ABSTRACT

SHIDHORE, ANIRUDDHA VILAS. Use of Lime as Anti-Strip Additive for Mitigating Moisture Susceptibility of Asphalt Mixes Containing Baghouse Fines. (Under the direction of Dr. Akhtarhusein A. Tayebali)

Recent NCDOT research suggests that baghouse fines with gradation similar to the natural and manufactured fines passing #200 sieve seems to have beneficial effect on stiffness and rutting characteristics of the asphalt mix. However, these studies conclude that mixes containing baghouse fines were highly moisture susceptible, and recommended that baghouse fines be metered into the mix to create a uniform percentage throughout the mix.

This study assesses the effectiveness of hydrated lime as an anti-strip additive in mixes containing excess baghouse fines. Comparison of test results of the mixes containing hydrated lime versus the mixes containing organic anti-stripping additive (LOF 6500) was also done. Two different types of baghouse fines, one from Boone, NC and one from Enka, NC, were used in HMA mixtures in the amounts of 1.5, 5.5 and 6.5-percent. Modifications were made to the available JMF and specimens were prepared in the laboratory and several different tests were performed.

Wet sieve analysis was first done to check the gradation of materials. Using this gradation and the available JMF, aggregate proportioning was done to satisfy NCDOT mix design criteria. Moisture susceptibility of mixes was determined by performing TSR tests on mixes with different proportions of BHF, and with or without lime. TSR testing showed that moisture susceptibility was dependant on both the concentration of baghouse

fines and anti-strip additive. Presence of hydrated lime in mixes increased the resistance to moisture damage.

Specimens were also tested using the SST machine. Samples were compacted and sawed and one half of the specimens were moisture conditioned. The FSCH and RSCH tests were then performed on the samples to determine the material properties as well as the rutting resistance and fatigue life. In general, the test results indicate that addition of lime enhances the mix performance - |G*| values are higher, rut depths are lower, and fatigue resistance is higher.

Based on the results of this study, it may be concluded that, addition of 1-percent hydrated lime to asphalt mixtures with up to 5-percent additional BHF (total of 6.5-percent) enhances the mix performance. Addition of lime also helped in the mitigation of moisture susceptibility of asphalt mixes. It is thus recommended that NCDOT should consider addition of 1-percent hydrated lime (by weight of dry aggregates) to mixes which are expected to have excess BHF content.

Use of Lime as Anti-Strip Additive for Mitigating Moisture Susceptibility of Asphalt Mixes Containing Baghouse Fines

by

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To My Parents for Their Unwavering Support.

PERSONAL BIOGRAPHY

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NOTATIONS

AASHTO	American Association of State Highway Transportation Officials
AC	asphalt cement
ASTM	American Society of Testing Materials
BHF	baghouse fines
ESAL	equivalent single axle load
FSCH	frequency sweep at constant height
HMA	hot mix asphalt
ITS	indirect tensile strength
NCDOT	North Carolina Department of Transportation
NCSU	North Carolina State University
PG	performance graded
RSCH	repeated shear at constant height
SGC	SUPERPAVE Gyratory Compactor
SST	Superpave™ shear testing machine
Superpave™	Superior performing pavements
VMA	voids in mineral aggregate
$\|G^*\|$	magnitude of dynamic shear modulus
δ	Phase angle

DISCLAIMER

The contents of this report reflect the views and opinions of the author(s) and not necessarily the views of the University. The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

1. BACKGROUND

1.1 Introduction

Presently, in North Carolina the baghouse materials used in hot-mix-asphalt (HMA) are purged intermittently into the AC mixtures rather than being stored in a silo and added to the mixture as mineral filler in a uniform, controlled manner. A survey of departments of transportation (DOT's) conducted by Hanson and Cooley [5] indicates that 18 states consider baghouse fines to be detrimental to the life of (HMA). Five states – Arizona, Montana, Nevada, North Dakota, and Wyoming – require the contractor to waste the baghouse fines. This is because, depending on the source and gradation, the percentage of baghouse fines greatly influences the volumetric properties of HMA and therefore laboratory mix design must include the use of these fines when developing the job mix formula.

Recently completed NCDOT research studies [15, 16 and 17] indicated that several performance properties of HMA were enhanced with the use of baghouse materials. However, even though the TSR moisture sensitivity test (AASHTO T238) indicated that mixes containing baghouse fines with organic anti-strip additive were acceptable based on the NCDOT Job mix formula (JMF), the collective conclusion from these studies was that mixes containing excess baghouse fines over the JMF were highly moisture sensitive. To complicate the matter, there have been instances in North Carolina where pavements have been constructed without using the anti-strip additive [18]. Also, it may be possible that the organic anti-strip additive is not uniformly distributed in asphalt binder; and prolonged heating and storage of the asphalt binder prior to its use may actually result in some loss and effectiveness of the organic anti-strip additive. In this case, mixes containing excess purged baghouse fines will be extremely susceptible to moisture damage and leading to premature pavement failure.

Currently, NCDOT has the following alternatives in dealing with purging baghouse fines in mixes – 1) waste all excess baghouse fines; and 2) uniformly meter baghouse fines into mixes in addition to using liquid anti-strip additives. The first alternative may not be viable as it will not only be expensive to rid the fines but could have environmental repercussions. The second alternative can be implemented at significant cost to mix producers, keeping in mind that it will still require close control over the use of organic anti-strip additive. Any slip in control may result in significant cost to NCDOT.

Many states such as South Carolina, Georgia, Mississippi, Texas, and Utah, exclusively require use of lime as an anti-strip additive. Some states allow contractors to choose between lime and organic liquid anti-strip additive. Lime as an anti-strip additive is not currently used in North Carolina. Therefore, the purpose of the study was to investigate if lime was an effective anti-strip additive for North Carolina mixes containing excess (purged) baghouse fines.

1.2 Objectives and Scope

The objective of this research was to evaluate the use of lime as anti-strip additive for mitigating the moisture susceptibility of asphalt mixes containing baghouse fines. Two baghouse fines – Boone and Enka that were used in prior NCDOT studies [15, 17] were evaluated, so that a direct comparison of mixes containing lime as anti-strip additive could be made to those containing organic liquid anti-strip additive.

One percent lime by the weight of dry aggregates is generally used in mixes [20]. However, there are three methods of incorporating it in to the mix. First is the dry method, in which lime is added directly to aggregates during mixing. In the second method, aggregates are soaked in lime slurry and then dried. These lime coated aggregates are then used for preparing mixes. In the third method, dry lime is added to wet aggregates, mixed thoroughly, dried and then used in mixes. In this study, the third method of incorporating lime was evaluated based on recommendations by NCDOT personnel. In particular, the principal work tasks undertaken during the course of this study were:

a) Provide summary of literature review to determine the current state of practice regarding use of lime to mitigate moisture susceptibility.

b) Evaluate volumetric properties of mixes containing 1% lime and up to 5.5% Boone and Enka baghouse fines to check if they meet the NCDOT design standards.

c) Determine the moisture susceptibility of the mixes using the TSR test.

d) Evaluate the performance of the mixes containing lime in terms of shear stiffness, rutting, and fatigue resistance.

Chapter 2 summarizes the practices followed by different states in the US and findings of previous research conducted on mixes containing hydrated lime and its effect on properties of mixes. Chapter 3 details the research approach and the test methodology. Chapter 4 deals with the validation of volumetric properties of all mixes; Chapters 5 and 6 present the details of moisture sensitivity testing and performance characterization of mixes respectively. Comparison of performance of mixes containing lime with those containing organic anti-strip additive is detailed in Chapter 7, followed by conclusions and recommendations in Chapter 8.

2. LITERATURE REVIEW

This chapter provides a brief background on baghouse fines followed by review of practices with regards to use of hydrated lime as anti-strip additive in asphalt mixes. Various methods of incorporating hydrated lime in asphalt mixes have also been presented.

2.1 Background of Baghouse Fines

During the production of asphalt concrete, aggregate is first batched and then dried in drums. During the drying process, small particles in the aggregate mixture become airborne. Collection systems in the form of bags are used to remove the fines from the exhaust stream. The fines so collected are called as "Baghouse Fines". In many states these fines are wasted. However, in North Carolina these baghouse fines are reintroduced in to mixes. Baghouse fines affect the HMA performance and, depending on the particle size distribution, may act as an asphalt extender. A detailed summary on baghouse fines can be obtained in NCDOT research report FHWA/NC/2003-04 [15].

2.2 Hydrated Lime

Hydrated lime ($Ca(OH)_2$) was used in this study as anti-strip additive, which should not be confused with quicklime (CaO). The term "LIME" refers to hydrated lime in this study. The difference between lime and quicklime is in the amount of chemically combined water. Both lime and quicklime are available in fine powder form. Quicklime is highly receptive of water.

2.3 Hydrated Lime as an Additive

Stripping occurs due to loss of adhesion between aggregates and asphalt. This is caused primarily caused by the presence of moisture. Addition of lime is reported to improve the adhesive bond between asphalt and aggregate, thus reducing moisture sensitivity of the mix [9].

Addition of lime not only improves the stripping resistance of the mix but also enhances mix performance in terms of resistance to rutting, cracking and aging [13] where results in prolonged life of pavement [6]. Life cycle cost analysis of asphalt pavements with lime have shown that lime used as an anti-strip additive is cost effective in the long run [6].

2.4 Methods of Incorporating Hydrated Lime in Mixes

Lime has an extensive track record nationally and is acknowledged to be a superior anti-stripping agent [10]. Various states in the USA use different methods of incorporating hydrated lime in mixtures. There are three common methods of incorporating lime in mixes – in dry form, in slurry form, or dry powder added to wet aggregates. Different states have formulated a variety of methods that are most effective in their own states based on these three basic methods. However, it may be noted that most states use lime in hydrated form rather than quicklime.

Quicklime if used in dry form may eventually react with moisture resulting in loss of mix strength and reduction in pavement life. Table 2.1 summarizes methods used by various states.

2.4.1 Addition of Dry Hydrated Lime to Dry Aggregates:

Addition of lime powder to dry aggregates is the simplest method of incorporating hydrated lime to asphalt mixes. This method was first adopted by the State of Georgia in early 1980's. In this method, hydrated lime and mineral filler is introduced in a drum mixer just after the point at which asphalt is introduced. Hydrated lime thus introduced comes in contact with aggregates and directly results in improved bond between aggregate and asphalt. Some portion of lime that fails to come in contact with aggregate will get mixed with asphalt. This results in lime reacting with highly polar molecules in asphalt to form insoluble salts that no longer attract water thus reducing stripping and oxidation potential [12]. The amount of hydrated lime used in this method is usually 0.9% by the weight of dry aggregates.

2.4.2 Addition of Dry Hydrated Lime to Wet Aggregates:

Addition of lime powder to wet aggregates is the most common method of incorporating of hydrated lime in asphalt mixes. In this method, hydrated lime is metered into aggregate that has a moisture content of 2-3% over its saturated-surface-dry (SSD) condition. After hydrated lime is added to wet aggregates, the lime-aggregate mix is run through a pug mill to ensure thorough mixing. The advantage of adding dry hydrated lime to wet aggregates is to ensure a better coverage and proper application compared to the previous method. This is possible because moisture ionizes lime and helps distribute it on the surface of aggregate. The portion of hydrated lime that does not adhere to the aggregates eventually gets mixed with asphalt and contributes to the improvements that are described in the dry method. The main disadvantage of using this method is the extra effort and fuel required to dry the aggregates before mix production.

When using this method of adding hydrated lime, many states require that lime-aggregate mix be marinated for duration of about 48 hours. This marination process has the following advantages: 1) moisture content is reduced over the period of stockpiling; and 2) due to stockpiling lime treatment can be carried out separately from the main HMA production providing some economic advantage. Disadvantages of marination are: 1) additional effort required for handling aggregate load; 2) additional space required for stocking both lime-treated and untreated aggregates; 3) carbonation of aggregates could occur due to chemical reaction.

2.4.3 Addition of Hydrated Lime in the Form of Slurry:

In this method of incorporating lime, a slurry of lime and water is metered and applied to aggregates to achieve a superior coverage of the stone surfaces. Lime slurries are made from hydrated lime but sometimes quicklime is also used. As indicated in the previous method, the treated aggregates can be marinated or used directly further. Advantages of using this method are as follows: 1) improved resistance of HMA to stripping; 2) as lime slurry is used, lime dispersion due to dusting and blowing is minimized; and 3) this method results in the best coverage of lime over aggregate. The disadvantages of using lime slurries are: 1) use of lime slurries can substantially increase the water content of aggregate resulting increased fuel consumption during drying process; and 2) use of this method requires specialized equipment that is costly to purchase and maintain.

2.5 Summary and Findings from Previous Studies

Based on the information presented in Table 2.1, it can be observed that the most common method used for incorporating lime is the addition of dry lime to wet aggregates. Except for Nevada most states either do not require marination, or it is optional. Several states have conducted studies to evaluate the efficacy of various methods of incorporating lime in asphalt mixes with and without marination process. A brief summary of findings from these studies is presented in the following section.

- The State of Georgia (GDOT) primarily uses the dry method for addition of lime. GDOT conducted several laboratory TSR tests to determine the efficacy of the dry as well as the slurry method of lime addition. The TSR test results reported by Collins [4] are shown in Figure 2.1. The conclusion based on Collins [4] study derived by GDOT was that the difference in results between dry and slurry methods was minor. The study also concluded that addition of dry lime to dry aggregates in the drum mixer near the asphalt binder feed line (towards the end of the drum) was more economical as compared to the use of lime slurry.

- Texas Department of Transportation (TxDOT) and Texas Hot Mix Asphalt Pavement Association conducted a series of TSR tests to study the efficacy of various methods of lime addition. Results reported by Button and Epps [3] are presented in Figures 2.2 & 2.3. Figure 2.2 shows the TSR test results for lime added to the mix in a batch plant; Figure 2.3 shows the results for a drum plant. Button and Epps concluded that the lime slurry was the best method of lime addition, followed by dry lime added to wet aggregates. Stockpiling or marination also had a beneficial effect for both methods of lime addition. They have reported that addition of dry lime to the drum mixer was not an effective method. They attributed the ineffectiveness to the lack of specialized lime addition equipment in their study.

- The State of Utah extensively uses the method of dry lime over wet aggregates. Marination after addition of lime is optional. Utah Department of Transportation conducted both TSR and immersion compression tests on mixes. Results reported by Betenson [2] summarized in Figures 2.4 and 2.5 show that addition of lime to wet aggregate has beneficial effect on TSR values. As can be seen in these figures, marination process also has a positive effect on TSR values.

- Similar to the practice by Utah DOT, the Nevada Department of Transportation also uses the method of dry lime addition to wet aggregates. Marination of lime-aggregate mix is required by Nevada DOT. Tables 2.2 and 2.3 show results of the TSR tests for laboratory mixes and field mixes, respectively, both in marinated and non-marinated state. Although Tables 2.2 and 2.3 show some variation in test results, in general, the marination process has some beneficial effects on TSR values

2.6 Summary

Literature on the use of lime as anti-strip additive in asphalt mixes indicates that there are three basic methods of lime incorporation in mixes:

- Dry hydrated lime to dry aggregates.
- Dry hydrated lime to wet aggregates (with or without marination).
- Adding hydrated lime in form of slurry.

The method of adding dry hydrated lime to wet aggregate seems to be the most widely used method. Most states using this method require no marination. Based on these findings and upon recommendation from NCDOT personnel, the method of adding dry lime to wet aggregates without marination was adopted for this study.

Table 2.1 – Summary of Methods Adopted for Incorporating Lime by Various States

State	Method of adding hydrated lime to asphalt				
	Dry hydrated lime to dry aggregate		Dry hydrated lime to wet aggregate	Lime slurry to aggregate	Marination
	Drum	Batch			
Arizona			*		No
California				*	Yes
Colorado			*	*	Optional
Georgia	*	*			No
Mississippi			*		No
Nevada			*		Yes
Oregon			*		Optional
South Carolina			*		No
Texas	*		*	*	No
Utah			*		Optional
Florida	*			*	-
Montana	*				-
Wyoming			*		-
New Mexico			*		-
South Dakota			*		-

Table 2.2 – TSR Test Results of Nevada Department of Transportation [11]

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

Table 2.3 - TSR Test Results of Nevada Department of Transportation Field (Behind Paver) Samples [11]

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

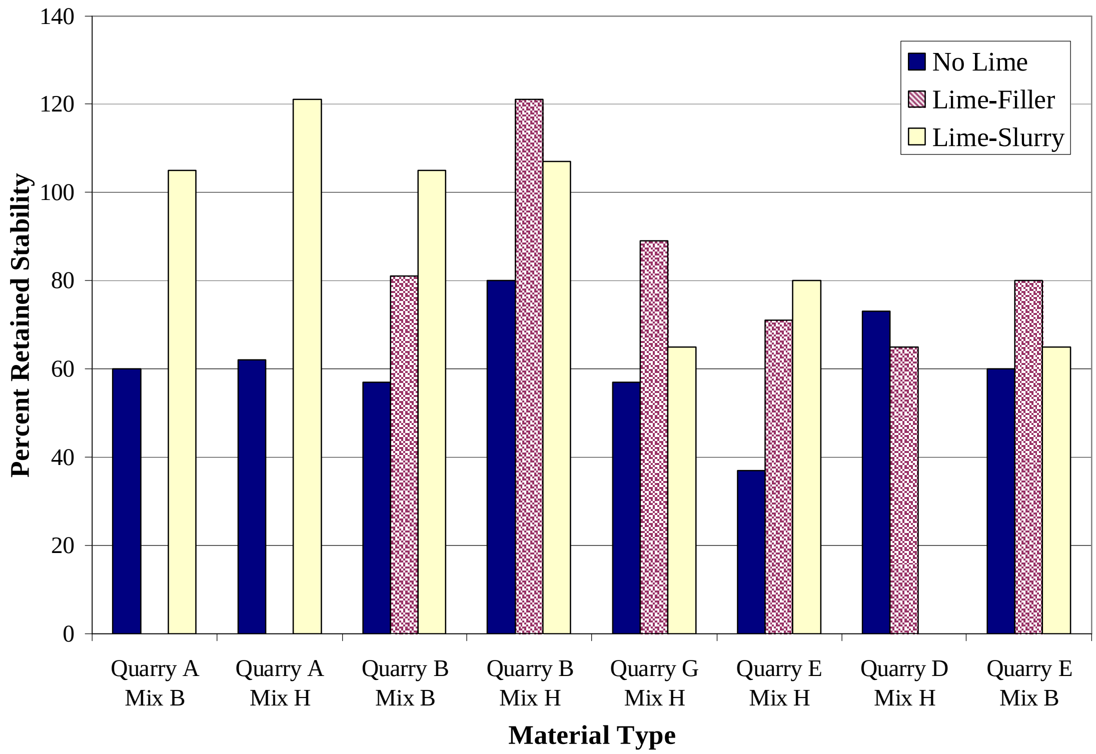

Figure 2.1 - Effect of the Addition of Lime and Method of Addition on the Retained Stability for Georgia DOT Mixtures (Regenerated) (Collins [4])

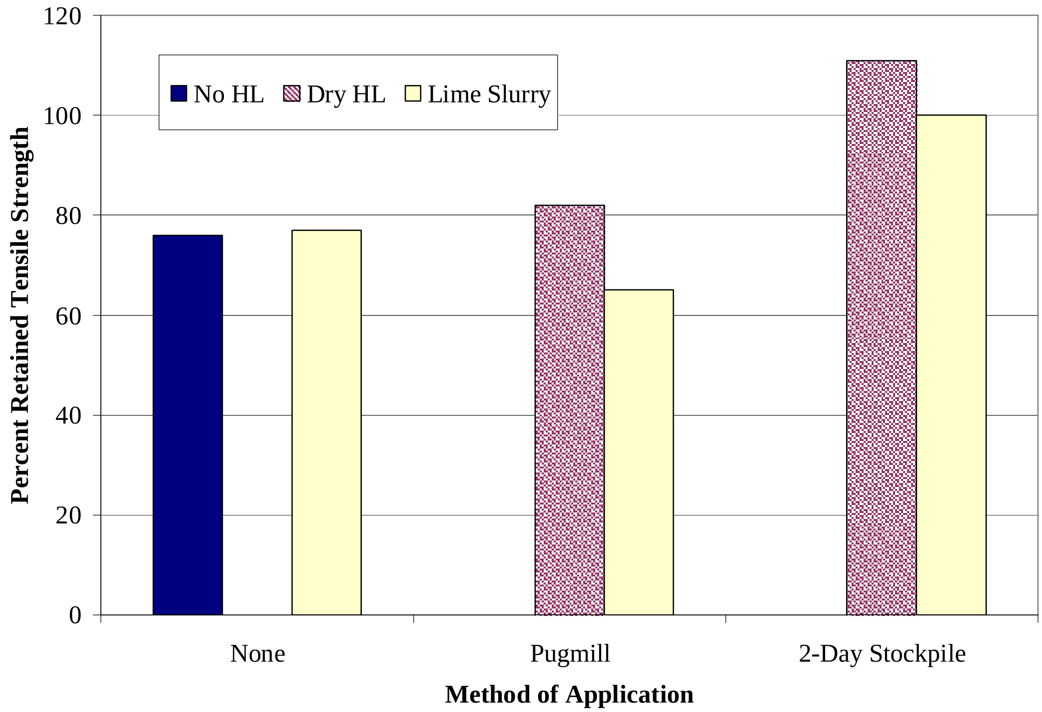

Figure 2.2 - Effect of Method of Application on Retained Tensile Strengths of Batch Plant Operations in Texas (Regenerated) (Button and Epps [3])

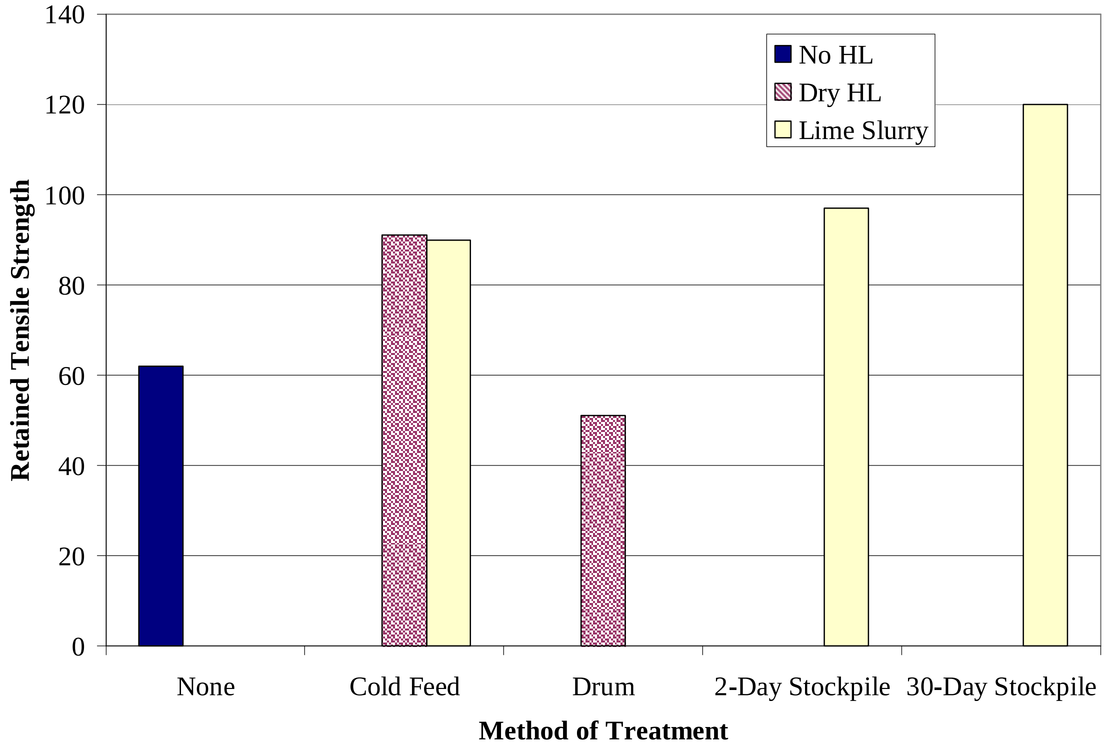

Figure 2.3 - Effect of Method of Application on retained Tensile Strength, Drum Plant, Texas (Regenerated) (Button and Epps [3])

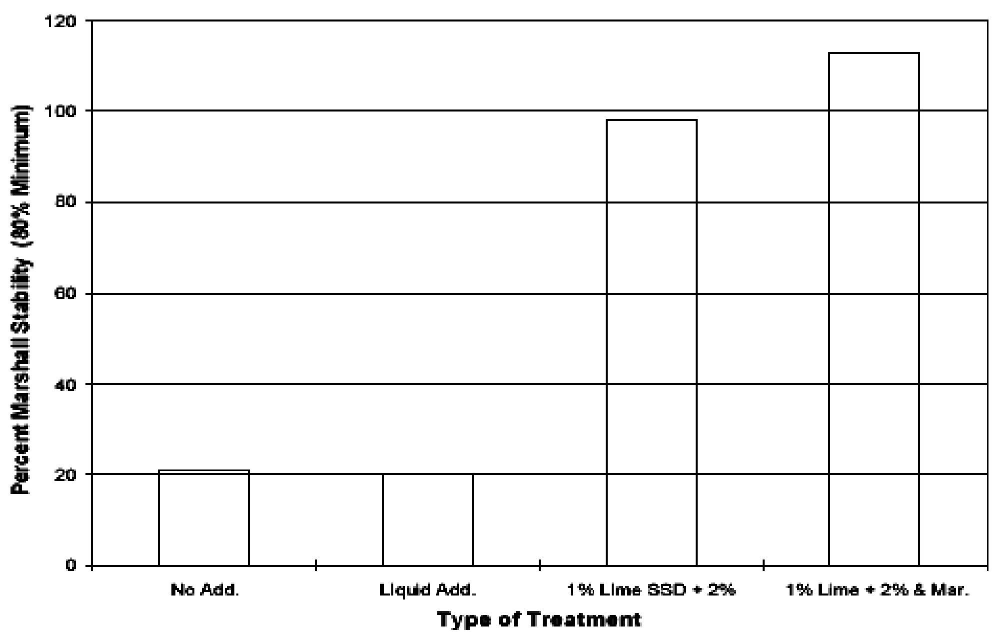

Figure 2.4 - Effect of the Type of Additive and Method of Addition on the Retained Tensile Strength of Materials from SR-50, Millard County Line to Salina, Utah (Betenson [2])

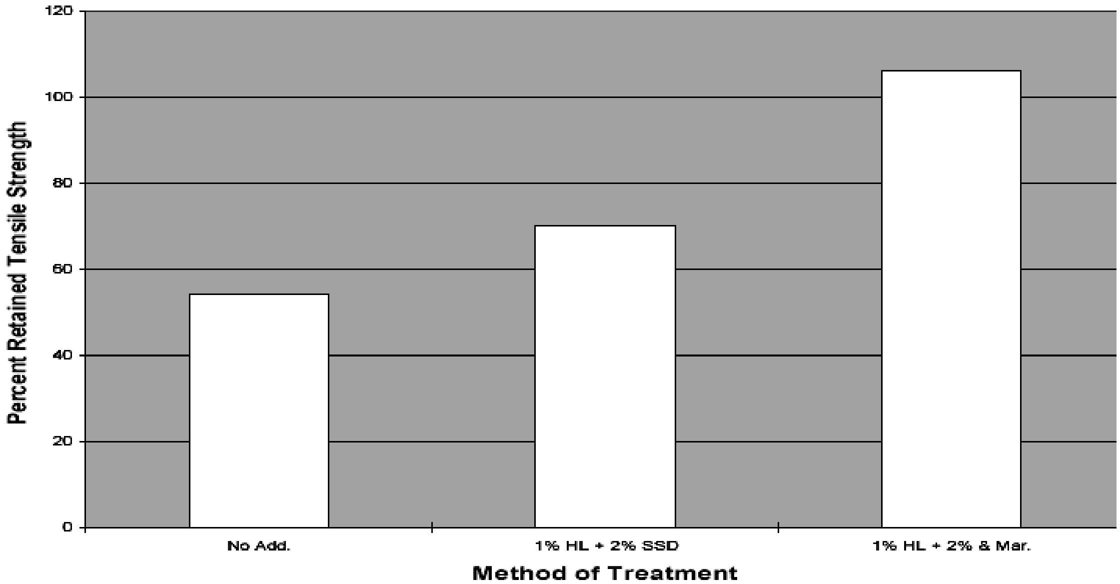

Figure 2.5 - Effect of Method of Lime Addition on Tensile Strength Ratio for Materials from I-70 Wetwater to Colorado Line, Utah DOT (Betenson [2])

3. RESEARCH APPROACH AND METHODOLOGY

3.1 Introduction

The effectiveness of lime as an anti-strip additive for mitigating moisture sensitivity of mixes containing excess baghouse fines is evaluated in this study. As a starting point, NCDOT Job-Mix-Formula (JMF) (Appendix A) was utilized. Laboratory specimens were prepared for several different tests to evaluate moisture damage as well as changes in performance associated with changes in baghouse fines content.

The research approach is outlined in Figure 3.1 that shows the various tasks undertaken. The following sections briefly summarize the main research tasks.

3.2 Research Tasks

3.2.1 Selection of Materials and Job-Mix-Formula

Pavement distress attributed to moisture damage was observed in NCDOT Division 13. In order to determine the causes of damage, JMF and materials were provided from plants in this area. Baghouse fines from a plant in Boone (NCDOT Division 11) and from Buncombe County (NCDOT Division 13) were used in this study. Wet sieve analysis was conducted on the received material and its gradation was compared with that of the previous project by Tayebali et al [15]. Batching was slightly modified to obtain a gradation within NCDOT specified limits.

3.2.2 Moisture Susceptibility Testing

In this study, a modified AASHTO T-283 test (TSR) was performed by NCDOT to access the moisture damage to the specimens. The modified NCDOT procedure does not require freeze/thaw cycle. Each subset for TSR test contained 8 specimens. The specimen size for the TSR test was 150 mm in diameter and 95 mm tall with an air-void content of 7±1 percent. In all, six sets, each with different fines and anti-strip additive content, were prepared using a Superpave™ Gyratory Compactor (SGC). After the air void content was determined, the samples were delivered to NCDOT for conditioning and testing. The conditioned subset was saturated and indirect tensile tests were performed on the dry and conditioned subsets. A TSR value was then calculated for each subset. These values were compared to the NCDOT criteria of 85 percent retained strength and the effectiveness of the additive was evaluated.

3.2.3 Mix Performance Evaluation

The mix performance was evaluated using the Simple Shear Test (SST) equipment. Tests conducted were: Frequency Sweep at Constant Height (FSCH) test and Repeated Shear at Constant Height (RSCH) test. 150 mm diameter specimens were compacted in the SGC to a height of 115mm and sawed to the specified height of 50 mm. The air-void range for the sawed specimens was reduced to 6.3±0.5 percent. Each set consisted of four samples with two conditioned and two dry specimens. FSCH tests were conducted to determine the shear modulus, $|G^*|$, and the phase angle, δ, at 20°C and at various frequencies. $|G^*|$ and δ values were used to determine fatigue resistance. The RSCH test was subsequently run and the plastic shear strain was determined. From these values comparisons were drawn on the effects of type of baghouse fines and anti-strip additive on mix performance.

3.3 Selection of Test Temperature

Testing temperature plays a significant role in the behavior and properties of asphalt concrete. Asphalt design must take into account the in-situ environment with considerations such as pavement temperature and moisture. There are a few different procedures for determining the appropriate testing temperature. AASHTO TP7 – Procedure F, dealing with the repeated shear test, uses the seven-day temperature at the selected pavement depth. The suggested depth is 20 mm from the surface and the surface temperature data is determined using the SHRPBIND program in the Superpave™ software.

Prior testing in western North Carolina by Tayebali [15] provided the steps in the determination of the testing temperature. The area falls within climate zone IC with maximum temperatures between 35° and 38°C. The pavement depth chosen corresponded to the interface layer at approximately 33 mm. These values were placed into the SHRPBIND program and the equations:

$$T_{surf} - T_{air} = -0.00618*(lat.)^2 + 0.2289*(lat.) + 24.4 \quad (3.1)$$

$$T_d = T_{surf} * (1-0.063*d + 0.007*d^2 - 0.0004*d^3) \quad (3.2)$$

Where T_{surf}, T_{air}, and T_d are the temperatures, in degrees C, of the surface, air, and at depth d, in inches, respectively and lat. is latitude in degrees. The two computed values were within 3°C and were averaged to a value of 50.2°C. This temperature was rounded to 50°C in this study due to the accuracy of the thermometers and instruments. The

RSCH tests were run at this temperature for comparison. FSCH testing was done at 20°C. The fatigue life comparison was also done at 20°C using the FSCH test results.

3.4 Specimen Nomenclature

In this study, six different mixes were evaluated. The mix designation or nomenclature, the source, and the amount of baghouse fines are shown in Table 3.1. For the mix nomenclature, the first two letters refer to the source of baghouse fines – Boone or Enka fines, followed by the actual amount of baghouse fines percentage used. The last two letters correspond to percentage of lime added as anti-strip additive (0% or 1%). Note that all mixes contained 6.5% combined mineral fillers. For those mixes that contained 1% lime, the baghouse fines content was reduced to 5.5%. Additionally numbers may follow mix nomenclature to distinguish samples used for testing. Finally, the characters 'U' and 'C' were used to denote whether the samples were unconditioned or moisture conditioned, respectively.

