FINAL REPORT

RESEARCH PROJECT 2002-08

Effect of Percentage Baghouse Fines on the Amount and Type of Anti-Stripping Agent Required to Control Moisture Sensitivity

by

Akhtarhusein A. Tayebali, Ph.D., P.E.

W. Kevin Fischer

Y. X. Huang

M. B. Kulkarni

June 30, 2003

Department of Civil Engineering

North Carolina State University

Technical Report Documentation Page

1. Report No. FHWA/NC/2003-04	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Effect of Percentage Baghouse Fines on the Amount and Type of Anti-Stripping Agent required to control Moisture Sensitivity.		5. Report Date June 30, 2003 6. Performing Organization Code
7. Author(s) A. A. Tayebali, W. K. Fischer, Y. X. Huang, M. B. Kulkarni		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering North Carolina State University Raleigh, NC 27695-7908		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Analysis Group 1 South Wilmington Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report 7/01/2002-3/31/2003 14. Sponsoring Agency Code 2002-08
15. Supplementary Notes:		

16. Abstract

This study investigated the effect of moisture and amount of baghouse fines on AC mixes. Two types of baghouse fines, each with a different gradation, were used in varying concentrations to prepare laboratory samples. The binder used was PG64-22 and the anti-strip additive used was LOF 6500.

TSR (AASHTO T283) test results showed a reduction in retained strength for specimens without additive as compared to the specimens containing additive showing the effectiveness of the additive in preventing the moisture damage. Mixes with highest amount of baghouse fines showed resistance to moisture damage in presence of the anti-strip additive. However, absence of additive reduced the strength ratio considerably to the point that these mixes would be unacceptable under current NCDOT criterion.

The mix performance was evaluated using the SST machine to determine the rutting and fatigue characteristics of the mixes. In general, it was observed that moisture conditioning reduced rutting and fatigue resistance of the mixes considerably, although, the TSR test result showed that an LOF-6500 anti-strip dosage of 0.5% was sufficient to reduce moisture damage to the point that the mixes would be acceptable under the current NCDOT criterion of 85% retained strength.

17. Key Words baghouse fines, anti-strip additive, LOF 6500, fatigue, asphalt pavement analyzer, repeated shear test, frequency sweep, rutting, moisture sensitivity	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 120	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Disclaimer

The contents of this report reflect the views and opinions of the authors 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.

Acknowledgements

The authors extend sincere appreciation to the authorities of the North Carolina Department of Transportation (NCDOT) for funding this project as well as performing laboratory tests. Thanks to Mr. Chris Bacchi, who was instrumental in coordinating the testing at NCDOT Material and Testing Unit.

Thanks are also due to National Center for Asphalt Technology (NCAT) for their help in conducting the particle analysis for the baghouse fines.

Executive Summary

In this study, the effects of baghouse fines concentrations on moisture sensitivity of asphalt mixes were determined for mixes with and without anti-strip additive. Two different types of baghouse fines, one from Boone, NC and one from Enka, NC, were used in HMA mixtures in different concentrations. Anti-strip additive used was LOF-6500. Using a JMF and materials provided by NCDOT, specimens were prepared in the laboratory and several different tests were performed.

Sieve analysis and particle analysis were used to produce gradations for aggregate mixtures with different baghouse fines. TSR testing was conducted to determine the severity of moisture damage due to concentrations of baghouse fines. The TSR testing was also conducted on specimens without anti-strip additive to determine the effectiveness of the additive. The TSR tests showed that the concentration of baghouse fines had a slight effect on moisture susceptibility while the anti-strip additive had a profound effect in preventing moisture damage.

In order to determine the effects of conditioning on rutting resistance, APA testing was performed on the specimens. Samples were tested dry as well as conditioned and the rut depth results were compared. Due to testing differences, the dry values were not comparable to the conditioned specimens. The results showed an increase in permanent deformation (rut depth) in the specimens without additive for both baghouse fines types.

Finally, specimens were tested using the SST machine to determine mix performance characteristics for rutting and fatigue. In general, it was observed that moisture conditioning reduced rutting resistance and fatigue resistance of the mixes.

Although, the TSR test result showed that an LOF-6500 anti-strip dosage of 0.5% was sufficient to reduce moisture damage to the point that the mixes would be acceptable under the current NCDOT criterion of 85% retained strength, the FSCH and RSCH test results indicated that severe damage will be prevalent in mixes, especially those with high percentage of BHF. The FSCH and RSCH test results indicate that in general, moisture conditioning will lead to reduction in stiffness, rutting resistance, and fatigue resistance.

Based on the results of this study, it is recommended that NCDOT should seriously reconsider the current practice by asphalt mix plants to purge baghouse fines intermittently into the mix. As the results in this study have shown, this practice will produce mixes with highly variable material properties and moisture sensitivity. At the least, the baghouse fines should be metered into the mix. However, it may be desirable to waste some of these fines completely as is the practice by several state departments of transportations.

TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

NOTATIONS

AASHTO	American Association of State Highway Transportation Officials
AC	asphalt cement
APA	Asphalt Pavement Analyzer
ASTM	American Society of Testing Materials
BHF	baghouse fines
DSR	dynamic shear rheometer
ESAL	equivalent single axle load
F/A	ratio of fines to asphalt, by volume
FSCH	frequency sweep at constant height
HMA	hot mix asphalt
ITS	indirect tensile strength
LVDT	Linear variable differential transformer
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

1. BACKGROUND

1.1 Introduction

In order to expand and maintain the immense road infrastructure in the US, between 450 and 500 million tons of hot-mix-asphalt is produced annually [15]. This asphalt concrete is produced in approximately 3600 asphalt plants throughout the country. With such a large number of plants, variability of materials and methods produces mixes with unique properties.

One variable aspect of asphalt concrete production is the collection and use of fine particulate matter carried in plant exhaust gases. Asphalt plants use large drums and hot air to dry aggregate before mixing. This air blast carries away a fraction of the smallest aggregate particles. These particles pose environmental and health problems if released into the atmosphere. Currently collection systems are used to remove the fine material before the exhaust gas is released into the air.

One of these collection systems is the baghouse. It consists of filters that trap the airborne fines and collect the fines, which are known as baghouse fines. These fines can then be wasted or recycled back into the mix. A majority of asphalt plants reintroduce baghouse fines, and there are many methods for reintroduction. Many plants do not meter these fines and intermittently purge them back into the mix, which leads to concentrations of baghouse fines in the mix.

Many transportation materials designers and agencies have noted that the use of baghouse fines accelerates pavement deterioration and moisture damage. For this reason some agencies require the waste of all baghouse fines while others require a controlled addition of the fines. Many studies have been performed on the contribution of baghouse fines to the performance of asphalt binder and asphalt concrete. Variability in the properties of the baghouse fines makes general conclusions and guidelines difficult to draw.

Moisture sensitivity in asphalt pavements can lead to performance problems and should be minimized by designers. Some evidence has shown that the introduction of the finely graded baghouse fines can increase asphalt mix moisture susceptibility. However, an increase in stiffness with the addition of baghouse fines is a positive.

Most asphalt plants are required to use anti-strip additives to reduce the moisture sensitivity of the asphalt concrete. These additives work with both the aggregates and binder to increase the adhesion between aggregate and asphalt and reduce the attraction between water and aggregate to prevent the stripping of asphalt by water.

This project involved the evaluation of laboratory mixes for moisture susceptibility. Some of the mixes were made with excess quantities of baghouse fines to simulate the intermittent reintroduction of the fines into the mixes. The effectiveness of an anti-strip additive was also determined by producing samples with and without the additive.

1.2 Objectives and Scope

The objective of this study was to determine the effects baghouse fines have on asphalt concrete mixtures. The study also addressed the effectiveness of anti-strip additives in preventing moisture damage.

In order to find the effects of the baghouse fines on material properties, different percentages of fines were used. The mixes were made in accordance with materials and job-mix-formula provided by NCDOT. The first step was the evaluation of baghouse fines on the moisture susceptibility of the mixes. This included a determination of the effectiveness of the anti-strip additive. The second step was to evaluate the effect of baghouse fines on the rutting resistance of both dry and moisture-conditioned mixes. The final step was to determine the effect of baghouse fines on the performance properties of the asphalt pavement.

There were five tasks involved in this study. The first was a verification of the job-mix-formula and volumetric properties of the mix. This was performed with gradation analyses, particle analyses for the baghouse fines, and volumetric analyses. Two types of fines were used, at various concentrations, and with different anti-strip additive contents, to produce the samples in the laboratory. The second task was the evaluation of moisture susceptibility with the Tensile Strength Ratio (TSR) test. The third task involved the determination of rutting resistance of conditioned and unconditioned specimens using the Asphalt Pavement Analyzer (APA) test. Finally, the mix performance of dry and conditioned samples was evaluated using the Frequency Sweep at Constant Height (FSCH) and Repeated Shear at Constant Height (RSCH) tests in the fourth task. The data was analyzed in the fifth task.

1.3 Significance

The ability to predict and prevent moisture damage in asphalt pavement is of great importance to the North Carolina Department of Transportation (NCDOT). A poorly performing pavement will be costly to repair and drivers will be inconvenienced with poor ride quality. A previous project was performed addressing the concerns of NCDOT with pavement distress [11] in western North Carolina. That project looked at the improper use of tack coats as well as the improper use of baghouse fines. In that study it was determined that baghouse fines had some effect on the moisture sensitivity, but the extent was not determined. This research further investigates the contribution of baghouse fines to asphalt concrete behavior as well as evaluates the effectiveness of additives in negating any moisture susceptibility.

The following chapter is an overview of all the previous research in the effects of baghouse fines and additives. Chapter 3 details the research approach and the methods used in each step of the project. Chapter 4 deals with the verification of the job-mix-formula and necessary adjustments. The evaluation of the moisture sensitivity of the different asphalt concrete mixes is discussed in Chapter 5 while Chapter 6 deals with the rutting resistance in the APA testing. Chapter 7 details the mix performance using the FSCH and RSCH tests to determine mixture properties for pavement performance in rutting and fatigue. Finally, Chapter 8 provides a summary as well as future recommendations.

2. LITERATURE REVIEW

The purpose of the present study is to determine the effect baghouse fines have on the properties of hot-mix-asphalt (HMA). These properties include moisture sensitivity, rutting and fatigue resistance, and strength among others. This chapter presents previous research conducted in all areas of this project and will present a body of knowledge to build conclusions on.

2.1 Definition of Baghouse Fines

The production of asphalt concrete involves several steps at the mixing plant. The aggregate is first batched and then dried. The aggregate is dried using drums with hot gas passing over the aggregate to heat the aggregate for mixing as well as remove excess moisture. During this drying process, fine particulate matter in the aggregate mix gets airborne. Collection systems are used to remove the fines from the exhaust stream. These fines are often reintroduced into the mix and, due to the fineness of the material, may have an effect on the mixture properties. The next sections will discuss the various aspects of these fines.

2.1.1 Fines Collection Systems

In order to prevent the release of fine dust into the air, many asphalt plants have installed collection systems to remove the fines from the exhaust gas. There are many different types of collection systems used in HMA plants including cyclones, knockout boxes, baghouses, and wet scrubbers. The cyclones and knockout boxes are known as primary collectors while the baghouses and wet scrubbers are secondary collectors. Often the exhaust gases are filtered through a combination of primary and secondary collectors.

Primary collectors operate by reducing the speed of the exhaust gases. The reduction of air speed causes the coarser particles to fall out of suspension. Knockout boxes increase the cross sectional area, which reduces air speed. In cyclone systems, the exhaust gas is forced to spin inside the cyclone. The heavier particles are forced to the outside of the chamber and slowed by friction until they slide down into a collection bin. When a primary collector is used, the baghouse fines are finer and have a more consistent gradation [5].

Secondary systems are used to remove material down to 1μm from the exhaust gases. The two systems used for this process are wet-scrubbers and baghouses. Studies have shown that secondary systems are 99 percent efficient in filtering particles larger than 10μm while they are only 75 percent efficient in removing particles 1μm and smaller [6]. Wet-scrubbers inundate the fine particles with water droplets and the heavy particles fall from the air stream. The resulting slurry of water and fines is often sent to a settling pond. The downside of this method is the wasting of the fines as well as environmental impacts.

Baghouse systems consist of a chamber with a series of very fine mesh filters, which remove the fine particles from the exhaust as it passes through the filter. As the fines build on the bags they cake which increases the efficiency of the system by reducing the spaces in the filter. If left uncleaned, however, the cake would restrict all airflow. For this reason the filters must be cleaned by pulsing at specified intervals. The fine cake is either blown off with a reverse pulse of air or the filter is stretched to remove the cake. As the cake is removed, the fines fall into a storage bin and can be returned to the mix. This process allows for the more efficient use of materials because the fines are not wasted.

2.1.2 Variability of Baghouse Fines

The composition of the baghouse fines varies depending on the type of plant, aggregate type, and the configuration of the collection system. There are two types of plants: batch plants and drum plants. The two plants differ in the method of mixing as well as exhaust gas velocity. Batch plants have exhaust gas velocities around 800 fpm while drum plants often have velocities of 1000 fpm or more [6]. With a higher velocity, more and larger particles will be picked up by the airstream. The type of aggregate also affects the baghouse fines according to the dust content. Natural aggregates may be covered with clay that will be picked up during drying. Mixes with large fractions of fine material may also increase the baghouse fines collection and change the gradation as well.

Exhaust systems containing primary and secondary collectors will produce different gradations from a system with only secondary collectors. The primary collectors remove the larger particles from the gas, which produces a finer gradation of baghouse fines. Anderson and Tarris [3] suggested that the gradation variability is mainly related to the coarser fines. This suggests that the more efficient the primary collector, the more uniform the gradation of baghouse fines. There is still variability in baghouse fines gradations between plants as well as within a plants day-to day operation. In a study conducted by Eick [5], five different plants provided baghouse fines samples with widely scattered gradations. Since the gradation of fines for different plants is inconsistent, job-mix-formulae (JMF) will be unique for each plant.

2.1.3 Recycling of Baghouse Fines

Another concern that arises in this process is how the fines are reintroduced into the mix. Fines may be wasted, as with the wet scrubbers, or reintroduced to the mix. Environmental concerns have led a majority of plants to recycle baghouse fines. The fines must, however, be returned to the aggregate in a uniform manner. This can be accomplished by storing the fines in bins and metering, or even weighing them, into the mix. Figure 2.1 [15] shows layouts of the two types of plants and the methods of baghouse fines reintroduction. If the material is not metered into the mix, surges can produce large changes in the concentration of baghouse fines in the mix. This can lead to changes in the mix composition and performance, which will be addressed later in this chapter.

2.2 Definition of Mineral Filler

The two constituent parts that make up HMA are asphalt cement and mineral aggregate. A further breakdown of the mineral aggregate produces three categories: coarse aggregate, fine aggregate, and mineral filler. Coarse aggregate is defined as the fraction of aggregate retained on the #4 sieve and higher. Fine aggregate is then classified as the material passing the #8 sieve.

There is no universal definition, however, for mineral filler. ASTM D242 [2] defines mineral filler as: *"Mineral filler shall consist of finely divided mineral matter such as rock dust, slag dust, hydrated lime, hydraulic binder, fly ash, loess, or other suitable mineral matter."* Baghouse fines are acceptable as mineral fillers by this definition. This definition is too broad, however, and does not provide criteria to determine the suitability of the filler.

Tunnicliff [13] tried to define mineral fillers in terms of what is filled, what does the filling, and why the filling is done. One definition he provided was: *"Filler is that portion of the mineral aggregate generally passing the 200 sieve and occupying void spaces between the coarser aggregate particles in order to reduce the size of these voids and increase the density and stability of the mass."* In this definition the filler reduces the voids as well as increases the stability and is composed of material passing the #200 sieve. Another definition given is: *"Filler is the mineral material that is in colloidal suspension in the asphalt cement and results in a cement with a stiffer consistency."* The filler in this definition is in the asphalt mastic and stiffens the asphalt as well.

Another definition was proposed by Tunnicliff [14] in 1967. He proposed that filler is the portion of aggregate that passes the #200 sieve, will perform satisfactorily in the presence of moisture, and has, through experience, been deemed to produce successful pavements. Therefore, mineral filler must not contribute to the moisture damage of the asphalt pavement.

Puzinauskas [10] provided another mineral filler definition as follows:

> *"Mineral fillers play a dual role in paving mixtures. First, they are a part of the mineral aggregate – they fill the interstices and provide contact points between larger aggregate particles and thereby strengthen the mixture. Second, when mixed with the asphalt, mineral fillers form a high-consistency binder or matrix which cements larger aggregate particles together."*

This definition combines the two points that Tunnicliff expressed separately. It describes the dual nature of the mineral filler in asphalt concrete.

All of the definitions of mineral fillers allow baghouse fines to be classified as filler. The effects of baghouse fines on asphalt cement and asphalt concrete will be discussed in following sections. Baghouse fines must also not contribute to stripping or other moisture damage in asphalt pavement. Moisture susceptibility of asphalt concrete with baghouse fines will be discussed in this chapter and is an objective in this research project.

2.3 Effects of Baghouse Fines

It has been shown that mineral fillers can increase the stiffness of both the asphalt cement as well as the asphalt pavement. Baghouse fines, a constituent of the mineral filler, also affects both the asphalt cement and the HMA performances, depending on the particle size distribution. Baghouse fines interact with the asphalt cement as an extender as well as a stiffener. In asphalt concrete the fines fill the spaces between the larger aggregates producing a stiffer mix, which can lead to compaction problems. The following sections discuss these issues further.

2.3.1 Asphalt Cement – Fines Interaction

The properties of the asphalt used in HMA mixes are altered by the addition of baghouse fines. As filler is added to the asphalt cement, the binder becomes stiffer and its properties can be affected. The creation of an asphalt-filler mastic is referred to in Tunnicliff's definition as a colloidal suspension. Many tests have been run on the properties of asphalt cement containing mineral filler such as baghouse fines. These tests include viscosity, softening point, and penetration tests as well as Dynamic Shear Rheometer (DSR) testing.

Anderson [3] performed a study on the behavior of the asphalt-filler mastic using the penetration, softening point and ductility. He used five filler/asphalt (F/A) ratios and five different types of filler. These F/A ratios are calculated by volume of material to allow for comparison between filler types. As expected, he found the penetration to decrease with an increase in the F/A ratio. He also found the softening point and viscosities increased with an increasing F/A ratio. The results showed a large increase in the viscosity at an F/A ratio of 0.4. This F/A ratio is lower than those found in many HMA mixtures. The much higher viscosity can affect the compactibility of the HMA [3] and require more compactive effort or higher compaction temperatures.

Eick [5] also performed viscosity testing on baghouse fines and asphalt binder mastics. His results show a correlation between viscosity ratio and fineness of the baghouse fines. He performed viscosity tests on mastics as well as neat asphalt with no filler. The two values were used to find a viscosity ratio for each F/A ratio. The results showed increasing viscosity ratios as the F/A ratio increased. The results also showed a correlation between the fineness of the baghouse fines and the viscosity ratio. As the percent of baghouse fines material passing the #200 sieve increased, the viscosity ratio also increased.

Tayebali [11] conducted DSR testing on asphalt mastics containing baghouse fines. Samples of virgin PG 64-22 asphalt as well as mastics containing 50 percent baghouse fines or mineral filler were tested. The results showed an increase in stiffness and rut resistance of the mastics over the asphalt binder. An increase in stiffness was also observed in one of the baghouse fines mastics over the regular mineral filler.

An important concept that illustrates the fine-asphalt interaction is the fractional voids. Figure 2.2 [6] graphically describes the fractional voids concept. If a filler sample is dry-compacted to its maximum density, the internal voids will be at a minimum. This condition is represented by V_{ds} in the figure. If a volume of asphalt is added to the dust, the amount of asphalt required to fill these voids is considered fixed asphalt while the remaining asphalt is free asphalt, V_{af}. The total volume of fines and fixed asphalt is the bulk volume of compacted dust, V_{db}. These values show that as the percent bulk volume of fines increases, the percent free asphalt decreases and the mortar becomes stiffer.

2.3.2 Influence on Mixture Properties

The introduction of baghouse fines to HMA mixes produces a profound affect on the in-place properties of the pavement. The thickness of the asphalt film on the aggregate in HMA is between 9 to 25 microns [3], depending on the type of mixture. The addition of baghouse fines to the binder acts as an asphalt extender if the fines are of sufficient fineness. For baghouse fines with a significant fraction finer than 25 microns, the particles will become embedded in the asphalt film and increase the effective asphalt volume. This is known as asphalt extension. In a study by Anderson [3], the results showed an increase in the flow values with an increase in F/A ratio. His explanation was a lubricating, or extending, of the asphalt by the fine particles. The increased effective asphalt volume counteracted the stiffening effect of the increased filler content. If, however, the fines are coarse they will protrude through the film and increase the required asphalt content as well as the voids in mineral aggregate (VMA) [17]. This will in turn stiffen the mix as well as provide a greater potential for stripping.

Tunnicliff's [13] definition of mineral filler, discussed previously, states that filler reduces the voids between aggregates. The contact increases aggregate interlock, which increases the Marshall stability and flow values [5]. A result of the increased stiffness is the possibility of compaction difficulties. Compactive effort is related to the binder viscosity, which has been shown to increase with the addition of filler. Kandhal [8] suggests that there is a relation between bulk volume of fines in the mix and resistance to compaction. This relation is straightforward since as bulk volume increases, free binder decreases, decreasing the flow. Using the Ridgen voids test, the bulk volume of fines is determined. If the value is below 50 percent, the HMA mixture is acceptable. If, however, the bulk volume is greater than 50 percent, a softening point test is used to determine the suitability of the HMA mixture.

The increased effort leads to compaction problems and higher in-situ air voids, which increase the stripping potential. This in turn can lead to raveling, bleeding, or shoving of asphalt mixes. If excess fines are added, the mix can become tender and rutting or shoving may occur. If, however, too less fines are added, the pavement may have high voids and raveling may be observed.

2.4 Moisture Sensitivity in HMA

Many highway departments have reported problems, such as raveling, shoving, delamination, and cracking, related to moisture damage [7]. This moisture damage is called stripping and occurs when the asphalt film surrounding the aggregate is "stripped" by the water in the pavement. The main cause of this stripping is the higher affinity for water over asphalt in the aggregate. If the moisture penetrates the asphalt film it will displace the asphalt film and weaken the pavement. Moisture damage occurs due to loss of cohesion or adhesion and aggregate degradation. Stripping is caused by the loss of cohesion and adhesion and will be discussed.

2.4.1 Adhesion and Cohesion Loss

The loss of bond between the asphalt binder and the aggregate is adhesion loss. There are four theories, which together explain the adhesion of asphalt to aggregate. They are: the Mechanical Theory, the Chemical Reaction Theory, the Surface Energy Theory, and the Molecular Orientation Theory. The chemical theory is applicable to acidic aggregates having a greater tendency to strip [7]. An acidic aggregate may reduce the chemical reaction on the aggregate surface, reducing adhesion.

The surface energy theory is based on the wettability of the aggregate by the asphalt and is dependent on the viscosity and surface tension of the asphalt. Water has a lower viscosity and surface tension than asphalt, which increases water's wettability of the aggregate. The molecular orientation theory deals with the polarity of the water molecule. Water is a polar molecule while asphalt is nonpolar. The charged surface of the aggregate will then have a greater affinity for water molecules.

The mechanical theory is based on the shape, texture, and several other physical attributes of the aggregate. Rough shaped and porous aggregates provide more surface area for bonding as well as increased aggregate interlock. Surface dust and moisture will affect asphalt adhesion. If the surface is dusty or moist before mixing, the asphalt will not bond as well to the aggregate.

Cohesion is the bond developed throughout the asphalt concrete by the asphalt cement. Loss of cohesion is primarily evident in the softening of asphalt in the pavement. The viscosity of the asphalt and the asphalt-fines mastic determine the susceptibility for cohesion loss. Both cohesion and adhesion loss are closely related and contribute simultaneously to stripping in asphalt concrete.

2.4.2 Moisture Sensitivity Testing

The most widely used testing method for determining the moisture susceptibility of asphalt pavement is AASHTO T-283 or Modified Lottman Test. This test is performed on sets of six to eight specimens compacted to 7±1 percent air-voids. Half of the specimens are saturated to between 50 and 80 percent. An indirect tensile strength (ITS) test is performed on the specimens and an average for each subset is used to find the tensile strength ratio (TSR). The TSR is the ratio of moisture conditioned strength to dry strength. A minimum value is set to determine the acceptable moisture damage. The NCDOT minimum value is 85 percent retained strength.

