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Use of Moisture Induced Stress Tester (M.i.S.T) to Determine Moisture Sensitivity of Asphalt Mixtures

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Abstract

The objectives of the research were: (1) to investigate possible modifications to the existing TSR test protocol or develop an alternate test method, and a conditioning procedure that can quantify the adhesive and cohesive damage in asphalt mixtures due to moisture; (2) to quantify adhesive damage in asphalt mixture using the boil test along with color measuring device; (3) to investigate the use of M.i.S.T conditioning procedure to quantify the cohesive damage in asphalt mixtures; (4) to explore the viability of the Impact Resonance test in assessing moisture damage in asphalt mixtures; (5) to evaluate the effect of different antistrip additives on asphalt mixtures and determine optimum antistrip additive content using the boil test with colorimeter device for different asphalt mixtures.

The objectives were achieved by performing IDT test to obtain TSR from AASHTO T283 (currently used by NCDOT) and M.i.S.T conditioning (proposed conditioning procedure). The Boil Test (ASTM D3625) was done along with colorimeter device to quantify adhesive damage. The test were performed on six different HMA mixtures prepared from three different aggregate source. The Impact Resonance test was performed to study the effect of various support conditions on resonant frequency and its ability to detect moisture damage. The Boil Test along with colorimeter device was done on fifty four different loose mixtures prepared from three different aggregate source and three different antistrip additives with varying additive content. The most compatible and optimum antistrip additive content for a particular asphalt mixture was determined.

Key Words	Distribution Statement
Moisture Sensitivity, Adhesive damage, Cohesive damage, Asphalt Mixture, Colorimeter, Impact Resonance, Antistrip Additives	

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EXECUTIVE SUMMARY

Moisture damage is one of the major concerns in asphalt concrete mixtures. Moisture damage mostly occurs due to two mechanisms – adhesive failure between aggregate and asphalt, and cohesive failure within asphalt binder and mixture. The most commonly used test to evaluate moisture sensitivity, tensile strength ratio (TSR) test uses AASHTO T 283 conditioning which has been shown to mostly determine the adhesive failure. There is a need for a test method or conditioning procedure that can be used to measure both adhesive and cohesive behavior of mixtures.

The objectives of the research were: (1) to investigate possible modifications to the existing TSR test protocol or develop an alternate test method, and a conditioning procedure that can quantify the adhesive and cohesive damage in asphalt mixtures due to moisture; (2) to quantify adhesive damage in asphalt mixture using the boil test along with colorimeter device; (3) to investigate the use of M.i.S.T conditioning procedure to quantify the cohesive damage in asphalt mixtures; (4) to explore the viability of the Impact Resonance test in assessing moisture damage in asphalt mixtures; (5) to evaluate the effect of different antistrip additives on asphalt mixtures and determine optimum antistrip additive content using the boil test with colorimeter device for different asphalt mixtures.

These objectives were accomplished by performing three different test methods to evaluate moisture sensitivity of asphalt concrete. The first test method is the boil test (ASTM D3625) with a colorimeter device (Colorimeter CR400) to measure loss of adhesion (stripping). Colorimeter was used to quantify stripping in asphalt mixtures. The second test method presented in this study is Indirect Tensile Test (IDT) test to determine TSR value with two different types of conditioning – modified AASHTO T 283 (currently used by NCDOT) and Moisture Induced Stress Tester (M.i.S.T) conditioning (proposed conditioned procedure). M.i.S.T conditioning procedure includes two conditioning cycle – specimen placed in hot water for 20 hours followed by application of hydraulic pumping. M.i.S.T conditioning is able to determine both adhesive and cohesive failure. The third test method conducted in this study is the Impact Resonance (IR) test, to explore the effect of different support conditions and its ability to detect moisture damage. All tests were done on six different HMA mixtures prepared using three different aggregate sources.

The Boil test (ASTM D3625) is very simple and easy method to determine stripping in asphalt mixtures but it was not widely accepted in the past because of its subjective nature. However, currently boil test results can be quantified using a colorimeter device. The Boil Test along with colorimeter device turns out be an effective test procedure in not only quantifying the striping potential in asphalt mixtures but also in determining the optimum antistrip additive content for any particular asphalt mixture. Also, this test method is helpful in selecting a more compatible and cost effective antistrip additive for any particular asphalt mixtures.

This report presents a new approach to evaluate moisture sensitivity. Currently, NCDOT uses 85% TSR criteria based on modified AASHTO T 283 conditioning. This study proposes combining the use of two different test methods to detect the adhesive and cohesive failure due to moisture in asphalt mixtures – the boil test with colorimeter device and the M.i.S.T device. The colorimeter device was used to determine the percentage stripping in asphalt mixtures due to loss of adhesion

between asphalt and aggregate. Percentage stripping can be used to estimate the adhesive failure, and volume change from the M.i.S.T conditioning to determine the cohesive failure in the mixtures. This report presents a test method to determine optimum antistrip additive content for asphalt mixtures that can be used in selecting a more cost effective antistrip additive.

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1. Introduction

1.1 Background and Need for Study

Moisture sensitivity of asphalt mixtures is a major distress affecting the performance of pavements. Presence of moisture in asphalt pavements and with the application of traffic loads induce two main mechanisms as loss of adhesion (stripping) between asphalt and aggregate, and loss of cohesion within the asphalt binder (strength). Due to this reason, most of the mixtures are subjected to moisture sensitivity criteria before mix design approval. Indirect Tensile Test (IDT) to determine Tensile Strength Ratio (TSR) is the most commonly used test method to evaluate moisture sensitivity. TSR test use AASHTO T 283 or modified AASHTO T 283 conditioning procedure to evaluate moisture damage.

Currently, North Carolina Department of Transportation (NCDOT) uses only the tensile strength ratio (TSR) test to evaluate the moisture sensitivity of the asphalt concrete mixtures. NCDOT requires that the moisture sensitivity criteria be met for the job mix formula to be approved. There have been instances where the asphalt mixtures pass the moistures sensitivity criteria but perform poor in the field or vice-versa. Possible reason to this problem can be the following drawbacks of the existing test method.

1. The AASHTO T 283 moisture conditioning procedure used for TSR test requires vacuum saturation of the specimens to ensure that 70.0 to 80.0 percent of the air voids are saturated which will artificially impart internal damage to the compacted asphalt concrete specimens where the voids are not interconnected.
2. The saturation level imparted during the TSR conditioning procedure does not happen in in-situ field conditions, i.e. the moisture will saturate the voids naturally depending on the porosity and the permeability (the void content and the interconnection of the voids) of the compacted mixture.
3. Asphalt mixtures are subjected not only to moisture (that affects the adhesive properties) but also the pumping action of moisture due to traffic loading. The pumping action is believed to affect the cohesive strength of the mixtures which is not accounted in this existing method.

This study proposes combining the use of two different test methods to detect the adhesive and cohesive failure due to moisture in asphalt mixtures – the boil test, and the TSR test with M.i.S.T device. The colorimeter device was used to determine the percentage stripping in asphalt mixtures after the boil test. Percentage stripping can be used to estimate the adhesive failure, and volume change from the M.i.S.T conditioning can be used to determine the cohesive failure in the mixtures. There is a need for either possible modifications to the current TSR test protocol or develop a new test protocol which accounts for both adhesive and cohesive failure.

1.2 Organization of Report

This report presents literature review on moisture damage and impact resonance test in section 2; followed by research approach and methodology in section 3. The Boil Test and the TSR test procedure along with interpretation of test results are presented in section 4. Sections 5 present the Impact Resonance test and interpretation of results from the IR test, the Boil test, and the TSR test. Study on effect of different antistrip additives in asphalt concrete and determining optimum antistrip additive content are presented in section 6. Summary, conclusions and recommendations are presented in section 7. Material characterization and different test conducted in this study are presented in the appendices.

2. Literature Review

Moisture damage is considered to be a major issue causing distress in asphalt pavement and leading to the premature failure in the pavement. Due to this reason, all mixtures are subjected to moisture sensitivity criteria before the mix design approval. The topic of evaluating and quantifying moisture sensitivity using laboratory testing has been researched for decades now. Yet the efforts to develop a simple, practical, and more reliable test method to quantify moisture sensitivity are still ongoing.

2.1 Moisture Damage

Extensive literature is available about moisture sensitivity of asphalt mixtures. These include the Lottman Test on which the AASHTO T283 test is based on, Hamburg wheel testing, APA test, and an assortment of tests on measuring the stiffness before, during and after moisture conditioning such as the resilient modulus (SHRP A-003), shear stiffness, and dynamic modulus (AMPT) test method. Researchers have described the two main mechanisms involved in moisture damage of asphalt pavements as loss of adhesion (stripping) between asphalt and aggregate, and loss of cohesion within the asphalt binder (strength) (2-7). Hicks explained the action of water at the asphalt-aggregate interface as the major cause of weakening of the adhesive bond between asphalt and aggregate surface. He explains that the reason behind the cohesive failure is the action of water through an emulsification process which weakens the bond between asphalt binder molecules (2).

A lot of research has been done on the topic of evaluating and quantifying the moisture sensitivity of asphalt mixtures using various laboratory test methods (7). Popular test methods include static immersion test (ASTM D1664), boil test (ASTM D3625), the PATTI Test which is like a standard pull-off strength test (ASTM D4541), and surface energy test to determine the adhesion properties of asphalt-aggregate systems (3, 8).

The most commonly used test method to evaluate moisture sensitivity in the laboratory is the tensile strength ratio (TSR) test using the AASHTO T283 or the modified AASHTO T283 procedure (1, 5, 7 & 9). This test method uses the ratio of indirect tensile strength (ITS) of the mixture in moisture saturated and unsaturated conditions to quantify the moisture sensitivity of an asphalt mixture. Recent research indicates that the TSR test only measures the loss in adhesion between the asphalt and aggregate (9). In the field, asphalt mixtures are subjected not only to moisture (that affects the adhesive properties) but also the pumping action of moisture due to traffic loading. The pumping action is believed to affect the cohesive strength of the mixtures (9, 10). Moreover, the AASHTO T 283 moisture conditioning procedure used for the TSR test requires vacuum saturation of the specimens to ensure that 70.0 to 80.0 percent of the air voids are saturated. However, this method of conditioning the specimens has two drawbacks – 1) the saturation level imparted during the TSR conditioning procedure does not happen in in-situ field conditions, i.e. the moisture will saturate the voids naturally depending on the porosity and the permeability (the void content and the interconnection of the voids) of the compacted mixture; and 2) the vacuum saturation will artificially impart internal damage to the compacted asphalt concrete specimens where the voids are not interconnected (9). Although this test identifies the moisture sensitive mixtures well, there have been cases where moisture sensitive mixtures have passed the TSR test or mixtures that failed the TSR test have performed well in the field (11).

Another simple test method to evaluate moisture sensitivity is the boil test (ASTM D3625). This is a quick and easy test to determine the loss of adhesion (or stripping) in asphalt mixtures. The drawback to this test method is that it is a visually subjective test method (12). However, Tayebali et al. successfully used a color measuring device, colorimeter, to quantify the boil test. They used the colorimeter to determine the percentage stripping in asphalt mixtures due to the boil test (1).

Jimenez studied the effect of pore water pressure and saturation on the de-bonding of asphalt mixtures (13). He found that volume change due to cyclically varying water pressure provided a good indication of moisture damage. Mallick et al. developed this concept into a device with a pressure chamber that has the capability to generate a hydrostatic pressure in the specimens when they are submerged in water inside the chamber (10). This is called the Moisture-Induced Stress Tester (M.i.S.T) conditioning procedure. This procedure simulates the pumping action of moisture in the field due to traffic loading and conditions asphalt mixtures more realistically. Several researchers found that this method enhances the identification of moisture-sensitive mixtures (9, 14 & 15).

This study proposes combining the use of two different test methods to detect the adhesive and cohesive failure due to moisture in asphalt mixtures – the boil test and the M.I.S.T device. The colorimeter device was used to determine the percentage stripping in asphalt mixtures before and after the boil test. Percentage stripping can be used to estimate the adhesive failure, and volume change from the M.I.S.T conditioning to determine the cohesive failure in the mixtures. Additionally, the study proposes to use the boil test along with color measuring device to select more compatible and cost effective antistrip additive for a particular asphalt mixture. The test results are further described in section 4 and section 5.

2.1.1 Colorimeter CR 400

In this research, the color measuring device used along with the boil test to quantify stripping in asphalt mixtures is Colorimeter CR400. The Colorimeter CR400 device is manufactured by Konica Minolta and is shown in figure 2-1.

Colorimeter was used to measure the color of the loose asphalt mixture specimens before and after the boil test. There are many other similar devices manufactured and sold by other companies that could also be used effectively. Tayebali et al. have used this device to quantify the stripping in asphalt mixtures due to the boil test and the TSR test using the modified AASHTO T283 conditioning (*1*). A standard light source is emitted from the device onto the target object and the reflection from the material is used to measure the color of the object. The light emitting outlet is placed on the specimen such that there is no interference from the background light sources. The device analyzes the color as per the standard terminology of appearance, ASTM E284-17. This study uses the widely recognized L^*, a^*, and b^* method to measure color (*17*). The same method was used by Tayebali et al. to quantify stripping in asphalt mixtures. In this method, an L^* reading measures the lightness or darkness of an object and hence only the L^* reading was used in this study to measure stripping.

The colorimeter device was used to take measurements to get the L^* values for the virgin aggregates from all three sources. The L^* value is used as a reference value to calculate the amount of stripping in asphalt mixtures. L^* values for all six mixtures was measured in two different states – 30 minutes boiling and un-boiled. All the loose mixtures were boiled for 30 minutes rather than 10 minutes as recommended in standard to reduce user variability. All colorimeter readings were taken on loose asphalt mixtures. The L^* values of a mixture in un-boiled conditioned and after boiling can be used to calculate a parameter called L^*_{RB}, which is an indicator of the amount of stripping in the asphalt mixture due to boiling. Colorimeter CR 400 can also be used for color aggregates and asphalt as in that case c* readings will be used to evaluate stripping instead of L* readings.

Figure 2-1. CR 400 Colorimeter (Source: Konica Minolta Website)

2.1.2 Asphalt Compatibility Tester (ACT)

Another color measuring device used to evaluate stripping is Asphalt Compatibility Tester (ACT). Figure 2-2 shows the ACT device manufactured by Instrotek Inc. The image on the right side of the figure shows the extension where the loose mixture is placed. The loose mixture is placed in this extension and the pushed inside the green box (as seen in the image on the left side). The sensor (one with the handle on top) is used to take L* readings on the loose mixture. This device can only measure the lightness to darkness (grey scale) of an object.

Figure 2-2. Asphalt Compatibility Tester (ACT) Device by Instrotek Inc.

2.1.3 Moisture Induced Stress Tester (M.i.S.T) Device

The objective of the M.I.S.T conditioning method is to use the M.I.S.T device (Figure 2-3) to simulate the stresses caused by traffic load over moisture saturated asphalt concrete. The specimens are placed in the M.I.S.T device in a chamber filled with water and hydraulic pumping is generated to simulate the stresses. The procedure has two parts – adhesion cycle and cohesion cycle. The adhesion cycle is run first where the specimens are placed in the chamber filled with hot water at 60°C for 20 hours. This is followed by a cohesion cycle where the specimens remain in the hot water chamber at 60°C and are subjected to 3,500 cycles of 270 kPa (40 psi) hydraulic pumping at a rate of 3.5 seconds per pressure cycle (*9*, *16*). In the M.i.S.T conditioning, the specimens are not saturated before placing them in the water chamber, unlike the AASHTO T 283 procedure. The specimens are saturated during the conditioning procedure based on the surface voids of the specimens and the interconnectivity of the voids inside the specimens. This method of saturating the specimens ensures that they are saturated in a natural way and not in a forced way in AASHTO T 283 procedure where the specimens are required to have a saturation between 70% to 80% regardless of the surface air voids and the interconnectivity of the voids for the specimens. Standard ITS specimens are used for the M.i.S.T conditioning test method and they are compacted to 7.0% ± 0.5% air voids.

Figure 2-3. Moisture Induced Stress Tester (M.i.S.T) Device (Source: InstroTek Inc.)

2.2 Impact Resonance Test

The Impact Resonance (IR) test is a non-destructive test. The main advantages of non-destructive testing is examining the concrete structures where direct testing is not applicable, and minimizing structural impact for testing. Dynamic elastic modulus can be estimated using vibration, and wave propagation methods but it can be difficult due to geometry and boundary conditions of specimen tested. Therefore, the relative reduction in dynamic modulus which is the ratio of dynamic elastic moduli, before and after damage, can be determined using the resonant frequency in vibration based methods. The relative reduction in dynamic modulus can be used to quantify moisture damage in asphalt mixtures. The reduction in dynamic modulus for Portland cement concrete prisms can be determined by the square ratio of the resonance frequency, before and after exposure to freeze-thaw loading (*21*). Methods for measuring the vibration response and resonance frequency of materials are discussed in ASTM E 1876-09 (*22*). ASTM C215-14 is a standard procedure to determine Portland Cement Concrete (PCC) using the IR test method (*23*).

Dynamic modulus of material can be estimated for a specific geometry with specific boundary conditions. Kim et al. estimated dynamic elastic modulus of asphalt concrete for thick disk geometries (*24*). Kweon et al. estimated dynamic elastic modulus of for cylindrical geometry (*25, 26*). The dynamic elastic modulus was estimated using the analytical solution provide by Hutchinson and other researchers (*27-35*).

