from the DSR and the fracture-damage testing device support this hypothesis. The rank of mixes in terms of stripping performance was also consistent with the testing from the APA, Hamburg, and the AASHTO T-283 with multiple F-T cycles. Hydrated lime-treated mixes performed better than untreated mixes, which indicates that hydrated lime improved mix potential to resist stripping. This has been successfully validated from surface free energy testing-analysis results. Therefore, it can be concluded that hydrated lime-treatment makes HMA mixes more resistant to moisture damage due to synergistic effects by producing a stiffer mastic that can resist damage by moisture diffusion and by enhancing asphalt-aggregate interfacial bonding so that the mix is more resistible to stripping. However, lime needs to be treated to aggregates in a controlled way to maximize the benefits from lime addition. Evenly distributed and well-dispersed lime treatment is necessary. Better performance observed from dry lime than lime slurry infers that homogeneous lime treatments really come into play.

Table 4.6 Summary of Test Results

Test	Performance/Property	Rank of Mixtures
Performance Testing of Asphalt Concrete		
APA under water	Rutting	B2 > B1 > B3 > B0
	Stripping	B2 > B3 > B1 > B0
Hamburg	Rutting	B2 > B1 > B3
	Stripping	B2 > B3 > B1
AASHTO T-283	Tensile Strength Ratio (1 F/T Cycle)	B2 > B1 > B3 > B0
	Tensile Strength Ratio (6 F/T Cycles)	B2 > B3 > B1 >B0
Property Testing of Components		
DSR	Stiffness of Binder/Mastic	B1 > (B2, B3) > B0
Fracture Test	Strength of Binder/Mastic	B1 > (B2, B3) > B0
Surface Energy	Adhesive Bonding of Asphalt/Aggregate	(B2, B3) > B1 > B0

As expected, performance testing results of asphalt concrete samples appear to be strongly linked to fundamental properties of mix components. Evaluation of fundamental material properties aided to identify moisture damage mechanisms and their impacts on pavement performance in a more detailed view. Measurements of fundamental surface energy properties and material characteristics of asphalt binder/mastic and aggregates can provide an appropriate guideline for selecting better performing asphalt-aggregate combinations. Use of directly-measured component properties will be significantly beneficial, since testing of mix components are much more economical and efficient than testing of asphalt concrete samples, and also component properties can be simply used to judge (or predict) HMA performance due to strong relationships between component properties and HMA performance, as demonstrated from this study.

CHAPTER 5
CONCLUDING REMARKS

Performance changes and fundamental material characteristics associated with moisture damage due to additives in HMA mixtures were studied through various experimental approaches. Based on this study, the following conclusions and suggested follow-up studies can be drawn:

5.1. CONCLUSIONS

- Research approach employed in this study was successful to accomplish study objectives: 1) to identify moisture-related damage mechanisms; 2) to characterize additives, more specifically hydrated lime as moisture damage resisters; and 3) to develop reasonable guidelines and testing protocols for selecting better materials combinations to resist moisture-related damage.

- Hydrated lime-treated mixes performed better than untreated mixes due to combined effects of hydrated lime: mastic stiffening that induces better resistance of mastic to moisture diffusion and enhancement of asphalt-aggregate interfacial bonding that produces better resistance to stripping. Performance testing results of asphalt concrete samples and fundamental properties of mix components support the usefulness of hydrated lime.

- Mineral fillers resisted moisture damage in an early stage due to stiffening effects from filler addition, but the stiffening effect may degrade with severe moisture attacks, which has been demonstrated from the AASHTO T-283 testing with multiple freeze-thaw cycles.

- To maximize benefits from lime addition, evenly-distributed and well-dispersed lime treatment is necessary. Specifically, treatments of lime slurry need more care.

- Fundamental characteristics of mix components were closely related to macroscopic performance behavior of asphalt concrete samples. This testing-analysis protocol based on the mix components presented in this study can be a basis for potential specification-type technique for evaluating (and/or predicting) moisture damage of HMA mixtures and pavements.

