# LABORATORY EVALUATION OF BOTTOM ASH ASPHALT MIXES


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## DISCLAIMER

# ABSTRACT

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The main objective of this study was to investigate the effect of the addition of a coal combustion remnant called bottom ash into asphalt mixes. The intent was to determine if mixes prepared with bottom ash showed degradation of desirable performance measures when compared to control mixes. This was done through evaluation of Georgia loaded wheel, thermal strength restrained specimen, and tensile strength test results. Two types of aggregates, granite and limestone were mixed with three types of mixes, lab mix with lime, lab mix without lime, and plant mix with lime. Ash from four power plant sources in Wyoming, Control, Dave Johnston, Jim Bridger, and Laramie River, was used to produce the tested mixture combinations. Mixes were then tested for tensile strength, rutting potential and low temperature performance. All data collected during this study was summarized in a computer database and statistically analyzed. The ash mixes displayed, even in the absence of lime, the quality of maintaining desirable tensile strength properties when compared to control mixes. Even more favorable was the fact that ash mixes displayed slightly improved properties over control mixes in the presence of lime.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# 1. INTRODUCTION

## 1.1 Background

Asphalt pavement is susceptible to a vast array of distress types. The prevalence of asphalt pavement in the United States necessitates that tests for these distresses as well as methods to correct discovered deficiencies be investigated. The increasing use of asphalt type pavement in new roadway construction also requires large quantities of materials. Bottom ash is a waste product with few commercial uses. It is produced in coal-burning power plants and may prove to be a suitable replacement for a portion of the aggregate commonly used in asphalt pavement. Increasing environmental awareness makes it difficult to find landfill sites which will accept the bottom ash, therefore necessitating the discovery of a suitable use for the ash. Possible transportation-related applications of the ash that have been considered include use as embankment fill, roadway fill, sub-base, and base courses [Pandeline et al. 1997]. For these reasons, it is desirable to know if the addition of bottom ash into hot mix asphalt (HMA) pavement will allow it to maintain desirable strength, rutting, and low-temperature properties when compared with pavements prepared with no bottom ash.

The infiltration of moisture into hot mix asphalt pavements is one of the most common causes of degradation in pavement structures. When moisture enters the pavement structure, it can find its way between the aggregate and the asphalt cement, leading to a loss of cohesion within the pavement. This separation of aggregate from the asphalt cement by an aqueous boundary layer is commonly referred to as stripping. Stripping is a failure mode that can be manifested in many different ways. The effects of stripping are most often very evident in surface features such as ruts or cracks in the asphalt [Lottman 1989]. However, the effects of stripping can also be seen in situations where shoving of the asphalt matrix has taken place. Many factors in addition to the presence of water can contribute to stripping. Relevant factors include, but are not limited to: asphalt mix characteristics, traffic loading, and climate. However, it is believed that pavement experiences the greatest destructive effect when an interaction occurs between one or more of the aforementioned effects while moisture is present.

Several laboratory and field tests have been established to evaluate how moisture-susceptible a paving mix is. The tests performed have been both quantitative and qualitative in nature. The quantitative tests are numerous and include the Texas Freeze-Thaw Pedestal Test, the Immersion-Compression Test, the Tunnicliff and Root Conditioning, the Lottman Test, and the Modified Lottman Test. Qualitative measures to determine moisture susceptibility include the Boiling Water Test and the Static Immersion Test.

## 1.2 Problem Statement

The intent of the research is to determine what effect, if any, the addition of bottom ash from power plants in Wyoming will have on various properties of HMA mixes. Analyses of rutting tendency, low temperature performance, and multiple freeze-thaw cycling will be utilized to help determine whether there are any negative effects experienced when adding bottom ash to asphalt mixes. Many current tests only observe the characteristics of a sample after one freeze-thaw cycle. For this reason, the effects of multiple freeze-thaw cycles are not yet fully known. Multiple freeze-thaw cycling will allow the determination of both the short-term and long-term effects of the addition of bottom ash on the performance of the HMA mixes.

## 1.3 Research Objectives

The main objective of this study is to evaluate the effectiveness of bottom ash addition to asphalt mixes. This objective will be satisfied by:

1. Evaluating the effect of various numbers of freeze-thaw cycles on the mechanical properties of HMA mixes prepared with and without bottom ash.
2. Evaluating the potential for rutting of HMA mixes prepared with and without bottom ash.
3. Evaluating the low temperature performance of HMA mixes prepared with and without bottom ash.

## 1.4 Report Organization

The second chapter of this report is a literature review of bottom ash and its possible reasons for use, test methods for determining the degree of moisture susceptibility of an asphalt mix, and methods for limiting asphalt moisture susceptibility. Also included in Chapter 2 is background on loaded wheel tests to evaluate rutting characteristics, the thermal stress restrained specimen test to evaluate low temperature cracking, and indirect tensile strength test for HMA mixes. Chapter 3 contains the experimental design and explains the test procedures used throughout the study. Collected data from all tests performed in this study is discussed in Chapter 4, with that data being listed in appendices B through G. The analysis of the results from tests conducted appears in Chapter 5 Chapter 6 presents conclusions learned from this research as well as recommendations based on these conclusions.

# 2. LITERATURE REVIEW

## 2.1 Introduction

About 2.3 million miles (3.7 million kilometers) of road in the United States are surfaced with asphalt or concrete while the remaining are surfaced with gravel, stone, soil, or not surfaced at all. Of the hard-surfaced roads, 2.2 million miles (3.5 million kilometers) are surfaced with asphalt. In the United States each year, approximately 500 million tons (453 billion kilograms) of hot mix asphalt are produced and placed at a cost of roughly $10.5 billion dollars [Roberts et al. 1991]. Of this material, approximately 465 million tons (421 billion kilograms) is aggregate-related material [Stephen 1999]. A possible alternative aggregate material that may be used in highway construction is coal bottom ash produced by utility power plants. Use of this ash in asphalt paving mixes can be beneficial because disposing of bottom ash as a waste product is costly, puts a strain on limited landfill space, and may pose environmental problems. If productive use of ash becomes more common, this disposal problem may be solved and demand for virgin aggregate may be reduced.

The incredible amount of asphalt pavement present in the United States is unfortunately susceptible to damage. Moisture susceptibility of an asphalt mix can be a good indicator of the degree of moisture damage to be expected from a pavement section during in-field performance. Multiple test methods exist to evaluate moisture susceptibility of asphalt mixes. These tests include, but are not limited to: static immersion test, boiling water test, Texas freeze-thaw pedestal test, Tunnicliff and Root conditioning, Lottman test, and the modified Lottman test. The purpose of these test methods is to closely model conditions that pavement may experience in the field.

The boiling water test and the freeze-thaw pedestal test by Parker and Gharaybeh [1987] were used in an attempt to predict the stripping potential of asphalt mixes. They later concluded that the percent of tensile strength retained compared to unconditioned samples was a more representative measure of stripping tendencies.

Lottman and Maupin recommend that a minimum acceptable percent of tensile strength to be retained is 70 percent. They determined that percentages between 70 percent and 75 percent differentiated between stripping and non-stripping mixtures. It has been argued that the Lottman procedures are too severe because the warm-water soak of vacuum-saturated and frozen specimens can develop internal water pressure [Brown et al. 2001]. However, Stuart [1986] and Parker and Gharaybeh [1987] typically found a good correlation between laboratory and field results.

This chapter presents background information concerning bottom ash as well as the possible use and benefits of bottom ash as a construction material. Moisture susceptibility of asphalt mixes and available tests for determining the degree of moisture susceptibility, including the three tests used in this study are discussed. Finally, current methods and techniques used to limit moisture damage are presented.

## 2.2 Bottom Ash

In the United States, coal fired electric power plants consume approximately 1100 million tons of coal each year [DOE 2002]. Burning this coal produces more than 70 million tons of coal ash. Between 1993 and 1997, the rise in demand for electricity caused coal consumption to increase by an average of 2.9 percent per year [DOE 1998]. This trend is expected to continue and will result in the increase of coal ash production.

Coal ash consists of fly ash and bottom ash. The light ash component is referred to as fly ash. It is carried through the furnace by exhaust gasses and is collected in ash precipitators. The heavy ash component is called bottom ash. The bottom ash produced by the majority of power plants in Wyoming is considered wet bottom ash. The bottom ash exits through the boiler bottom into water-filled hoppers. It is then ground into material measuring one-inch or less and sluiced to a settling pond. This process provides a water wash where the larger particles settle near the edge of the pond.

The majority of unused coal ash is the bottom ash. It is often disposed of in landfills or mined-out areas of coal mines prior to their reclamation. Research into the use of coal ash as a construction material has largely been focused on fly ash rather than bottom ash because benefit has been found for the addition of fly ash into concrete. However, recent studies have indicated that bottom ash may possess desirable engineering properties and will not degrade performance properties of asphalt pavement when used to replace a portion of the fine aggregate in the asphalt mix. However, to be used in HMA mixes as an asphalt substitute, the bottom ash must be free of pyrites or other metals that can cause localized future distresses in the asphalt.

It is thought that the widespread incorporation of bottom ash into asphalt mixes would save large power plants millions of dollars per year in disposal costs as well as saving construction contractors on material procurement fees by using the bottom ash in pavement mixes. Another benefit is that the unused ash would no longer have to be put into landfills.

## 2.3 Moisture Susceptibility

The moisture susceptibility of an asphalt mix can be defined as its propensity to allow the infiltration of water into the matrix to form a boundary layer between asphalt cement and aggregate. This separation of the asphalt cement from the aggregate is known as stripping. Stripping can be defined as a loss or weakening of the cohesive bond between asphalt cement and aggregate. Once the bond begins to lose cohesion, the decrease in the asphalt mixes' strength is often great. The phenomenon typically occurs first at the bottom of the asphalt layer due to water running downward and residing in the lowest pores in the pavement. Various modes of infiltration will allow water to reach the bottom of the asphalt layer. Commonly, asphalt can become saturated if water is left standing on the pavement surface due to inadequate drainage. Secondly, poor local sub-surface drainage will allow the local water table to rise which can encourage a wicking action. This allows the water to enter the asphalt from below. Also, due to nearby bodies of water, a locally elevated water table will allow lateral flow of water from the phreatic surface into the asphalt. The internal pore pressure then leads to a weakening of the bond. As the bottom of the pavement gradually weakens, more water is allowed into the asphalt which lets the water level rise. The higher water level promotes further stripping in the lowest reaches of the pavement as well as beginning the stripping process further up into the matrix. In this manner, stripping travels upward through the pavement until it reaches the surface. At the surface, the weakened asphalt may exhibit rutting in the travel lanes or shoving where vehicles are required to make repeated stops. In many cases, identification of stripping as the pavement failure mode takes years. This is because surface indicators such as rutting, shoving, and cracking can be slow to appear. The primary cause for stripping is thought to be based on the physical and/or chemical properties of the aggregate used in the mix [Yoon and Tarrer 1988].

Because of the degree of damage caused by stripping, it is essential to have the correct mix design for the paving application. However, even with the correct mix design, stripping can still occur due to improper compaction of the asphalt during placement at the job site. An under-compacted mix will typically exhibit a higher percentage of air voids than is desirable. These voids provide a place for water to enter the pavement and to reside. Properly compacted mixes will have fewer voids where water can reside. It has been shown that asphalts prepared with air voids in the range of 5 percent or less will significantly reduce moisture infiltration into the asphalt mix, even to the point of becoming nearly impervious. Conversely, asphalt mixes exhibiting air voids of 8 percent or greater will allow an unimpeded influx of water into the asphalt matrix. For this reason, many test procedures used to predict the moisture susceptibility of an asphalt mix specify an air void content of 7 ±1 percent. One such test is the modified Lottman or AASHTO T-283 test. The minimum acceptable value from this test for tensile strength retained is 70 percent [Parker and Gharaybeh 1987]. Failure of a sample to meet this 70 percent criterion signifies that the mix will be susceptible to moisture-induced damage. A description of the modified Lottman test is provided later in this chapter.

Several other factors can have contributing effects to the stripping process. Open-graded aggregates, wet aggregates, or poor-quality aggregates with low tensile strength can increase the amount and magnitude of stripping a given asphalt may experience. Use of anti-stripping additives can sometimes decrease an asphalt's susceptibility to stripping [Tunnicliff and Root 1984]. However, use of chemically incompatible anti-stripping additives can actually have the reverse effect and promote stripping within the pavement.

## 2.4 Methods for Evaluating Moisture Susceptibility

The static immersion test, boiling water test, Texas boiling water test, Texas freeze-thaw pedestal test, Tunnicliff and Root conditioning, Lottman test, and the modified Lottman test are tests used to evaluate moisture susceptibility in HMA mixes. Descriptions of these tests are contained in the following sub-sections.

### 2.4.1 Static Immersion Test (AASHTO T182)

In this qualitative test, the asphalt sample is submerged in distilled water at a temperature of 77ºF (25ºC) for 18 hours. The percentage of visible aggregate that remains coated with asphalt is observed while the sample is still submerged. An estimate is then made as to whether the asphalt coating on the aggregate is greater than 95 percent or less than 95 percent. Again, this is a subjective method with high variability and does not involve any strength tests [Brown et al. 2001].

### 2.4.2 Boiling Water Test (ASTM D-3625)

Also qualitative in nature, the boiling water test is used to visually determine the moisture susceptibility characteristics of an HMA mix. Here, uncompacted asphalt mix is placed in boiling water for 10 minutes. The percentage of visible aggregate that remains coated with asphalt is observed while the sample is still submerged. An estimate is then made as to whether the asphalt coating on the aggregate is greater than 95 percent or less than 95 percent. The primary use of this test is for the preliminary investigation of asphalt mixes. The use of this test for production quality control is accepted so long as the technician administering the test is aware of the fact the stripping characteristics of fine aggregates cannot accurately be predicted by this test.

### 2.4.3 Texas Boiling Water Test

This test is partially visual in nature yet returns quantitative results lending themselves to analysis. The determination of the degree of stripping can be made by visual observation after boiling the mixture. In this test, the asphalt cement is heated at a temperature of 325ºF (103ºC) for 24 hours.Unwashed aggregate samples of 100 grams or 300 grams are also heated at 325ºF (103ºC), but only for approximately one hour to remove residual moisture. A large beaker filled with 500ml of distilled water is brought to a boil. After mixing, the dried unwashed aggregate and the asphalt cement are then placed into the beaker of boiling water for 10 minutes. After the 10 minutes has elapsed, any asphalt cement floating free from the mix should be skimmed off the water surface. The water and asphalt mix in the beaker are then allowed to slowly cool at room temperature. The cooled water can then be poured from the beaker. The asphalt mixture is poured onto a paper towel. Three people then individually grade the mix. The same three people grade the mix again on the following day when the mix is fully dry. A mix that remains 65 percent to 75 percent coated with asphalt is deemed to be suitable for use in the field.

### 2.4.4 Texas Freeze-Thaw Pedestal Test

This is a unique test designed to be performed on asphalt mixes with uniform aggregate sizes. The use of uniform aggregate sizing helps to reduce the effects of the mechanical bonding properties that well-graded aggregate mix would lend to an asphalt mix. This in turn allows only the chemical bonding properties of the asphalt mix to be observed. In essence, one variable has been removed from the equation. The aggregate and asphalt are mixed in accordance with the Texas mixture design procedure. After the initial mixing, the mix is reheated and broken apart. It is then re-mixed twice more.

Cylindrical samples of 0.75 in. (19.05mm) height and 1.6 in. (41.3mm) diameter are produced in molds. A load of 6,200 lbs (27.6 KN) is applied to a sample for twenty minutes. The samples are allowed to sit for three days at room temperature to allow them to consolidate. A sample is then placed in a jar filled with distilled water to a distance of 0.5 in. (12.7mm) over the top of the sample. This jar is then placed on a pedestal where it is cycled for 12 hours at 10ºF (-12ºC) and then for 120ºF (49ºC) for another 12 hours [Kennedy and Anagnos 1984]. The number of freeze-thaw cycles that a sample can endure is indicative of its level of moisture susceptibility. Brown et al. determined that samples failing before the completion of 10 cycles were quite susceptible to moisture. Conversely, mixes being more resistant to moisture damage lasted for twenty cycles or more.

### 2.4.5 Tunnicliff and Root Conditioning

This test, named after the people who developed it, is performed on six samples compacted to achieve air voids of between 6 percent and 8 percent. The six samples are put into two groups of three samples each. One group is the control group and will not be subject to manipulation of any kind. The second group is vacuum saturated at 20 inches (508mm) of mercury for five minutes. A saturation level between 55 percent and 80 percent is desired. After saturation, the samples are placed in a 140ºF (60ºC) water bath for 24 hours. All of the samples are then subjected to indirect tensile strength testing at 77ºF (25ºC) at a loading rate of 2 inches/minute [Tunnicliff and Root 1984]. The minimum allowable percent of tensile strength to be retained versus the control samples is 75 percent to 80 percent.

### 2.4.6 Lottman Test (NCHRP 246)

This quantitative strength test was developed by Robert P. Lottman at the University of Idaho. This test also predicts the moisture susceptibility of asphalt mixes. In the Lottman procedure, nine samples are made and compacted to the desired field air void content. Three groups are then made from the nine samples. The first group is the control group and is subject to no manipulation of any kind. The second group is vacuum-saturated at 26 inches (660mm) of mercury for 30 minutes. The laboratory performance of these three samples is indicative of the field performance of the mix for up to four years after placement. The third group of three samples must endure freeze-thaw cycling after they are saturated. They are placed in a freezer at 0ºF (-18ºC) for 15 hours, then heated at 140ºF (60ºC) for 24 hours. This third group of samples is indicative of the field performance of the mix from four to twelve years after placement.

After the recommended number of freeze-thaw cycles, all of the samples are then subjected to indirect tensile strength testing and/or resilient modulus testing. The minimum allowable percent of tensile strength to be retained versus the control samples is 70 percent.

### 2.4.7 Modified Lottman Test (AASHTO T-283)

This test bears similarities to both the Lottman test and the Tunnicliff and Root test. The test was adopted by AASHTO in 1985. In the test, six samples with air voids of between 6 percent and 8 percent are made. These are split into two groups of three samples each. The first group of three is denoted as the control group. The second group of three samples is vacuum-saturated saturation level between 55 percent and 80 percent. They are then placed in a freezer at 0ºF (-18ºC) for 16 hours. They are then moved to a 140ºF (60ºC) water bath for 24 hours. All of the samples are then subjected to Indirect Tensile Strength testing and/or Resilient Modulus testing. The Indirect Tensile Strength test is performed at 77ºF (25ºC) at a loading rate of 2 inches/minute. The minimum allowable percent of Tensile Strength to be retained versus the control samples is 70 percent.

## 2.5 Methods for Limiting Moisture Susceptibility

Moisture-sensitive pavements can experience severely reduced service life when subjected to more than trace amounts of moisture. Additives have been developed to address the issues of poor pavement performance and high maintenance costs experienced by moisture-susceptible pavements. These anti-stripping additives, whether solid or liquid, are used to promote adhesion of asphalt cement onto the aggregate surface.

The effects of commercially available liquid anti-stripping agents on asphalt cement were evaluated by Anderson et al. [1982]. Their research showed that the addition of liquid anti-stripping additives can alter the physical characteristics and composition of an asphalt cement, typically increasing asphalt cement viscosity to the point of non-compliance with standard specifications. To date, there has been little guidance as to whether the undesirable effects of anti-stripping agents outweigh their positive moisture-resistive effects.

### 2.5.1 Anti-Stripping Agents

Water-sensitive asphalt mixes, or mixes to be used in very wet locales can greatly benefit from the use of anti-stripping agents. However, incorrect use of anti-stripping additives such as incorrect proportion of the additive or introduction of the additive at the wrong time could actually be counterproductive. This would most likely be manifested in the form of increased cost due to high maintenance demands or early rehabilitation costs. Unfortunately, the best time to introduce the additives to the asphalt mixes has not yet been determined. So far there is also no instrument that can directly assess the amount of anti-stripping additive in an asphalt pavement after the material has been mixed. Although there are some indirect ways to measure existence of additives through measuring the performance of the asphalt pavements, such as AASHTO T-283, the method generally takes days for test results to be available. Due to a lack of a quick and convenient way of checking the amount of anti-stripping additives, the asphalt pavement material is not checked as often as it should be for the correct level of anti-stripping additives. The most commonly used anti-stripping agents are lime additives and liquid additives [Tunnicliff and Root 1984]. These additive types will be discussed further in the next two sections.

#### 2.5.1.1 Addition of Lime

Lime has been shown to be very effective at preventing stripping in HMA mixes. It is thought that this is due to the chemical reaction that occurs when lime interacts with silicate aggregates to form a layer of calcium around the aggregate. This calcium layer bonds to the aggregate well while still maintaining a sufficient level of porosity to allow asphalt cement to penetrate the voids in the aggregate. It has also been theorized that the lime leftover from the initial reaction can react with acids present in the asphalt cement, resulting in the thorough coating of the aggregate. Generally, lime accounts for approximately 1 percent to 1.5 percent of the mix by weight. The percentage of lime should be increased accordingly if a gradation containing substantial amounts of fine aggregate is used. This compensates for the disproportionate increase in aggregate surface area due to the fine materials.

Both hydrated lime $Ca(OH)_2$ and quick lime CaO are effective, although the former is most commonly used. Dolomitic limes (both Type S and N) have also been used as antistripping additives. However, as a carbonate CaC03 lime is not as effective [Kandhal 1992].

The common hydrated lime is actually a dry powder, and is added to the aggregate before mixing with the asphalt cement. The main drawback of the application method that hydrated lime requires is that it is difficult to retain an adequate surface coating of lime on the aggregate. Hydrated Lime can also be added to undried aggregate with water content from 3-5 percent. The addition of lime in this manner does however reduce HMA production capabilities because additional water needs to be added to prepare the lime and aggregate slurry.

#### 2.5.1.2 Liquid Anti-Stripping Agents

Most liquid anti-stripping agents are of the surface active type. This means they reduce surface tension of any existing water on the aggregate and promote better adhesion of the asphalt cement to the aggregate.

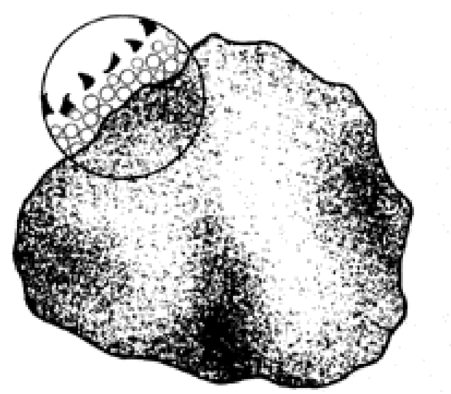

**Figure 2.1 Aggregate not Treated with Anti-Strip Additive**
*[Source: www.rohmhaas.com]*

Aggregates have a natural affinity for water. As can be seen in Figure 2.1, untreated aggregates are much more likely to be damaged by water breaking the asphalt/aggregate bond.

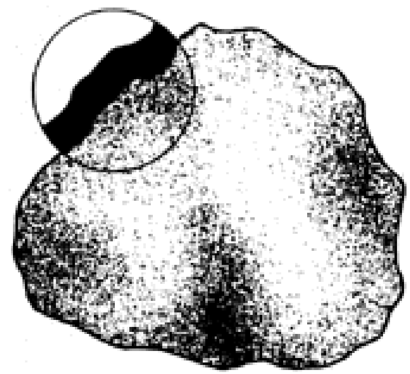

**Figure 2.2 Aggregate Treated with Anti-Strip Additive**
*[Source: www.rohmhaas.com]*

Figure 2.2 shows how liquid anti-stripping additives allow the asphalt cement to create a strong bond between the asphalt and aggregate which will help reduce the chance of moisture damage.

The simplest method of applying the liquid anti-stripping additive is to mix it directly with the asphalt cement immediately before its application onto the aggregate. This method is only partially effective because only a small portion of the additive comes into contact with the aggregates. A better method is to treat the aggregates with the liquid anti-strip additive before the addition of the asphalt cement. This is the most efficient application method. Unfortunately, even though this pre-treatment method is favored, it still does not allow uniform application to all aggregate due to the small volume of additive generally used. The effectiveness of liquid anti-stripping agents to reduce moisture susceptibility has not been well-documented.