Ryden used thick disk geometry to determine the mastercurve for asphalt concrete (*36, 37).* LaCroix et al. used cylindrical geometry for determining the mastercurve (*38*). Gudmarsson et al. used acoustic spectroscopy technique on asphalt concrete beams with rectangular cross-section to estimate their dynamic elastic modulus (*39, 40*).

The aforementioned work shows that the dynamic elastic modulus of asphalt concrete can be estimated using vibration and wave propagation methods. The research question of this present work is whether the IR test can detect and quantify the moisture damage in HMA mixtures using relative reduction in dynamic modulus. To answer that question, axisymmetric flexural vibration of a thick free circular plate was used to measure the elastic modulus of asphalt concrete disks with different moisture conditioning procedure. The effect of various support conditions on resonant frequency using this method was also investigated. This method was also used by many researchers (Kim et al. and Ryden) to estimate the dynamic elastic modulus of asphalt concrete. The NCDOT project RP 2014-04 used this method to quantify moisture damage in Warm Mix Asphalt mixtures.

To quantify moisture damage in HMA mixtures, one inch thick disk geometry is used to carry out Impact Resonance testing. Thick disk geometry is considered as a desirable geometry to evaluate moisture damage as it allows to carry out testing on asphalt concrete field core also. Dynamic modulus of the circular asphalt concrete disk can be determined from resonant frequency obtained from this test and its non-destructive nature allows to carry out other test on the same sample. The IR test method induces an excitation by striking a mass onto a specimen and then measuring the natural vibrations of the specimen. The natural or resonant frequency of material vibration is an intrinsic property of for any material with elastic property and mass. The dynamic modulus values determined from IR test are based on resonant frequency. A Fast Fourier Transform (FFT) matrix is used to obtain an amplitude-frequency domain output from the time domain signal. The resonant frequency is the frequency corresponds to the highest peak in amplitude. The presence of moisture damage can cause the change in resonant frequency resulting into a reduction in elastic modulus. The relative reduction (ER) in dynamic modulus can be calculated using equation 2-1 (*21, 41 & 42*).

$$ER = \frac{E_d^{\ c}}{E_d^{\ 0}} = \left(\frac{f^{\,c}}{f^{\,0}} \right)^2 \quad \text{Equation 2-1}$$

where $E_d^{\ c}$ and $f^{\,c}$ are dynamic elastic modulus and resonance frequency of conditioned disk specimen, $E_d^{\ 0}$ and $f^{\,0}$ are dynamic elastic modulus and resonance frequency of intact specimen.

This study shows that the Impact Resonance test is able to detect moisture damage in HMA mixtures. The IR test is also able to evaluate the effect of various support conditions on resonant frequency. The results of impact resonance test method and its comparison with the conventional TSR test method is elaborated in section 6.

3. Research Approach and Methodology

3.1 Research Objective

The primary objectives of the research were:

1. To investigate possible modification to the existing TSR test protocol or develop an alternate test method, and a conditioning procedure that can quantify the adhesive and cohesive damage in asphalt mixtures due to moisture.
2. To quantify adhesive damage in asphalt mixture using the boil test along with colorimeter device.
3. To investigate the use of M.i.S.T conditioning procedure to quantify the cohesive damage in asphalt mixtures.
4. To explore the viability of the Impact Resonance test in assessing moisture damage in asphalt mixtures.
5. To evaluate the effect of different antistrip additives on asphalt mixtures and determine optimum antistrip additive content using the boil test with colorimeter device for different asphalt mixtures.

3.2 Research Methodology

The objectives of this study were accomplished through the following specific tasks:
Task 1. Literature Review: A comprehensive literature review on moisture damage conditioning procedures, moisture damage test methods, and various approaches to visual quantification of stripping in asphalt concrete mixtures was done. The failure mechanism involved in moisture damage was studied and drawbacks in the existing test methods were examined. Literature review was done on use of M.i.S.T device to moisture condition the asphalt concrete samples along with the recently developed nondestructive test methods such as AFV test. Additionally, literature review was done on the use of antistrip additives on asphalt mixtures and use of color measuring devices to quantify moisture damage.

Task 2. Materials: Two different types of aggregates were used in this study: Granite and Limestone. Granite aggregate was obtained from two different quarries in North Carolina: Crabtree Quarry in Raleigh and Garner Quarry. Limestone aggregate was obtained from a quarry in Tulsa, Oklahoma. Three different types of antistrip additives were used in this study.

Task 3. Tensile Strength Ratio (TSR) Test: The most commonly used test to evaluate moisture sensitivity, TSR test uses AASHTO T 283 conditioning procedure. The Indirect Tensile (IDT) Strength test was performed on the mixtures to determine the ITS values and the TSR values are calculated. TSR testing was done with two different types of conditioning – modified AASHTO T 283 and M.i.S.T conditioning. In the modified AASHTO T 283 procedure the specimens are compacted to 7.0% ± 0.5% air voids. The specimens are saturated between 70% and 80% and immediately placed in a hot water bath at 60°C for 24.0 ± 1.0 hours. In M.i.S.T conditioning, the specimens are placed in the M.i.S.T device in a chamber filled with water and hydraulic pumping is generated to simulate the stresses. All the TSR testing were done at Trimat Materials Testing Inc.

Task 4. Boil Test using colorimeter devices: This task involved determining percentage stripping by conducting the boil test and using colorimeter device to give stripping a value. The Boil test was performed on all asphalt mixtures and colorimeter device was used before and after the boil test to determine percentage stripping. The Boil Test (ASTM D3625) is a simple and quick test method to evaluate moisture sensitivity but it's a visually subjective test. Therefore, colorimeter device is used to quantify the test as done by Tayebali et al.

Task 5. Impact Resonance Test: The Impact Resonance (IR) test is a non-destructive test which is used to determine the material properties. The IR test method induces an excitation by striking a mass (steel ball or hammer) onto a specimen and measuring the resonant frequency of specimens. The resonant frequency obtained from the test is further used to determine the dynamic elastic modulus values. In this study, the IR test was done on the conditioned and unconditioned specimens and relative reduction (ER) in dynamic modulus was determined using equation 2-1.

Task 6. Optimum antistrip additive content using boil test: The Boil test was done on several asphalt mixtures prepared using three different aggregate source, each with three different antistrip additives with different dosage of additives. The optimum content for each antistrip additive was determined using relative reduction in percentage stripping. Later on, this methodology of determining optimum antistrip additive content for different asphalt mixtures will be used in the upcoming NCDOT project RI 2020-005 for quality control on field asphalt mixtures.

Task 7. Development of test protocol and specifications: Based on the test results, new specifications were developed to quantify adhesive and cohesive failure separately caused by moisture damage. The use of color measuring device along with the boil test is proposed for quality control of field asphalt mixtures. New protocol is developed which will help in selecting a more compatible and cost effective antistrip additive for a specific asphalt mixture.

4. Boil Test and Tensile Strength Ratio Test

Tensile Strength Ratio (TSR) Test and Boil Test carried out for the mixtures are described in this section. The Boil test was performed according to ASTM D3625, “Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water”. However, the boiling time was increased to 30 minutes against 10 minutes given in ASTM D3625 to reduce user variability. The TSR test was performed per the modified AASHTO T 283, “Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage”, guidelines, specified by NCDOT. The indirect tensile strength TSR test was done on M.i.S.T conditioned samples. Colorimeter device was used to quantify the stripping on both boil test samples and TSR split samples. The TSR test results were then compared to the boil test results.

4.1 Mixtures

A total of six different asphalt mixtures were used in this study (Table 4-1). Two different types of aggregates were used - Limestone aggregate and granite aggregate. Limestone aggregate was obtained from Tulsa, OK. Two different sources of granite aggregate were used - Crabtree Quarry, Raleigh, NC and Garner Quarry, NC. Two mixtures with the same gradation were prepared using materials from each aggregate source – one without antistrip additive and the other with an antistrip additive. PG 64-22 binder was used to prepare all six mixtures. An amine based antistrip additive (Evotherm) was used at a dosage of 0.5% by weight of the binder. The limestone aggregate mixture is a 19.0 mm dense graded mixture while the granite aggregate mixtures were 9.5 mm dense graded mixtures.

Loose mixture specimens of 450 grams each were used for the boil test. For Indirect Tensile (IDT) Strength test, 95.0 mm tall and 150.0 mm diameter specimens were prepared using a Superpave gyratory compactor. Four gyratory specimens were tested at each moisture conditioning state – dry, AASHTO T 283, and M.i.S.T.

Table 4-1 List of mixtures used in this research study

Aggregate Source	**Aggregate Type**	**Mixture Designation**	**Evotherm - Antistrip additive content (%)**
Tulsa, OK	Limestone	Limestone	None
		Limestone_A	0.5%
Crabtree Quarry, Raleigh, NC	Granite	Crabtree	None
		Crabtree_A	0.5%
Garner Quarry, Raleigh, NC	Granite	Garner	None
		Garner_A	0.5%

4.2 Boil Test

The Boil test method (ASTM D3625 and Tex-530-C) is a standard test practice used to visually determine the moisture sensitivity of asphalt mixtures. It is used to determine the moisture sensitivity by measuring the loss of adhesion (or stripping) between the asphalt binder and aggregate materials. It is a simple and quick test method that requires less effort and material. As per the ASTM standard, the loose asphalt mixture is boiled in distilled water for 10 minutes. The boiling of asphalt mixtures will lead to the stripping of asphalt from the aggregate material if there is poor adhesion between the asphalt and aggregate material in the asphalt mixture hence leading to adhesive failure (stripping). The stripping in the mixture will lead to exposed aggregates and a noticeable color change compared to the unboiled mixture. This change in color can be compared to standard charts and visually estimate the amount of stripping. In this study, the loose asphalt mixture was boiled for 30 minutes instead of the standard recommendation of 10 minutes to reduce user variability.

Tayebali et al. developed a method to calculate the stripping percentage in asphalt concrete mixtures due to the boil test using a color measuring device (*1*). They used the L^* values of aggregate, unboiled loose asphalt mixture, and boiled loose asphalt mixture to develop an equation to calculate the percentage stripping for that asphalt mixture. The damage ratios are defined in equation 4-1 and equation 4-2. L^*_{RB} is the damage ratio in percent relative to the original loose mixture. LD^*_R is the colorimeter damage ratio or percent stripping relative to the virgin aggregate blend. In case of colored aggregates and/or asphalt binder is used, L^* can be replaced by C^* (ASTM E284-13b) to determine stripping.

$$L^*_{RB} = \frac{Boiled\ L^* - Unboiled\ L^*}{Unboiled\ L^*} \times 100 \qquad \text{Equation 4-1}$$

$$LD^*_R = \frac{(Boiled\ L^* - Unboiled\ L^*) \times 100}{Aggregate\ L^* - Unboiled\ L^*} \qquad \text{Equation 4-2}$$

Equation 4-2 was developed to use a colorimeter to calculate percentage stripping for any test that can cause stripping in asphalt mixtures such as the Boil test or the TSR test using the modified AASHTO T 283 or M.i.S.T conditioning procedures.

Table 4-2 shows the colorimeter CR 400 reading of aggregate L^* value and L^* value of loose mixture before and after boil test. L^*_{RB} and LD^*_R (percentage stripping) due to the boil test was calculated for all the six mixtures (Table 4-1) using equation 4-1 and 4-2 as shown in table 4-2. The amount of stripping decreases from a mixture without antistrip additive to the same mixture with antistrip additive for each aggregate source.

Table 4-2. L* values and Percentage stripping values for the mixtures after boil test using Colorimeter CR 400

Mixtures	Aggregate L* (Colorimeter)	Un-boiled L* (Colorimeter)	Boiled L* (Colorimeter)	L^*_{RB}	LD^*_R (Percentage Stripping)
Limestone	43.07	18.30	20.85	13.9	10.3
Limestone_A		18.18	19.84	9.1	6.7
Crabtree	34.99	17.61	19.61	11.4	11.5
Crabtree_A		17.34	17.93	3.4	3.3
Garner	38.90	17.08	19.70	15.3	12.0
Garner_A		17.20	17.65	2.6	2.1

The same procedure was followed for boil test and ACT device was used to determine the L* values for asphalt mixtures. Table 4-3 shows the ACT reading of aggregate L^* value and L^* value of loose mixture before and after boil test. L^*_{RB} and LD^*_R (percentage stripping) was calculated using equation 4-1 and 4-2 as shown in table 4-3. However, note that in case of color aggregates and/or asphalt binder is used, ACT device cannot be used to determine to percentage stripping in asphalt mixtures. Colorimeter CR 400 can be used for asphalt mixtures prepared with colored aggregates and/or asphalt binder. Figure 4-1 depicts the loss of adhesion between asphalt and aggregate in Boil test.

Table 4-3. L* values and Percentage stripping values for the mixtures after boil test using ACT

Mixtures	Aggregate L* (ACT)	Un-boiled L* (ACT)	Boiled L* (ACT)	L^*_{RB}	LD^*_R (Percentage Stripping)
Limestone	30.14	19.9	22.04	10.75	20.9
Limestone_A		19.4	20.98	8.14	14.7
Crabtree	33.62	17.04	18.58	9.04	9.2
Crabtree_A		17.47	17.8	1.89	2.0
Garner	39.59	17.11	18.98	10.93	8.3
Garner_A		16.89	17.41	3.08	2.3

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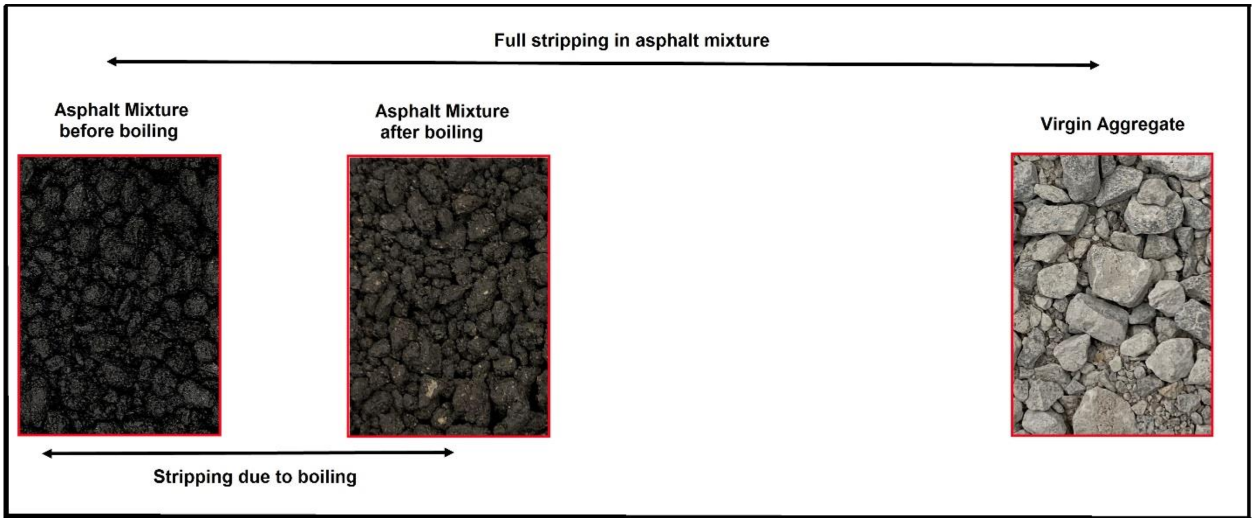

Figure 4-1 Visual Depiction of the loss of adhesion between asphalt and aggregate in Boil Test

Two different color measuring devices from different manufacturers were used along with the boil test to determine L* reading for each asphalt mixtures used in this study. The L* data obtained from both devices (Colorimeter CR 400 and ACT) are shown in table 4-2 and table 4-3. Table 4-4 shows the percentage change in L* readings obtained from two devices for both unboiled L* and boiled L* readings. The percentage difference in L* values for all the mixtures except limestone is less than 5 %.

Table 4-4. Percentage difference between L* values obtained from Colorimeter CR 400 and ACT

Mixtures	Percentage change in Un-boiled L*	Percentage change in Boiled L*
Limestone	8.7	5.7
Limestone_A	6.7	5.7
Crabtree	3.2	5.3
Crabtree_A	0.7	0.7
Garner	0.2	3.7
Garner_A	1.8	1.4

L^*_{RB} values calculated from Colorimeter CR 400 and ACT device are plotted as shown in figure 4-2. R^2 value of 0.96 shows that a good correlation exist between L^*_{RB} values. Therefore, the good correlation implies that L* reading obtained from ACT device are similar to the L* reading obtained from the Colorimeter CR 400 device.