5.2. RECOMMENDED FURTHER STUDIES

- Based on successful accomplishments of this project, consequential research with an extended scope including different types of Superpave mixes and alternative moisture damage resisting agents is recommended. A similar process developed for this project can be employed to estimate the effects of hydrated lime and other general mineral fillers for the case of premium Superpave mixes such as the SP5 mix that consists of high-quality aggregates and polymer-modified binder PG 70-28. Alternative materials such as Portland cement and/or fly ash can also be investigated as a potential (supplemental) anti-stripping agent, because they are more accessible than hydrated lime that has to be transported from other states.

- Findings from this study should be correlated with some more laboratory data and field performance observations to be more general and comprehensive guidelines for selecting better material combinations that can resist longer and perform better to moisture damage.

5.3. NDOR IMPLEMENTATION PLAN

The results of this study verified that continued use of adding lime via the slurry or dry processes, on low volume mixes, provides NDOR with significant protection against moisture sensitivity. NDOR does not currently allow any anti-stripping agents other than lime to be used, and will continue to do so, as a result of this research. Future research to evaluate the effects of using lime on higher volume roads, such as an SP-5, is being considered for funding by the FY-2008 NDOR Research Program.

REFERENCES

Aschenbrener, T., (1995). "Evaluation of Hamburg Wheel-Tracking Device to Predict Moisture Damage in Hot Mix Asphalt." In *Transportation Research Record 1492*, TRB, National Research Council, Washington, D.C., pp. 193-201.

Aschenbrener, T., McGennis, R. B. and Terrel, R. L., (1995). "Comparison of Several Moisture Susceptibility Tests to Pavement of Know Field Performance." *Journal of the Association of Asphalt Paving Technologists*, Vol. 64, pp. 163-208.

Bhasin, A., and Little, D. N. (2006). "Characterization of aggregate surface energy using the universal sorption device." *Journal of Materials in Civil Engineering*, ASCE, Accepted for Publication.

Bhasin, A., Masad, E., Little, D. N., and Lytton, R. (2006). "Limits on Adhesive Bond Energy for Improved Resistance of Hot-Mix Asphalt to Moisture Damage." In *Transportation Research Record*, In Press.

Bhasin, A., Little, D. N., Vasconcelos, K. L., and Masad, E. (2007). "Use of Surface Free Energy to Identify Moisture Sensitivity of Materials for Asphalt Mixes." In *Transportation Research Record*, Accepted for Publication.

Cheng, D. (2002). "Surface Free Energy of Asphalt-Aggregate System and Performance Analysis of Asphalt Concrete." Ph.D. Dissertation, Texas A&M University, College Station, Texas.

Cheng, D., Little, D. N., Lytton R. L. and Holste J. C., (2003). "Moisture Damage Evaluation of Asphalt Mixture by Considering Both Moisture Diffusion and Repeated Load Conditions." In *Transportation Research Record 1832*, TRB, National Research Council, Washington, D.C., pp. 42-58.

Cooley, L. A. Jr., Kandhal, P. S., Buchanan M. S., Fee, F. and Epps, A., (2000). "Loaded Wheel Testers in the United States: State of the Practice." Transportation Research E-Circular. No. EC016.

Epps, J. A., Sebaaly, P. E., Penaranda, J., Maher, M. R., McCann, M. B., and Hand, A. J., (2000). "Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design." NCHRP Report 444, Transportation Research Board - National Research Council, Washington, D.C.

Freitas, F. A. C., Kim, Y., Allen, D. H., and Aragao, F. T. S., (2006). "A Theoretical and Experimental Technique to Characterize Fracture in Asphalt Mixtures and Pavements." Submitted to the Transportation Research Board, Washington, D. C.

Fwa, T. F. and Ong, B. K., (1994). "Effect of Moisture in Aggregates on Performance of Asphalt." In *Transportation Research Record 1454*, TRB, National Research Council, Washington, D.C., pp. 28-35.

Hefer, A. W., Bhasin, A., and Little, D. N. (2006). "Bitumen surface energy characterization using a contact angle approach." *Journal of Materials in Civil Engineering*, ASCE, Accepted for Publication.