### 2.5.2 Preparation of Aggregate

Taking the correct steps in preparing aggregate can add substantially to the ability of the aggregate to absorb and bond with asphalt cement. The most important of the preparation processes is the heating of the aggregate to remove any excess moisture. Other commonly taken steps are to wash the aggregate to remove very fine dust, or to process the aggregate in a crusher. It should also be noted that proper aggregate selection can play an important role in the ability of the binder to adhere to the aggregate because some aggregate types are more suitable for paving uses than others.

## 2.6 Indirect Tensile Test

The indirect tensile strength test is commonly used to predict the degree of moisture-induced damage a pavement will suffer. This test, ASTM D4123, involves compressive loading of a cylindrical specimen of 4 inch (101.6mm) diameter and 2.5 inch (63.5mm) height. The single compressive load is applied vertical to the diametric plane of the cylinder. The test is performed with the specimen at 77ºF (25ºC) with a loading rate of 2 inches/minute [Brown et al. 2001]. Failure of the specimen is characterized by the development of a split along the vertical diameter.

The tensile strength is measured after conditioning of the core. This measurement is then compared to the tensile strength for an unconditioned core to determine the tensile strength retained (TSR) as a percentage of the original unconditioned strength.

$$TSR = \frac{\text{Tensile Strength After Conditioning}}{\text{Tensile Strength Before Conditioning}}$$

TSR values range from 0 to 1. Values in the range of 0.8 to 1 indicate good performance of the HMA mix in terms of moisture susceptibility. Conversely, values below 0.7 typically represent a pavement that will likely be susceptible to moisture induced damage [Brown et al. 2001].

## 2.7 Loaded Wheel Tests to Evaluate Rutting

Rutting most often occurs due to high air voids in the asphalt mix due to insufficient compaction in the field. Also, asphalt is most likely to incur moisture damage in areas where ruts have formed because the rut will act like a reservoir to retain water. This water can then infiltrate the higher-than-normal air voids in the area of the rut. Because of this relationship, rutting can indirectly lead to a problem of localized stripping. Therefore, loaded wheel tests which allow the determination of the field rutting potential of an HMA mix also indirectly indicate the probability of the potential for stripping to occur.

### 2.7.1 Georgia Loaded Wheel Test

This standardized laboratory equipment and test procedure predicts field rutting potential. This can be of great benefit to the hot mix asphalt (HMA) industry. The Georgia Loaded Wheel Tester (GLWT) is one of the most common types of laboratory equipment of this nature. The GLWT, shown in Figure 2.3, was developed during the mid-1980s through a cooperative research study between the Georgia Department of Transportation and the Georgia Institute of Technology.

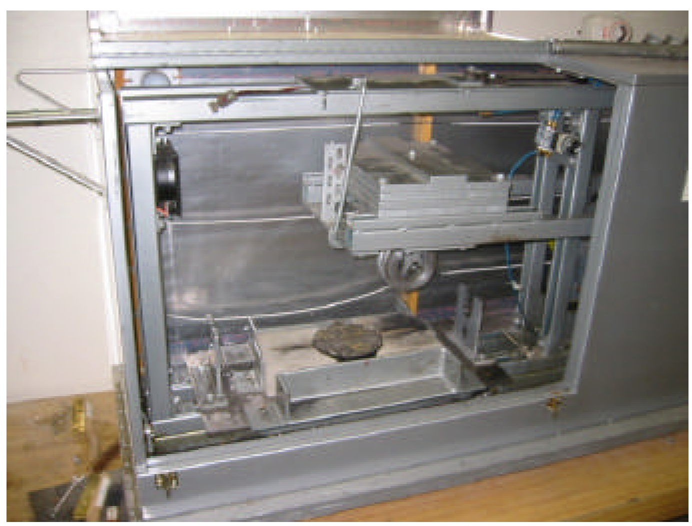

**Figure 2.3 Georgia Loaded Wheel Tester**

Development of the GLWT consisted of modifying a wheel-tracking device originally designed by C.R. Benedict of Benedict Slurry Seals, Inc., to test slurry seals [Cooley Jr., et al. 2000]. The primary purpose for developing the GLWT was to perform efficient, effective, and routine laboratory rut-proof testing and field-production quality control of HMA. Testing of samples within the GLWT generally consists of applying a 100 lb(445-N) load onto a pneumatic linear hose pressurized to 100 psi (690 kPa). The load is applied through an aluminum wheel onto the linear hose, which resides on the sample. The aluminum wheel is tracked back and forth over the applied stationary specimens. Testing is typically accomplished for a total of 8,000 loading cycles (one cycle is defined as the backward and forward movement over a sample by the wheel).

Test temperatures for the GLWT have ranged from 95°F to 140°F (35°C to 60°C). Initial work was conducted at 95°F (35°C). This temperature was selected because it was Georgia's mean summer air temperature. Test temperatures subsequently tended to increase to 105°F (40.6°C), 115°F (46.1°C), 122°F (50°C), and 140°F (60°C) [Cooley Jr., et al. 2000].

At the conclusion of the 8,000 cycle loadings, permanent deformation (rutting) is measured. Rut depths are obtained by determining the average difference in specimen surface profile before and after testing.

### 2.7.2 Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking Device is known as a Spurbildungsgerat in Germany where it has been used as a specification tool since the mid 1970's [Koch Pavement Solutions Website 2002]. Since Hamburg is the major seaport for Germany, the nearby roads are subjected to a large number of heavily loaded, slow-moving trucks. These conditions can cause severe rutting. The Road Authority uses the wheel tracking test as a specification requirement for their most severely stressed pavements. The Hamburg Wheel Tracking Device is currently being used to evaluate rutting and stripping characteristics of pavement samples from projects throughout North America.

The test consists of two separate steel wheels moving back and forth on asphalt concrete specimens. The device can be used for testing 10" road cores, but is more often run simultaneously on two laboratory compacted asphalt concrete slabs, which are mounted and placed in a temperature-controlled water bath. The slabs are compacted using the linear kneading compactor, as seen in Figure 2.4. The kneading action of the compactor achieves the desired density without fracturing aggregates.

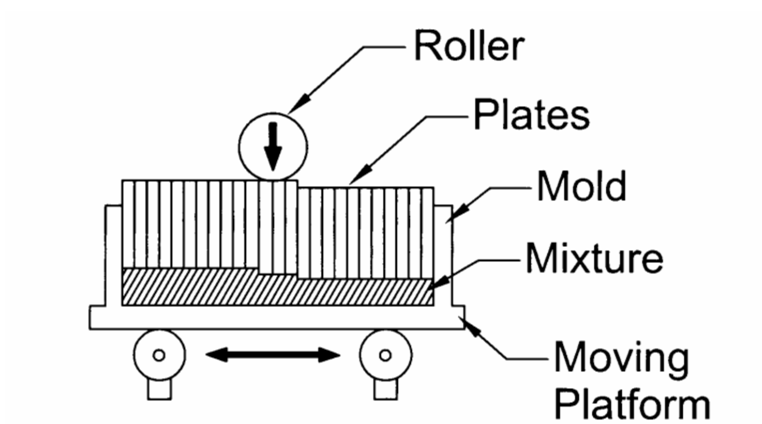


**Figure 2.4 Linear Kneading Compactor**
*[Source: www.kochpavementsolutions.com]*

After duplicate specimens are prepared, pre-conditioned, and placed in the device, the wheels are set in motion and automatic data recording starts. This data, collected per wheel pass, includes rut depth and bath temperature. The test continues for 20,000 cycles or 0.80 inches (20 mm) of deformation, whichever occurs first.

Four indices are measured from the graph of permanent deformation versus wheel passes as seen in Figure 2.5 [Koch Pavement Solutions Website 2002].

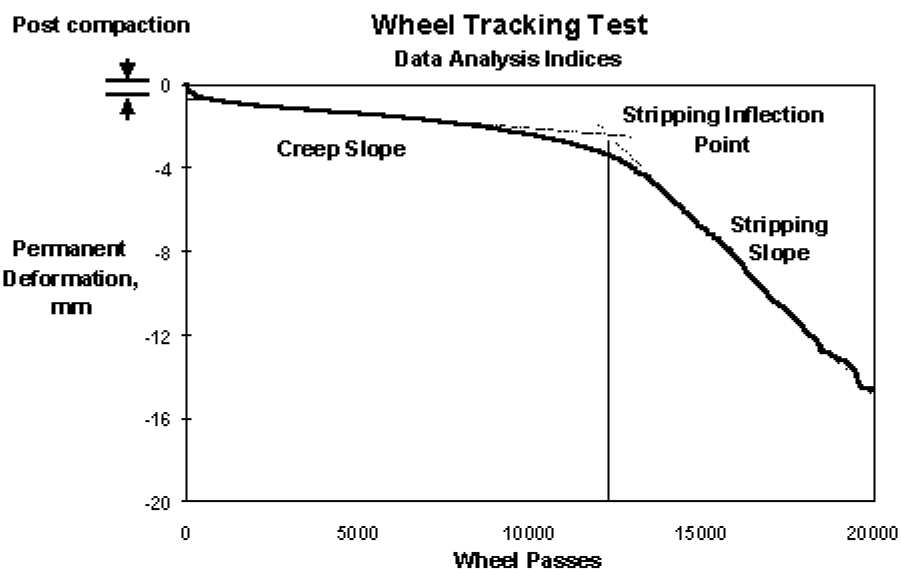


**Figure 2.5 Typical Hamburg Wheel Tracking Test Results**
*[Source: www.kochpavementsolutions.com]*

The post compaction consolidation is the amount of deformation which rapidly occurs during the first few minutes of the test. The steel wheel has some compacting effects on the mixes. A point of inflection occurs after this initial consolidation is completed. The inverse creep slope is reported in passes per mm. The higher this value the more resistant the mix is to permanent deformation. The stripping inflection point is determined where the creep slope and stripping slope intersect. It is defined as the number of passes at which moisture damage begins to adversely affect the mixture. The curve of permanent deformations vs. wheel passes abruptly turns downward. The stripping inflection point is related to the amount of mechanical energy required to produce stripping under the test conditions. A higher stripping inflection point would mean that a pavement would be less likely to strip.

## 2.8 Thermal Stress Restrained Specimen Test (AASHTO TP10-93)

This standardized test method determines the tensile strength and temperature at fracture for asphalt mixtures by measuring the tensile load in a specimen which is cooled at a constant rate while being restrained from contraction. The basic requirement for the test system is that it maintains the test specimen at constant length during cooling. A schematic of TSRST is shown in Figure 2.6. The system consists of a load frame, screw jack, computer data acquisition and control system, low temperature cabinet, temperature controller, and specimen alignment stand. This closed-loop process continues as the specimen is cooled and ultimately fails by cracking [Brown, et al. 2001].

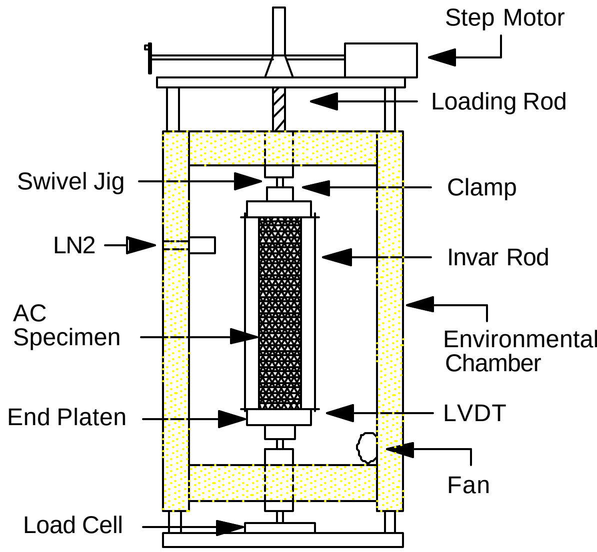


**Figure 2.6 TSRST Schematic**
*[Source: SHRP-A-400]*

A typical result from a TSRST is shown in Figure 2.7. The thermally induced stress gradually increases as the temperature decreases, until the specimen fractures. At the break point the stress reaches its maximum value—the fracture strength at the corresponding fracture temperature. The fracture strengths and temperatures can then be compared among samples to determine relative differences in quality.

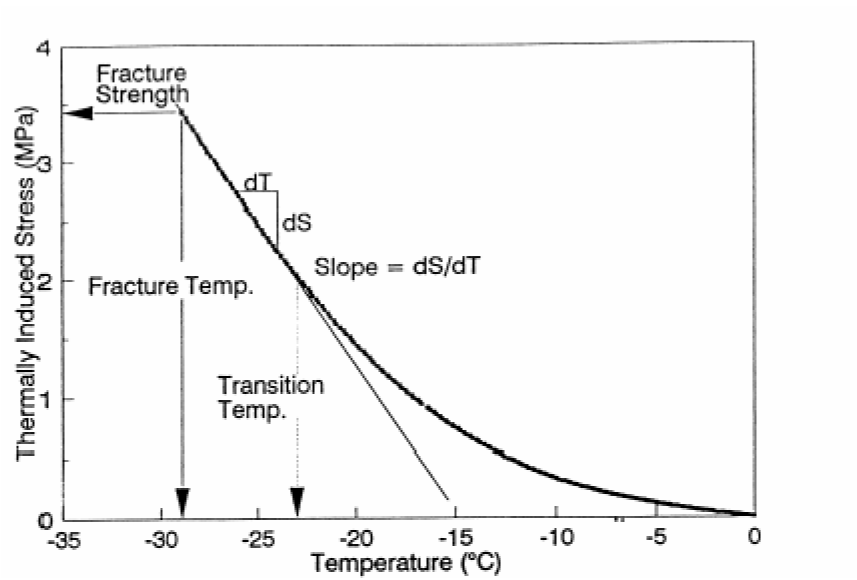


**Figure 2.7 Typical TSRST Results for Monotonic Cooling**
*[Source: SHRP-A-400]*

## 2.9 Summary

The problem of stripping is very serious with a potentially expensive solution. Many test methods have been developed to predict the moisture susceptibility of HMA mixes. These tests can be categorized as either qualitative or quantitative. The qualitative tests are subjective tests that do not give concrete results. Among the quantitative strength tests, those tests which use TSR data are most widely accepted. Other tests give quantitative results such as the GLWT which predicts rutting potential, and the TSRST which predicts low temperature crack resistance. Both of these tests provide very valuable information, but each can also indirectly give some indication of the potential for stripping in HMA mixes.

# 3. EXPERIMENT DESIGN AND TESTING PROCEDURES

## 3.1 Introduction

The intent of this study is to determine the benefit, if any, of the addition of bottom ash to HMA mixes. There are three main aspects to the research. The first part of the study is concerned with the determination of the effects of multiple freeze-thaw cycles on the strength of HMA mixes prepared with bottom ash. After preparing 16 mixes from combinations of aggregate, ash, and mix types, a testing procedure to condition the mix samples and test the tensile strength was developed. Wyoming Modified AASHTO T-283 was followed in the preparation and testing of the mix samples.

The second part of the study dealt with the use of the Georgia Loaded Wheel Tester to evaluate the rutting potential of bottom ash asphalt mixes. Due to the cause and effect relationship between rutting and stripping, the GLWT can also be somewhat indicative of stripping potential.

In the final part of this study, data from the TSRST was observed. This test was used to determine whether asphalt mixes prepared with bottom ash performed better in resisting low temperature cracking than those asphalt mixes containing no bottom ash.

Samples of different configurations mandated by their respective tests were used in this study. The designs of the experimental procedures used throughout this study are discussed in detail in this chapter.

## 3.2 Experiment Design: Factors and Procedures

This section describes the experimental procedures and specimen preparation needed to conduct the indirect tensile strength test, the thermal stress restrained specimen test, and the Georgia loaded wheel test for this study.

To begin with, the aggregate and asphalt were placed in an oven maintained at 140ºF (60ºC) for 16 hours. After this time, the oven temperature was increased to 280ºF (138ºC) for 2 hours before the aggregate and asphalt are mixed. This temperature simulates in-field mixing temperatures. After removal from the oven, specimens were then prepared using the Troxler Gyratory Compactor. Specimens were allowed to cool to room temperature before the bulk specific gravity of each specimen was determined according to AASHTO T-166.

Specimens to be used in the indirect tensile strength test underwent freeze-thaw cycles on the order of: 0, 1, 2, 4, 6, 8, 10, and 15 cycles. Two cores were tested for each cycle to provide replicate data should one of the cores for a given cycle fail or be otherwise unusable. Each freeze-thaw (conditioning) cycle consisted of freezing the specimen for 16 hours and then placing it in a water bath at 140ºF (60ºC) for 24 hours to completely remove any ice. Specimens were then removed from the 140ºF water bath and placed in a 77ºF (25ºC) water bath for two hours prior to performing the indirect tensile strength test. The maximum tensile strength values were regarded as those of the specimens that underwent 0 cycles, meaning they were unconditioned.

Sixteen specimens were prepared for each of the 12 asphalt mix designs tested for the indirect tensile strength test, meaning that 192 specimens were needed for the indirect tensile testing portion of the study. Twenty-four specimens were prepared for each of the eight asphalt mix designs used for the thermal stress restrained specimen test, and 24 specimens were prepared for each of the eight mix designs tested with the Georgia Loaded Wheel Tester, meaning that 24 specimens were needed for the thermal stress restrained specimen testing portion of the study, and 24 specimens were needed for the Georgia loaded wheel testing portion of the study. Specimens with an air void content of 7 ±1 percent were used for the indirect tensile strength test and for lab compacted specimens used in the thermal stress restrained specimen test and the Georgia loaded wheel test. The time needed to produce one specimen and condition it through one freeze-thaw cycle was approximately one week. Specimens needing to be conditioned for 15 freeze-thaw cycles before undergoing the indirect tensile strength test required approximately five weeks time. The conditioning of the specimens took place so that the majority of the indirect tensile tests took place between 8 a.m. and 6 p.m. The completion of conditioning and testing of all specimens took approximately nine months.

### 3.2.1 Aggregate

Two types of aggregate were used in this study; granite and limestone. Indirect tensile tests, Georgia loaded wheel tests, and thermal stress restrained specimen tests were performed on the limestone aggregate. Only indirect tensile testing was performed on the granite aggregate due to time limitations of the study. Further testing will be performed on the granite at a later date.

These two aggregate types were chosen for this study because of their availability and common use in Wyoming. The granite aggregate was procured from stockpiles at Granite Canyon Quarry in Granite Canyon Wyo. The limestone aggregate came from North Rawlins Quarry in Rawlins Wyo. Physical characteristics of the aggregates used in this study were obtained from WYDOT in conjunction with the Wyoming State Geological Survey.

Aggregate gradation can greatly affect the stability and durability of HMA mixes. Therefore, it is one of the most important properties associated with the aggregate and is a primary consideration in mix design. A gradation is normally determined by sieve analysis. This analysis can be characterized by the stacking of a number of sieves with sieves near the top of the stack having larger openings and a trend of progressively smaller openings toward the bottom of the stack. Aggregate being retained on each individual screen is then weighed. Gradation is then expressed as the percent of material passing each of the sieve sizes.

The overall granite blend was a combination of three gradations obtained from Granite Canyon Quarry at a 15/32/53 split. The limestone blend was a combination of only two gradations, both sourced from North Rawlins Quarry. Gradations for these aggregates can be seen in Table 3.1 and Table 3.2.

**Table 3.1 Gradation of Granite Aggregate used in Experiment**

| Sieve Size | Percent Passing | | | |
|---|---|---|---|---|
| | Aggregates | | | Aggregate Blend (%) |
| | > #4 | medium | < #4 | |
| 3/4" | 57 | 100 | 100 | 100 |
| 1/2" | 22 | 100 | 100 | 94 |
| 3/8" | 3 | 81 | 100 | 82 |
| #4 | 1 | 8 | 74 | 42 |
| #8 | 1 | 3 | 54 | 30 |
| #16 | 1 | 2 | 40 | 22 |
| #30 | 1 | 2 | 30 | 16 |
| #50 | 1 | 1 | 22 | 12 |
| #100 | 1 | 1 | 16 | 9 |
| #200 | 0.5 | 0.8 | 10.8 | 6.1 |

**Table 3.2 Gradation of Limestone Aggregate used in Experiment**

| Sieve Size | Percent Passing | | |
|---|---|---|---|
| | Aggregates | | Aggregate Blend (%) |
| | > #4 | < #4 | |
| 1" | 100 | 100 | 100 |
| 3/4" | 99 | 100 | 99 |
| 1/2" | 67 | 100 | 83 |
| 3/8" | 38 | 100 | 67 |
| #4 | 0 | 100 | 47 |
| #8 | 0 | 59 | 28 |
| #16 | 0 | 35 | 16 |
| #30 | 0 | 22 | 10 |
| #50 | 0 | 15 | 7 |
| #100 | 0 | 11 | 5 |
| #200 | 0 | 8.7 | 4.1 |

### 3.2.2 Asphalt Cement

One type of asphalt cement was used to produce all test specimens in this study. This asphalt cement has a performance grade of PG 64-22 and was provided by the Casper Refinery of Sinclair Oil Corporation. The specific gravity of the asphalt was determined by following the procedures outlined in ASTM D70-82. In this method, a partially filled 600 mL low-form beaker was used along with 3 pycnometers. The weights of the empty pycnometer, the pycnometer with water, the pycnometer with asphalt, and the pycnometer with water and asphalt were recorded. The specific gravity was then calculated by the following equation:

$$\text{Specific Gravity} = \frac{(C - A)}{[(B - A) - (D - C)]} \tag{3.1}$$

Where,

A = weight of dry pycnometer,
B = weight of pycnometer filled with water,
C = weight of pycnometer filled with asphalt,
D = weight of pycnometer filled with asphalt and water.

Using this method, the specific gravity of the asphalt was calculated to be 1.0269. The mixing and compaction temperatures used were 300ºF (149ºC) and 280ºF (138ºC) corresponding to asphalt cement viscosities of 0.17(±0.02) and 0.28(±0.03) Pa, respectively.

### 3.2.3 Preparation of Samples

Three types of samples were needed in this study as each of the three tests performed require samples of different dimensions. The indirect tensile test requires cylindrical samples of 2.5 inch (63.5 mm) height and 4 (100 mm) inch diameter. Samples for the thermal stress restrained specimen test are cylindrical with a 2 inch (51 mm) diameter and a height of 9.5 inches (241 mm). Samples for the Georgia loaded wheel test are cylindrical with a height of 3 inches (76 mm) and a diameter of 6 inches (150 mm).

All samples prepared for the indirect tensile strength test were prepared with the Troxler Gyratory Compactor as seen in Figure 3.1.

**Figure 3.1 Troxler Gyratory Compactor**

This compactor is used in the sample preparation phase of the Superpave mix design because it is most representative of the method of compaction the asphalt would receive in the field. Adequate and uniform compaction of the specimens is essential because the increase or decrease in air void from improper compaction would affect the moisture susceptibility of the compacted specimens.

The Gyratory Compactor operates by compacting the loose HMA mix with a constant pressure of 87 psi (600kPa) while the specimen mold is gyrated at an angle of 1.25 degrees from vertical. The specimen height is constantly monitored during compaction. The asphalt and aggregate are mixed at 140ºF (60ºC). The loose mixes and the specimen molds were then heated to the 280ºF (138ºC) compaction temperature. The loose HMA mix is then poured into a heated cylindrical mold having an inside diameter of 4 inches (100mm) and a moveable lower puck. The amount of HMA mix needed to achieve a 2.5 inch by 4 inch core with 6 percent to 8 percent air voids is placed in the mold. The mold is then placed in the Gyratory Compactor, the ram is lowered, and compaction begins. During compaction, the mold is tilted at the aforementioned angle of 1.25 degrees while the upper and lower pucks remain parallel to each other and perpendicular to the original axis of the mold. The mold is gyrated about its original central axis at 30 rpm. As the loose mix is compacted, the specimen height is automatically measured to the nearest 0.1 mm. The gyrate-to-height feature of the compactor allows specimens with air voids of 7 percent ± 1 percent to be made once the correct volume of loose HMA mix to be placed in the mold is determined.

Samples prepared for the Georgia loaded wheel test are prepared in much the same way as samples prepared for the indirect tensile strength test. The procedure is the same except for the substitution of a mold with a 6 inch (150 mm) inside diameter to replace the 4 inch (100 mm) diameter mold. The loose HMA mix is then compacted to a height of 3 inches (76 mm) to achieve the desired percent air void.