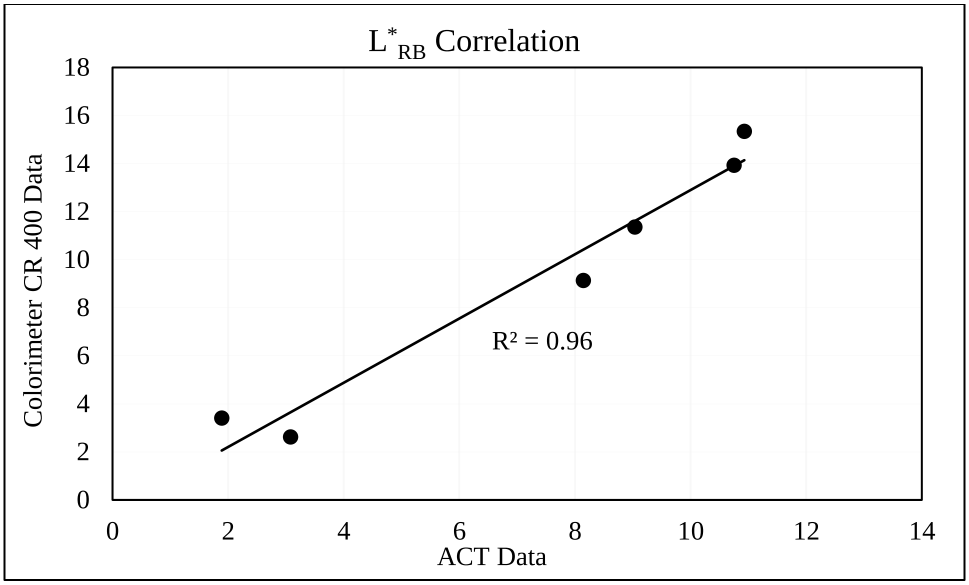

Figure 4-2. Correlation between L^*_{RB} values obtained from Colorimeter CR 400 and ACT device

4.2.1 Effect of Time Delay on Boil Test

The effect of time delay in performing the Boil test was conducted in this study. The Boil test was done on the loose mix prepared with and without antistrip additive. A total of six different asphalt mixtures were used as listed in table 4-1. Boil test with interpretation using colorimeter device. The loose mixture was cured for 2 hours at 135°C before performing the boil test. The loose mix specimen was boiled for 30 minutes. Each loose mixture was split into four sets of specimens. The Boil test was done on the first set of specimens immediately after curing. The second set was tested after 4 hours, the third set after 24 hours and the final set after 1 week. This was done to evaluate the effect of time delay on the boil test results.

Colorimeter CR 400 device was used to determine the L^* readings. L^* values obtained for the six different mixtures with different time intervals are listed in appendix B. Statistical analysis was performed to determine whether the effect of time delay in boil test is significant or not. Two tailed-test was done on the L^* readings obtained at different time intervals. The null hypothesis assumed was the difference between the mean value of L^* reading obtained at 0 hour and 4 hours is zero. It was found that there was no significant difference in mean L^* reading obtained at 0 hour and 4 hour at 95% confidence level. Similar statistical analysis was done for other time interval and table 4-5 summarize the results of comparison between the L^* readings obtained at different time interval by t-test.

Table 4-5 Statistical analysis results to evaluate the effect of time delay on boil test

Mixtures	0 and 4 hour L^* reading		0 and 24 hour L^* reading		0 and 168 hour L^* reading	
	Significant	p-value	Significant	p-value	Significant	p-value
Limestone	No	0.5019	No	0.8036	Yes	0.0084
Limestone_A	No	0.2617	No	0.7003	No	0.8522
Crabtree	Yes	0.0028	No	0.8781	Yes	0.0493
Crabtree_A	No	0.3666	No	0.2027	No	0.7169
Garner	No	0.0807	No	0.4466	Yes	0.0006
Garner_A	No	0.5263	Yes	0.0110	Yes	1.2E-07

The statistical analysis results show that there is no significant difference in the L^* readings taken at 0 hour, 4 hour and 24 hour in most of the mixtures (The L^* readings at different time interval are statistically equivalent). The difference in L^* readings between 0 hour and 168 hour is significant in most mixtures. The inference from these results recommends that the boil test can be performed anytime within 24 hour after boiling the loose mixture.

5. Tensile Strength Ratio (TSR) Test & Interpretation of Results

The TSR (Tensile Strength Ratio) value was used in this study to quantify the moisture sensitivity of asphalt mixtures. Indirect Tensile Strength (ITS) values are needed to calculate the TSR values for each mixture. The Indirect Tensile (IDT) Strength test was performed on the mixtures to calculate the ITS values. As per the modified AASHTO T 283 test method, the specimens must be loaded at a constant actuator displacement of 50.8 mm/min (2.00 in. /min) using a load frame to measure the ITS value of the specimens. The moisture-saturated specimens are conditioned at 25°C (77°F) for 2 hours in a water bath before testing while the dry specimens are kept dry. To measure the TSR value for a mixture, the IDT test is performed on four specimens in the dry state and four specimens in the moisture conditioned state to measure the ITS values. The TSR value was calculated as a percentage ratio of the median value of the four specimens in moisture conditioned state to the median value of four specimens in the dry state as shown in equation 5-1.

$$Tensile\ Strength\ Ratio\left(TSR\right)=\frac{S_2}{S_1} \qquad \text{Equation 5-1}$$

Where S_1 and S_2 are the median tensile strength of dry specimens and conditioned specimens respectively (*18*).

Two types of conditioning procedures were used in this study – modified AASHTO T 283 and M.i.S.T conditioning procedures. Standard ITS specimens – 95.0 mm tall and 150.0 mm diameter are used in this test method. The TSR value was calculated for all six mixtures (Table 5-1) for both conditioning procedures – modified AASHTO T 283 and M.i.S.T. The TSR value is used to quantify the moisture sensitivity of asphalt mixtures.

5.1 AASHTO T 283

In the modified AASHTO T 283 procedure, the specimens are compacted to 7.0% ± 0.5% air voids. The specimens are saturated between 70% and 80% and immediately after placed in a hot water bath at 60°C for 24.0 ± 1.0 hours. The modification from AASHTO T 283 is that the specimens are not subjected to a freezing cycle after soaking in the hot water bath.

5.2 Moisture Induced Stress Tester (M.i.S.T)

The M.i.S.T device (figure 2-3) is used to simulate the stresses occurring in the asphalt pavement due to combined action of water and traffic loading. The M.i.S.T conditioning procedure includes two cycles – adhesion cycle followed by cohesion cycle. The adhesion cycle simulates the adhesive failure in pavement due to presence of moisture. The cohesion cycle simulates the cohesive failure in pavement due to pumping action - combined action of moisture and traffic loading. In the adhesion cycle, the specimen is conditioned with hot water at 60°C for 20 hours. In the cohesion cycle, specimens remain in the hot water at 60°C and are subjected to 3,500 cycles of 270 kPa (40 psi) hydraulic pumping at a rate of 3.5 seconds per pressure cycle (*9, 16*). In M.i.S.T conditioning, specimens are saturated in a more natural way unlike forced saturation in AASHTO T 283 procedure eliminating the risk of artificial damage in the later conditioning procedure. Standard ITS specimens are used for the M.i.S.T conditioning test method and they are compacted to 7.0% ± 0.5% air voids.

Tensile Strength Ratio (TSR) was calculated for all the mixtures used in this study using both modified AASHTO T 283 and M.i.S.T conditioning procedures (Table 5-1).

Table 5-1 TSR Value (%) for the mixtures for the modified AASHTO T 283 and M.i.S.T conditioning procedures

Mixtures	**AASHTO T 283**			**M.i.S.T**		
	ITS value (kPa)		**TSR Value (%)**	**ITS Value (kPa)**		**TSR Value (%)**
	Dry	**Wet**		**Dry**	**Wet**	
Limestone	884	428	49	884	454	51
Limestone_A	991	616	62	991	715	72
Crabtree	1027	527	51	1027	402	39
Crabtree_A	965	848	88	965	634	66
Garner	920	554	60	920	500	54
Garner_A	808	737	91	808	652	81

After the TSR test is done, the Colorimeter CR 400 device was used to calculate the percentage stripping from TSR test for both the conditioning procedures. To calculate the percentage stripping from the TSR test specimens (LD^*_{RT}), L^* readings were taken on the fractured surfaces of the unconditioned specimens and conditioned specimens. Equation 4-2 was used to calculate the percentage stripping by replacing the unboiled L^* with unconditioned L^* and boiled L^* with conditioned L^* values. The L^* values and percentage stripping values for TSR split specimens are show in table 5-2.

Table 5-2. L^* values and percentage stripping values of TSR split specimens using Colorimeter CR 400

Mixtures	Unconditioned L*	T283 Conditioned L*	M.I.S.T Conditioned L*	T 283 LD^*_{RT}	M.i.S.T LD^*_{RT}
Limestone	18.30	20.51	19.21	8.9	3.7
Limestone_A	19.67	21.87	20.53	9.4	3.7
Crabtree	16.89	19.78	18.18	16.0	7.1
Crabtree_A	16.53	16.98	16.61	2.5	0.5
Garner	16.57	19.65	17.74	13.7	5.2
Garner_A	16.47	16.73	17.37	1.1	4.0

5.3 Interpretation of Boil Test and TSR Test Results

This section presents the interpretations from the results obtained from the Boil test (section 4) and the TSR test. In Figures 5-1 to 5-5, the hollow circles and triangles represent the data points corresponding to limestone aggregate and the filled circles and triangles represent granite aggregates.

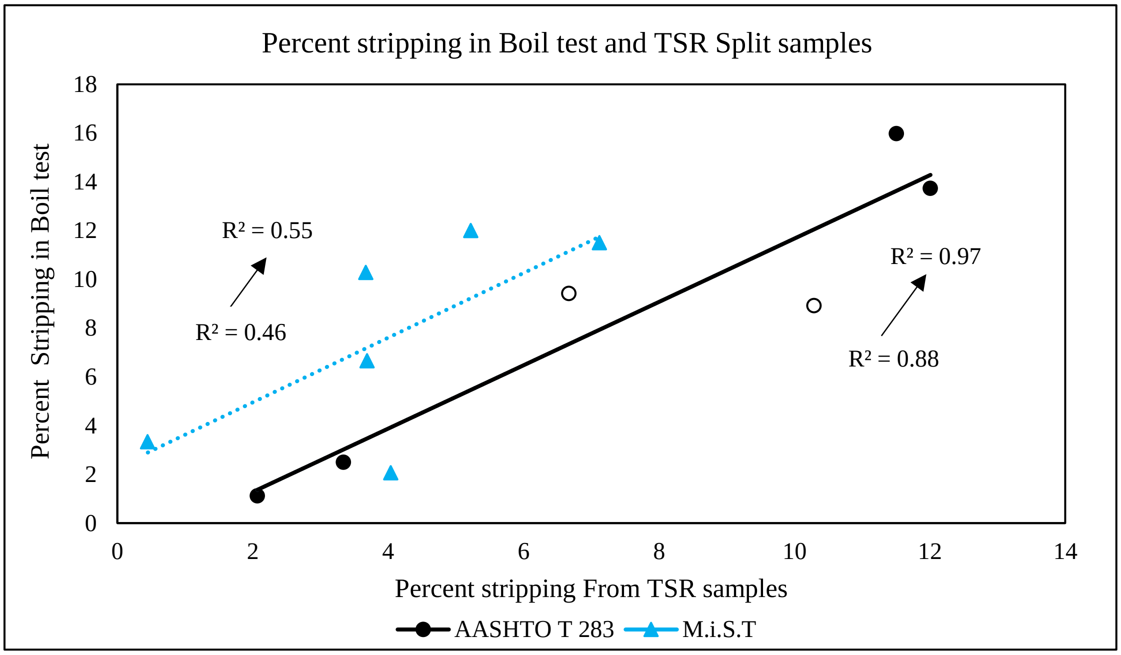

Figure 5-1 Relationship between percentage stripping from the boil test and TSR split specimens for both conditioning procedures

A good correlation exit between percentage stripping (LD^*_R) obtained from Boil test and AASHTO T283 conditioned TSR split specimens as shown in figure 5-1. However, a poor correlation can be observed for percentage stripping from the Boil Test and M.i.S.T conditioned TSR split specimens. The R^2 of the correlation between LD^*_R of Boil Test and AASHTO T283 increases from 0.88 to 0.97 if only granite aggregates is used (i.e. eliminating limestone aggregate data). Similarly, the R^2 of the correlation between LD^*_R of Boil Test and M.i.S.T increases from 0.46 to 0.55.

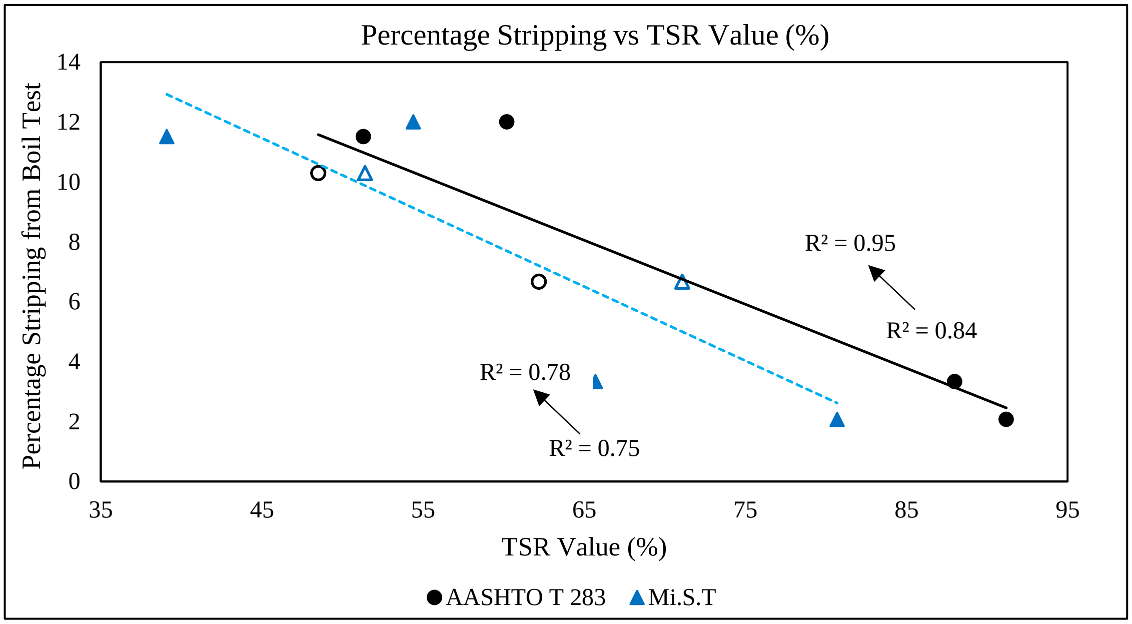

Figure 5-2 Relationship between percentage stripping from the boil test and TSR value from modified AASHTO T 283 and M.i.S.T conditioning procedures

Figure 5-2 shows the relationship between percentage stripping from the boil test and TSR Value from modified AASHTO T 283 and M.i.S.T conditioning procedures. When only granite aggregate was considered, the R^2 value for modified AASHTO T 283 increased from 0.84 to 0.95 while the R^2 went up to 0.78 from 0.75 for M.i.S.T. Percentage stripping correlates better with TSR values from the specimens with AASHTO T 283 conditioning than with TSR values from the specimens with M.i.S.T conditioning.

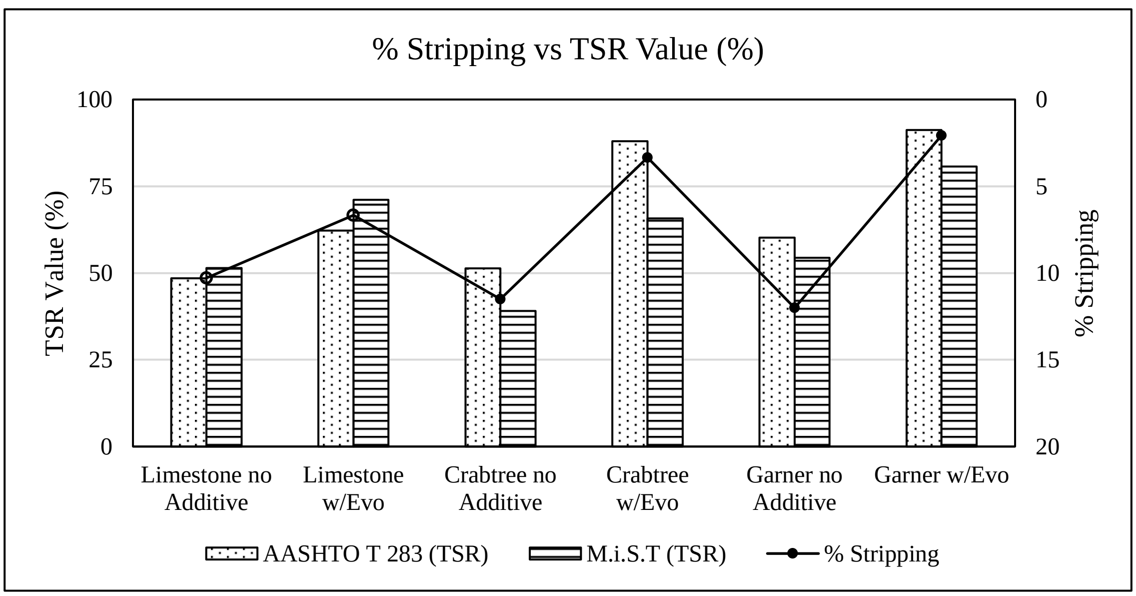

Figure 5-3 % Stripping vs TSR Value (%) for all the mixtures for both conditioning procedures

Figure 5-3 compares the change in TSR value and percentage stripping for all six mixtures for both the conditioning methods. The TSR value decreases for both conditioning methods as the percentage stripping increases. This indicates that for a given mixture, percentage stripping from boil test and TSR value from both conditioning procedures are inversely related. Figures 5-1 to 5-3 suggest that the percentage stripping can be a possible replacement to the TSR test as suggested by Tayebali et al., since they have the same trend and there seems to be a good correlation between percentage stripping from boil test and TSR for a given mixture for both conditioning procedures. North Carolina Department of Transportation (NCDOT) requires for all surface and intermediate course mixtures to have a minimum TSR value of 85% using the modified AASHTO T 283 procedure. According to the study done by Tayebali et al., 85% TSR value using the modified AASHTO T 283 conditioning corresponded to 5.0% stripping in asphalt mixtures from the boil test (*1*). Minimum TSR value of 85% and maximum stripping of 5.0% from boil test were used as criteria to evaluate if the mixture will meet NCDOT's moisture sensitivity criteria (Table 5-3). Since there is no specification by NCDOT for a minimum TSR value using M.i.S.T conditioning procedure, 80% was used since the TSR for a mixture will reduce due to the additional cohesive damage during the conditioning process. 80 % TSR for M.i.S.T is used based on the recommendation from previous researchers *(9)*.