Much research has been reported on the effects of baghouse fines on moisture susceptibility. Tayebali [11] performed TSR tests on specimen sets using two different mixes. A set was made of each mix as well as sets with baghouse fines replacing the mineral filler. All sets contained an anti-strip additive. The results showed the two sets with mineral filler passed the TSR test while the sets with baghouse fines were below the minimum value. Another test by Hanson [6] performed TSR testing on thirty different sets with different fine types, asphalt types, and F/A ratios. Using the NCDOT requirement of 85 percent, none of the sets passed.

Kandhal [8] carried out moisture susceptibility testing using the Asphalt Institute Water Sensitivity Test and the Idaho Test. The Asphalt Institute test follows the AASHTO test while the Idaho test includes a freeze-plus-soak cycle. Specimens were prepared using ten different baghouse fines at fine-asphalt ratios of 0.3 and 0.5. Kandhal [8] used a minimum TSR value of 50 percent and four fines types failed. Using the NCDOT criteria of 85 percent, only Portland cement passed the TSR testing. These results show a connection between baghouse fines and moisture damage.

2.5 Prevention of Moisture Damage

2.5.1 Types of Anti-Strip Additives

In order to reduce pavement damage related to stripping, additives are used to decrease moisture susceptibility. There are two types of anti-strip additives used in HMA production: hydrated lime and liquid surfactants. The hydrated lime is applied to the aggregates before mixing in several different ways. The lime can be added as a dry powder to wet or dry aggregates or as a slurry to the aggregates which are then dried before mixing. Lime is typically added to the aggregates at 1 percent of the aggregate weight. Lime increases the adhesion between asphalt and aggregates through different chemical reactions. The increase in adhesion reduces stripping, providing a more durable pavement.

Liquid surfactants reduce the surface tension of the asphalt, allowing for greater adhesion between the asphalt and aggregate. Due to the increased affinity and wettability of the asphalt for the aggregate, moisture stripping is reduced. Liquid amines and liquid phosphate ester are the two types of anti-strip additives used in HMA. They are mixed with the asphalt prior to mixing at a dosage of about 0.5 to 1 percent of the asphalt weight. Unlike the application of the hydrated lime, the liquid additives can be mixed with large amounts of asphalt and stored for use before mixing. These advantages save time and money by using less material and not affecting the production process greatly. A disadvantage of the liquid surfactants is possible heat degradation [4]. If the asphalt mixture is held at high temperature for long periods of time, the effectiveness may be reduced. Also, it has to be added uniformly and mixed consistently throughout the asphalt cement.

2.5.2 Studies of Additive Effectiveness

Previous studies have been conducted on the subject of moisture sensitivity and anti-strip additives. Birdsall performed a study using three different aggregates and three different additives as well as a control set without additives. The results showed significant increases in the tensile strength and the TSR values with the use of lime, amine, and ester [4]. Another test showed an increase of tensile strength as the fraction of baghouse fines increased. The fines were sampled from an asphalt plant using lime to treat the aggregate. A portion of the lime escapes in the exhaust gas and is retained in the baghouse fines, which are reintroduced into the mix [6]. The addition of lime as an anti-strip additive in the baghouse fines outweighs the detrimental effects of baghouse fines on moisture susceptibility.

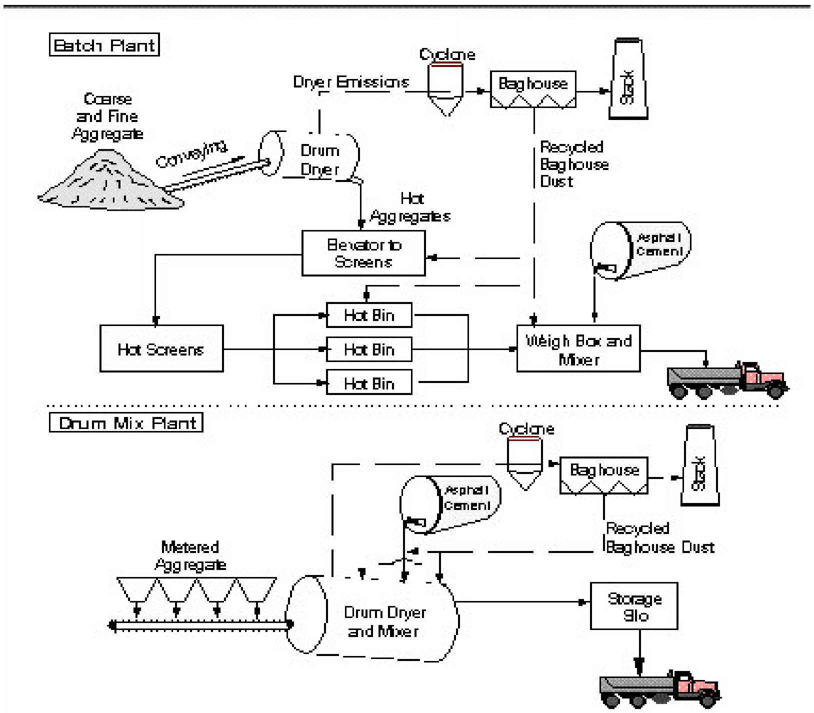


Figure 2.1 – Batch Plant and Drum Mix Plant Layouts [14]

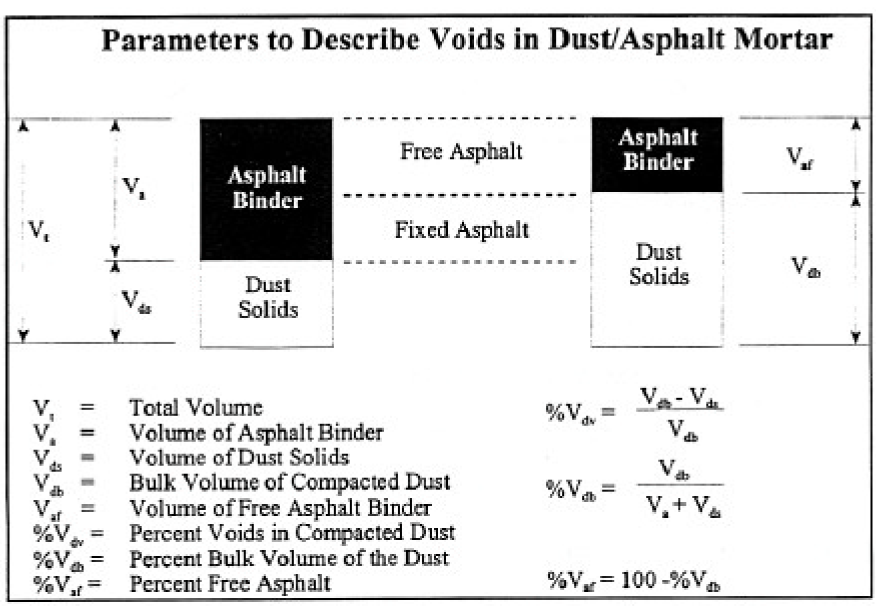


Figure 2.2 – Fractional Voids in Dust/Asphalt System [6]

3. RESEARCH APPROACH AND METHODOLOGY

3.1 Introduction

Previous testing performed for NCDOT [11] demonstrated moisture susceptibility in asphalt pavement containing baghouse fines. These fines were purged into the mix producing large changes in the mix composition and performance. Further testing was necessary to determine the extent of the moisture damage as well as effective additives to prevent stripping. Using a job mix formula (JMF) provided by NCDOT, 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 and anti-strip additive.

The research approach is outlined in a flow chart that details each individual step. This flowchart is shown in Figure 3.1. Each step will be discussed in the following sections.

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 the damage, JMFs and materials were provided by NCDOT from plants in this area. Two types of baghouse fines, one from a plant in Boone (NCDOT Division 11) and another from Buncombe County (NCDOT Division 13), were supplied. Sieve analysis and particle analysis were performed to determine the gradation of the baghouse fines. Next, the resulting gradation and volumetric properties from the JMF were verified. Batching was adjusted slightly to provide a gradation within acceptable limits.

3.2.2 Moisture Susceptibility Testing

The test performed by NCDOT for moisture sensitivity is a modified AASHTO T-283. The freeze/thaw cycle is removed from the testing and each subset contains 8 specimens. The specimens are required to be 150 mm in diameter and 95 mm tall with an air-void content of 7±1 percent. Several sets, each with different fines and anti-strip additive content, were prepared in the lab using a Superpave™ gyratory compactor (SGC). After the air void percentage 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 Asphalt Pavement Analyzer Testing

Specimens were prepared using a gyratory compactor and the air void percentages were measured. The sets were then delivered to NCDOT where the Asphalt Pavement Analyzer (APA) testing was performed. Each set contained eight samples, half of which were moisture conditioned. The samples were 150 mm in diameter and 75 mm in height with an air-void content of 7±0.5 percent. The tests were run on two samples at a time and the maximum rut depth was recorded. An average rut depth was then calculated for comparison between subsets and specifications.

3.2.4 Specimen Shear Testing

The final testing was the frequency sweep (FSCH) and repeated shear (RSCH) testing on the Superpave™ Shear Testing (SST) apparatus. 150 mm diameter specimens were compacted in the SGC to a height of 127 mm and sawed to the specified height of 50 mm. The air-void range for the cut specimens was reduced to 6.3±0.5 percent. Each set consisted of four samples with two conditioned and two dry specimens. A FSCH test was run on each specimen to determine the shear modulus, $|G^*|$, and the phase angle, δ, at various frequencies. These values were used to determine the fatigue resistance of the mixes. The RSCH test was subsequently run and the plastic shear strain was determined. From these values comparisons were drawn on the effects 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 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 [12] provided the steps in the determination of the testing temperature. The area falls within climate zone IC with maximum air temperatures between 35 and 38°C. The pavement depth chosen corresponded to the interface layer at approximately 33 mm. These values were used for the SHRPBIND program.

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

$$T_d = T_{surf} * (1-0.063*d + 0..007*d^2 – 0.0004*d^3) \qquad (3.2)$$

Where T_{surf}, T_{air}, and T_d are the temperatures, in degree celcius, 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 both 50°C as well as 20°C. The fatigue life comparison was done at 20°C using the FSCH test results.

3.4 Specimen Nomenclature

In order to keep track of the large number of samples produced and tested throughout this project, the following specimen designation system was developed. The names of the subsets had 4 characters describing the test type, percentage baghouse fines (BHF), type of BHF, and type and quantity of anti-strip additive. A list of the terms and meanings follows:

First Character – Testing type
- A – Asphalt Pavement Analyzer test
- S – Simple Shear Testing

T – TSR test

Second Character – Percentage of Baghouse Fines
0 – no additional BHF added to the mix
2 – 2 percent additional BHF added to the mix
5 – 5 percent additional BHF added to the mix

Third Character – Type of Baghouse Fines
A – (Maymead) Boone BHF
B – Enka BHF

Fourth Character – Type and Percentage of Anti-Strip Additive
0 – 0.5 percent, Ad-Here 6500 LOF
1 – no additive used

Additional numbers follow these characters to distinguish samples within a set. Finally, the characters ‘U’ and ‘C’ were used to denote whether the samples were unconditioned or moisture conditioned respectively. Some tables and figures will refer to the specimens with these designations.

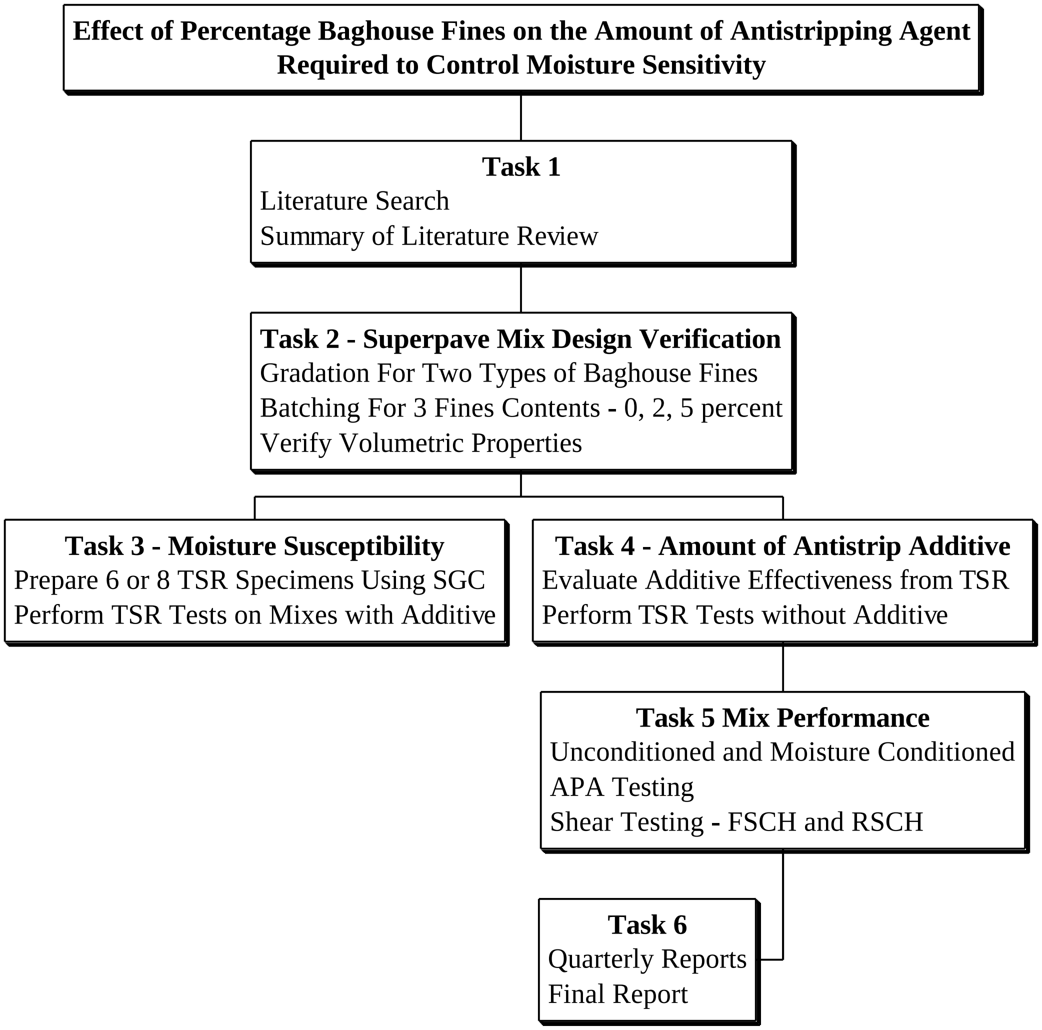


Figure 3.1 – Summary of Research Approach and Methodology

4. EVALUATION OF MATERIAL AND JOB-MIX-FORMULA

4.1 Introduction

This investigation was motivated by the pavement distress observed by NCDOT in western North Carolina. Previous studies have pointed to moisture damage, related to the unmetered introduction of baghouse fines into mixes, as a factor in this distress. Therefore, the materials needed for HMA production, asphalt, aggregates, baghouse fines, and additives, were provided from plants in that area. A JMF was also provided for the laboratory production of HMA that is indicated in Appendix B.

4.2 Baghouse Fines

Two different baghouse fines samples were used in this study. One sample was from a Maymead Materials plant in Boone (NCDOT Division 11), North Carolina and the other was from a plant in Enka (NCDOT Division 13), North Carolina. In order to determine the gradation of the two samples, a wet sieve analysis was performed in accordance with ASTM – C117 [2]. The material was wet sieved on the #16 and #200 sieves. Unlike typical wet sieve procedure, the water and the aggregate passing the #200 sieve was retained. The fines-water slurry was dried in an oven and the fine aggregate was collected for further analysis.

The aggregate retained on the #16 and #200 sieves was dried and sieved as well following the ASTM C-136 [2] method. Figure 4.1 shows the gradation of the Boone and Enka baghouse fine material that was retained on the #200 sieve. Both fines show similar gradations from the #30 to the #200 sieves. The Enka fines are slightly finer than the Boone sample over this range.

The fines passing the #200 sieve were sent to the National Center for Asphalt Technology (NCAT) in Auburn, Alabama for fine particle analysis. Using the Coulter Particle Size Analyzer, two trials were performed for each fine and an average gradation was determined. A mixture of water and 1 percent sodium hexametaphosphate was used to create a suspension of the baghouse fines. Light was passed through the sample and optical sensors detected the intensity. When the intensity data is compared to a measurement of the fluid with no fine material present, a particle distribution is generated.

The particle distributions give the gradation of the fines in suspension. The Boone and Enka gradations are shown in Figure 4.2 and more detailed graphs are shown in Appendix A. From the graph it is evident that the Boone baghouse fines are finer than the Enka fines. The mean particle size for the Boone and Enka fines is 29.4 μm and 32.4 μm respectively. The Boone fines are about 7-8% finer than the Enka fines at the 20-micron level. The 20-micron level is important because it is the upper level of thickness for the asphalt film. Particles below this size are likely to get embedded in the asphalt film and act as asphalt extenders.

4.3 Job-Mix-Formula Evaluation and Revision

4.3.1 Gradation Analysis

The next step was the implementation of the job-mix-formula (JMF) provided by NCDOT. A copy of the original JMF provided by NCDOT is attached as Appendix B. The JMF had batching percentages for the four aggregate constituents, baghouse fines, asphalt and anti-strip additive. The aggregate fractions were 30 percent 78-M stone, 26 percent manufactured sand, 19.5 percent dry screenings, and 23 percent washed screenings. The Maymead Boone baghouse fines accounted for 1.5 percent of the aggregate weight.

The aggregates were first combined using the JMF batching and a wet sieve analysis was performed. The aggregates were washed over the #16 and #200 sieves to remove the material passing the #200 sieve. The remaining aggregate was dried and sieved and a gradation was plotted. The mass lost in the wet sieving was added to the mass of the material passing the #200 sieve in this gradation. Two trials produced gradations similar to the given JMF gradation, however, the experimental gradation passed through the restricted zone. After several adjustments to the batching, an acceptable gradation, which passed below the restricted zone, was produced. The new batching data is presented in Table 4.1 and the final gradation and that of the experimental JMF are shown in Figure 4.3 and Table 4.2.

4.3.2 Evaluation of Volumetric Properties

Once the proper batching was determined, the volumetric properties of the laboratory mix were evaluated. The asphalt used in this JMF was a PG 64-22 produced by Citgo in Bristol, Virginia. The design asphalt content was determined to be 5.8 percent by weight of the mix. Finally the anti-strip additive, LOF 6500, was added to the asphalt cement at 0.5 percent by weight of the asphalt. The asphalt concrete was mixed in the laboratory at 149°C and the maximum specific gravity was determined. Using the Rice specific gravity test the maximum specific gravity, G_{mm}, was found to be 2.509 compared to the G_{mm} of 2.510 for the JMF.

Using the experimental G_{mm} value, Superpave gyratory compactor (SGC) samples were compacted for testing. These specimens were required to have 4±0.5 percent air voids that were verified using the bulk specific gravity. With the height data from the compactor and the specific gravities, the volumetric properties were calculated. The values found experimentally and those provided with the JMF were close and both were within the acceptable NCDOT limits. The data are shown in Table 4.3.

4.3.3 Batching Adjustment for Various Fine Contents

Once the gradation and volumetric properties of the JMF were verified, two different baghouse fines contents were considered. The original JMF required 1.5 percent Boone baghouse fines. Because this study deals with high concentrations of baghouse fines in HMA mixtures due to intermittent surges, this fines content is referred to as 0 percent baghouse fines. Additional baghouse fines concentrations of 2 and 5 percent over the JMF required 1.5 percent, provided total baghouse fines concentrations of 3.5 and 6.5 percent, respectively. In consultation with NCDOT, it was decided that the additional baghouse fines would replace the fraction of dry screenings that passed the #200 sieve. Calculations and sieve analysis indicated that only 65 percent of the dry screening material passing the #200 sieve was required for the additional 2 percent BHF concentration. For the 5 percent BHF batching, the material passing the #200 sieve was entirely wasted. The batching and the gradations of the 2 and 5 percent BHF contents are shown in Tables 4.4 and 4.5, respectively, and Figure 4.4 shows the gradations for the mixes containing 2 and 5 percent BHF.

Table 4.1 – Batching for Original JMF and 0% BHF Revision

Batch Type	Aggregate Fraction: 78M	Manufactured Sand	Dry Screenings	Washed Screenings	Boone BHF
JMF Batching	30	26	19.5	23	1.5
0% Revision	30	21.5	19.5	27.5	1.5

Table 4.2 – Gradations for Original JMF and 0% BHF Revision

Sieve Size	Sieve Opening (mm)	Percent Passing		Control Points
		JMF Batching	0% Revision	
1/2"	12.5	100.00	100.00	100
3/8"	9.5	98.45	99.00	90-100
4	4.75	76.79	76.96	<90
8	2.36	46.33	44.60	32-67
16	1.18	33.09	29.24	<31.6, >37.6
30	0.6	25.47	22.55	<23.5, >27.5
50	0.3	18.08	16.69	
100	0.15	10.20	10.44	
200	0.075	5.02	6.44	2.0-10.0
Pan	-	0.00	0.00	

Table 4.3 – Volumetric Properties for Original JMF and 0% BHF Revision

Mix Type	Trial Asphalt Content (%)	Est. Asphalt Content (%)	% Air Voids	% VMA	% VFA	% G_{mm} @ N=8	% G_{mm} @ N=174	Dust Portion
0% Boone	5.8	5.79	4.76	16.7	76.0	87.3	97.3	0.86
JMF	5.8	5.1	4.8	15.8	75.9	86.6	96.4	0.98
Superpave			4%	15% min	65-76%	<89%	<98%	.6-1.2

Table 4.4 – Batching for 2% and 5% BHF Revisions

Batch Type	Aggregate Fraction: 78M	Manufactured Sand	Dry Screenings Ret. #200	Washed Screenings	Boone BHF	Dry Screenings Pass. #200
2% Revision	32	19.5	16.1	27.5	3.5	1.4
5% Revision	31	19.5	15.5	27.5	6.5	0

Table 4.5 – Gradations for 2% and 5% Boone Revisions

Sieve Size	Sieve Opening (mm)	Percent Passing		Control Points
		2% Boone	5% Boone	
1/2"	12.5	100.00	100.00	100
3/8"	9.5	98.05	98.51	90-100
4	4.75	78.11	76.50	<90
8	2.36	50.20	43.85	32-67
16	1.18	34.28	30.12	<31.6, >37.6
30	0.6	25.27	23.95	<23.5, >27.5
50	0.3	17.85	18.02	
100	0.15	10.61	11.75	
200	0.075	5.48	7.17	2.0-10.0
Pan	-	0.00	0.00	