Samples prepared for the thermal stress restrained specimen test are generally obtained by sawing an appropriate longitudinal section from the pavement. This cut section is then stood on end and a 2-inch (51 mm) diameter core with a 9.5 inch (241 mm) length is removed from the center of the section. The complete procedures followed to prepare specimens for all three tests mentioned in this section are given in Appendix A.

### 3.2.4 Percent Air Voids

The percent air voids for specimens used in this study were determined by the procedure described in AASHTO T-166. Using this procedure, the bulk specific gravity of each specimen was calculated. Before calculating the bulk specific gravity, the percent of water absorbed by each specimen is calculated by this equation:

$$\text{Absorbed water (\%)} = \frac{C - A}{C - B} \text{ x } 100 \tag{3.2}$$

Where,

A = Mass of specimen in air,
B = Mass of specimen in water,
C = Mass of saturated surface dried specimen.

If the percent of water absorbed was less than 2 percent, the bulk specific gravity was calculated by this equation:

$$G_{SB} = \frac{A}{C - B} \tag{3.3}$$

Where, A, B, and C are as previously defined in equation (3.1)

The percent of air voids in compacted paving mixes is then determined by the following equation:

$$\text{Air voids (\%)} = 100 \text{ x } \left(1 - \frac{A}{B}\right) \tag{3.4}$$

Where,

A = Bulk specific gravity (AASHTO T-166),
B = Theoretical maximum specific gravity (AASHTO T-209).

### 3.2.5 Saturation and Cycling

Wyoming modified AASHTO T-283 provides a method to determine the susceptibility of a compacted asphalt mix to moisture induced damage. The specimens for the indirect tensile strength test were conditioned and cycled according to this procedure.

Before the specimens underwent any freeze-thaw cycling, they were saturated with water until the air voids within the specimen were filled to between 55 percent and 80 percent capacity. This saturation was done by submerging the cores in a vacuum container filled with distilled water. Vacuum was then applied over the water to allow any air bubbles to exit the void space in the specimen and to allow water to infiltrate the voids. After the saturation, the cores were left in the vacuum vessel for an additional five minutes under atmospheric pressure to allow them to reach an equilibric state before proceeding. After the equilibrium time has elapsed, the specimens are removed from the vacuum container and the bulk specific gravity of each specimen is determined. The achieved saturation level was also determined by multiplying the specimen's volume by its air void content. Then, the amount of water absorbed was divided by the previously determined product, and expressed as a percentage.

The freeze-thaw cycles the specimens underwent were characterized by 16 hours of freezing temperatures and then 24 hours in a water bath at 140ºF (60ºC). Each core was wrapped in plastic wrap as well as being placed inside a sealable freezer bag. Ten ml of distilled water was added to each bag before being placed in the freezer. After 16 hours, the specimens were removed from the freezer, taken out of the freezer bag and plastic wrap, and placed into the water bath. This process was repeated until the prescribed number of freeze-thaw cycles had been completed. Specimens completing their prescribed freeze-thaw cycling were placed in the water bath at 77ºF (25ºC) for two hours to reach thermal equilibrium prior to use in the indirect tensile strength test.

### 3.2.6 Indirect Tensile Strength Test

This quantitative test measures the change in tensile strength of HMA mixes due to the effects of freeze-thaw cycling performed in the laboratory. The Soiltest machine was used to perform this test. The results of this test are primarily used as an indicator of the degree of moisture susceptibility a pavement may exhibit under actual field conditions. Another possible use of this test is the evaluation of the addition of anti-stripping agents to HMA mixes. The ability of asphalt mixes to resist the destructive effects of moisture can be expressed as a ratio of the original unconditioned specimen's tensile strength to the tensile strength retained by a conditioned specimen.

### 3.2.7 Georgia Loaded Wheel Test

The benefit of this test is that it returns quantitative data in the form of rut depths measured from test samples. Rutting performance of the asphalt mix is simulated in the GLWT machine as a roller travels back and forth on a pressurized hose placed atop the specimen. This test is performed at a temperature of 140ºF (60ºC) to simulate typical summer time temperatures that a pavement may reach in actual service. The results of this test are primarily used as an indicator of the potential for rutting pavement may exhibit under actual field conditions.

### 3.2.8 Thermal Stress Restrained Specimen Test

This test is an analytical tool to determine how well pavement will perform in low temperature conditions as experienced in Wyoming. As the temperature inside the test chamber is lowered, the specimen will contract and a tensile force will be applied to the specimen to ensure that the original length is retained. The lower the temperature the specimen can withstand before failure indicates the likelihood of better low temperature service under actual conditions. The viability of this test is greatly reduced if the asphalt to be tested is intended for use only in areas which rarely or never see low temperatures such as the southern part of the United States. In these warm areas, this test is simply not needed.

## 3.3 Summary

This chapter discussed the design of the experiment undertaken in this study as well as the test procedures followed. For the indirect tensile test, 16 specimens were tested for each asphalt mix. Twenty-four specimens were tested for each asphalt mix for both the thermal stress restrained specimen test and the Georgia loaded wheel test. Data was collected for the indirect tensile strength test, the thermal stress restrained specimen test, and the Georgia loaded wheel test.

# 4. LABORATORY TESTING

## 4.1 Introduction

This study involved the preparation of specimens from 16 HMA mixes using the gyratory compactor and testing them with the Soiltest indirect tensile testing machine. Also prepared were specimens from eight mixes for the TSRST test and specimens from 24 mixes for the GLWT test. The purpose of these three tests was to determine if the addition of bottom ash to HMA mixes would affect the performance of the asphalt in resisting moisture damage, resisting low-temperature cracking, or reducing the potential for rutting under heavy load conditions.

## 4.2 Materials

Limestone and granite were the two aggregate types used in the preparation of test specimens in this study. The job mix designs for both the limestone and granite aggregate were provided by Consolidated Engineers & Materials Testers (CE & MT) in Gillette, Wyo. The granite was obtained from quarries near Rock Springs, Wyo., and provided by Lewis and Lewis Inc. The limestone was obtained from quarries near Gillette, Wyo., and was provided by Cundy Asphalt Paving Construction Inc. The gradations of the aggregates used in the study and the appropriate WYDOT specification limits can be seen in Figure 4.1 and Figure 4.2.

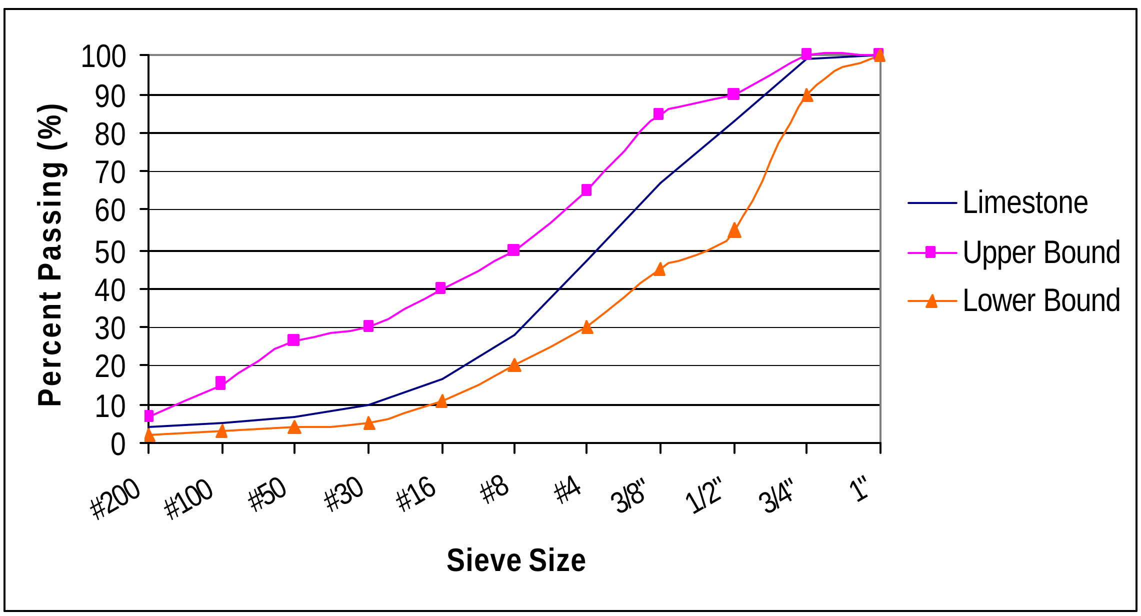


**Figure 4.1 Limestone Gradation and Associated Specification Limits**

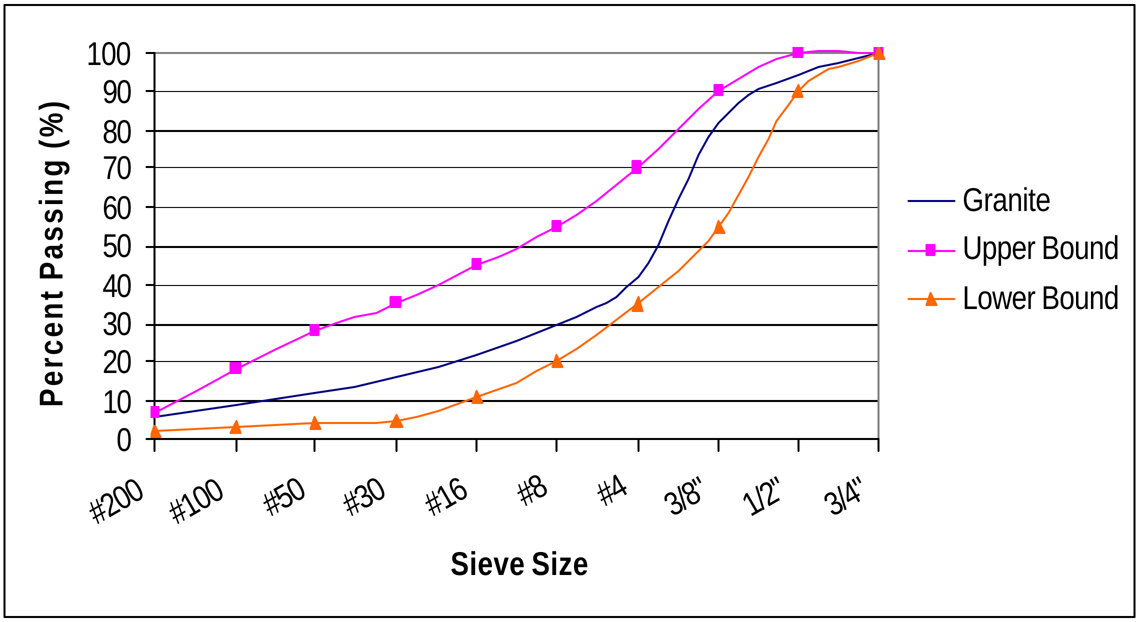


**Figure 4.2 Granite Gradation and Associated Specification Limits**

### 4.2.1 Asphalt Cement

One type of asphalt cement was used in this study. This asphalt, having a performance grade of 64-22 was provided by the Casper Refinery of the Sinclair Oil Corporation. The specific gravity of the asphalt used was determined to be 1.0269 by the procedure outlined in equation 3.1 in Chapter 3. The mixing and compaction temperatures were 300ºF (149ºC) and 280ºF (138ºC) which correspond to viscosities of 0.17 and 0.28 Pa. respectively.

### 4.2.2 Asphalt Mixes

Asphalt specimens for all three test types were prepared with no ash or with bottom ash from one of three power plants within Wyoming. The power plants were Dave Johnston (DJ) power plant near Glenrock, Jim Bridger (JB) power plant near Rock Springs, and Laramie River (LR) power plant near Wheatland.

Eight aggregate-bottom ash lab mixes were made with the granite aggregate. They were the control mix without ash, and the DJ mix prepared with DJ bottom ash. Each of these two mixes was divided into two subgroups: one lab mix with lime and one lab mix without lime. Twelve aggregate-bottom ash mixes were made with the limestone aggregate. They included a control mix made with no bottom ash, and DJ, JB, and LR mixes, each made with 15 percent bottom ash by dry weight of total aggregate including bottom ash from their respective sources. Each of the four aggregate-bottom ash mixes made with the limestone was divided into three subgroups: two lab mixes, one with lime and one without, and also into a plant mix with lime. The addition of 1 percent lime by dry weight of aggregate is based on the consideration that this study is to investigate the moisture susceptibility of asphalt mixes and lime is commonly used as an anti-stripping agent in areas where moisture damage is a problem.

The asphalt mixes studied here were designed in accordance with Superpave mix design in AASHTO MP2 and PP28. These mixes were designed for a pavement with an assumed ESAL between 0.3 million and 3 million. The compaction parameters were $N_{ini} = 7$ for $G_{sb} \leq 90.5\%$ of $G_{mm}$, $N_{des} = 75$ for $G_{sb} =$

96% of $G_{mm}$, and $N_{max}$ = 115 for $G_{sb} \leq$ 98% of $G_{mm}$, where $G_{mm}$ is the theoretical maximum specific gravity and $G_{sb}$ is the bulk specific gravity. $G_{mm}$ and $G_{sb}$ were determined in accordance with AASHTO T-209 and T-166 respectively. The mixes were numbered from 1 to 16 for ease of discussion. The results of the mix design can be seen in Table 4.1.

**Table 4.1 Mix Design Characteristics**

| Aggregate | Bottom Ash | Mix Number | Nominal Maximum Aggregate Size | Lime Addition | Asphalt Content (%) |
|---|---|---|---|---|---|
| Limestone | Control Lab Mix | 1 | 3/4 in. (19.0 mm) | No | 4.6 |
| | Control Lab Mix | 2 | | Yes | 4.6 |
| | Control Plant Mix | 3 | | Yes | 4.6 |
| | 15% DJ Lab Mix | 4 | | No | 6.1 |
| | 15% DJ Lab Mix | 5 | | Yes | 6.1 |
| | 15% DJ Plant Mix | 6 | | Yes | 6.1 |
| | 15% JB Lab Mix | 7 | | No | 5.2 |
| | 15% JB Lab Mix | 8 | | Yes | 5.2 |
| | 15% JB Plant Mix | 9 | | Yes | 5.2 |
| | 15% LR Lab Mix | 10 | | No | 5.7 |
| | 15% LR Lab Mix | 11 | | Yes | 5.7 |
| | 15% LR Plant Mix | 12 | | Yes | 5.7 |
| Granite | Control Lab Mix | 13 | 1/2 in. (12.5 mm) | No | 5.5 |
| | Control Lab Mix | 14 | | Yes | 5.5 |
| | 15% DJ Lab Mix | 15 | | No | 6.2 |
| | 15% DJ Lab Mix | 16 | | Yes | 6.2 |

## 4.3 Indirect Tensile Strength Test

The indirect tensile strength test was performed at 77º F (25ºC) at a loading rate of 2 inches/minute (50.8 mm/minute). This test requires a cylindrical specimen with dimensions of 2.5 inches (63.5 mm) in height and 4 inches (100 mm) in diameter. Specimen data for indirect tensile tests can be viewed in Appendix B. The Soiltest machine is used for this test and can be seen in Figure 4.3. The apparatus applies a load through two loading strips with concave surfaces to firmly hold the core in place.

**Figure 4.3 Soiltest Stabilometer**

The maximum compressive load applied to the specimen is recorded, and the tensile strength of the asphalt mix in psi was calculated as follows:

$$\text{Tensile Strength} = \frac{2P}{phD} \qquad (4.1)$$

Where P = maximum load, pounds,
h = specimen height, inches,
D = specimen diameter, inches.

The resistance of an asphalt mix to moisture infiltration can be expressed as a ratio of the tensile strength of the conditioned specimen to the tensile strength of an unconditioned specimen as follows:

$$\text{Tensile strength ratio (TSR)} = \frac{TS_c}{TS_u} \qquad (4.2)$$

Where $TS_c$ = average tensile strength of conditioned specimen,
$TS_u$ = average tensile strength of unconditioned specimen.

The minimum allowable percent of tensile strength to be retained versus the control samples after one freeze-thaw cycle is 70 percent.

In addition to TSR after one freeze-thaw cycle, percentages of tensile strength retained were determined for specimens that underwent up to 15 cycles. To better evaluate the effects of multiple freeze-thaw cycles, the relationship between TSR and the number of freeze-thaw cycles is expressed by this linear equation:

$$TSR = 1.0 - TSRR \times N \tag{4.3}$$

Where TSRR = TSR rate, and

N = number of freeze-thaw cycles

TSRR represents the average loss of TSR per freeze-thaw cycle. A TSRR of zero signifies an asphalt mix that is in no way susceptible to moisture. A higher TSRR value signifies an asphalt mix that will be more susceptible to moisture induced damage. Average TSR values and TSRR data are summarized by mix type and number of freeze-thaw cycles in Table 4.2. Tensile strength ratio graphs are displayed in Appendix E.

**Table 4.2 Tensile Strength, TSR, and TSRR Data for 16 HMA Mixes**

| Aggregate | Limestone | | | | | | | | | | | | Granite | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mix Number** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
| | **Unconditioned Tensile Strength (psi)** | | | | | | | | | | | | | | | |
| | 71.4 | 67.6 | 120.8 | 59.1 | 52.6 | 107.8 | 98.1 | 75.3 | 113.0 | 96.8 | 66.9 | 111.7 | 73.4 | 76.0 | 77.3 | 92.2 |
| **Number of Freeze-Thaw Cycles** | **Percent of Tensile Strength Retained** | | | | | | | | | | | | | | | |
| **0** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| **1** | 79.0 | 92.0 | 77.0 | 84.0 | 94.0 | 75.0 | 63.0 | 94.0 | 70.0 | 66.0 | 95.0 | 67.0 | 88.0 | 90.0 | 84.0 | 96.0 |
| **2** | 75.0 | 89.0 | 72.0 | 82.0 | 92.0 | 65.0 | 66.0 | 84.0 | 65.0 | 58.0 | 87.0 | 79.0 | 57.0 | 99.0 | 79.0 | 90.0 |
| **4** | 65.0 | 89.0 | 65.0 | 77.0 | 91.0 | 66.0 | 42.0 | 75.0 | 60.0 | 44.0 | 84.0 | 70.0 | 34.0 | 97.0 | 66.0 | 82.0 |
| **6** | 51.0 | 82.0 | 66.0 | 54.0 | 89.0 | 64.0 | 37.0 | 74.0 | 55.0 | 41.0 | 84.0 | 67.0 | 23.0 | 84.0 | 60.0 | 74.0 |
| **8** | 49.0 | 79.0 | 60.0 | 46.0 | 89.0 | 64.0 | 37.0 | 71.0 | 55.0 | 42.0 | 82.0 | 68.0 | 19.0 | 80.0 | 44.0 | 74.0 |
| **10** | 47.0 | 74.0 | 65.0 | 40.0 | 86.0 | 61.0 | 29.0 | 73.0 | 51.0 | 42.0 | 80.0 | 64.0 | 20.0 | 77.0 | 42.0 | 69.0 |
| **15** | 33.0 | 68.0 | 54.0 | 23.0 | 91.0 | 53.0 | 31.0 | 58.0 | 46.0 | 36.0 | 71.0 | 58.0 | 13.0 | 72.0 | 44.0 | 72.0 |
| | **TSR Rate** | | | | | | | | | | | | | | | |
| | 0.055 | 0.024 | 0.040 | 0.059 | 0.011 | 0.041 | 0.066 | 0.032 | 0.049 | 0.061 | 0.022 | 0.036 | 0.080 | 0.021 | 0.052 | 0.027 |

## 4.4 Georgia Loaded Wheel Test

Testing of specimens within the GLWT consisted of applying a 100 lb(445-N) load onto a pneumatic linear hose pressurized to 100 psi (689 kPa). The test was performed with the inside of the test chamber maintained at a temperature of 115ºF (46ºC). The load was applied through an aluminum wheel onto the linear hose, which resided on the specimen. This test required a cylindrical specimen with dimensions of 2.5 inches (63.5 mm) in height and 6 inches (150 mm) in diameter. The aluminum wheel was tracked back and forth over the applied stationary specimens. Testing was accomplished for a total of 8,000 loading cycles (one cycle is defined as the backward and forward movement over a specimen by the wheel).

At the conclusion of the 8,000 cycle loadings, permanent deformation (rutting) was measured. Rut depths were obtained by determining the average difference in specimen surface profile before and after testing. Results for specimens that underwent the Georgia loaded wheel tests can be viewed in Table 4.3.

**Table 4.3 GLWT Data for the 24 HMA Mixes**

| Ash Source | Mix Type | Rut Depth (in.) @ 8000 cycles |
|---|---|---|
| Control | Lab Mix w/Lime | 0.054 |
| Control | Lab Mix w/Lime | 0.048 |
| Control | Plant Mix, Field Compacted | 0.400 |
| Control | Plant Mix, Field Compacted | 0.245 |
| Control | Plant Mix, Lab Compacted | 0.135 |
| Control | Plant Mix, Lab Compacted | 0.075 |
| Dave Johnston | Lab Mix w/Lime | 0.071 |
| Dave Johnston | Lab Mix w/Lime | 0.063 |
| Dave Johnston | Plant Mix, Field Compacted | 0.361 |
| Dave Johnston | Plant Mix, Field Compacted | 0.351 |
| Dave Johnston | Plant Mix, Lab Compacted | 0.098 |
| Dave Johnston | Plant Mix, Lab Compacted | 0.100 |
| Jim Bridger | Lab Mix w/Lime | 0.074 |
| Jim Bridger | Lab Mix w/Lime | 0.087 |
| Jim Bridger | Plant Mix, Field Compacted | 0.333 |
| Jim Bridger | Plant Mix, Field Compacted | *No data* |
| Jim Bridger | Plant Mix, Lab Compacted | 0.073 |
| Jim Bridger | Plant Mix, Lab Compacted | 0.112 |
| Laramie River | Lab Mix w/Lime | 0.037 |
| Laramie River | Lab Mix w/Lime | 0.047 |
| Laramie River | Plant Mix, Field Compacted | 0.275 |
| Laramie River | Plant Mix, Field Compacted | 0.356 |
| Laramie River | Plant Mix, Lab Compacted | 0.103 |
| Laramie River | Plant Mix, Lab Compacted | 0.098 |

## 4.5 Thermal Stress Restrained Specimen Test

In this test, a specimen was secured in the test cabinet and the testing process began. The closed-loop process continued as the specimen was cooled and ultimately failed by cracking. The thermally induced stress gradually increased as the temperature decreased, until the specimen fractured. At the break point, the stress reached its maximum value—the fracture strength, at the corresponding fracture temperature. The fracture strengths and temperatures were then compared among specimens to determine relative differences in quality. Fracture strength and temperature data for the thermal stress restrained specimen test can be viewed in Table 4.4. No lab compacted plant mix was available for production of specimens, hence the cells containing "No Data."

**Table 4.4 TSRST Data for the 24 HMA Mixes**

| Ash Source | Mix Type | Fracture Temperature ($^0$C) | Fracture Strength (psi) |
|---|---|---|---|
| Control | Lab Mix w/Lime | -33.6 | 120.4 |
| Control | Lab Mix w/Lime | -28.5 | 415.3 |
| Control | Plant Mix, Field Compacted | -32.9 | 394.3 |
| Control | Plant Mix, Field Compacted | -37.5 | 505.4 |
| Control | Plant Mix, Lab Compacted | no data | no data |
| Control | Plant Mix, Lab Compacted | no data | no data |
| Dave Johnston | Lab Mix w/Lime | -28.8 | 429.2 |
| Dave Johnston | Lab Mix w/Lime | -27.3 | 213.6 |
| Dave Johnston | Plant Mix, Field Compacted | -33.5 | 454.5 |
| Dave Johnston | Plant Mix, Field Compacted | -37.1 | 476.8 |
| Dave Johnston | Plant Mix, Lab Compacted | no data | no data |
| Dave Johnston | Plant Mix, Lab Compacted | no data | no data |
| Jim Bridger | Lab Mix w/Lime | -26.1 | 296.80 |
| Jim Bridger | Lab Mix w/Lime | -27.6 | 252.20 |
| Jim Bridger | Plant Mix, Field Compacted | -38.1 | 382.5 |
| Jim Bridger | Plant Mix, Field Compacted | -32.3 | 444.5 |
| Jim Bridger | Plant Mix, Lab Compacted | no data | no data |
| Jim Bridger | Plant Mix, Lab Compacted | no data | no data |
| Laramie River | Lab Mix w/Lime | -25.0 | 180.10 |
| Laramie River | Lab Mix w/Lime | -25.2 | 321.30 |
| Laramie River | Plant Mix, Field Compacted | -38.7 | 546.5 |
| Laramie River | Plant Mix, Field Compacted | -38.0 | 511.5 |
| Laramie River | Plant Mix, Lab Compacted | no data | no data |
| Laramie River | Plant Mix, Lab Compacted | no data | no data |

## 4.6 Summary

This chapter discussed the data collection procedures and the results obtained. The TSR , GLWT, and TSRST values were used to evaluate moisture susceptibility, rutting potential, and low temperature crack resistance, respectively. The following chapter discusses the statistical analysis performed on the results obtained from all testing methods.