Table 5-3 Pass/Fail evaluation of the mixtures based on moisture sensitivity criteria for TSR and percentage stripping values

Mixtures	**Pass/Fail based on TSR Test**		**Pass/Fail**
	AASHTO T 283	**M.i.S.T**	**% Stripping from Boil test**
Limestone	Fail	Fail	Fail
Limestone_A	Fail	Fail	Fail
Crabtree	Fail	Fail	Fail
Crabtree_A	**Pass**	Fail	**Pass**
Garner	Fail	Fail	Fail
Garner_A	**Pass**	**Pass**	**Pass**

Crabtree_A and Garner_A mixes pass the moisture sensitivity criteria if percentage stripping from boil test or TSR value from AASHTO T 283 conditioning is used. When TSR value from M.i.S.T conditioning is used only Garner_A passes the criteria.

5.3.1 Change in Volume

A study performed by Schram and Williams showed that swell or change in air voids is one of the best and simplest ways to estimate the moisture sensitivity of a mixture (*14*). LaCroix et al. found that swell or change in density is a good and simple way to estimate the moisture sensitivity of an asphalt mixture and can predict its cohesive strength (9). The operating guide for the M.i.S.T device suggests that a 1.5% change in density after conditioning can be used to separate good mixes from bad mixes (*16*). In this study, the percentage change in volume (same as the percentage change in density) was used instead of swell to evaluate the moisture sensitivity of the mixtures due to the two conditioning methods. The percentage change in volume was calculated using the following equation.

$$\% \, Change \, in \, volume = \frac{(Volume \, after \, conditioning - Initial \, volume)}{Initial \, volume} \times 100 \qquad \text{Equation 5-2}$$

The volume of the specimens was calculated using the AASHTO T 166 procedure using the saturated-surface-dry weight (SSD) and weight of specimen submerged in water (equation 5-3). The SSD weight and weight of specimen submerged in water were noted before conditioning and after conditioning for the two conditioning procedures.

$$Volume \, of \, specimen = Saturated \, surface \, Dry \, weight - Submerged \, Weight \qquad \text{Equation 5-3}$$

The percentage of change in volume due to modified AASHTO T 283 and M.i.S.T conditioning procedures was calculated for all the mixtures used in this study. Table 5-4 shows the % change in volume values for the mixtures for both the conditioning procedures.

Table 5-4 Volume change (%) for the mixtures due to modified AASHTO T 283 and M.i.S.T conditioning

Mixtures	**% Change in Volume**	
	AASHTO T 283	**M.i.S.T**
Limestone	1.2	1.7
Limestone_A	1.0	1.3
Crabtree	0.2	4.9
Crabtree_A	0.1	3.2
Garner	0.2	2.3
Garner_A	-0.2	1.4

NCDOT has no standard specification for moisture sensitivity based on percentage volume change. Hence, the suggested value of 1.5% was used to separate the mixes that are moisture sensitive from the mixes that aren't (*9, 10 &16*). All mixtures pass the moisture sensitivity criteria when percentage volume change from AASHTO T 283 conditioning is used while only Limestone_A and Garner_A mixes pass when percentage volume change from M.i.S.T conditioning is used (Table 5-5).

Table 5-5 Pass/Fail evaluation of the mixtures based on moisture sensitivity criteria for percentage volume change

Mixtures	**Pass/Fail based on % Volume Change**	
	AASHTO T 283	**M.i.S.T**
Limestone	Pass	Fail
Limestone_A	Pass	**Pass**
Crabtree	Pass	Fail
Crabtree_A	Pass	Fail
Garner	Pass	Fail
Garner_A	Pass	**Pass**

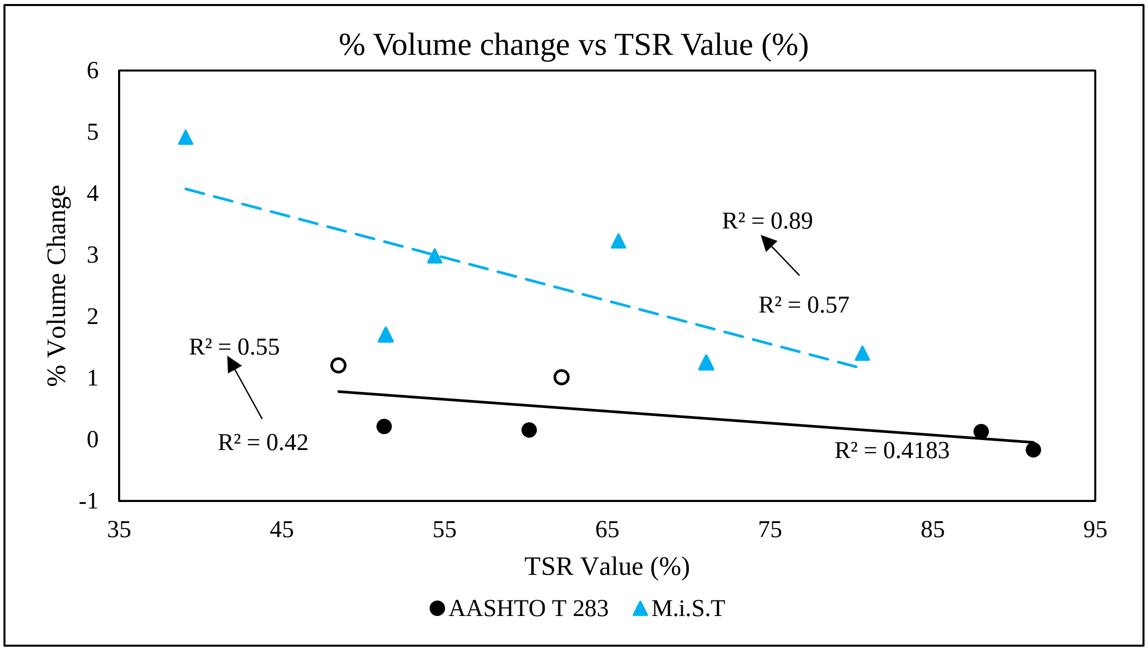

Figure 5-4 Relationship between percentage volume change and TSR value for both the conditioning procedures

Figure 5-4 shows the relationship between percentage volume change and TSR Value for both the conditioning procedures. The correlation is poor for both the conditioning procedures. However, when only single aggregate type (granite) is considered then the R^2 value for M.i.S.T conditioning increases from 0.56 to 0.89 while for AASHTO T 283 the R^2 increases from 0.42 to 0.55. AASHTO T 283 conditioning is expected to have a poor correlation because pore pressure which leads to volume change is being generated only during the initial saturation of the specimens. Hence the volume change is usually very low in this procedure as seen in Figure 5-5. M.i.S.T conditioning has a good correlation as the procedure has two components and one of which involves 3500 cycles of pore pressure which causes volume change. The poor R^2 values in Figure 5-4 might be because the volume change or cohesive behavior might depend on the type of materials (aggregates and asphalt) being used.

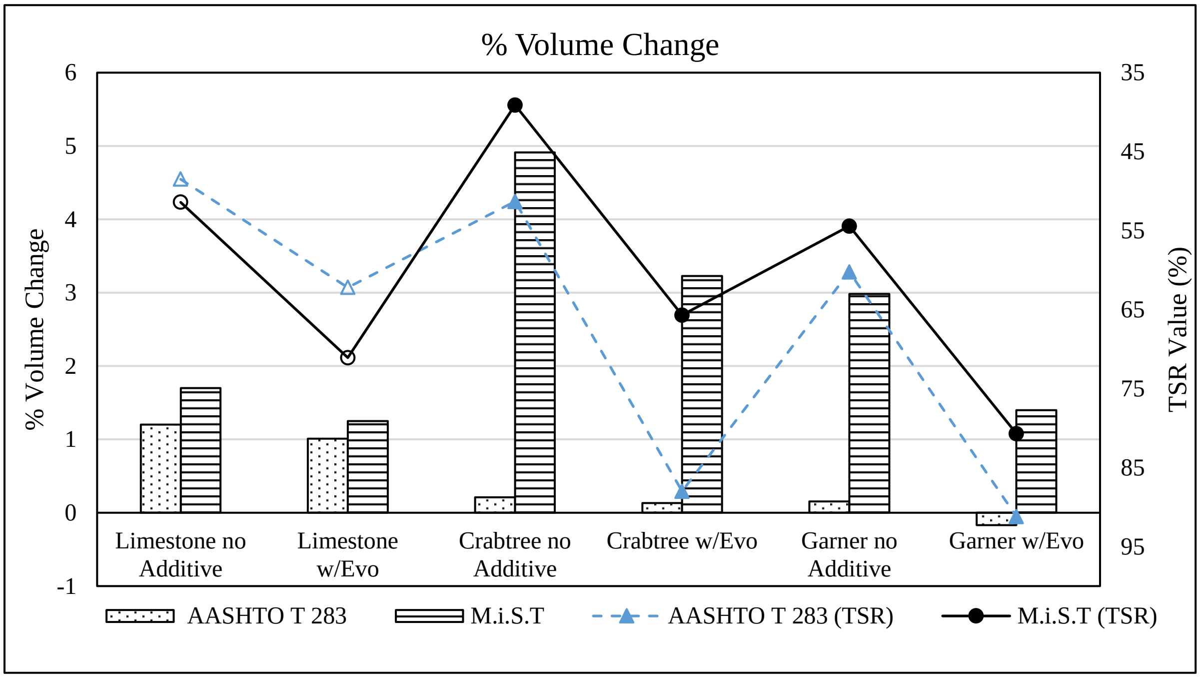

Figure 5-5 Percentage volume change for all the mixtures for both the conditioning procedures

Figure 5-5 compares the change in TSR value and percentage volume change for the six mixtures for both conditioning procedures. For limestone aggregate, the percent volume change is similar for both the conditioning methods. However, for the granite aggregates (Crabtree and Garner aggregate), the percentage change in volume is much higher for the M.i.S.T conditioning than AASHTO T 283 conditioning. For granite aggregates, there is no difference in the percentage change in volume for the AASHTO T 283 conditioning for mixtures with and without additives. However, there is a considerable change in the TSR value for AASHTO T 283 conditioning for mixtures with and without additives. For M.i.S.T conditioning, the percentage volume change and TSR value vary similarly for the mixtures with granite aggregates.

5.3.2 Regression analysis

A linear regression analysis was performed, and an equation was developed to predict TSR value from % stripping, and % volume Change for both conditioning methods. Equations 5-4 and 5-5 are the regression equations for AASHTO T 283 and M.i.S.T, respectively.

$$TSR\ (\%) = 98.013 - 3.376 \times \left(\%\ Stripping\right) - 12.537 \times \left(\%\ Volume\ Change\right) \qquad \text{Equation 5-4}$$

$$TSR\ (\%) = 95.751 - 2.476 \times \left(\%\ Stripping\right) - 4.684 \times \left(\%\ Volume\ Change\right) \qquad \text{Equation 5-5}$$

The R^2 for equations 5-4 and 5-5 are 0.96 and 0.91 which shows good correlations. The equations developed using regression analysis are statistically significant at the 95% confidence level.

5.3.3 Statistical Analysis

Statistical analysis was done at 95% confidence level to check if – (a) percentage volume change from AASHTO T 283 and M.i.S.T conditioning are statistically similar, (b) percentage stripping from the boil test, AASHTO T 283, and M.i.S.T conditioning are statistically similar, and (c) percentage stripping and percentage volume change are independent variables.

A two-tailed t-test was done to test the hypotheses (a) and (b) and it was found that –

1. Percentage volume change from AASHTO T 283 and M.i.S.T conditioning are significantly different.
2. Percentage stripping from boil test and AASHTO T 283 conditioning are not significantly different.
3. Percentage stripping from boil test and M.I.S.T conditioning are significantly different.
4. Percentage stripping from AASHTO T 283 and M.i.S.T conditioning are significantly different.

A chi-squared test was done to test the hypothesis (c) and it was found that –

1. Percentage stripping from boil test and percentage volume change are statistically independent for AASHTO T 283 and M.i.S.T conditioning procedures.
2. Percentage stripping and percentage volume change conditioning are statistically independent for AASHTO T 283 and M.i.S.T conditioning procedures.

5.4 Conclusion

This study shows that TSR value from AASHTO T 283 conditioning has a good correlation with percentage stripping from boil test and poor correlation with percentage volume change; TSR value from M.i.S.T conditioning has a good correlation with both percentage stripping from boil test and percentage volume change. From tables 5-1 and 5-3 when only TSR value from AASHTO T 283 conditioning or percentage stripping from boil test is used as a criterion then Crabtree_A and Garner_A mixes pass the moisture sensitivity test. When TSR value from M.i.S.T conditioning is used only Garner_A passes the test, and when volume change from M.i.S.T is used Limestone_A and Garner_A mixes pass. However, when volume change from M.i.S.T and percentage stripping from boil test are used as a criterion then only Garner_A mixture passes the test. If only adhesive damage or cohesive damage criteria is used, then Crabtree_A and Limestone_A mixes will pass the moisture sensitivity criteria but may perform poorly in the field. Hence the moisture sensitivity criteria should include both adhesive and cohesive damage.

This study and previous studies (9,*10*) show that AASHTO T 283 conditioning only accounts for adhesive damage and may not be able to identify mixtures which fail due to cohesive damage; whereas M.i.S.T conditioning can measure adhesive and cohesive failure. Percentage stripping from the boil test can successfully predict adhesive behavior which was also observed by Tayebali et al. (*1*).

The current conditioning procedures – AASHTO T 283 and 20-hour soaking in M.i.S.T to measure adhesive damage in asphalt mixtures is very time-consuming. Moreover, the adhesive damage cannot be quantified using this method. However, by using a colorimeter and the boil test together the adhesive strength of the asphalt mixtures can be measured, and loss of adhesion can be quantified. Statistical analysis suggests that adhesive and cohesive damage are an independent phenomenon, so the two damage mechanisms can be performed separately. Hence the boil test in addition to the cohesive part of M.i.S.T conditioning (3500 cycles) can be used to measure the moisture sensitivity of asphalt mixtures more effectively, reduce the testing time, and quantify the amount of stripping.

6. Impact Resonance Test

This section describes the ability of the impact resonance test in assessing the moisture damage. The Impact Resonance (IR) test is a non-destructive test which is used to determine the material properties. In IR test, excitation is induced by striking a mass (steel ball or hammer) onto a specimen and the data extracted was recorded by the sensor using a data acquisition system. MATLAB was used to plot the data in time domain and then using Fast Fourier Transformation, time domain data was converted to frequency domain to determine the resonant frequency. The test setup is shown in figure 6-1. The resonant frequency obtained from the test is further used to determine the relative reduction in dynamic modulus as calculated using equation 2-1. The relative reduction (*ER*) in dynamic elastic modulus can be used to quantify the damage in asphalt concrete mixture. Previous research studies show that both vibration based and wave propagation based methods can be used to determine the dynamic elastic modulus of the material. This study was more focused on evaluating the effect of different support conditions, impact location, and impact source on resonant frequency obtained from the test and assessing the viability of IR test to detect moisture damage in asphalt mixtures.

Figure 6-1. Impact Resonance Test Setup

6.1. Effect of different support conditions

Granite aggregates from Crabtree Valley are used in preparing two different asphalt mixtures; one with Coarse Fraction (CF) of Crabtree Valley mixture with target air voids of 20% and other with complete JMF gradation (FG) of Crabtree Valley mix with a target air voids of 9%. The gradation of Crabtree aggregate for coarse fraction and complete JMF gradation is shown in appendix A. The IR test was done on disk specimen 150 mm diameter and 25.4 mm(1 inch) thickness. Figure 6-2 shows the acceleration signal in time domain. Table 6-1 and table 6-2 shows the resonant frequency values for different support conditions for coarse fraction and JMF mixtures respectively. Figure B-1 in appendix B shows the different support conditions.