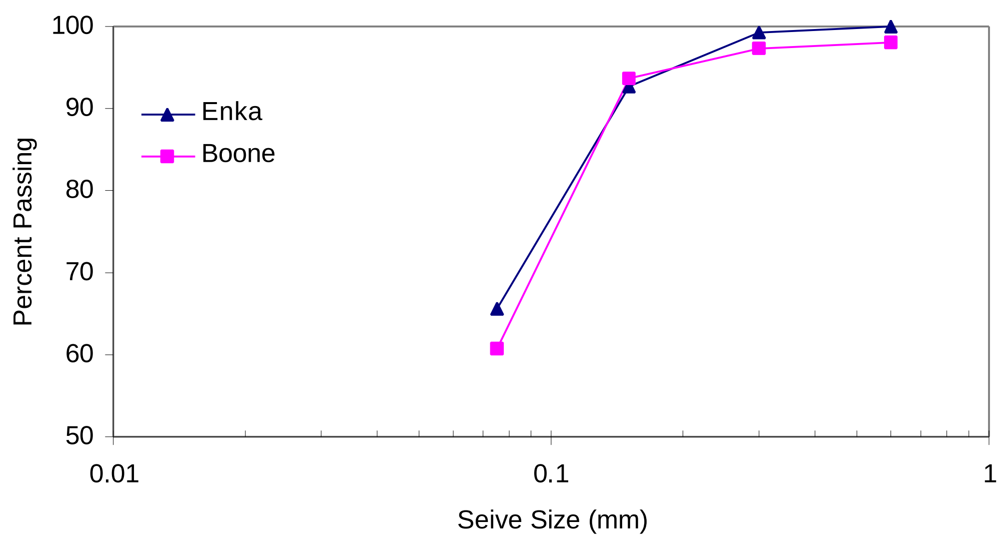


Figure 4.1 – Gradation of Boone and Enka Baghouse Fines Retained on #200 Sieve

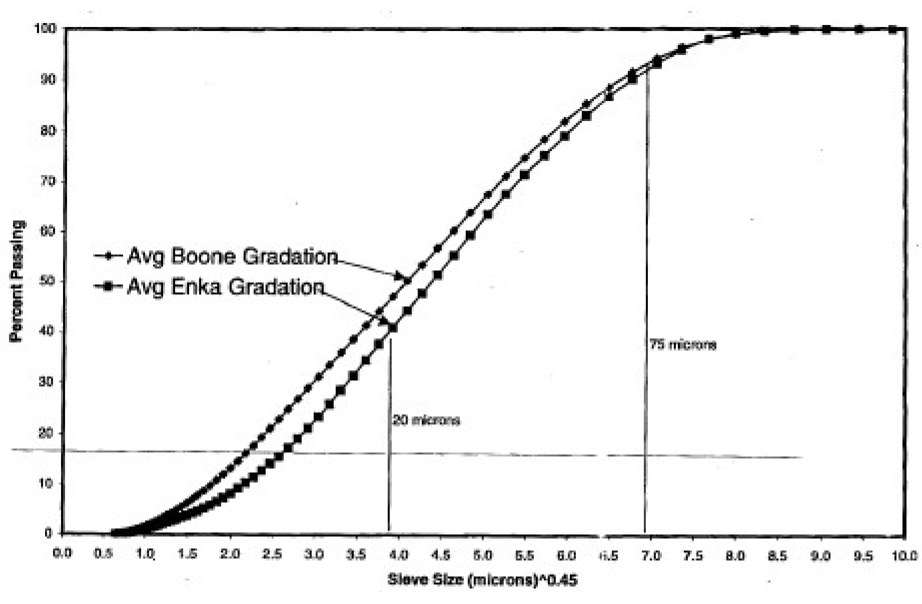


Figure 4.2 – Gradation of Boone and Enka Baghouse Fines Passing #200 Sieve

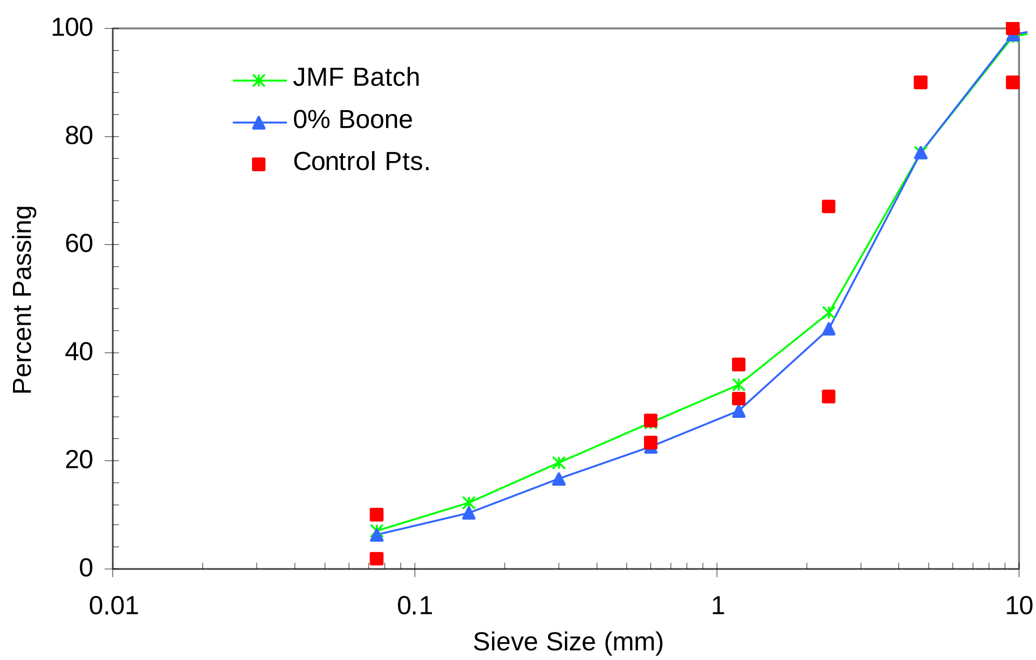


Figure 4.3 – Gradation Curves for 0% BHF Aggregate Batching

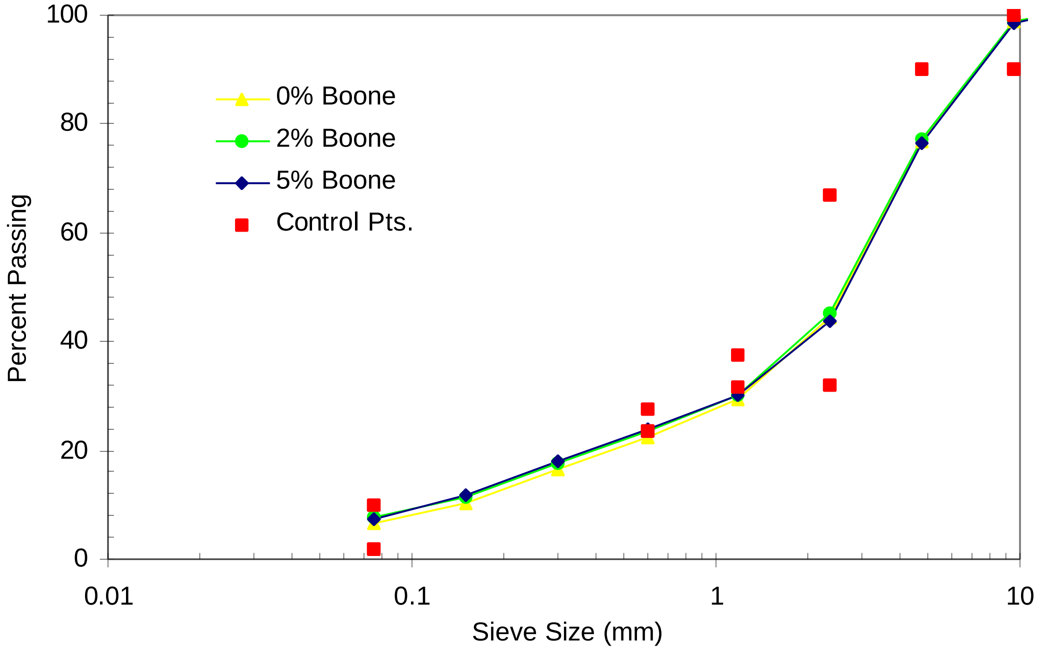


Figure 4.4 – Gradation Curves for 0, 2, and 5% BHF Aggregate Batching

5. MOISTURE SUSCEPTIBILITY TESTING

5.1 Introduction

For this project task, samples were prepared using different fines and fine percentages and different anti-strip additive contents. The samples were manufactured at NCSU labs and sent to NCDOT for the TSR testing. The first set included samples using Boone baghouse fines at 0, 2, and 5 percent contents as well as the 0.5 percent anti-strip additive specified in the JMF. Based on the results of these tests, samples were made using 0 and 5 percent Enka fines and additive. Finally, samples without anti-strip additive were also produced to determine the effectiveness of the additive in preventing moisture damage.

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. These specimens were compacted to a 7±1 percent air-void level. The specimens were then divided into subsets with half being dry and the other half being moisture conditioned. The samples were conditioned in a 60°C water bath until saturated between 50 and 80 percent. Once saturated, a Marshall indirect tensile test is performed on each specimen. The average tensile strength for each subset is then used to calculate the TSR value as shown in Equation 5.1 below:

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

After the TSR is calculated it is 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 first three subsets, containing various Boone fines contents, had six samples while the remaining subsets consisted of eight specimens. 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 mm with a 75 mm radius. The first three sets contained 0, 2, and 5 percent additional Boone baghouse fines with the required dosage of anti-strip additive. Each specimen was mixed 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 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 then used in the air-void calculations.

The specimens were then delivered to NCDOT for conditioning and testing. Using the air-void data, the conditioned specimens were saturated between 50 and 80 percent. The indirect tensile strengths were evaluated and the TSR was determined. Once the performance of the Boone specimens was determined, specimens containing additive and 5 percent Enka fines were also produced and tested. Finally, sets containing no anti-strip additive were produced to determine the influence of the anti-strip additive on moisture damage. Only two sets were prepared with 5 percent Boone or Enka fines since this represented the worst-case scenario for testing. A total of 42 specimens were produced for this task.

5.2.3 Test Results

The results of the TSR tests indicate the effects of both fine amount and use of anti-strip additive on moisture damage. Tables 5.1 through 5.6 show the test results for each of the six sets and Table 5.7 and Figure 5.1 show the TSR values for each mix. The first tests were performed on the sets containing additive and Boone fines, and all three fine contents produced passing results. The TSR values were 91.6, 96.6, and 90.4 percent retained strength for the 0, 2, and 5 percent Boone baghouse fines contents, respectively. All three values are greater than the 85 percent minimum prescribed by NCDOT.

The average tensile strength increased with the concentration of baghouse fines as well. As the fines contents increased the dry tensile strength went from 849.7 to 856.0 to 926.3 psi. This represents a 9 percent increase in tensile strength between the 0 and 5 percent Boone subsets. The conditioned or wet tensile strength progressed from 778.5 to 826.6 to 837.2 psi, a 7.5 percent increase. The increase in the tensile strength with increasing fines contents illustrates the stiffening effect due to baghouse fines in the asphalt concrete.

The sample set containing 5 percent Enka baghouse fines and the additive also passed the TSR test with an 88.5 percent. This is comparable to the 90.4 percent retained strength of the Boone samples. The average dry tensile strength of the Enka samples with 5 percent BHF was 780.2 psi and the conditioned strength was 690.6 psi. Both of these values are around 80 percent of the corresponding values of the 5 percent Boone samples.

The final two sample sets contained no additive. One set contained 5 percent Boone fines and the other contained 5 percent Enka fines. Both sets fell well below the minimum required TSR value. The TSR value for the Boone subset was 48.4 percent with an average dry tensile strength of 843.0 psi and a wet strength of 407.7 psi. The dry strength is 91 percent of the dry strength of the sample with additive. The wet strength, however, is only half of the conditioned specimens with additive. The large reduction in tensile strength shows the effect of the anti-strip additive in preventing moisture damage.

The TSR value for the Enka subset was 64.5 percent with a dry and conditioned strength of 868.9 and 560.5 psi respectively. Although the TSR value is below the minimum, the reduction in retained strength is much smaller than that observed for the Boone samples. The dry strength of the Enka samples without additive increased from 780.2 to 868.9 psi, a change of more than 10 percent. The average conditioned strength, however, decreased nearly 20 percent. The reduction in retained strength, from 88.5 to 64.5 percent, also reinforces the effectiveness of anti-strip additive in preventing moisture damage. For specimens containing both Boone and Enka BHF with no anti-strip additive, visual stripping was observed as shown in Figures 5.2 and 5.3.

5.3 Summary and Conclusions

Baghouse fines have often been attributed to accelerating moisture damage in asphalt pavement. The varying concentrations of baghouse fines in the subsets were used to approximate the surges of fines into asphalt plant mixes with 5 percent additional BHF (over the JMF) representing a worst-case scenario. The use of anti-strip additive is recommended for mixtures that may be exposed to moisture. The results of the moisture sensitivity testing show that, both, BHF concentration and anti-strip additive content affect moisture sensitivity. As the concentration of Boone baghouse fines increased, the indirect tensile strength increased and the TSR value decreased. A change in type of fines also affected the mix properties. The coarser Enka fines produced samples with lower indirect tensile strength than the Boone BHF samples. When the anti-strip additive was removed from the mixes, the asphalt mix containing baghouse fines was found to be extremely moisture sensitive and the retained strength fell by nearly half. It is therefore imperative that proper amount of anti-stripping agent be used with uniform and consistent distribution of anti-strip when using the BHF in NCDOT mixes.

Table 5.1 – TSR Results: 0% Boone fines with 0.5% Additive

Unconditioned Specimens			Conditioned Specimens			
Sample ID	Air Voids (%)	Max Load (N)	Sample ID	Saturation (%)	Air Voids (%)	Max Load (N)
T0A0-1	7.0	877.3	T0A0-3	78.0	7.2	778.5
T0A0-2	7.1	849.7	T0A0-5	72.6	7.0	757.9
T0A0-4	7.2	805.2	T0A0-6	74.6	7.0	795.5
Average	7.1	849.7			7.1	778.5

Table 5.2 – TSR Results: 2% Boone fines with 0.5% Additive

Unconditioned Specimens			Conditioned Specimens			
Sample ID	Air Voids (%)	Max Load (N)	Sample ID	Saturation (%)	Air Voids (%)	Max Load (N)
T2A0-3	6.8	958.3	T2A0-1	73.1	6.9	828.6
T2A0-6	6.6	783.8	T2A0-2	71.0	6.5	830.1
T2A0-7	6.7	856	T2A0-5	77.6	6.7	801.6
Average	6.7	856.0			6.7	826.6

Table 5.3 – TSR Results: 5% Boone fines with 0.5% Additive

Unconditioned Specimens			Conditioned Specimens			
Sample ID	Air Voids (%)	Max Load (N)	Sample ID	Saturation (%)	Air Voids (%)	Max Load (N)
T5A0-1	6.7	891.6	T5A0-3	73.6	6.4	821.2
T5A0-2	6.3	928.3	T5A0-4	75.9	6.6	854.2
T5A0-5	6.3	928.3	T5A0-6	75.0	6.4	837.2
Average	6.4	926.3			6.4	837.2

Table 5.4 – TSR Results: 5% Boone fines with 0% Additive

Unconditioned Specimens			Conditioned Specimens			
Sample ID	Air Voids (%)	Max Load (N)	Sample ID	Saturation (%)	Air Voids (%)	Max Load (N)
T5A1-1	7.0	879.2	T5A1-2	79.5	7.3	365.2
T5A1-5	7.4	848.8	T5A1-3	74.5	7.3	358.3
T5A1-6	7.2	837.2	T5A1-4	78.5	7.0	460.3
T5A1-7	7.1	815.0	T5A1-8	78.7	7.0	490.4
Average	7.2	843.0			7.2	407.7

Table 5.5 – TSR Results: 5% Enka fines with 0.5% Additive

Unconditioned Specimens			Conditioned Specimens			
	Air Voids	Max Load		Saturation	Air Voids	Max Load
Sample ID	(%)	(N)	Sample ID	(%)	(%)	(N)
T5B0-4	7.6	815.8	T5B0-1	66.5	7.3	651.6
T5B0-5	7.6	775.7	T5B0-2	76.5	7.2	682.1
T5B0-6	7.9	784.6	T5B0-3	71.3	6.9	699.2
T5B0-7	7.8	762.3	T5B0-8	70.4	7.0	748.2
Average	7.7	780.2			7.1	690.6

Table 5.6 – TSR Results: 5% Enka fines with 0% Additive

Unconditioned Specimens			Conditioned Specimens			
	Air Voids	Max Load		Saturation	Air Voids	Max Load
Sample ID	(%)	(N)	Sample ID	(%)	(%)	(N)
T5B1-4	7.6	869.3	T5B1-1	79.0	8.0	561.1
T5B1-5	7.6	868.4	T5B1-2	79.5	8.0	530.8
T5B1-6	7.9	813.3	T5B1-3	75.7	7.8	560
T5B1-7	7.8	889.3	T5B1-8	76.6	7.8	587.9
Average	7.7	868.9			7.9	560.5

Table 5.7 – Boone and Enka TSR Values

Boone BHF Specimens		Enka BHF Specimens	
Sample ID	TSR (%)	Sample ID	TSR (%)
T0A0	91.6	-	-
T2A0	96.6	-	-
T5A0	90.4	T5B0	88.5
T5A1	48.4	T5B1	64.5

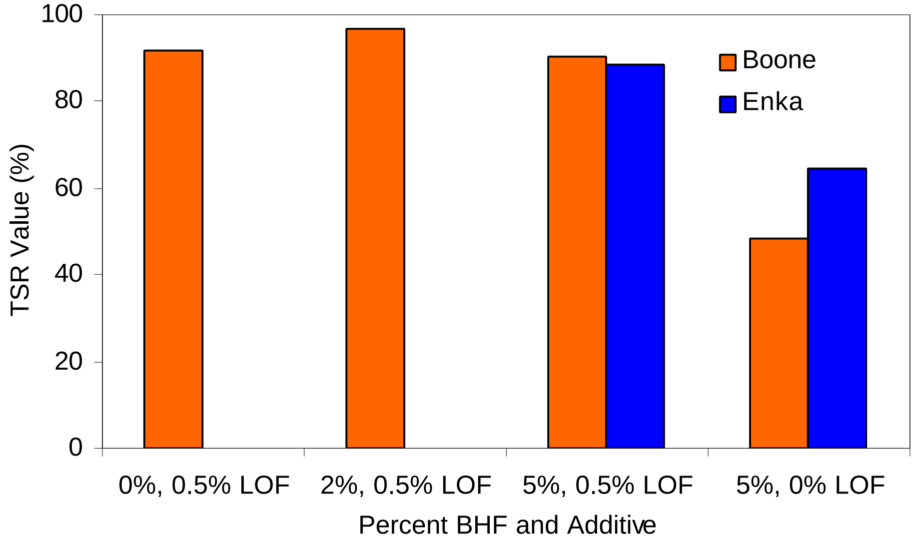


Figure 5.1 – Boone and Enka TSR Values

Figure 5.2 – TSR Specimen Failure: 5% Boone BHF, 0% LOF

Figure 5.3 – TSR Specimen Failure: 5% Enka BHF, 0% LOF

6. ASPHALT PAVEMENT ANALYZER TESTING

6.1 Introduction

The Asphalt Pavement Analyzer (APA) measures the rutting resistance of laboratory or field samples. This test repeatedly loads the samples at or above the load limit for the specimen in an accelerated time span. The damage accumulated is measured and compared to standard values to determine rutting performance. In this section, APA testing on dry and conditioned samples will be reviewed.

6.2 APA Specimen Testing

6.2.1 Test Method Description

The APA specimens were prepared at NCSU and delivered to NCDOT for the APA testing. Specimens were produced with a SGC and were to measure 75 mm in height and with 150 mm diameter. The target air-voids for the specimens was 7±0.5 percent, which is a narrower range than the TSR specimen requirements. Each subset contained eight specimens with four remaining dry and four being conditioned. The wet specimens were conditioned at NCDOT between 50 and 80 percent saturation in a 60^0C water bath. The conditioned specimens are tested underwater in the APA machine to retain the specimen internal moisture.

The APA test is performed using two six-inch specimens. These specimens are placed into a mold that restricts lateral deformation. The machine runs tests simultaneously on three sets of specimens. The mold is placed in the machine and a rubber hose is lowered over the samples. For the conditioned specimens, the water bath is maintained at 60°C while the air temperature in the chamber, for both conditioned and unconditioned tests, is maintained at 64°C.

The hoses are pressurized to 0.69 MPa (100 psi) and a steel wheel is passed over the tube at a speed of 2.0 km/h (33±1 cycles/min). This loading system approximates the interaction between asphalt concrete and pressurized vehicle tire. The test is conducted for 8000 cycles and the rut depth is measured at three different points at various intervals during the test. The three rut depths are then averaged to produce a deformation curve as well as a final rut depth value. The results from all the specimens in the subsets are then averaged to provide a rut depth for comparison between subsets.

There are several different criteria for maximum rut depth for the APA test. The Georgia Department of Transportation (GDOT) specified the maximum limit at 7.6 mm while the FHWA sets the rut depth limit at 5 mm. The NCDOT limit is between these two values at 6.25 mm. The standard temperatures for these tests are different however. The GDOT test is performed at 40.6^{0}C while the NCDOT test is normally conducted at the maximum temperature rating of the asphalt binder. Since PG 64-22 was used in this study, the NCDOT criteria would require the test be run at 64^{o}C.

6.2.2 Sample preparation and testing

All the specimens tested were produced in the laboratory using the SGC. The samples were 75 mm tall, 75 mm in diameter, and had an air-void content of 7±0.5 percent. There were six sets produced which correspond to the sets produced for the TSR testing. The sets were: 0 and 5 percent Boone fines with 0.5 percent additive, 0 and 5 percent Enka fines with 0.5 percent additive, and 5 percent Boone and Enka fines with no additive. A set containing 2 percent Boone baghouse fines and 0.5 percent additive was not produced since this was an intermediate mix.

The mixing was performed at 149^{o}C, after which the mix was aged at 60^{o}C for four hours. The mix was then heated for two hours at 138^{o}C and then compacted in the SGC. The samples were compacted to 75 mm with varying compactive efforts. The specimens were then tested to determine bulk specific gravity and air voids to be used in the saturation process. The samples were then transported to NCDOT for conditioning and testing.

6.2.3 Test Results

None of the subsets tested passed the NCDOT specification of rut depth less than 6.25 mm. Another observation was that the average rut depth of the conditioned specimens is lower than the dry subsets. The TSR testing results showed a decline in strength between conditioned and dry sets. It is hypothesized that the lower rut depths of the conditioned specimens may be due to the water pressure filling the air voids in the sample. The dry subsets have empty air voids that allow for deformation when loaded. The voids in the conditioned samples are filled almost 80 percent with water, which restricts the deformation. Because of this difference in testing, comparisons cannot be made between the results of the dry and conditioned subsets. Therefore, dry subset results and the conditioned subset results were compared separately.

Figures 6.1 and 6.2 show two specimens after APA testing. In Figure 6.1, a dry sample with 5% Boone fines and no additive is shown. The average rut depth for the specimens was 10.29 mm. Figure 6.2 shows a conditioned specimen with the same properties. The average rut depth for the specimens was 11.74 mm. The sample in Figure 6.2 shows signs of stripping with much more aggregate exposed compared to dry sample. The second sample also shows an upheaval of the aggregate around the rut while the first sample does not display this behavior. This upheaval suggests a loss of cohesive strength that allowed for severe deformation.

The average rut depths for the unconditioned and conditioned APA testing are shown in Tables 6.1 and 6.2 respectively and in Figure 6.3 graphically. For the dry specimens with Boone fines, the set containing 5 percent BHF with no anti-strip additive had the lowest rut depth at 9.81 mm. It was followed by the specimens containing 0 percent BHF with additive at 10.56 mm. The set with 5 percent BHF and additive had the highest rut depth at 11.93 mm. It should be noted that these differences are minor and may be due to test variability. At the same time, they are way above the NCDOT limit of 6.25 mm.

The dry Enka set with the lowest rut depth contained 5 percent BHF with anti strip additive. The rut depth for this set was 7.67 mm. The set with 5 percent BHF and no additive had a rut depth of 9.64 mm. Finally, the set with 0 percent BHF with additive had the highest rut depth at 10.67 mm. The unconditioned sets containing Enka BHF displayed a decrease in rut depth with an increase in fines content

The results of the APA testing on the conditioned subsets show the effectiveness of the anti-strip additive in preventing moisture damage. The conditioned specimens containing 5 percent Boone BHF and anti-strip additive had a rut depth of 8.43 mm. The rut depth for the subsets with 0 percent BHF and additive was 8.92 mm. Finally the 5 percent BHF sets without additive had a rut depth of 10.50 mm. The removal of the anti-strip additive increased the conditioned rut depth by 25 percent for the specimens containing Boone BHF.

The conditioned Enka samples followed the same rut depth order as the Boone samples. The subset with 5 percent Enka BHF and additive had a rut depth of 6.75 mm. The rut depth for the conditioned subset with 5 percent BHF without additive was 7.53 mm. The subset with 0 percent BHF and additive had the largest rut depth at 8.91 mm. For the conditioned Enka specimens, the removal of anti-strip additive led to a 12 percent increase in rut depth.