# 5. DATA ANALYSIS

## 5.1 Introduction

Statistical analyses were performed on the T-283, TSRST, GLWT, and TSR data that was recorded after the completion of the laboratory experiments. The analyses were performed using analysis of variance and multiple regression techniques. Calculations were made with Minitab Release 13 and Microsoft Excel.

This chapter will discuss the statistical analyses used to evaluate data gathered in this study. Appendix F contains the details of the calculations from the analyses.

## 5.2 Statistical Analysis of the T-283, TSRST, and GLWT Data

The results from each of these three tests were a single value for each combination of ash and mix. This data format allowed results from all three tests to be most easily analyzed by an analysis of variance (ANOVA). The purpose of the ANOVA was to determine if the mean laboratory test results for a group of asphalt mixes were significantly different. An ANOVA is based on separation of the sums of squares and degrees of freedom associated with a response variable. ANOVA simplifies calculation of the F-test statistic and P-value so that significance of a difference in mean responses can be determined [Neter, Kutner, Nachtsheim, and Wasserman 1996]. The P-value calculated by MINITAB is the probability of observing the F-value or larger when the mean test results are equal. So, if a P-value less than the desired level of significance ($\alpha$) was observed, the hypothesis that two or more mean test results were equal was rejected. The level of significance used to determine whether laboratory test results were equal was 0.05.

The analyses for the T-283, TSRST, and GLWT tests in this project consisted of a two way analysis of variance. This ANOVA is termed "two way" because two factors, ash source and mix type were analyzed. The third factor concerning aggregate source was not relevant in these comparisons because these tests were performed only on samples prepared with Limestone aggregate. The ANOVA was also used to determine whether any interaction existed between the ash source and mix type. It can be seen from the P-values reported in Table 5.1 that neither ash source nor the ash*mix interaction had any statistically significant effects on the results of any of these tests. This indicates that an asphalt mix which has had bottom ash added as a replacement for a portion of the fine aggregate will maintain desirable strength, rutting, and low temperature properties when compared with pavements prepared with no bottom ash.

**Table 5.1 ANOVA-Based P-Values**

| | | Factor | | |
|---|---|---|---|---|
| | | **Ash Source** | **Mix Type** | **Ash*Mix** |
| **T-283** | P-value | 0.788 | 0.049 | 0.696 |
| | Effect | Insignificant | Significant | Insignificant |
| **TSRST** | P-value | 0.688 | 0.000 | 0.153 |
| | Effect | Insignificant | Significant | Insignificant |
| **GLWT** | P-value | 0.811 | 0.000 | 0.963 |
| | Effect | Insignificant | Significant | Insignificant |
| **Error df** | | 8 | 8 | 11 |

Table 5.1 does however show that mix type did have a significant effect in the outcome of all three tests. Confidence intervals of 95 percent were determined for mix type as it was the only factor significantly affecting results in any of the three tests shown in Table 5.1. The results of the confidence intervals can be seen in Figures 5.1, 5.2, & 5.3.

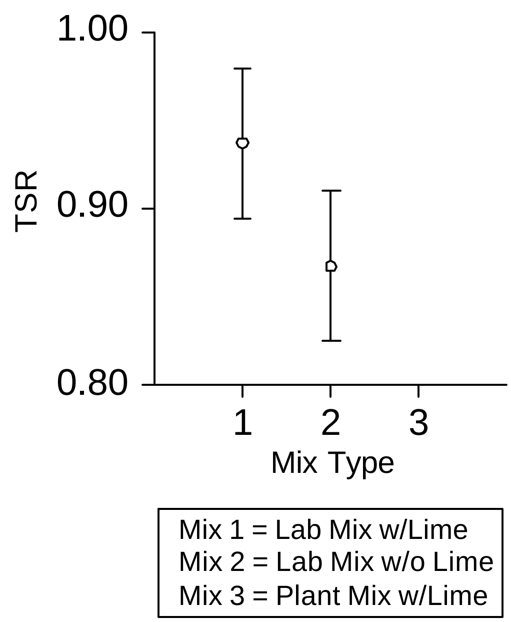


**Figure 5.1 95 Percent Confidence Intervals for AASHTO T-283 Mixes**

There were no T-283 tests done on mix type 3 because specimens prepared with limestone aggregate were available while specimens prepared with granite aggregate were not available for testing. In this test, the confidence intervals for the two available mix types overlap, but not by much, and absence of overlap is sufficient but not necessary for statistical difference. The results of the ANOVA indicate that the difference in average TSR based on mix type is significant. This means that the lab mix with lime performs better than the lab mix without lime.

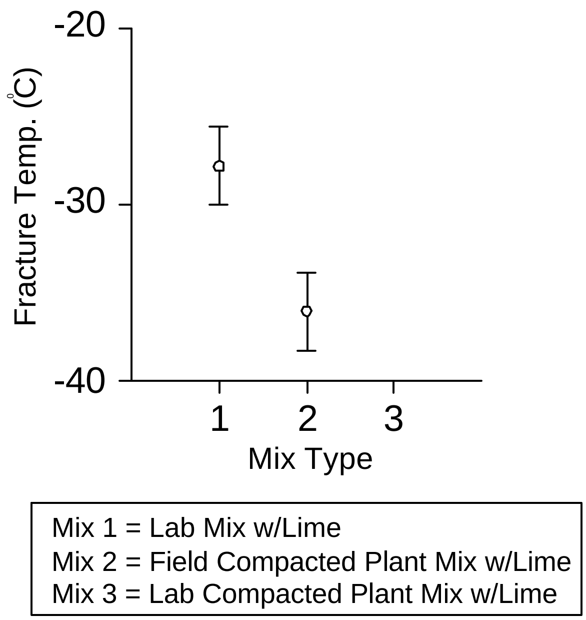


**Figure 5.2 95 Percent Confidence Intervals for TSRST Mixes**

There were no TSRST tests done on mix type 3 because specimens prepared with limestone aggregate were available while specimens prepared with granite aggregate were not available for testing. Figure 5.2 concerns TSRST results, and clearly shows that the field compacted plant mix with lime gives better low temperature performance than the lab mix with lime.

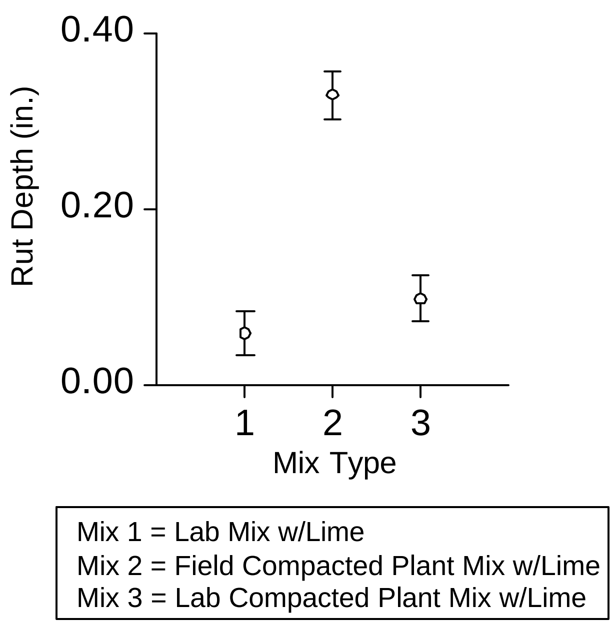


**Figure 5.3 95 Percent Confidence Intervals for GLWT Mixes**

Finally, it can be seen from Figure 5.3 that the confidence intervals for the lab mix with lime and the lab compacted plant mix with lime overlap slightly. However, the results of the ANOVA again indicate that the difference in average rut depth based on mix type is significant. Therefore, it can be said that both the lab mix with lime and the lab compacted plant mix with lime perform well with the lab mix showing slightly less susceptibility to rutting than the plant mix. The GLWT graph also shows poor performance and a high susceptibility to rutting of the field compacted plant mix with lime.

## 5.3 Statistical Modeling of TSR Results

Two separate analyses were performed on the collected TSR data. The first analysis looked within one aggregate type (limestone) and across three levels of mix and four levels of ash to determine the effects that changes in mix type or addition of ash would produce. The second analysis dealt with two aggregate types (limestone and granite) and two levels each of mix type and ash source. This second analysis was to determine if aggregate type became significant with certain ash sources, mix types, or combinations of ash and mix.

Both analyses of the TSR results were based on the following exponential decay model:

$$\text{TSR (t)} = T_0 * 10^{\,(b_1 \text{t})} \qquad (5.1)$$

Where,

$T_0$ = the baseline performance at zero Freeze-Thaw conditioning cycles,
$b_1$ = decay parameter,
t = the number of conditioning cycles the core was subjected to.

This model can also be expressed in an equivalent manner which lends itself more readily to standard linear regression methods,

$$\text{Log (TSR (t))} = b_0 + b_1 \text{t} \qquad (5.2)$$

where,

$$b_0 = \text{Log}\,(t_0)$$

This form of the equation was used for analysis purposes in this study. For each ash and mix combination (TSR analysis 1) or each ash, mix, aggregate combination (TSR analysis 2), a multiple regression was used to simultaneously estimate 95 percent confidence intervals for the slopes and intercepts for all HMA mixes. Table 5.2 shows the confidence intervals for slopes and intercepts of TSR analysis 1. Table 5.3 shows the confidence intervals for slopes and intercepts of TSR analysis 2.

**Table 5.2 95 Percent Confidence Intervals for TSR Analysis 1**

| Mix Type | $ß_0$ (Intercept) | | $ß_1$ (Slope) | |
|---|---|---|---|---|
| | Upper bound for $ß_0$ | Lower bound for $ß_0$ | Upper bound for $ß_1$ | Lower bound for $ß_1$ |
| Control, Lab Mix w/Lime | 100.00 | 87.58 | -0.003 | -0.016 |
| Control, Lab Mix w/o Lime | 90.30 | 78.93 | -0.022 | -0.035 |
| Control, Plant Mix w/Lime | 82.09 | 71.75 | -0.005 | -0.018 |
| DJ, Lab Mix w/Lime | 100.00 | 87.62 | 0.000 | -0.009 |
| DJ, Lab Mix w/o Lime | 100.00 | 90.51 | -0.034 | -0.046 |
| DJ, Plant Mix w/Lime | 78.32 | 68.45 | -0.003 | -0.016 |
| JB, Lab Mix w/Lime | 99.00 | 86.53 | -0.008 | -0.021 |
| JB, Lab Mix w/o Lime | 72.64 | 63.49 | -0.028 | -0.040 |
| JB, Plant Mix w/Lime | 75.56 | 66.04 | -0.008 | -0.021 |
| LR, Lab Mix w/Lime | 100.00 | 87.87 | -0.002 | -0.015 |
| LR, Lab Mix w/o Lime | 69.12 | 60.42 | -0.018 | -0.030 |
| LR, Plant Mix w/Lime | 77.43 | 67.67 | 0.000 | -0.011 |

*Note: all mixes in TSR analysis 1 were prepared with limestone aggregate.*

**Table 5.3 95 Percent Confidence Intervals for TSR Analysis 2**

| Mix Type | $ß_0$ (Intercept) | | $ß_1$ (Slope) | |
|---|---|---|---|---|
| | Upper bound for $ß_0$ | Lower bound for $ß_0$ | Upper bound for $ß_1$ | Lower bound for $ß_1$ |
| Limestone Control, Lab Mix w/Lime | 100.00 | 85.80 | -0.001 | -0.018 |
| Limestone Control, Lab Mix w/o Lime | 100.00 | 90.99 | -0.002 | -0.018 |
| Limestone DJ, Lab Mix w/Lime | 92.17 | 77.32 | -0.020 | -0.037 |
| Limestone DJ, Lab Mix w/o Lime | 95.84 | 80.40 | -0.068 | -0.084 |
| Granite Control, Lab Mix w/Lime | 100.00 | 85.84 | 0.000 | -0.011 |
| Granite Control, Lab Mix w/o Lime | 100.00 | 88.43 | -0.006 | -0.022 |
| Granite DJ, Lab Mix w/Lime | 100.00 | 88.67 | -0.032 | -0.048 |
| Granite DJ, Lab Mix w/o Lime | 96.97 | 81.35 | -0.021 | -0.038 |

Based on the criterion of failure occurring when the core falls to 70 percent of the original performance, the number of cycles until failure was found to be:

$$N = \text{Log}\ (0.7)/(b_1) \qquad (5.3)$$

From equation 5.3, a standard 95 percent confidence interval [L, U] for the number of cycles to failure can be obtained. This confidence interval is calculated by [(Log (0.7) - lower bound $b_0$)/ lower bound $b_1$, (Log (0.7) - upper bound $b_0$)/ upper bound $b_1$]. Tables 5.4 and 5.5 summarize the confidence intervals for the expected number of cycles to failure for TSR analysis 1 and TSR analysis 2 respectively.

**Table 5.4 95 Percent Confidence Intervals for Cycles to Failure in TSR Analysis 1**

| Mix Type | Upper bound | Lower bound |
|---|---|---|
| Control, Lab Mix w/Lime | 52.74 | 6.21 |
| Control, Lab Mix w/o Lime | 4.95 | 1.49 |
| Control, Plant Mix w/Lime | 14.30 | * |
| DJ, Lab Mix w/Lime | 8 | 10.72 |
| DJ, Lab Mix w/o Lime | 5.04 | 2.40 |
| DJ, Plant Mix w/Lime | 16.03 | * |
| JB, Lab Mix w/Lime | 18.62 | 4.43 |
| JB, Lab Mix w/o Lime | 0.58 | * |
| JB, Plant Mix w/Lime | 4.09 | * |
| LR, Lab Mix w/Lime | 78.95 | 6.72 |
| LR, Lab Mix w/o Lime | * | * |
| LR, Plant Mix w/Lime | 8 | * |

*Note: Specimen may fail on average very soon after 1st conditioning cycle begins.

**Table 5.5 95 Percent Confidence Intervals for Cycles to Failure in TSR Analysis 2**

| Mix Type | Upper bound | Lower bound |
|---|---|---|
| Limestone Control, Lab Mix w/Lime | 162.61 | 5.02 |
| Limestone Control, Lab Mix w/o Lime | 125.32 | 6.29 |
| Limestone DJ, Lab Mix w/Lime | 5.85 | 1.17 |
| Limestone DJ, Lab Mix w/o Lime | 2.01 | 1.06 |
| Granite Control, Lab Mix w/Lime | 8 | 8.03 |
| Granite Control, Lab Mix w/o Lime | 32.22 | 4.59 |
| Granite DJ, Lab Mix w/Lime | 5.63 | 2.12 |
| Granite DJ, Lab Mix w/o Lime | 6.76 | 1.74 |

*Note: Specimen may fail on average very soon after 1st conditioning cycle begins

## 5.4 Moisture Susceptibility Properties of HMA Mixes

Modeled TSR values were categorized by mix type, and are shown in Figures 5.4, 5.5, & 5.6 for Analysis 1.

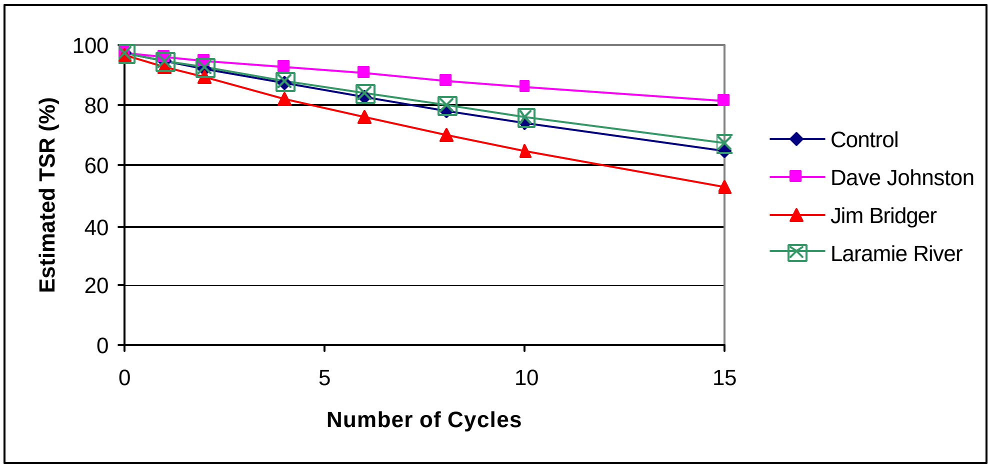


**Figure 5.4 Modeled Tensile Strength Ratio for Lab Mixes with Lime**

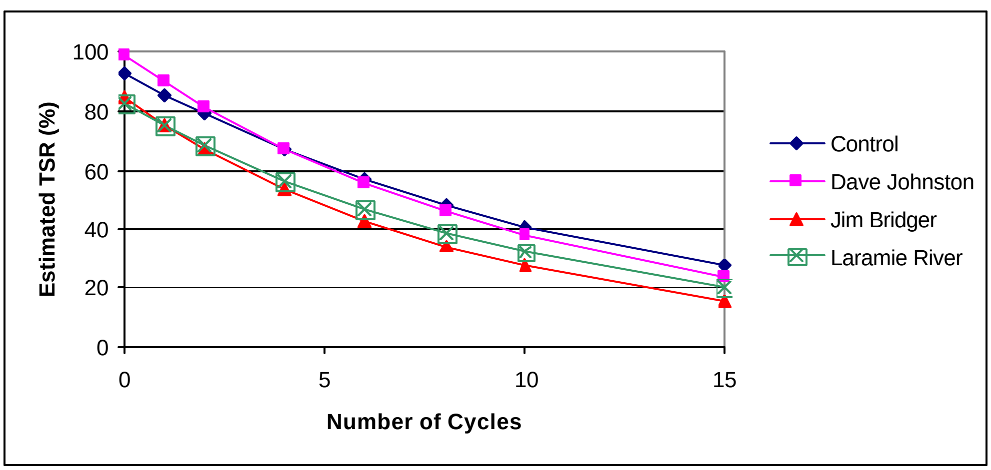


**Figure 5.5 Modeled Tensile Strength Ratio for Lab Mixes without Lime**

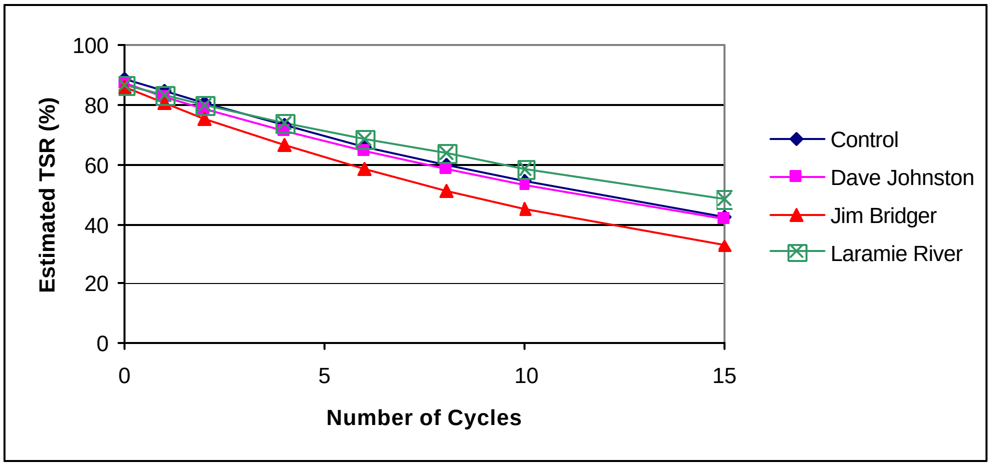


**Figure 5.6 Modeled Tensile Strength Ratio for Plant Mixes with Lime**

It can be determined from the modeled TSR results displayed in Figures 5.4, 5.5, and 5.6 that in mix types containing lime additive, the performances of ash mixes prepared with either Dave Johnston ash or Laramie River ash were either comparable, or the ash mixes exceeded the performance of the control mix in some cases. No appreciable degradation was experienced with either of these two limestone ash mixes. This is true for both initial strength and decay rate. A trend common to all mix types was the poor performance of the Jim Bridger ash mix. The mixes prepared with ash from the Jim Bridger power plant consistently showed the lowest initial strength values and the highest rate of decay.

Overall comparisons between mix types within this aggregate type (limestone) generally showed that lab mixes with lime additive showed lower rates of decay when compared to lab mixes produced with no lime additive. This is to say that lab mixes with lime had a better (numerically lower) TSR ratio (TSRR). However, initial strength was comparable between both lab mix types. Plant mixes also showed lower initial strengths than those of lab mixes with lime. However, plant mixes did display lower TSRR values than lab mixes with no lime additive. Both types of lab mixes displayed higher initial strength values than plant mixes.

In analysis 2 of the TSR data, two aggregate sources with four mixes each were compared. Figures 5.7, & 5.8 display modeled TSR values categorized by mix type for analysis 2.

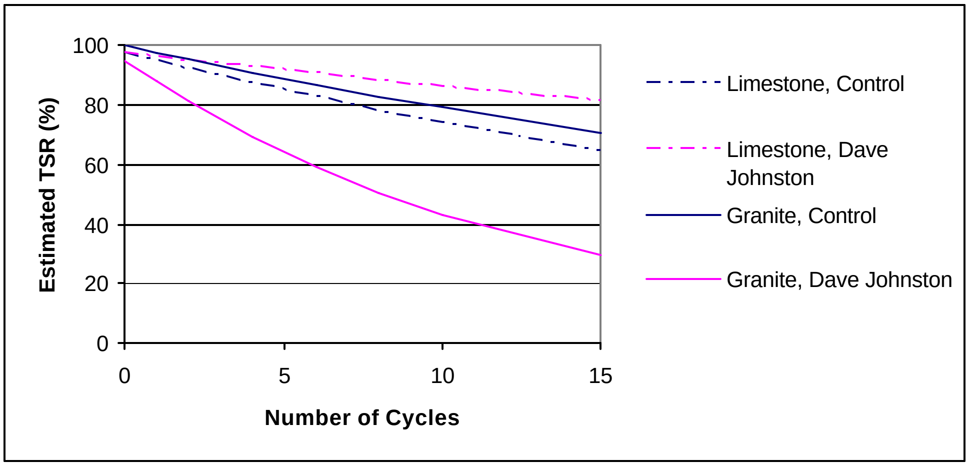


**Figure 5.7 Modeled Tensile Strength Ratio for Lab Mixes with Lime**

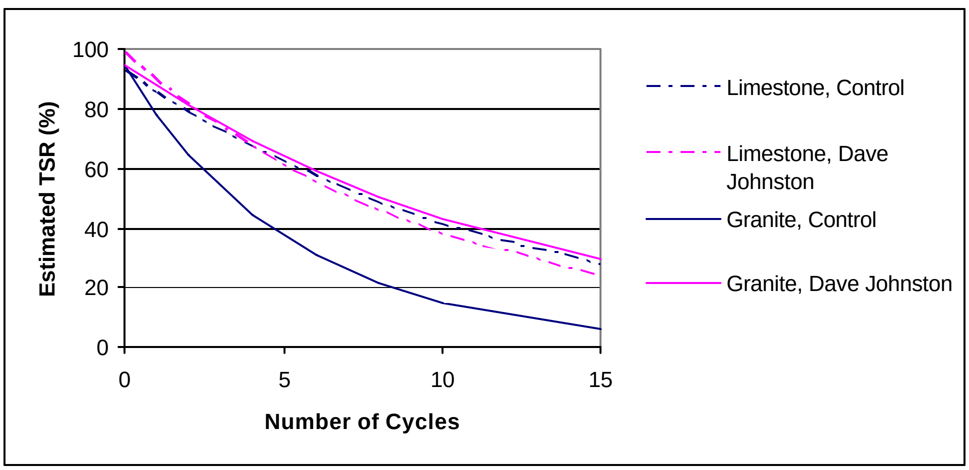


**Figure 5.8 Modeled Tensile Strength Ratio for Lab Mixes without Lime**

For TSR analysis 2, no plant mix specimens prepared with granite aggregate were available. Thus, we have a comparison of plant mix with lime additive versus plant mix without lime for combinations of two levels of aggregate (granite and limestone) and two levels of ash (control and Dave Johnston).