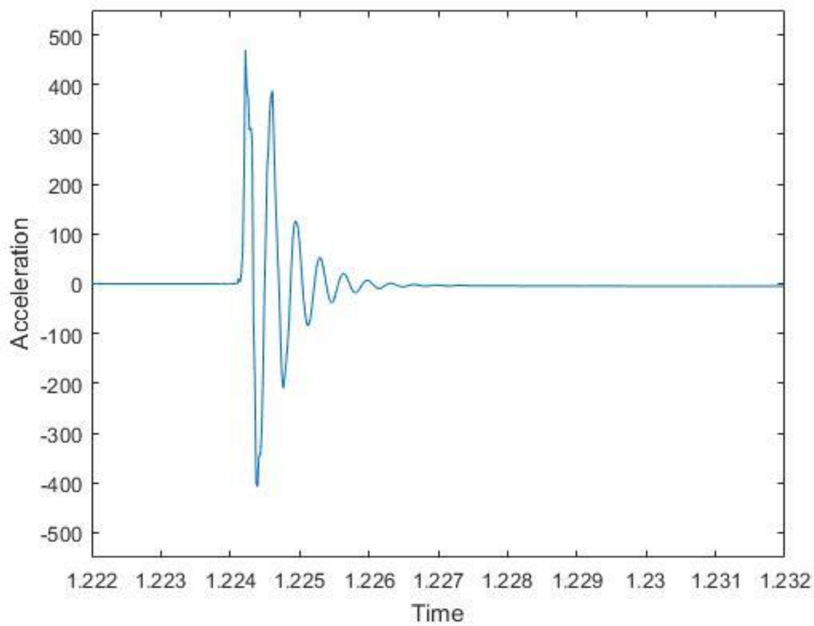

Figure 6-2 Acceleration spectrum in time domain

Table 6-1: Resonant Frequency (Hz) values of coarse fraction sample

Boundary Condition	1 inch thick foam	2 inch thick foam	Wooden plank	1 inch thick foam + wooden plank	2 inch thick foam + wooden plank
Test	Resonant Frequency (Hz)	Resonant Frequency (Hz)	Resonant Frequency (Hz)	Resonant Frequency (Hz)	Resonant Frequency (Hz)
1	2934	2873	2947	2931	2847
2	2882	2799	2934	2934	2853
3	2819	2828	3026	2944	2732
4	2836	2814	2925	2928	2773
5	2875	2826	2954	2875	2827
Mean	2869	2828	2957	2922	2806
Standard Deviation	44.8	27.7	40.1	27.2	52.2
CoV (%)	1.56	0.98	1.36	0.93	1.86

Plot of frequency spectrum of coarse fraction specimen with different support conditions is shown in figure B-2 in appendix B.

Table 6-2: Resonant Frequency (Hz) values of complete JMF gradation sample

Boundary Condition	1 inch thick foam	2 inch thick foam	Wooden plank	1 inch thick foam + wooden plank	2 inch thick foam + wooden plank
Test	Resonant Frequency (Hz)	Resonant Frequency (Hz)	Resonant Frequency (Hz)	Resonant Frequency (Hz)	Resonant Frequency (Hz)
1	4183	4148	4116	4138	4140
2	4117	3927	4012	3999	4175
3	4170	4117	4130	4094	4002
4	4157	4124	4018	4110	4151
5	4123	4159	4048	4074	4162
Mean	4150	4095	4065	4083	4126
Standard Deviation	28.9	95.5	55.1	52.5	70.5
CoV (%)	0.70	2.33	1.35	1.29	1.71

In this study, the coefficient of variation of the mean resonant frequency for different boundary conditions is 2.19 % for coarse fraction specimen while it is 0.83% for complete JMF gradation specimen. The coefficient of variation in coarse fraction specimen is three times greater than that of complete JMF gradation specimen; which can be explained by high air void content in coarse fraction specimen. The combined plot of frequency spectrum of coarse fraction specimen and complete JMF gradation specimen is shown in figure 6-3. Considering these results, to check the variability with different impact location, more IR test were done on same specimen with different impact location.

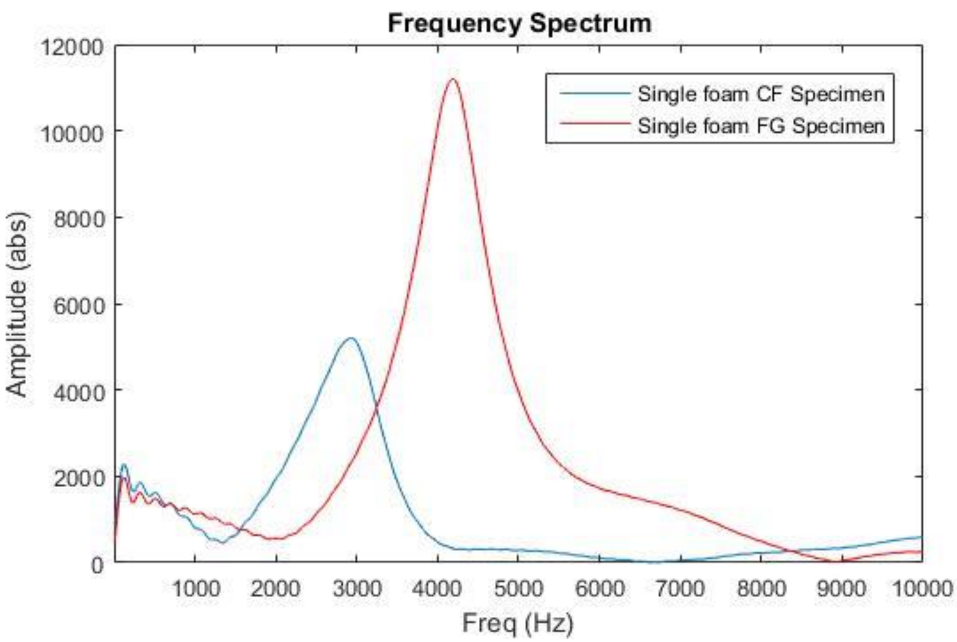

Figure 6-3. Frequency spectrum of two different specimen

Statistical analysis was performed on resonant frequency obtained with different support conditions. Initially two sample data of coarse fraction specimen were taken; 1 inch thick foam and 2 inch thick form resonant frequency data. The population variance was assumed to be unknown but finite. The null hypothesis assumed was that the difference between the average resonant frequency with boundary condition 1 inch thick foam and 2 inch thick foam is zero. A *t* test was conducted and degree of freedom (dof) is determined. The value of *t* statistics was 1.75, with 6.67 dof calculated. The critical *t* value for a two sided, 0.05 confidence limit, with 7 dof is 2.365. The statistical analysis shows that the average resonant frequency obtained with two different boundary conditions are statistically equivalent. Similarly, the *t* test statistics was also done on the resonant frequency obtained from rest of the different support condition as presented in table 6-1. The inference from this study is that resonant frequency obtained on 1 inch thick form and wooden plank are not statistically equivalent. The resonant frequencies obtained from rest of the boundary conditions are statistically equivalent. Similar results were obtained as for IR test on complete JMF gradation sample with different support conditions. The statistical analysis shows the resonant frequency obtained from 1 inch thick form and wooden plank are not statistically equivalent. But the resonant frequency obtained from 1 inch thick form base is statistically equivalent to that obtained from rest of the boundary conditions.

6.2 Effect of impact location and impact source on resonant frequency

To study the effect of impact location, IR testing was done on specimen prepared with complete JMF gradation of Crabtree Valley mixtures with different impact locations. Two different impact sources; steel ball and hammer were used to induce excitation. The IR test results were compared between two boundary conditions, and specimen supported on four nodes and specimen supported on 2 inch thick foam. Nine impact location were chosen along the diameter and the distance between two impact locations is 15 mm. The impact location on specimen in shown in figure 6-4.

Figure 6-4. Different impact source and impact location

Five tests were done at each location and resonant frequency was obtained. The results of IR test conducted with different support conditions does not show noticeable difference in resonant frequency values. The variability in resonant frequency values was observed when the impact location is around the periphery and this can be explained by the air void distribution. It is recommended that the impact location should be chosen inside the center core of diameter 4 inch. The resonant frequency data of impact location close to edges was removed. Table 6-3 shows the mean values of resonant frequency. The coefficient of variation for resonant frequency is less than 1 %.

Table 6-3. Mean Resonant Frequency values

Position	Impact by Hammer with Specimen on 2 inch thick Foam	Impact by Hammer with Specimen supported by 4 nodes	Impact by Steel Ball with Specimen supported by 4 nodes	Impact by Steel Ball with Specimen on 2 inch thick Foam
Centre	4201	4228	4278	4217
P1	4199	4264	4284	4226
P2	4249	4317	4288	4242
P12	4205	4316	4287	4233
P13	4238	4320	4331	4239
Mean	4218	4289	4294	4233
Standard Deviation	21.3	38.5	10.5	7.1
CoV (%)	0.50	0.90	0.25	0.17

*Note: P1 stand for impact location 1 shown in figure 5-3.

Figure 6-5 shows the frequency spectrum for different impact location when impact induced by hammer and specimen rest on 2 inch thick foam. The frequency spectrum of rest of three cases are shown in appendix B. The location of the peaks is more important than its magnitude as it gives the value of resonant frequency. The magnitude of peak has no effect on resonant frequency values as it depends on the intensity of impact.

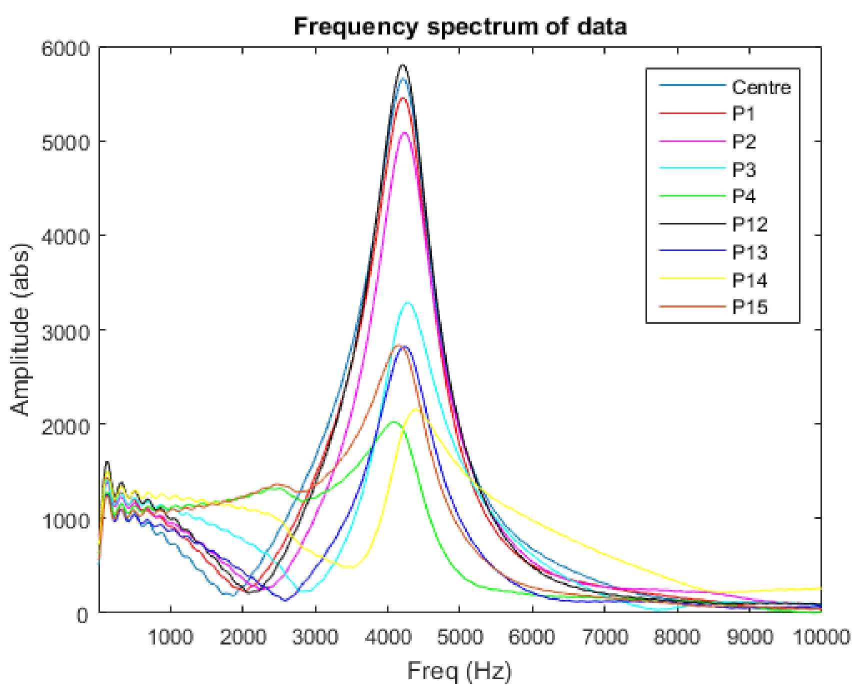

Figure 6-5 Frequency spectrum for different impact location

A statistical study was done to determine the effect of impact source on resonant frequency. The t-test was done. The results of the statistical analysis shows the mean resonant frequency obtained from two different impact source are statistically equivalent. It can be inferenced from these results that the impact source doesn't alter the resonant frequency of a specimen.

All the test were done on a single specimen while varying the other testing parameters like support conditions, and impact location. Considering all the results obtained in IR testing done reported above, it was decided to make new thin disk specimens and perform the IR testing. This will give a better understanding of the variability in results among different specimens. To study the effect of air voids; it was decided to core the thin disk specimen of 6 inch diameter to 4 inch diameter. The air voids were calculated before and after coring. The IR test was done before and after coring and the results were compared.

6.3 Repeatability Study

In order to the check the repeatability of the IR test method to determine the resonant frequency, the IR test was done on nine different specimens. Three full size specimen (150 mm in diameter by 178 mm in height) were made using the complete JMF gradation of the Crabtree Valley mix and sliced into thin disk of one inch thickness. Three out of four specimen were taken from each full size specimen. Therefore, there is total of nine specimen chosen and IR test is done on all the nine specimen at varying impact location along the diameter. Also the bulk specific gravity (Gmb) test was done before and after coring to determine the bulk specimen specific gravity and air voids. The bulk specific gravity and air void data are presented in table B-4 in appendix B. The IR resonance test was done on nine different location on each specimen. The specimen was supported on four hard points (nodal points) and excitation was induced by dropping 16 mm diameter steel ball from a height of 20 cm. Resonant Frequency was obtained from the IR tests.

Once the IR test on all the nine specimens was done then each specimen was cored to 4 inch diameter. The specimen was dried and IR test was done again on all specimen. The mean values of resonant frequency at the center of the specimen were taken for both cored and un-cored specimen shown in table 6-4.

Table 6-4: Resonant frequency (Hz) of different specimen at center

Specimen	Un-cored (6 inch disk)	Cored (4 inch disk)
S11	4444	8946
S12	4304	8805
S13	4365	8925
S21	3967	8387
S22	3972	8123
S23	4083	8387
S31	4290	8708
S32	4112	8430
S33	4108	8430
mean	4183	8572
SD	172.9	284.6
CoV (%)	4.13	3.32

The coefficient of variation (CoV) of mean resonant frequency for nine different specimen was found to be 4.13 % for un-cored specimen and 3.32 % for cored specimen at center. The CoV values obtained is considerable acceptable as the recommended CoV for the mean of three specimens is 7.5 % based on the current AASHTO T342-11 standard. The CV of three specimen S11, S12 and S13 obtained from a single large specimen was found to be 1.6 %.

The results show that there is an increase in resonant frequency values of the cored specimen as compared un-cored specimens. Statistical analysis of the resonant frequency of cored and un-cored specimen was done. The comparison of resonant frequency values was based on the hypothesis that the difference between the average resonant frequency of cored thin disk specimen and un-cored thin disk specimen was zero. A t test was conducted due to limited number of degree of freedom (dof). The population variance was assumed to be unknown. The value of t statistics was 2.94, with 14.85 dof calculated. The critical t value for a two sided, 0.05 confidence limit, with 15 dof is 2.131. This indicates that the difference between resonant frequency of cored and un-cored specimen is significantly different from zero. The hypothesis was rejected. The statistical analysis shows that the average resonant frequency of cored and un-cored thin disk specimen are not statistically equivalent. The t test statistics was also done on the resonant frequency values obtained at impact location P1. The hypothesis was rejected in this case also; means the difference between the average resonant frequency values of un-cored and cored specimen at impact location P1 are significantly different from zero. The inference from this study is that the effect of the air voids on dynamic modulus is statistically significant.

6.4 Evaluating Moisture Damage using Impact Resonance Test

To study whether impact resonance test can detect moisture damage or not, Impact Resonance test was done on three different gradation; Coarse fraction, Fine Fraction and full JMF gradation. The aggregate source used in this study is Crabtree Valley aggregates. The aggregate gradation is shown in appendix A. Three different asphalt mixtures are prepared using antistrip additive LOF 6500. For each mixture, four thin disk specimens were prepared and Impact resonance test was done on them. After that, M.i.S.T conditioning is done on specimens followed by the Impact resonance test. Resonant frequency for both before and after M.i.S.T conditioning of the specimens were determined. The relative reduction (ER) was calculated using equation 1. The relative reduction (ER) for specimen made from coarse fraction, fine fraction and complete JMF gradation are 87 %, 106 % and 84.5 % respectively.

From the test results, it may be observed that average ER value of fine fraction gradation increases due to conditioning with average of 106% (6% increase) as opposed to decreasing due to cohesive damage (adhesion is controlled by inclusion of antistrip additive). This is contrary to the expectations. However, for this fine aggregate mixture that can be considered as tender or unstable mixture; it is apparent that the mixture is undergoing consolidation under cyclic pumping in the M.i.S.T conditioning process and therefore, the increase in stiffness due to lower air voids. This behavior will likely not occur in AASHTO T283 moisture conditioning (except for statistical anomaly) due to the forced saturation produced under vacuum pressure. The M.i.S.T device protocol does not have vacuum saturation. It is also apparent that from now on the air voids must be measured before and after moisture conditioning to ascertain that the mixture specimens have not been subjected to consolidation. On the other hand, the M.i.S.T moisture conditioning method can be very useful in identifying tender or unstable mixtures. These mixtures will undergo consolidation and can be eliminated and/or the gradation adjusted.

6.5 Comparison of ER ratio for six different mixture exposed to two different kind of conditioning procedure

In this study, two different type of moisture conditioning procedure is used; AASHTO T283 and M.i.S.T conditioning. Three different aggregate source and an antistrip additive were used to prepare six different asphalt mixtures. Evotherm (0.5 % by weight of asphalt content) was used as antistrip additive. For each asphalt mixture, 12 thin disk specimen were used. Four were conditioned according to AASHTO T283 procedure, four were conditioned according to M.i.S.T conditioning procedure and rest four remained unconditioned. Impact resonance test was done before and after conditioning on each specimen and the relative reduction (ER ratio) for dynamic modulus was then determined using equation 1. The ER ratio determined is shown in table 6-5.

Table 6-5. ER ratio from impact resonance test

Aggregate Source	Aggregate Type	Mixture Designation	AASHTO T283 Conditioning	M.i.S.T conditioning
Tulsa, OK	Limestone	Limestone	69.5%	86.5%
		Limestone_A	68.5%	78.1%
Crabtree Quarry, Raleigh, NC	Granite	Crabtree	96.6%	65.3%
		Crabtree_A	86.3%	51.0%
Garner Quarry, Raleigh, NC	Granite	Garner	95.5%	63.9%
		Garner_A	84.1%	55.8%

AASHTO T 283 conditioning only accounts for adhesive damage while in M.i.S.T conditioning procedure simulates both adhesive and cohesive damage. The cohesive damage in M.i.S.T is generated by pumping action. The M.i.S.T conditioning best replicates the field condition as the cohesive damage also occur during conditioning. Figure 6-6 shows the ER ratio for different asphalt mixtures. The ER ratio for Crabtree valley aggregate source and Garner aggregate for M.i.S.T conditioning is lower as compared to AASHTO T 283 conditioning. This decrease in ER ratio for M.i.S.T conditioning explains the significance of cohesive damage in material.