In all the conditioned subsets and the unconditioned Enka subsets, the samples containing 5 percent baghouse fines and additive were the most rut resistant. This corresponds to the TSR data with the 5 percent samples having the highest indirect tensile strength. This demonstrates the stiffening effect of the baghouse fines on the asphalt concrete as well as the effectiveness of the anti-strip additive. The wet Enka subsets are also more rut resistant than the corresponding Boone samples. Finally, the conditioned APA results show the effectiveness of the anti-strip additive in preventing moisture damage on a relative basis. The sets containing 5 percent Boone and Enka BHF had increases in rut depth of 25 and 12 percent, respectively, due to the absence of anti-strip additive.

6.3 Summary and Conclusions

The results of the APA testing do not show any significant changes in the average rut depths between any of the subsets. The range of values was from 6.75 mm to 11.93 mm although the lowest value is from conditioned samples and the highest from a dry subset. These results are contrary to *a priori* notion and results from TSR testing – i.e., conditioned specimens should have shown higher level of rutting compared to unconditioned specimens. This trend in results may be due to the fact that the current APA testing methodology does not allow the pore pressure to be dissipated during loading. However, despite the lower average rut depth for the conditioned specimens, the moisture damage in these samples was evident.

Table 6.1 – Average APA Results for Unconditioned Subsets

Sample ID	Type of BHF (%)	BHF Content (%)	Additive Content (%)	Air Voids (%)	Rut Depth (mm)
A0A0 – U	Boone	0	0.5	6.9	10.6
A5A0 – U	Boone	5	0.5	7.4	11.9
A5A1 – U	Boone	5	0	7.0	9.8
A0B0 – U	Enka	0	0.5	7.0	10.7
A5B0 – U	Enka	5	0.5	6.8	7.7
A5B1 - U	Enka	5	0	7.2	9.6

Table 6.2 – Average APA Results for Conditioned Subsets

Sample ID	Type of BHF (%)	BHF Content (%)	Additive Content (%)	Air Voids (%)	Rut Depth (mm)
A0A0 – C	Boone	0	0.5	6.8	8.9
A5A0 - C	Boone	5	0.5	7.1	8.4
A5A1 - C	Boone	5	0	7.2	10.5
A0B0 - C	Enka	0	0.5	7.2	8.9
A5B0 - C	Enka	5	0.5	6.7	6.7
A5B1 - C	Enka	5	0	7.0	7.5

Figure 6.1 – APA Test Specimen, 5% Boone BHF, 0% LOF, Dry

Figure 6.2 – APA Test Specimen, 5% Boone BHF, 0% LOF, Conditioned

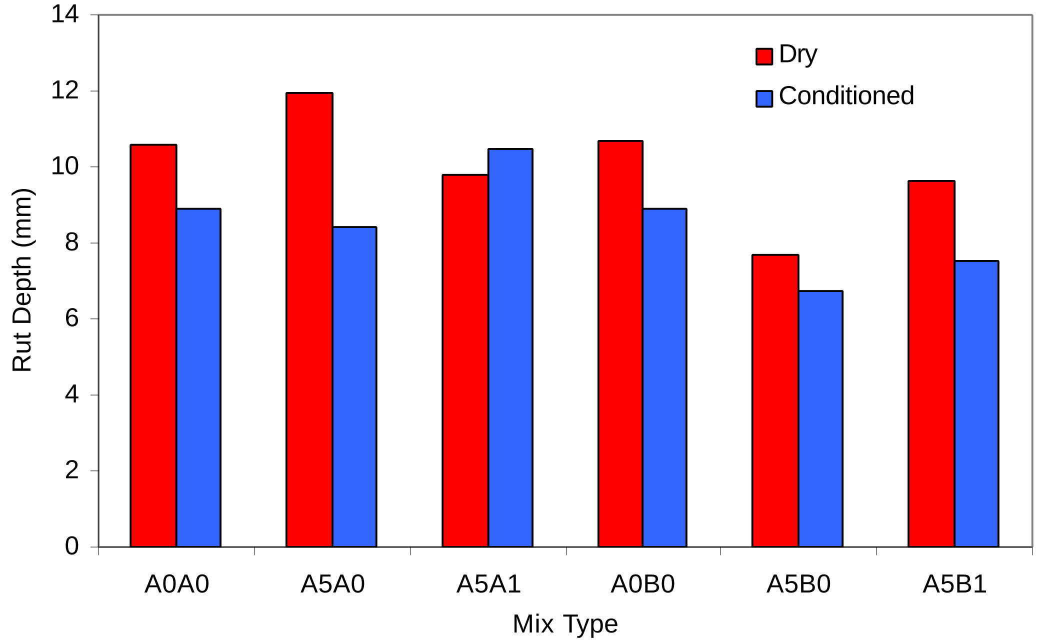


Figure 6.3 – Average APA Rut Depth Results

7. SUPERPAVE SHEAR TESTING

7.1 Introduction

The final testing phase of the project involved the Superpave™ Shear Testing (SST) device. Using a SST machine, specimens were subjected to stress and strain controlled tests and material properties were determined. There were two types of tests run using the SST: the frequency sweep and repeated shear tests. The results of these tests provide the values for the shear modulus as well as permanent deformation and phase angle. Using the shear test data, fatigue life of mixes can also be determined. Differences in mixture performance were determined using this data, and discussed in the following sections.

7.2 SST Specimen Testing

7.2.1 Test Method Description

The two types of tests performed using the SST apparatus are the frequency sweep at constant height (FSCH) and the repeated shear at constant height (RSCH). The testing system consists of an environmental chamber that maintains a constant temperature and two hydraulic actuators that apply horizontal and vertical loads. A hydraulic pump runs the actuators and the displacement and loading is controlled by computer. For both the FSCH and RSCH tests, the computer applies a standard loading or displacement pattern and the deformations are measured using LVDTs.

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. Before testing, the samples were conditioned in an oven for 2-3 hours and then loaded into the chamber. FSCH test was performed first at 50^{o}C followed by a change of LVDTs and a short reconditioning period. The RSCH test followed at the same temperature once the chamber returned to testing temperature. The first five RSCH samples were run to 100,000 cycles to determine the full stress strain response. Little additional permanent deformation was accumulated in the specimens after 5,000 cycles so subsequent tests were performed according to the AASHTO TP-7 procedure upto 5,000 cycles. FSCH tests were also performed at 20^{o}C on a different set of specimens to determine material properties for the fatigue characterization of mixtures.

7.2.2 Sample Preparation and Testing

All the SST samples were prepared in the laboratory using the SGC. Samples were compacted to a height of 127 mm and a radius of 75 mm. For comparison of the TSR and APA results, air-void content of 7±0.5 percent was maintained. The specimens were compacted to the same height using different compactive efforts. Once the air-voids of the specimens were determined, each specimen was sawed into two 50 mm specimens. The sawing produced samples with two smooth faces for better adhesion with the epoxy. The cutting lowered the air-void content by reducing the voids on the surface of the specimens. For this reason, the target air-voids were lowered to 6.3±0.5 percent. This drop in air-voids was consistent with findings from other research projects [11].

Each set of specimens contained two dry and two conditioned samples. There were six sets corresponding to the specimen sets used in the APA testing for a total of 24 testing specimens at 50^{o}C and 24 more for 20^{o}C. After all the specimens were prepared, the samples to be conditioned were delivered to NCDOT. The samples were saturated between 50 and 80 percent following the conditioning procedure in the AASHTO T-283 standard. The samples were returned to NCSU in plastic bags to retain moisture until testing.

Before testing, the height of each sample was determined using a caliper. The sample was measured at four points on the circumference and the heights were averaged. The sample surface were then cleaned with rubbing alcohol and epoxied to the metal test platens using Devcon Plastic Steel epoxy. A platen-specimen assembly device provided pressure on the specimen while the epoxy hardened. After epoxy hardened, the samples were conditioned at 20°C or 50°C for 2-3 hours. The testing sample was then fitted with axial and horizontal LVDTs and placed into the machine. The sample was then conditioned for another half hour to allow the chamber and sample to return to testing temperature.

7.2.3 Frequency Sweep Testing

The frequency sweep at constant height (FSCH) test is performed to determine the dynamic shear modulus and the phase angle of the HMA specimen at different frequencies. The specimen is loaded in a prescribed manner for each frequency and the viscoelastic properties are measured. Throughout the test, the axial force prevents axial deformation and maintains a constant height. The following sections describe the FSCH testing procedure.

7.2.3.1 Testing Procedure

The FSCH test was performed in the Superpave™ SST machine in a strain-controlled mode. 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. As the test is run, the strains and stresses are recorded. Using these values, the dynamic shear modulus (|G*|) and the phase angle (δ) are calculated. The phase angle represents the relationship between the shear loss and shear storage moduli. As δ increases, the plastic shear strain increases and the elastic strain decreases. The dynamic shear modulus is the ratio of the peak stress to the peak strain. As |G*| increases, the stiffness of the mix increases as well. The value of G*/sin δ is a measure of the rutting resistance of the HMA mixture. As this value increases, the rutting resistance also increases.

7.2.3.2 FSCH Test Results @ 50^{o}C and 20^{o}C

The FSCH test results for each mix are presented both numerically and graphically. Tables 7.1 through 7.12 and Figures 7.1 through 7.12 shows the results for 50^{o}C. The results for 20^{o}C, are presented in Tables 7.13 through 7.16 and Figures 7.13 through 7.24.

From the dataset, it should be noted that there is a fair amount of variability in the data, especially for mixes containing the Boone BHF. These variabilities may be attributed to the following factors: 1) specimen production and difference in air void, 2) moisture conditioning, 3) testing. Nevertheless, as will be discussed consequently, there are some general trends that are fairly obvious with regard of use of BHF.

As mentioned earlier, FSCH testing was conducted at two temperatures -- 50 and 20°C. The results at 50°C, especially the value of $G^*/\sin\delta$ is indicative of the rutting resistance of the mixes; whereas, the results at 20°C are needed for the fatigue characterization of the mixes.

In order for the reader to assimilate the data easily, and for simplicity of presentation and discussion, the data for both temperatures are reduced to averages and presented in Table 7-A. It should be noted that for each mix and temperature, 2 specimens were tested, in conditioned and unconditioned state, and the results averaged. The data in Table 7-A represents averages over all the testing frequencies -- 10, 5, 2, 1, 0.5, 0.2, 0.1 Hz. For 50°C, Table 7-A shows the average values of $G^*/\sin\delta$ while for 20°C it shows the average value of dynamic shear modulus $|G^*|$.

Table 7-A Comparison of Average Shear Stiffness Values at 50°C and 20°C

Type of mix		50°C G*/sinδ (MPa)			20°C G* (MPa)		
Boone BHF %	LOF %	Dry	Wet	Difference %	Dry	Wet	Difference %
0	0.5	83.4	91.0	-8.4	1540	1250	18.8
5	0.5	125	70.5	43.6	2003	1100	45.1
5	0	140	101	27.0	1260	1370	8.0
Enka BHF %							
0	0.5	88.6	94.9	-6.6	1240	1190	4.0
5	0.5	103	87.6	14.9	1590	1170	26.4
5	0	105	74.5	29.0	1450	1230	15

Before discussion of the results it should be noted that generally the stiffness variability of about 9 to 10 percent is anticipated [18]. Based on this variability, the first conclusion that can be drawn from the FSCH test results is that in general both mixes containing no additional BHF (ie., 1.5 percent baghouse fines with 0.5 percent anti-strip agent as per the JMF used by NCDOT) show no difference in $G^*/\sin\delta$ values at 50^oC for mix containing Boone BHF. For mixes containing the Enka BHF, no significant differences exist in either $G^*/\sin\delta$ values or the $|G^*|$ values at both 50^oC and 20^oC, respectively. There is, however, an 18.8% difference in $|G^*|$ values at 20^oC between the unconditioned and conditioned specimens for mixes containing Boone BHF.

The second observation that can be made based on the result is that there is a definite increase in, both, $G^*/\sin\delta$ values at 50^oC and $|G^*|$ value at 20^oC with increase in BHF to 5% addition over the JMF requirement, at least in the unconditioned specimens. This stiffening effect is anticipated and it should be noted that the difference is relatively larger in mixes containing the Boone BHF as compared to mixes containing Enka BHF. This is, perhaps, because of the finer particle size distribution for the Boone BHF in comparison to the Enka BHF as shown in Figure 4.2.

The third observation that can be seen is that for the mixes containing additional 5 percent BHF(with and without anti-strip additive) there is a significant reduction in the stiffness values both at 50^oC and 20^oC when the specimen are conditioned (wet). Specimens containing Boone BHF show higher percentage difference in general as compared to the mixes containing Enka BHF. This behavior can again be attributed to the finer gradation of the Boone BHF.

The fourth observation is kind of puzzling and an explanation for this behavior is not obvious. For mixes containing 5% Boone BHF, addition of 0.5 percent anti-strip additive seems to be detrimental compared to mixes containing no anti-strip agent. This behavior can also be seen in mixes containing Enka BHF at 20^oC but not at 50^oC.

Based on the stiffness results, it can be summarized that in general, the NCDOT JMF that requires 1.5 percent BHF with 0.5 percent LOF6500 anti-strip agent should be able to contain the moisture damage with no significant effect on the in-situ performance of the pavement section in which these mixes are placed. However, it is obvious that intermittent purging of BHF into the mixes will have severe effect on the stiffness characteristics of theses mixes. The degree of detrimental effect will depend on the type and gradation of BHF.

7.2.4 Repeated Shear Testing

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

7.2.4.1 Testing Procedure

The RSCH test is 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 performed until the accumulated shear strain reaches 5 percent or the test reaches 100,000 cycles. After several samples were tested, graphs showed that the responses did not change appreciably after 5,000 cycles. Figure 7.25 shows the plot of plastic strain versus number of cycles for the five samples tested to 100,000 cycles. The remainder of the specimens were tested to 5,000 cycles following the AASHTO specification.

7.2.4.2 Test Results and Rutting Resistance of Mixes

The results of the RSCH tests for each mix are presented graphically in Figures 7.26 through 7.31. As was the case for the stiffness, the RSCH test results also show a considerable scatter in data. After analysis of the test results, it was found necessary to test seven more specimens in conditioned and unconditioned state for both mixes containing Boone and Enka BHF. Results of these additional RSCH tests are presented in Figure 7.32.

Average values of shear plastic strain at 5000 cycles for various mixes tested in conditioned and unconditioned state are presented in Table 7-B.

Table 7-B Plastic Shear Strain at 5,000 Cycles and Corresponding Rutting Depth, 50^{o}C

Type of Mix		Plastic Shear Strain		Rut Depth (in.)		% Difference
Boone BHF %	LOF %	Dry	Wet	Dry	Wet	
0	0.5	0.027	0.0281	0.30	0.31	-4.1
5	0.5	0.0298	0.0472	0.33	0.52	-36.9
5	0	0.0226	0.0325	0.25	0.36	-30.5
Enka BHF %						
0	0.5	0.0268	0.0304	0.29	0.33	-11.8
5	0.5	0.0206	0.0282	0.25	0.31	-19.9
5	0	0.0255	0.0202	0.28	0.22	20.8

Based on the plastic strain shown in Table 7-B, the corresponding rutting resistance of the various mixes in conditioned and unconditioned state were computed. These computations are presented in the following section.

7.2.4.3 Rutting Resistance

HMA pavements must withstand repeated traffic loadings without accumulating a large amount of permanent deformation. A mixture's resistance to permanent deformation is measured with the rutting resistance. The rutting resistance of an HMA pavement can be determined, in the laboratory, from the RSCH response. Using the maximum permanent shear strain at 5,000 cycles, the rut depth can be calculated using Equation 7.1 below:

$$\text{Rut Depth (in.)} = 11 * (\gamma_p) \qquad (7.1)$$

where:

γ_p = the maximum permanent shear strain in the RSCH test

The computed rut depths for various mixes are presented in Table 7-B. Although, as mentioned previously, there is some scatter in data, in general, the trend in rut depths are similar to those seen for the stiffness $G^*/\sin\delta$ result obtained at 50^oC. The negative sign for the percent difference in rut depths indicates that conditioned (wet) specimens experience larger rutting as compared to the unconditioned dry specimens.

Several observations can be made from the results presented in table 7-B. First, the mix containing no additional Boone BHF (with 0.5 percent LOF) does not show any significant difference between conditioned and unconditioned specimens. This is also the case for the mix containing no additional Enka BHF which shows the least percentage difference, again consistent with the observation in $G^*/\sin\delta$ value trends.

Second, with increasing amount of BHF the rut depth significantly increases under water conditioning. ie., the effect of moisture damage is quite prevalent with mixes containing additional 5 percent Boone BHF, experiencing higher rutting potential compared to mixes containing Enka BHF. Again, it should be noted that Boone BHF has finer particles than Enka BHF that may be a contributory factor.

Third, mix containing 5 percent additional Enka BHF (without additive) shows results contrary to those obtained from other mixtures, ie., the conditioned specimens are performing better. This trend may be the result of random scatter in data.

Similar to the result for the stiffness testing, rutting characterization of mixes indicate that in general, additional baghouse fines due to intermittent purging will be detrimental to the in-situ pavement life even with the use of anti-strip additive in the mixes.

7.3 Fatigue Analysis

It should be noted that unlike the rutting distress, which is solely dependent on mixture properties, fatigue distress is a function of, both, the mixture properties as well as the pavement structure layer thickness. The fatigue analysis procedure requires an estimate of the flexural stiffness modulus (S_0) of the asphalt-aggregate mix at the desired temperature. In this investigation it is assumed that the effective temperature for fatigue cracking is 20^{o}C. This estimated flexural stiffness is used in the multilayered elastic analysis to determine the critical strain to which the asphalt concrete mixture will be subjected to under a standard traffic loading. The critical strain is then used to compute fatigue life of the mixture. The multilayered elastic analysis in this study was conducted using the KENLAYER program. More details are available in reference [19]. 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.

The flexural properties of the mixtures were estimated from the FSCH tests using the following equations [19]:

$$S_0 = 8.560 \times (G_0)^{0.913} \quad (7.2)$$

$$S_0'' = 81.125 \times (G_0'')^{0.725} \quad (7.3)$$

where:

S_0 = dynamic flexural stiffness at 10Hz in psi,

G_0 = dynamic shear stiffness at 10 Hz in psi,

S_0'' = dynamic flexural loss stiffness at 10 Hz in psi, and

G_0'' = dynamic shear loss stiffness at 10 Hz in psi.

Based on the above relationships average material properties for Boone and Enka mixes were computed based on the FSCH test results at 10 Hz frequency and 20°C, and are summarized in Tables 7.17 and 7.18.

For the fatigue analysis, a typical pavement section shown in Figure 7-A was used. This pavement section consists of a 6 inch asphalt concrete layer over an 8 inch of aggregate base course (ABC) and 7 inch of cement treated subbase (CTB). Material properties for the ABC, CTB and subgrade are shown in Figure 7-A.

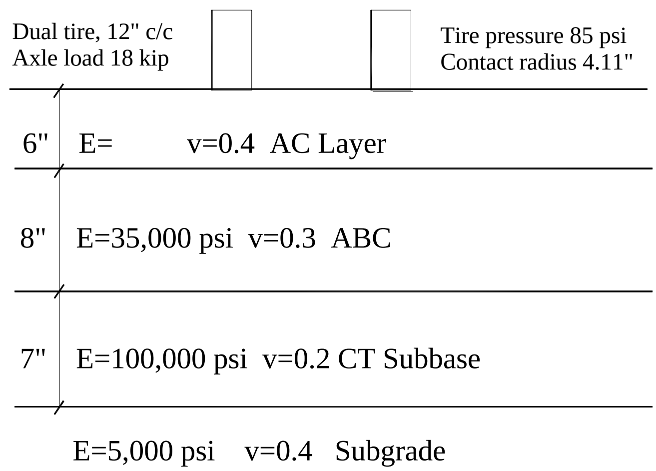


Figure 7-A Typical Pavement Section Used for Fatigue Analysis

To determine the critical tensile strain at the bottom of AC layer, estimated flexural stiffness for different mixes from Tables 7.17 and 7.18 were used. With the tensile strain determined using KENLAYER program, the following fatigue relationship developed during the SHRP program was used to evaluate the laboratory fatigue resistance (N_{supply}) of the mixes:

$$N_{\sup ply} = 273800 \times (e)^{0.077VFA} \times (e)^{-3.624} \times (S_0'')^{-2.720} \qquad (7.4)$$

where:

N_{supply} = the number of E18 load repetition to laboratory fatigue cracking;

e = base of the natural logarithms,

e = critical tensile strain,

S_0'' = the initial flexural loss stiffness in psi and,

VFA = the voids filled with asphalt in percent.

To account for the variability in estimation of N_{demand} (ie., number of 18 kip ESALs corrected for a given reliability) and N_{supply}, a safety factor "M" which is a reliability multiplier is used. For 90 percent reliability, the value of the M was determined to be 4.303. The following equation then relates the N_{demand} and N_{supply}:

$$N_{\sup ply} = M \times N_{demand} \qquad (7\text{-}5)$$

where:

N_{demand} is the number of 18 kip ESAL that the pavement section can withstand at 90 percent reliability.

The results of the fatigue analysis for all the subsets from Boone set and Enka set are numerically given in Tables 7.19 and 7.20 and summarized in Table 7-C.

Table 7-C Summary of Fatigue Resistance of Mixes

Type of Mix		No. of 18k ESALs in millions		
Boone BHF %	LOF %	Dry	Wet	% Difference
0	0.5	2.93	0.88	70%
5	0.5	5.24	1.45	72%
5	0	3.34	1.42	58%
Enka BHF %				
0	0.5	1.25	1.12	10%
5	0.5	4.95	1.46	70%
5	0	4.95	2.26	54%

Based on the results of the fatigue analysis summarized in Table 7-C, following may be noted: 1) the mix containing no additional Enka BHF (with 0.5 percent LOF) shows the least amount of difference between the unconditioned and conditioned specimens. This is consistent with the observation of only 4 percent difference in |G*| values at 20^{o}C in Table 7-A. However, this was not the case for the Boone mix containing no additional BHF that showing 70 percent deterioration in fatigue life due to moisture damage; 2) with increasing amount of BHF the fatigue resistance deteriorates significantly under moisture conditioning, ie., effect of moisture damage is quite prevalent with mixes containing additional 5 percent BHF; 3) Mixes containing 5 percent additional BHF (both Boone and Enka) without anti-strip additive show less damage compared to mixes containing anti-strip agent. This same observation was noted for the |G*| values at 20^{o}C, and since the fatigue life determination is based on the |G*| values directly, the trend is reflected in the fatigue life determination as well.

Similar to the results of stiffness testing and the rutting distress determination, fatigue analysis of mixes indicates that, in general, additional baghouse fines due to intermittent purging will be detrimental to the in-situ pavement life even with the use of anti-strip additive in the mixes. Moreover, it appears that the detrimental effect of additional BHF on fatigue life is far more than rutting resistance of the mix.