Figures 5.7 and 5.8 illustrate that the granite and limestone control mixes show very comparable performances in the presence of lime. However, the story changed when no lime was added to the mix. With no lime present, the granite control showed a very high rate of decrease compared to the limestone control. This would suggest that granite is not the best aggregate choice unless it can be assured that lime additive will be available for the asphalt mix.

The granite and limestone Dave Johnston mixes showed a large difference in performance based on whether or not lime was present. In the lab mix with lime, the limestone Dave Johnston mix displayed the best results of the four mixes while the granite Dave Johnston had the poorest showing. Any benefits of the limestone Dave Johnston mix over the granite Dave Johnston mix were nullified when the lime was not present. These two mixes performed almost identically in the absence of lime. This suggests that when lime additive is present, ash mixes (excepting Jim Bridger) perform better than control mixes. When lime additive is not present in the mix, ash mixes show near identical performance to control mixes with no loss of initial strength and no increase in the TSRR decay rate.

## 5.5 Summary

A statistical analysis was performed on the tensile strength, TSRST, and GLWT test results obtained from laboratory testing conducted in this study. The purpose of the analyses were to determine whether the addition of bottom ash into HMA mixes would allow those mixes to maintain or improve desirable performance properties when compared to control mixes.

The results of the analyses performed on the T-283, GLWT, and TSRST data showed that mix type had the most affect on their respective properties. It was also shown that the addition of bottom ash into these HMA mixes did not degrade their respective performance measures when compared to control mixes. Analyses on the multiple cycle TSR data revealed that mixes prepared with bottom ash from the Jim Bridger power plant showed very poor performance in the form of low initial strength values as well as a higher rate of strength decay whether lime additive was present in the mix or not. The remaining ash mixes displayed, even in the absence of lime, the quality of maintaining desirable tensile strength properties when compared to control mixes. Even more favorable was the fact that ash mixes displayed slightly improved properties over control mixes in the presence of lime. This improvement was generally evidenced by decreased TSRR values.

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Introduction

In this research, comprehensive laboratory testing was performed to evaluate the effects of the addition of bottom ash into HMA mixes. Evaluation included testing specimens for tensile strength, low temperature performance, and susceptibility to rutting. The HMA specimens tested in the study were obtained by combinations of aggregate from two sources, bottom ash from four sources, and three mix types. Tensile strength testing was performed on 2.5 in. by 4 in. specimens having air voids in the range of 7 ±1 percent. These specimens underwent freeze-thaw cycling and were then tested for tensile strength. Testing with the Georgia Loaded Wheel Tester was done on both field compacted and lab compacted 2.5 in. by 6 in. specimens. Lab-compacted GLWT specimens had air voids in the range of 7 ±1 percent while most of the field-compacted GLWT specimens exhibited air voids in the 8-11 percent range. A rubber hose inflated to 100 psi was then placed on the surface and loaded with a 100 lb steel wheel to simulate traffic loading. Rut depths after 8000 cycles were recorded. TSRST testing was performed on rectangular beam specimens with dimensions of 2.5 in. by 2.5 in. by 9 in. Testing of the TSRST specimens commenced at 14ºF (-10ºC) and ended when the specimens fractured. Time, fracture temperature, and fracture strength were recorded.

Finally, statistical analyses were performed on the data sets to determine if differences between the tensile strength, GLWT, and TSRST values of HMA mixes made with or without bottom ash were statistically significant.

## 6.2 Conclusions

Based on the analyses of data collected in this study, the following conclusions were drawn:

1. The tensile strength of all 16 HMA mixes decreased as the number of freeze-thaw cycles increased.
2. HMA mixes prepared with bottom ash did not show any significant degradation of tensile strength, low temperature properties, or rutting potential when compared to mixes containing no bottom ash.
3. Modeling decreases in tensile strength based on multiple freeze-thaw cycling is more accurate than modeling decreases based upon a single freeze-thaw cycle.
4. In the absence of lime additive, HMA mixes prepared with granite aggregate reached failure faster than those mixes prepared with limestone aggregate. This suggests that in the absence of lime, aggregate type will influence the time to failure.
5. Multiple freeze-thaw cycling typically showed a rapid strength decrease between the zero cycle (unconditioned specimens) and one freeze-thaw cycle for plant mix specimens of 4 in. diameter.
6. Excessive rut depth exhibited by specimens after the Georgia loaded wheel test is mostly due to higher than specified air void percentages. This tendency was displayed most frequently with field-compacted plant mixes.
7. Field-compacted plant mixes typically displayed better low temperature performance than lab mixes in the thermal stress restrained specimen test.

## 6.3 Recommendations

1. Lime additive is very effective in reducing the moisture susceptibility of HMA mixes and should be used to increase durability.
2. Without the addition of lime, HMA mixes prepared with granite aggregate are less durable than those mixes prepared with limestone aggregate. Therefore, limestone aggregate should be used for better durability.
3. The use of bottom ash in HMA mixes will maintain desirable strength properties, low temperature properties, and rutting properties, and may save money. However, the addition of bottom ash will require a corresponding increase in asphalt content. To determine potential cost savings, a study should be performed to determine the optimal percentage of ash that can be added without canceling out its cost savings with the cost of additional asphalt cement.
4. Due to the improvement in prediction of tensile strength properties of HMA mixes, multiple freeze-thaw cycling should be used as a test method instead of a single freeze-thaw cycle when possible.
5. A dramatic tensile strength difference was observed between zero freeze-thaw cycles and one freeze-thaw cycle for 4 in. diameter plant mix specimens. Further laboratory testing of plant mixes should occur with 6 in. diameter specimens to determine whether this strength difference is a true effect or due partly to the specimen size.
6. The cause of the tensile strength difference observed between zero freeze-thaw cycles and one freeze-thaw cycle for 4 in. diameter plant mix specimens should be determined. This apparent decrease may be due to an artificially inflated zero cycle value or some possible construction process which may contribute to the sudden decrease in the aforementioned time frame.
7. Excessive rut depth exhibited by specimens after the Georgia loaded wheel test was displayed most frequently with field-compacted plant mixes. However, field-compacted plant mixes typically displayed best low temperature performance in the thermal stress restrained specimen test. Further testing should be conducted to determine what properties of this mix allowed it to perform well in the TSRST but poorly in the GLWT.

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# APPENDIX A

## SPECIMEN PREPARATION PROCEDURES

## TENSILE TEST AND GLWT SPECIMENS:

These are the detailed steps followed in the production of lab mix specimens for the Indirect Tensile Test and the Georgia Loaded Wheel Test (GLWT). Steps 1-7 are not necessary for the production of plant mix specimens.

1. Weigh out aggregate for 5 to 10 specimens.
2. Heat aggregate and asphalt cement in 275 $^0$F (135 $^0$C) oven for 2 hours.
3. Use scale to weigh out appropriate amount of hot, dried aggregate and add appropriate amount of asphalt cement to achieve desired asphalt content.
4. Mix asphalt cement and large aggregate being sure all large aggregate is well coated. Then add smaller aggregate and mix until it is coated with asphalt.
5. Weigh out equal amounts of the mix and place the samples in individual containers to cure for two hours at room temperature.
6. Place mix samples in 140 $^0$F (60 $^0$C) oven for 16 hours.
7. Increase oven temperature to 275 $^0$F (135 $^0$C) for two hours. Place specimen mold (4 in. mold for indirect tensile test, 6 in. mold for GLWT) and lower puck into oven at this time.
8. Turn on Gyratory Compactor to allow it to warm up for 5 minutes.
9. Check settings on Gyratory Compactor to ensure that specified parameters are correct.
10. Place specimen paper into preheated mold and then pour in loose HMA mix. Level the top of the mixture with a heated spatula and place another specimen paper on top of the mix.
11. Place mold filled with loose HMA mix into Gyratory Compactor.
12. Compact HMA into a specimen.
13. Record number of gyrations for each specimen.
14. Let mold and specimen cool before extruding the specimen from the mold using the hydraulic ram. Remove top and bottom specimen papers. Mark specimen with paint pen with alphanumeric designation.
15. Allow specimens to sit at room temperature for 24 hours.
16. Determine the bulk specific gravity for each specimen.

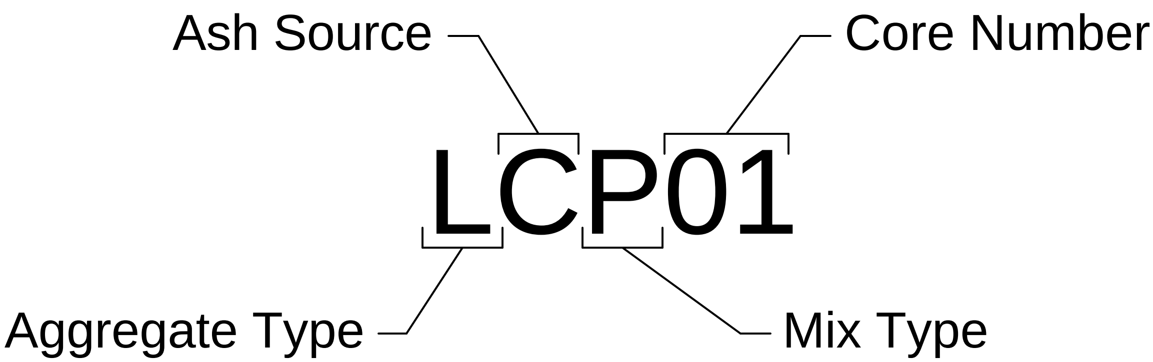
## TSRST SPECIMENS:

These are the detailed steps followed in the production of specimens for the Thermal Strength Restrained Specimen Test (TSRST).

1. Use a saw to cut a 2.5 in. (63.5 mm) wide by 2.5 in. (63.5 mm) deep by 9.5 in. (241 mm) long section from the field compacted pavement.
2. Use 2.5 in. diameter coring device to remove core from rectangular solid.
3. Retain the 2.5 inch diameter by 9.5 inch high asphalt cylinder; discard the asphalt the core was obtained from.

# APPENDIX B
## SPECIMEN DATA FOR INDIRECT TENSILE TESTS

## CORE DESIGNATION KEY




| Aggregate Type | |
|---|---|
| Limestone = | L |
| Granite = | G |

| Ash Source | |
|---|---|
| Control = | C |
| Dave Johnston = | DJ |
| Jim Bridger = | JB |
| Laramie River = | LR |

| Mix Type | |
|---|---|
| Plant Mix with Lime = | P |
| Lab Mix, No Lime = | L |
| Lab Mix with Lime = | LL |

| Core Designation | Agg. Type | Ash Source | Mix Type | # of Gyrations | Bulk Specific Gravity | % Air Voids | # of Freeze-Thaw Cycles | Tensile Strength (lbs) |
|---|---|---|---|---|---|---|---|---|
| LCP01 | L | C | 1 | 33 | 2.33 | 7.17 | 0 | 1897.20 |
| LCP02 | L | C | 1 | 41 | 2.35 | 6.40 | 0 | 1887.00 |
| LCP03 | L | C | 1 | 30 | 2.32 | 7.46 | 1 | 1428.00 |
| LCP04 | L | C | 1 | 39 | 2.32 | 7.38 | 1 | 1479.00 |
| LCP05 | L | C | 1 | 38 | 2.33 | 7.02 | 2 | 1417.80 |
| LCP06 | L | C | 1 | 43 | 2.33 | 7.04 | 2 | 1295.40 |
| LCP07 | L | C | 1 | 36 | 2.33 | 7.33 | 4 | 1203.60 |
| LCP08 | L | C | 1 | 41 | 2.35 | 6.57 | 4 | 1275.00 |
| LCP09 | L | C | 1 | 38 | 2.35 | 6.53 | 6 | 1295.40 |
| LCP10 | L | C | 1 | 37 | 2.33 | 7.27 | 6 | 1203.60 |
| LCP11 | L | C | 1 | 35 | 2.33 | 7.32 | 8 | 1132.20 |
| LCP12 | L | C | 1 | 27 | 2.30 | 8.27 | 8 | 1132.20 |
| LCP13 | L | C | 1 | 57 | 2.31 | 7.83 | 10 | 1234.20 |
| LCP14 | L | C | 1 | 41 | 2.35 | 6.40 | 10 | 1213.80 |
| LCP15 | L | C | 1 | 31 | 2.35 | 6.51 | 15 | 1071.00 |
| LCP16 | L | C | 1 | 39 | 2.33 | 7.33 | 15 | 958.80 |
| LDP01 | L | DJ | 1 | 24 | 2.28 | 7.01 | 0 | 1693.20 |
| LDP02 | L | DJ | 1 | 22 | 2.30 | 6.10 | 0 | 1723.80 |
| LDP03 | L | DJ | 1 | 26 | 2.26 | 7.84 | 1 | 1264.80 |
| LDP04 | L | DJ | 1 | 23 | 2.27 | 7.23 | 1 | 1305.60 |
| LDP05 | L | DJ | 1 | 24 | 2.29 | 6.53 | 2 | 1071.00 |
| LDP06 | L | DJ | 1 | 26 | 2.29 | 6.33 | 2 | 1162.80 |
| LDP07 | L | DJ | 1 | 23 | 2.30 | 6.21 | 4 | 1203.60 |
| LDP08 | L | DJ | 1 | 27 | 2.28 | 6.91 | 4 | 1050.60 |
| LDP09 | L | DJ | 1 | 29 | 2.28 | 6.97 | 6 | 1152.60 |
| LDP10 | L | DJ | 1 | 25 | 2.26 | 7.85 | 6 | 1040.40 |
| LDP11 | L | DJ | 1 | 29 | 2.27 | 7.32 | 8 | 1111.80 |
| LDP12 | L | DJ | 1 | 26 | 2.29 | 6.38 | 8 | 1060.80 |
| LDP13 | L | DJ | 1 | 34 | 2.27 | 7.40 | 10 | 1050.60 |
| LDP14 | L | DJ | 1 | 33 | 2.27 | 7.18 | 10 | 1020.00 |
| LDP15 | L | DJ | 1 | 25 | 2.26 | 7.86 | 15 | 928.20 |
| LDP16 | L | DJ | 1 | 28 | 2.28 | 6.90 | 15 | 897.60 |
| LJP01 | L | JB | 1 | 23 | 2.27 | 7.37 | 0 | 1774.80 |
| LJP02 | L | JB | 1 | 21 | 2.29 | 6.46 | 0 | 1723.80 |
| LJP03 | L | JB | 1 | 25 | 2.26 | 7.86 | 1 | 1254.60 |
| LJP04 | L | JB | 1 | 22 | 2.26 | 7.59 | 1 | 1315.80 |
| LJP05 | L | JB | 1 | 23 | 2.28 | 6.89 | 2 | 1132.20 |
| LJP06 | L | JB | 1 | 27 | 2.28 | 6.81 | 2 | 1152.60 |
| LJP07 | L | JB | 1 | 24 | 2.29 | 6.69 | 4 | 1111.80 |
| LJP08 | L | JB | 1 | 28 | 2.27 | 7.39 | 4 | 999.60 |
| LJP09 | L | JB | 1 | 30 | 2.27 | 7.45 | 6 | 958.80 |
| LJP10 | L | JB | 1 | 26 | 2.26 | 7.73 | 6 | 979.20 |
| LJP11 | L | JB | 1 | 27 | 2.27 | 7.20 | 8 | 969.00 |
| LJP12 | L | JB | 1 | 24 | 2.30 | 6.26 | 8 | 948.60 |
| LJP13 | L | JB | 1 | 32 | 2.27 | 7.28 | 10 | 877.20 |

| Core Designation | Agg. Type | Ash Source | Mix Type | # of Gyrations | Bulk Specific Gravity | % Air Voids | # of Freeze-Thaw Cycles | Tensile Strength (lbs) |
|---|---|---|---|---|---|---|---|---|
| LJP14 | L | JB | 1 | 33 | 2.28 | 7.06 | 10 | 907.80 |
| LJP15 | L | JB | 1 | 26 | 2.26 | 7.74 | 15 | 816.00 |
| LJP16 | L | JB | 1 | 29 | 2.28 | 6.78 | 15 | 795.60 |
| LLP02 | L | LR | 1 | 19 | 2.27 | 7.79 | 0 | 1560.60 |
| LLP03 | L | LR | 1 | 21 | 2.27 | 7.70 | 1 | 1122.00 |
| LLP04 | L | LR | 1 | 19 | 2.27 | 7.83 | 1 | 1101.60 |
| LLP05 | L | LR | 1 | 42 | 2.30 | 6.64 | 2 | 1336.20 |
| LLP06 | L | LR | 1 | 35 | 2.30 | 6.58 | 2 | 1275.00 |
| LLP07 | L | LR | 1 | 32 | 2.28 | 7.35 | 4 | 1071.00 |
| LLP08 | L | LR | 1 | 25 | 2.29 | 6.87 | 4 | 1244.40 |
| LLP09 | L | LR | 1 | 33 | 2.31 | 6.20 | 6 | 1173.00 |
| LLP10 | L | LR | 1 | 30 | 2.30 | 6.60 | 6 | 1050.60 |
| LLP11 | L | LR | 1 | 28 | 2.29 | 7.21 | 8 | 1142.40 |
| LLP12 | L | LR | 1 | 24 | 2.29 | 7.07 | 8 | 1122.00 |
| LLP13 | L | LR | 1 | 22 | 2.28 | 7.51 | 10 | 1091.40 |
| LLP14 | L | LR | 1 | 27 | 2.29 | 7.26 | 10 | 1040.40 |
| LLP15 | L | LR | 1 | 31 | 2.29 | 7.15 | 15 | 928.20 |
| LLP16 | L | LR | 1 | 32 | 2.29 | 7.07 | 15 | 1009.80 |
| LCL01 | L | C | 2 | 26 | 2.25 | 7.94 | 0 | 1122.00 |
| LCL02 | L | C | 2 | 27 | 2.26 | 7.84 | 0 | 1111.80 |
| LCL03 | L | C | 2 | 30 | 2.27 | 7.39 | 1 | 867.00 |
| LCL04 | L | C | 2 | 29 | 2.27 | 7.33 | 1 | 907.80 |
| LCL05 | L | C | 2 | 43 | 2.27 | 7.35 | 2 | 826.20 |
| LCL06 | L | C | 2 | 26 | 2.26 | 7.59 | 2 | 846.60 |
| LCL07 | L | C | 2 | 55 | 2.25 | 7.92 | 4 | 693.60 |
| LCL08 | L | C | 2 | 25 | 2.28 | 6.94 | 4 | 765.00 |
| LCL09 | L | C | 2 | 70 | 2.26 | 7.83 | 6 | 520.20 |
| LCL10 | L | C | 2 | 26 | 2.28 | 7.10 | 6 | 612.00 |
| LCL11 | L | C | 2 | 65 | 2.26 | 7.84 | 8 | 530.40 |
| LCL12 | L | C | 2 | 24 | 2.30 | 6.21 | 8 | 571.20 |
| LCL13 | L | C | 2 | 45 | 2.27 | 7.31 | 10 | 489.60 |
| LCL14 | L | C | 2 | 24 | 2.26 | 7.57 | 10 | 571.20 |
| LCL15 | L | C | 2 | 59 | 2.26 | 7.83 | 15 | 346.80 |
| LCL16 | L | C | 2 | 35 | 2.28 | 6.74 | 15 | 387.60 |
| LDL01 | L | DJ | 2 | 25 | 2.28 | 6.88 | 0 | 928.20 |
| LDL02 | L | DJ | 2 | 37 | 2.29 | 6.42 | 0 | 948.60 |
| LDL03 | L | DJ | 2 | 37 | 2.28 | 6.91 | 1 | 795.60 |
| LDL04 | L | DJ | 2 | 23 | 2.27 | 7.23 | 1 | 785.40 |
| LDL05 | L | DJ | 2 | 35 | 2.27 | 7.20 | 2 | 724.20 |
| LDL06 | L | DJ | 2 | 25 | 2.30 | 6.15 | 2 | 805.80 |
| LDL07 | L | DJ | 2 | 28 | 2.29 | 6.52 | 4 | 673.20 |
| LDL08 | L | DJ | 2 | 23 | 2.29 | 6.58 | 4 | 775.20 |
| LDL09 | L | DJ | 2 | 18 | 2.28 | 7.10 | 6 | 520.20 |
| LDL10 | L | DJ | 2 | 25 | 2.27 | 7.11 | 6 | 499.80 |

| Core Designation | Agg. Type | Ash Source | Mix Type | # of Gyrations | Bulk Specific Gravity | % Air Voids | # of Freeze-Thaw Cycles | Tensile Strength (lbs) |
|---|---|---|---|---|---|---|---|---|
| LDL11 | L | DJ | 2 | 57 | 2.29 | 6.31 | 8 | 448.80 |
| LDL12 | L | DJ | 2 | 54 | 2.28 | 6.71 | 8 | 418.20 |
| LDL13 | L | DJ | 2 | 58 | 2.30 | 6.18 | 10 | 377.40 |
| LDL14 | L | DJ | 2 | 25 | 2.28 | 6.86 | 10 | 367.20 |
| LDL15 | L | DJ | 2 | 57 | 2.28 | 6.86 | 15 | 112.20 |
| LDL16 | L | DJ | 2 | 60 | 2.27 | 7.17 | 15 | 316.20 |
| LJL01 | L | JB | 2 | 25 | 2.26 | 7.54 | 0 | 1540.20 |
| LJL02 | L | JB | 2 | 23 | 2.26 | 7.75 | 0 | 1458.60 |
| LJL03 | L | JB | 2 | 18 | 2.27 | 7.12 | 1 | 948.60 |
| LJL04 | L | JB | 2 | 27 | 2.26 | 7.55 | 1 | 928.20 |
| LJL05 | L | JB | 2 | 30 | 2.26 | 7.70 | 2 | 1111.80 |
| LJL06 | L | JB | 2 | 24 | 2.26 | 7.56 | 2 | 867.00 |
| LJL07 | L | JB | 2 | 29 | 2.26 | 7.75 | 4 | 632.40 |
| LJL08 | L | JB | 2 | 30 | 2.27 | 7.40 | 4 | 627.30 |
| LJL09 | L | JB | 2 | 30 | 2.27 | 7.47 | 6 | 612.00 |
| LJL10 | L | JB | 2 | 33 | 2.27 | 7.22 | 6 | 510.00 |
| LJL11 | L | JB | 2 | 26 | 2.27 | 7.14 | 8 | 550.80 |
| LJL12 | L | JB | 2 | 28 | 2.27 | 7.39 | 8 | 550.80 |
| LJL13 | L | JB | 2 | 23 | 2.26 | 7.60 | 10 | 367.20 |
| LJL14 | L | JB | 2 | 30 | 2.27 | 7.28 | 10 | 499.80 |
| LJL15 | L | JB | 2 | 29 | 2.25 | 7.94 | 15 | 418.20 |
| LJL16 | L | JB | 2 | 32 | 2.26 | 7.86 | 15 | 499.80 |
| LLL01 | L | LR | 2 | 15 | 2.29 | 6.65 | 0 | 1519.80 |
| LLL02 | L | LR | 2 | 14 | 2.29 | 6.48 | 0 | 1377.00 |
| LLL03 | L | LR | 2 | 18 | 2.29 | 6.42 | 1 | 928.20 |
| LLL04 | L | LR | 2 | 20 | 2.27 | 7.24 | 1 | 989.40 |
| LLL05 | L | LR | 2 | 12 | 2.29 | 6.62 | 2 | 999.60 |
| LLL06 | L | LR | 2 | 13 | 2.28 | 6.98 | 2 | 673.20 |
| LLL07 | L | LR | 2 | 16 | 2.28 | 6.94 | 4 | 673.20 |
| LLL08 | L | LR | 2 | 12 | 2.28 | 6.70 | 4 | 591.60 |
| LLL09 | L | LR | 2 | 12 | 2.29 | 6.43 | 6 | 622.20 |
| LLL10 | L | LR | 2 | 17 | 2.26 | 7.57 | 6 | 561.00 |
| LLL11 | L | LR | 2 | 11 | 2.27 | 7.18 | 8 | 612.00 |
| LLL12 | L | LR | 2 | 15 | 2.27 | 7.26 | 8 | 601.80 |
| LLL13 | L | LR | 2 | 14 | 2.28 | 6.98 | 10 | 601.80 |
| LLL14 | L | LR | 2 | 13 | 2.27 | 7.40 | 10 | 612.00 |
| LLL15 | L | LR | 2 | 11 | 2.28 | 6.76 | 15 | 510.00 |
| LLL16 | L | LR | 2 | 14 | 2.29 | 6.53 | 15 | 520.20 |
| LCLL01 | L | C | 3 | 23 | 2.35 | 6.48 | 0 | 1061.00 |
| LCLL02 | L | C | 3 | 17 | 2.34 | 7.03 | 0 | 1000.00 |
| LCLL03 | L | C | 3 | 21 | 2.35 | 6.53 | 1 | 938.00 |
| LCLL04 | L | C | 3 | 15 | 2.34 | 6.90 | 1 | 949.00 |
| LCLL05 | L | C | 3 | 24 | 2.34 | 6.71 | 2 | 938.00 |
| LCLL06 | L | C | 3 | 23 | 2.33 | 7.40 | 2 | 898.00 |

| Core Designation | Agg. Type | Ash Source | Mix Type | # of Gyrations | Bulk Specific Gravity | % Air Voids | # of Freeze-Thaw Cycles | Tensile Strength (lbs) |
|---|---|---|---|---|---|---|---|---|
| LCLL07 | L | C | 3 | 25 | 2.34 | 7.00 | 4 | 928.00 |
| LCLL08 | L | C | 3 | 15 | 2.34 | 6.94 | 4 | 898.00 |
| LCLL09 | L | C | 3 | 29 | 2.33 | 7.09 | 6 | 836.00 |
| LCLL10 | L | C | 3 | 14 | 2.35 | 6.39 | 6 | 857.00 |
| LCLL11 | L | C | 3 | 24 | 2.36 | 6.19 | 8 | 867.00 |
| LCLL12 | L | C | 3 | 14 | 2.35 | 6.51 | 8 | 755.00 |
| LCLL13 | L | C | 3 | 26 | 2.32 | 7.59 | 10 | 734.00 |
| LCLL14 | L | C | 3 | 16 | 2.36 | 6.17 | 10 | 796.00 |
| LCLL15 | L | C | 3 | 17 | 2.36 | 6.13 | 15 | 643.00 |
| LCLL16 | L | C | 3 | 23 | 2.33 | 7.34 | 15 | 765.00 |
| LDLL01 | L | DJ | 3 | 17 | 2.25 | 7.81 | 0 | 826.00 |
| LDLL02 | L | DJ | 3 | 17 | 2.25 | 7.84 | 0 | 775.00 |
| LDLL03 | L | DJ | 3 | 21 | 2.25 | 7.76 | 1 | 734.00 |
| LDLL04 | L | DJ | 3 | 18 | 2.25 | 7.79 | 1 | 775.00 |
| LDLL05 | L | DJ | 3 | 21 | 2.25 | 7.83 | 2 | 734.00 |
| LDLL06 | L | DJ | 3 | 20 | 2.27 | 7.20 | 2 | 734.00 |
| LDLL07 | L | DJ | 3 | 17 | 2.26 | 7.60 | 4 | 694.00 |
| LDLL08 | L | DJ | 3 | 16 | 2.25 | 7.93 | 4 | 765.00 |
| LDLL09 | L | DJ | 3 | 19 | 2.25 | 7.92 | 6 | 704.00 |
| LDLL10 | L | DJ | 3 | 19 | 2.26 | 7.62 | 6 | 724.00 |
| LDLL11 | L | DJ | 3 | 24 | 2.24 | 8.11 | 8 | 734.00 |
| LDLL12 | L | DJ | 3 | 24 | 2.26 | 7.50 | 8 | 683.00 |
| LDLL13 | L | DJ | 3 | 22 | 2.26 | 7.52 | 10 | 694.00 |
| LDLL14 | L | DJ | 3 | 26 | 2.25 | 7.73 | 10 | 683.00 |
| LDLL15 | L | DJ | 3 | 28 | 2.26 | 7.58 | 15 | 755.00 |
| LDLL16 | L | DJ | 3 | 25 | 2.26 | 7.26 | 15 | 704.00 |
| LJLL01 | L | JB | 3 | 58 | 2.25 | 7.07 | 0 | 1183.20 |
| LJLL02 | L | JB | 3 | 28 | 2.23 | 7.76 | 0 | 1111.80 |
| LJLL03 | L | JB | 3 | 58 | 2.24 | 7.31 | 1 | 1040.40 |
| LJLL04 | L | JB | 3 | 27 | 2.26 | 6.34 | 1 | 1111.80 |
| LJLL05 | L | JB | 3 | 48 | 2.25 | 6.91 | 2 | 938.40 |
| LJLL06 | L | JB | 3 | 26 | 2.24 | 7.14 | 2 | 979.20 |
| LJLL07 | L | JB | 3 | 55 | 2.23 | 7.82 | 4 | 877.20 |
| LJLL08 | L | JB | 3 | 25 | 2.24 | 7.28 | 4 | 846.60 |
| LJLL09 | L | JB | 3 | 70 | 2.26 | 6.61 | 6 | 867.00 |
| LJLL10 | L | JB | 3 | 26 | 2.24 | 7.35 | 6 | 836.40 |
| LJLL11 | L | JB | 3 | 65 | 2.25 | 6.79 | 8 | 805.80 |
| LJLL12 | L | JB | 3 | 24 | 2.24 | 7.38 | 8 | 816.00 |
| LJLL13 | L | JB | 3 | 45 | 2.25 | 6.86 | 10 | 836.40 |
| LJLL14 | L | JB | 3 | 24 | 2.24 | 7.21 | 10 | 846.60 |
| LJLL15 | L | JB | 3 | 59 | 2.25 | 6.80 | 15 | 663.00 |
| LJLL16 | L | JB | 3 | 35 | 2.24 | 7.34 | 15 | 673.20 |
| LLLL01 | L | LR | 3 | 15 | 2.28 | 7.60 | 0 | 1051.00 |
| LLLL02 | L | LR | 3 | 18 | 2.29 | 7.14 | 0 | 1081.00 |

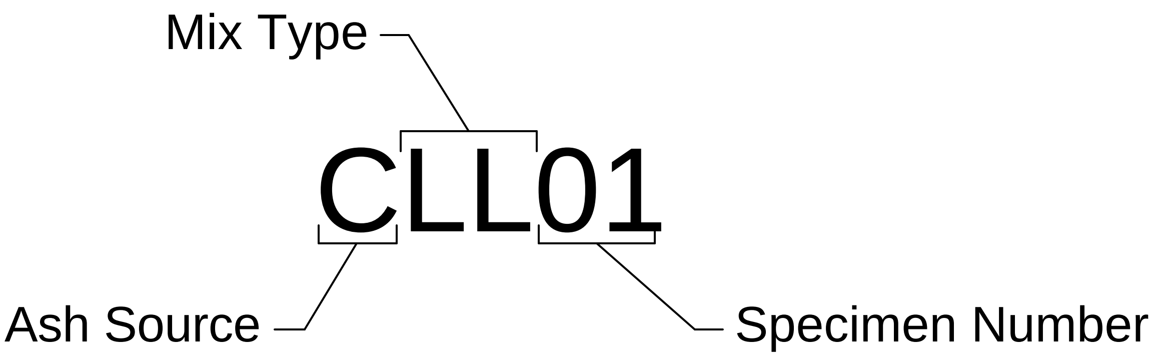
| Core Designation | Agg. Type | Ash Source | Mix Type | # of Gyrations | Bulk Specific Gravity | % Air Voids | # of Freeze-Thaw Cycles | Tensile Strength (lbs) |
|---|---|---|---|---|---|---|---|---|
| LLLL03 | L | LR | 3 | 23 | 2.28 | 7.62 | 1 | 1000.00 |
| LLLL04 | L | LR | 3 | 27 | 2.27 | 7.94 | 1 | 1030.00 |
| LLLL05 | L | LR | 3 | 17 | 2.27 | 7.92 | 2 | 918.00 |
| LLLL06 | L | LR | 3 | 28 | 2.30 | 6.88 | 2 | 938.00 |
| LLLL07 | L | LR | 3 | 15 | 2.29 | 7.24 | 4 | 938.00 |
| LLLL08 | L | LR | 3 | 16 | 2.29 | 7.30 | 4 | 857.00 |
| LLLL09 | L | LR | 3 | 19 | 2.28 | 7.82 | 6 | 918.00 |
| LLLL10 | L | LR | 3 | 22 | 2.27 | 7.83 | 6 | 877.00 |
| LLLL11 | L | LR | 3 | 23 | 2.29 | 7.03 | 8 | 898.00 |
| LLLL12 | L | LR | 3 | 18 | 2.28 | 7.43 | 8 | 857.00 |
| LLLL13 | L | LR | 3 | 20 | 2.30 | 6.90 | 10 | 765.00 |
| LLLL14 | L | LR | 3 | 21 | 2.28 | 7.58 | 10 | 938.00 |
| LLLL15 | L | LR | 3 | 24 | 2.28 | 7.58 | 15 | 724.00 |
| LLLL16 | L | LR | 3 | 26 | 2.27 | 7.88 | 15 | 796.00 |
| GCL01 | G | C | 2 | 9 | 2.24 | 7.08 | 0 | 1153.00 |
| GCL02 | G | C | 2 | 13 | 2.25 | 6.61 | 0 | 1163.00 |
| GCL03 | G | C | 2 | 7 | 2.24 | 7.20 | 1 | 1040.00 |
| GCL04 | G | C | 2 | 12 | 2.25 | 6.89 | 1 | 989.00 |
| GCL05 | G | C | 2 | 9 | 2.24 | 7.10 | 2 | 653.00 |
| GCL06 | G | C | 2 | 9 | 2.24 | 7.14 | 2 | 673.00 |
| GCL07 | G | C | 2 | 10 | 2.24 | 7.35 | 4 | 449.00 |
| GCL08 | G | C | 2 | 9 | 2.24 | 7.39 | 4 | 347.00 |
| GCL09 | G | C | 2 | 9 | 2.24 | 7.05 | 6 | 306.00 |
| GCL10 | G | C | 2 | 6 | 2.24 | 7.25 | 6 | 224.00 |
| GCL11 | G | C | 2 | 23 | 2.24 | 7.03 | 8 | 255.00 |
| GCL12 | G | C | 2 | 23 | 2.25 | 6.83 | 8 | 194.00 |
| GCL13 | G | C | 2 | 21 | 2.24 | 7.27 | 10 | 326.00 |
| GCL14 | G | C | 2 | 21 | 2.24 | 7.27 | 10 | 133.00 |
| GCL15 | G | C | 2 | 26 | 2.24 | 7.02 | 15 | 153.00 |
| GCL16 | G | C | 2 | 26 | 2.24 | 7.01 | 15 | 143.00 |
| GDL01 | G | DJ | 2 | 14 | 2.22 | 6.90 | 0 | 1214.00 |
| GDL02 | G | DJ | 2 | 14 | 2.21 | 7.32 | 0 | 1265.00 |
| GDL03 | G | DJ | 2 | 6 | 2.23 | 6.51 | 1 | 1010.00 |
| GDL04 | G | DJ | 2 | 16 | 2.23 | 6.84 | 1 | 1081.00 |
| GDL05 | G | DJ | 2 | 10 | 2.24 | 6.44 | 2 | 959.00 |
| GDL06 | G | DJ | 2 | 5 | 2.22 | 7.04 | 2 | 989.00 |
| GDL07 | G | DJ | 2 | 7 | 2.21 | 7.53 | 4 | 836.00 |
| GDL08 | G | DJ | 2 | 15 | 2.23 | 6.63 | 4 | 806.00 |
| GDL09 | G | DJ | 2 | 14 | 2.24 | 6.14 | 6 | 826.00 |
| GDL10 | G | DJ | 2 | 16 | 2.23 | 6.90 | 6 | 653.00 |
| GDL11 | G | DJ | 2 | 14 | 2.22 | 7.12 | 8 | 541.00 |
| GDL12 | G | DJ | 2 | 12 | 2.21 | 7.51 | 8 | 561.00 |
| GDL13 | G | DJ | 2 | 9 | 2.24 | 6.46 | 10 | 530.00 |
| GDL14 | G | DJ | 2 | 15 | 2.22 | 7.12 | 10 | 510.00 |

| Core Designation | Agg. Type | Ash Source | Mix Type | # of Gyrations | Bulk Specific Gravity | % Air Voids | # of Freeze-Thaw Cycles | Tensile Strength (lbs) |
|---|---|---|---|---|---|---|---|---|
| GDL15 | G | DJ | 2 | 12 | 2.22 | 7.03 | 15 | 530.00 |
| GDL16 | G | DJ | 2 | 13 | 2.22 | 7.06 | 15 | 561.00 |
| GCLL01 | G | C | 3 | 17 | 2.24 | 7.09 | 0 | 1193.00 |
| GCLL02 | G | C | 3 | 7 | 2.23 | 7.79 | 0 | 1204.00 |
| GCLL03 | G | C | 3 | 6 | 2.24 | 7.21 | 1 | 1112.00 |
| GCLL04 | G | C | 3 | 10 | 2.25 | 6.87 | 1 | 1142.00 |
| GCLL05 | G | C | 3 | 7 | 2.23 | 7.78 | 2 | 1142.00 |
| GCLL06 | G | C | 3 | 8 | 2.23 | 7.59 | 2 | 1224.00 |
| GCLL07 | G | C | 3 | 6 | 2.24 | 7.41 | 4 | 1102.00 |
| GCLL08 | G | C | 3 | 9 | 2.23 | 7.82 | 4 | 1214.00 |
| GCLL09 | G | C | 3 | 7 | 2.23 | 7.46 | 6 | 1030.00 |
| GCLL10 | G | C | 3 | 7 | 2.24 | 7.35 | 6 | 979.00 |
| GCLL11 | G | C | 3 | 8 | 2.23 | 7.76 | 8 | 959.00 |
| GCLL12 | G | C | 3 | 10 | 2.23 | 7.83 | 8 | 949.00 |
| GCLL13 | G | C | 3 | 14 | 2.26 | 6.28 | 10 | 959.00 |
| GCLL14 | G | C | 3 | 14 | 2.24 | 7.20 | 10 | 898.00 |
| GCLL15 | G | C | 3 | 10 | 2.23 | 7.42 | 15 | 826.00 |
| GCLL16 | G | C | 3 | 12 | 2.23 | 7.49 | 15 | 908.00 |
| GDLL01 | G | DJ | 3 | 5 | 2.22 | 7.10 | 0 | 1448.00 |
| GDLL02 | G | DJ | 3 | 5 | 2.22 | 7.29 | 0 | 1489.00 |
| GDLL03 | G | DJ | 3 | 7 | 2.23 | 6.65 | 1 | 1418.00 |
| GDLL04 | G | DJ | 3 | 5 | 2.21 | 7.45 | 1 | 1408.00 |
| GDLL05 | G | DJ | 3 | 10 | 2.20 | 7.74 | 2 | 1336.00 |
| GDLL06 | G | DJ | 3 | 10 | 2.20 | 7.87 | 2 | 1306.00 |
| GDLL07 | G | DJ | 3 | 14 | 2.22 | 7.20 | 4 | 1122.00 |
| GDLL08 | G | DJ | 3 | 11 | 2.22 | 7.28 | 4 | 1285.00 |
| GDLL09 | G | DJ | 3 | 9 | 2.20 | 7.87 | 6 | 1040.00 |
| GDLL10 | G | DJ | 3 | 10 | 2.21 | 7.72 | 6 | 1142.00 |
| GDLL11 | G | DJ | 3 | 9 | 2.23 | 6.67 | 8 | 1051.00 |
| GDLL12 | G | DJ | 3 | 17 | 2.23 | 6.67 | 8 | 1132.00 |
| GDLL13 | G | DJ | 3 | 12 | 2.22 | 7.00 | 10 | 1000.00 |
| GDLL14 | G | DJ | 3 | 10 | 2.22 | 7.31 | 10 | 1030.00 |
| GDLL15 | G | DJ | 3 | 10 | 2.23 | 6.81 | 15 | 1071.00 |
| GDLL16 | G | DJ | 3 | 10 | 2.22 | 7.05 | 15 | 1030.00 |

# APPENDIX C

## SPECIMEN DATA FOR GEORGIA LOADED WHEEL TESTS

## SPECIMEN DESIGNATION KEY




| Ash Source | |
|---|---|
| Control = | C |
| Dave Johnston = | DJ |
| Jim Bridger = | JB |
| Laramie River = | LR |

| Mix Type | |
|---|---|
| Lab Mix with Lime = | LL |
| Plant Mix, Field Compacted = | PF |
| Plant Mix, Lab Compacted = | PL |

| Core Designation | Ash Source | Mix Type | Air Voids (%) | Asphalt Content (%) | Rut Depth @ 4000 cycles | Rut Depth @ 8000 cycles |
|---|---|---|---|---|---|---|
| CLL01 | Control | Lab Mix, with Lime | 4.1 | 4.6 | 0.048 | 0.054 |
| CLL02 | Control | Lab Mix, with Lime | 3.3 | 4.6 | 0.027 | 0.048 |
| CPF01 | Control | Plant Mix, Field Compacted | 8.2 | 4.5 | 0.318 | 0.400 |
| CPF02 | Control | Plant Mix, Field Compacted | 9.2 | 4.5 | 0.181 | 0.245 |
| CPF03 | Control | Plant Mix, Field Compacted | 9.8 | 4.5 | 0.262 | 0.424 |
| CPF04 | Control | Plant Mix, Field Compacted | 8.0 | 4.7 | 0.144 | 0.229 |
| CPF05 | Control | Plant Mix, Field Compacted | 8.7 | 4.7 | 0.139 | 0.355 |
| CPF06 | Control | Plant Mix, Field Compacted | 11.0 | 4.7 | 0.339 | - |
| CPL01 | Control | Plant Mix, Lab Compacted | 4.0 | 4.5 | 0.117 | 0.135 |
| CPL02 | Control | Plant Mix, Lab Compacted | 3.9 | 4.5 | 0.068 | 0.075 |
| CPL03 | Control | Plant Mix, Lab Compacted | 4.0 | 4.7 | 0.056 | 0.068 |
| CPL04 | Control | Plant Mix, Lab Compacted | 4.0 | 4.7 | 0.097 | 0.120 |
| DLL01 | DJ | Lab Mix, with Lime | 3.4 | 6.1 | 0.061 | 0.071 |
| DLL02 | DJ | Lab Mix, with Lime | 3.1 | 6.1 | 0.052 | 0.063 |
| DPF01 | DJ | Plant Mix, Field Compacted | 5.7 | 6.0 | 0.404 | - |
| DPF02 | DJ | Plant Mix, Field Compacted | 4.5 | 6.0 | 0.266 | 0.361 |
| DPF03 | DJ | Plant Mix, Field Compacted | 6.7 | 6.0 | 0.295 | 0.351 |
| DPF04 | DJ | Plant Mix, Field Compacted | 5.2 | 5.9 | 0.285 | 0.374 |
| DPF05 | DJ | Plant Mix, Field Compacted | 5.3 | 5.9 | 0.337 | - |
| DPF06 | DJ | Plant Mix, Field Compacted | 7.2 | 5.9 | 0.444 | - |
| DPL01 | DJ | Plant Mix, Lab Compacted | 1.3 | 6.0 | 0.082 | 0.098 |
| DPL02 | DJ | Plant Mix, Lab Compacted | 1.3 | 6.0 | 0.080 | 0.100 |
| DPL03 | DJ | Plant Mix, Lab Compacted | 1.7 | 5.9 | 0.093 | 0.111 |
| DPL04 | DJ | Plant Mix, Lab Compacted | 1.4 | 5.9 | 0.059 | 0.074 |
| JLL01 | JB | Lab Mix, with Lime | 4.0 | 5.2 | 0.056 | 0.074 |
| JLL02 | JB | Lab Mix, with Lime | 5.3 | 5.2 | 0.066 | 0.087 |
| JPF01 | JB | Plant Mix, Field Compacted | 6.8 | 5.6 | 0.244 | 0.333 |
| JPF02 | JB | Plant Mix, Field Compacted | 7.1 | 5.6 | 0.315 | - |
| JPF03 | JB | Plant Mix, Field Compacted | 7.9 | 5.6 | 0.423 | - |
| JPF04 | JB | Plant Mix, Field Compacted | 5.9 | 5.4 | 0.282 | - |
| JPF05 | JB | Plant Mix, Field Compacted | 6.9 | 5.4 | 0.364 | - |
| JPF06 | JB | Plant Mix, Field Compacted | 6.9 | 5.4 | 0.269 | - |
| JPL01 | JB | Plant Mix, Lab Compacted | 3.7 | 5.6 | 0.054 | 0.073 |
| JPL02 | JB | Plant Mix, Lab Compacted | 3.5 | 5.6 | 0.095 | 0.112 |
| JPL03 | JB | Plant Mix, Lab Compacted | 3.5 | 5.4 | 0.069 | 0.083 |
| JPL04 | JB | Plant Mix, Lab Compacted | 3.5 | 5.4 | 0.079 | 0.098 |
| LLL01 | LR | Lab Mix, with Lime | 3.1 | 5.7 | 0.026 | 0.037 |
| LLL02 | LR | Lab Mix, with Lime | 4.0 | 5.7 | 0.039 | 0.047 |
| LPF01 | LR | Plant Mix, Field Compacted | 5.7 | 5.6 | 0.172 | 0.275 |
| LPF02 | LR | Plant Mix, Field Compacted | 4.5 | 5.6 | 0.266 | 0.356 |
| LPF03 | LR | Plant Mix, Field Compacted | 6.9 | 5.6 | 0.246 | 0.346 |
| LPF04 | LR | Plant Mix, Field Compacted | 5.4 | 5.8 | 0.193 | 0.291 |
| LPF05 | LR | Plant Mix, Field Compacted | 4.9 | 5.8 | 0.231 | 0.31 |
| LPF06 | LR | Plant Mix, Field Compacted | 5.8 | 5.8 | 0.267 | - |

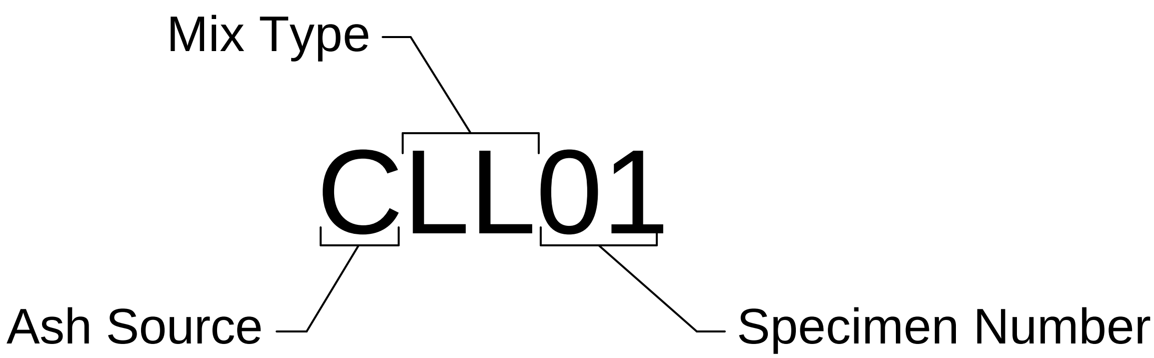
| Core Designation | Ash Source | Mix Type | Air Voids (%) | Asphalt Content (%) | Rut Depth @ 4000 cycles | Rut Depth @ 8000 cycles |
|---|---|---|---|---|---|---|
| LPL01 | LR | Plant Mix, Lab Compacted | 2.5 | 5.6 | 0.091 | 0.103 |
| LPL02 | LR | Plant Mix, Lab Compacted | 2.5 | 5.6 | 0.080 | 0.098 |
| LPL03 | LR | Plant Mix, Lab Compacted | 2.8 | 5.8 | 0.077 | 0.094 |
| LPL04 | LR | Plant Mix, Lab Compacted | 2.6 | 5.8 | 0.059 | 0.074 |

Note: All GLWT samples were prepared with limestone aggregate

# APPENDIX D

## SPECIMEN DATA FOR THERMAL STRESS RESTRAINED SPECIMEN TESTS

## **SPECIMEN DESIGNATION KEY**



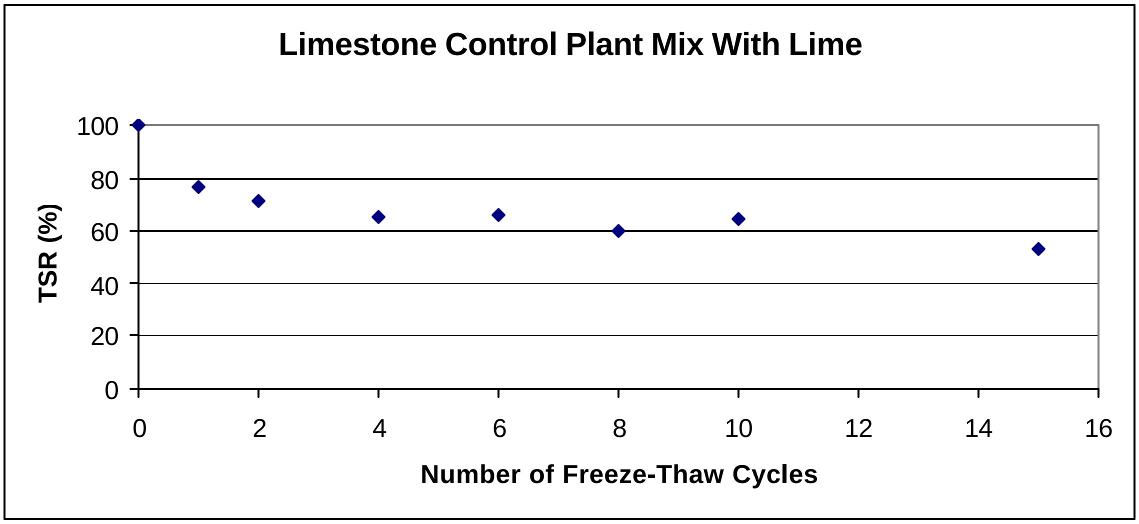

| Ash Source | |
|---|---|
| Control = | C |
| Dave Johnston = | DJ |
| Jim Bridger = | JB |
| Laramie River = | LR |

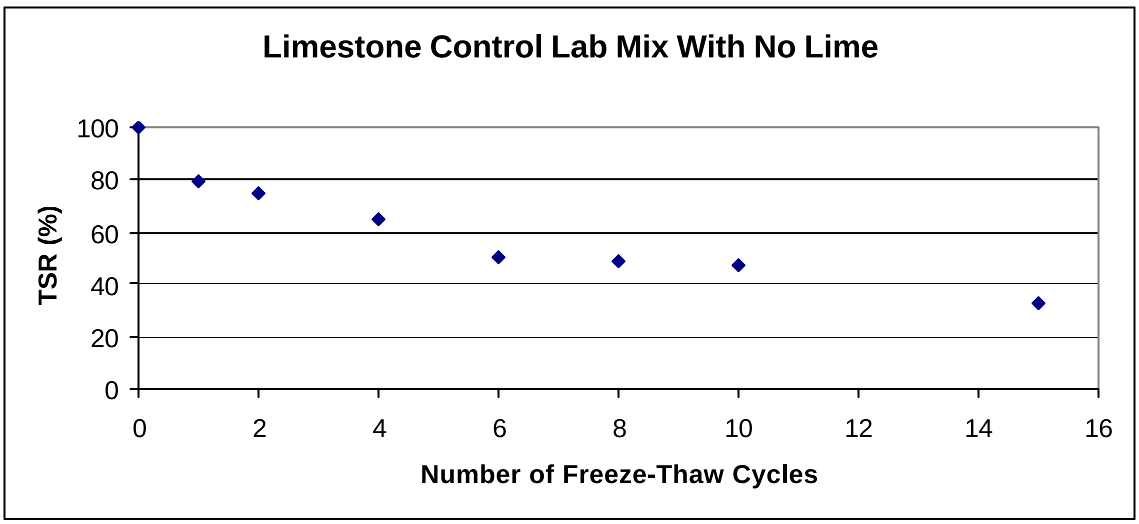
| Mix Type | |
|---|---|
| Lab Mix with Lime = | LL |
| Plant Mix, Field Compacted = | PF |

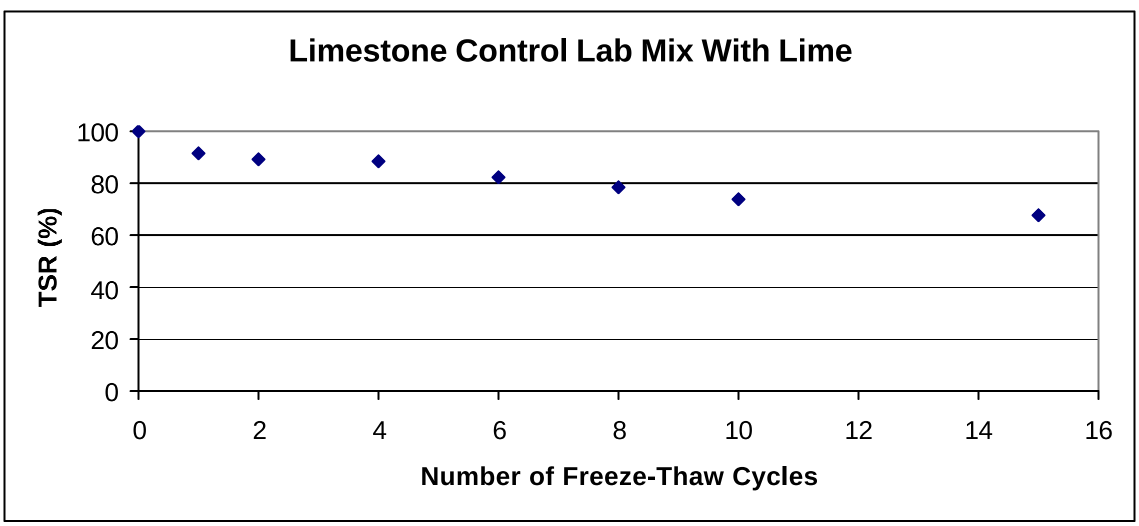
| Specimen Designation | Ash Source | Mix Type | Fracture Stress (psi) | Fracture Temp. ($^0$C) |
|---|---|---|---|---|
| CLL01 | Control | Lab Mix w/Lime | 120.40 | -33.6 |
| CLL02 | Control | Lab Mix w/Lime | 415.30 | -28.5 |
| CPF01 | Control | Plant Mix, Field Compacted | 394.30 | -32.9 |
| CPF02 | Control | Plant Mix, Field Compacted | 505.40 | -37.5 |
| DLL01 | DJ | Lab Mix w/Lime | 429.20 | -28.8 |
| DLL02 | DJ | Lab Mix w/Lime | 213.60 | -27.3 |
| DPF01 | DJ | Plant Mix, Field Compacted | 454.50 | -33.5 |
| DPF02 | DJ | Plant Mix, Field Compacted | 476.80 | -37.1 |
| JLL01 | JB | Lab Mix w/Lime | 296.80 | -26.1 |
| JLL02 | JB | Lab Mix w/Lime | 252.20 | -27.6 |
| JPF01 | JB | Plant Mix, Field Compacted | 382.50 | -38.1 |
| JPF02 | JB | Plant Mix, Field Compacted | 444.50 | -32.3 |
| LLL01 | LR | Lab Mix w/Lime | 180.10 | -25.0 |
| LLL02 | LR | Lab Mix w/Lime | 321.30 | -25.2 |
| LPF01 | LR | Plant Mix, Field Compacted | 546.50 | -38.7 |
| LPF02 | LR | Plant Mix, Field Compacted | 511.50 | -38.0 |

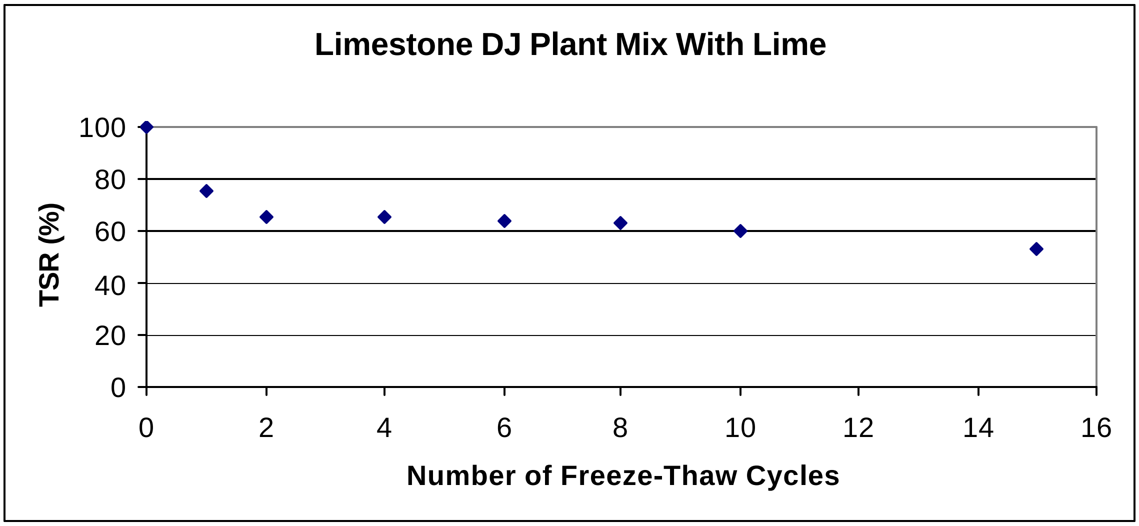
# APPENDIX E

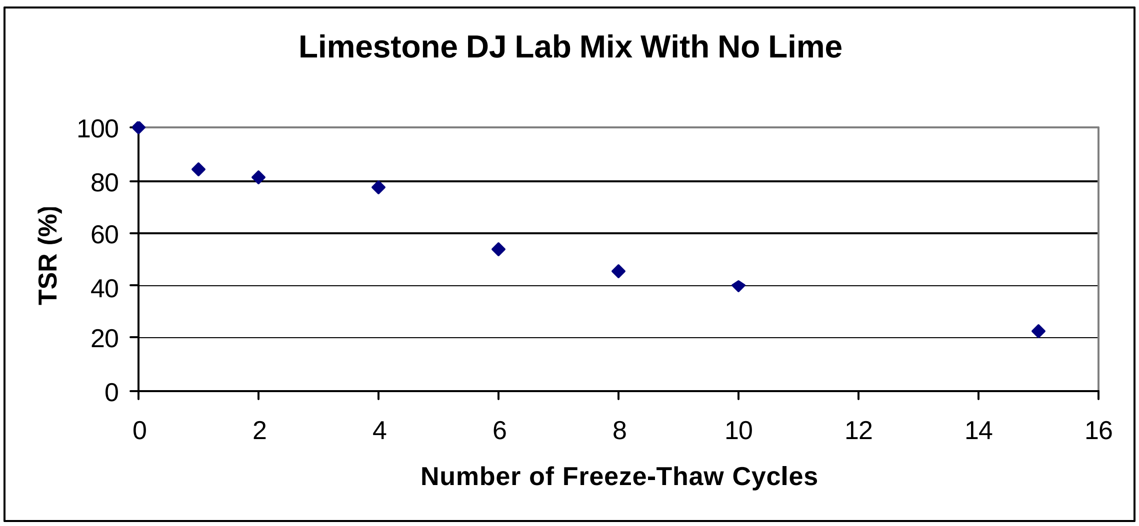
## TENSILE STRENGTH RATIO GRAPHS

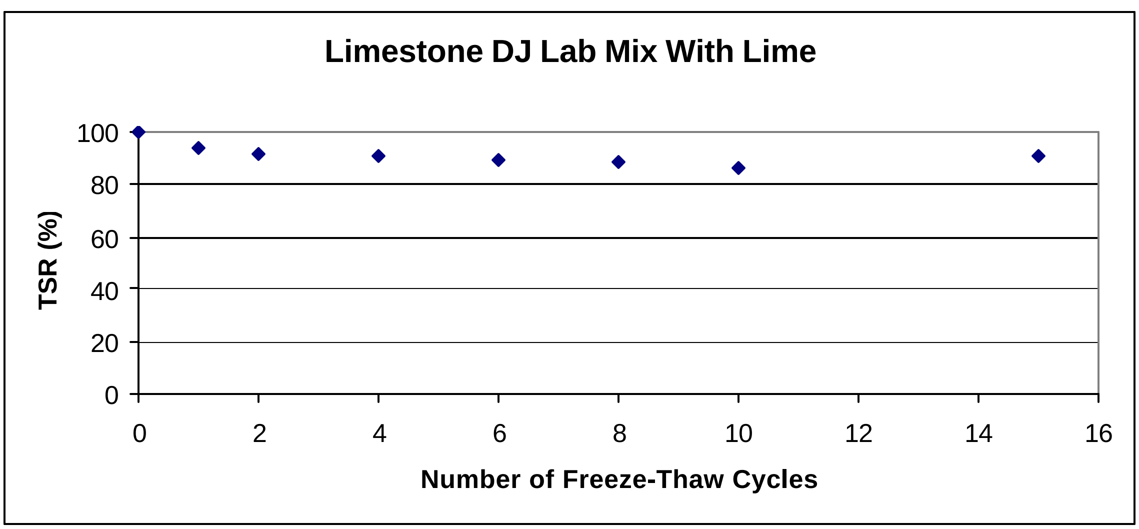

Limestone Control Plant Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles

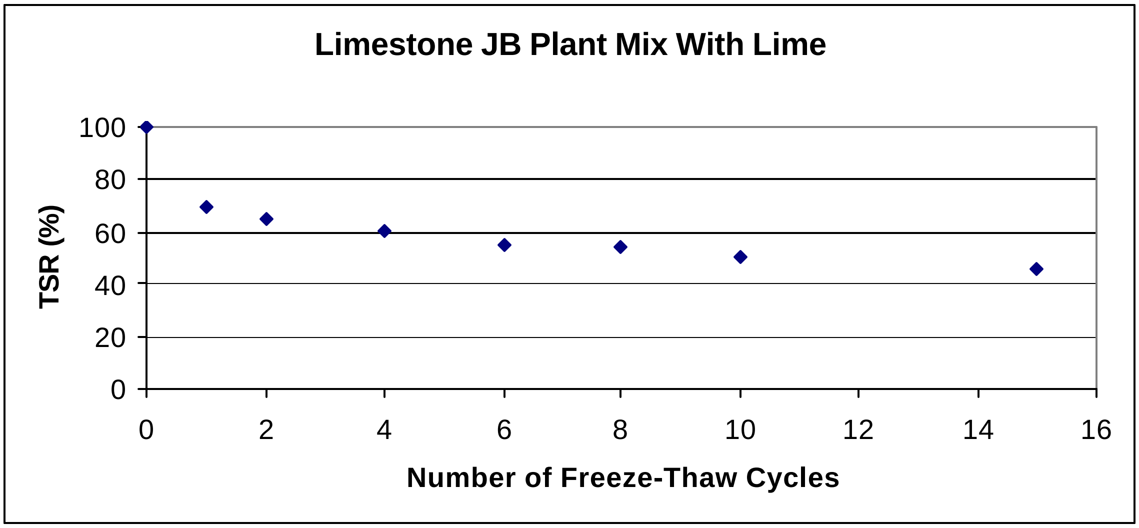

Limestone Control Lab Mix With No Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Limestone Control Lab Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles

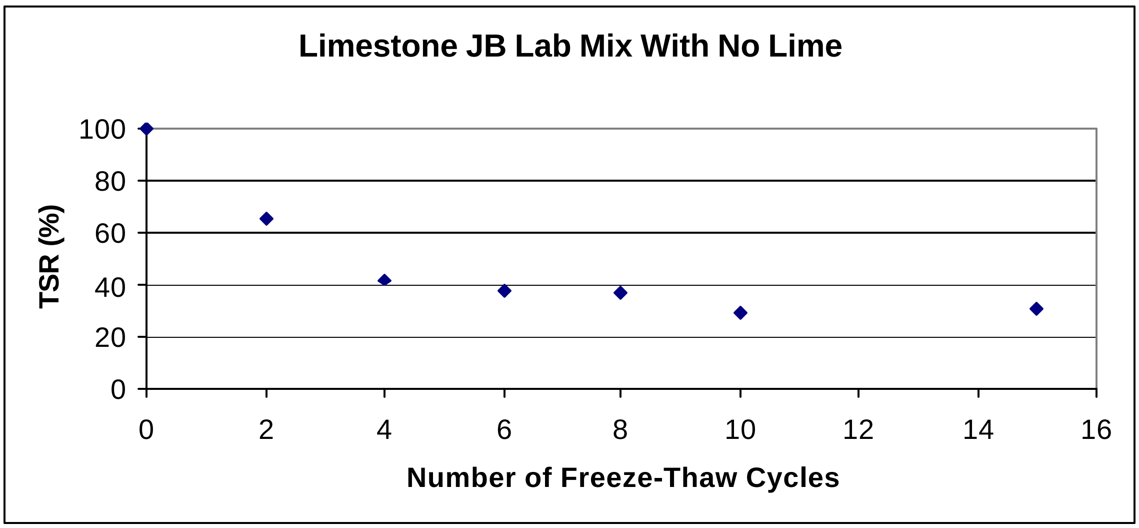

Limestone DJ Plant Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Limestone DJ Lab Mix With No Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles

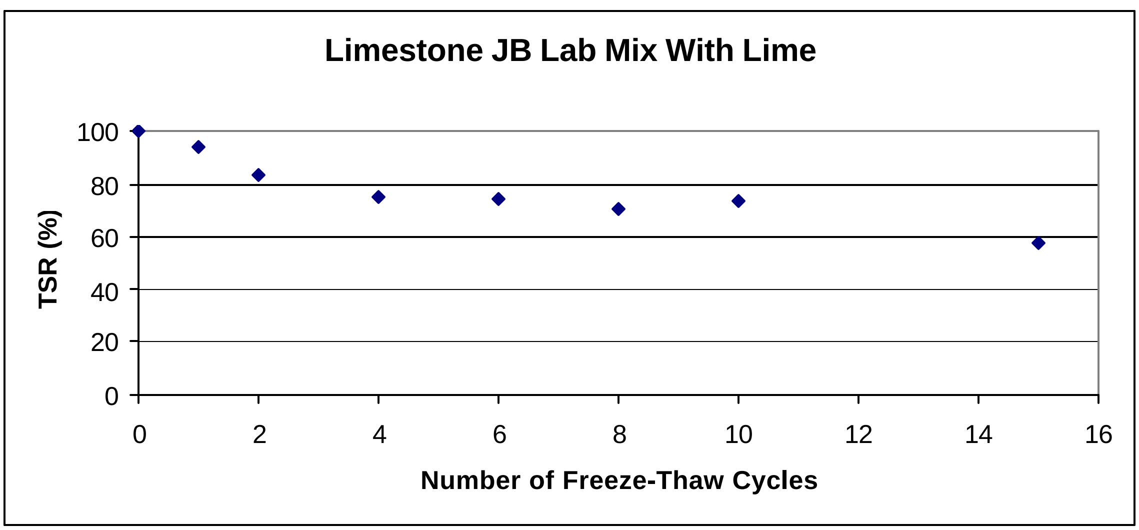

Limestone DJ Lab Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles



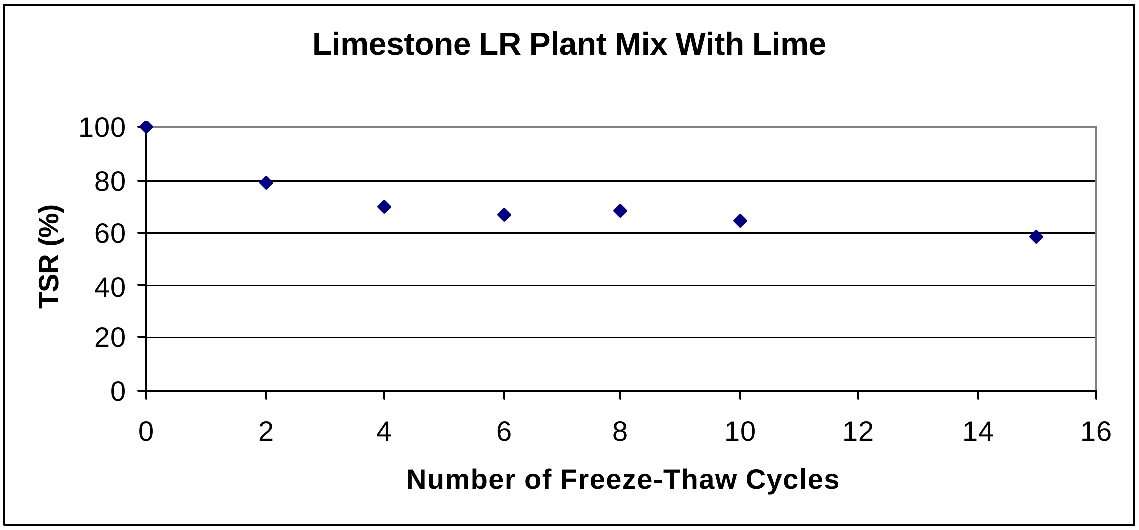
Limestone JB Plant Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles

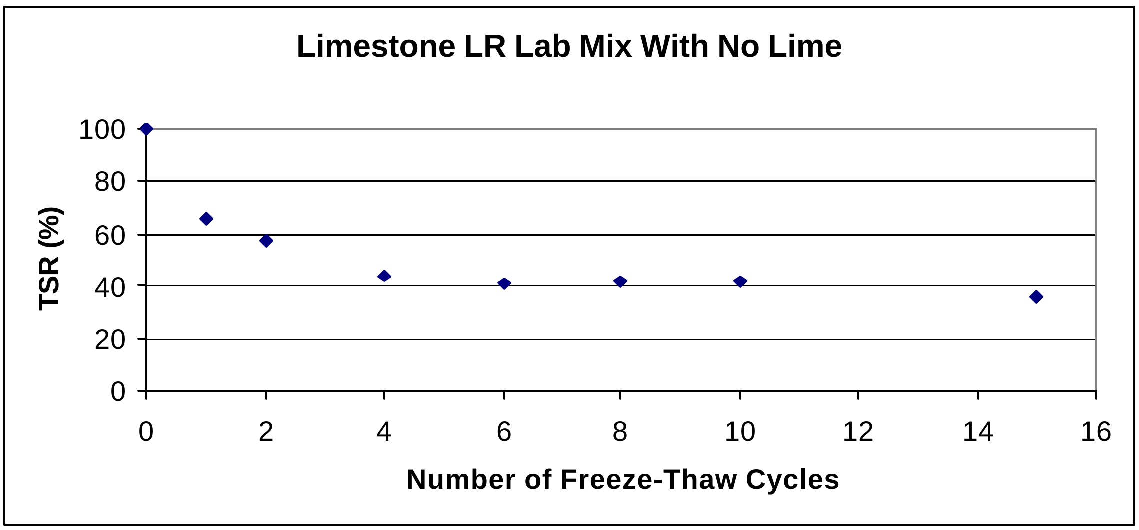



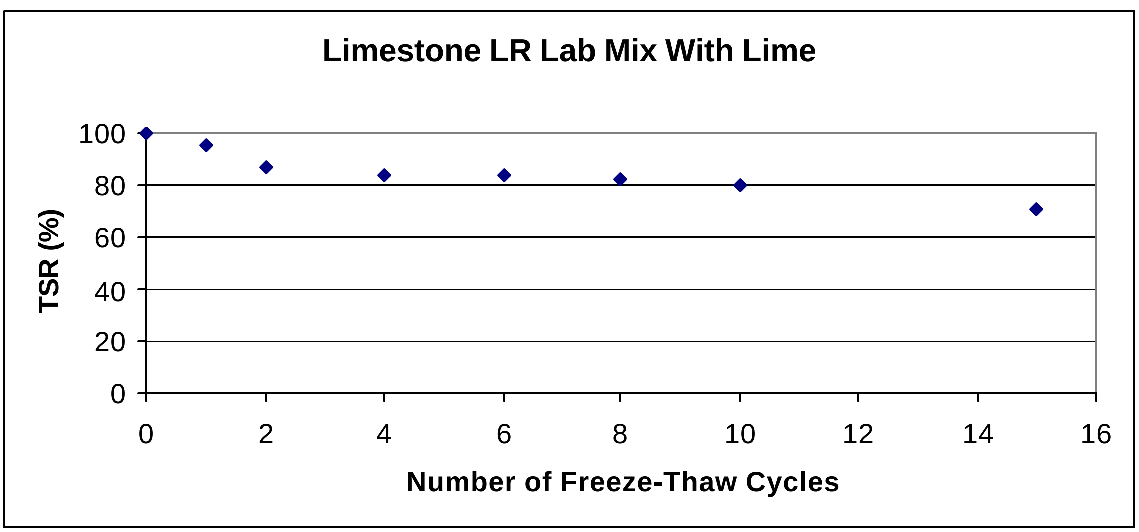
Limestone JB Lab Mix With No Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles

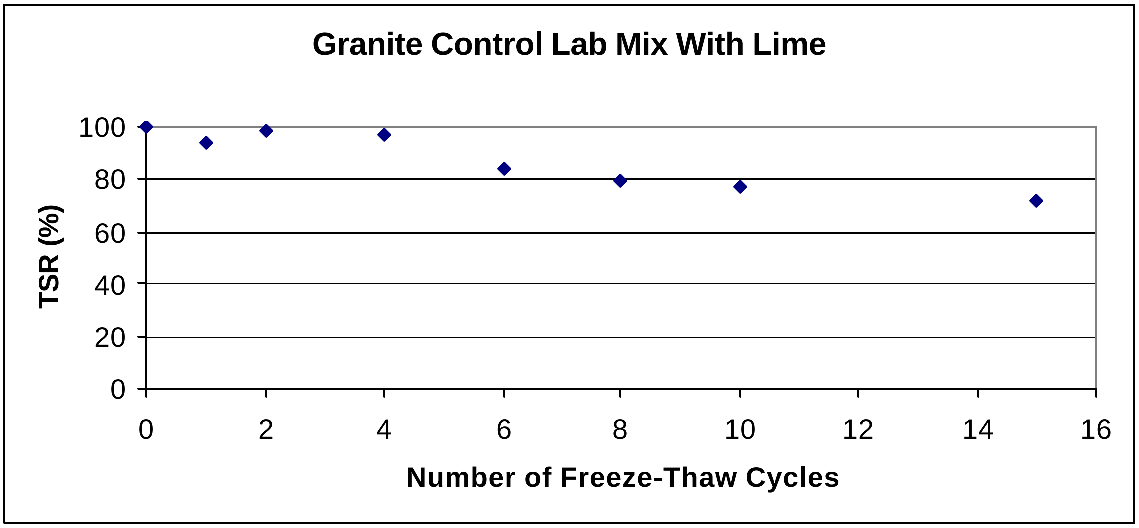



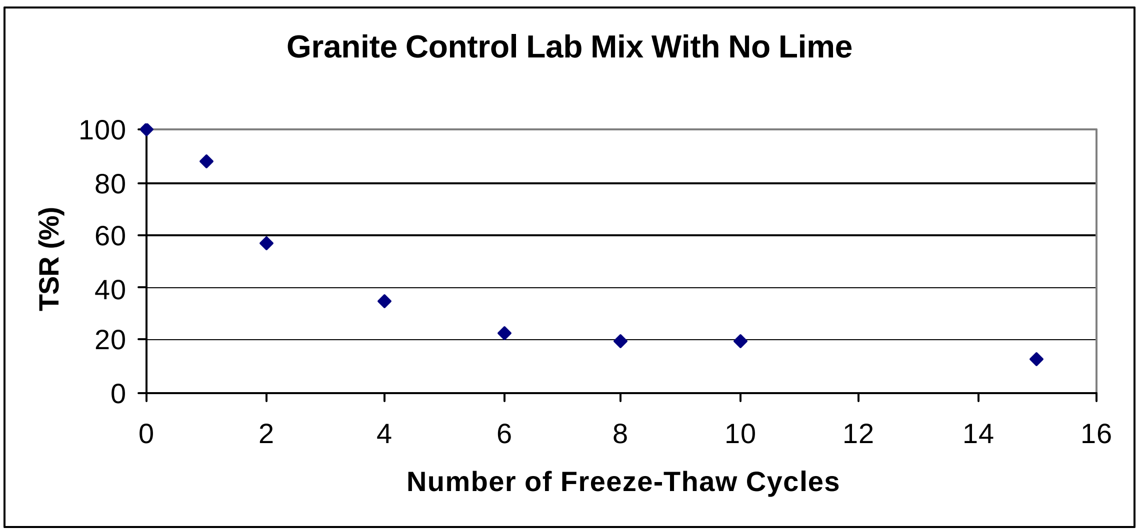
Limestone JB Lab Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Limestone LR Plant Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Limestone LR Lab Mix With No Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Limestone LR Lab Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Granite Control Lab Mix With Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles


Granite Control Lab Mix With No Lime
TSR (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
Number of Freeze-Thaw Cycles

# APPENDIX F

## MINITAB ANALYSIS

# Analysis of Variance for T-283

## General Linear Model: T283 versus Ash, Mix

| Factor | Type | Levels | Values |
|---|---|---|---|
| Ash | fixed | 4 | 0 1 2 3 |
| Mix | fixed | 2 | 1 3 |

Analysis of Variance for T283, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Ash | 3 | 0.003825 | 0.003825 | 0.001275 | 0.35 | 0.788 |
| Mix | 1 | 0.019321 | 0.019321 | 0.019321 | 5.36 | 0.049 |
| Ash*Mix | 3 | 0.005347 | 0.005347 | 0.001782 | 0.49 | 0.696 |
| Error | 8 | 0.028860 | 0.028860 | 0.003608 | | |
| Total | 15 | 0.057353 | | | | |

Unusual Observations for T283

| Obs | T283 | Fit | SE Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 17 | 0.82800 | 0.91700 | 0.04247 | -0.08900 | -2.10R |
| 18 | 1.00600 | 0.91700 | 0.04247 | 0.08900 | 2.10R |

R denotes an observation with a large standardized residual.

# Analysis of Variance for TSRST

## General Linear Model: TSRST versus Ash, Mix

| Factor | Type | Levels | Values |
|---|---|---|---|
| Ash | fixed | 4 | 0 1 2 3 |
| Mix | fixed | 2 | 1 2 |

Analysis of Variance for TSRST, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Ash | 3 | 9.388 | 9.387 | 3.129 | 0.51 | 0.688 |
| Mix | 1 | 272.250 | 272.250 | 272.250 | 44.09 | 0.000 |
| Ash*Mix | 3 | 42.820 | 42.820 | 14.273 | 2.31 | 0.153 |
| Error | 8 | 49.400 | 49.400 | 6.175 | | |
| Total | 15 | 373.858 | | | | |

# Analysis of Variance for GLWT

## General Linear Model: GLWT versus Ash, Mix

```
Factor     Type Levels Values
Ash       fixed      4 0 1 2 3
Mix       fixed      3 1 2 3

Analysis of Variance for GLWT, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
Ash         3   0.004122   0.001581   0.000527    0.32  0.811
Mix         2   0.312591   0.296571   0.148286   90.11  0.000
Ash*Mix     6   0.002148   0.002148   0.000358    0.22  0.963
Error      11   0.018103   0.018103   0.001646
Total      22   0.336963

Unusual Observations for GLWT

Obs      GLWT       Fit      SE Fit  Residual   St Resid
  3  0.400000  0.322500    0.028685  0.077500      2.70R
  4  0.245000  0.322500    0.028685 -0.077500     -2.70R
 15  0.333000  0.333000    0.040567 -0.000000          * X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

# Analysis of Variance for TSR Analysis 1

## General Linear Model: Log TSR versus Ash, Mix

| Factor | Type | Levels | Values |
|---|---|---|---|
| Ash | fixed | 4 | 0 1 2 3 |
| Mix | fixed | 3 | 1 2 3 |

Analysis of Variance for Log TSR, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Ash | 3 | 40.391 | 17.591 | 5.864 | 13.00 | 0.000 |
| Mix | 2 | 231.546 | 51.100 | 25.550 | 56.65 | 0.000 |
| Time | 1 | 147.190 | 147.190 | 147.190 | 326.34 | 0.000 |
| Ash*Mix | 6 | 31.262 | 25.605 | 4.268 | 9.46 | 0.000 |
| Ash*Time | 3 | 5.029 | 5.029 | 1.676 | 3.72 | 0.013 |
| Mix*Time | 2 | 58.765 | 58.765 | 29.382 | 65.15 | 0.000 |
| Ash*Mix*Time | 6 | 6.541 | 6.541 | 1.090 | 2.42 | 0.030 |
| Error | 144 | 64.948 | 64.948 | 0.451 | | |
| Total | 167 | 585.673 | | | | |

| Term | | | Coef | SE Coef | T | P |
|---|---|---|---|---|---|---|
| Constant | | | 1.90800 | 0.00427 | 446.99 | 0.000 |
| Time | | | -0.016764 | 0.000928 | -18.06 | 0.000 |
| Time*Ash | | | | | | |
| | 0 | | 0.000360 | 0.001607 | 0.22 | 0.823 |
| | 1 | | -0.000652 | 0.001607 | -0.41 | 0.685 |
| | 2 | | -0.004202 | 0.001607 | -2.61 | 0.010 |
| Time*Mix | | | | | | |
| | 1 | | 0.008056 | 0.001312 | 6.14 | 0.000 |
| | 2 | | -0.014966 | 0.001312 | -11.40 | 0.000 |
| Time*Ash*Mix | | | | | | |
| | 0 | 1 | -0.000959 | 0.002273 | -0.42 | 0.674 |
| | 0 | 2 | 0.002655 | 0.002273 | 1.17 | 0.245 |
| | 1 | 1 | 0.006621 | 0.002273 | 2.91 | 0.004 |
| | 1 | 2 | -0.007731 | 0.002273 | -3.40 | 0.001 |
| | 2 | 1 | -0.001529 | 0.002273 | -0.67 | 0.502 |
| | 2 | 2 | 0.001947 | 0.002273 | 0.86 | 0.393 |

Unusual Observations for Log TSR

| Obs | Log TSR | Fit | SE Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 62 | 1.91700 | 1.82548 | 0.01038 | 0.09152 | 2.50R |
| 69 | 1.07800 | 1.38423 | 0.03883 | -0.30623 | -3.71R |
| 101 | 1.87000 | 1.76399 | 0.01104 | 0.10601 | 4.07R |
| 104 | 1.62200 | 1.69602 | 0.01038 | -0.07402 | -2.03R |
| 106 | 1.53200 | 1.62805 | 0.01328 | -0.09605 | -2.10R |
| 112 | 1.52300 | 1.32219 | 0.03883 | 0.20081 | 2.43R |
| 114 | 1.87600 | 1.83457 | 0.01265 | 0.04143 | 2.10R |
| 142 | 1.83400 | 1.78629 | 0.01265 | 0.04771 | 2.41R |
| 143 | 1.83900 | 1.76219 | 0.01104 | 0.07681 | 2.95R |
| 144 | 1.66700 | 1.76219 | 0.01104 | -0.09519 | -3.65R |
| 146 | 1.61100 | 1.71397 | 0.01038 | -0.10297 | -2.82R |
| 157 | 1.90600 | 1.85094 | 0.01104 | 0.05506 | 2.11R |

R denotes an observation with a large standardized residual.

# Regression for TSR Analysis 1

## Regression Analysis: Log TSR versus a0m1, a0m2, ...

```
Weighted analysis using weights in Weights

The regression equation is
Log TSR = 1.97 a0m1 + 1.93 a0m2 + 1.89 a0m3 + 1.97 a1m1 + 1.99 a1m2 + 1.86 a1m3
          + 1.97 a2m1 + 1.83 a2m2 + 1.85 a2m3 + 1.97 a3m1 + 1.81 a3m2
          + 1.86 a3m3 - 0.00931 a0m1*t - 0.0287 a0m2*t - 0.0112 a0m3*t
          - 0.00274 a1m1*t - 0.0401 a1m2*t - 0.00940 a1m3*t - 0.0144 a2m1*t
          - 0.0340 a2m2*t - 0.0145 a2m3*t - 0.00835 a3m1*t - 0.0241 a3m2*t
          - 0.00436 a3m3*t

Predictor        Coef     SE Coef         T        P
Noconstant
a0m1          1.97162     0.01479    133.34    0.000
a0m2          1.92646     0.01479    130.28    0.000
a0m3          1.88503     0.01479    127.48    0.000
a1m1          1.97184     0.01479    133.35    0.000
a1m2          1.98593     0.01479    134.31    0.000
a1m3          1.86462     0.01479    126.10    0.000
a2m1          1.96640     0.01479    132.98    0.000
a2m2          1.83195     0.01479    123.89    0.000
a2m3          1.84905     0.01479    125.05    0.000
a3m1          1.97307     0.01479    133.44    0.000
a3m2          1.81040     0.01479    122.43    0.000
a3m3          1.85965     0.01479    125.77    0.000
a0m1*t      -0.009308    0.003215     -2.90    0.004
a0m2*t      -0.028715    0.003215     -8.93    0.000
a0m3*t      -0.011190    0.003215     -3.48    0.001
a1m1*t      -0.002740    0.003215     -0.85    0.395
a1m2*t      -0.040113    0.003215    -12.48    0.000
a1m3*t      -0.009396    0.003215     -2.92    0.004
a2m1*t      -0.014439    0.003215     -4.49    0.000
a2m2*t      -0.033984    0.003215    -10.57    0.000
a2m3*t      -0.014474    0.003215     -4.50    0.000
a3m1*t      -0.008346    0.003215     -2.60    0.010
a3m2*t      -0.024106    0.003215     -7.50    0.000
a3m3*t      -0.004357    0.003215     -1.36    0.177

S = 0.6716

Analysis of Variance

Source            DF          SS          MS         F        P
Regression        24    180267.2      7511.1  16653.30    0.000
Residual Error   144        64.9         0.5
Total            168    180332.2

Source       DF      Seq SS
a0m1          1     16445.2
a0m2          1     14633.5
a0m3          1     14908.6
a1m1          1     16823.0
a1m2          1     14977.5
a1m3          1     14676.9
a2m1          1     16068.3
a2m2          1     12896.0
a2m3          1     14160.5
```

```
a3m1          1     16524.3
a3m2          1     13068.4
a3m3          1     14867.6
a0m1*t        1         3.8
a0m2*t        1        36.0
a0m3*t        1         5.5
a1m1*t        1         0.3
a1m2*t        1        70.2
a1m3*t        1         3.9
a2m1*t        1         9.1
a2m2*t        1        50.4
a2m3*t        1         9.1
a3m1*t        1         3.0
a3m2*t        1        25.4
a3m3*t        1         0.8

Unusual Observations
Obs       a0m1    Log TSR        Fit      SE Fit    Residual    St Resid
 62       0.00     1.9170     1.8255      0.0104      0.0915       2.50R
 69       0.00     1.0780     1.3842      0.0388     -0.3062      -3.71R
101       0.00     1.8700     1.7640      0.0110      0.1060       4.07R
104       0.00     1.6220     1.6960      0.0104     -0.0740      -2.03R
106       0.00     1.5320     1.6281      0.0133     -0.0961      -2.10R
112       0.00     1.5230     1.3222      0.0388      0.2008       2.43R
114       0.00     1.8760     1.8346      0.0126      0.0414       2.10R
142       0.00     1.8340     1.7863      0.0126      0.0477       2.41R
143       0.00     1.8390     1.7622      0.0110      0.0768       2.95R
144       0.00     1.6670     1.7622      0.0110     -0.0952      -3.65R
146       0.00     1.6110     1.7140      0.0104     -0.1030      -2.82R
157       0.00     1.9060     1.8509      0.0110      0.0551       2.11R

R denotes an observation with a large standardized residual

MTB > cdf c34 c35
MTB > let c36=2*c35
MTB > invcdf .975;
SUBC> t 144.
```

### Inverse Cumulative Distribution Function

```
Student's t distribution with 144 DF

P( X <= x )          x
    0.9750      1.9766
```

# Analysis of Variance for TSR Analysis 2

## General Linear Model: Log TSR versus Aggregate, Ash, Mix

| Factor | Type | Levels | Values |
|---|---|---|---|
| Aggregat | fixed | 2 | 1 2 |
| Ash | fixed | 2 | 0 1 |
| Mix | fixed | 2 | 1 2 |

Analysis of Variance for Log TSR, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Aggregat | 1 | 11.145 | 0.083 | 0.083 | 0.11 | 0.742 |
| Ash | 1 | 17.618 | 0.708 | 0.708 | 0.93 | 0.338 |
| Mix | 1 | 186.171 | 3.781 | 3.781 | 4.96 | 0.028 |
| Time | 1 | 240.336 | 240.336 | 240.336 | 315.28 | 0.000 |
| Aggregat*Ash | 1 | 4.676 | 1.157 | 1.157 | 1.52 | 0.221 |
| Aggregat*Mix | 1 | 11.070 | 0.896 | 0.896 | 1.18 | 0.281 |
| Aggregat*Time | 1 | 12.641 | 12.641 | 12.641 | 16.58 | 0.000 |
| Ash*Mix | 1 | 19.061 | 1.519 | 1.519 | 1.99 | 0.161 |
| Ash*Time | 1 | 7.914 | 7.914 | 7.914 | 10.38 | 0.002 |
| Mix*Time | 1 | 104.711 | 104.711 | 104.711 | 137.36 | 0.000 |
| Aggregat*Ash*Mix | 1 | 19.378 | 0.450 | 0.450 | 0.59 | 0.444 |
| Aggregat*Ash*Time | 1 | 12.439 | 12.439 | 12.439 | 16.32 | 0.000 |
| Aggregat*Mix*Time | 1 | 3.404 | 3.404 | 3.404 | 4.47 | 0.037 |
| Ash*Mix*Time | 1 | 5.924 | 5.924 | 5.924 | 7.77 | 0.006 |
| Aggregat*Ash*Mix*Time | 1 | 25.888 | 25.888 | 25.888 | 33.96 | 0.000 |
| Error | 96 | 73.180 | 73.180 | 0.762 | | |
| Total | 111 | 755.556 | | | | |

| Term | | | | Coef | SE Coef | T | P |
|---|---|---|---|---|---|---|---|
| Constant | | | | 1.96620 | 0.00680 | 289.30 | 0.000 |
| Time | | | | -0.026236 | 0.001478 | -17.76 | 0.000 |
| Time*Aggregat | | | | | | | |
| | 1 | | | 0.006017 | 0.001478 | 4.07 | 0.000 |
| Time*Ash | | | | | | | |
| | 0 | | | -0.004761 | 0.001478 | -3.22 | 0.002 |
| Time*Mix | | | | | | | |
| | 1 | | | 0.017317 | 0.001478 | 11.72 | 0.000 |
| Time*Aggregat*Ash | | | | | | | |
| | 1 | 0 | | 0.005969 | 0.001478 | 4.04 | 0.000 |
| Time*Aggregat*Mix | | | | | | | |
| | 1 | 1 | | -0.003122 | 0.001478 | -2.11 | 0.037 |
| Time*Ash*Mix | | | | | | | |
| | 0 | 1 | | 0.004119 | 0.001478 | 2.79 | 0.006 |
| Time*Aggregat*Ash*Mix | | | | | | | |
| | 1 | 0 | 1 | -0.008611 | 0.001478 | -5.83 | 0.000 |

Unusual Observations for Log TSR

| Obs | Log TSR | Fit | SE Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 55 | 1.07800 | 1.38423 | 0.05048 | -0.30623 | -2.85R |
| 71 | 1.95300 | 1.86724 | 0.01644 | 0.08576 | 3.34R |
| 72 | 1.93100 | 1.86724 | 0.01644 | 0.06376 | 2.48R |
| 76 | 1.47700 | 1.63879 | 0.01350 | -0.16179 | -3.40R |
| 78 | 1.28700 | 1.48648 | 0.01726 | -0.19948 | -3.35R |
| 81 | 1.45000 | 1.18188 | 0.03081 | 0.26812 | 3.29R |
| 83 | 1.12100 | 0.80112 | 0.05048 | 0.31988 | 2.98R |
| 84 | 1.09200 | 0.80112 | 0.05048 | 0.29088 | 2.71R |

```
R denotes an observation with a large standardized residual.

MTB > Regress 'Log TSR' 16 c9-c24;
SUBC>   Weights 'Weights';
SUBC>   NoConstant;
SUBC>   Brief 2.
```

# Regression for TSR Analysis 2

## Regression Analysis: Log TSR versus a0m1agg1, a0m2agg1, ...

```
Weighted analysis using weights in Weights

The regression equation is
Log TSR = 1.97 a0m1agg1 + 2.00 a0m2agg1 + 1.93 a1m1agg1 + 1.94 a1m2agg1
           + 1.97 a0m1agg2 + 1.98 a0m2agg2 + 1.99 a1m1agg2 + 1.95 a1m2agg2
           - 0.00931 a0m1g1*t - 0.00981 a0m2g1*t - 0.0287 a1m1g1*t
           - 0.0762 a1m2g1*t - 0.00274 a0m1g2*t - 0.0138 a0m2g2*t
           - 0.0401 a1m1g2*t - 0.0292 a1m2g2*t
```

| Predictor | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Noconstant | | | | |
| a0m1agg1 | 1.97162 | 0.01922 | 102.56 | 0.000 |
| a0m2agg1 | 1.99715 | 0.01922 | 103.89 | 0.000 |
| a1m1agg1 | 1.92646 | 0.01922 | 100.21 | 0.000 |
| a1m2agg1 | 1.94340 | 0.01922 | 101.10 | 0.000 |
| a0m1agg2 | 1.97184 | 0.01922 | 102.58 | 0.000 |
| a0m2agg2 | 1.98475 | 0.01922 | 103.25 | 0.000 |
| a1m1agg2 | 1.98593 | 0.01922 | 103.31 | 0.000 |
| a1m2agg2 | 1.94849 | 0.01922 | 101.36 | 0.000 |
| a0m1g1*t | -0.009308 | 0.004179 | -2.23 | 0.028 |
| a0m2g1*t | -0.009813 | 0.004179 | -2.35 | 0.021 |
| a1m1g1*t | -0.028715 | 0.004179 | -6.87 | 0.000 |
| a1m2g1*t | -0.076152 | 0.004179 | -18.22 | 0.000 |
| a0m1g2*t | -0.002740 | 0.004179 | -0.66 | 0.514 |
| a0m2g2*t | -0.013814 | 0.004179 | -3.31 | 0.001 |
| a1m1g2*t | -0.040113 | 0.004179 | -9.60 | 0.000 |
| a1m2g2*t | -0.029233 | 0.004179 | -6.99 | 0.000 |

S = 0.8731

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 16 | 123974.6 | 7748.4 | 10164.63 | 0.000 |
| Residual Error | 96 | 73.2 | 0.8 | | |
| Total | 112 | 124047.8 | | | |

| Source | DF | Seq SS |
|---|---|---|
| a0m1agg1 | 1 | 16445.2 |
| a0m2agg1 | 1 | 16851.9 |
| a1m1agg1 | 1 | 14633.5 |
| a1m2agg1 | 1 | 12457.7 |
| a0m1agg2 | 1 | 16823.0 |
| a0m2agg2 | 1 | 16412.6 |
| a1m1agg2 | 1 | 14977.5 |
| a1m2agg2 | 1 | 14960.0 |
| a0m1g1*t | 1 | 3.8 |
| a0m2g1*t | 1 | 4.2 |

```
a1m1g1*t      1        36.0
a1m2g1*t      1       253.1
a0m1g2*t      1         0.3
a0m2g2*t      1         8.3
a1m1g2*t      1        70.2
a1m2g2*t      1        37.3

Unusual Observations
Obs   a0m1agg1    Log TSR        Fit      SE Fit    Residual    St Resid
 55       0.00     1.0780     1.3842      0.0505     -0.3062      -2.85R
 71       0.00     1.9530     1.8672      0.0164      0.0858       3.34R
 72       0.00     1.9310     1.8672      0.0164      0.0638       2.48R
 76       0.00     1.4770     1.6388      0.0135     -0.1618      -3.40R
 78       0.00     1.2870     1.4865      0.0173     -0.1995      -3.35R
 81       0.00     1.4500     1.1819      0.0308      0.2681       3.29R
 83       0.00     1.1210     0.8011      0.0505      0.3199       2.98R
 84       0.00     1.0920     0.8011      0.0505      0.2909       2.71R

R denotes an observation with a large standardized residual

MTB > invcdf .975;
SUBC> t 96.
```

## Inverse Cumulative Distribution Function

```
Student's t distribution with 96 DF

P( X <= x )          x
    0.9750        1.9850
```