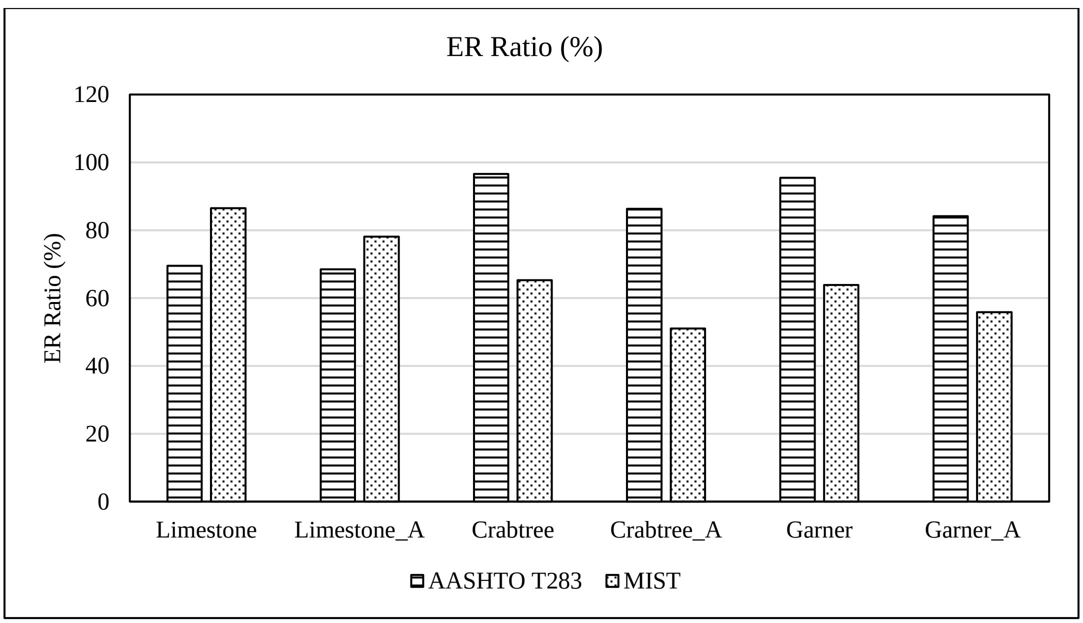

Figure 6-6 ER Ratio (%) of six different asphalt mixtures

6.6 Interpretation of IR Test, Boil Test, and TSR Test Results

Figure 6-7 shows the relationship between percentage stripping (LD^*_R) determine from Boil Test, and Relative Reduction in dynamic modulus (ER) values from AASHTO T283 and M.i.S.T conditioning. In Figures 6-7 and 6-8, the hollow circles and triangles represent the data points corresponding to limestone aggregate and the filled circles and triangles represent granite aggregates. The correlation between percentage stripping (LD^*_R) and ER values are poor for both conditioning procedure. However, The R^2 of the correlation between LD^*_R of Boil Test and ER value for AASHTO T 283 increases from 0.06 to 0.99 if only granite aggregates is used (i.e. eliminating limestone aggregate data). Similarly, the R^2 of the correlation between LD^*_R of Boil Test and ER value for M.i.S.T increases from 0.28 to 0.84.

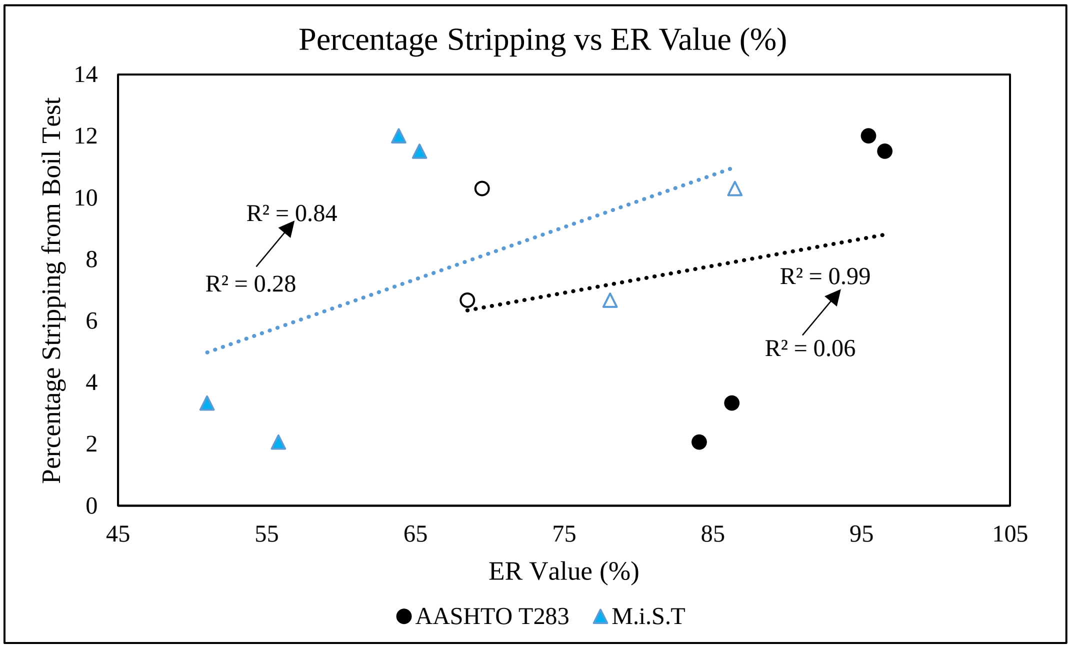

Figure 6-7 Relationship between Percentage stripping from Boil Test (LD^*_R) and ER value

Figure 6-8 shows the relationship between ER values determine from IR Test, and TSR values determined from TSR Test for both AASHTO T283 and M.i.S.T conditioning. The correlation between ER values and TSR values for both conditioning procedure is poor. However, if the limestone aggregate data is removed, the R^2 of the correlation between increases from 0.01 to 0.98 for AASHTO T 283 and 0.09 to 0.57 for M.i.S.T conditioning.

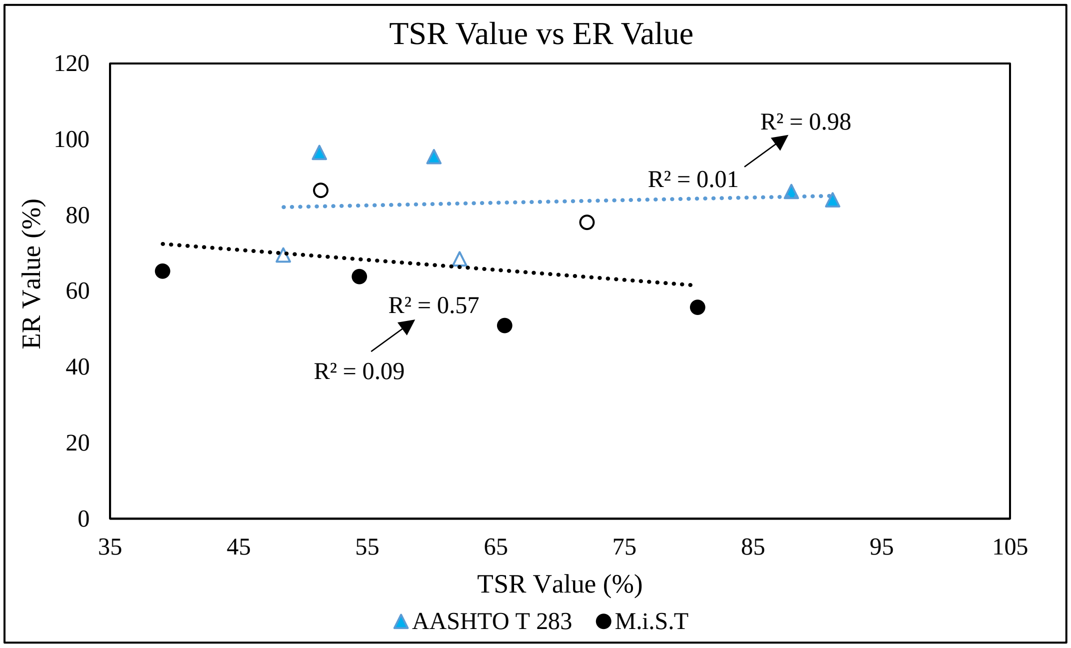

Figure 6-8 Relationship between ER Value and TSR Value

7. Optimum Antistrip Additive Content

This section details a method to determine optimum antistrip additive content for asphalt mixtures. Loss of adhesion between asphalt and aggregate or stripping is one of the major reasons of moisture damage and use of antistrip additives can reduce the stripping in asphalt mixtures. To improve adhesion between asphalt and aggregate in the asphalt mixture and thus improve the resistance of the asphalt mixtures to moisture damage various antistrip additives are used in asphalt mixtures. Therefore, it is important to determine the compatibility of an antistrip additive and its optimum additive content for a particular asphalt mixture. Wasiuddin et al. used surface free energy concept to evaluate the effect of antistrip additive on asphalt binder. It was observed that the total surface free energy of asphalt binder increased with the increase in additive content and the increase in surface energy enhanced the adhesion between aggregate and asphalt binder (*43*). Zhu et al. studied the effect of antistrip agents on rheological properties of asphalt binder at high temperature (*44*). The results show that rheological properties like rotational viscosity, G^*, δ, and $G^*/\sin\delta$ depends on antistrip agents and their dosage. Aksoy et al. studied the effect of additives Wetfix I, Lilamin VP 75P, Chemcrete and rubber on stripping of asphalt mixture (*45*). The effect of additives on moisture induced damage of asphalt mixture were evaluated by using Marshall conditioning and retained tensile strength ratio after vacuum saturation and after Lottman accelerated moisture conditioning.

In this study, Boil Test (ASTM D3625) along with colorimeter device is used to determine the optimum antistrip additive content for asphalt mixtures.

7.1 Experimental Plan

The mixtures used in this study had a wide range of moisture sensitivity with and with-out antistrip additive. Asphalt mixtures are prepared with varying antistrip additive content. The Boil test (ASTM D3625) was conducted on all the mixtures. A colorimeter device was used after the boil test to evaluate stripping in asphalt mixtures. The percent stripping determined using colorimeter device was plotted against the antistrip additive content and optimum antistrip additive content was determined.

7.2 Materials and Specimen Preparation

Two different types of aggregates were used to prepare the asphalt mixtures - Limestone aggregate and granite aggregate. Limestone aggregate was obtained from Tulsa, OK. Two different sources of granite aggregate were used - Crabtree Quarry, Raleigh, NC and Garner Quarry, NC. Six different asphalt mixtures were prepared for each aggregate source by varying the amount of antistrip additive content ranging from 0% to 1% by weight of asphalt binder. Three different antistrip additives were used in this study. PG 64-22 binder was used to prepare all mixtures. In total, fifty-four asphalt mixtures were prepared. For each asphalt mixture, four different samples were prepared to do the boil test. The testing plan carried out in this study is shown in table 7-1.

Table 7-1. List of asphalt mixtures used for this study

Aggregate Source	**Aggregate Type**	**Antistrip Additive**	**Antistrip additive content (%) (% by weight of asphalt content)**
Garner Quarry, Raleigh, NC	Granite	LOF 65-00	0, 0.15, 0.25, 0.50, 0.75 & 1
		Evotherm U3	0, 0.15, 0.25, 0.50, 0.75 & 1
		Morelife 5000	0, 0.15, 0.25, 0.50, 0.75 & 1
Crabtree Quarry, Raleigh, NC	Granite	LOF 65-00	0, 0.15, 0.25, 0.50, 0.75 & 1
		Evotherm U3	0, 0.15, 0.25, 0.50, 0.75 & 1
		Morelife 5000	0, 0.15, 0.25, 0.50, 0.75 & 1
Tulsa, OK	Limestone	LOF 65-00	0, 0.15, 0.25, 0.50, 0.75 & 1
		Evotherm U3	0, 0.15, 0.25, 0.50, 0.75 & 1
		Morelife 5000	0, 0.15, 0.25, 0.50, 0.75 & 1

7.3 Testing Procedures

The boil test was conducted on loose mixtures only. Each loose mixture specimen weighed 450 grams. One specimen remained un-boiled and rest three specimens were boiled as per ASTM D3625. Boil test was done on all asphalt mixtures. A colorimeter device was used on specimens before and after the boil test to calculate percentage stripping for all the asphalt mixtures. In this study, the loose mixture was boiled for 30 minutes instead of 10 minutes to reduce operator variability. The Colorimeter device gives an L* reading that measures the color index based on a grey scale. The L^* value obtained was then used to determine the percent stripping or stripping potential (LD^*_{RB}) using equation 2. The percentage stripping or LD^*_{RB} is calculated for the asphalt mixtures and plotted against antistrip additive content to determine the optimum antistrip additive content. Figure 7-1 shows the boil test setup.

Figure 7-1 Boil test setup

7.4 Results

7.4.1 Boil Test Results

L^* readings were obtained before and after the boil test using colorimeter device. The L^* values were used to calculate percentage stripping **(**LD^*_{RB}) using equation 1. Table 7-2 shows the average percentage stripping **(**LD^*_{RB}) values of asphalt mixtures prepared from Crabtree aggregate source and antistrip additive with their varying additive content from 0% to 1% (% by weight of asphalt binder).

Table 7-2 Average LD^*_{RB} (%) values for Crabtree aggregates

Antistrip Additive content (%) (% by weight of asphalt content)	LD^*_{RB} (%)		
	LOF 65-00	Evotherm U3	Morelife 5000
0	9.12	8.16	8.97
0.15	1.95	1.26	2.11
0.25	1.58	0.81	1.75
0.50	1.45	0.80	1.62
0.75	0.92	0.44	1.01
1.0	0.33	0.15	0.77

Figure 7-2 shows the plot of percentage stripping (LD^*_{RB}) against (%) antistrip additive for all three antistrip additive used in this study for Crabtree aggregate source.

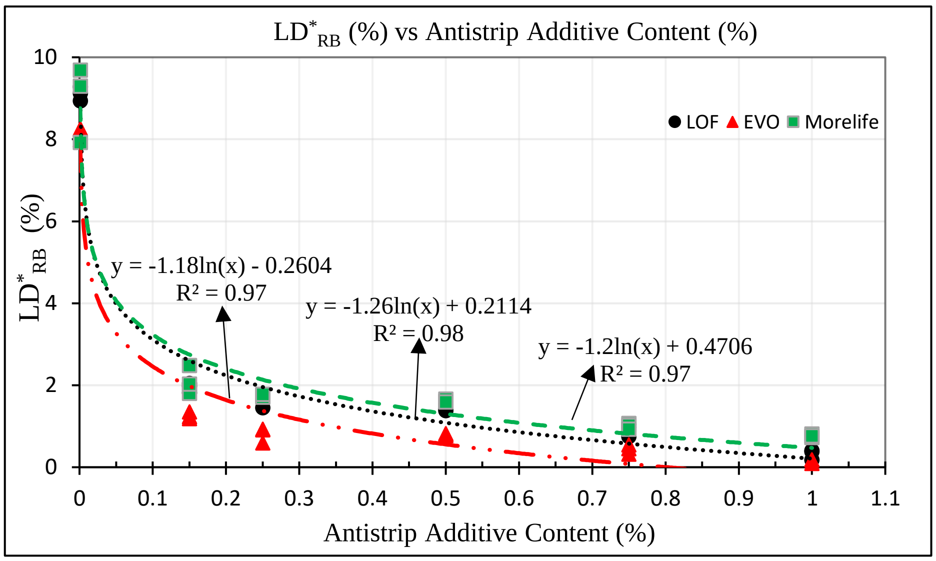

Figure 7-2 Combined plot of LD^*_{RB} (%) versus Antistrip Additive Content (%) for three different additive type used with Crabtree Aggregate

Figure 7-2 shows that all three antistrip additives follow the same trend for varying additive content. There is a good logarithmic correlation for all three antistrip additives with $R^2 > 0.95$. Also, it can be observed from the figure that there is a significant decrease in percentage stripping value for asphalt mixture with no dosage to 0.25% dosage of antistrip additive.

A similar procedure was repeated for asphalt mixtures prepared from garner aggregate source and limestone aggregate. Table 7-3 shows the average percentage stripping **(**LD^*_{RB}) values of asphalt mixtures prepared from Garner aggregate source with varying antistrip additive content.

Table 7-3 Average LD^*_{RB} (%) values for Garner aggregates

Antistrip Additive content (%) (% by weight of asphalt content)	LD^*_{RB} (%)		
	LOF 65-00	Evotherm U3	Morelife 5000
0	13.64	9.88	8.22
0.15	1.94	1.68	2.62
0.25	1.21	1.58	1.05
0.50	0.93	1.19	0.82
0.75	0.60	0.68	0.79
1	0.03	0.46	0.69

Figure 7-3 show the plot of percentage stripping (LD^*_{RB}) against antistrip additive for the three antistrip additive used in this study for garner aggregate source. The plot shows the similar trend as observed in asphalt mixtures prepared from Crabtree aggregate source. A good logarithmic correlation also exist in this case for all three antistrip additives with $R^2 > 0.95$.