Table 7.1 – Dynamic Shear Modulus versus Frequency; 0% Boone, 0.5% LOF @50 Celsius

	Shear Modulus, |G*|, (Pa)			
Frequency (Hz)	S0A0-1U	S0A0-3C	S0A0-5C	S0A0-7U
15	1.34E+08	1.27E+08	1.01E+08	1.03E+08
10	1.09E+08	1.05E+08	8.03E+07	8.23E+07
5	7.90E+07	7.81E+07	5.58E+07	5.72E+07
2	5.28E+07	5.68E+07	3.57E+07	3.91E+07
1	4.24E+07	4.79E+07	2.84E+07	3.06E+07
0.5	3.48E+07	4.13E+07	2.11E+07	2.46E+07
0.2	2.80E+07	3.62E+07	1.64E+07	1.91E+07
0.1	2.53E+07	3.31E+07	1.46E+07	1.37E+07
Average |G*|	**6.32E+07**	**6.56E+07**	**4.41E+07**	**4.62E+07**

Table 7.2 – Phase Angle versus Frequency; 0% Boone, 0.5% LOF @50 Celsius

	Phase Angle, δ, (degree)			
Frequency (Hz)	S0A0-1U	S0A0-3C	S0A0-5C	S0A0-7U
15	48.72	46.65	55.25	55.36
10	47.66	44.63	54.34	54.46
5	45.16	41.03	52.46	51.94
2	40.52	35.27	47.35	47.48
1	38.39	32.16	46.56	43.14
0.5	33.57	26.49	40.65	38.20
0.2	28.81	21.57	37.12	35.71
0.1	23.62	18.20	26.90	37.68
Average d	**38.31**	**33.25**	**45.08**	**45.50**

Table 7.3 – Dynamic Shear Modulus versus Frequency; 5% Boone, 0.5% LOF @50 Celsius

	Shear Modulus, |G*|, (Pa)			
Frequency (Hz)	S5A0-3C	S5A0-4U	S5A0-5C	S5A0-6U
15	1.14E+08	1.33E+08	8.25E+07	1.50E+08
10	9.25E+07	1.14E+08	6.69E+07	1.22E+08
5	6.71E+07	8.86E+07	4.90E+07	9.01E+07
2	4.63E+07	6.94E+07	3.42E+07	6.28E+07
1	3.63E+07	5.41E+07	2.37E+07	5.03E+07
0.5	2.70E+07	3.51E+07	1.97E+07	4.07E+07
0.2	2.01E+07	3.18E+07	1.55E+07	3.30E+07
0.1	1.50E+07	3.01E+07	1.50E+07	2.67E+07
Average |G*|	**5.22E+07**	**6.95E+07**	**3.83E+07**	**7.20E+07**

Table 7.4 – Phase Angle versus Frequency; 5% Boone, 0.5% LOF @50 Celsius

	Phase Angle, δ, (degree)			
Frequency (Hz)	S5A0-3C	S5A0-4U	S5A0-5C	S5A0-6U
15	51.33	44.54	52.59	47.46
10	49.92	41.74	50.41	46.68
5	47.74	37.91	46.72	44.38
2	44.15	34.07	40.39	40.82
1	39.79	31.57	36.92	36.79
0.5	36.49	24.99	26.96	35.08
0.2	31.11	18.44	24.71	30.86
0.1	31.59	13.01	25.45	29.00
Average delta	**41.52**	**30.78**	**38.02**	**38.88**

Table 7.5 – Dynamic Shear Modulus versus Frequency; 5% Boone, 0% LOF @50 Celsius

	Shear Modulus, |G*|, (Pa)			
Frequency (Hz)	S5A1-1U	S5A1-2U	S5A1-6C	S5A1-7C
15	1.69E+08	2.09E+08	1.21E+08	1.38E+08
10	1.42E+08	1.67E+08	1.00E+08	1.13E+08
5	1.09E+08	1.18E+08	7.50E+07	8.15E+07
2	8.00E+07	7.75E+07	5.54E+07	5.68E+07
1	6.51E+07	5.88E+07	4.42E+07	4.52E+07
0.5	5.44E+07	4.50E+07	3.72E+07	3.51E+07
0.2	4.17E+07	3.48E+07	3.14E+07	2.72E+07
0.1	3.69E+07	2.96E+07	2.97E+07	2.32E+07
Average |G*|	**8.72E+07**	**9.24E+07**	**6.18E+07**	**6.50E+07**

Table 7.6 – Phase Angle versus Frequency; 5% Boone, 0% LOF @50 Celsius

	Phase Angle, δ, (degree)			
Frequency (Hz)	S5A1-1U	S5A1-2U	S5A1-6C	S5A1-7C
15	44.97	51.57	48.36	49.60
10	43.51	51.49	46.23	48.88
5	41.24	50.58	42.90	47.34
2	37.38	48.40	37.63	44.09
1	34.74	43.87	36.44	41.87
0.5	32.62	42.12	29.97	39.85
0.2	28.52	37.40	25.80	35.07
0.1	24.40	32.13	21.91	30.87
Average delta	**35.92**	**44.69**	**36.16**	**42.20**

Table 7.7 – Dynamic Shear Modulus versus Frequency; 0% Enka, 0.5% LOF @50 Celsius

	Shear Modulus, |G*|, (Pa)			
Frequency (Hz)	S0B0-1U	S0B0-2C	S0B0-3U	S0B0-4C
15	1.45E+08	1.39E+08	1.24E+08	8.18E+07
10	1.18E+08	1.16E+08	9.93E+07	6.59E+07
5	8.45E+07	8.86E+07	7.05E+07	4.75E+07
2	5.69E+07	6.66E+07	4.82E+07	3.28E+07
1	4.31E+07	5.43E+07	3.72E+07	2.55E+07
0.5	3.42E+07	4.64E+07	2.98E+07	2.29E+07
0.2	2.68E+07	3.93E+07	2.32E+07	1.93E+07
0.1	2.26E+07	3.54E+07	2.03E+07	1.73E+07
Average |G*|	**6.64E+07**	**7.32E+07**	**5.66E+07**	**3.91E+07**

Table 7.8 – Phase Angle versus Frequency; 0% Enka, 0.5% LOF @50 Celsius

	Phase Angle, δ, (degree)			
Frequency (Hz)	S0B0-1U	S0B0-2C	S0B0-3U	S0B0-4C
15	50.47	45.62	53.59	53.51
10	50.21	44.01	52.96	51.65
5	48.97	41.36	50.72	47.47
2	46.63	36.23	45.84	41.01
1	45.18	29.96	40.99	34.52
0.5	40.16	32.28	40.53	30.76
0.2	36.29	27.26	35.02	27.46
0.1	33.27	23.99	31.85	23.51
Average delta	**43.90**	**35.09**	**43.94**	**38.74**

Table 7.9 – Dynamic Shear Modulus versus Frequency; 5% Enka, 0.5% LOF @50 Celsius

	Shear Modulus, |G*|, (Pa)			
Frequency (Hz)	S5B0-2U	S5B0-3C	S5B0-5C	S5B0-7U
15	1.54E+08	1.22E+08	1.25E+08	1.34E+08
10	1.26E+08	9.83E+07	1.02E+08	1.10E+08
5	9.25E+07	7.02E+07	7.39E+07	8.00E+07
2	6.53E+07	4.77E+07	5.19E+07	5.56E+07
1	4.95E+07	3.73E+07	3.89E+07	4.45E+07
0.5	4.13E+07	3.03E+07	3.33E+07	3.72E+07
0.2	3.29E+07	2.07E+07	2.64E+07	2.52E+07
0.1	2.94E+07	1.75E+07	2.35E+07	1.64E+07
Average |G*|	**7.39E+07**	**5.54E+07**	**5.93E+07**	**6.28E+07**

Table 7.10 – Phase Angle versus Frequency; 5% Enka, 0.5% LOF @50 Celsius

	Phase Angle, δ, (degree)			
Frequency (Hz)	S5B0-2U	S5B0-3C	S5B0-5C	S5B0-7U
15	48.51	51.91	49.76	49.54
10	47.89	51.27	48.54	48.91
5	46.23	49.32	46.23	47.44
2	43.00	45.89	42.04	43.65
1	39.32	43.31	37.77	44.23
0.5	37.09	39.30	34.16	40.24
0.2	32.50	36.21	30.41	40.60
0.1	28.47	25.87	25.40	31.20
Average delta	**40.38**	**42.88**	**39.29**	**43.23**

Table 7.11 – Dynamic Shear Modulus versus Frequency; 5% Enka, 0% LOF @50 Celsius

	Shear Modulus, |G*|, (Pa)			
Frequency (Hz)	S5B1-1U	S5B1-2C	S5B1-3C	S5B1-4U
15	1.58E+08	1.11E+08	1.04E+08	1.30E+08
10	1.29E+08	8.95E+07	8.47E+07	1.05E+08
5	9.30E+07	6.44E+07	6.17E+07	7.48E+07
2	6.29E+07	4.43E+07	4.24E+07	3.12E+07
1	4.82E+07	3.52E+07	3.29E+07	2.53E+07
0.5	3.77E+07	2.74E+07	2.71E+07	1.69E+07
0.2	2.93E+07	2.20E+07	2.11E+07	1.52E+07
0.1	2.49E+07	1.90E+07	1.86E+07	1.09E+07
Average |G*|	**7.28E+07**	**5.16E+07**	**4.91E+07**	**5.11E+07**

Table 7.12 – Phase Angle versus Frequency; 5% Enka, 0% LOF @50 Celsius

	Phase Angle, δ, (degree)		
Frequency (Hz)	S5B1-1U	S5B1-2C	S5B1-3C
15	48.92	50.97	50.80
10	48.92	50.19	49.94
5	48.07	47.95	48.05
2	46.34	44.28	44.68
1	44.95	42.13	42.12
0.5	41.16	36.71	39.51
0.2	37.11	31.00	35.26
0.1	34.89	29.95	37.03
Average delta	**43.80**	**41.65**	**43.42**

Table 7.13 – Average Dynamic Shear Modulus versus Frequency: Boone BHF @20 Celsius

	Shear Modulus, |G*|, (pa)					
	BHF:5%, LOF:0.5%		BHF:5%, LOF:0.0%		BHF:0%, LOF:0.5%	
Frequency (HZ)	Dry	Wet	Dry	Wet	Dry	Wet
10	4.39E+09	2.51E+09	2.44E+09	3.29E+09	3.35E+09	3.39E+09
5	2.96E+09	1.86E+09	1.96E+09	2.22E+09	2.43E+09	1.93E+09
2	1.61E+09	1.03E+09	1.21E+09	1.27E+09	1.39E+09	1.12E+09
1	2.44E+09	9.65E+08	1.25E+09	1.21E+09	1.59E+09	9.79E+08
0.5	1.47E+09	6.50E+08	9.24E+08	7.65E+08	9.86E+08	6.68E+08
0.2	7.86E+08	4.07E+08	6.01E+08	4.73E+08	5.92E+08	4.19E+08
0.1	5.61E+08	2.93E+08	4.45E+08	3.36E+08	4.27E+08	3.03E+08
Average	**2.03E+09**	**1.10E+09**	**1.26E+09**	**1.37E+09**	**1.54E+09**	**1.25E+09**

Table – 7.14 Average Phase Angle versus Frequency: Boone BHF @20 Celsius

	Phase Angle, δ, (degree)					
	BHF:5%, LOF:0.5%		BHF:5%, LOF:0.0%		BHF:0%, LOF:0.5%	
Frequency (HZ)	Dry	Wet	Dry	Wet	Dry	Wet
10	3	18	12	18	12	22
5	11	22	16	25	18	27
2	17	28	21	30	22	29
1	25	32	23	32	26	35
0.5	26	37	28	38	33	38
0.2	33	41	34	42	38	41
0.1	36	43	37	44	41	42
Average	**22**	**32**	**24**	**33**	**27**	**33**

Table 7.15 – Average Dynamic Shear Modulus versus Frequency: Enka BHF @20 Celsius

	Shear Modulus, |G*|, (pa)					
	BHF:5%, LOF:0.5%		BHF:5%, LOF:0.0%		BHF:0%, LOF:0.5%	
Frequency (HZ)	Dry	Wet	Dry	Wet	Dry	Wet
10	3.36E+09	2.46E+09	3.10E+09	2.99E+09	3.00E+09	2.46E+09
5	2.41E+09	1.86E+09	2.29E+09	1.91E+09	2.03E+09	1.96E+09
2	1.36E+09	1.14E+09	1.30E+09	1.09E+09	1.14E+09	1.18E+09
1	1.77E+09	1.07E+09	1.43E+09	1.07E+09	1.03E+09	1.11E+09
0.5	1.13E+09	7.65E+08	9.86E+08	7.38E+08	7.03E+08	7.89E+08
0.2	6.47E+08	4.86E+08	6.06E+08	4.67E+08	4.45E+08	4.92E+08
0.1	4.67E+08	3.55E+08	4.43E+08	3.41E+08	3.25E+08	3.56E+08
Average	**1.59E+09**	**1.17E+09**	**1.45E+09**	**1.23E+09**	**1.24E+09**	**1.19E+09**

Table 7.16 – Average Phase Angle versus Frequency: Enka BHF @20 Celsius

	Phase Angle, δ, (degree)					
	BHF:5%, LOF:0.5%		BHF:5%, LOF:0.0%		BHF:0%, LOF:0.5%	
Frequency (HZ)	Dry	Wet	Dry	Wet	Dry	Wet
10	9	17	10	14	19	20
5	15	21	16	20	23	22
2	20	23	21	25	27	26
1	26	28	23	28	32	29
0.5	29	33	30	34	37	34
0.2	34	37	35	37	40	38
0.1	37	40	38	40	42	40
Average	**24**	**28**	**25**	**28**	**31**	**30**

Table 7.17 – Summary of Average Material Properties for Boone Set @ 20 Celsius at 10 Hz Frequency

		G* 10 Hz (psi)	δ 10 Hz (degree)	S_0 (psi)	S_0'' (psi)	VFA (%)	Air Voids (%)
BHF: 5%, LOF:0.5%	Dry	6.36E+05	10	1.70E+06	3.68E+05	68.45	5.77
	Wet	3.64E+05	18	1.02E+06	3.72E+05	67.30	6.05
BHF: 5%, LOF: 0%	Dry	3.54E+05	12	9.97E+05	2.74E+05	67.91	5.75
	Wet	4.77E+05	18	1.31E+06	4.53E+05	66.65	6.07
BHF: 0%, LOF: 0.5%	Dry	4.86E+05	12	1.33E+06	3.45E+05	65.92	6.11
	Wet	4.92E+05	22	1.35E+06	5.33E+05	65.30	6.28

Table 7.18 – Summary of Average Material Properties for Enka Set @ 20 Celsius at 10 Hz Frequency

		G* 10 Hz (psi)	δ 10 Hz (degree)	S_0 (psi)	S_0'' (psi)	VFA (%)	Air Voids (%)
BHF: 5%, LOF:0.5%	Dry	4.87E+05	9	1.33E+06	2.81E+05	65.52	6.15
	Wet	3.57E+05	17	1.00E+06	3.53E+05	66.04	6.02
BHF: 5%, LOF: 0%	Dry	4.50E+05	10	1.24E+06	2.86E+05	68.20	5.73
	Wet	4.33E+05	14	1.20E+06	3.54E+05	66.50	6.16
BHF: 0%, LOF: 0.5%	Dry	4.35E+05	19	1.20E+06	4.40E+05	66.56	6.12
	Wet	3.57E+05	20	1.00E+06	3.95E+05	66.63	6.10

Table 7.19 – Comparison of Fatigue Life for Boone Set @ 20 Celsius

		VFA (%)	Strain ε	S_0'' (psi)	N_{supply}	M*	N_{demand}	Difference
BHF: 5%, LOF: 0.5%	Dry	68.5	84.3×10^{-6}	3.68×10^{5}	2.25×10^{7}	4.303	5.24×10^{6}	72%
	Wet	67.3	116×10^{-6}	3.72×10^{5}	6.25×10^{6}	4.303	1.45×10^{6}	
BHF: 5%, LOF: 0%	Dry	67.9	118×10^{-6}	2.74×10^{5}	1.44×10^{7}	4.303	3.34×10^{6}	58%
	Wet	66.7	99.4×10^{-6}	4.53×10^{5}	6.11×10^{6}	4.303	1.42×10^{6}	
BHF: 0%, LOF: 0.5%	Dry	65.9	98.5×10^{-6}	3.45×10^{5}	1.26×10^{7}	4.303	2.93×10^{6}	70%
	Wet	65.3	97.6×10^{-6}	5.33×10^{5}	3.80×10^{6}	4.303	8.82×10^{5}	

Table 7.20 – Comparison of Fatigue Life for Enka Set @ 20 Celsius

		VFA (%)	Strain ε	S_0'' (psi)	N_{supply}	M*	N_{demand}	Difference
BHF: 5%, LOF: 0.5%	Dry	65.5	98.5×10^{-6}	2.81×10^{5}	2.13×10^{7}	4.303	4.95×10^{6}	70%
	Wet	66.0	118×10^{-6}	3.53×10^{5}	6.29×10^{6}	4.303	1.46×10^{6}	
BHF: 5%, LOF: 0%	Dry	68.2	103×10^{-6}	2.86×10^{5}	2.13×10^{7}	4.303	4.95×10^{6}	54%
	Wet	66.5	99.4×10^{-6}	3.54×10^{5}	9.73×10^{6}	4.303	2.26×10^{6}	
BHF: 0%, LOF: 0.5%	Dry	66.6	105×10^{-6}	4.40×10^{5}	5.39×10^{6}	4.303	1.25×10^{6}	10%
	Wet	66.6	105×10^{-6}	3.95×10^{5}	4.84×10^{6}	4.303	1.12×10^{6}	

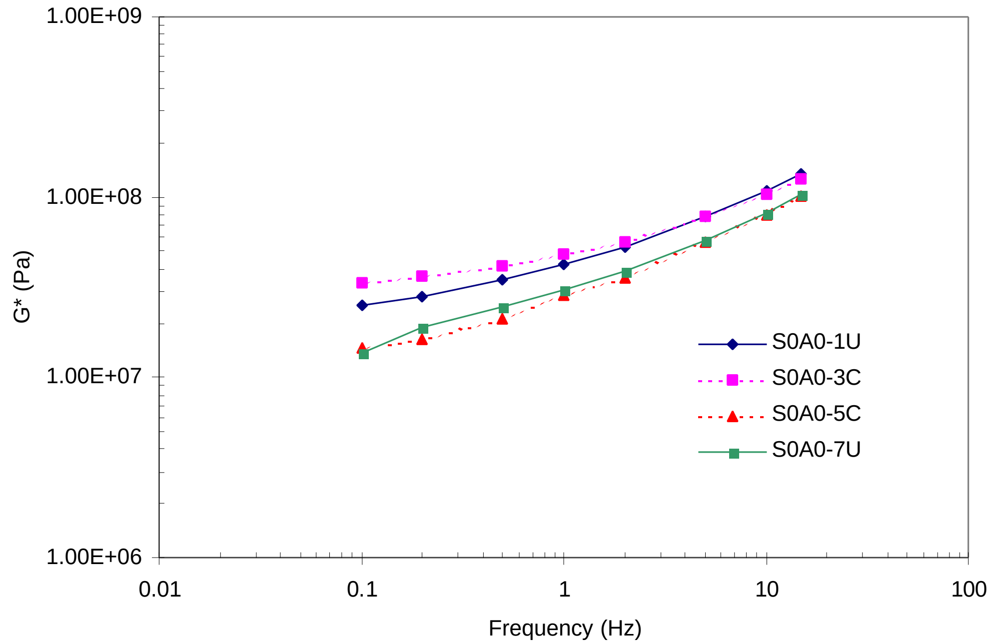


Figure 7.1 - Dynamic Shear Modulus versus Frequency; 0% Boone, 0.5% LOF, @50 Celsius

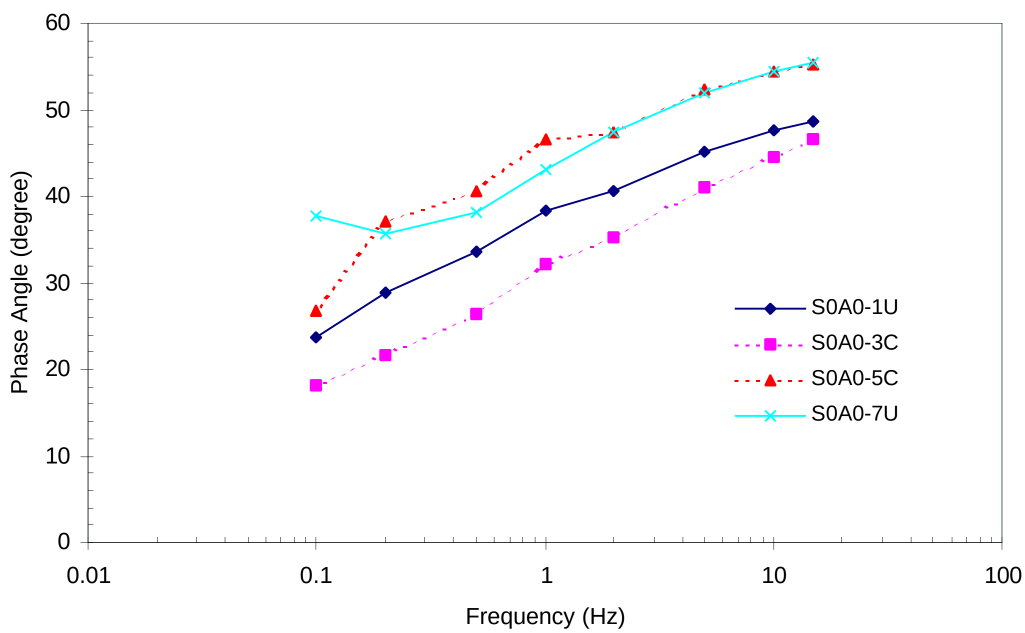


Figure 7.2 – Phase Angle versus Frequency; 0% Boone, 0.5% LOF, @50 Celsius

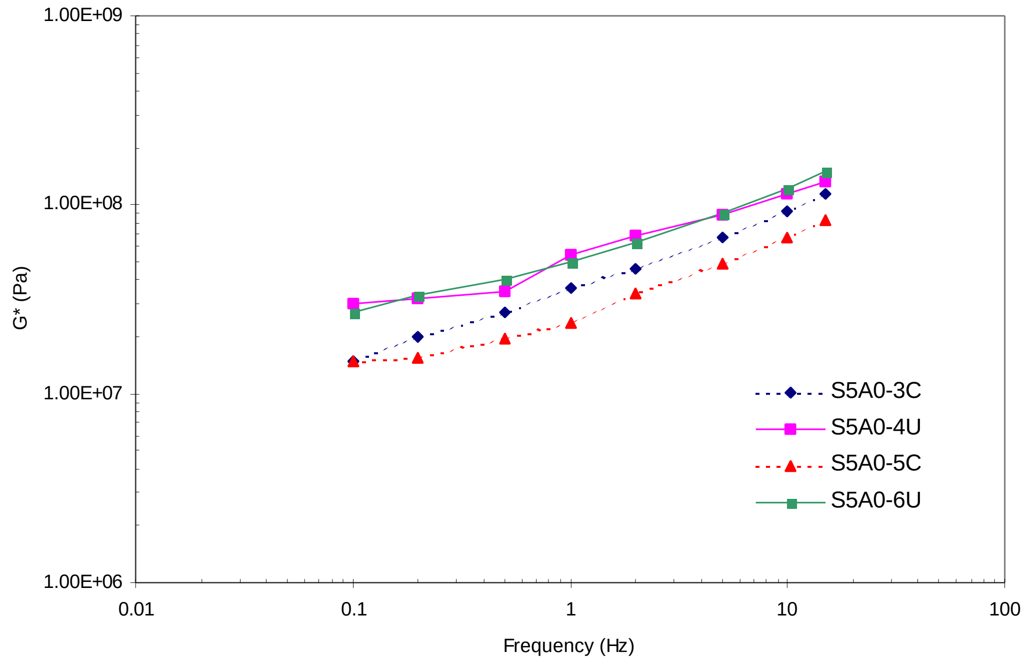


Figure 7.3 - Dynamic Shear Modulus versus Frequency; 5% Boone, 0.5% LOF, @50 Celsius