Table 3.1 - Baghouse Fine Proportioning

Nomenclature	BHF Source	Existing Materials	Added Materials		Total Fines %
		Fines %	BHF %	Lime %	
BF1.5L0	Boone	5	1.5	0	6.5
BF6.5L0	Boone	0	6.5	0	6.5
BF5.5L1	Boone	0	5.5	1	6.5
EF1.5L0	Enka	5	1.5	0	6.5
EF6.5L0	Enka	0	6.5	0	6.5
EF5.5L1	Enka	0	5.5	1	6.5

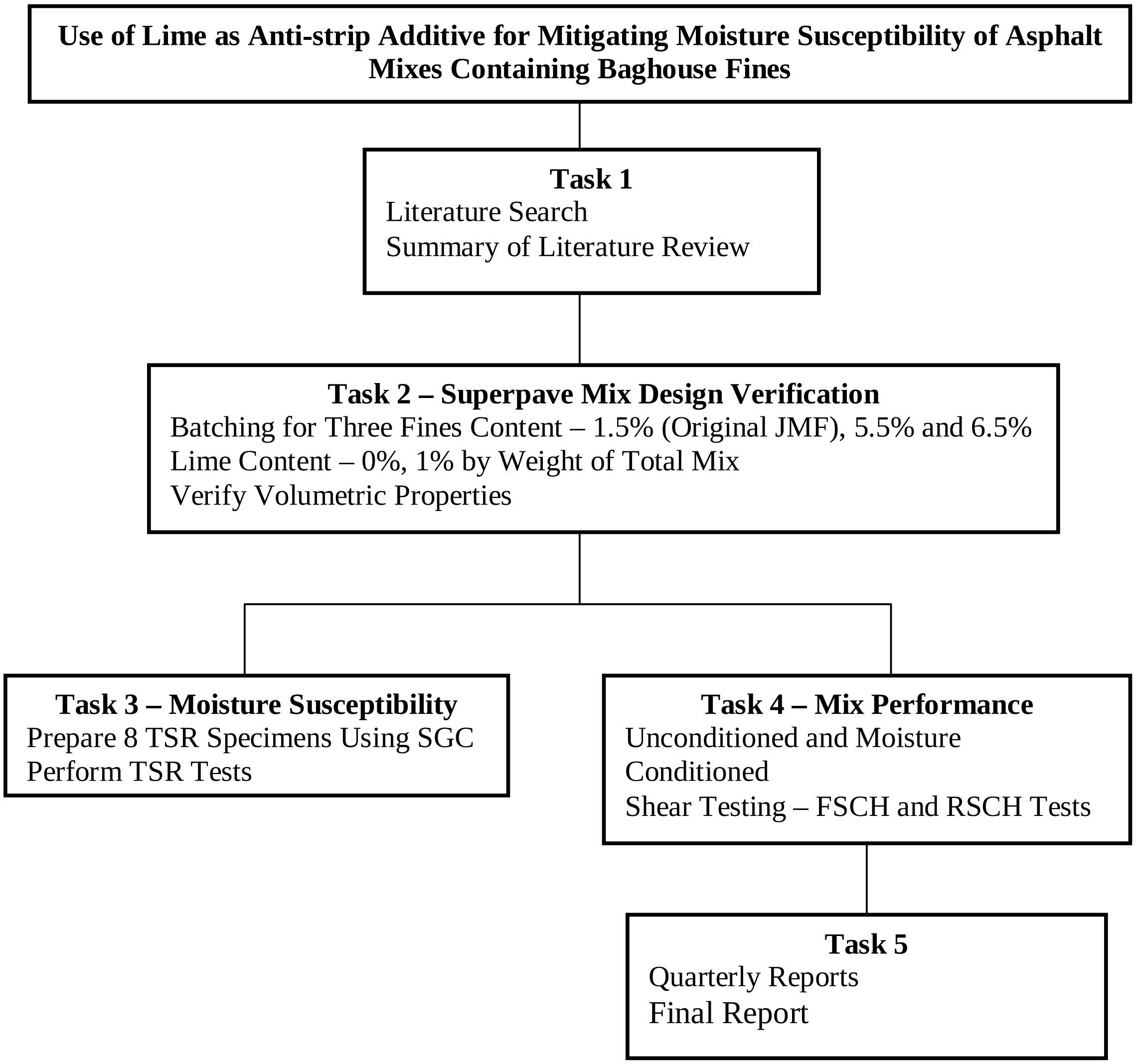

Figure 3.1 – Summary of Research Approach and Methodology

4. EVALUATION OF MATERIAL AND JOB-MIX-FORMULA

4.1 Introduction

The JMF used in this study was provided by NCDOT (Appendix A) for the laboratory production of HMA. Batching was slightly modified in order to incorporate the different fines content and to obtain a gradation that was within the specified NCDOT limits. Volumetric properties of mixes were evaluated and compared to the NCDOT requirements.

4.2 Job-Mix-Formula Evaluation and Revisions

4.2.1 Gradation Analysis

Wet sieve analysis was conducted to check the gradation of each individual fraction of the materials received from NCDOT. Gradation results are presented in Table 4.1. The gradations were then compared to the individual gradations in the JMF (Appendix A) and were found to be satisfactory. The original JMF proportions for aggregate fractions required were 30 percent 78-M stone, 26 percent manufactured sand, 19.5 percent dry screenings, and 23 percent washed screenings. Maymead Boone baghouse fines accounted for 1.5 percent of the aggregate weight.

For the aggregates in this project, the proportions for individual fraction were adjusted to achieve the required JMF gradation. The proportions used in this study are shown in Table 4.2, and the gradations for combined aggregate is presented in Table 4.3 and shown graphically in Figure 4.1. Note, that the JMF gradation blend requires 5-percent mineral filler. However, in consultation with NCDOT the percent mineral filler used for mixes in this study was 6.5%.

To accommodate the baghouse fines, the portion of all of the mineral filler in the original blend was wasted by sieving the aggregates over #200 sieve.

4.2.2 Evaluation of Volumetric Properties

Once the batching proportions were determined, the volumetric properties of the laboratory mixes were evaluated. PG 64-22 asphalt produced by Citgo in Bristol, Virginia was used in this study. The design asphalt content was 5.8 percent by weight of the mix. Hydrated lime was added at a level of 1.0 percent by weight of dry aggregates as shown in Table 4.4. The asphalt concrete was mixed at 149°C and maximum specific gravity was evaluated using Rice specific gravity test. During preparation of a specimen, hot mixed asphalt was aged for four hours at 65°C following NCDOT specifications. The mix was then heated for two hours at 138°C, after which it was compacted using a Superpave gyratory compactor. The maximum compactive effort used was 115 gyrations (N_{max}). Bulk specific gravities were evaluated and volumetric properties were determined for all six mixes. Average results based on two replicates are shown in Table 4.5.

Based on Table 4.5, it may be seen that all six mixes with BHF and hydrated lime met the required criteria. Based on the results no modification to design asphalt content was made and the asphalt content of 5.8% by weight of mix was used for all mix sample preparation for TSR test and for mix performance characterization.

Table 4.1 – Material Gradation

Sieve size	% Passing			
	78m	Manufactured Sand	Dry Screenings	Washed Screenings
12.5	100%	100%	100%	100%
9.5	85%	100%	100%	100%
#4	28%	98%	100%	74%
#8	4%	79%	90%	23%
#16	0.90%	62%	67%	4%
#30	0.75%	51%	49%	1%
#50	0.72%	34%	33%	0.93%
#100	0.70%	15%	24%	0.90%
#200	0.65%	3.88%	18.61%	0.86%

Table 4.2 – Batching proportions

	Aggregate Fraction				
Batch Type	78M	Manufactured Sand	Dry Screenings	Washed Screenings	BHF
JMF Batching	30.0%	26.0%	19.5%	23.0%	1.5%
Present Study	28.0%	21.5%	20.0%	29.0%	1.5%

Table 4.3 – Gradation Analysis

Sieve size	Sieve Opening (mm)	% Passing	% Passing (JMF)	Control Points
12.5	12.5	100%	100%	100
9.5	9.5	98%	98%	90-100
#4	4.75	74%	76%	<90
#8	2.36	45%	48%	32-67
#16	1.18	30%	31%	<31.6, >37.6
#30	0.6	23%	22%	<23.5, >27.5
#50	0.3	17%	16%	
#100	0.15	11%	8%	
#200	0.075	6.4%	5.0%	2.0-10.0

Table 4.4 – Baghouse Fine Proportioning

Nomenclature	BHF Source	Existing Materials	Added Materials		Total Fines %
		Fines %	BHF %	Lime %	
BF1.5L0	Boone	5	1.5	0	6.5
BF6.5L0	Boone	0	6.5	0	6.5
BF5.5L1	Boone	0	5.5	1	6.5
EF1.5L0	Enka	5	1.5	0	6.5
EF6.5L0	Enka	0	6.5	0	6.5
EF5.5L1	Enka	0	5.5	1	6.5

Table 4.5 – Volumetric Properties

Description	Nomenclature	G_{mm}	Va	%VMA	%VFA	$\%G_{mm}@N_{ini}$	$\%G_{mm}@N_{max}$	Dust Portion
1.5% Boone BHF, 0% Lime	BF1.5L0	2.517	3.6	15.2	73.7	88.3	98.0	1.26
1.5% Enka BHF, 0% Lime	EF1.5L0	2.514	3.3	15.1	73.4	88.3	97.7	1.25
6.5% Boone BHF, 0% Lime	BF6.5L0	2.516	4.4	16.0	74.9	87.4	96.7	1.26
6.5% Enka BHF, 0% Lime	EF6.5L0	2.517	4.4	15.9	74.8	87.8	96.7	1.26
5.5% Boone BHF, 1% Lime	BF5.5L1	2.510	3.1	15.1	73.4	88.5	97.7	1.24
5.5% Enka BHF, 1% Lime	EF5.5L1	2.511	3.4	15.3	73.8	88.3	97.6	1.24
JMF	JMF	2.510	3.6	15.8	75.9	86.6	96.4	0.98
NCDOT Requirement		-	4%	15% Min	65-76%	≤ 89%	≤ 98%	0.6-1.2

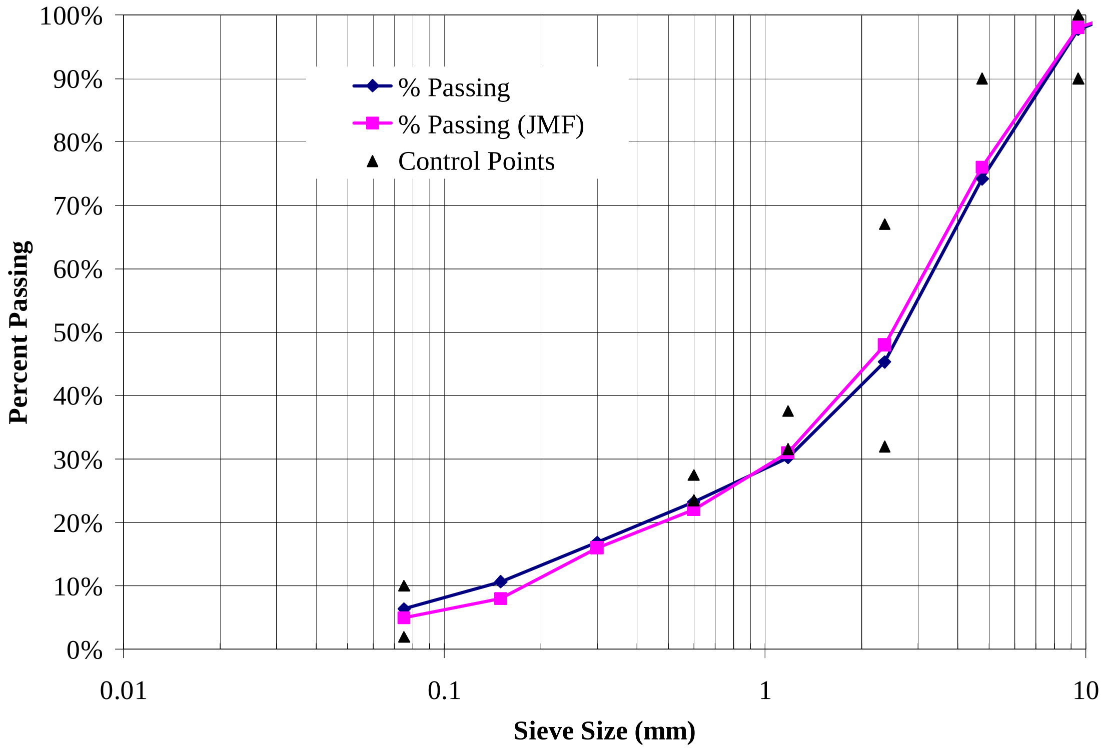

Figure 4.1 – Comparison of Gradation Curves

5. MOISTURE SUSCEPTIBILITY TESTING

5.1 Introduction

For this project task, samples were prepared using two different sources of baghouse fines (Boone and Enka), with or without hydrated lime. The samples were manufactured at NCSU labs and sent to NCDOT for TSR testing. Six mixes were tested and for each, 8 specimens were used for the TSR testing, for a total of 48 specimens. Test results of mixes containing lime were compared to mixes without lime and the effectiveness of the additive in preventing moisture damage was determined.

5.2 Moisture Sensitivity Testing

5.2.1 Test Method Description

The moisture susceptibility testing performed in this study followed the NCDOT modified AASHTO T-283 standard. This standard calls for sets of 6 to 8 specimens with a 150 mm diameter and a height of 95 mm with 7±1 percent air-voids level. The specimens were divided into subsets with half remaining dry and the other half being moisture conditioned. The unconditioned and conditioned specimens were subjected to Marshall Indirect Tensile Strength test (ITS). The average tensile strength for each subset was then used to calculate the TSR value as shown in Equation 5.1 below:

$$TSR = \frac{\text{Average Conditioned ITS}}{\text{Average Unconditioned ITS}} \tag{5.1}$$

After the TSR value was determined it was compared to a minimum value to determine the level of moisture damage. The NCDOT acceptable minimum retained strength is 85 percent or greater. Any mix that falls below this value is unsatisfactory and action must be taken to inhibit moisture damage. Two notable differences between the T-283 standard and the test performed by NCDOT is the number of specimens and the freeze/thaw cycle. NCDOT uses eight specimens per subset while T-283 requires six. The freeze/thaw cycle, which is optional in T-283, is not used by NCDOT.

5.2.2 Sample Preparation and Testing

The specimens were compacted to 7±1 percent air voids and measured 95±2 mm with a 150 mm diameter. Mixing was done at 149°C and subsequently aged for four hours at 65°C following the NCDOT specifications. The mixes were then heated for two hours at 138°C, after which they were compacted using a Superpave gyratory compactor. Each specimen was compacted to a height of 95±2 mm using a varied compactive effort. The bulk specific gravity and air-void content of the specimens was then found. The maximum specific gravity, G_{mm}, was also found for all six mixes using an average of two trials using the Rice method. The G_{mm} value was used in the air-void calculations. Table 5.1 shows the G_{mm} values for the mixes used.

The specimens were delivered to NCDOT for conditioning and testing. Based on the air-void data, the conditioned specimens were saturated to 50 and 80 percent. The indirect tensile strengths were evaluated and the TSR value was determined. Test results are presented in Tables 5.2 to 5.7

5.2.3 Test Results

Tables 5.2 through 5.7 show the test results for each of the six mixes. These results are summarized in Table 5.8 and Figure 5.1 show the TSR values for each mix. Mixes containing 1.5% and 6.5% Boone fines with no lime had a TSR value of 74.8 and 63.3 percent respectively. Mixes containing 1.5% and 6.5% Enka fines with no lime had a TSR value of 74.2 and 70.1 percent respectively. TSR values of all four mixes without lime as anti-strip additive are less than 85 percent minimum required by NCDOT and therefore fails the TSR test. Test mixes containing 5.5% Boone and Enka fines with 1% lime as anti-strip additive has TSR values of 85.7 and 93.8 respectively. Both mixes pass the 85 percent minimum TSR criteria.

Dry tensile strength seemed to reduce with increase in percent additional BHF. Dry tensile strength of mixes containing Boone BHF reduced from 1158 psi to 1052 psi, which represents a 9.1% reduction between 1.5% and 6.5% Boone BHF subsets. Dry tensile strength of mixes containing Enka BHF reduced from 1116 psi to 1049 psi, which represents a 5.9% reduction between 1.5% and 6.5% Enka BHF subsets. Whereas, conditioned or wet tensile strength of mixes containing Boone BHF reduced from 870 psi to 685 psi, which represents a 21.2% reduction between 1.5% and 6.5% Boone BHF subsets. Also, wet tensile strength of mixes containing Enka BHF reduced from 817 psi to 736 psi, which represents a 9.9% reduction between 1.5% and 6.5% Enka BHF subsets.

The last two sets had 5.5% Boone/Enka fines and 1% hydrated lime. Dry tensile strength of mixes which had Boone fines with lime (BF5.5L1) was higher than mixes which had no lime (BF6.5L0) by 13.9% with a corresponding increase in wet tensile strength of 49.7%. But dry tensile strength of mixes which had Enka fines with lime (EF5.5L1) was lower than mixes which had no lime (EF6.5L0) by 11.6% with a corresponding increase in wet tensile strength of 17.8%. Enka mix with 1% lime (EF5.5L1) had a TSR value of 93.8%, which is 33.8% higher than the corresponding mix without lime (EF6.5L0). Boone mix with 1% lime (BF5.5L1) had a TSR value of 85.7% which is 35.4% higher than the corresponding mix without lime (BF6.5L0).

5.3 Summary and Conclusions

The TSR test results show that 1% hydrated lime (by weight of dry aggregates) is an effective anti-strip additive for the North Carolina mixes with excess baghouse fines used in this study. The effect of lime on performance characteristics of unconditioned and conditioned mixes containing excess baghouse fines is explored in the following sections.

Table 5.1 – Rice Specific Gravity (G_{mm})

Description	Nomenclature	G_{mm}
1.5% Boone BHF, 0% Lime	BF1.5L0	2.517
1.5% Enka BHF, 0% Lime	EF1.5L0	2.514
6.5% Boone BHF, 0% Lime	BF6.5L0	2.516
6.5% Enka BHF, 0% Lime	EF6.5L0	2.517
5.5% Boone BHF, 1% Lime	BF5.5L1	2.510
5.5% Enka BHF, 1% Lime	EF5.5L1	2.511

Table 5.2 – TSR Results: 1.5% Boone fines with 0% Lime

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
BF1.5L0-1	6.6	1157	BF1.5L0-5	75.3	6.6	859
BF1.5L0-2	6.7	1127	BF1.5L0-6	74.9	6.9	840
BF1.5L0-3	6.6	1139	BF1.5L0-7	74.2	6.6	859
BF1.5L0-4	6.7	1209	BF1.5L0-8	72.1	6.7	921
Average =	6.7	1158			6.7	870
		TSR =	**74.8**			

Table 5.3 – TSR Results: 1.5% Enka fines with 0% Lime

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
EF1.5L0-1	6.4	1102	EF1.5L0-5	71.8	7.0	814
EF1.5L0-2	6.5	1102	EF1.5L0-6	75.9	6.6	784
EF1.5L0-3	6.4	1119	EF1.5L0-7	71.9	6.5	833
EF1.5L0-4	6.7	1139	EF1.5L0-8	73.3	6.5	838
Average =	6.5	1116			6.7	817
		TSR =	**74.2**			

Table 5.4 – TSR Results: 6.5% Boone fines with 0% Lime

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
BF6.5L0-1	6.7	992	BF6.5L0-5	70.5	6.6	676
BF6.5L0-2	6.4	1081	BF6.5L0-6	68.9	6.6	712
BF6.5L0-3	6.7	1068	BF6.5L0-7	72.3	6.6	677
BF6.5L0-4	6.4	1069	BF6.5L0-8	76.1	6.5	676
Average =	6.6	1052			6.6	685
		TSR =	**63.3**			

Table 5.5 – TSR Results: 6.5% Enka fines with 0% Lime

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
EF6.5L0-1	6.8	1042	EF6.5L0-5	55.0	6.8	764
EF6.5L0-2	7.0	1057	EF6.5L0-6	61.1	7.0	711
EF6.5L0-3	6.9	1050	EF6.5L0-7	67.0	6.8	724
EF6.5L0-4	7.0	1048	EF6.5L0-8	61.1	7.0	747
Average =	6.9	1049			6.9	736
		TSR =	**70.1**			

Table 5.6 – TSR Results: 5.5% Boone fines with 1% Lime

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
BF5.5L1-1	6.4	1153	BF5.5L1-5	66.3	6.5	1040
BF5.5L1-2	6.6	1210	BF5.5L1-6	63.4	6.3	997
BF5.5L1-3	6.3	1201	BF5.5L1-7	60.5	6.6	1032
BF5.5L1-4	6.4	1228	BF5.5L1-8	58.0	6.3	1033
Average =	6.4	1198			6.4	1025
		TSR =	**85.7**			

Table 5.7 – TSR Results: 5.5% Enka fines with 1% Lime

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
EF5.5L1-1	6.9	937	EF5.5L1-5	75.2	6.8	844
EF5.5L1-2	6.5	906	EF5.5L1-6	70.8	6.8	855
EF5.5L1-3	6.7	901	EF5.5L1-7	74.5	6.7	872
EF5.5L1-4	6.6	965	EF5.5L1-8	75.8	6.6	900
Average =	6.7	927			6.7	868
		TSR =	**93.8**			

Table 5.8 – Boone and Enka TSR Values

Boone BHF Specimens		Enka BHF Specimens	
Sample ID	**TSR (%)**	**Sample ID**	**TSR (%)**
BF1.5L0	74.8	EF1.5L0	74.2
BF6.5L0	63.3	EF6.5L0	70.1
BF5.5L1	85.7	EF5.5L1	93.8

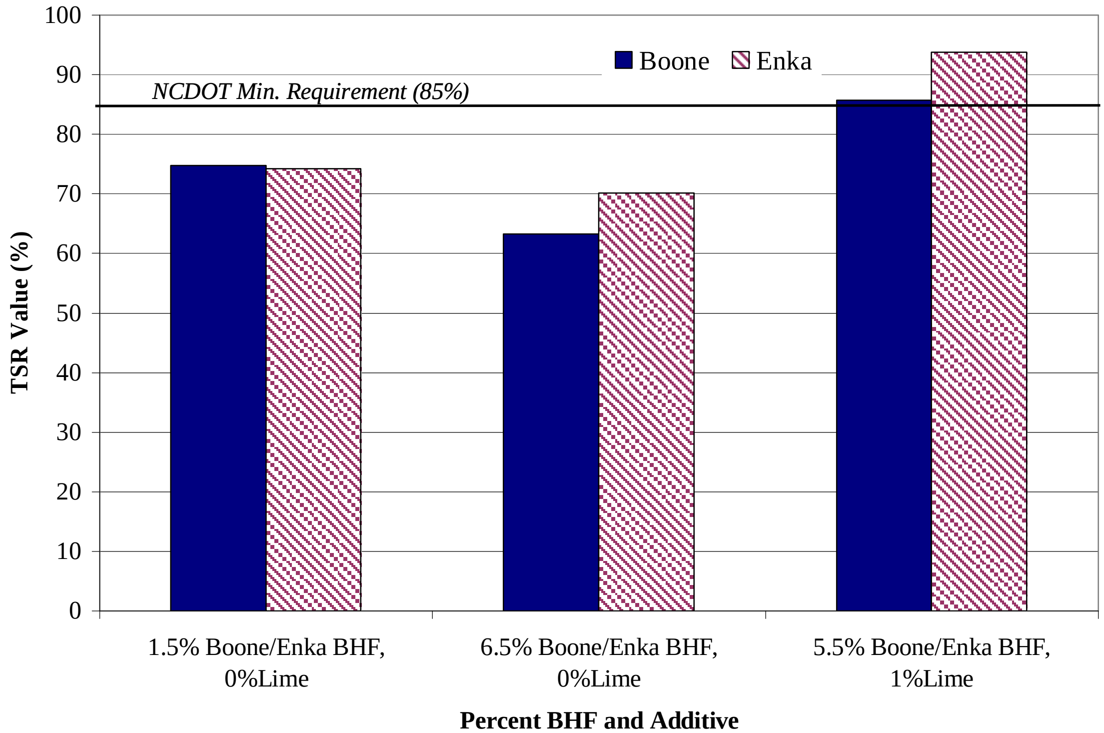

Figure 5.1 – Boone and Enka TSR Values

6. Mix Performance Evaluation

6.1 Introduction

In this testing phase, specimens were subjected to stress and strain controlled tests and material properties were determined using the Simple Shear Testing (SST) device. Two types of test were run using SST: Frequency Sweep at Constant Height (FSCH), and Repeated Shear at Constant Height (RSCH) tests. The data collected from these tests were analyzed for shear modulus $|G^*|$, phase angle (δ) and plastic shear strain. The effectiveness of lime in mitigating moisture susceptibility was evaluated by comparing the test results for mixes in the unconditioned and the moisture conditioned state.

6.2 SST Specimen Testing

6.2.1 Test Method Description

The testing system consisted of an environmental chamber that maintains a constant temperature and two hydraulic actuators controlled by a computer that apply horizontal and vertical loads. The load and displacement are measured using load cells and Linear Variable Displacement Transducers (LVDT), respectively.

The specimens for these tests are required to be 50 mm in height and 150 mm in diameter. Specimens are glued to aluminum platens designed to fit into the SST machine. The specimen was first subjected to a FSCH test that is nondestructive, followed by the RSCH test. For the FSCH test, specimens were conditioned inside the chamber at the specified temperature of 20°C. For RSCH tests, the specimens were heated in a forced draft oven for 2 hours at 50°C, and then loaded into the chamber for 1 hour of conditioning before testing. The FSCH and RSCH tests were conducted following the AASHTO TP-7 procedures.

6.2.2 Sample Preparation and Testing

SST samples were prepared in the laboratory using the Superpave Gyratory Compactor (SGC). Samples were compacted to a height of 115 mm and a diameter of 150 mm. The compaction effort was varied to achieve void content of 6.3±0.5 percent for sawed specimen. The SGC specimen was sawed into two specimens to the required height of 50±2 mm.

Six sets of specimens were prepared, each set containing two dry and two conditioned samples, for a total of 24 test specimens. Moisture conditioning of the sample was conducted at NCDOT Materials and Test Unit following the NCDOT Modified AAHTO T-283 procedure.

Before gluing the specimens to the platens, the platens were first cleaned with rubbing alcohol. A platen-specimen assembly device provided pressure on the specimen while the applied epoxy hardened. After hardening, the samples were conditioned for 2-3 hours at the respective test temperature before testing. The sample was then fitted with axial and horizontal LVDT's and placed into the SST machine for testing.

6.2.3 Frequency Sweep Testing

The frequency sweep at constant height (FSCH) test was performed to determine the shear modulus and the phase angle of the HMA specimen at several different frequencies. The specimen was loaded in compliance with AASHTO TP-7 for each frequency and the viscoelastic properties were measured. Throughout the testing, an axial force was applied to prevent dilation and maintain the specimen at constant height. The following sections describe the FSCH testing.

6.2.3.1 Testing Procedure

For the FSCH test, a sinusoidal shearing strain of amplitude ±0.005 percent was applied at frequencies of 10, 5, 2, 1, 0.5, 0.2, and 0.1 Hz. During testing applied load and displacements are recorded. Using these values, the dynamic shear modulus (|G*|) and the phase angle (δ) are calculated. The dynamic shear modulus is the ratio of the peak shear stress and the peak shear strain; and δ is the lag between the applied stress and strain response.

6.2.3.2 FSCH Test Results

The detailed results of the FSCH test for each mix tested in this study are presented in Appendix B. The average values based on two replicate specimens are summarized in Tables 6.1 through 6.4. The shear stiffness |G*| values are also presented graphically in Figures 6.1 through 6.6 for the six mixes tested in this study.

For simplicity in presentation of the data, Table 6.5 shows the average values of |G*| in MPa over all tested frequencies – 10 Hz to 0.1 Hz. Based on Table 6.5 it can be observed that:

1. Mixes without lime as anti-strip additive, the moisture conditioned samples show a lower |G*| value for both mixes containing Boone and Enka baghouse fines;

2. Increasing the amount of baghouse fines increases the |G*| value for unconditioned specimens. This behavior is expected as increase in baghouse fines content will usually stiffen the mixes. For moisture conditioned specimens, increasing the baghouse fines content results in decreased |G*| values indicating that excess baghouse fines results in more moisture sensitive mixes;
3. For mixes containing 1% hydrated lime as an anti-strip additive, there is a considerable increase in |G*| values for both unconditioned and conditioned samples for mixes with either Boone or Enka baghouse fines;
4. Mixes containing lime as anti-strip additive show very little reduction in |G*| values (0.4 to 6.5%) moisture conditioning indicating that lime is effective in arresting moisture damage in mixes containing excess baghouse fines, which is consistent with the TSR test findings.

The trend in the results based on the average |G*| values can also be seen graphically in Figures 6.1 to 6.6 over the testing frequency range. Based on the results of the FSCH tests, it can be concluded that lime is not only effective in mitigating moisture sensitivity of mixes, but will enhance the mix properties by increasing the shear resistance of the mixes and eventually should decrease the potential for rutting. The rutting performance is evaluated using the RSCH test in the following section.

6.2.4 Repeated Shear Testing

The repeated shear at constant height (RSCH) test was performed at 50°C to determine the HMA response to repeated traffic loading. The RSCH test is designed to determine the rutting potential of HMA. The specimen is subjected to a shear loading pattern repeatedly and the shear stress and accumulated strain is measured.

6.2.4.1 Testing Procedure

The RSCH test was performed in the Superpave SST machine following AASHTO TP-7, Procedure F [1]. It is a stress-controlled test with a cyclic haversine shearing stress applied to the sample for a period of 0.1 s followed by a 0.6 s rest period. The maximum shear stress applied during loading is 69±5 kPa. The test is conducted to 5000 loading cycles or to 5% shear accumulated plastic shear strain.

6.2.4.2 RSCH Test Results

The results of RSCH tests for each mix are graphically shown in Figures 6.7 through 6.12. Average values based on two replicates of plastic shear strain at 5000 cycles for mixes in the conditioned and unconditioned state are presented in Table 6-6. Based on these strain values, rutting resistance of various mixes was computed using the following relationship:

$$\text{Rut Depth (in.)} = 11 * (\gamma_p) \quad (6.1)$$

Where: γ_p = the maximum permanent shear strain in the RSCH test.

Computed rut depths are also presented in Table 6.6. The negative sign for the percent difference in the rut depths indicate that moisture conditioned specimens show higher rutting potential than unconditioned specimens.

The results presented in Table 6.6 show that behavior of mixes containing Boone baghouse fines is consistent with the trend observed based on TSR as well as the FSCH test. Excess baghouse fines produces more moisture sensitive mixes with conditioned specimens having rut depth 25% more than unconditioned specimens. Also, addition of lime appears to mitigate the moisture sensitivity.

With regards to the mixes containing Enka baghouse fines, the results are variable (and perplexing). Mixes containing 1.5% Enka baghouse fines show higher rut depth for conditioned specimens. However, higher (6.5%) Enka baghouse fines content shows the opposite, contrary to the TSR and FSCH findings. For this particular mix, similar behavior was observed in previous NCDOT study reported by Tayebali et al [15], where an organic anti-strip additive LOF6500 was used. Nevertheless, it appears that lime does have a beneficial affect in reducing not only the moisture sensitivity of mixes containing Boone and Enka baghouse fines, but also in reducing the overall rut depth even though these mixes contain excess baghouse fines (5.5%).

6.3 Fatigue Analysis

Fatigue distress is dependant on both mixture properties as well as the pavement structure. Fatigue analysis in this study is based on a model presented in NCDOT Report FHWA/NC/2004-11 [16]. The fatigue analysis requires an estimate of flexural stiffness modulus (S_0) of the mix at 20°C. The $|G^*|$ value at 10 Hz and 20°C temperature presented earlier were used to compute S_0 values based on Equation 6.2:

$$\mathbf{S_0 = 8.560 \times (G_0)^{0.913}} \tag{6.2}$$

Where:

S_0 = Dynamic flexural stiffness at 10 Hz in psi,

G_0 = $|G^*|$ = Dynamic shear stiffness at 10 Hz in psi,

The computed S_0 values for different mixes are shown in Tables 6.7 and 6.8 along with the volumetric data. The estimated flexural stiffness (S_0) presented in Tables 6.7 and 6.8 were used in multilayer elastic analysis to determine the critical strain (ε) to which the asphalt concrete mixture will be subjected under standard traffic loading. Multilayered elastic analysis in this study was conducted using the KENLAYER program. For fatigue analysis, a typical section, shown in Figure 6.13, was used.

The pavement section consists of a 6 inch asphalt concrete layer over an 8 inch aggregate base course (ABC) and 7 inches of cement treated Subbase (CTB). Material properties for ABC, CTB and Subgrade are as shown in Figure 6.13. The loading used in this study was a standard 18 kip single axle load with dual tires inflated to 85 psi with 12 inches center to center spacing.

Using the estimated flexural stiffness, the critical tensile strain (ε) at the bottom of the AC layer was calculated; results are in Tables 6.9 and 6.10. Using the fatigue equation suggested by Tayebali et al [16] (equation 6.3), the life of the pavement section was evaluated:

$$\mathbf{N_f = 4.9016 \times 10^{-2} \times (e)^{0.03029\ VFA} \times (\varepsilon)^{-3.28034} \times (S_0)^{-0.98505}} \qquad (6.3)$$

where:

N_f = the number of 18 kip ESAL's that the pavement section can withstand,

e = base of the natural logarithm,

ε = critical tensile strain,

S_0 = dynamic flexural stiffness (psi), and,

VFA = voids filled with asphalt (percent).

The results of the fatigue analysis for all subsets for mixes containing Boone or Enka fines are presented in Table 6.9 and 6.10, respectively. The summary of fatigue life of pavement sections containing different mixes is presented in Table 6.11.

Based on the results presented in Table 6.11, the following observations can be made:

1. Consistent with the results of TSR, FSCH and RSCH tests, the estimated fatigue life of the typical pavement section is reduced by 10 to 15 % when excess baghouse fines are present in the mixes.
2. The addition of lime as an anti-strip additive mitigates the moisture sensitivity of mixes containing excess baghouse fines. The difference in estimated life for unconditioned versus conditioned mixes is around 0.1 – 3.4%.
3. In addition to reducing the moisture sensitivity of mixes, the addition of lime appears to actually increase the fatigue resistance of pavement section containing mixes with excess Boone and Enka baghouse fines.

6.4 Summary and Conclusions

Mix performance was evaluated using the FSCH and RSCH tests. The |G*| values from FSCH tests were further used to estimate the fatigue resistance of the mixes containing Boone and Enka baghouse fines.

Consistent with the TSR test results, the mix performance evaluation suggests that in general, lime is effective as an anti-strip additive in mitigating moisture sensitivity of mixes containing excess baghouse fines. In addition, the test results indicate that addition of lime enhances the mix performance - |G*| values are higher, rut depths are lower, and fatigue resistance is higher.

Table 6.1 – Average Dynamic Shear Modulus versus Frequency; Boone BHF

Frequency (Hz)	Shear Modulus, |G*|, (MPa)					
	BF1.5L0		BF6.5L0		BF5.5L0-1	
	Unconditioned	Conditioned	Unconditioned	Conditioned	Unconditioned	Conditioned
0.1	272	248	314	256	390	401
0.2	362	328	412	333	504	513
0.5	524	475	583	471	693	697
1	684	607	749	608	867	869
2	977	860	1045	844	1225	1155
5	1225	1070	1270	1035	1390	1395
10	1475	1320	1515	1275	1635	1645
Average |G*|	788	701	841	689	958	953

Table 6.2 – Average Phase Angle versus Frequency; Boone BHF

Frequency (Hz)	Phase Angle, δ, (degree)					
	BF1.5L0		BF6.5L0		BF5.5L0-1	
	Unconditioned	Conditioned	Unconditioned	Conditioned	Unconditioned	Conditioned
0.1	45.1	43.9	43.4	42.4	41.1	39.8
0.2	44.5	43.6	42.2	41.4	39.6	38.7
0.5	42.1	40.7	39.5	39.1	36.4	35.7
1	39.5	38.9	36.9	37.2	33.7	33.2
2	33.5	34.4	32.9	33.3	27.7	29.9
5	30.2	30.4	28.1	28.9	24.8	25.2
10	27.2	27.3	25.5	26.3	22.8	23.2
Average δ	37.4	37.0	35.5	35.5	32.3	32.2

Table 6.3 – Average Dynamic Shear Modulus versus Frequency; Enka BHF

Frequency (Hz)	Shear Modulus, |G*|, (MPa)					
	EF1.5L0		EF6.5L0		EF5.5L0-1	
	Unconditioned	Conditioned	Unconditioned	Conditioned	Unconditioned	Conditioned
0.1	286	247	311	233	408	369
0.2	382	322	410	304	523	474
0.5	548	458	581	436	715	649
1	712	579	744	559	891	817
2	1045	861	1040	779	1170	1110
5	1240	1040	1270	968	1415	1340
10	1500	1280	1530	1195	1655	1580
Average |G*|	816	684	841	639	968	905

Table 6.4 – Average Phase Angle versus Frequency; Enka BHF

Frequency (Hz)	Phase Angle, δ, (degree)					
	EF1.5L0		EF6.5L0		EF5.5L0-1	
	Unconditioned	**Conditioned**	**Unconditioned**	**Conditioned**	**Unconditioned**	**Conditioned**
0.1	45.1	43.0	44.2	42.6	40.5	40.6
0.2	44.0	43.2	42.8	42.1	39.0	39.3
0.5	41.4	42.3	39.6	40.8	35.7	36.6
1	38.5	38.4	37.5	38.6	32.7	33.8
2	33.1	34.4	34.9	34.7	27.4	29.7
5	29.1	30.7	28.1	30.4	23.9	26.0
10	26.2	27.6	26.8	27.6	21.9	23.8
Average δ	36.8	37.1	36.3	36.7	31.6	32.8

Table 6.5 – Comparison of Average Shear Stiffness Values at 20° C

Type of Mix		|G*| (MPa)		
Boone BHF %	**Lime %**	**Unconditioned**	**Conditioned**	**Difference %**
1.5	**0**	788	701	11.1%
6.5	**0**	841	689	18.1%
5.5	**1**	958	953	0.4%
Enka BHF %				
1.5	**0**	816	684	16.2%
6.5	**0**	841	639	24.0%
5.5	**1**	968	905	6.5%

Table 6.6 – Plastic Shear Strain at 5000 Cycles and Corresponding Rutting Depth @ 50° C

Type of Mix		Plastic Shear Strain		Rut Depth (in)		% Difference
Boone BHF %	**Lime %**	**Dry**	**Wet**	**Dry**	**Wet**	
1.5	0	0.0186	0.0200	0.204	0.220	-7.9%
6.5	0	0.0142	0.0178	0.157	0.195	-24.8%
5.5	1	0.0133	0.0140	0.147	0.154	-5.0%
Enka BHF %						
1.5	0	0.0155	0.0178	0.171	0.195	-14.2%
6.5	0	0.0171	0.0161	0.188	0.177	5.8%
5.5	1	0.0133	0.0137	0.146	0.150	-3.1%

Table 6.7 – Summary of Average Material Properties for Boone Set @ 20° C at 10 Hz

		|G*| @ 10 Hz (psi)	δ @ 10 Hz (degrees)	S_0 (psi)	VFA (%)	Air Voids (%)
BHF: 1.5%, LIME: 0%	**Dry**	2.14E+05	27.2	6.29E+05	62.67	6.70
	Wet	1.91E+05	27.3	5.69E+05	64.20	6.30
BHF: 6.5%, LIME: 0%	**Dry**	2.20E+05	25.5	6.45E+05	64.85	6.15
	Wet	1.85E+05	26.3	5.51E+05	65.25	6.05
BHF: 5.5%, LIME: 1%	**Dry**	2.37E+05	22.8	6.91E+05	64.85	6.25
	Wet	2.39E+05	23.2	6.95E+05	64.66	6.30

Table 6.8 – Summary of Average Material Properties for Enka Set @ 20° C at 10 Hz

		|G*| @ 10 Hz (psi)	δ @ 10 Hz (degrees)	S_0 (psi)	VFA (%)	Air Voids (%)
BHF: 1.5%, LIME: 0%	**Dry**	2.18E+05	26.2	6.39E+05	64.79	6.20
	Wet	1.86E+05	27.6	5.53E+05	64.20	6.35
BHF: 6.5%, LIME: 0%	**Dry**	2.22E+05	26.8	6.51E+05	63.05	6.60
	Wet	1.73E+05	27.6	5.19E+05	63.24	6.55
BHF: 5.5%, LIME: 1%	**Dry**	2.40E+05	21.9	6.99E+05	64.59	6.30
	Wet	2.29E+05	23.8	6.70E+05	64.59	6.30

Table 6.9 – Comparison of Fatigue Life for Boone Set @ 20° C

		VFA (%)	Strain (ε)	S_0 (psi)	N_f	Difference
BHF: 1.5%, Lime: 0%	**Dry**	62.67	1.34E-04	6.29E+05	3.19E+06	2.9%
	Wet	64.20	1.42E-04	5.69E+05	3.10E+06	
BHF: 6.5%, Lime: 0%	**Dry**	64.85	1.33E-04	6.45E+05	3.48E+06	10.3%
	Wet	65.25	1.44E-04	5.51E+05	3.12E+06	
BHF: 5.5%, Lime: 1%	**Dry**	64.85	1.28E-04	6.91E+05	3.67E+06	0.1%
	Wet	64.66	1.27E-04	6.95E+05	3.67E+06	

Table 6.10 – Comparison of Fatigue Life for Enka Set @ 20° C

		VFA (%)	Strain (ε)	S_0 (psi)	N_f	Difference
BHF: 1.5%, Lime: 0%	**Dry**	64.79	1.33E-04	6.39E+05	3.44E+06	11.9%
	Wet	64.20	1.44E-04	5.53E+05	3.03E+06	
BHF: 6.5%, Lime: 0%	**Dry**	63.05	1.32E-04	6.51E+05	3.31E+06	15.0%
	Wet	63.24	1.49E-04	5.19E+05	2.81E+06	
BHF: 5.5%, Lime: 1%	**Dry**	64.59	1.27E-04	6.99E+05	3.68E+06	3.4%
	Wet	64.59	1.30E-04	6.70E+05	3.55E+06	

Table 6.11 – Summary of Fatigue Resistance of Mixes

Type of mix		**No. of 18k ESAL's in millions**		
Boone BHF %	**Lime %**	**Unconditioned**	**Conditioned**	**% Difference**
1.5	0	3.19	3.10	2.9%
6.5	0	3.48	3.12	10.3%
5.5	1	3.67	3.67	0.1%
Enka %				
1.5	0	3.44	3.03	11.9%
6.5	0	3.31	2.81	15.0%
5.5	1	3.68	3.55	3.4%

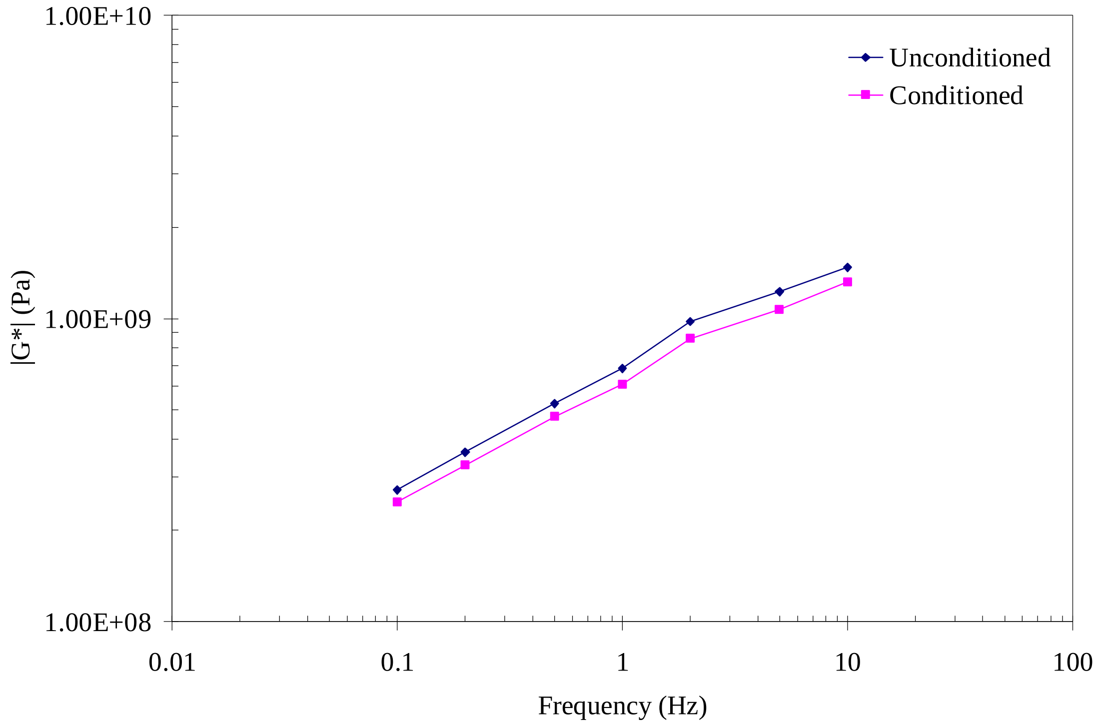

Figure 6.1 – Dynamic Shear Modulus vs. Frequency: 1.5% Boone BHF, 0% Lime, @20°C

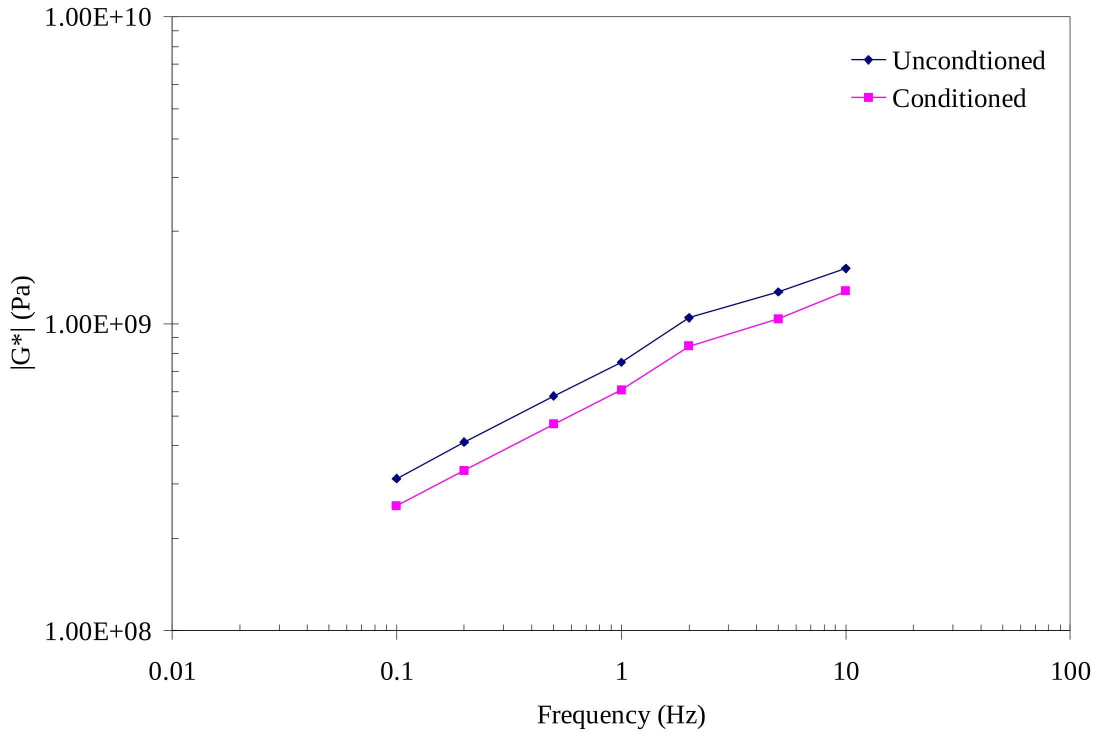

Figure 6.2 – Dynamic Shear Modulus vs. Frequency: 6.5% Boone BHF, 0% Lime, @20°C

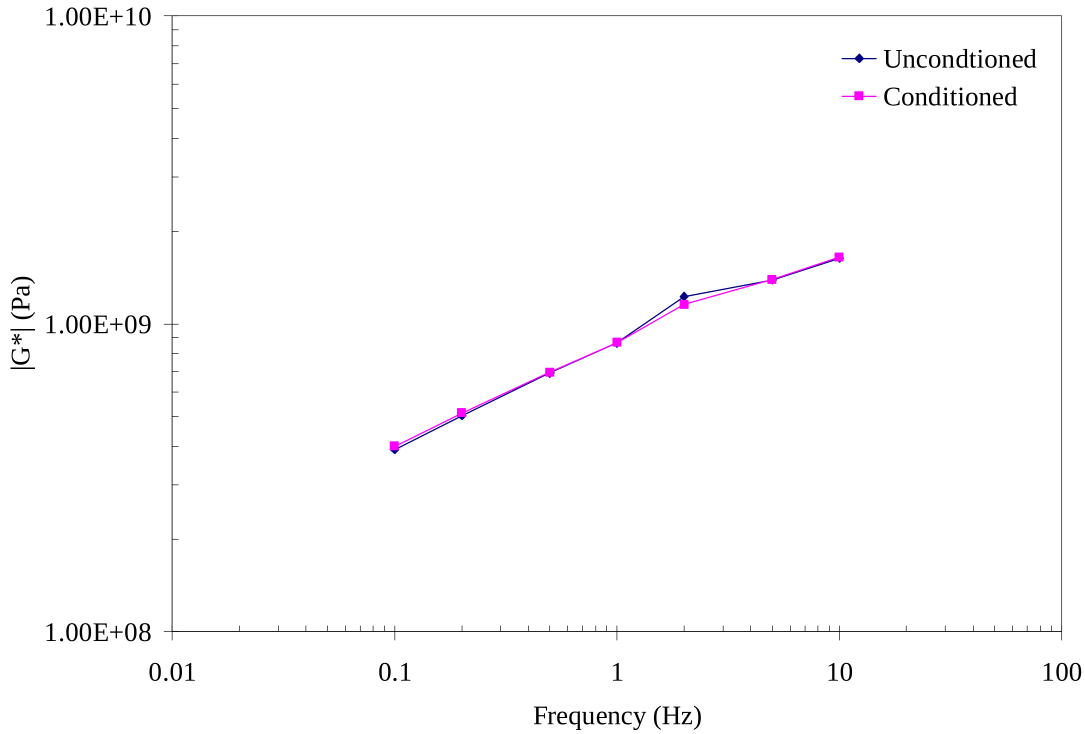

Figure 6.3 – Dynamic Shear Modulus vs. Frequency: 5.5% Boone BHF, 1% Lime, @20°C

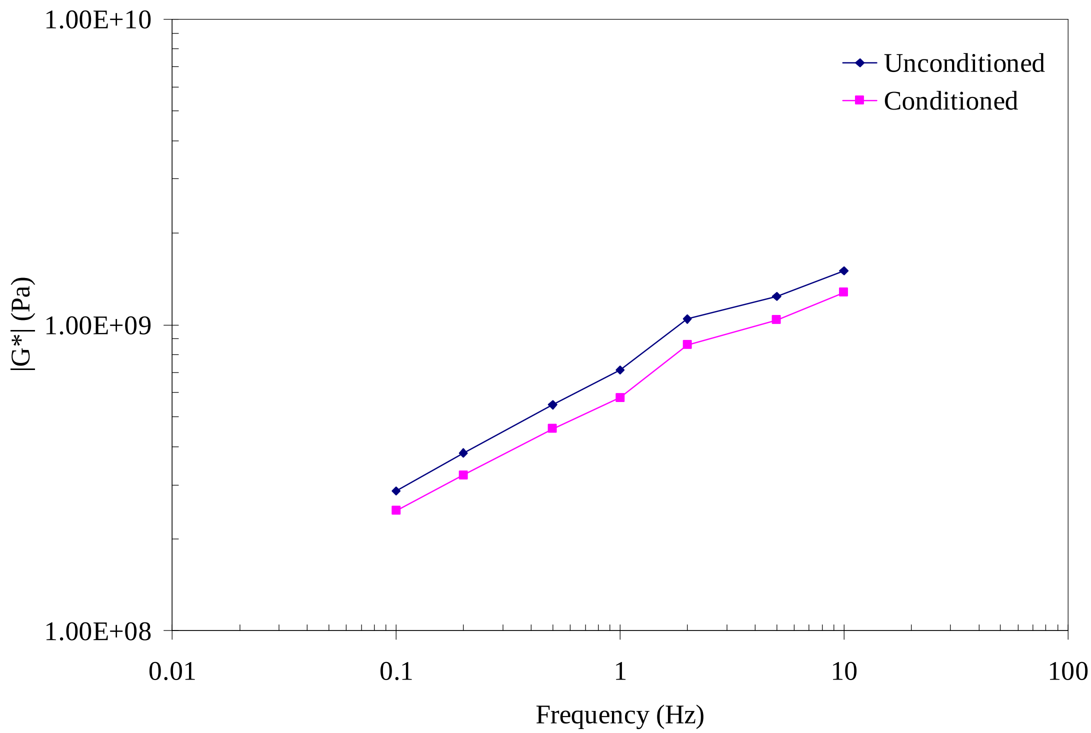

Figure 6.4 – Dynamic Shear Modulus vs. Frequency: 1.5% Enka BHF, 0% Lime, @20°C

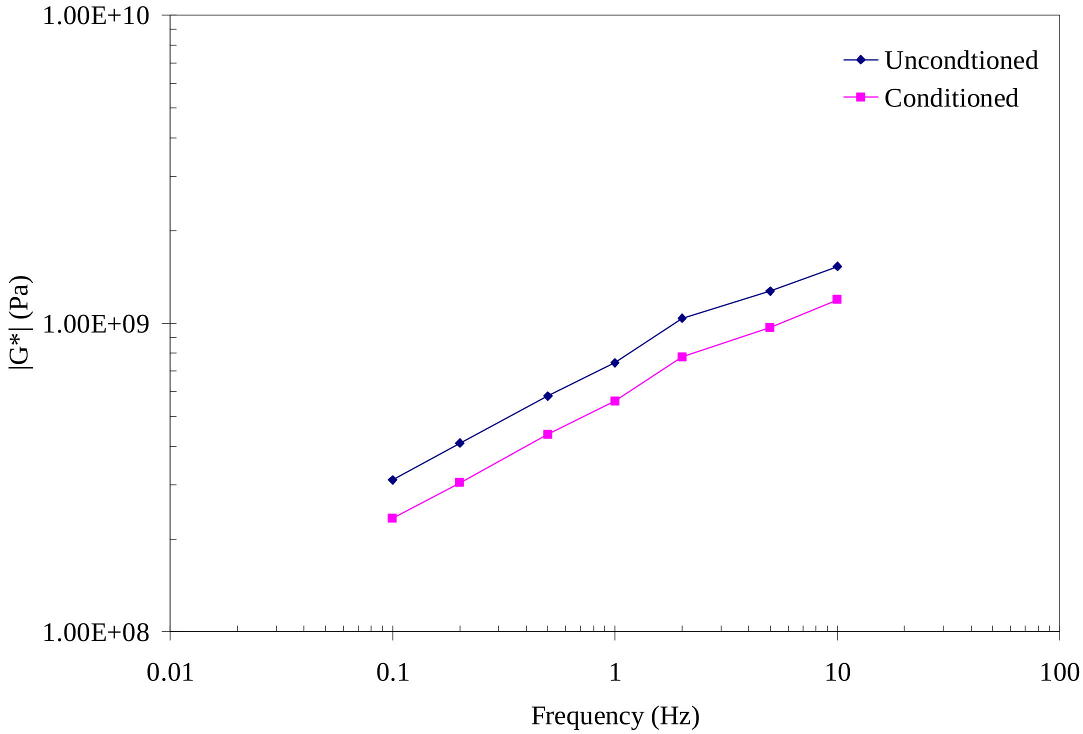

Figure 6.5 – Dynamic Shear Modulus vs. Frequency: 6.5% Enka BHF, 0% Lime, @20°C

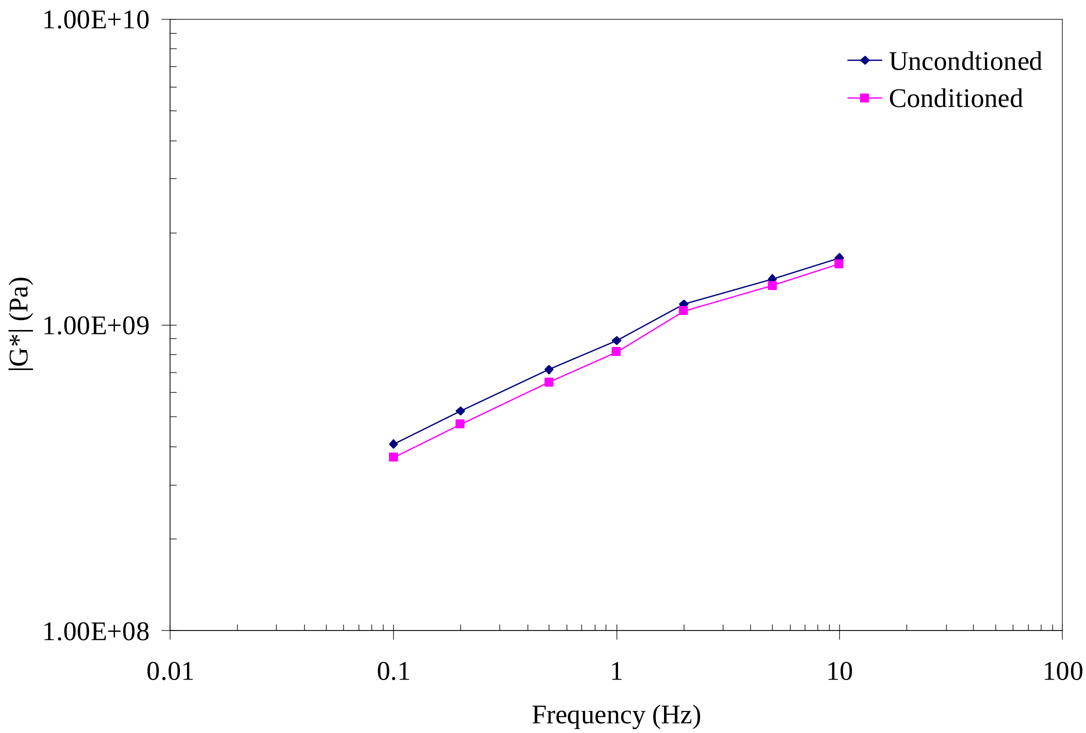

Figure 6.6 – Dynamic Shear Modulus vs. Frequency: 5.5% Enka BHF, 1% Lime, @20°C

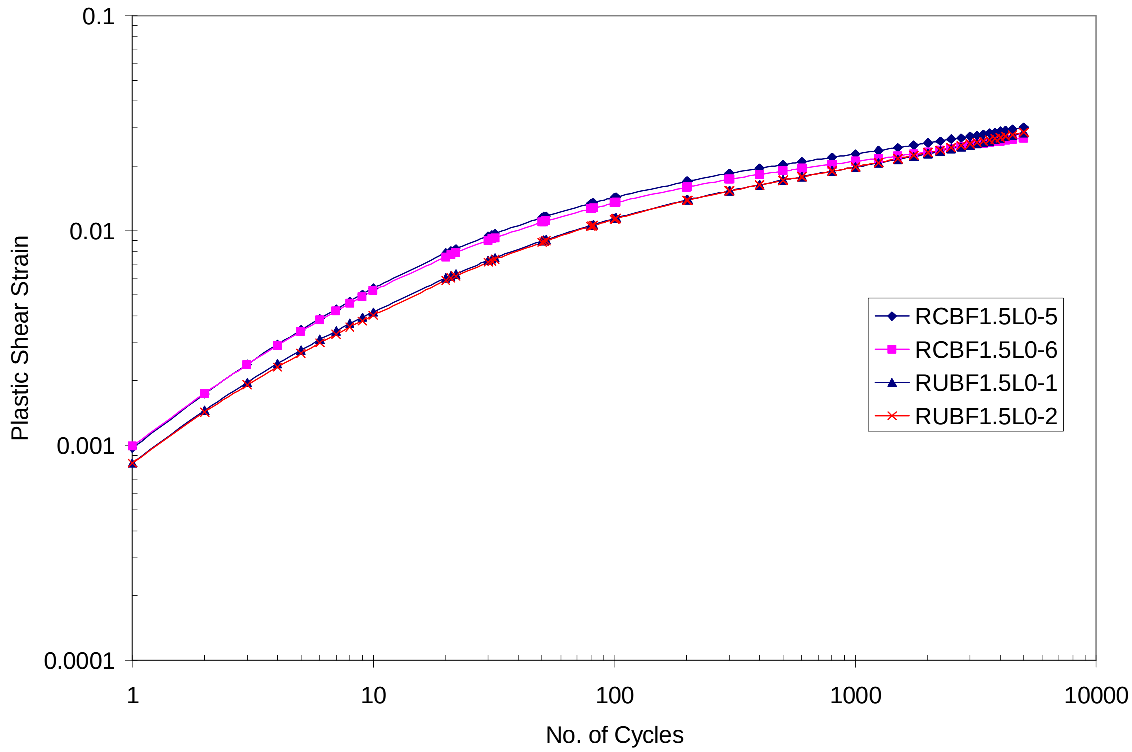

Figure 6.7 – Plastic Shear Strain vs. Number of Cycles; 1.5% Boone BHF, 0% Lime

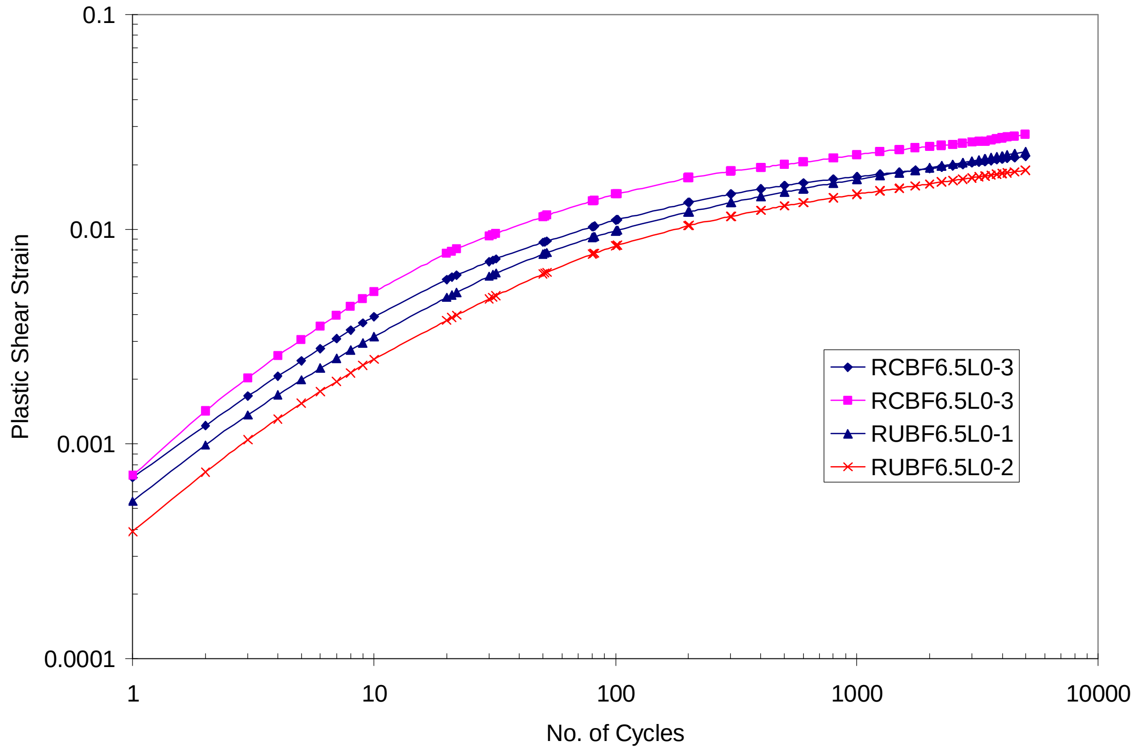

Figure 6.8 – Plastic Shear Strain vs. Number of Cycles; 6.5% Boone BHF, 0% Lime

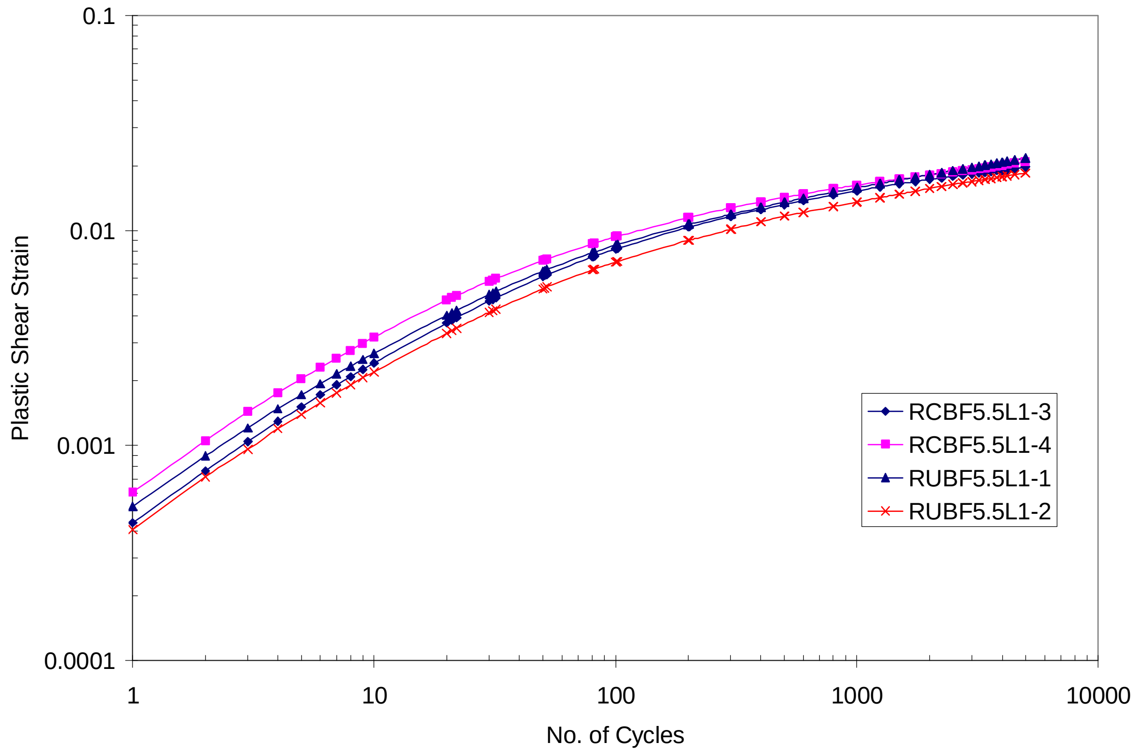

Figure 6.9 – Plastic Shear Strain vs. Number of Cycles; 5.5% Boone BHF, 1% Lime

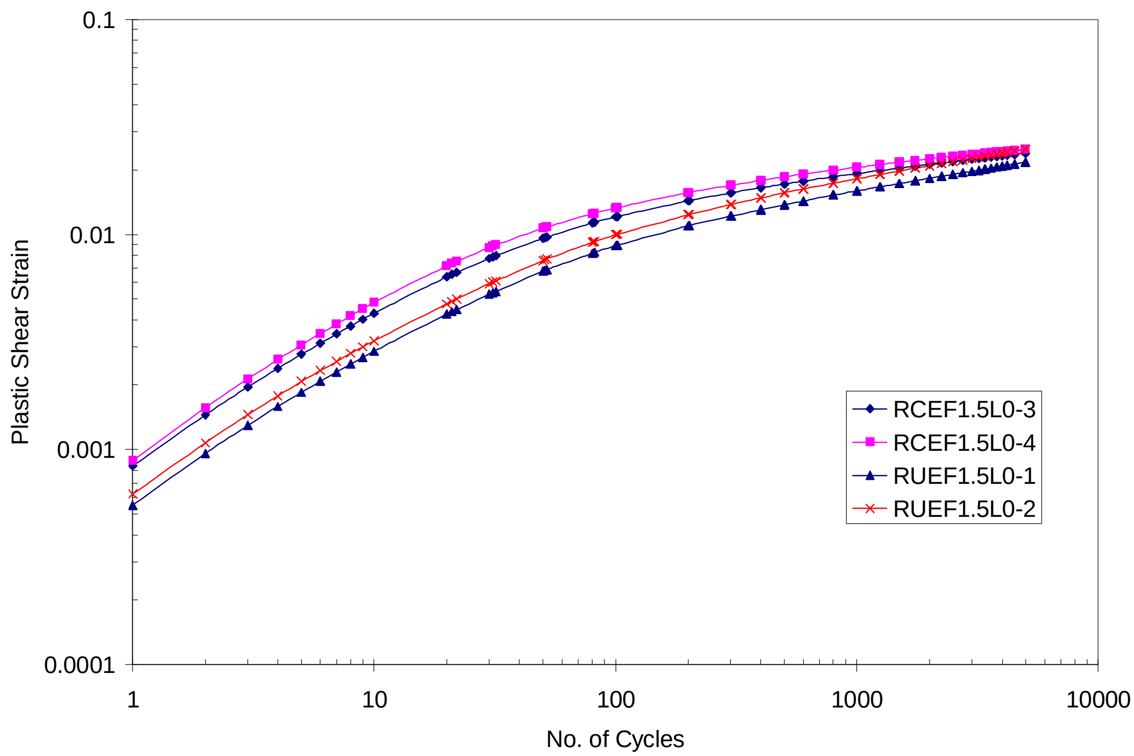

Figure 6.10 – Plastic Shear Strain vs. Number of Cycles; 1.5% Enka BHF, 0% Lime

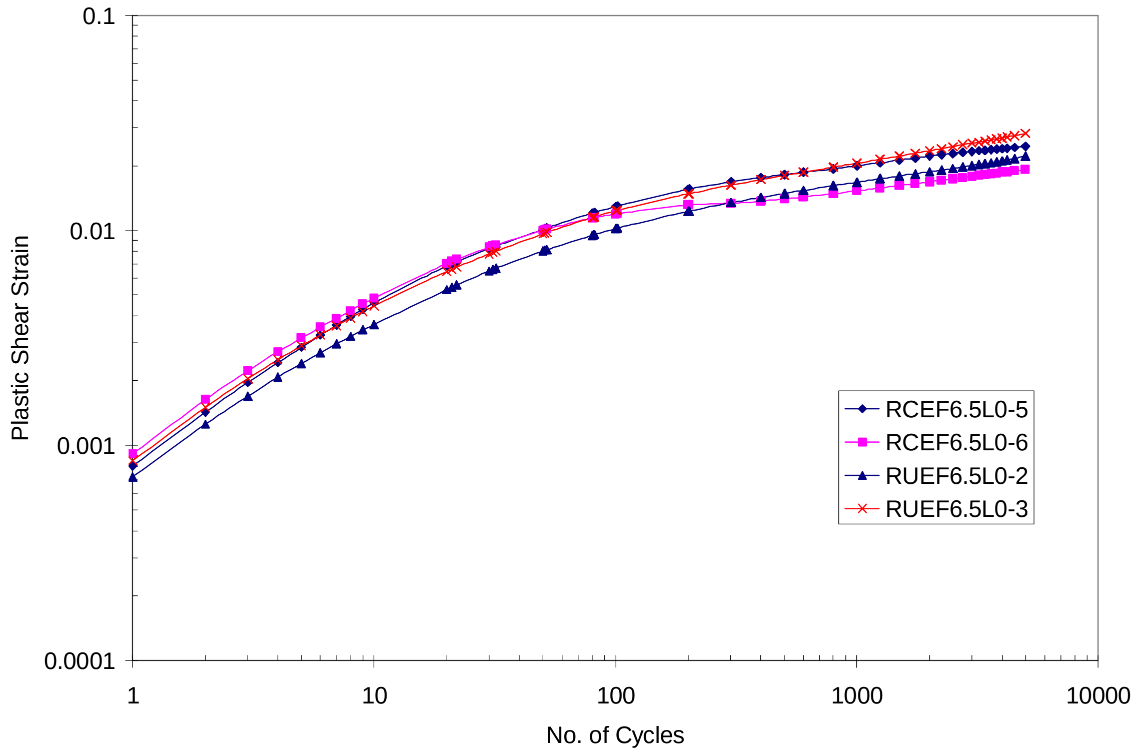

Figure 6.11 – Plastic Shear Strain vs. Number of Cycles; 6.5% Enka BHF, 0% Lime

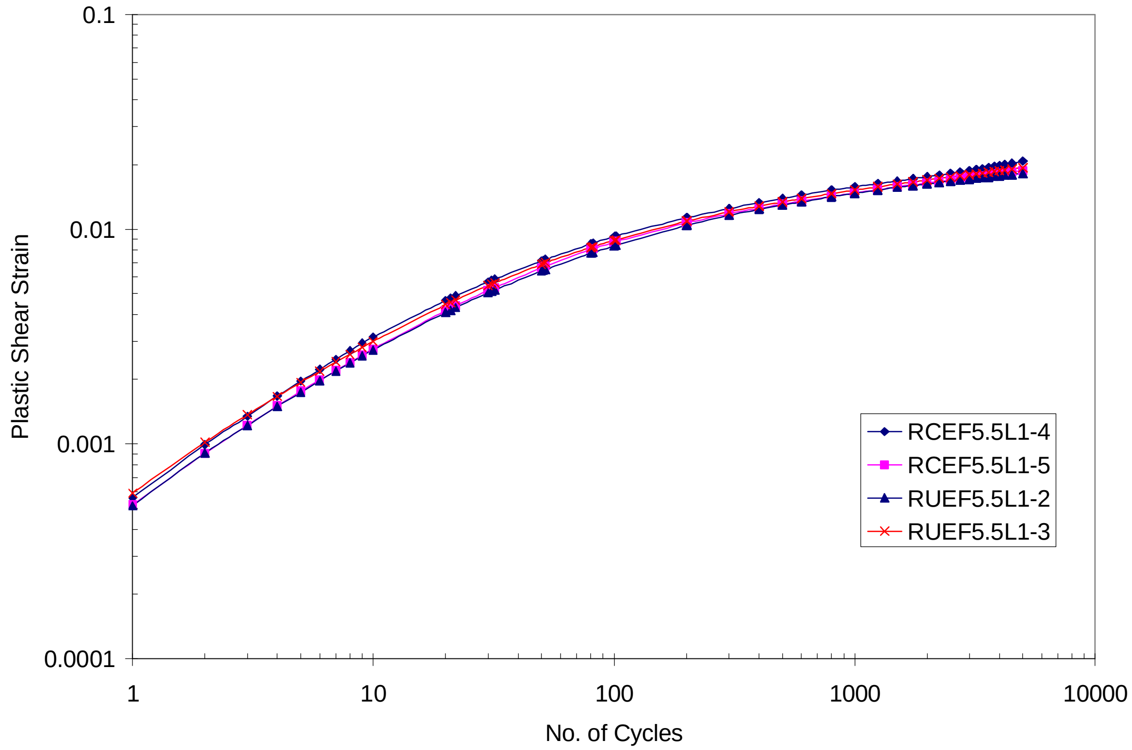

Figure 6.12 – Plastic Shear Strain vs. Number of Cycles; 5.5% Enka BHF, 1% Lime

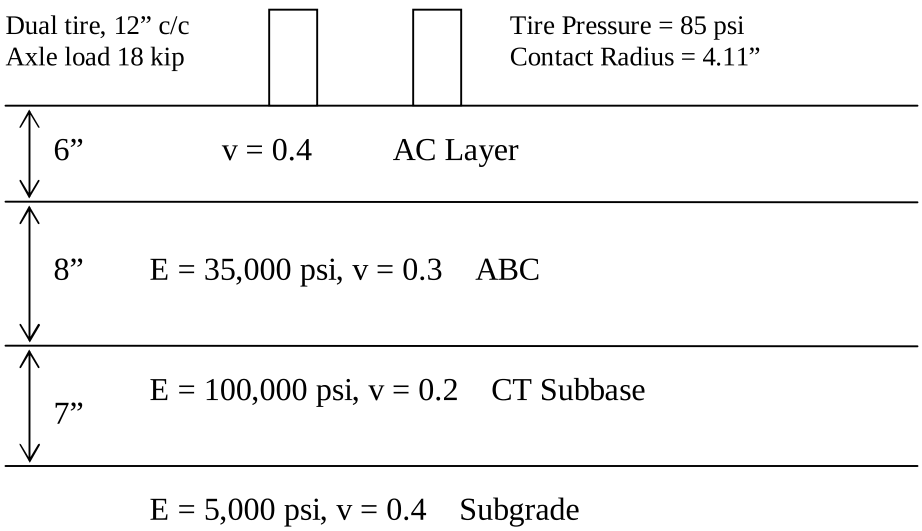

Figure 6.13 – Typical Pavement Section Used for Fatigue Analysis

7. COMPARISON OF ANTI-STRIP EFFECTIVENESS BETWEEN LIME AND AN ORGANIC LIQUID (LOF 6500)

7.1 Introduction

In this study, lime was used as anti-strip additive in NCDOT mixes containing excess Boone and Enka baghouse fines. Previous NCDOT Research Report FHWA/NC/2003-04 (Tayebali et al [15]) outlines a study conducted using same materials as in this study where amine-based organic liquid anti-strip additive LOF 6500 was used. It is therefore prudent to compare the results of this study where lime was used as anti-strip additive with the results of previous study where LOF 6500 anti-strip additive was used.

It may be noted that there are some differences in the baghouse fines content for mixes used in this study compared to the previous study. Because lime is considered mineral filler, in this study, the maximum amount of Boone or Enka baghouse fines used was 5.5%. Together with the lime content of 1%, the maximum mineral filler content was 6.5%. In the previous study using LOF 6500 the amount of Boone and Enka fines used in the mixes was 6.5%

In this section, the results of the TSR, FSCH, and RSCH tests are compared for mixes containing lime versus mixes containing LOF 6500 as anti-strip additive.

7.2 TSR Test Results

Table 7.1 and Figure 7.1 show the comparison of TSR test results for mixes containing lime and LOF 6500 as anti-strip additives. The TSR tests for both this and the previous study were conducted by NCDOT Materials and Test Unit. The results indicate that mixes with excess Boone and Enka baghouse fines not containing any anti-strip additives fail the NCDOT requirement of minimum 85% TSR value, and are deemed to be prone to moisture damage. Both lime (1% by weight of dry aggregates) and LOF 6500 (0.5% by weight of asphalt binder) are effective as anti-strip additives and reduce the moisture susceptibility of mixes to an acceptable level based on the NCDOT criterion.

7.3 Comparison of Mix Performance with Lime and LOF 6500

Table 7.2 summarizes the average |G*| values for mixes containing lime and LOF 6500 as anti-strip additives. The |G*| values of mixes from this study are different than the previous study containing LOF 6500. This is probably due to variability in materials and differences in gradation. Nevertheless, the results indicate that lime is very effective in reducing moisture sensitivity of mixes – minimal difference in |G*| values were found between unconditioned and moisture conditioned state. Moreover, lime seems to actually increase the absolute value of the average |G*| values.

Although the LOF 6500 anti-strip additive was found to reduce moisture sensitivity based on TSR test results, data in table 7.2 indicate that in general, mixes containing excess baghouse fines with LOF 6500 anti-strip additive still show a fair reduction in |G*| values between unconditioned and moisture conditioned mixes.

Similar results are also evident when comparison is made based on the rut depths presented in Table 7.3 and fatigue lives presented in Table 7.4.

The overall conclusion that can be derived based on the results presented is that addition of 1% hydrated lime as anti-strip additive appears to be more effective than

0.5% organic liquid anti-strip additive LOF 6500 for mitigating moisture sensitivity of mixes with excess baghouse fines.

Table 7.1 – Comparison of TSR Test Results, Lime vs. LOF 6500

Additive Type and Content	BHF Source	% BHF	TSR (%)	Pass/Fail (Min. 85%)
0% - Lime	Boone	6.5	63.3	Fail
0% - LOF 6500	Boone	6.5	48.4	Fail
0% - Lime	Enka	6.5	70.1	Fail
0% - LOF 6500	Enka	6.5	64.5	Fail
1% - Lime	Boone	5.5	85.7	Pass
0.5% - LOF 6500	Boone	6.5	90.4	Pass
1% - Lime	Enka	5.5	93.8	Pass
0.5% - LOF 6500	Enka	6.5	88.5	Pass

Table 7.2 – Comparison of Average |G*| Values, Lime vs. LOF 6500

Type of Mix		|G*| (MPa)			Air Void (%)
Boone BHF %	**Lime %**	**Unconditioned**	**Conditioned**	**Difference (%)**	
1.5	**0**	788	701	11.1%	6.5
6.5	**0**	841	689	18.1%	6.2
5.5	**1**	958	953	0.4%	6.3
Enka BHF %					
1.5	**0**	816	684	16.2%	6.3
6.5	**0**	841	639	24.0%	6.4
5.5	**1**	968	905	6.5%	6.3
Type of Mix		**|G*| (MPa)**			
Boone BHF %	**LOF %**	**Unconditioned**	**Conditioned**	**Difference (%)**	**Air Void (%)**
1.5	**0.5**	1540	1250	18.8%	6.2
6.5	**0.5**	2003	1100	45.1%	5.9
6.5	**0**	1260	1370	-8.7%	5.9
Enka BHF %					
1.5	**0.5**	1240	1190	4.0%	6.1
6.5	**0.5**	1590	1170	26.4%	6.1
6.5	**0**	1450	1230	15.2%	6.0

Table 7.3 – Comparison of Rut Depth, Lime vs. LOF 6500

Type of Mix		Plastic Shear Strain		Rut Depth (in)		% Difference
Boone BHF %	**Lime %**	**Dry**	**Wet**	**Dry**	**Wet**	
1.5	**0**	0.0186	0.0200	0.204	0.220	-7.9%
6.5	**0**	0.0142	0.0178	0.157	0.195	-24.8%
5.5	**1**	0.0133	0.0140	0.147	0.154	-5.0%
Enka BHF %						
1.5	**0**	0.0155	0.0178	0.171	0.195	-14.2%
6.5	**0**	0.0171	0.0161	0.188	0.177	5.8%
5.5	**1**	0.0133	0.0137	0.146	0.150	-3.1%
Type of Mix		**Plastic Shear Strain**		**Rut Depth (in)**		**% Difference**
Boone BHF %	**LOF %**	**Dry**	**Wet**	**Dry**	**Wet**	
1.5	**0.5**	0.0270	0.0281	0.30	0.31	-4.1%
6.5	**0.5**	0.0298	0.0472	0.33	0.52	-36.9%
6.5	**0**	0.0226	0.0325	0.25	0.36	-30.5%
Enka BHF %						
1.5	**0.5**	0.0268	0.0304	0.29	0.33	-11.8%
6.5	**0.5**	0.0206	0.0282	0.23	0.31	-19.9%
6.5	**0**	0.0255	0.0202	0.28	0.22	20.8%

Table 7.4 – Comparison of Fatigue Life, Lime vs. LOF 6500

Type of mix		No. of 18k ESAL's in millions		
Boone BHF %	**Lime %**	**Unconditioned**	**Conditioned**	**% Difference**
1.5	0	3.19	3.10	2.9%
6.5	0	3.48	3.12	10.3%
5.5	1	3.67	3.67	0.1%
Enka %				
1.5	0	3.44	3.03	11.9%
6.5	0	3.31	2.81	15.0%
5.5	1	3.68	3.55	3.4%
Type of mix		**No. of 18k ESAL's in millions**		
Boone BHF %	**LOF %**	**Unconditioned**	**Conditioned**	**% Difference**
1.5	0.5	2.39	3.05	-27.9%
6.5	0.5	2.67	2.59	2.8%
6.5	0	2.29	2.85	-24.7%
Enka BHF %				
1.5	0.5	2.79	2.62	6.2%
6.5	0.5	2.15	2.42	-12.7%
6.5	0	2.51	2.46	1.8%

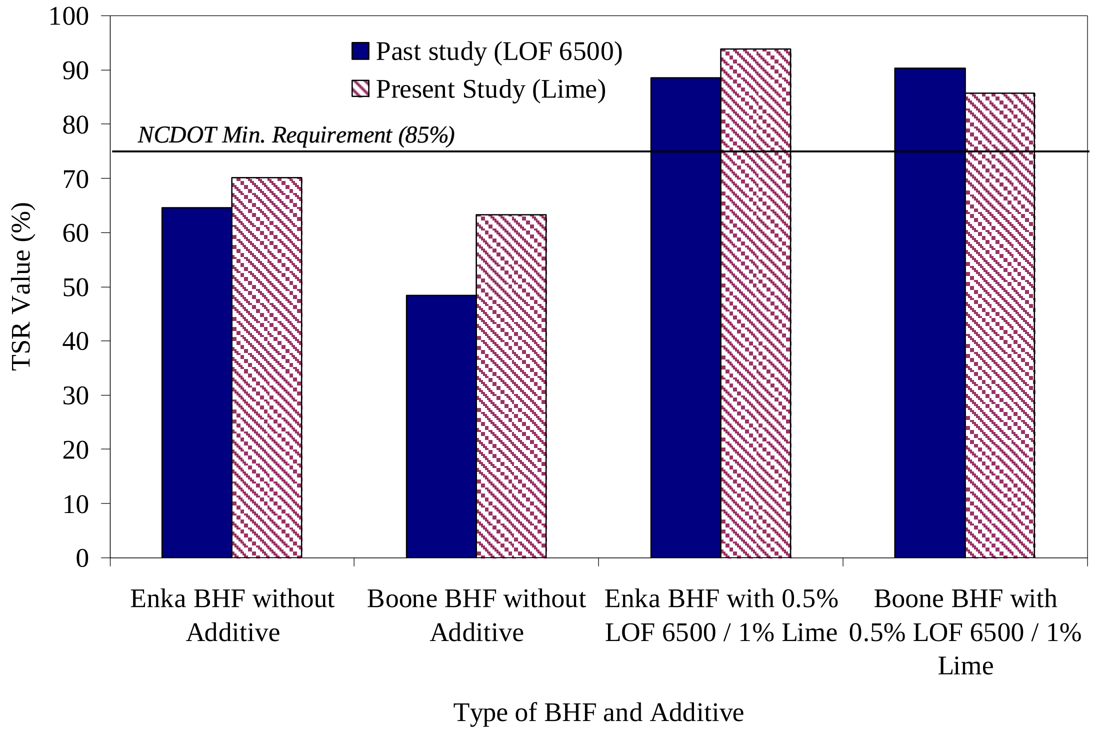

Figure 7.1 – Comparison of TSR Results of Past and Present Study

8. SUMMARY AND CONCLUSIONS

8.1 Summary

This study examines the effectiveness of hydrated lime as an anti-strip additive in mixes containing excess baghouse fines. A comparison between mixes containing hydrated lime and mixes containing organic anti-stripping additive (LOF 6500) was also conducted. Two different types of baghouse fines, one from Boone, NC, and one from Enka, NC, were used in HMA mixtures in different concentrations. Modifications were made to the available JMF and specimens were prepared in the laboratory and several different tests were performed.

Wet sieve analysis was first done to check the gradation of materials. Using this gradation and the available JMF, aggregate proportioning was done to satisfy NCDOT mix design criteria. Moisture susceptibility of mixes was determined by performing TSR tests on mixes with different proportions of BHF, and with or without lime. TSR testing showed that moisture susceptibility was dependant on both the concentration of baghouse fines and the presence of an anti-strip additive. The presence of hydrated lime in mixes increased the resistance to moisture damage.

Specimens were also tested using the SST machine. Samples were compacted and sawed and one half of the specimens were moisture conditioned. The FSCH and RSCH tests were then performed on the samples to determine the material properties as well as the rutting resistance and fatigue life. In general, the test results indicate that addition of lime enhances the mix performance: the values of $|G^*|$ are higher, rut depths are lower, and fatigue resistance is higher.

8.2 Conclusions

1. Baghouse fines, both type and concentration, influence mix behavior.
2. TSR test results indicate that 1-percent hydrated lime (by weight of dry aggregates) was an effective anti-strip additive for North Carolina mixes with excess baghouse fines used in this study.
3. The rutting resistance of the conditioned specimens was increased by the presence of hydrated lime.
4. HMA stiffness increased with an increase in baghouse fines contents and presence of hydrated lime.
5. Fatigue life of all mixtures increased with the addition of lime.

8.3 Recommendations

Based on the results of this study, the addition of 1-percent hydrated lime to asphalt mixtures with up to 5.5-percent additional BHF (for a total of 6.5-percent) enhances the mix performance. Addition of lime increases the resistance to stripping and reduces rutting. Stiffness of mixtures also increases by the addition of lime and there is an improvement in fatigue life. Addition of lime helped in the mitigation of moisture susceptibility of asphalt mixes. It is thus recommended that NCDOT should consider addition of 1-percent hydrated lime (by weight of dry aggregates) to mixes which are expected to have excess BHF content.

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Appendix A: Maymead Materials Job-Mix-Formula

REVISED 12-10-99

Maymead Materials, Inc.

Asphalt Design Laboratory
Mountain City, Tennessee

REPORT ON SUPERPAVE MIX DESIGN

MD# ________

DATE SUBMITTED:	1/5/0	DATE APPROVED:			
PROJECT NO.:	various	ASPHALT:	Shell Bristol	PG 64-22	
COUNTY:	Watauga	ADDITIVE:	ARR-MAZ	Ad-Here 6500 LOF	(.5 %)
CONTRACTOR:	Maymead Materials	Vulcan Materials	Boone	78-M Stone	
PLANT & NO.:	Boone S-725	Vulcan Materials	Morganton	Manufact. Sand	
DESIGNED BY:	Donald Greer	Vulcan Materials	Boone	Screenings	
SPECIFICATION:	S 9.5 B Surface Mix	Maymead Limstn.	Mountain City	Washed Scrgs	
GYRATIONS:	7/75/115 150 mm 141 °C				
TRAFFIC LEVEL:	< 3.0 Million ESALs				
AC SPECIFIC GRAVITY:	1.031				

GRADATION OF MATERIALS USED

MATERIAL	78m	Man/Sand	Screenings	Wash Scrgs		0	EgHsFines	Rap	BLEND	CONTROL POINTS
PERCENT (MD)	30.0	26.0	19.5	23.0		0.0	1.5	0.0	100.0	
PERCENT (JMF)	30.0	26.5	18.5	23.5		0.0	0.0	0.0	0.0	
Sieves(mm) 50.0	100.0	100.0	100.0	100.0			100.0		100	
37.5	100.0	100.0	100.0	100.0			100.0		100	
25.0	100.0	100.0	100.0	100.0			100.0		100	
19.0	100.0	100.0	100.0	100.0			100.0		100	
12.5	100.0	100.0	100.0	100.0			100.0		100	100.0
9.5	93.0	100.0	100.0	99.6			100.0		98	90.0 - 100.0
4.75	33.0	99.0	99.7	84.0			100.0		78	< 90.0
2.36	6.0	73.0	81.0	42.0			100.0		48	32.0 - 67.0
1.18	1.2	59.0	60.2	8.0			100.0		31	<31.6,>37.6
0.600	1.1	46.0	41.0	3.0			99.0		22	<23.5,>27.5
0.300	1.0	33.0	27.0	1.1			93.0		16	
0.150	0.9	13.0	18.0	0.7			76.0		8	
0.075	0.8	3.9	14.0	0.5			63.0		5.0	2.0 - 10.0
Ign. Furn. Corr.Factor	0.03	0.02	0.39	0.50					0.21	
Agg. Bulk Dry S.G.	2.685	2.841	2.701	2.621			2.737		2.706	
Agg. Apparent S.G.	2.715	2.885	2.727	2.691			2.737		2.749	
							Agg. Effective S.G.:		2.753	

Mix Properties at N design

	Nmax				
% Asphalt Binder-Total Mix	5.8	5.3	5.8	6.3	6.8
Gmb @ Ndes (or Nmax)	2.419	2.400	2.409	2.413	2.424
Max. Specific Gravity(Gmm)	2.510	2.529	2.510	2.491	2.472
% Voids-Total Mix (VTM)	3.6	5.1	4.0	3.1	1.9
% Solids-Total Mix	96.4	94.9	96.0	96.9	98.1
% Effective AC Content (Pbe)	5.1	4.6	5.1	5.6	6.1
Dust to AC Ratio (P0.075/Pbe)	0.98	1.09	0.98	0.89	0.82
% By Volume of Effective AC	12.0	10.7	11.9	13.1	14.3
% Solids by Vol. of Agg. Only	84.4	84.2	84.1	83.8	83.8
% Voids in Mineral Agg. (VMA)	15.6	16.0	16.1	16.4	16.5
% Voids Filled w/AC (VFA)	75.9	68.9	73.9	79.9	86.7
% Gmm @ Nini 7	88.6	86.0	86.7	87.4	88.4
% Gmm @ Ndes 75	95.2	94.9	96.0	96.9	98.1
% Gmm @ Nmax 115	96.4				

% RAP / % Virgin:	
% AC in RAP:	0.0
% AC from RAP:	0.0
% AC Absorption:	0.7
% ASH:	
TSR % Retained:	85.1
Ignition Furn. Calibr.:	0.21
% AC (Design):	
Bulk Specific Gravity:	
Max Specific Gravity:	
Percent Air Voids:	
Percent VMA:	
Percent VFA:	
DUST/AC Ratio:	0.97
% Gmm @ N initial:	
% Gmm @ N max:	
% AC TOTAL:	5.8
% AC from RAP:	
% AC ADDED:	

Sand Equivalent:	72.6
C. Agg. Angularity:	100/100
F. Agg. Angularity:	46.6
Flat & Elongated:	3.0

COMMENTS:
Add Baghouse to Screenings

DESIGNED BY:

APPROVAL:

Appendix B: FSCH Test Results

Table B-1 – Dynamic Shear Modulus versus Frequency; 1.5% Boone BHF, 0 % Lime

Frequency (Hz)	Shear Modulus, |G*|, (MPa)			
	Unconditioned		Conditioned	
	BF1.5L0-2	BF1.5L0-3	BF1.5L0-1	BF1.5L0-2
0.1	272	272	261	235
0.2	361	363	346	310
0.5	522	526	498	452
1	682	685	632	581
2	981	972	929	791
5	1210	1240	1120	1020
10	1460	1490	1380	1260
Average |G*|	**784**	**793**	**738**	**664**

Table B-2 – Phase Angle versus Frequency; 1.5% Boone BHF, 0 % Lime

Frequency (Hz)	Phase Angle, δ, (degree)			
	Unconditioned		Conditioned	
	BF1.5L0-2	BF1.5L0-3	BF1.5L0-1	BF1.5L0-2
0.1	45.1	45.0	43.8	44.1
0.2	44.5	44.5	43.2	44.0
0.5	42.1	42.2	40.2	41.2
1	39.2	39.8	39.5	38.3
2	34.4	32.5	34.7	34.0
5	30.3	30.2	30.0	30.9
10	27.2	27.3	27.0	27.6
Average δ	**37.5**	**37.3**	**36.9**	**37.1**

Table B-3 – Dynamic Shear Modulus versus Frequency; 6.5% Boone BHF, 0 % Lime

Frequency (Hz)	Shear Modulus, |G*|, (MPa)			
	Unconditioned		Conditioned	
	BF6.5L0-1	BF6.5L0-2	BF6.5L0-1	BF6.5L0-2
0.1	319	308	249	262
0.2	418	405	325	341
0.5	588	577	462	480
1	755	742	577	639
2	1070	1020	796	892
5	1260	1280	1010	1060
10	1500	1530	1230	1320
Average |G*|	**844**	**837**	**664**	**713**

Table B-4 – Phase Angle versus Frequency; 6.5% Boone BHF, 0 % Lime

Frequency (Hz)	Phase Angle, δ, (degree)			
	Unconditioned		Conditioned	
	BF6.5L0-1	BF6.5L0-2	BF6.5L0-1	BF6.5L0-2
0.1	42.8	43.9	42.4	42.4
0.2	41.8	42.6	41.5	41.2
0.5	38.6	40.3	39.5	38.8
1	36.1	37.8	37.8	36.6
2	31.6	34.2	33.5	33.1
5	27.2	29.0	28.8	28.9
10	24.4	26.6	26.4	26.2
Average δ	**34.6**	**36.4**	**35.7**	**35.3**

Table B-5 – Dynamic Shear Modulus versus Frequency; 5.5% Boone BHF, 1 % Lime

Frequency (Hz)	Shear Modulus, |G*|, (MPa)			
	Unconditioned		Conditioned	
	BF5.5L1-1	BF5.5L1-2	BF5.5L1-3	BF5.5L1-4
0.1	341	439	426	375
0.2	445	563	539	487
0.5	615	771	728	666
1	777	956	897	840
2	1100	1350	1200	1110
5	1280	1500	1460	1330
10	1500	1770	1650	1640
Average |G*|	**865**	**1050**	**986**	**921**

Table B-6 – Phase Angle versus Frequency; 5.5% Boone BHF, 1 % Lime

Frequency (Hz)	Phase Angle, δ, (degree)			
	Unconditioned		Conditioned	
	BF5.5L1-1	BF5.5L1-2	BF5.5L1-3	BF5.5L1-4
0.1	42.1	40.2	38.2	41.3
0.2	40.6	38.6	37.5	39.9
0.5	37.6	35.2	34.5	36.8
1	35.0	32.5	31.8	34.5
2	29.7	25.7	27.0	32.8
5	26.0	23.6	24.6	25.9
10	23.4	22.2	21.9	24.5
Average δ	**33.5**	**31.2**	**30.8**	**33.7**

Table B-7 – Dynamic Shear Modulus versus Frequency; 1.5% Enka BHF, 0 % Lime

Frequency (Hz)	Shear Modulus, |G*|, (MPa)			
	Unconditioned		Conditioned	
	EF1.5L0-1	EF1.5L0-2	EF1.5L0-5	EF1.5L0-6
0.1	279	293	234	260
0.2	373	390	309	335
0.5	540	556	447	469
1	705	718	551	606
2	1050	1040	853	868
5	1240	1240	1020	1060
10	1510	1490	1240	1320
Average |G*|	**814**	**818**	**665**	**703**

Table B-8 – Phase Angle versus Frequency; 1.5% Enka BHF, 0 % Lime

Frequency (Hz)	Phase Angle, δ, (degree)			
	Unconditioned		Conditioned	
	EF1.5L0-1	EF1.5L0-2	EF1.5L0-5	EF1.5L0-6
0.1	45.6	44.6	44.2	41.8
0.2	44.6	43.3	44.3	42.1
0.5	42.2	40.5	43.8	40.7
1	39.2	37.8	37.6	39.3
2	32.8	33.4	33.9	34.9
5	29.7	28.5	30.8	30.6
10	26.7	25.7	27.7	27.5
Average δ	**37.3**	**36.2**	**37.5**	**36.7**

Table B-9 – Dynamic Shear Modulus versus Frequency; 6.5% Enka BHF, 0 % Lime

Frequency (Hz)	Shear Modulus, |G*|, (MPa)			
	Unconditioned		Conditioned	
	EF6.5L0-1	EF6.5L0-2	EF6.5L0-3	EF6.5L0-4
0.1	328	293	238	228
0.2	430	389	309	299
0.5	610	551	445	426
1	777	711	562	555
2	1050	1030	807	750
5	1300	1240	984	951
10	1560	1500	1220	1170
Average |G*|	**865**	**816**	**652**	**626**

Table B-10 – Phase Angle versus Frequency; 6.5% Enka BHF, 0 % Lime

Frequency (Hz)	Phase Angle, δ, (degree)			
	Unconditioned		Conditioned	
	EF6.5L0-1	EF6.5L0-2	EF6.5L0-3	EF6.5L0-4
0.1	43.7	44.6	42.0	43.2
0.2	42.3	43.3	41.6	42.6
0.5	39.0	40.2	39.9	41.8
1	36.6	38.4	39.2	38.0
2	33.6	36.2	35.7	33.6
5	27.8	28.4	30.1	30.7
10	26.7	26.8	27.5	27.8
Average δ	**35.7**	**36.8**	**36.6**	**36.8**

Table B-11 – Dynamic Shear Modulus versus Frequency; 5.5% Enka BHF, 1 % Lime

Frequency (Hz)	Shear Modulus, |G*|, (MPa)			
	Unconditioned		Conditioned	
	EF5.5L1-1	EF5.5L1-2	EF5.5L1-4	EF5.5L1-5
0.1	440	376	370	367
0.2	561	485	476	471
0.5	766	663	657	641
1	954	827	832	802
2	1270	1070	1140	1080
5	1520	1310	1390	1290
10	1770	1540	1640	1520
Average |G*|	**1040**	**896**	**929**	**882**

Table B-12 – Phase Angle versus Frequency; 6.5% Enka BHF, 0 % Lime

Frequency (Hz)	Phase Angle, δ, (degree)			
	Unconditioned		Conditioned	
	EF5.5L1-1	EF5.5L1-2	EF5.5L1-4	EF5.5L1-5
0.1	40.2	40.7	41.4	39.8
0.2	38.7	39.3	40.3	38.4
0.5	35.4	36.0	37.4	35.7
1	32.5	32.8	34.7	33.0
2	27.6	27.2	29.5	29.8
5	23.9	23.9	26.8	25.2
10	21.7	22.2	24.3	23.3
Average δ	**31.4**	**31.7**	**33.5**	**32.2**