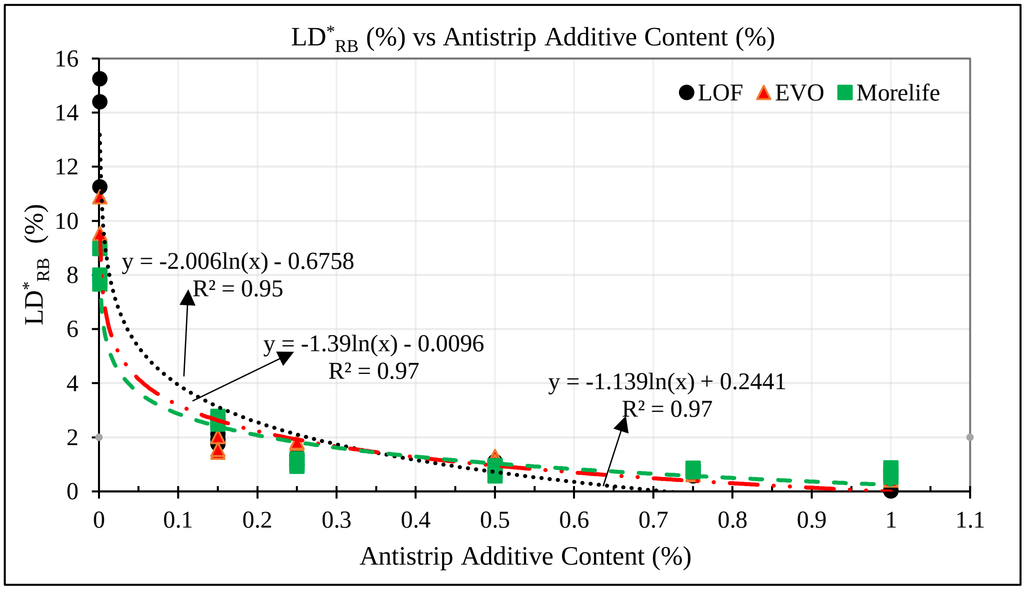

Figure 7-3 Combined plot of LD^*_{RB} (%) versus Antistrip Additive Content (%) for three different additive type used with Garner Aggregate

Table 7-4 shows the average percentage stripping values for each asphalt mixture prepared for limestone aggregate and the results are shown in figure 7-4.

Table 7-4 Average LD^{*}_{RB} (%) values for Limestone aggregates

Antistrip Additive content (%) (% by weight of asphalt content)	LD^{*}_{RB} (%)		
	LOF 65-00	Evotherm U3	Morelife 5000
0	8.32	7.77	7.62
0.15	6.95	5.6	6.17
0.25	6.36	4.34	5.52
0.50	5.91	3.77	4.13
0.75	5.82	3.37	3.32
1	4.83	2.28	2.71

In this case, a good linear correlation between percentage stripping and antistrip additive content is observed for limestone aggregate source compared to good logarithmic correlation observe for Crabtree and Garner aggregate source. However, there is a significant behavioral difference in percentage stripping values for LOF 6500 antistrip additive compared to the other two additives (fig 7-4).

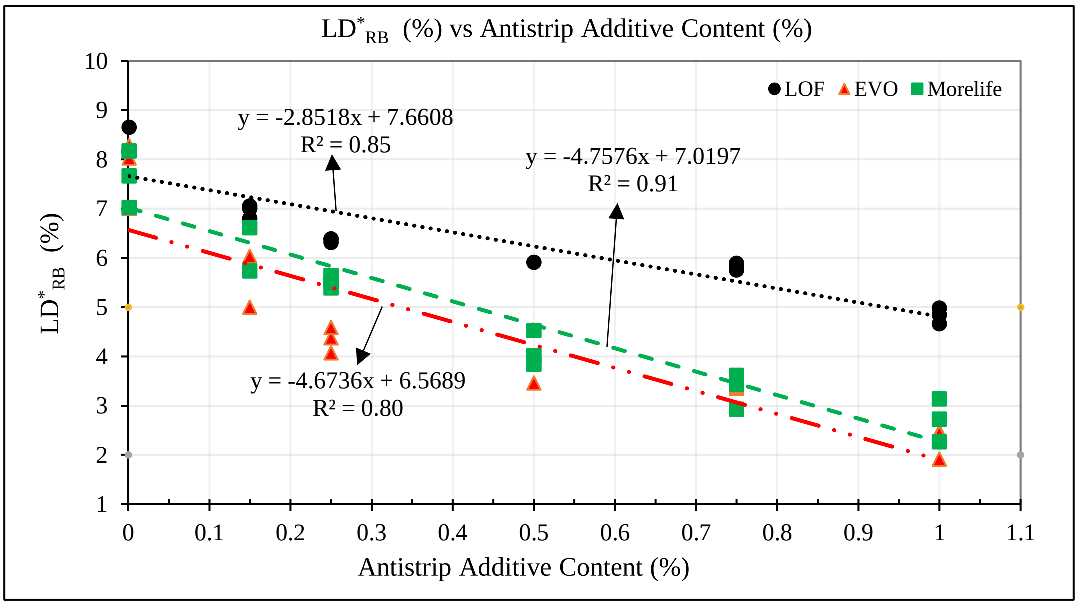

Figure 7-4 Combined plot of LD^{*}_{RB} (%) against Antistrip Additive Content (%) for three different additive type used with Limestone Aggregate

7.4.2 Optimum Antistrip Additive Content

After performing the boil test using colorimeter device on different asphalt mixtures prepared with varying antistrip additives, optimum antistrip additive content for all asphalt mixtures can be determined. To determine the optimum additive content (%) for an antistrip additive, the relative potential reduction in stripping or loss in adhesion was calculated. The percentage stripping determined for mixture with 0 % antistrip additive content was considered as 100 % loss in adhesion. Three different relative potential reduction (95%, 90% & 85%) in stripping or loss in adhesion (5 %, 10 % & 15 %) were calculated and corresponding to that the % antistrip additive content was determined using correlation obtained in figure 7-2. The % additive content value calculated is shown in table 7-5. Asphalt mixture prepared from Crabtree aggregates with LOF antistrip additive was taken as an example to calculate the optimum antistrip additive content as shown below.

Step 1: at 0 % antistrip additive, LD^*_{RB} (%) = 9.12
Step 2: LD^*_{RB} (%) value after 90 % reduction
LD^*_{RB} (%) = 0.9*9.12 = 8.2
Step 3: LD^*_{RB} (%) value left after 90 % reduction
LD^*_{RB} (%) = 9.2-8.2 = 1.0
Step 4: Determine the antistrip additive content corresponding to LD^*_{RB} (%) = 1.0 from the Correlation obtained in figure 7-2 for LOF antistrip additive.
$y = -1.26\ln(x) + 0.2114$
(Here y represents LD^*_{RB} (%) and x represents antistrip additive content)
At y = 0, value of x is 0.52

Therefore, the LOF antistrip additive content corresponding to 90 % relative reduction in stripping or 10 % loss in adhesion is 0.52 % by weight of asphalt binder.

Table 7-5 Optimum Antistrip additive content based on loss in adhesion

Loss in adhesion	**5%**	**10%**	**15%**
LOF additive content (%)	0.74	**0.52**	0.36
EVO additive content (%)	0.59	**0.42**	0.3
Morelife additive content (%)	0.96	**0.67**	0.47

The antistrip additive content at 10 % loss in adhesion of asphalt mixture is recommended to select an optimum antistrip additive content. The reason for selecting 10 % loss in adhesion was that from prior experiences with asphalt mixtures based on Tensile Strength Test TSR-value of 85% plus, and its corresponding percentage of antistrip percentages used.

7.4.3 Tensile Strength Ratio (TSR) Test Results

North Carolina Department of Transportation (NCDOT) currently uses TSR test with modified AASHTO T 283 conditioning procedure to test moisture sensitivity. Therefore, the TSR test was performed on asphalt mixture prepared from Crabtree aggregate source using this recommended optimum additive content. To calculate TSR, Indirect Tensile Strength (ITS) values are needed. For Indirect Tensile (IDT) Strength test 95.0 mm tall and 150.0 mm diameter specimens were prepared using a Superpave gyratory compactor. The modified AASHTO T 283 test procedure was followed to determine ITS value and using these values TSR values are calculated. The TSR limiting value or pass/fail criteria for NCDOT for moisture sensitivity of asphalt mixtures is 85 %. The antistrip additive content based on the methodology above, 0.5% for LOF 6500, 0.4% for Evotherm U3, and 0.7% for Morelife 3000 are recommended, respectively. The TSR test was performed on these mixtures with the recommended respective antistrip dosages for the Crabtree valley granite aggregate as this aggregate is the most moisture sensitive. TSR results are shown in table 7-6.

Table 7-6 TSR test results on asphalt mixtures prepared from Crabtree Aggregates

Asphalt Mixtures (Crabtree Aggregate)	TSR (%)	NCDOT 85 % Criteria
LOF @ 0.5 %	94.6	PASS
EVO @ 0.4 %	96.7	PASS
Morelife @ 0.7 %	99.5	PASS

The TSR test results show that all three asphalt mixtures prepared using optimum antistrip additive content determined using methodology used in this study pass the NCDOT 85% TSR criteria. It may be noted that current practices use a much higher percentage of antistrip additives. The optimum antistrip additive content determined are significantly less compared to the manufacture's recommendations. The manufacturer recommends 0.75% LOF content (% by weight of asphalt binder) while this method shows 0.5% LOF as the optimum content to be used and it passes the TSR criteria too. There is a decrease of 33 % additive content to be used which significantly affect the cost of construction. Similarly, for Evotherm U3, the manufacturer recommends 0.5 % while an optimum content determined in this study is 0.4% which also passes the TSR criteria. Using this method to determine the optimum antistrip additive content will result in significant economic benefits for the agency as it is one of the expensive components used in asphalt mixture preparation.

Additionally, the percent reduction is stripping or loss in adhesion can be very useful in quality control test for field asphalt mixtures. Once charts similar to one in figure 7-2 are prepared for a particular asphalt mixture, the optimum antistrip additive content can be recommended for that mixtures, and quality control test can be performed on field asphalt mixture to check whether the right amount of antistrip additive is used for field mixtures on daily basis.

7.5 Conclusion

The Boil test (ASTM D3625) along with colorimeter device was used in this study to determine optimum antistrip additive content to be used to reduce stripping in asphalt mixtures. A total of fifty four asphalt mixtures were prepared and the boil test was done. The TSR test was also done on the asphalt mixtures prepared from Crabtree aggregate and using optimum antistrip additive content determined from this method. The conclusion based on the results in this study are as follows:

1. A good correlation exists between percent stripping (LD^*_{RB}) and antistrip additive content for as asphalt mixtures.
2. For asphalt mixtures prepared from Crabtree and Garner aggregate source, a significant decrease in percentage stripping value for asphalt mixture with no dosage to 0.25% dosage of antistrip additive was observed.
3. For asphalt mixtures prepared from limestone aggregate source – antistrip additive LOF 6500 have lesser effect as compared to the other two additives used in this study.
4. Asphalt mixtures prepared from Crabtree aggregate source with optimum antistrip additives content determined in this study, passes the NCDOT 85 % TSR criteria.
5. There is decrease of 33 % LOF 6500 additive content to be used relative to what is recommended by manufacturers which significantly affect the cost of construction.

8 Summary, Conclusions, and Recommendations

Moisture damage in asphalt mixtures is mainly caused by two failure mechanisms – adhesive failure and cohesive failure. Currently, the TSR test with AASHTO T 283 conditioning is the most commonly used test to determine moisture sensitivity in asphalt mixtures. This research presents two different methodologies to evaluate moisture sensitivity in asphalt mixtures. In the first approach, two different test methods were used to determine moisture sensitivity of asphalt mixtures - Boil Test with a color measuring device, and the TSR test with two different types of conditioning – AASHTO T 283 and M.i.S.T conditioning. Percentage stripping from the Boil Test was used to measure the adhesive failure and volume change from M.i.S.T conditioning was used to measure the cohesive failure in asphalt mixtures. In second approach, Impact resonance test was done to evaluate moisture sensitivity. The effect of various support conditions, impact locations, and impact sources on resonant frequency, and ability of the IR test in assessing moisture damage were studied. Additionally, the effect of different antistrip additives on asphalt mixtures were studied. A more efficient and cost effective method to select optimum antistrip additive content for any asphalt mixtures was developed.

The conclusions based on the results in this study are as follows:

1. Percent stripping from the boil test and percentage volume change from the Moisture Induced Stress Tester (M.i.S.T) can be used to propose moisture sensitivity limits which account for both adhesive and cohesive damage in asphalt mixtures.
2. Absolute value of LD^*_{RB} (%) from boil test should be limited to 5.0% or less (for adhesive damage) to assure that the TSR value of 85 % is met from AASHTO T283 TSR test.
3. A maximum allowable volume change of 1.5% due to 3500 cycles of pore pressure in M.i.S.T (ASTM D7870) can be used to limit the cohesive damage.
4. The Colorimeter CR400 and ACT device were used along with the boil test and results shows that both color measuring device can be used to evaluate stripping in asphalt mixtures.
5. The Impact Resonance test can be used to detect moisture damage.
6. The Boil test along with colorimeter device can be used to determine optimum antistrip additive content for a given asphalt mixtures. This methodology can help in selecting a more compatible and cost effective antistrip additive for asphalt mixtures.
7. The Boil test along with colorimeter device can be used as a more effective and efficient quality control test on plant produced asphalt mixtures

Recommendations to NCDOT:

1. Percentage stripping from the boil test and percentage volume change from M.i.S.T conditioning should be used as an acceptance or rejection criteria for moisture sensitivity of asphalt mixtures.
2. Maximum values of 5.0% stripping (absolute value of LD^*_{RB} (%)) and 1.5% volume change can identify asphalt mixtures which are moisture sensitive due to lack of adhesive or cohesive strength.

3. The Boil test along with colorimeter device should be used to select the most cost effective and compatible antistrip additive and its optimum additive content for any asphalt mixtures.

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APPENDIX A – Material Characterization

Granite aggregates, limestone aggregates, and pond fines passing 75µm were used in this study. PG 64-22 binder was used for all asphalt mixtures. The granite aggregates were from two different quarries – Garner, NC and Crabtree valley, NC. Limestone aggregate was from Tulsa, OK. Details about the materials used in the study are presented below. Three different antistrip additives were used to prepare the mixtures– LOF 6500, Evotherm U3, and Morelife 3000.

A.1 Aggregates

The granite aggregates obtained from Crabtree quarry were highly moisture sensitive while the moisture sensitivity of granite aggregate obtained from Garner quarry were relatively less. The Limestone aggregates from Tulsa, OK used in this study had the intermediate moisture susceptibility relative to Crabtree and Garner aggregate. The mixtures used in this study were designed for 9.5B (12.5 mm NMSA) surface course mixture except the limestone aggregate mixtures was designed for intermediate course mixture.

The gradation of the Crabtree aggregates, Garner aggregates, and Limestone aggregates used in this study are shown in table A-1 to A-3.

Table A-1: Gradation for Granite aggregate - Crabtree Valley

Sieve Size		Percentage Passing
3/4"	19 mm	100
1/2"	12.5 mm	100
3/8"	9.5 mm	97
#4	4.75 mm	77
#8	2.36 mm	54
#16	1.18 mm	40
#30	600 µm	29
#50	300 µm	20
#100	150 µm	12
#200	75 µm	6.3

Table A-2: Gradation for Granite aggregate – Garner, Raleigh

Sieve Size		**Percentage Passing**
3/4"	19 mm	100
1/2"	12.5 mm	100
3/8"	9.5 mm	97
#4	4.75 mm	74
#8	2.36 mm	55
#16	1.18 mm	39
#30	600 µm	29
#50	300 µm	19
#100	150 µm	12
#200	75 µm	6.4

Table A-3: Gradation for Limestone aggregate – Tulsa, Ok

Sieve Size		**Percentage Passing**
3/4"	19 mm	100
1/2"	12.5 mm	95
3/8"	9.5 mm	87
#4	4.75 mm	65
#8	2.36 mm	45
#16	1.18 mm	29
#30	600 µm	19
#50	300 µm	11
#100	150 µm	7
#200	75 µm	5.7

The gradation for coarse fraction, fine fraction, and complete JMF gradation of Crabtree aggregates used in Impact resonance test are shown in table A-4 to A-6.

Table A-4: Gradation for Coarse Fraction, Crabtree Valley Aggregates

Sieve Size		**Percentage Passing**
3/8"	9.5 mm	94
#4	4.75 mm	50
#8	2.36 mm	0

Table A-5: Gradation for Fine Fraction of Crabtree Valley Aggregates

Sieve Size		Percentage Passing
#16	1.18 mm	71
#30	600 µm	52
#50	300 µm	36
#100	150 µm	20
#200	75 µm	8.5
PAN		0

Table A-6: Crabtree Valley JMF Aggregate Gradation

Sieve Size		Percentage Passing
3/8"	9.5 mm	97.2
#4	4.75 mm	78.3
#8	2.36 mm	56.2
#16	1.18 mm	39.9
#30	600 µm	29.2
#50	300 µm	20.1
#100	150 µm	11.3
#200	75 µm	4.8
PAN		0

A.2 Asphalt Binder

Superpave performance grade PG 64-22 asphalt binder was used in this study. NuStar Asphalt Refining Company located in River Road Terminal, Wilmington, NC, provided the binder. The manufacturer reported the specific gravity of the binders as 1.034.

A.2.1 Additives

Three different antistrip additives were used to prepare the mixtures– LOF 6500, Evotherm U3, and Morelife 3000. The additive content used in this study varying from 0% to 1 % by weight of asphalt binder for three antistrip additive.

APPENDIX B – Boil Test, TSR Test, and IR Test

B.1 Boil Test

Following are the steps in brief that were followed for the Boil Test:

1. 2500 gram of loose asphalt concrete mixture was prepared and four samples of 450 grams each were taken from it. Three loose asphalt mixture samples were boil as per the boil test procedure mentioned below. Keep the one sample unboiled and use as a reference.

2. Take a 1000 mL high heat resistant cylindrical beaker and pour 500 ml of distilled water in the beaker.

3. Heat the beaker with water in an oven over a flat material so that the beaker is not in direct contact with the oven shelves at 160ºC. Heat for 40 minutes at 160ºC.

4. Simultaneously heat the asphalt mixture to 85ºC.

5. Heat a hot plate to 220ºC (or higher) and after the temperature is reached, place the oven heated beaker on the hot plate. This procedure was followed from experience, as the beakers would crack if directly placed in the hot oven without first heating it in an oven. Wait until the water is boiling.

6. Place the asphalt mixture heated to 85ºC in the beaker filled with boiling water.

7. Start the timer after the water starts boiling.

8. The standard boiling time is 10 minutes ± 15 seconds but in this study the asphalt loose mixture was boiled for 30 minutes ± 15 seconds to reduce user variability.

9. After the set time is over, carefully remove the beaker, place it on a wooden surface or a cloth, and allow it to cool down.

10. Once room temperature is reached drain the water onto a 75-µm (#200 sieve). Use a spoon to scrape off the remaining mixture from the beaker and pour it onto the sieve. Dry the material retained on the sieve.

11. Spread the dried mixture on a surface such that the surface below the mixture is not visible. Before taking the colorimeter readings make sure that the loose mixture is dried enough – no or very little traces of moisture on the surface of the loose mixture.

12. The readings should only be taken on the dried loose mixture. This loose mixture should not be compacted.

13. Use the colorimeter to take the L^* (or the C^* for colored aggregates and/or asphalt binder) readings of the unboiled loose asphalt concrete mixture at four different locations on the loose mixture. Select the locations such that the complete surface area is covered.

14. Repeat Step 13 for dried – boiled loose asphalt concrete mixture.

15. Take the L^* (or C^*) readings for dry virgin aggregates used for the mixture when available using the colorimeter.

For time delay study on boil test, the loose mix specimens was split into four sets of specimens. Boil test was done on the first set of specimens immediately after curing. The second set was tested after 4 hours, the third set after 24 hours and the final set after 1 week. Table B-1, B-2, and B-3 shows the L* readings for asphalt mixture prepared from Limestone aggregates, Crabtree aggregates, and Garner aggregates respectively.

Table B-1 L* readings from Boil Test on asphalt mixtures prepared from Limestone aggregates

Condition	**Mixtures**	**Time Delay**	**L* reading**
Unboiled			18.3
Boiled	Limestone	0 hr	20.85
Boiled	Limestone_A	0 hr	19.84
Boiled	Limestone	4 hr	20.62
Boiled	Limestone_A	4 hr	19.44
Boiled	Limestone	24 hr	20.76
Boiled	Limestone_A	24 hr	19.29

Table B-2 L* readings from Boil Test on asphalt mixtures prepared from Crabtree aggregates

Condition	Mixtures	Time Delay	L* reading
Unboiled	Crabtree		17.61
Unboiled	Crabtree_A		17.34
Boiled	Crabtree	0 hr	19.61
Boiled	Crabtree_A	0 hr	17.93
Boiled	Crabtree	4 hr	19.02
Boiled	Crabtree_A	4 hr	18.04
Boiled	Crabtree	24 hr	19.58
Boiled	Crabtree_A	24 hr	17.80
Boiled	Crabtree	162 hr	19.16
Boiled	Crabtree_A	162 hr	17.89

Table B-3 L* readings from Boil Test on asphalt mixtures prepared from Garner aggregates

Condition	Mixtures	Time Delay	L* reading (Colorimeter)
Unboiled	Garner		17.08
Unboiled	Garner_A		17.2
Boiled	Garner	0 hr	19.70
Boiled	Garner_A	0 hr	17.65
Boiled	Garner	4 hr	19.40
Boiled	Garner_A	4 hr	17.42
Boiled	Garner	24 hr	19.56
Boiled	Garner_A	24 hr	18.61
Boiled	Garner	162 hr	19.17
Boiled	Garner_A	162 hr	17.71

B.2 Tensile Strength Ratio (TSR) Test

B.2.1 Specimen Preparation

Three sets of specimens were required for each mixture for TSR test. Two different conditioning procedure were used- AASHTO T283 and M.i.S.T. Four specimens were prepared for each set and hence 12 specimen in total were prepared for each mixture. One set was tested dry, the second set was tested after AASHTO T283 conditioning, and the third set was test after M.i.S.T conditioning. The specimens were prepared as per the standard specifications and were compacted to a target air void content of 7 ± 0.5%. The standard specimen dimensions were 150 mm diameter and 95 ± 5 mm height. The specimens were prepared using the same aggregate gradation listed above and the optimum asphalt content using the Superpave mix design.

As per standard specifications, the loose mixtures were prepared at mixing temperatures of 163°C for HMA. After mixing, the mixtures were heated for 2 hours to compaction temperatures of 149 °C for HMA and then compacted to a height of 95 ± 5 mm using the Superpave gyratory compactor.

B.2.2 Test Procedure

Total of 12 specimens were prepared. The 12 specimens for each mixture were divided randomly into three sets of 4 specimens each. One set was kept dry and tested at room temperature i.e. 25 °C (77 °F), while the second set was moisture conditioned according to AASHTO T283 procedure and the third set was moisture conditioned according to M.i.S.T procedure before testing. NCDOT follows AASHTO T283 specifications, therefore the set of specimens that were to be moisture saturated were first vacuum-saturated with water to a saturation level of 70 – 80% and then conditioned in a water bath at 60°C for 24 hours. After the 24 hours of conditioning, they were cooled for two hours in a water bath at 25 °C (77 °F). For M.i.S.T conditioning, no vacuum saturation is required. First the specimen is conditioned with hot water at 60°C for 20 hours followed by specimen subjected to 3,500 cycles of 270 kPa (40 psi) hydraulic pumping at a rate of 3.5 seconds per pressure cycle at 60°C.

For the testing, the specimens were set up in a loading jig and load was applied diametrically using a Marshall Loader. They were loaded at a rate of 50.8 mm (2 in.) per minute and the peak load vs. deflection data was recorded in a graph. The peak load for each specimen was noted and the indirect tensile strength of the specimen was calculated using the peak load. The median value of the indirect tensile strengths of each set of specimens (conditioned and unconditioned) was taken as the representative indirect tensile strength value of that set. The tensile strength ratio was then calculated for each mixture by taking the ratio of the average indirect tensile strength (ITS) value of conditioned specimens to unconditioned specimens.

$$TSR = \frac{ITS_{conditioned}}{ITS_{unconditioned}}$$

NCDOT requires all its mixtures to pass a minimum TSR value of 85%.

B.2.3 CALCULATIONS

The peak load for a specimen was calculated using the correction factors for the Marshall loader and the peak load reading from the graph. This peak load was used to calculate the ITS value using the following equation.

$$ITS = \frac{2P}{\pi d h}$$

where,

ITS = Indirect Tensile Strength (kPa or psi)

P = Peak Load (kg or lbs)

d = diameter of the specimen (mm or in)

h = height of the specimen (mm or in)

The ITS values for all the specimens were calculated and tabulated.

B.3 Impact Resonance (IR) Test

In this study, Impact Resonance test was done on thin disk specimens. The Impact Resonance (IR) test is a non-destructive test which is used to determine the material properties. Gyratory specimen 150 mm diameter and 180 ± 5 mm height were prepared. Approximately 50 mm each from top and bottom of the specimen was sliced and removed. Three disk specimen of 1 inch (25.5 cm) thick were sliced from the compacted specimen to be used for IR test. The sensor was attached at the center of the disk specimen with superglue. Specimen was placed on different support conditions as shown in figure B-2. Excitation was induced by striking at the middle of the other side of specimen with two different impact source – steel ball and steel hammer. The acceleration data was recorded by sensor and extracted using a data acquisition system. Using Fast Fourier Transformation in MATLAB, the acceleration data in time domain was converted into frequency domain. The location of the peak in frequency domain will give the resonant frequency value. To assess moisture damage, thin disk specimen was moisture conditioned and IR test was done. Relative reduction in dynamic modulus was calculated to evaluate moisture damage using equation 1.

Table B-4 shows the bulk specific study and air voids data from the repeatability study done for Impact Resonance test.

Table B-4. Bulk specific and air void data

Specimen	Bulk Specific Gravity (g/cm3)	Calculated Air Voids	Target Air voids
S11	2.247	7.5	9
S12	2.223	8.5	9
S13	2.223	8.5	9
S21	2.237	8.0	9
S22	2.219	8.7	9
S23	2.227	8.3	9
S31	2.244	7.7	9
S32	2.230	8.2	9
S33	2.217	8.8	9
S11(CORED)	2.261	7.0	9
S12(CORED)	2.273	6.5	9
S13(CORED)	2.243	7.7	9
S21(CORED)	2.274	6.4	9
S22(CORED)	2.275	6.4	9
S23(CORED)	2.260	7.0	9
S31(CORED)	2.294	5.6	9
S32(CORED)	2.279	6.2	9
S33(CORED)	2.273	6.5	9

(a) Think Disk Sample Supported on 1 inch thick foam

(b) Thin Disk Sample Supported on 2 inch thick foam

(c) Thin Disk Sample Suppored on wooden plank

(d) Thin Disk Sample Supported on 1 inch thick foam palced on wooden plank

(e) Thin Disk Sample Supported on 2 inch thick foam placed on wooden plank

Figure B-1. IR Test Setup with different support conditions

Figure B-2 shows the frequency spectrum of thin disk specimen prepared from coarse fraction gradation of Crabtree valley aggregate different support condition.

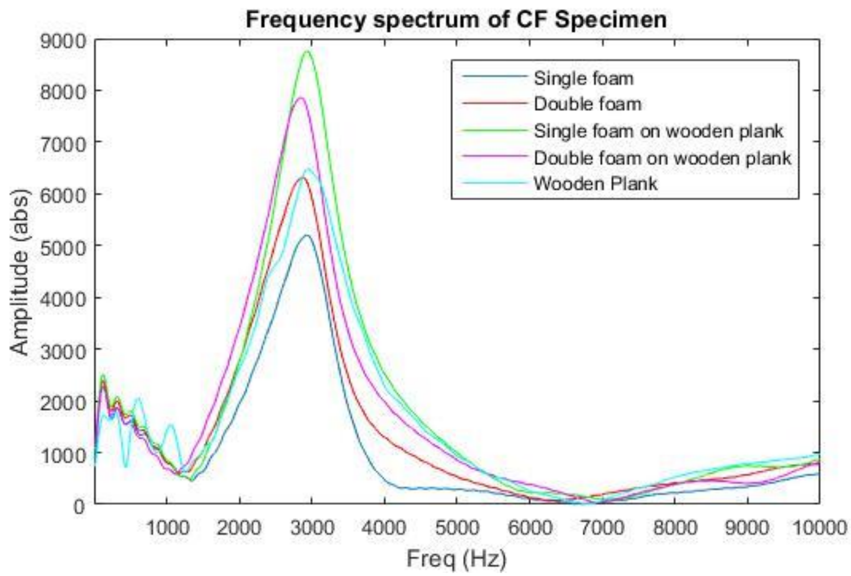

Figure B-2. Frequency spectrum of coarse fraction specimen for different support conditions

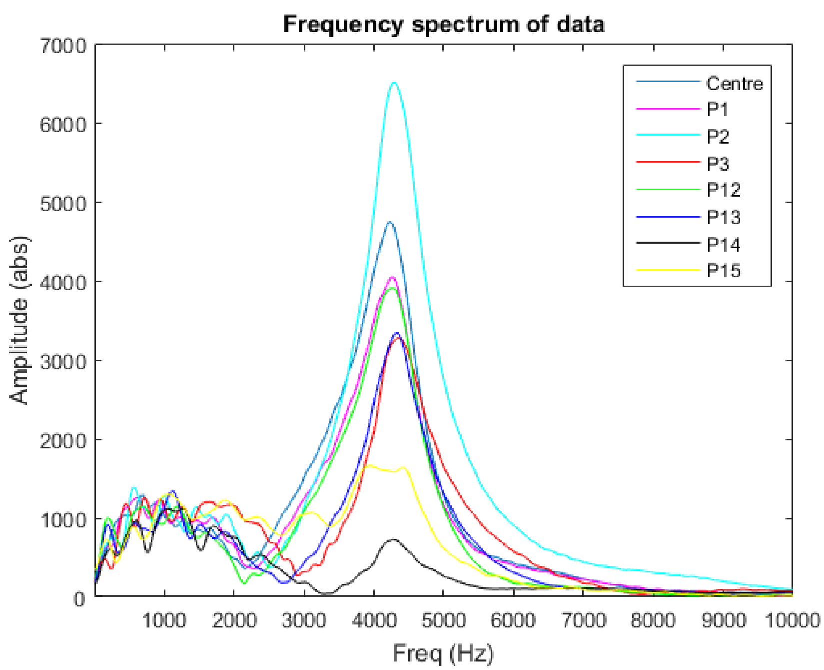

Figure B-3. Frequency spectrum for different impact location when specimen supported on four nodes and impact induced by hammer

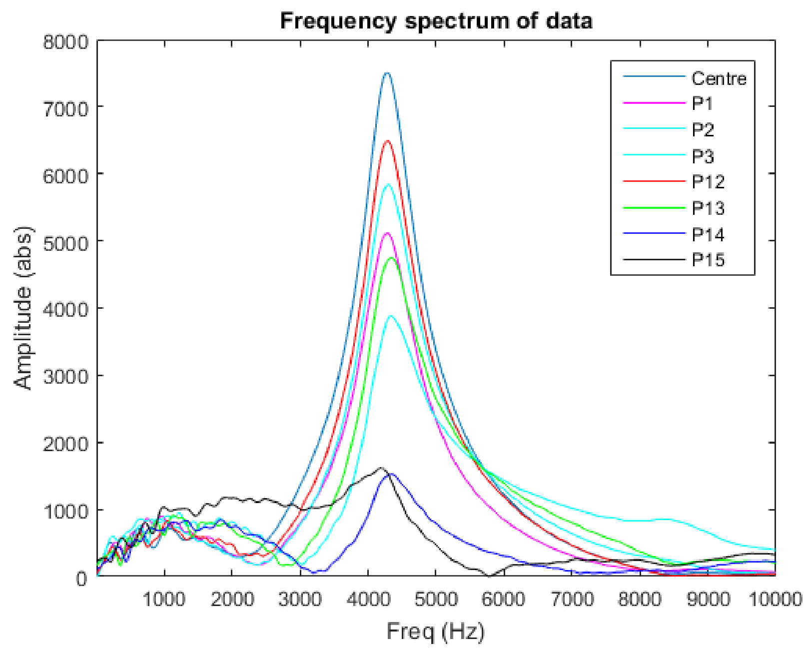

Figure B-4. Frequency spectrum for different impact location when specimen supported on four nodes and impact induced by steel ball

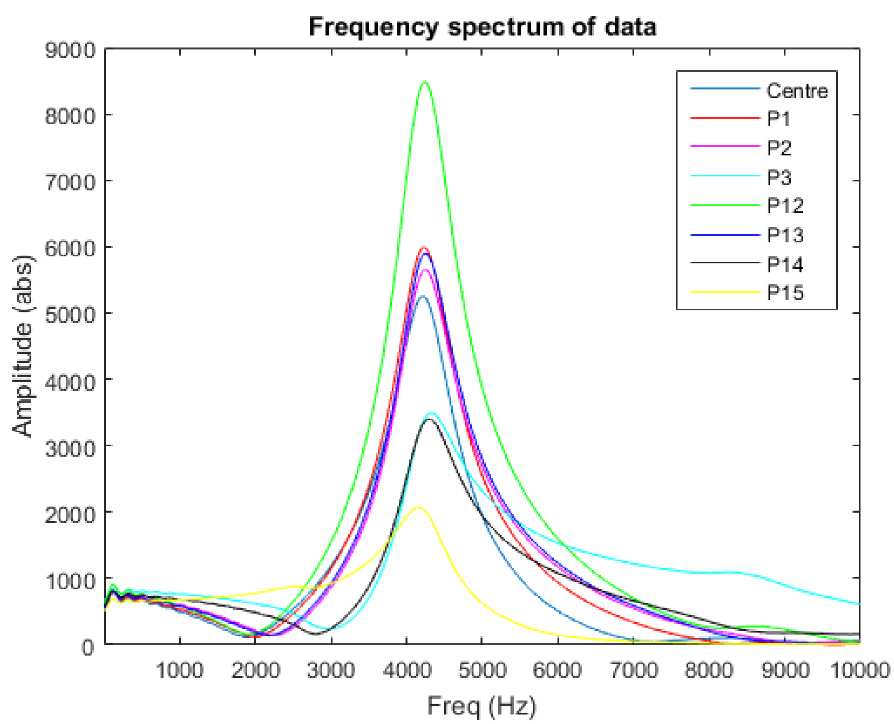

Figure B-5. Frequency spectrum for different impact location when specimen supported on 2 inch foam and impact induced by steel ball