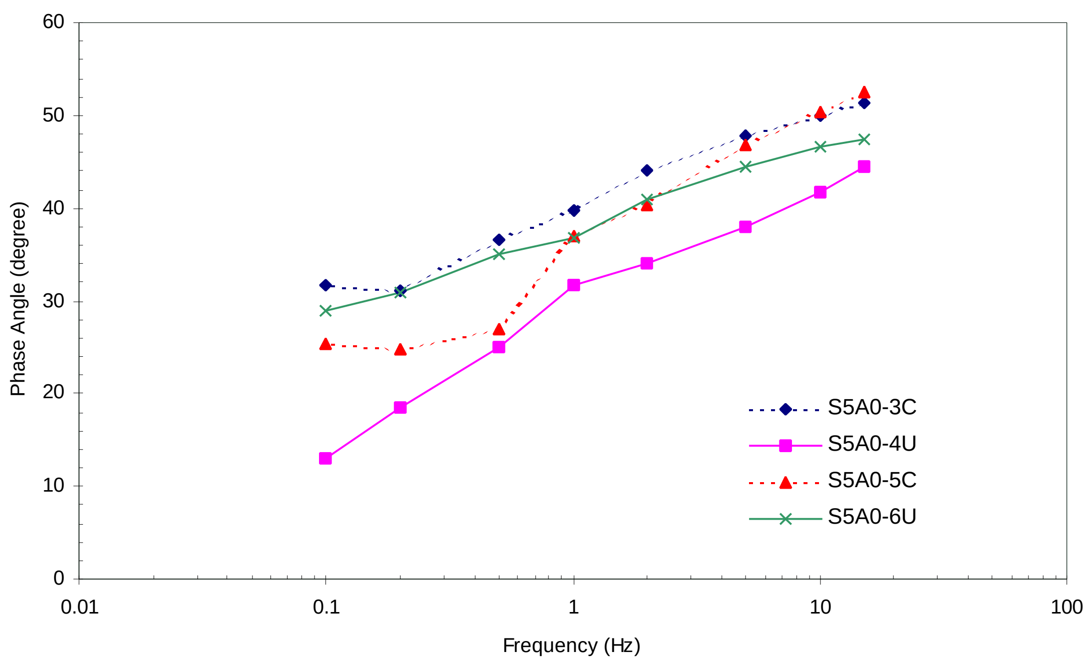


Figure 7.4 – Phase Angle versus Frequency; 5% Boone, 0.5% LOF, @50 Celsius

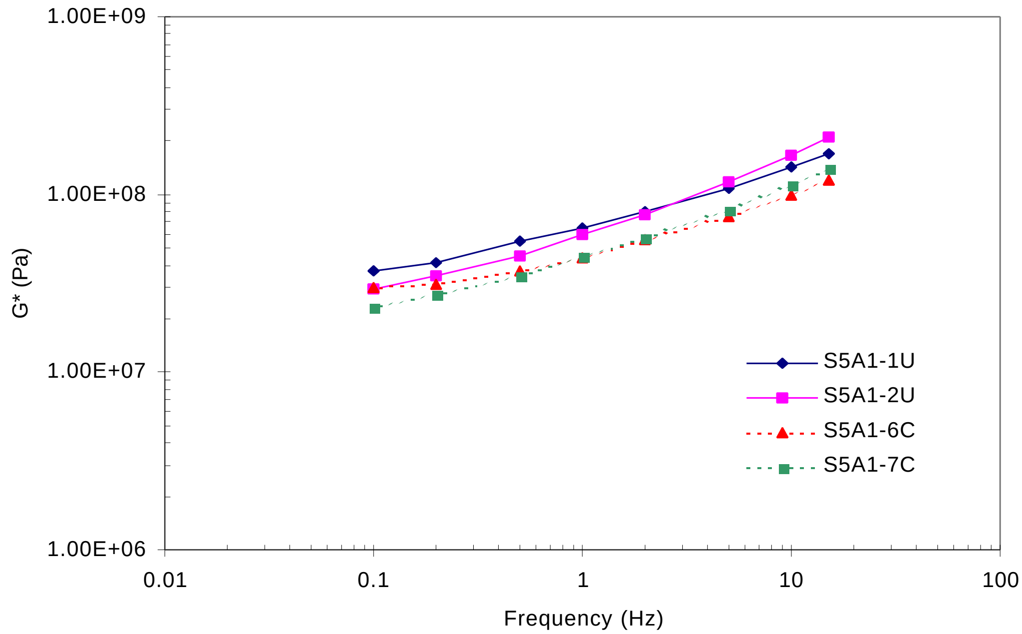


Figure 7.5 - Dynamic Shear Modulus versus Frequency; 5% Boone, 0% LOF, @50 Celsius

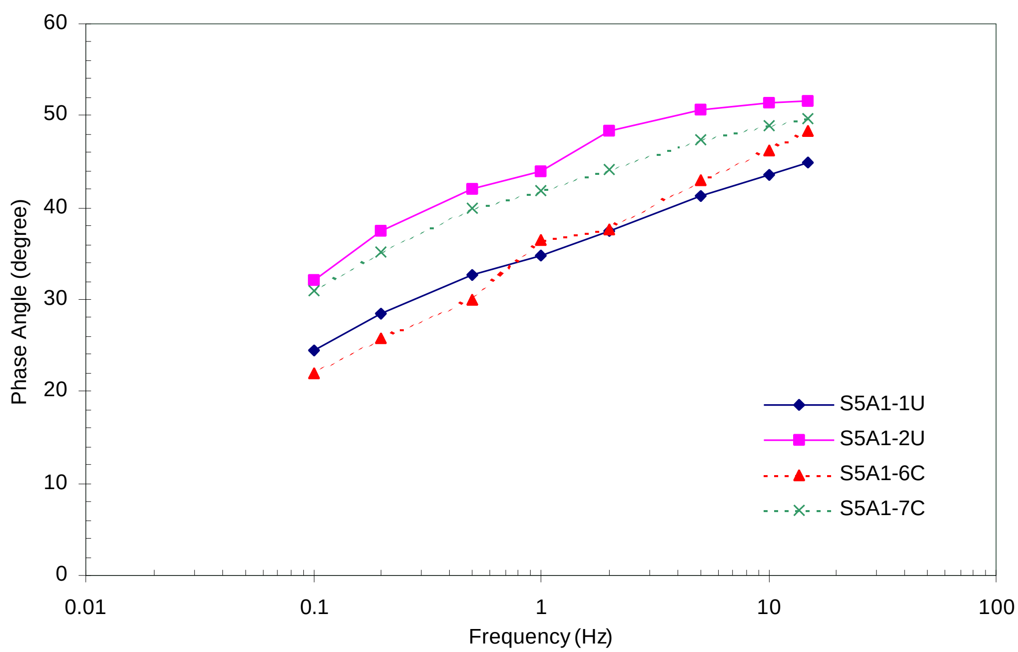


Figure 7.6 – Phase Angle versus Frequency; 5% Boone, 0% LOF, @50 Celsius

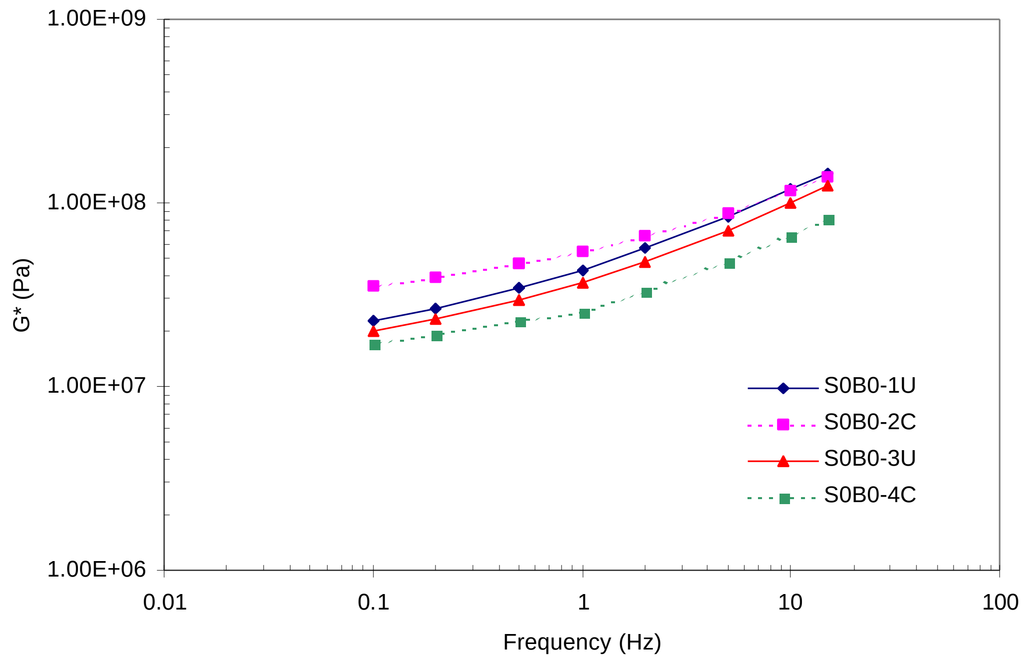


Figure 7.7 - Dynamic Shear Modulus versus Frequency; 0% Enka, 0.5% LOF, @50 Celsius

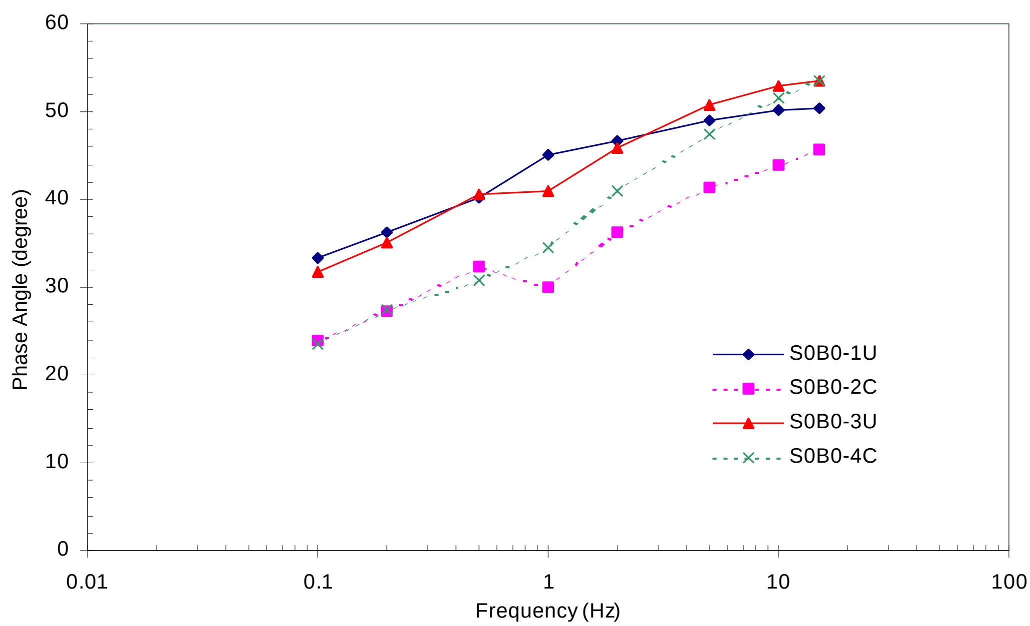


Figure 7.8 – Phase Angle versus Frequency; 0% Enka, 0.5% LOF, @50 Celsius

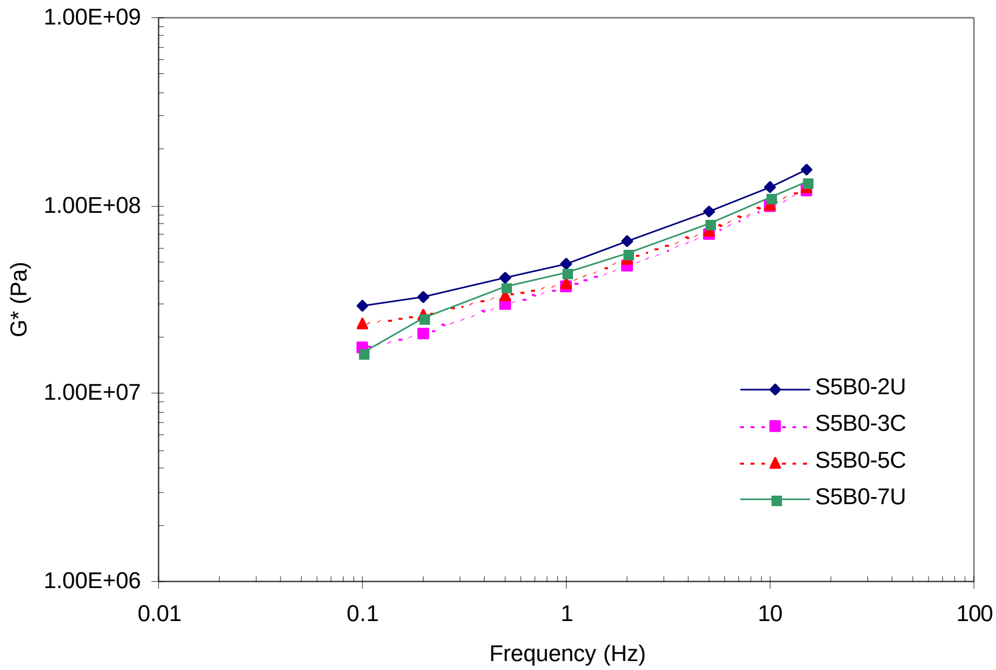


Figure 7.9 - Dynamic Shear Modulus versus Frequency; 5% Enka, 0.5% LOF, @50 Celsius

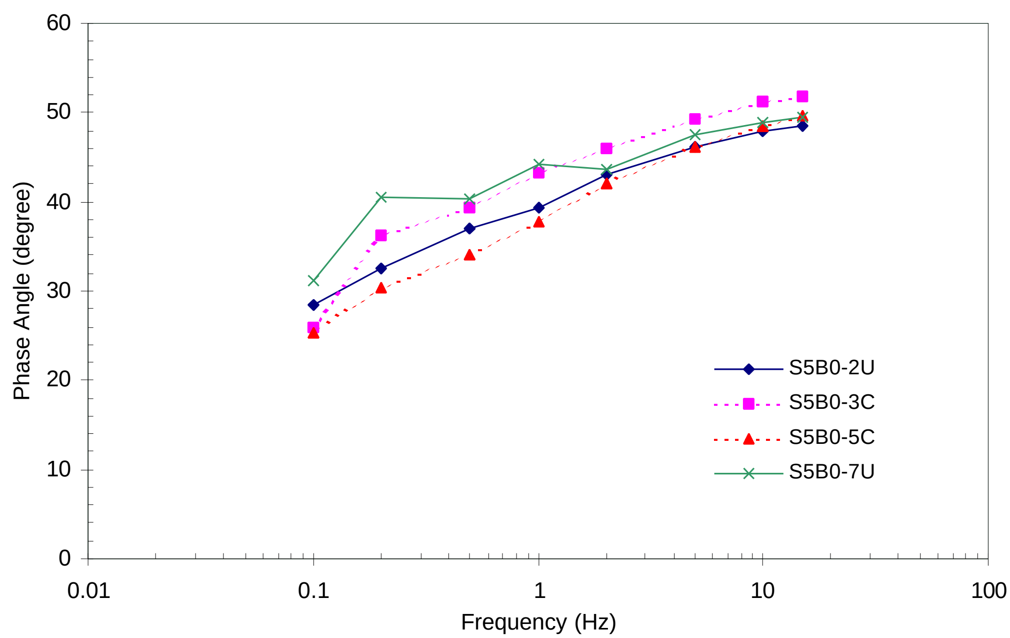


Figure 7.10 – Phase Angle versus Frequency; 5% Enka, 0.5% LOF, @50 Celsius

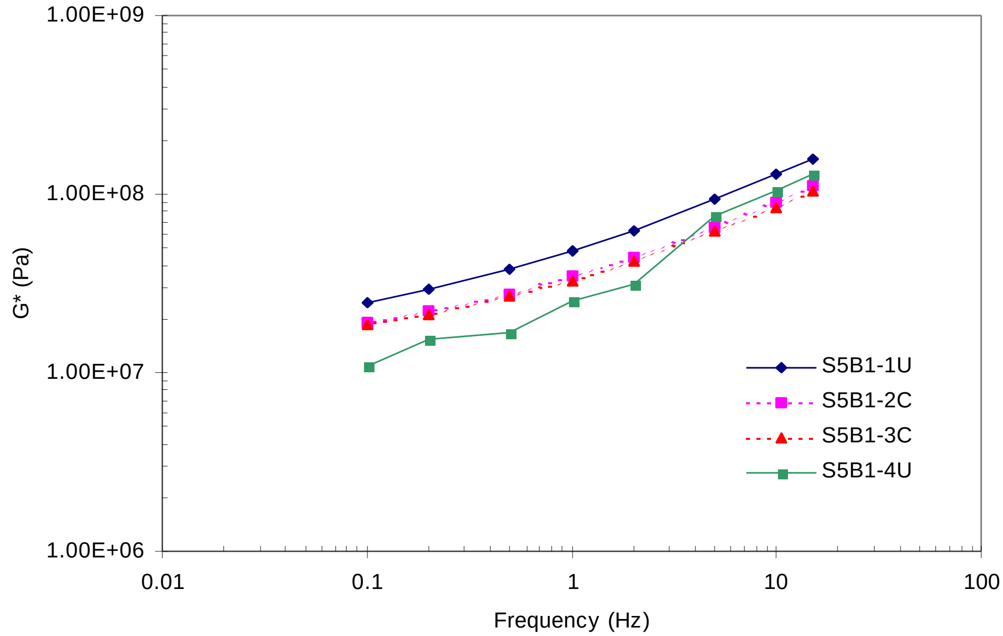


Figure 7.11 - Dynamic Shear Modulus versus Frequency; 5% Enka, 0% LOF, @50 Celsius

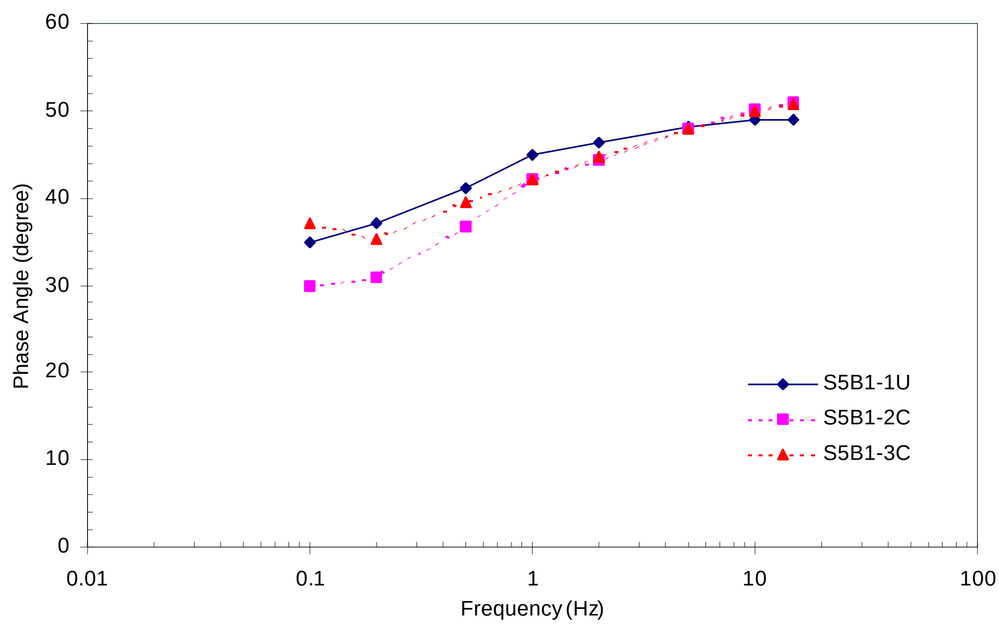


Figure 7.12 – Phase Angle versus Frequency; 5% Enka, 0% LOF, @50 Celsius

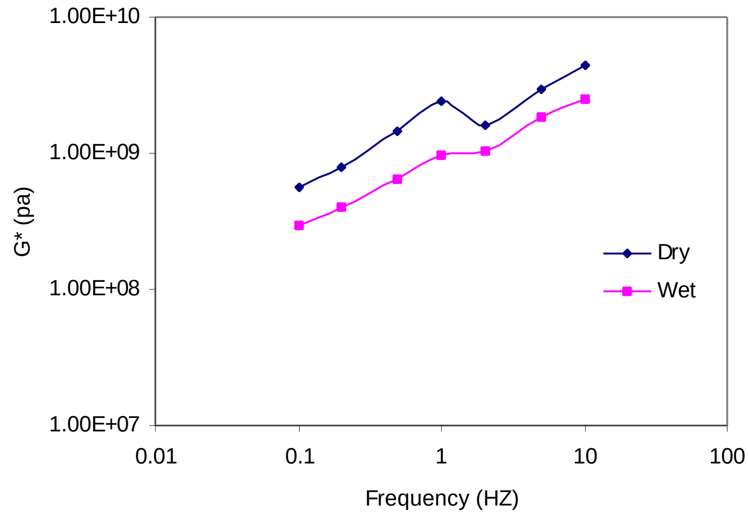


Figure 7.13 – Dynamic Shear Modulus vs. Frequency: 5% Boone, 0.5% LOF, @20 Celsius

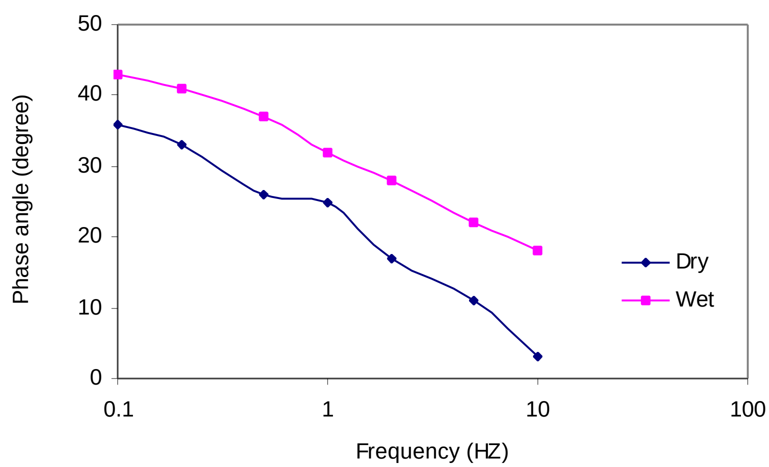


Figure 7.14 – Phase Angle vs. Frequency: 5% Boone, 0.5% LOF, @20 Celsius

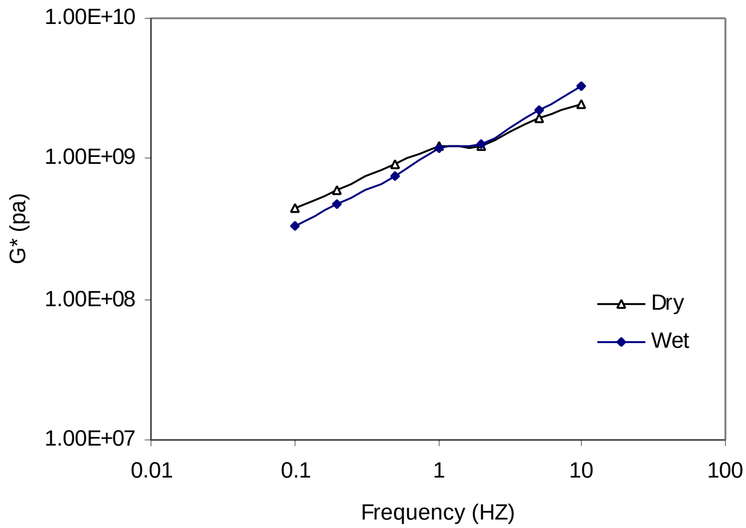


Figure 7.15 – Dynamic Shear Modulus vs. Frequency: 5% Boone, 0% LOF, @20 Celsius

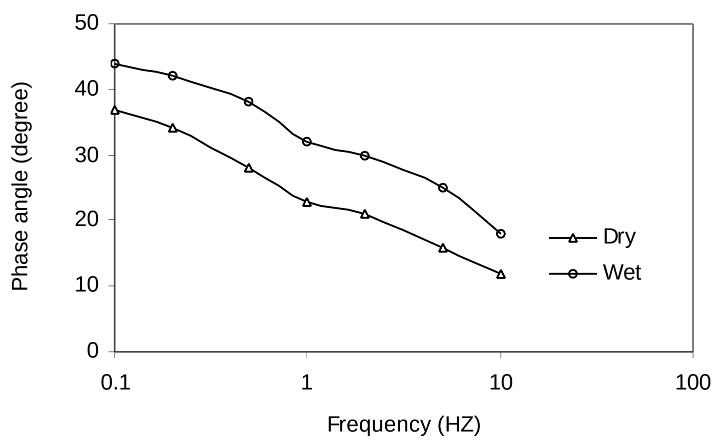


Figure 7.16 – Phase Angle vs. Frequency: 5% Boone, 0% LOF, @20 Celsius

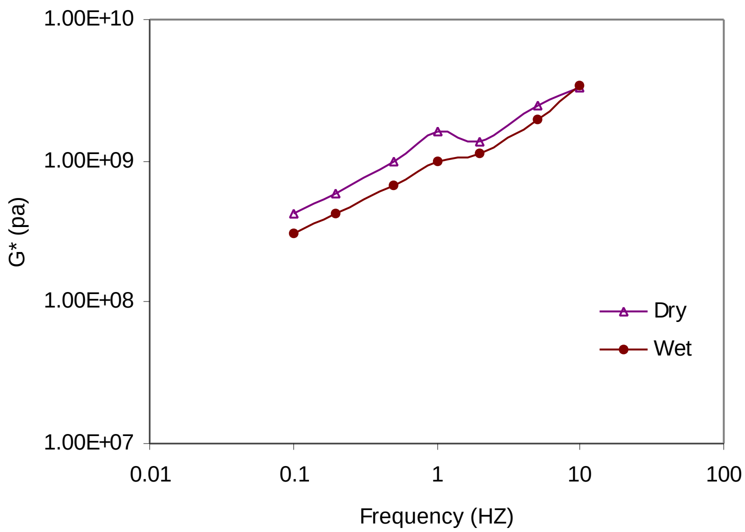


Figure 7.17 – Dynamic Shear Modulus vs. Frequency: 0% Boone, 0.5% LOF, @20 Celsius