Hicks, R. G., (1991). "Moisture Damage in Asphalt Concrete." NCHRP Synthesis of Highway Practices No. 175, Transportation Research Board - National Research Council, Washington, D.C.

Hines, M., (1991). "The Hamburg Wheel-Tracking Device." Proceedings of the Twenty-Eighth Paving and Transportation Conference. Civil Engineering Department, The University of New Mexico, Albuquerque, NM.

Huang, S., Robertson, R. E., Branthaver, J. F. and Petersen, J. C., (2005). "Impact of Lime Modification of Asphalt and Freeze-Thaw Cycling on the Asphalt-Aggregate

Interaction and Moisture Resistance Damage." *Journal of Materials in Civil Engineering*, ASCE, Vol. 17, No. 6, pp. 711-718.

Kim, Y., Little, D. N. and Lytton, R. L., (2004). "Effect of Moisture Damage on Material Properties and Fatigue Resistance of Asphalt Mixtures." In *Transportation Research Record 1832*, TRB, National Research Council, Washington, D.C., pp. 48-54.

Kim, Y., Aragao, F. T. and Lutif, J. E., (2006). "Restricted-Zone Requirements for Superpave Mixes Made with Local Aggregate Sources." NDOR Research Report No. P556.

Little, D. N. and Epps, J. A., (2001). "The Benefits of Hydrated Lime in Hot Mix Asphalt." National Lime Association.

Little, D. N., and Bhasin, A. (2006). "Using Surface Energy Measurements to Select Materials for Asphalt Pavement," Final Report for Project 9-37, Texas Transportation Institute.

Lottman, R. P., (1978). "Predicting Moisture-Induced Damage to Asphaltic Concrete." NCHRP Report 192, TRB, National Research Council, Washington, D.C.

Lytton, R. L., Masad, A. E., Zollinger, C., Bulut, R., and Little, D. N., (2005). "Measurements of Surface Energy and its Relationship with Moisture Damage." Technical Report No. FHWA/TX-05/0-4524-2.

McCann, M. and Sebaaly, P. E., (2003). "Evaluation of Moisture Sensitivity and Performance of Lime in Hot-Mix Asphalt." In *Transportation Research Record 1832*, TRB, National Research Council, Washington, D.C., pp. 09-16.

Mohamed, E. H., (1993). "Debonding Location in Asphalt Concrete Associated with Moisture Damage." *Journal of Materials in Civil Engineering*, ASCE, Vol. 5, No. 4, pp. 497-509.

Ping, W. V., (1993). "Lime Treatment of Asphalt Mixtures in Improving Resistance to Moisture." Airport Pavement Innovations, pp. 155-163.

Solamanian, M., Harvey, J., Tahmoressi, M., and Tandon, V., (2003). "Test Method to Predict Moisture Sensitivity of Hot-Mix Asphalt Pavements." In Moisture Sensitivity of Asphalt Pavements: A National Seminar, Topic 3.

Terrel, R. L., AL-Swailmi, S., (1994). "Water Sensitivity of Asphalt-Aggregate Mixes: Test Selection." Strategic Highway Research Program, SHRP-A-403, National Research Council, Washington, D. C.

Tunnicliff, D. G., and Root, R., (1982) "Antistripping Additives in Asphalt Concrete: State-of-the-Art." *Journal of the Association of Asphalt Paving Technologists*, Vol. 51.

Witczak, M. W., Kaloush, K., Pellinen, T., El-Basyouny, M. and Von Quintus, H., (2002). "Simple Performance Test for Superpave Mix Design.", NCHRP Report No. 465, Transportation Research Board, National Research Council, Washington, D.C.

ACKNOWLEDGMENTS

The authors thank the Nebraska Department of Roads (NDOR) for the financial support needed to complete this study. In particular, the authors thank NDOR Technical Advisory Committee (TAC), Moe Jamshidi, Laird Weishahn, Mick Syslo, Amy Starr, Jodi Gibson, and Lieska Halsey for their technical support and discussion. The authors also wish to thank John Dageforde, Larry Koves, Jody Gregory, John Gude, Amit Bhasin, and Rick Canatella for their sincere help in laboratory work.