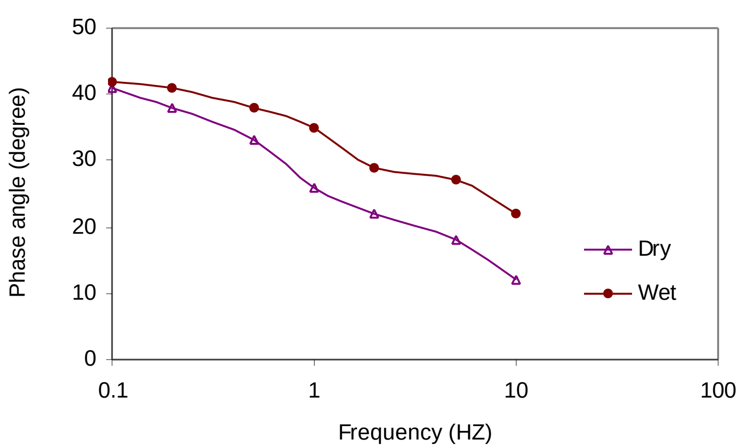


Figure 7.18 – Phase Angle vs. Frequency: 0% Boone, 0.5% LOF, @20 Celsius

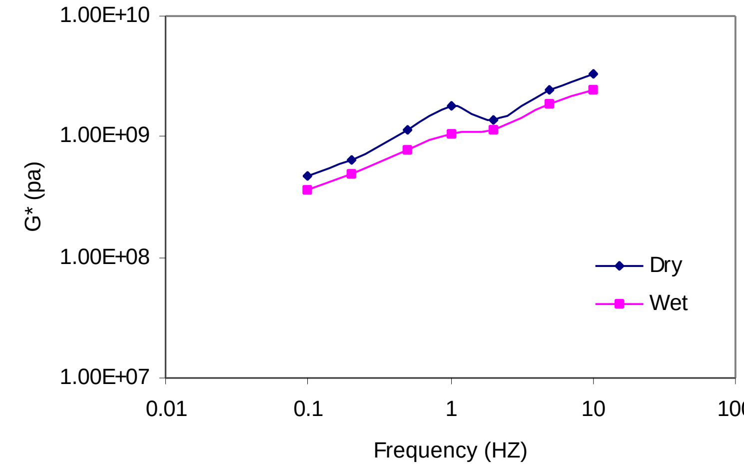


Figure 7.19 – Dynamic Shear Modulus vs. Frequency: 5% Enka, 0.5% LOF, @20 Celsius

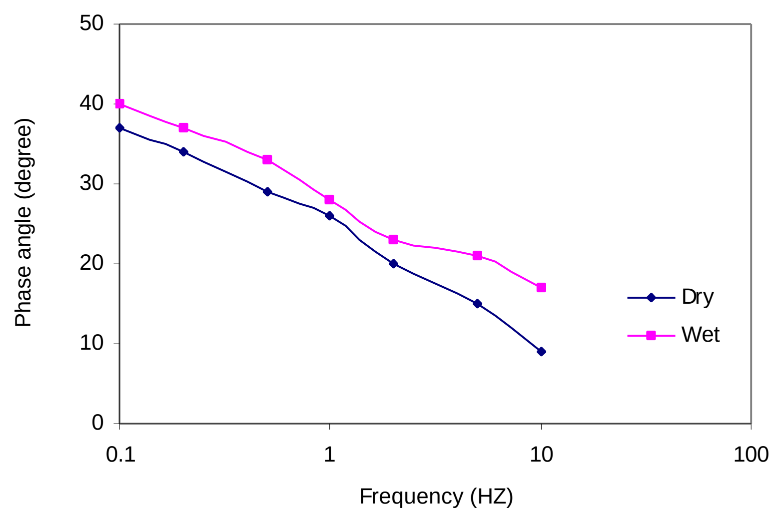


Figure 7.20 – Phase Angle vs. Frequency: 5% Enka, 0.5% LOF, @20 Celsius

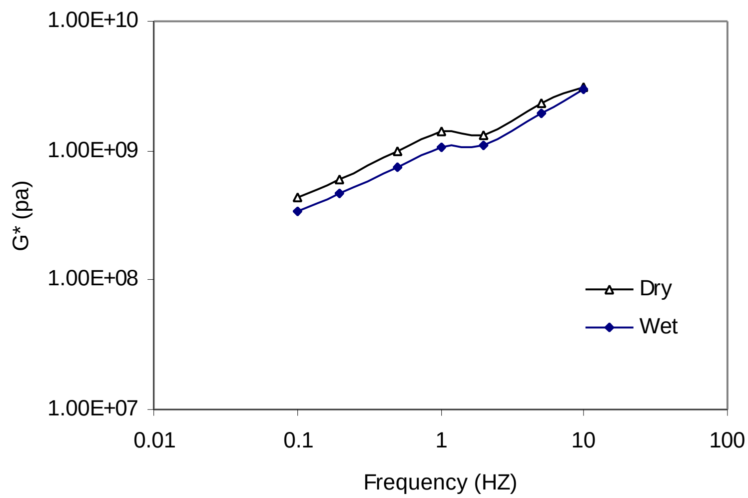


Figure 7.21 – Dynamic Shear Modulus vs. Frequency: 5% Enka, 0% LOF, @20 Celsius

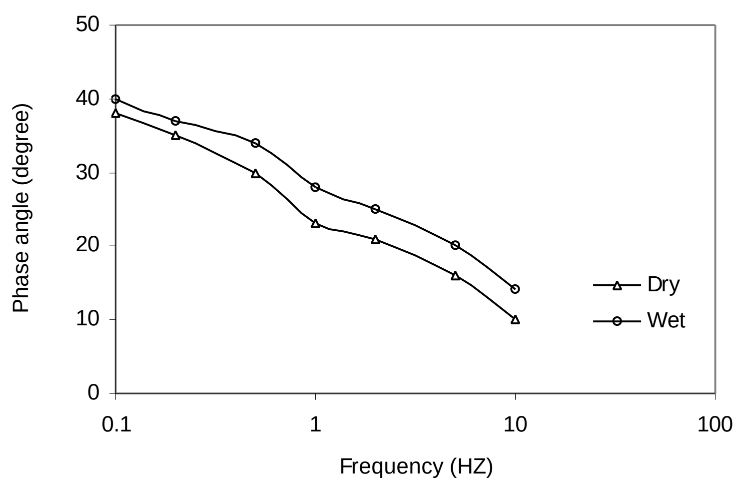


Figure 7.22 – Phase Angle vs. Frequency: 5% Enka, 0% LOF, @20 Celsius

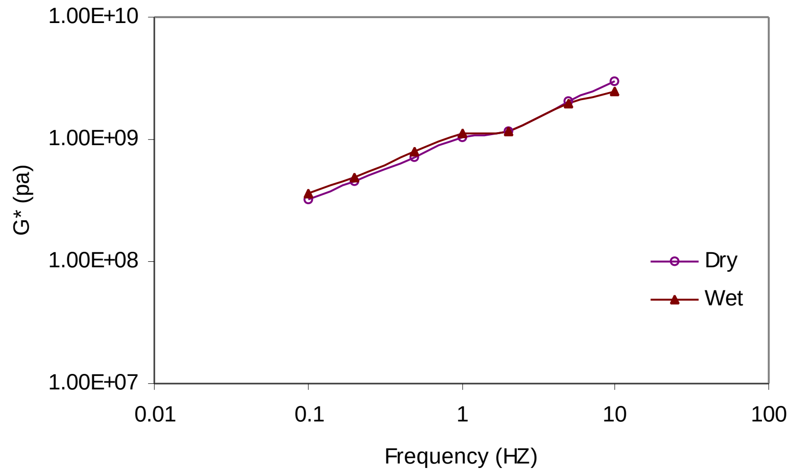


Figure 7.23 – Dynamic Shear Modulus vs. Frequency: 0% Enka, 0.5% LOF, @20 Celsius

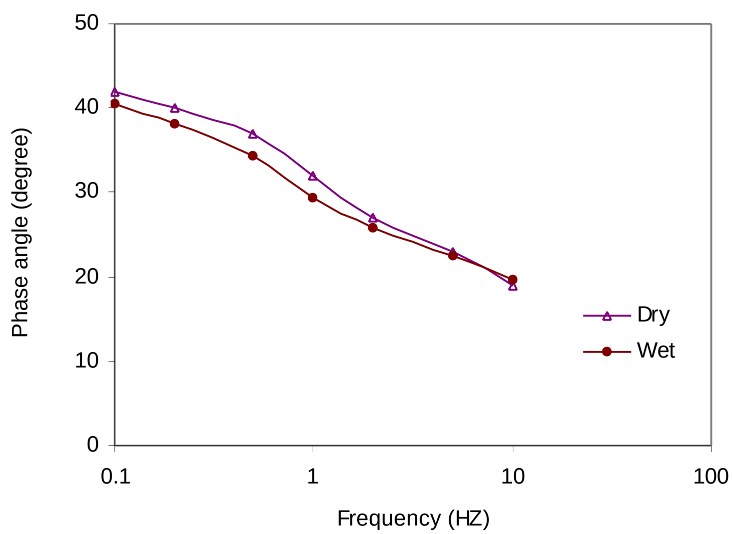


Figure 7.24 – Phase Angle vs. Frequency: 0% Enka, 0.5% LOF, @20 Celsius

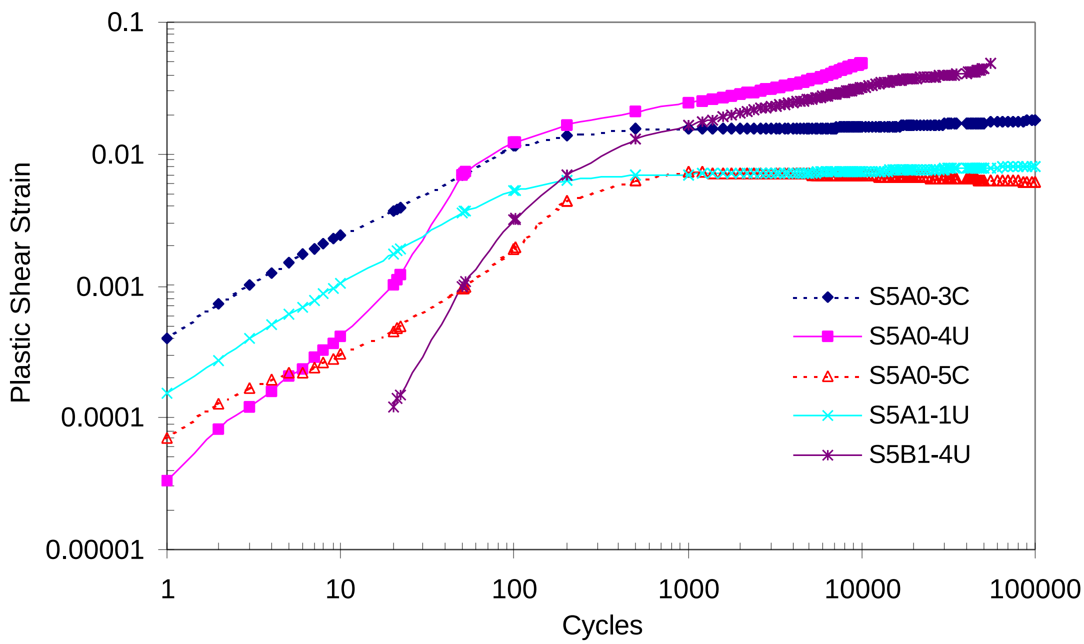


Figure 7.25 – Plastic Shear Strain versus Number of Cycles; 100,000 Cycle Trials

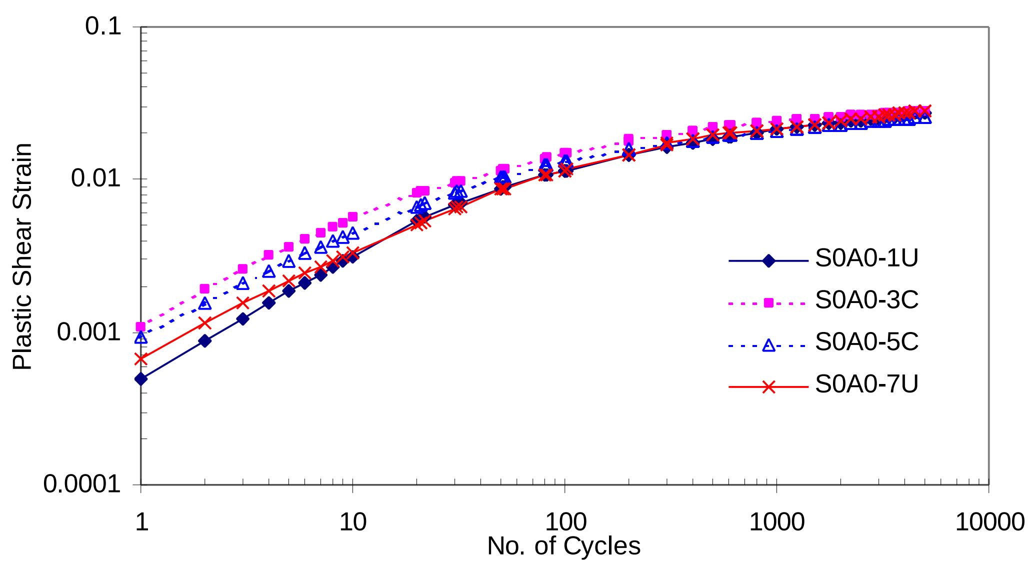


Figure 7.26 – Plastic Shear Strain versus Number of Cycles; 0% Boone, 0.5% LOF

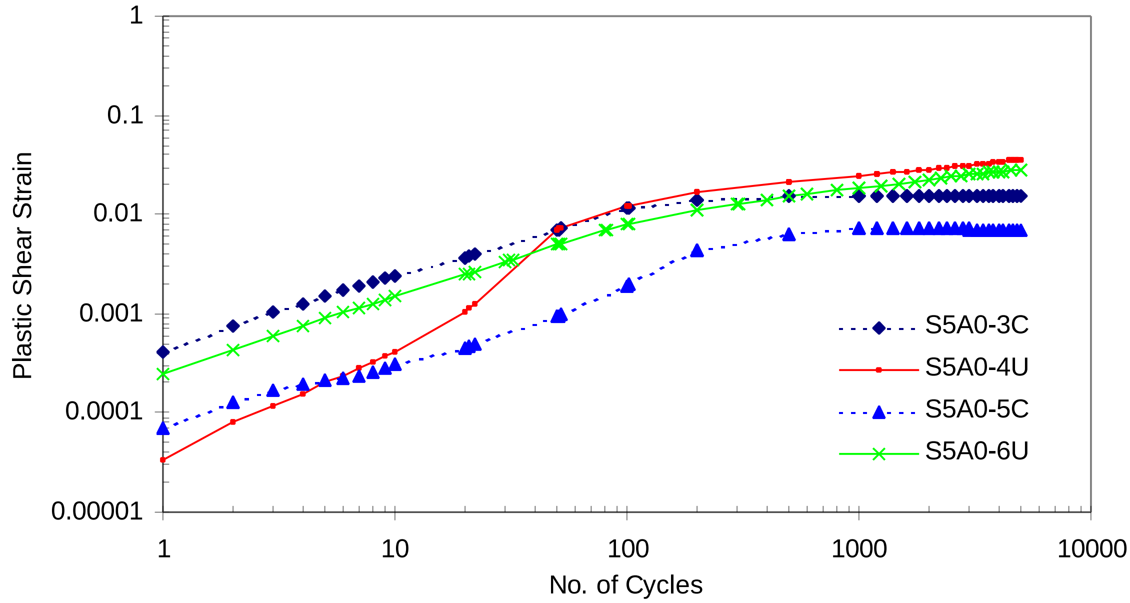


Figure 7.27 – Plastic Shear Strain versus Number of Cycles; 5% Boone, 0.5% LOF

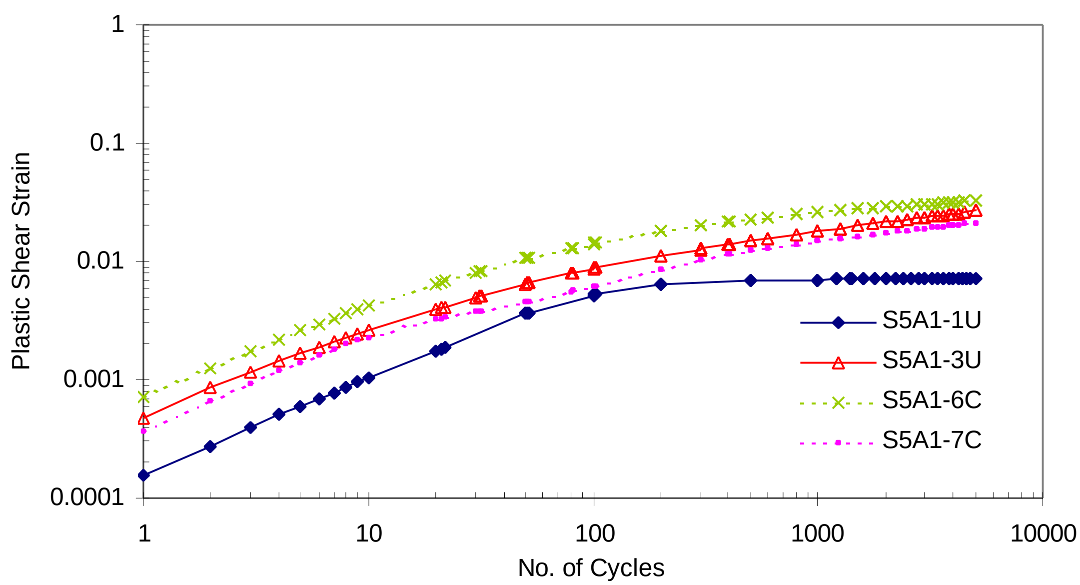


Figure 7.28 – Plastic Shear Strain versus Number of Cycles; 5% Boone, 0% LOF

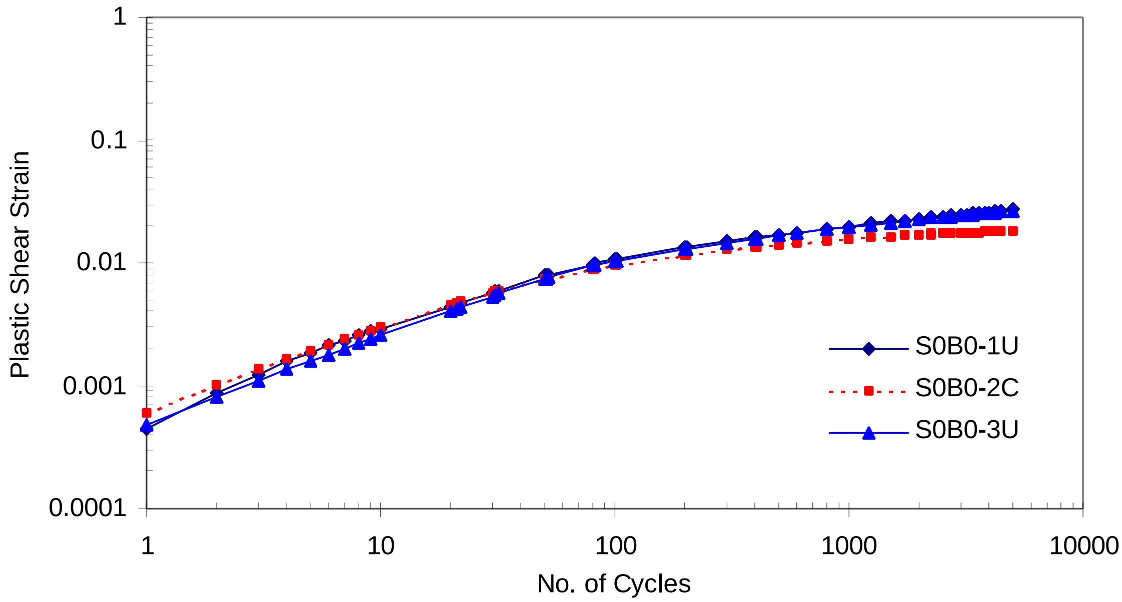


Figure 7.29 – Plastic Shear Strain versus Number of Cycles; 0% Enka, 0.5% LOF

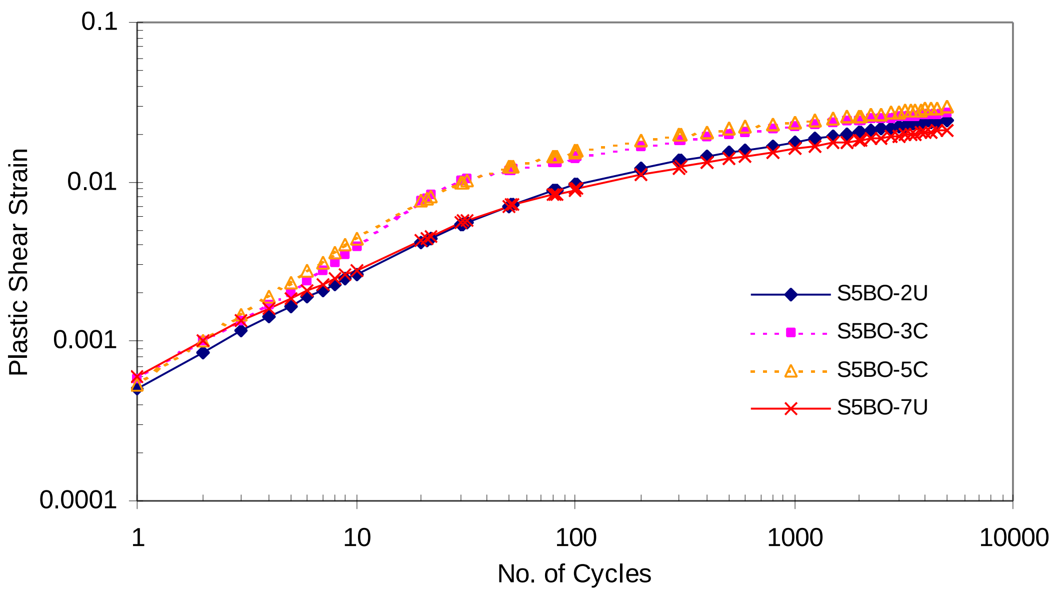


Figure 7.30 – Plastic Shear Strain versus Number of Cycles; 5% Enka, 0.5% LOF

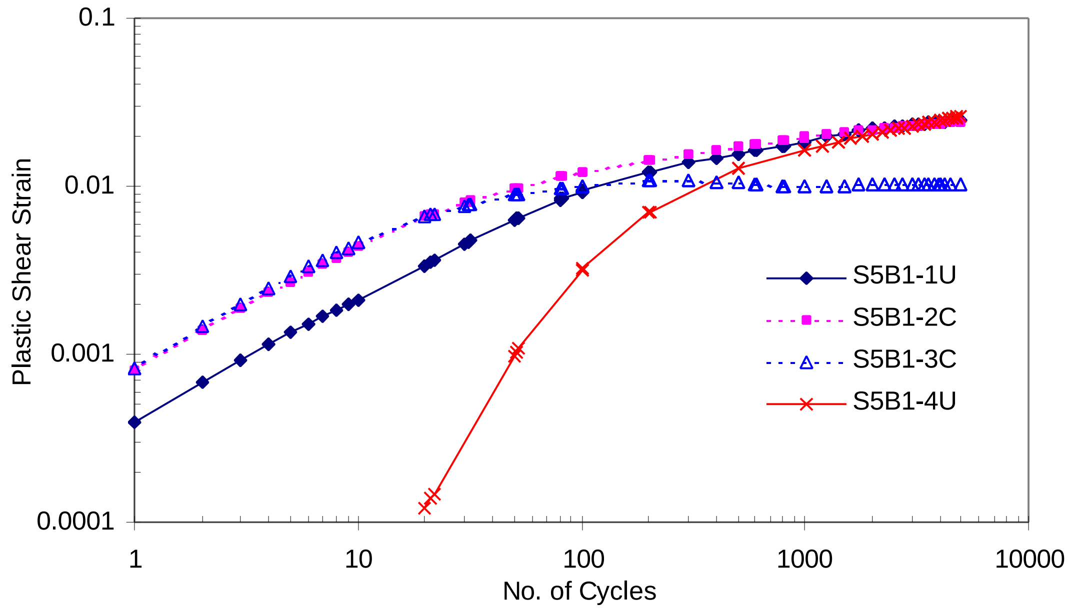


Figure 7.31 – Plastic Shear Strain versus Number of Cycles; 5% Enka, 0% LOF

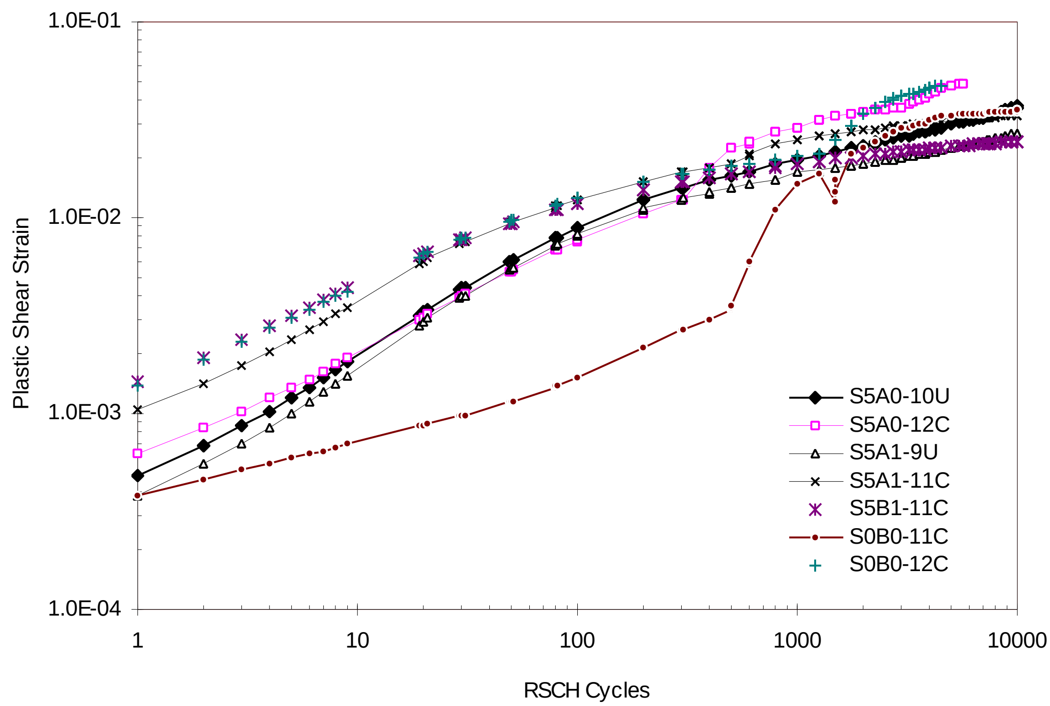


Figure 7.32 – Plastic Shear Strain versus Number of Cycles For Enka and Boone

8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

In this study, the effects of baghouse fines concentrations on moisture sensitivity of asphalt mixes were determined for mixes with and without anti-strip additive. Two different types of baghouse fines, one from Boone, NC and one from Enka, NC, were used in HMA mixtures in different concentrations. Anti-strip additive used was LOF-6500. Using a JMF and materials provided by NCDOT, specimens were prepared in the laboratory and several different tests were performed.

Sieve analysis and particle analysis were used to produce gradations for aggregate mixtures with different baghouse fines. TSR testing was conducted to determine the severity of moisture damage due to concentrations of baghouse fines. The TSR testing was also conducted on specimens without anti-strip additive to determine the effectiveness of the additive. The TSR tests showed that the concentration of baghouse fines had a slight effect on moisture susceptibility while the anti-strip additive had a profound effect in preventing moisture damage.

In order to determine the effects of conditioning on rutting resistance, APA testing was performed on the specimens. Samples were tested dry as well as conditioned and the rut depth results were compared. Due to testing differences, the dry values were not comparable to the conditioned specimens. The results showed an increase in permanent deformation (rut depth) in the specimens without additive for both baghouse fines types.

Finally, specimens were 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, conditioning reduced rutting resistance and fatigue resistance of the mixes. Although, the TSR test result showed that an LOF-6500 anti-strip dosage of 0.5% was sufficient to reduce moisture damage to the point that the mixes would be acceptable under the current NCDOT criterion of 85 percent retained strength, the FSCH and RSCH test results indicate that severe damage will be prevalent in mixes, especially those with high percentage of BHF. The FSCH and RSCH test results indicate that in general, moisture conditioning will lead to reduction in stiffness, rutting resistance, and fatigue resistance.

8.2 Conclusions

Conclusions based on the test results of this study are the following.

1. Variation in baghouse fines gradations and concentrations can lead to changes in mixture behavior.
2. The amount of LOF-6500 anti-strip additive required in the JMF was sufficient to prevent moisture damage as measured by TSR testing for both baghouse fines types, with up to 5 percent additional BHF (total of 6.5 percent). However, material characterization tests indicate that mixtures containing high amount of BHF are moisture sensitive and may lead to premature failure of the pavement.
3. The rutting resistance of the conditioned specimens was reduced by the absence of anti-strip additive as shown in the APA test.

4. In general, HMA stiffness increased with an increase in baghouse fines contents as shown in the TSR indirect-tensile-strength values and the FSCH shear moduli values.
5. Fatigue life of mixtures also increased with increased amount of BHF. However, these mixtures were moisture susceptible.

8.3 Recommendations

Based on the results of this study, it may be noted that although, the mixtures tested would be acceptable with higher amount of BHF as per the TSR test results and current NCDOT acceptance criterion of 85 percent retained strength, these mixtures were found to be susceptible to severe moisture damage based on the mix performance testing.

It is therefore recommended that NCDOT should reconsider the current practice by asphalt mix plants to purge baghouse fines intermittently into the mix. As the results in this study have shown, this practice has the potential to produce mixes with variable material properties and moisture sensitivity. At the least, the baghouse fines should be metered into the mix. However, it may be desirable to waste some of these fines completely as is the practice by several state departments of transportation.

9. REFERENCES

1. American Association of State Highway and Transportation Officials, "*Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt Using a Simple Shear Test Device*, " AASHTO Designation TP7, (1996).

2. American Society of Testing and Materials, 1994 Annual Book of ASTM Standards, Section 4, Volume 04.03, Philadelphia, PA, (1990).

3. Anderson, D.A., Tarris, J.P., and Brock, J.D., "Dust Collector Fines and Their Influence on Mixture Design," *Proceedings of the Association of Asphalt Paving Technologists,* Vol. 51 (1982), pp. 363-397.

4. Birdsall, B.G., "An Evaluation of Moisture Susceptibility of Asphalt Mixtures," *Department of Civil Engineering, North Carolina State University, Thesis*, (1999).

5. Eick, J.H. and Shook, J.F., "The Effects of Baghouse Fines on Asphalt Mixtures," *The Asphalt Institute Technical Report RR-78-3,* (Nov., 1978), pp. 3-44.

6. Hanson, D.I. and Cooley, A.L., "Baghouse Fines in Asphalt Mixes," *National Center for Asphalt Technology, Auburn University,* (Nov., 1997).

7. Hicks, R.G., "Moisture Damage in Asphalt Concrete," *NCHRP Synthesis of Highway Practice 175*, Transportation Research Board, Washington, D.C., (1991).

8. Kandhal, P.S., "Evaluation of Baghouse Fines in Bituminous Paving Mixtures," *Proceedings of the Association of Asphalt Paving Technologists,* Vol. 50 (1981), pp. 150-210.

9. Kulkarni, M.B., "A Study of Mineral Fillers and Their Effect on Mix Properties," *North Carolina State University,* (1998).

10. Puzinauskas, V.P., "Filler in Asphalt Mixtures," *The Asphalt Institute Research Report 69-2*, (1969).

11. Tayebali, A.A., Kulkarni, M.B., and Waller, H.F., "Delamination and Shoving of Asphalt Concrete Layers Containing Baghouse Fines," *Department of Civil Engineering, North Carolina State University, Technical Report*, (May 2000).

12. Tayebali, A.A., Natu, G.S., and Kulkarni, M.B., "Comparison of Material Properties and Life of Pavement Sections Containing Mixes With and Without Non-Strip Additives," *Department of Civil Engineering, North Carolina State University, Technical Report*, (June, 1998).

13. Tunnicliff, D.G., “A Review of Mineral Filler,” *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 31, pp. 118-150, (1962).

14. Tunnicliff, D.G., “Binding Effects of Mineral Filler,” *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 36, pp. 114-156, (1967).

15. Turner Fairbank Highway Research Center, “Baghouse Fines: Material Description,” www.tfhrc.gov/hnr20/recycle/waste/bd.htm.

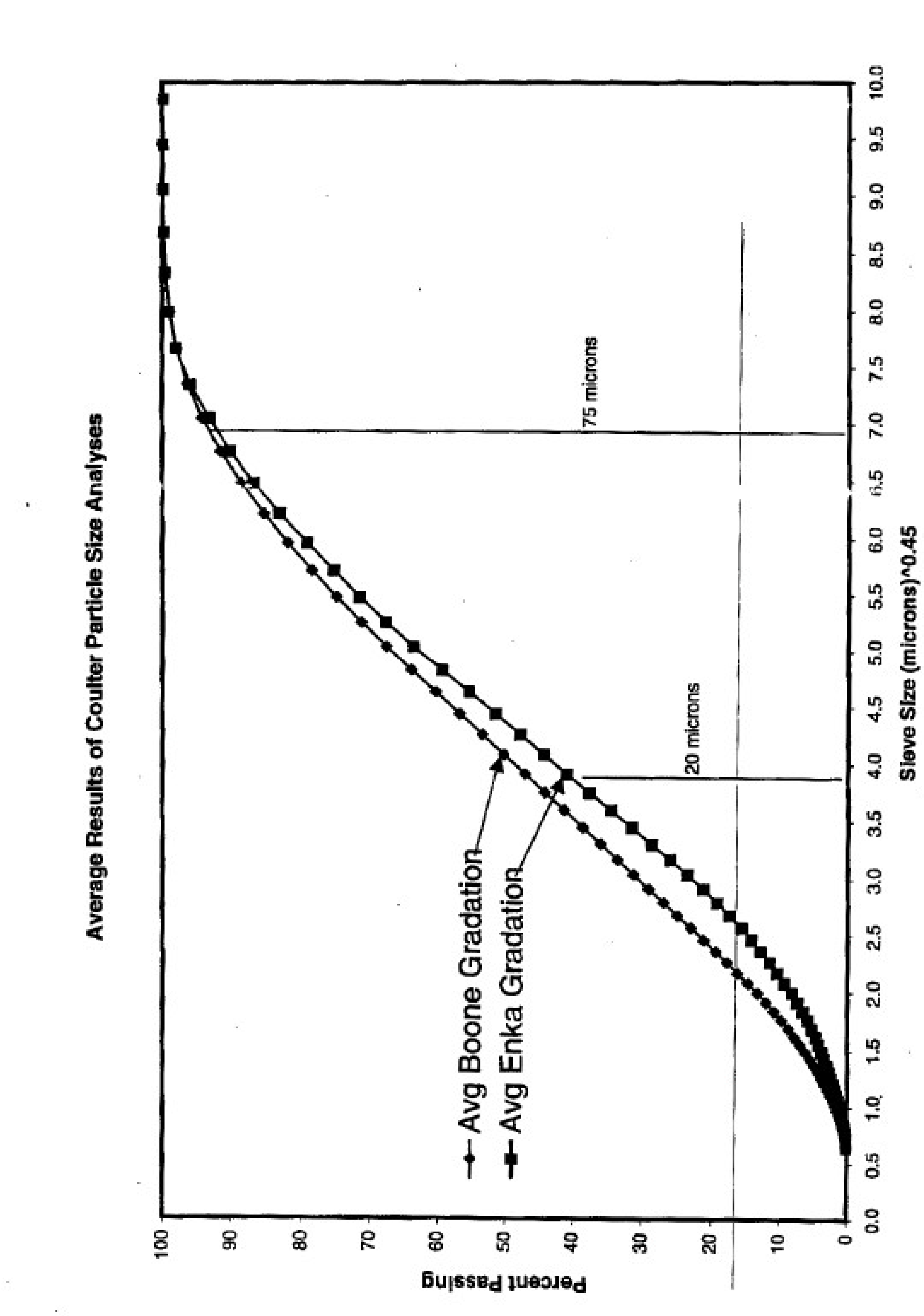
16. Turner Fairbank Highway Research Center, “Baghouse Fines: Asphalt Concrete,” www.tfhrc.gov/hnr20/recycle/waste/bd2.htm.

17. Waller, H.F., “The Use of Baghouse Fines in Hot-Mix Asphalt,” *The Asphalt Institute*, (May 1991).

18. Tayebali, A. A., Tsai, B. W., and Monismith, C. L., "Stiffness of Asphalt-Aggregate Mixtures", Report No. SHRP-A-388, Strategic Highway Research Program, National Research Council, Washington, D.C., 101 pp., April 1994.

19. Deacon, J. A., Tayebali, A. A., Coplantz, J. S., Finn, F. N., and Monismith, C. L., "Fatigue Response of Asphalt-Aggregate Mixtures, Part III - Mixture Design and Analysis", Report No. SHRP-A-404, Strategic Highway Research Program, National Research Council, Washington, D.C., pp. 225-309, June 1994.

APPENDIX A: BAGHOUSE FINES PARTICLE ANALYSIS RESULTS

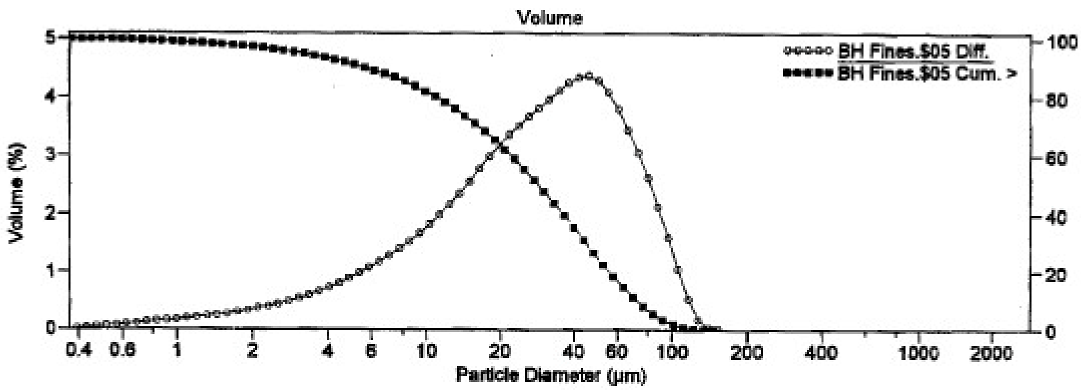


Average Results of Coulter Particle Size Analyses
Percent Passing
Sieve Size (microns)^0.45
Avg Boone Gradation
Avg Enka Gradation
75 microns
20 microns
0
10
20
30
40
50
60
70
80
90
100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0

LS Particle Size Analyzer

19 Oct 2001

File name:	BH Fines.$05	Group ID:	BH Fines
Sample ID:	Enka 2		
Run number:	5	Operator:	R. James
Optical model:	Garnet.rfz		
LS 200	Fluid Module		
Start time:	14:25 12 Oct 2001	Run length:	60 seconds
Pump speed:	100		
Obscuration:	9%		
Fluid:	Water		
Software:	3.01	Firmware:	1.35 0



Volume Statistics (Arithmetic) BH Fines.$05

Calculations from 0.375 µm to 2,000 µm

Volume:	100%		
Mean:	34.43 µm	S.D.:	25.94 µm
Median:	28.60 µm	C.V.:	75.3%
D(3,2):	11.69 µm		
Mode:	45.75 µm		

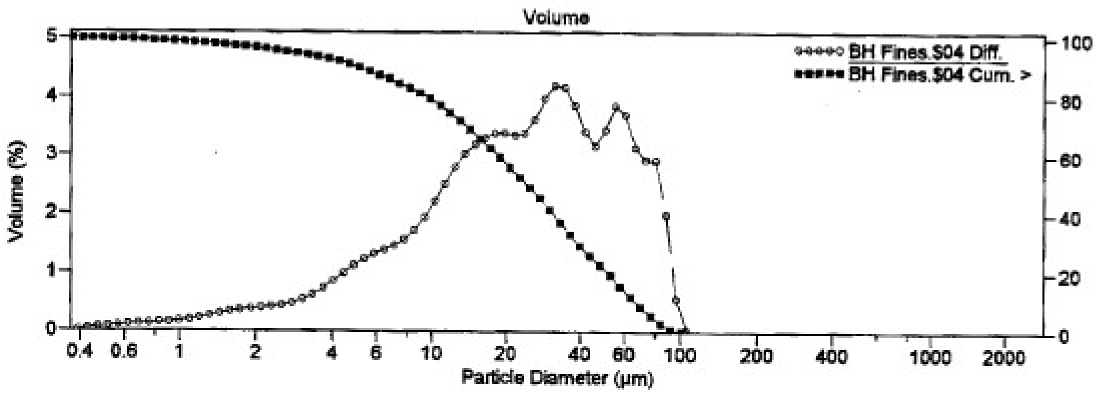
% <	10	25	50	75	90
µm	5.769	13.61	28.60	49.96	72.33

BECKMAN COULTER

LS Particle Size Analyzer

19 Oct 2001

File name:	BH Fines.$04	Group ID:	BH Fines
Sample ID:	Enka 1		
Run number:	4	Operator:	R. James
Optical model:	Garnet.rfz		
LS 200	Fluid Module		
Start time:	14:15 12 Oct 2001	Run length:	60 seconds
Pump speed:	100		
Obscuration:	13%		
Fluid:	Water		
Software:	3.01	Firmware:	1.35 0



Volume Statistics (Arithmetic) BH Fines.$04

Calculations from 0.375 µm to 2,000 µm

Volume:	100%		
Mean:	30.36 µm	S.D.:	23.19 µm
Median:	24.32 µm	C.V.:	76.4%
D(3,2):	10.45 µm		
Mode:	31.50 µm		

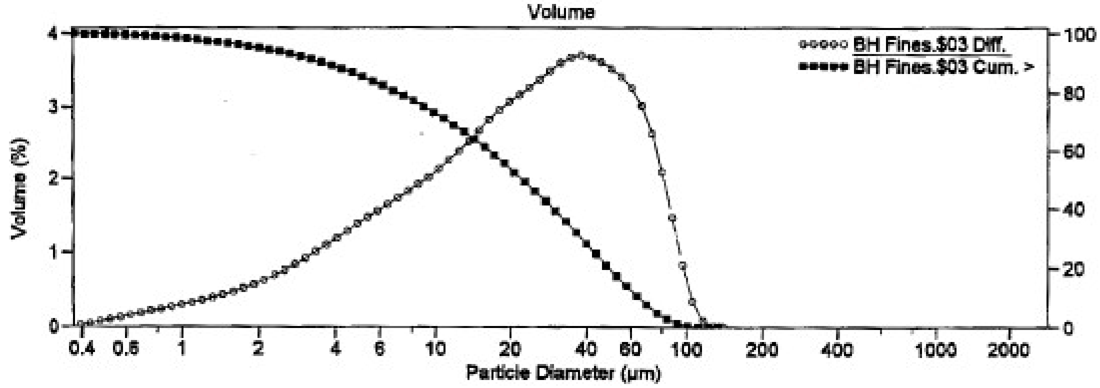
% <	10	25	50	75	90
µm	5.198	11.78	24.32	44.70	66.51

BECKMAN COULTER

LS Particle Size Analyzer

19 Oct 2001

File name:	BH Fines.$03	Group ID:	BH Fines
Sample ID:	Boone 2		
Run number:	3	Operator:	R. James
Optical model:	Garnet.rfz		
LS 200	Fluid Module		
Start time:	14:03 12 Oct 2001	Run length:	60 seconds
Pump speed:	100		
Obscuration:	10%		
Fluid:	Water		
Software:	3.01	Firmware:	1.35 0



Volume Statistics (Arithmetic) **BH Fines.$03**

Calculations from 0.375 µm to 2,000 µm

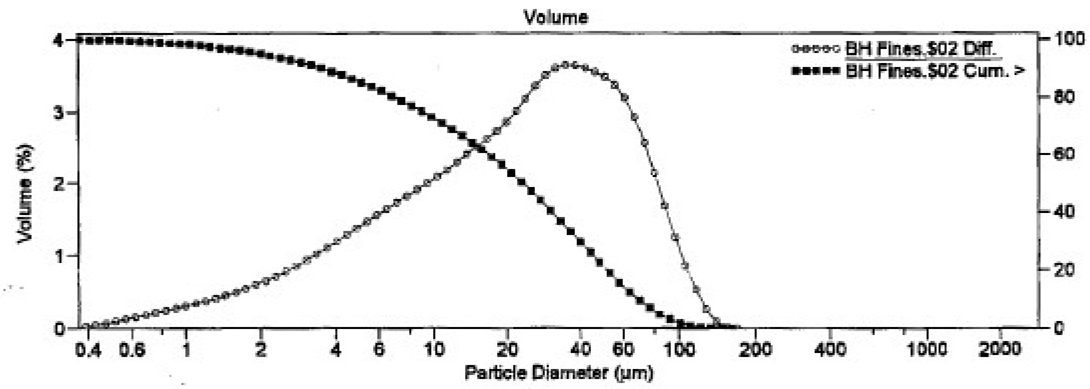
Volume:	100%		
Mean:	28.61 µm	S.D.:	23.71 µm
Median:	22.18 µm	C.V.:	82.9%
D(3,2):	8.350 µm		
Mode:	37.97 µm		

% <	10	25	50	75	90
µm	3.628	9.025	22.18	42.95	64.48

LS Particle Size Analyzer

19 Oct 2001

File name:	BH Fines.$02	Group ID:	BH Fines
Sample ID:	Boone 1		
Run number:	2	Operator:	R. James
Optical model:	Garnet.rfz		
LS 200	Fluid Module		
Start time:	13:39 12 Oct 2001	Run length:	60 seconds
Pump speed:	100		
Obscuration:	9%		
Fluid:	Water		
Software:	3.01	Firmware:	1.35 0



Volume Statistics (Arithmetic) BH Fines.$02

Calculations from 0.375 µm to 2,000 µm

Volume:	100%		
Mean:	30.19 µm	S.D.:	26.16 µm
Median:	23.05 µm	C.V.:	86.6%
D(3,2):	8.335 µm		
Mode:	34.58 µm		

% <	10	25	50	75	90
µm	3.567	8.993	23.05	44.77	68.32

APPENDIX B: MAYMEAD MATERIALS JOB-MIX-FORMULA

REVISED 12-16-99 M&T FORM 600 (SP)

Maymead Materials, Inc.

Asphalt Design Laboratory

Mountain City, Tennessee

REPORT ON SUPERPAVE MIX DESIGN

MD# ________

DATE SUBMITTED:	1/5/01		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 B-025		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	ManfSand	Screenings	Wash.Scrgs		0	BgHsFines	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		76	< 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.Fum. 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	2.855	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 ($P_{0.075}$/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	66.9	73.9	79.9	86.7
% Gmm @ Nini 7	86.6	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 Fum. Calibr.:	0.21
% AC (Design):	
Rice Specific Gravity:	
Lab 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:	

COMMENTS:
ADD BAGHOUSE TO SCREENINGS

Sand Equivalent:	72.6
C. Agg. Angularity:	100/100
F. Agg. Angularity:	48.6
Flat & Elongated:	3.0

DESIGNED BY:

APPROVAL: