RESEARCH & DEVELOPMENT

Alternate Methods for Evaluation of Moisture Sensitivity of Asphalt Mixtures

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Abstract

The objectives of the proposed research were: (1) to evaluate whether the residual trapped moisture in WMA mixes affects the TSR test results, and investigate if the curing of compacted specimens is required for WMA mixes that is different from the HMA mixes; (2) to evaluate the stiffness, fatigue performance, and rutting potential of the foaming-based WMA mixes in a moisture-conditioned state so that the actual degradation of these mixes can be compared directly to the results of TSR and indirect tensile (IDT) strength tests; and (3) to explore modifications to the current TSR test protocol or to develop alternative test methods such as impact resonance and colorimeter analysis that can be used in lieu of TSR tests for foaming-based WMA mixes.

These objectives were accomplished by performing IDT tests to obtain the TSR in the traditional manner, dynamic modulus (AASHTO TP79) and impact resonance (IR) tests for stiffness characterization. The feasibility of impact resonance technology to quantify the effect of moisture damage was explored. These tests were performed on a WMA and three hot mix asphalt (HMA) mixtures using the modified AASHTO T283 procedure that is currently used by NCDOT. The percentage of stripping determined from the colorimeter analysis of the fractured surfaces of the specimens was used as a reference test method to indicate the level of stripping in WMA and HMA mixes.

Key Words Asphalt Mixture, Moisture Sensitivity, TSR Test, Colorimeter, Spectrophotometer, Impact Resonance, Indirect Tensile Strength, Stiffness	Distribution Statement

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EXECUTIVE SUMMARY

The North Carolina Department of Transportation (NCDOT) requires that asphalt mixtures, used in pavement construction, meet the NCDOT moisture sensitivity specifications prior to approval of the job mix formula (JMF). Foaming based warm mix asphalt (WMA) mixes that use water injection WMA technologies such as Astec's Double Barrel® foamed technology, and use Zeolite additives such as Advera, tend to fail the current required tensile strength ratio (TSR) tests. However, pavements constructed with these same WMA mixes in the United States and in North Carolina have performed well to date. Either the current TSR test protocol needed to be modified or a new test(s) is needed for WMA mixes.

The objectives of the proposed research were: (1) to evaluate whether the residual trapped moisture in WMA mixes affects the TSR test results, and investigate if the curing of compacted specimens is required for WMA mixes that is different from the HMA mixes; (2) to evaluate the stiffness, fatigue performance, and rutting potential of the foaming-based WMA mixes in a moisture-conditioned state so that the actual degradation of these mixes can be compared directly to the results of TSR and indirect tensile (IDT) strength tests; and (3) to explore modifications to the current TSR test protocol or to develop alternative test methods such as impact resonance and colorimeter analysis that can be used in lieu of TSR tests for foaming-based WMA mixes.

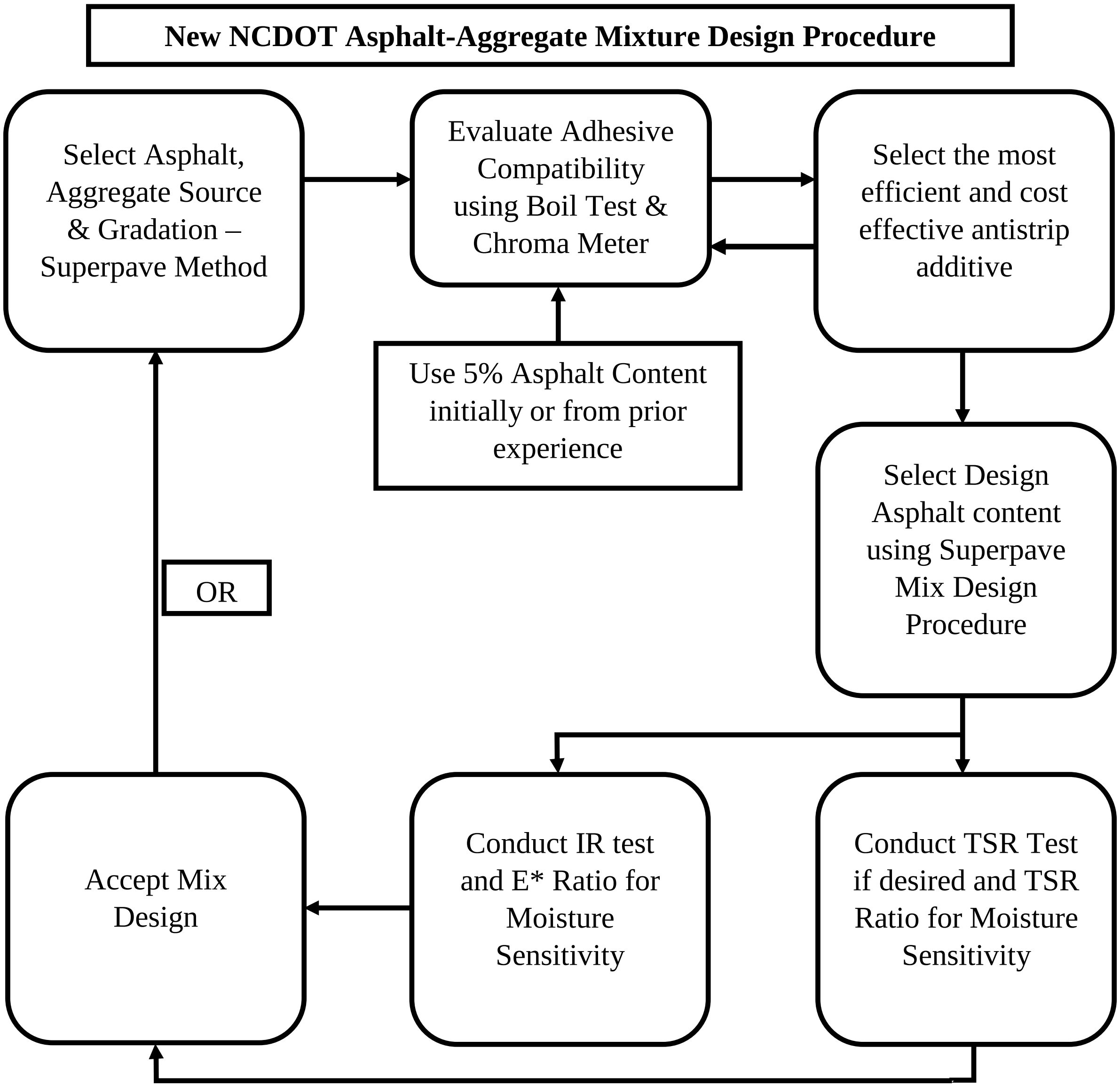
These objectives were accomplished by performing IDT tests to obtain the TSR in the traditional manner, dynamic modulus (AASHTO TP79) and impact resonance (IR) tests for stiffness characterization. The feasibility of impact resonance technology to quantify the effect of moisture damage was explored. These tests were performed on a WMA and three hot mix asphalt (HMA) mixtures using the modified AASHTO T283 procedure that is currently used by NCDOT. The percentage of stripping determined from the colorimeter analysis of the fractured surfaces of the specimens was used as a reference test method to indicate the level of stripping in WMA and HMA mixes.

At the advent of this research project, the title of the project was "Effectiveness of TSR Test for Evaluating Moisture Sensitivity of WMA Mixes." However, it was quickly realized that just looking at the curing period for WMA mixes versus the HMA mixes was not a viable way to explore the moisture sensitivity of the mixtures. The fact that the current TSR test protocol needs to be different for different mixtures is a major weakness of the AASHTO T283 test method among others.

In the past, asphalt technologists used to first test the compatibility of asphalt and aggregate source using tests such as Texas Boil Test and ASTM Test Method D3625. However, these tests fell out of favor since they were subjective in nature. Although, not part of the initial research objectives, a methodology evolved using colorimeter (Chroma meter) that now allows the boil test results to be quantified. This is the single most important breakthrough in evaluating the adhesive compatibility of asphalt and aggregate for any mixture design process.

This report presents a new approach to asphalt-aggregate mixture design process. Currently, the moisture sensitivity is evaluated as the final step in the mixture design process. This report suggests

a methodology that first evaluates the moisture sensitivity or the adhesive compatibility of asphalt-aggregate in the presence of moisture before a mixture design process is even considered. The advantages are savings in time, material resources, and manpower. The “New NCDOT Asphalt-Aggregate Mixture Design” process is shown in the flow chart below.


New NCDOT Asphalt-Aggregate Mixture Design Procedure

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1. Introduction

1.1 Background and Need for Study

Warm Mix Asphalt (WMA) technologies are being used more commonly in pavement construction, as they are more cost effective and/or produce lower emissions. Two methodologies used in the production of foaming based WMA, i.e., Double Barrel® foamed technology and Zeolite additives such as Advera, add moisture to the mix to achieve lower mixing and compaction temperatures compared to that of Hot Mix Asphalt (HMA) mixes. Using WMA results in economic and environmental benefits due to lower energy demand during production and reduced emissions at the plant and with the paving during construction. However, concerns remain regarding the moisture susceptibility for these mixes and its effect on pavement performance.

Moisture susceptibility is an important parameter during the asphalt concrete mix design. That is because moisture susceptible asphalt mixtures lead to stripping of asphalt from aggregate and is a major cause of asphalt pavement distresses leading to premature failure of the pavement. Therefore, evaluating the resistance to moisture susceptibility is an important and integral step in the asphalt mixture design process.

NCDOT requires that the moisture sensitivity criteria be met for the job mix formula to be approved. Currently, the NCDOT uses only the tensile strength ratio (TSR) test to evaluate the moisture sensitivity of the asphalt concrete mixtures. This test is used to evaluate moisture susceptibility of the conventional HMA mixtures as well as asphalt mixtures manufactured using new technologies such as WMA mixtures. There have been instances where WMA mixtures produced using foaming-based technologies have failed the moisture sensitivity specifications; even when antistrip additives were used. However, field performance of these mixtures has been observed to be comparable to the performance of the conventional HMA mixtures. Therefore, the validity of using the current TSR test to evaluate moisture susceptibility of WMA mixtures is in question. There is a need to either modify the current TSR test protocol or develop an entirely new test(s) that is applicable to all asphalt mixtures for moisture sensitivity evaluation.

There are many reasons for the discrepancy between the TSR test results and the field performance. Some of these factors are listed below:

1. The moisture conditioning procedure in the AASHTO T283 specifications, which the TSR test follows, does not adequately simulate the conditions to which foaming-based WMA mixes are subjected in the field.
2. The indirect tensile strength (IDT) test used to determine the TSR is not a reliable test method for determining the moisture susceptibility of foaming-based WMA mixes.
3. The foaming-based WMA mixture's state at the time that TSR measurements are taken (i.e., the mixture's state when it is obtained during the paving process) is different from the state the WMA mixture is in for its longer-term performance when moisture is present.

This study investigated possible modifications to the current TSR test protocol and proposed new tests for not only foaming-based WMA mixtures but also applicable to all asphalt-aggregate mixtures.

1.2 Organization of Report

This report presents a brief literature review in section 2; followed by research methodology in section 3. The traditional TSR test results are presented in section 4. Sections 5 and 6 present the quantitative interpretation of Boil Test results and use of colorimeter for quantitative interpretation of the TSR test results, respectively. The impact resonance (IR) test and its results are presented in section 7. Section 8 presents the stiffness ratio from the AMPT test, and the pavement performance evaluated using the dynamic stiffness obtained in section 8 is presented in section 9. Summary, conclusions and recommendations are presented in section 10. Material characterization and the mixture design data are presented in the appendices.

2. Literature Review

In the field of asphalt mixture and pavement design, moisture susceptibility of asphalt-aggregate mixtures and the asphalt-aggregate compatibility are very important issues. That is because moisture susceptible asphalt mixtures lead to stripping of asphalt from aggregate, which is a major cause of asphalt pavement distress, and is one of the leading cause of premature failure in the pavement. No asphalt mixture design process is complete without the final step to ascertain that the mixture is adequately resistant to potential moisture damage. Research for finding a solution to evaluate the moisture damage in asphalt concrete or stripping of asphalt has been conducted for many years. Yet, the search to find a simple, practical and reliable solution is still going on.

2.1 Moisture Susceptibility

Solaimanian, et al. [1] and Mehrara et al. [2] have summarized a considerable list of research done on this topic to date. Mehrara et al. [2] have a comprehensive summary of all the test methods used to determine stripping in asphalt concrete. They divided the test methods into five different categories – tests on loose mixtures, destructive mechanical tests on asphalt concrete, nondestructive mechanical tests on asphalt concrete, energy methods and nondestructive non-mechanical tests. According to them, most tests on loose mixtures except for the boil test do not consider the stripping potential of the whole gradation in a mixture. The tests on loose mixtures are simple, fast and low cost approaches to the problem. Solaimanian et al. have categorized the moisture sensitivity test into two categories – 1) qualitative visual subjective tests, and 2) quantitative strength tests, that are listed in Table 2-1. Various moisture sensitivity tests on loose mixture samples are presented in Table 2-2.

Table 2-1 Moisture Sensitivity Test Categories (Solaimanian, et al. (2003))

The visual subjective test	The quantitative strength tests
1. Boiling water test	1. Immersion–compression test
2. Freeze–thaw pedestal test	2. Indirect tensile test
3. Quick bottle test	3. Marshall immersion test
4. Rolling bottle method	4. Double punch method
	5. Resilient modulus tests

From the tests listed in the tables, tensile strength ratio (TSR) test is the most commonly used test to evaluate moisture susceptibility. TSR test uses the ratio of the indirect tensile strength of dry specimens and moisture conditioned specimens to evaluate moisture susceptibility. However, the shortcoming of the TSR test is evident when determining the moisture susceptibility of mixtures produced with Warm Mix Asphalt Technology (WMA), specifically the foaming based technology. Studies done at NC State University (NCSU) and nationally have shown that foaming-based WMA asphalt mixes often fail the TSR specifications requirements yet do not show any significant deterioration in performance as compared to the HMA mixes.

Table 2-2 Moisture Sensitivity Tests on Loose Samples (Solaimanian, et al. (2003))

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

* No longer available as ASTM standard.

Due to this contradiction, there is a need to investigate the issue of evaluating moisture sensitivity of foaming-based WMA mixes. The effectiveness of any moisture sensitivity test(s) will depend on three distinct aspects: 1) sample preparation method, 2) moisture conditioning procedure, and 3) test methods.

Lee et al. [3] have reported that adhesive failure between the aggregate and asphalt binder mainly causes moisture damage. They also reported that tensile stress is the most suitable state of stress to test the adhesive properties at the interface of two materials. They found that the direct tension test is the simplest form of a test method that measures the tensile properties of a material. The NCHRP 9-26A [4] project results suggest that the use of cyclic direct tension tests that employ cored and cut specimens should be investigated for moisture susceptibility evaluation, because such tests may be able to overcome the high variability of air void distribution in the specimens and high variability in the strength test results for compressive mode testing.

2.1.1 Colorimeter

Tayebali et al. [5] and Lee et al. [3] have successfully shown the degradation of dynamic shear and axial modulus, respectively, due to moisture damage and its effect on pavement design. Lee et al. have also shown the effect of moisture damage on fatigue life of asphalt mixes in direct tension test. In addition, they have successfully employed digital imaging technique to quantify visual effects of moisture damage on fractured surfaces from fatigue testing. Lee et al. reported that visual observation using digital imaging using mesh selection method is accurate, but it is also a relatively time-consuming approach to determine the stripping percentage. Another promising method for the visual determination of stripping percentage may be the use of Spectrophotometer (Colorimeter, Chroma Meter) that is commercially available and widely used in the consumer industry. It should be possible to measure the difference in color spectrum between the nonstripped and stripped surfaces with relative ease. An example of such a typical handheld device is shown in Figure 2-1.

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

Wistuba, et al. [6], Liu, et al. [7], Apeagyei, et al. [8] and Zhang, et al. [9] have used quantitative strength test approach by calculating bond energy, surface energy or other physiochemical properties on loose mixtures to quantify stripping in asphalt concrete. Other studies done by Kennedy et al. [10]; Pavol, et al. [11]; Amelian, et al. [12], and Bayazit et al. [13] have tried to visually evaluate stripping in loose asphalt mixtures, either through visual observation or other computerized image processing techniques.

This study focuses on using the colorimeter to evaluate stripping in asphalt concrete for the boil test and TSR tests. This study also introduces a new way to quantify the results from visually subjective test methods like the asphalt boil test. Additionally, the study correlates the moisture sensitivity results from the impact resonance test to the TSR test and the asphalt boil test. Further description of the method is elaborated in section 5.

2.2 Impact Resonance

While in TSR test, the indirect tensile strength is used, the damage in asphalt concrete mixture may also be quantified by measuring the dynamic elastic modulus. It is well established that the dynamic elastic modulus of materials can be estimated using wave propagation or vibration based methods. In many instances, however, calculating the absolute values of dynamic elastic modulus using these methods can be difficult due to the geometry and boundary conditions of the specimen tested. Therefore, generally, wave propagation and vibration based methods are used to estimate the ratio of dynamic elastic moduli of materials, before and after damage, by calculating the ratio of wave travel time in wave propagation or resonance frequency in vibration based methods. For example, the square ratio of the resonance frequency of Portland cement concrete prisms, before and after exposure to freeze-thaw loading, is used as a measure of reduction in dynamic elastic modulus (ASTMC666 2008). Methods for measuring the vibration response and resonance frequency of materials are discussed in (ASTM E 1876-09 2009). Similarly, square of the ratio of the wave travel time is used as a measure of reduction in elastic modulus in concrete materials (Li et al. [14], Ghasemzadeh et al. [15], and Rashetnia et al. [16]).

In certain circumstances, i.e., for a specific geometry with specific boundary conditions, under certain assumptions, the actual (absolute) value of the elastic modulus can be estimated from the vibration response of the material. For example, Kweon and Kim [17, 18] used cylindrical geometry to estimate the dynamic elastic modulus of asphalt concrete. Kim and Kim [19] used thick disk geometries to estimate the dynamic elastic modulus of asphalt concrete. These works are based on the analytical solution by Huchinson [20] and the prior work of Leming and co [21-28] in estimating the dynamic elastic modulus of Portland cement concrete. Ryden [29, 30] used thick disk geometry to determine the mastercurve for asphalt concrete. Similarly, LaCroix et al. [31] used cylindrical geometry for determining the mastercurve. Gudmarsson et al. [32, 33] used acoustic spectroscopy technique on asphalt concrete beams with a rectangular cross-section to estimate their dynamic elastic modulus.

Like vibration-based tests, under certain assumptions, the dynamic elastic modulus can be estimated from acoustic and ultrasonic wave propagation measurements. For example, Norambuena-Contreras et al. [34] and Mounier et al. [35] used ultrasonic measurements to estimate elastic modulus of asphalt concrete and Van Velsor et al. [36] used ultrasonic testing for measuring complex modulus of asphalt concrete.

The abovementioned works clearly show that both vibration based and wave propagation based methods can be used to determine the dynamic elastic modulus of asphalt concrete. One of the research question of this project was whether the change in dynamic elastic modulus, as opposed to the change in the indirect tensile strength, can be used to quantify the susceptibility of asphalt mixtures to moisture damage. To answer this question, we utilized the so-called axisymmetric flexural vibration of a thick free circular plate [20] to measure the elastic modulus of asphalt concrete disks of different composition subjected to various levels of moisture conditioning. We also investigated whether this method can effectively quantify the effect of aging and temperature on the dynamic elastic modulus of asphalt materials. We note here that this method, axisymmetric flexural vibration of a thick free circular plate, has been previously used for estimating dynamic elastic modulus of Portland cement concrete [21], and damage in Portland cement concrete due to high-temperature exposure [22] and freeze-thaw loading [16]. This method was also used by Kim and Kim [19] and Ryden [29, 30] to estimate the dynamic elastic modulus of asphalt concrete. The method in question, however, has not been used to quantify the effect of moisture damage in asphalt concrete. In this study, we investigated whether linear impact resonance shift can be used to determine the moisture sensitivity of the WMA mixtures. To this end, the axisymmetric flexural impact resonance technique is applied to the asphalt concrete disks to quantify moisture damage [16].

In short, in axisymmetric flexural vibration (AFV) test the resonance frequency of a thick freely vibrating circular disk is measured using an accelerometer under the influence of a slight impact. The resonance frequency is used then, to compute elastic modulus. The presence of moisture damage will, in principle, result in the shift of the frequency of vibration, which in turn translates, into a reduction in elastic modulus.

The axisymmetric flexural impact resonance technique quantifies the damage level based on the change in the resonance frequency of materials and frequency spectrum bandwidth change. This vibration-based method provides the vibration response of the specimen and carries the global response to it [17]. The proposed technique lets us deal with disk geometries that are desirable geometry and applicable to test the cores from constructed facilities. Linear elastic wave propagation based methods measure the local response of the material that does not lead to evaluate distributed changes in the material. However, the axisymmetric flexural impact resonance technique as a vibration-based method leads us to measure the global response changes due to moisture distributed damage.

In this study, we show that the axisymmetric flexural vibration of asphalt concrete disks can be used as a new test to determine the moisture sensitivity of the WMA mixtures. This method requires impact resonance measurement experiment and computation of the frequency resonance parameter to solve axisymmetric flexural vibration of asphalt concrete disks. The sensitivity of the elastic modulus estimation to the temperature and age of specimens are discussed. Comparison of the proposed method to the conventional TSR test is elaborated in section 7.

3. Research Approach and Methodology

3.1 Research Objective

The primary objectives of the proposed research are:

(1) To evaluate the stiffness, pavement fatigue and rutting performance of the foaming-based WMA and the HMA mixes in a moisture-conditioned state so that the actual degradation of these mixes can be compared directly to the results from TSR and indirect tensile (IDT) strength tests;
(2) To evaluate the viability of the use of impact resonance (IR) technology along with colorimeter analysis in assessing moisture damage;
(3) To explore modifications to the current TSR test protocol or to develop alternative test methods that can be used in lieu of TSR tests.

3.2 Research Methodology

The objectives of the proposed study were accomplished through the following specific tasks:

Task 1. Literature Review: An exhaustive literature review on various test methods to evaluate moisture sensitivity was done. The test methods were divided into different categories based on the literature. The pros and cons of each category were examined and a simple test method to evaluate moisture sensitivity of asphalt concrete was selected. A literature review was done on various approaches to visual quantification of stripping in asphalt concrete mixtures. Additionally, a literature review on how various nondestructive tests were used to determine moisture sensitivity of asphalt concrete mixtures.

Task 2. Materials: The aggregates used in this study were from two different sources. The aggregates (granite) from one source were relatively less moisture sensitive, and the aggregates (Crabtree Valley) from the other source were highly moisture sensitive. These sources were chosen based on previous experiences of working with asphalt concrete mixtures made using the aggregates from these sources. A foaming device manufactured by Pavement Technology, Inc., The Foamer, was used to manufacture WMA mixtures manufactured using foaming technology. Additionally, two different antistrip additives were used in this study – one is a proprietary antistrip additive while the second was LOF 6500 that is commonly used in the mixtures in North Carolina.

Task 3. Visual Quantification of stripping: From the literature review, it was found that many researchers used the asphalt boil test or one of its variations to come up with test methods to visually quantify stripping in asphalt concrete mixtures. In this study, a different approach was used on the asphalt boil test to quantify stripping by using a colorimeter.

Task 4. Impact Resonance and colorimeter Analysis: This task involved the determination of the level of stripping (moisture induced damage intensity) in visually quantifiable term based on the use of colorimeter, as well as mechanically quantifiable value based on impact resonance testing. The impact resonance testing was used to assess moisture damage on samples conditioned based on the modified AASHTO T283 procedure. The colorimeter was used on the exposed surfaces of the cracked TSR test samples as well as on loose mixture in the asphalt boil test to evaluate moisture damage.

Task 5. Investigation of Moisture Damage Using Performance Test: In this task, the dynamic modulus test using the Asphalt Mixture Performance Tester (AMPT) device was conducted to evaluate moisture damage of HMA as well as WMA mixtures. The results were compared to the moisture damage results from the TSR test. The dynamic modulus data from the AMPT test were used to evaluate the impact of moisture damage on typical NC pavement’s performance and its impact on pavement thickness design.

Task 6. Development of Recommended Moisture Susceptibility Test Protocol(s): This task presents a recommendation for a new or refined moisture susceptibility test protocol based on the test results.

4. Tensile Strength Ratio Test

This section details the mixtures for which the Tensile Strength Ratio (TSR) was measured. The test was performed per the guidelines specified by NCDOT, which is a modification of the AASHTO T 283, “Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage.” TSR test is the standard test used by various Transportation agencies including NCDOT to evaluate moisture sensitivity. Therefore, it was used as a basis to compare with the results from other moisture susceptibility tests – boil test and impact resonance test.

4.1 Mixtures

The TSR test was done on five different mixtures. Three mixtures were prepared using the materials from the Garner Quarry and two mixtures were prepared using materials from Crabtree Quarry. The five mixtures are detailed in Table 4-1. Mixtures HMA 1, HMA 2 and HMA 3 were prepared using the materials from Garner Quarry. Crabtree 1 and Crabtree 2 were prepared using the materials from Crabtree Quarry.

Table 4-1 Summary of mixtures used for TSR Test

Mixture	Additive Type	Additive Dosage (%)	Conditioning Time (hours)
HMA 1	None	None	24, 36, 48
HMA 2	LOF6500	0.75	24
FOAM	None	None	24
Crabtree 1	LOF6500	0.75	24
Crabtree 2	None	None	24

4.2 Test Results and Interpretation

Table 4-2 Tensile Strength Values for HMA 1 Mixture 24-hour conditioning

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	1	7.1	132.95	917	947	**81.0**
	3	6.9	139.49	962		
	4	6.8	137.31	947		
	5	6.7	137.31	947		
Wet	2	7.1	106.8	736	766	
	3	6.9	108.98	751		
	4	6.8	113.33	781		
	5	6.7	119.87	826		

Table 4-3 Tensile Strength Values for HMA 1 Mixture 36-hour conditioning

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	1	7.1	132.95	917	947	**50.8**
	3	6.9	139.49	962		
	4	6.8	137.31	947		
	5	6.7	137.31	947		
Wet	1	6.6	78.46	541	481	
	2	6.6	65.39	451		
	4	6.5	69.74	481		
	5	6.7	69.74	481		

Table 4-4 Tensile Strength Values for HMA 1 Mixture 48-hour conditioning

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	1	7.1	132.95	917	947	**31.7**
	3	6.9	139.49	962		
	4	6.8	137.31	947		
	5	6.7	137.31	947		
Wet	1	6.9	47.95	331	301	
	2	6.8	45.77	316		
	3	6.9	41.41	286		
	4	6.9	39.23	270		

Table 4-5 Tensile Strength Values for HMA 2 Mixture

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	2	7.0	220.13	1518	1480	**87.8**
	3	7.0	215.77	1488		
	6	6.7	213.59	1473		
	7	6.9	213.59	1473		
Wet	4	6.9	176.54	1217	1300	
	5	6.9	196.16	1352		
	8	6.8	187.44	1292		
	9	7.2	189.62	1307		

Table 4-6 Tensile Strength Values for FOAM Mixture 24-hour conditioning

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	2	6.7	193.98	1337	1345	**36.3**
	3	6.6	185.26	1277		
	7	6.6	196.16	1352		
	8	6.6	196.16	1352		
Wet	1	6.6	71.92	496	488	
	4	6.6	71.92	496		
	5	6.5	69.74	481		
	6	6.7	69.74	481		

Table 4-7 Tensile Strength Values for Crabtree 1 Mixture

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	2	6.9	178.72	1232	1172	**92**
	3	6.9	180.90	1247		
	5	6.9	152.57	1052		
	6	7.0	161.28	1112		
Wet	1	6.9	161.28	1112	1082	
	4	6.8	137.31	947		
	7	6.9	159.10	1097		
	8	6.9	154.75	1067		

Table 4-8 Tensile Strength Values for Crabtree 2 Mixture

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	1	6.9	165.64	1142	1172	**56**
	3	6.9	178.72	1232		
	6	6.9	170.00	1172		
	7	7.0	170.00	1172		
Wet	2	6.9	95.90	661	661	
	4	6.8	95.90	661		
	5	6.9	87.18	601		
	8	6.9	98.08	676		

Very low TSR values for FOAM mixture and Crabtree mixture without LOF 6500 antistrip additive indicate that they both are highly moisture susceptible mixtures. When antistrip is added to the Crabtree mixture the TSR value increases significantly. HMA 1 mixture (HMA mixture without LOF 6500 antistrip additive) is not highly moisture susceptible when moisture conditioned to 24 hours. However, as the conditioning time increases from 34 to 48 hours, the TSR value decreases indicating a steady decline increase in moisture susceptibility.

5. Boil Test

The boil test is a test method used to determine the stripping potential in asphalt concrete mixtures and predominantly measures the loss of adhesion between the aggregate and asphalt cement. It is a simple test and requires less testing and personnel time, and material. Loose asphalt mixture is boiled in distilled water for a certain amount of time, generally 10 minutes per ASTM D3625 [51] and Tex 520-C method [52]. Boiling of loose asphalt mixture leads to the stripping of asphalt from the aggregates if the mixture is moisture sensitive. The stripping of asphalt may expose the aggregates, it may emulsify and change color, and thus there can be a visible color change and in some cases complete loss of asphalt cement for highly moisture sensitive mixtures. This color change and/or exposed aggregate surface can be used to visually estimate the amount of stripping. The current procedure uses a visual chart such as that developed for Texas Boil test by Kennedy, et al. [53], shown in Figure 5-1 to categorize the boiled asphalt mixture based on the amount of asphalt retained. The disadvantage of using this process is that the evaluation of stripping is done visually and qualitatively, and not quantitatively. Therefore, the interpretation of results may vary based on the observers and is only categorized as “Low”, “Medium” or Severe”.

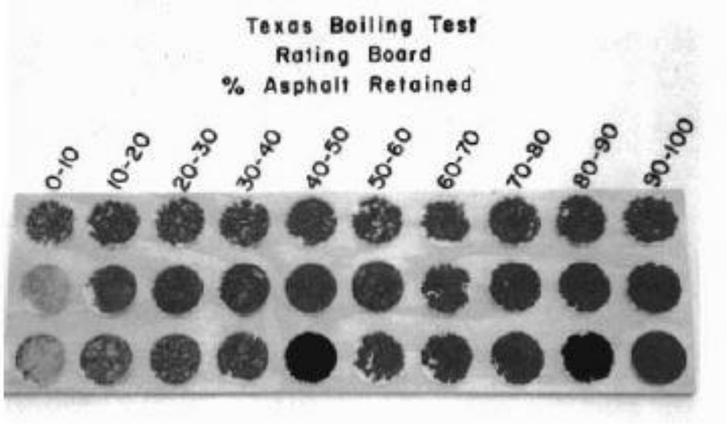


Figure 5-1 Texas Boiling Test Rating Board (Kennedy, et al. 1984)

The colorimeter device used in this study allows quantitative determination of more precise changes in color in Boil Test in a very short time frame (10 to 15 minutes) removing the operator bias for visual assessment. The idea behind the development of the loss of adhesion due to moisture sensitivity between asphalt and aggregate in Boil Test is depicted in Figure 5-2.

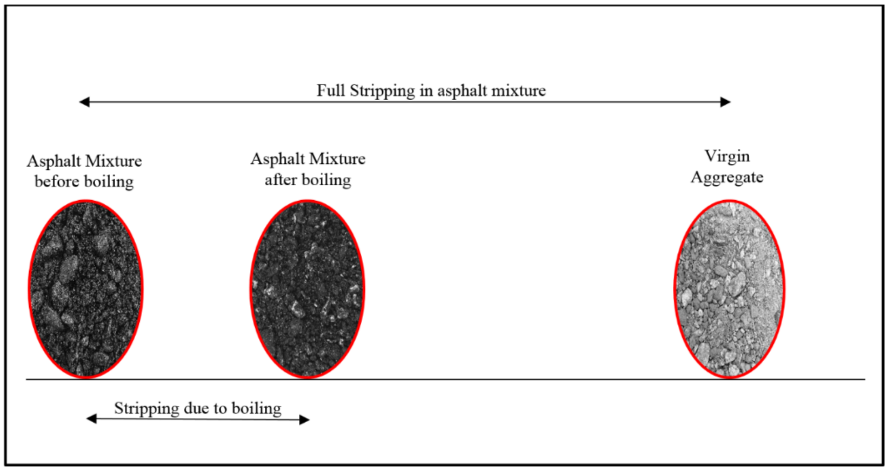


Figure 5-2 Visual depiction of the loss of adhesion between asphalt and aggregate in Boil Test

In Figure 5-2, the asphalt mixture before boiling is shown on the left, and the virgin aggregate blend is shown on the right. The difference in the color index between the two represents a complete 100% asphalt stripping. This color index of the asphalt mixture and the virgin aggregate blend can be easily and precisely obtained using the colorimeter device in a matter of minutes. Once the asphalt mixture is boiled using any standard method, the color index of the boiled asphalt mixture can then be obtained. The results can then be interpreted in a couple of ways as damage ratios that are reflective of the loss of adhesion vis-à-vis moisture susceptibility. The damage ratios are defined in Eqs 5-1 and 5-2. Eq 5-1 can be used if the colorimeter readings on virgin aggregate blend are not available for the mixture. Eq 5-2 can be used when the colorimeter reading on virgin aggregate is available. In the formulae below, L^* refers to colorimeter readings. L^*_R is the damage ratio in percent relative to the original loose mixture. CD^*_R is the colorimeter damage ratio in percent relative to the virgin aggregate blend. If colored aggregates and/or asphalt binder is used, then the L^* readings can be replaced by C^* (ASTM E284-13b) in Eqs 5-1, and 5-2.

$$\mathrm{L}^*_{\mathrm{R}} = \frac{(\text{Boiled L}^* - \text{Unboiled L}^*) * 100}{\text{Unboiled L}^*} \qquad \text{Equation 5-1}$$

$$\mathrm{CD}^*_{\mathrm{R}} = \frac{(\text{Boiled L}^* - \text{Unboiled L}^*) * 100}{\text{Aggregate L}^* - \text{Unboiled L}^*} \qquad \text{Equation 5-2}$$

5.1 Boil Test Mixtures

The following mixtures were tested and are represented in Table 5-1.

1. HMA 1 mixture was used to show how colorimeter device can be used to determine the antistrip dosage for the asphalt mixture. The antistrip additive used for this mixture was a proprietary product and the actual dosage used is masked by an arbitrary multiplier.
2. HMA 2 mixture used had 0.75% LOF6500 antistrip additive and the boiling times used were 10 and 60 minutes.

3. HMA 3 mixture had no antistrip additive and the boiling times used were 10, 20 and 30 minutes to investigate the effect of boiling time and the sensitivity of the colorimeter readings.
4. A high moisture sensitive aggregate referred to as Crabtree mixture with and without antistrip additive was used for verification of the test approach.

It should be noted that the aggregates and asphalt binder used for the HMA 1 mixtures are not the same as HMA 2 and 3 mixtures. In total, therefore, 5 mixtures were used with and without antistrip additive and 3 different aggregate sources.

Table 5-1 Summary of the mixtures used for Boil Test

Mixture	Additive Type	Additive Dosage* (%)	Boiling Times (minutes)
HMA 1	Proprietary	0, 1.5, 2.5, 3.5	60
HMA 2	LOF6500**	0.75	10, and 60
HMA 3	None	None	10, 20, and 30
Crabtree 1	LOF6500**	0.75	10
Crabtree 2	None	None	10

5.1.1 HMA 1 Loose Mixture

Boil Test was used to determine the optimum amount of antistrip additive that should be used to effectively minimize the moisture sensitivity of an asphalt mixture. In this case, the antistrip additive is a proprietary product and the actual percentages used are multiplied by an arbitrary number to protect client confidentiality. Asphalt mixtures were prepared using four different doses of antistrip additive - 0 (control), 1.5, 2.5, and 3.5% by the weight of asphalt binder. The colorimeter readings, L^*, were obtained for loose mixtures before and after boil test and are presented in Table 5-2. At the same time, colorimeter reading on virgin aggregate (source and gradation unknown) supplied was also determined.

Figure 5-3 shows the visual differences in the boil test results for the HMA 1 mixture with varying amounts of antistrip additives. Figure 5-4 shows a visual representation of mixture with 0% antistrip along with the colorimeter readings as to how to interpret the damage ratio. In Figure 5-4, on the far left is a visual of a perfectly black color; whereas the far right shows the visual of a perfectly white color. For the colorimeter used in this research, a perfectly black color will have an L^* reading of zero; whereas, a perfectly white color will have a reading of L^* of 100. Any color (gray scale) between these two will have a reading in the range of 0 to 100.

Table 5-2 L^* values from colorimeter test on dry and boiled HMA 1 mixture

Additive Content	Unboiled L^*	Boiled L^*	L^*_{RB} (%)	CD^*_{RB} (%)
0	17.29	20.68	19.6	12.4
1.5	16.84	20.03	18.9	11.4
2.5	16.69	19.58	17.3	10.3
3.5	17.64	18.01	2.1	1.4
Virgin Aggregate	44.77	NA		

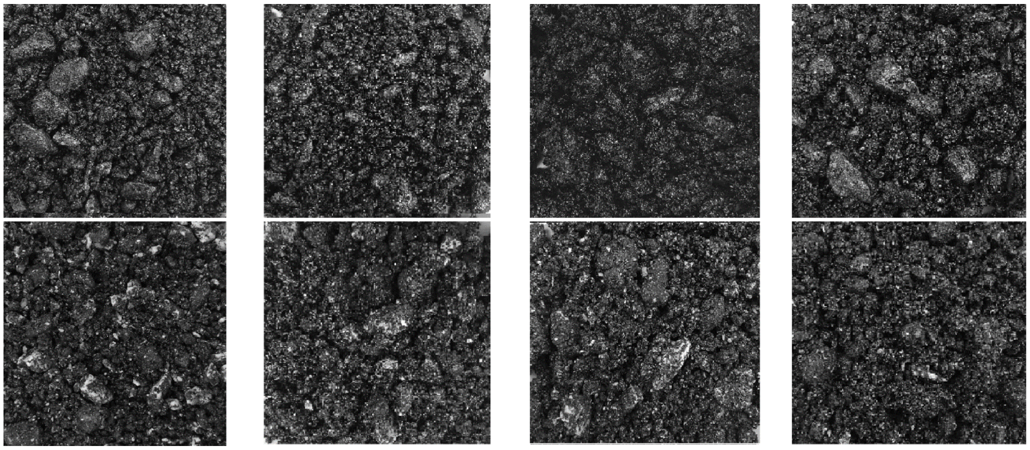


Figure 5-3 Visual stripping due to Boil Test in asphalt mixtures with different additive content. The top pictures are of dry asphalt mixtures and the bottom ones are of boiled asphalt mixtures. (L to R): No antistrip additive, 1.5% antistrip additive, 2.5% antistrip additive, 3.5% antistrip additive

Using Eqs 5-1 and 5-2, the damage (moisture sensitivity), i.e., loss of adhesion between asphalt and aggregate, were computed and are presented in Table 5-2 and Figures 5-5 and 5-6. The graphs between L^*_{RB} and CD^*_{RB} vs anti-strip additive dosage (Figures 5-5 and 5-6) were used to determine the antistrip additive dosage that should be used for the asphalt mixture. The inflection point in these graphs was determined as the antistrip additive dosage for the asphalt mixture. It is interesting to note that what would have been in the past a visual qualitative boil test is now a quantitative test capable of showing the loss of adhesion as a function of antistrip content. Interestingly, when a TSR test was conducted for HMA 1 mixture containing 2.5% antistrip additive by the weight of asphalt content, resulted in a TSR value of 85%.

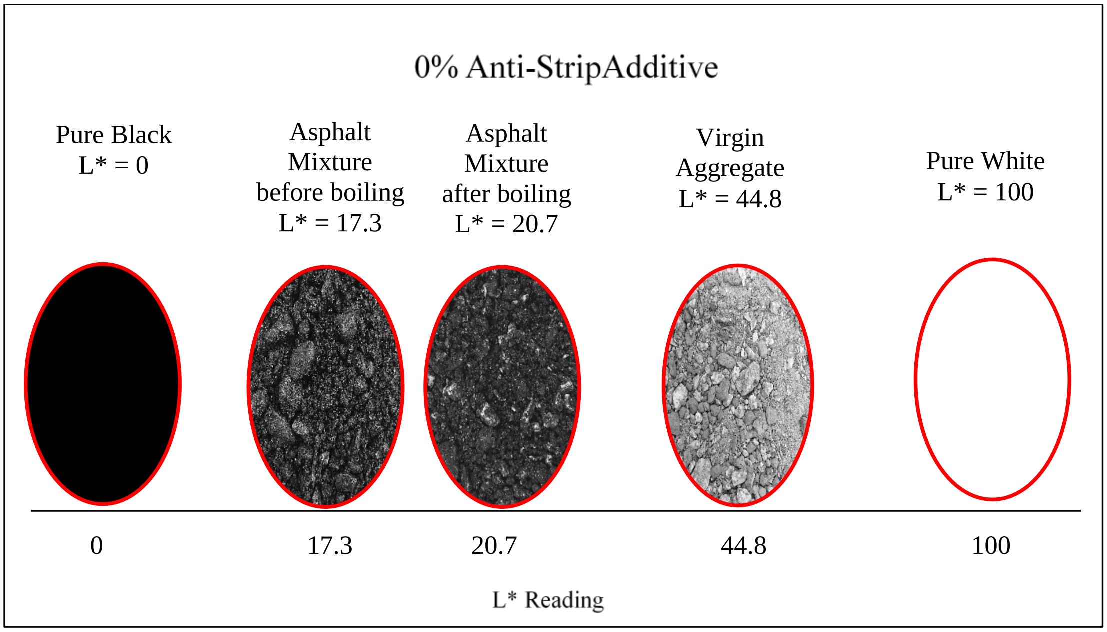


Figure 5-4 Comparison of L^* values for asphalt concrete mixtures with no additives and dry virgin aggregate to the L^* value of pure black and pure white color

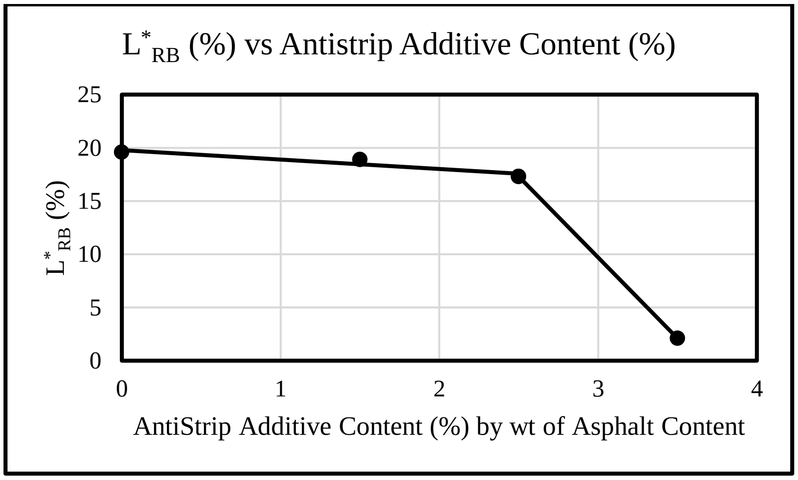


Figure 5-5 Variation of L^*_{RB} (%) damage with change in Antistrip Additive Content (%)

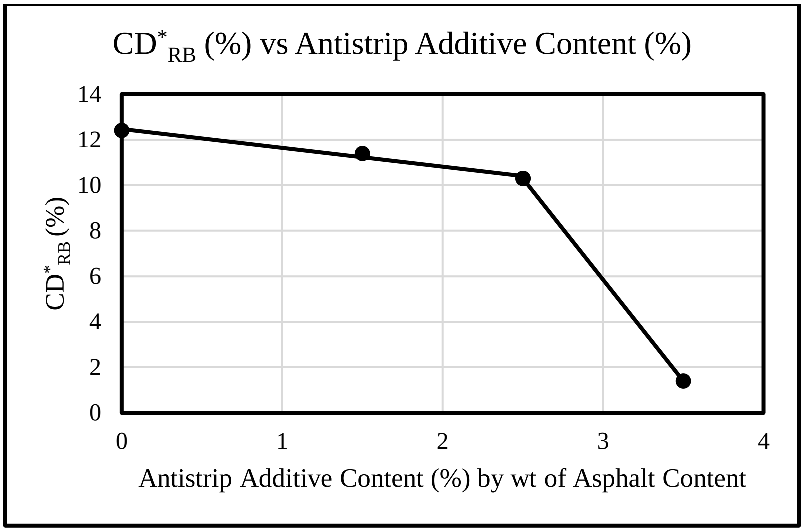


Figure 5-6 Variation of CD^*_{RB} (%) damage with change in Antistrip Additive Content (%)

5.2 HMA 2 and 3 Loose Mixtures

HMA mixtures were prepared for boil test to evaluate the effect of antistrip additive and boiling times on stripping in asphalt mixtures. Table 5-3 and 5-4 show the L^*, L^*_{RB} and CD^*_{RB} values for HMA mixtures for different boiling times with and without antistrip additive, respectively. Figure 5-7 visually shows the effect boiling time for mixture without antistrip additive. Figures 5-8 and 5-9 show the test results for the variation in L^*_{RB} and CD^*_{RB} values respectively, for the HMA mixtures with and without antistrip additive. These figures show that HMA mixture without antistrip additive are more prone to stripping (severely moisture sensitive) while HMA mixture with antistrip additive shows very little stripping with even increase in boiling time. It should be noted that in Figure 5-14, for the damage ratio L^*_{RB} of about 15% and CD^*_{RB} of about 10%, the corresponding TSR for this mix was 80% (without antistrip additive). For mixture with antistrip additive LOF6500, the TSR ratio for the mixture was about 90% with corresponding colorimeter damage ratio L^*_{RB} below 10%, and the CD^*_{RB} below 5%.

Table 5-3 L^*, L^*_{RB} and CD^*_{RB} values for HMA 2 mixture with antistrip additive and increasing boiling times

Boiling Time	Unboiled L^*	Boiled L^*	L^*_{RB}(%)	CD^*_{RB} (%)
10 minutes	17.72	18.90	6.6	4.1
60 minutes	17.77	19.32	8.8	5.4
Virgin Aggregate	46.443	NA		

Table 5-4 L^*, L^*_{RB} and CD^*_{RB} values for HMA 3 mixture without antistrip additive and increasing boiling times

Boiling Time	Unboiled L^*	Boiled L^*	L^*_{RB} (%)	CD^*_{RB} (%)
10 minutes	18.67	21.55	15.4	10.4
20 minutes	19.09	24.67	29.2	20.4
30 minutes	19.09	25.42	54.1	32.0
Virgin Aggregate	46.443	NA		

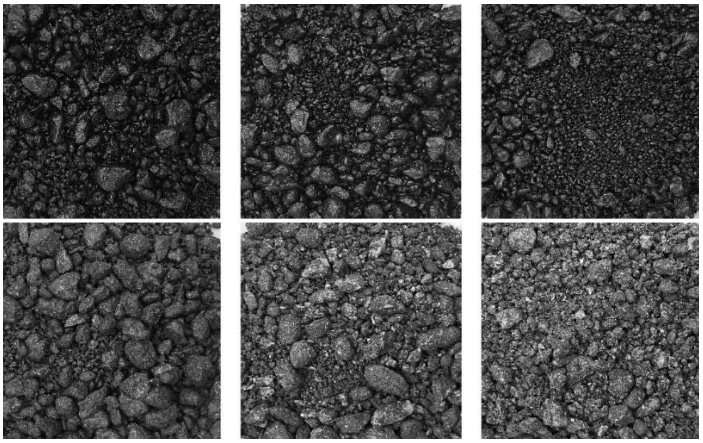


Figure 5-7 Visual stripping due to Boil Test for HMA 3 mixture without antistrip additive for different boiling times. The top pictures are of dry asphalt mixtures and the bottom ones are of boiled asphalt mixtures. (L to R):10-minutes boiling, 20-minutes boiling, 30-minutes boiling.

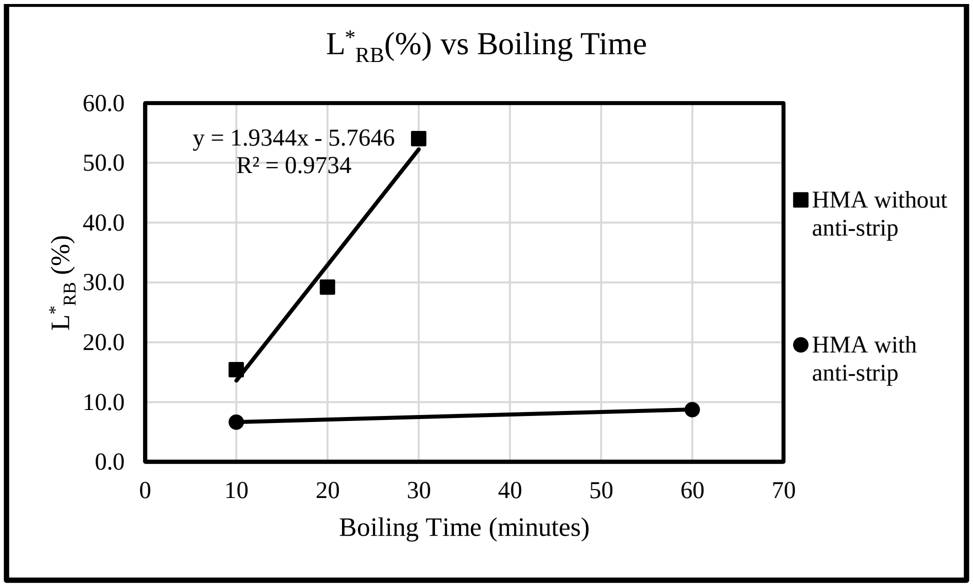


Figure 5-8 Variation of L^*_{RB} (%) with change in boiling times for HMA mixtures with antistrip additive and without antistrip additive

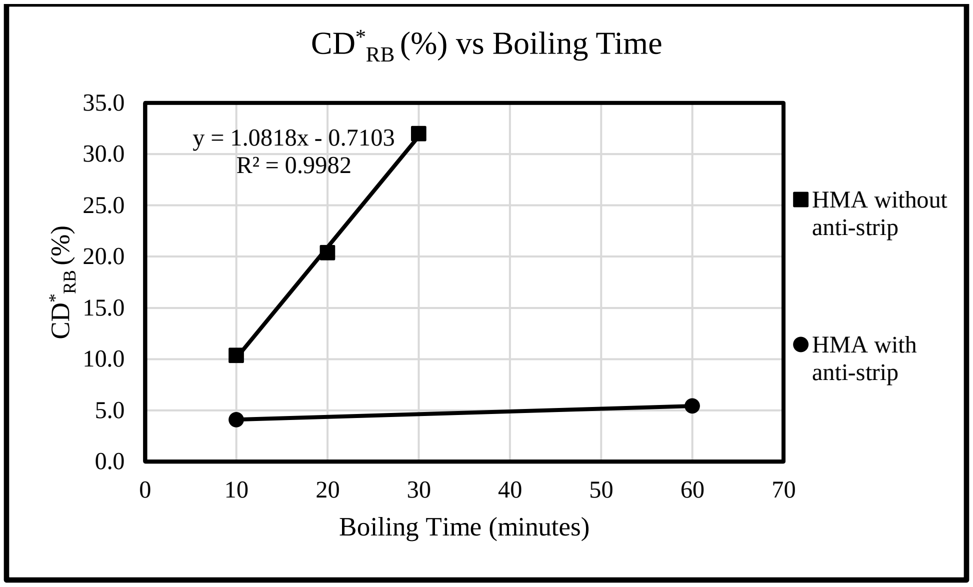


Figure 5-9 Variation of CD^*_{RB} (%) with change in boiling times for HMA mixtures with antistrip additive and without antistrip additive

5.3 Applying Colorimeter Damage Ratio to TSR Test

Eqs 5-1 and 5-2 describe the concept of damage due to moisture sensitivity in Boil Test on loose asphalt mixtures that are the measure of the loss of adhesion between asphalt and aggregate. To determine if the same concept and methodology apply to AASHTO T283 test (TSR test) that is currently used in the Superpave mixture design procedure; the HMA 3 mixture (without antistrip additive) was subjected to TSR test for which the conditioning procedure AASHTO T283 was used. However, to determine the sensitivity of the colorimeter damage ratio concept, these mixtures were subjected not only to 24-hour conditioning but additionally also to 36-hours and 48-hours. Results of the TSR test along with the damage ratios defined by Eqs 5-1 and 5-2 are presented in Table 5-5 and visual stripping is shown in Figure 5-10. It should be noted that if Eqs 5-1 and 5-2 are used for the TSR tests, the damage ratios are denoted by L^*_{RT} and CD^*_{RT} where "T" stands for Tensile Strength Ratio, as opposed to "B" that stands for the Boil Test. The colorimeter readings were taken on the broken samples from the TSR indirect tensile testing.

Table 5-5 TSR, L^*_{RT} and CD^*_{RT} values for HMA 3 mixture without antistrip additive and different conditioning time

Conditioning Time	TSR (%)	L^*_{RT} (%)	CD^*_{RT} (%)
24 hours	80.7	4.2	2.7
36 hours	50.8	11.9	7.7
48 hours	31.8	19.7	12.8

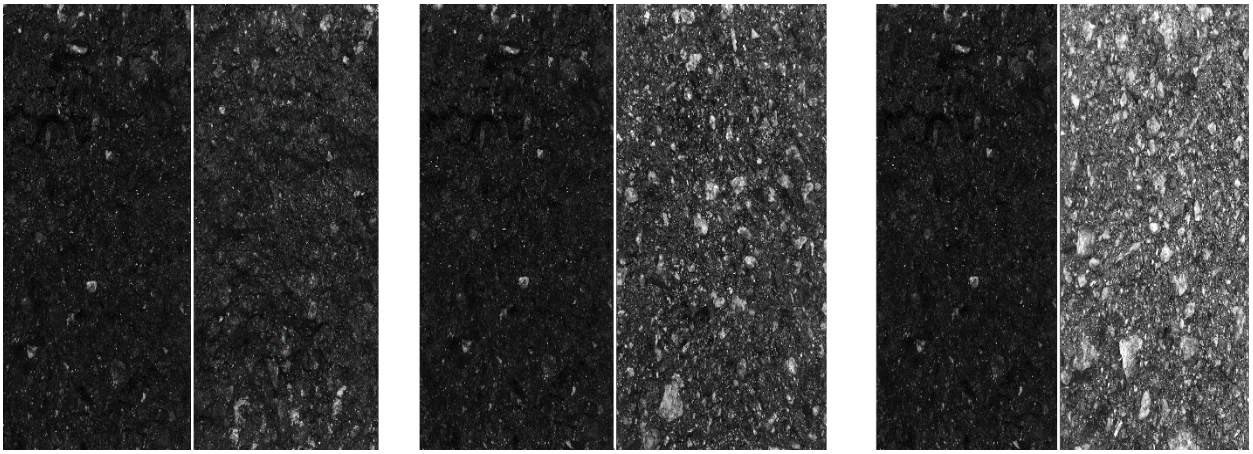


Figure 5-10 Visual stripping due to moisture conditioning using AASHTO T283 procedure for TSR Test in HMA 3 mixture without antistrip additive with an increase in conditioning times. The unconditioned mixture is on the left while the conditioned mixture is on the right. (L to R): 24-hour conditioning, 36-hour conditioning, 48-hour conditioning

Figure 5-11 shows the TSR test results for HMA 3 mixture as a function of moisture conditioning time as per the AASHTO T283 procedure. For the broken specimens from the indirect tensile testing for the TSR tests, the colorimeter readings were obtained on the broken (split) specimens and the damage ratios were determined and are presented in Figures 5-12 and 5-13. It may be noted that the colorimeter damage ratio is sensitive to the TSR values reduction due to moisture damage. However, unlike the boiling test, the colorimeter damage ratios are lower because the boil test is purely a measure of adhesive failure; while the AASHTO T283 conditioning procedure has not only adhesive but as well as cohesive failure mechanism among others.

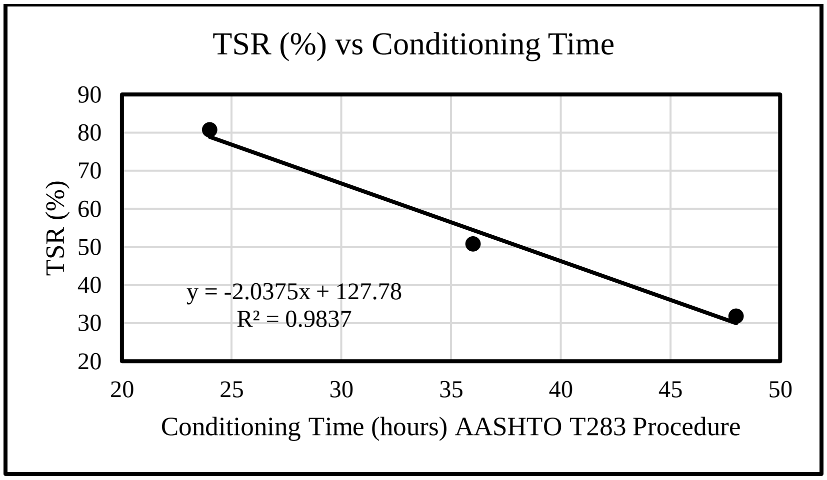


Figure 5-11 Variation of TSR (%) value with increase in conditioning time during TSR Test for HMA mixtures without antistrip additive

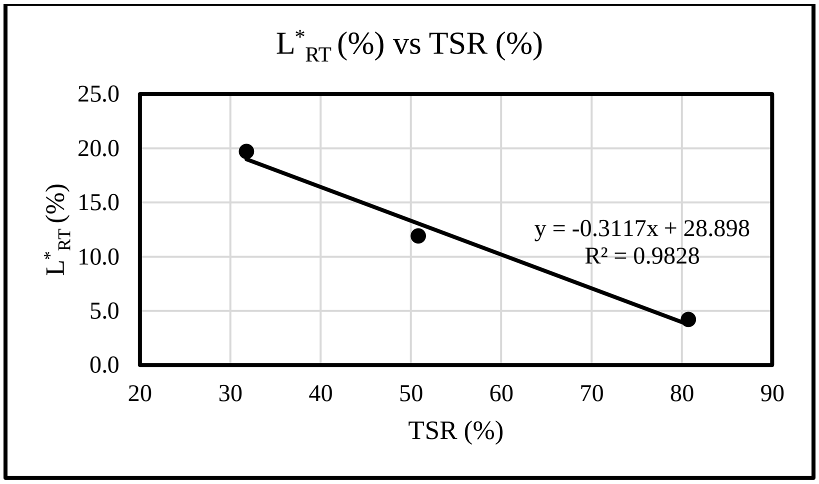


Figure 5-12 Relationship between L^*_{RT} (%) and TSR (%) with increase in conditioning time during TSR Test for HMA mixtures without antistrip additive

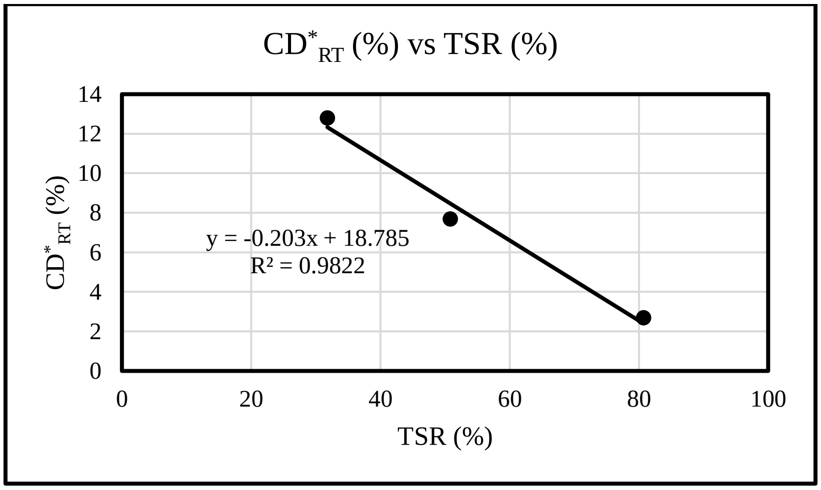


Figure 5-13 Relationship between CD^*_{RT} (%) and TSR (%) with increase in conditioning time during TSR Test for HMA mixtures without antistrip additive

Additionally, to verify the concept, a highly moisture sensitive Crabtree mixture with and without antistrip additive was tested using the boiled tests as well as the TSR test. The idea behind it was to investigate whether the boil test that measures the loss of adhesion between asphalt and aggregate is correlated to the TSR test. Figures 5-14 and 5-15 present the results of the correlation between the colorimeter damage ratios obtained using the boil test to the TSR test results.

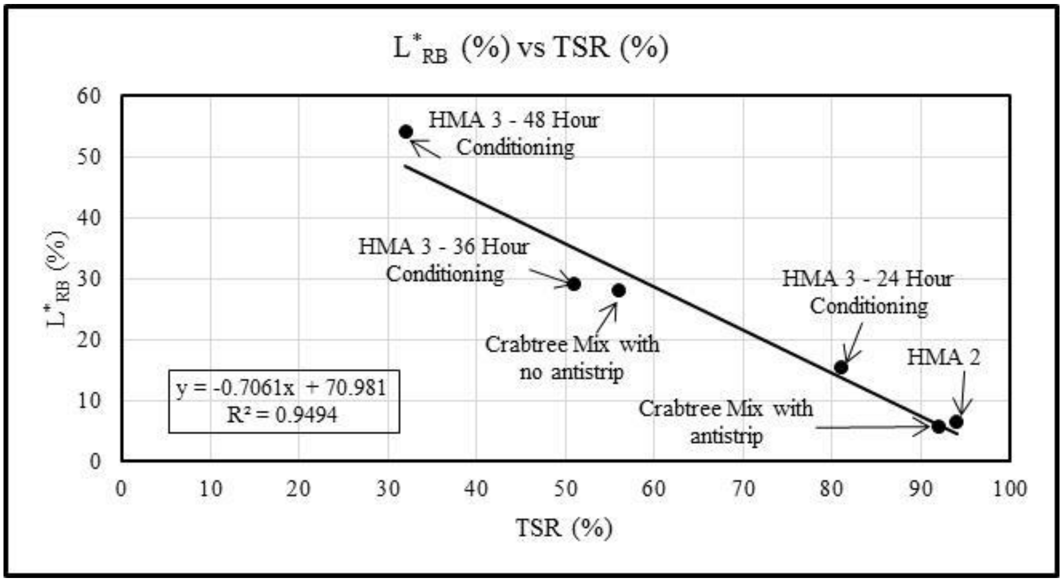


Figure 5-14 Relationship between L^*_{RB} (%) and TSR (%) for all mixtures

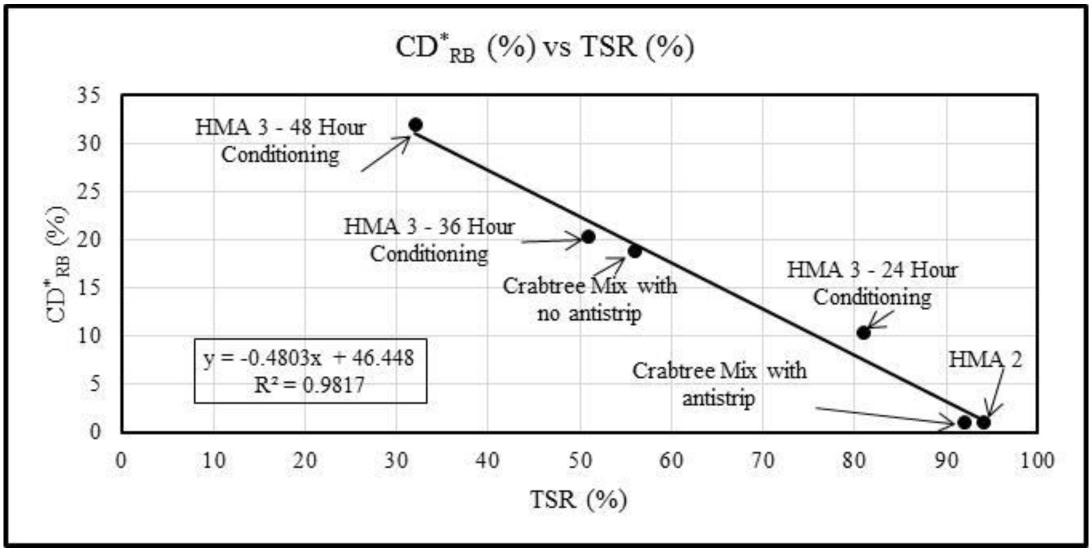


Figure 5-15 Relationship between CD^*_{RB} (%) and TSR (%) for all mixtures

Figures 5-14 and 5-15 show a very good correlation between the boil test and the TSR tests. Based on these figures, the correlation equations are presented as:

L^*_{RB} = -0.7061(TSR value) + 70.98 Equation 5-3

CD^*_{RB} = -0.4803(TSR value) + 46.45 Equation 5-4

The form of Eqs 5-3 and 5-4 is the first preliminary step in the interpretation of visual test methods to objectively quantifying the moisture sensitivity of asphalt mixtures. In this study, the boil test was used and correlated with the TSR test. However, any other visual test method can now be interpreted objectively using a colorimeter device. The acceptance or rejection criterion by agencies will depend on the type of moisture sensitivity tests used on loose asphalt mixtures versus compacted mixtures. For example, Table 5-6 shows the acceptance or rejection of mixture criterion based on TSR test versus the Boiled Test. From Table 5-6, it may be noted that if the TSR acceptance criterion by an agency is 85% retained strength, then in the boil test the damage ratio should not exceed 10% for the L^*_{RB} or 5% for CD^*_{RB}.

Table 5-6 L^*_{RB} and CD^*_{RB} values based on TSR value as acceptance/rejection criteria

TSR value (%)	$\mathbf{L^*_{RB}}$ **(%)**	$\mathbf{CD^*_{RB}}$ **(%)**	**Visual Inspection/Severity**
85	11.0	5.6	Low
75	18.0	10.5	Medium
65	25.0	15.0	Severe

6. Using Colorimeter on Split TSR samples

The colorimeter device was used on the exposed fractured surfaces of the tested specimens from TSR test. L^* readings were taken using the colorimeter on the fractured surfaces of the specimens. Average L^* value was calculated for each set. Using these average L^* values, L^*_{RT} (ratio based on TSR tests) was calculated.

Field samples were provided by NCDOT M&T Lab and an independent laboratory. TSR test was already performed on these samples and the TSR value was provided. L^* readings were taken on the moisture conditioned set of specimens and the dry set of specimens. From these readings, L^*_{RT} was calculated for both the set of specimens. The results of the tests are shown in Tables 6-1 and 6-2.

Two additional mixtures – HMA 2 and HMA 3 were prepared in the laboratory for TSR Test. TSR values as well as the L^*_{RT} and CD^*_{RT} values were calculated and are shown in Tables 6-3 and 6-4.

Table 6-1 TSR and L^*_{RT} for NCDOT Field Specimens from Source 1

Moisture Conditioning	ITS Values (kPa)	TSR (%)	L* Readings	L^*_{RT} Ratio
Dry Sample 1	1288.9	64.0	16.188	7.8%
Wet Sample 1	824.3		17.448	
Dry Sample 2	1342.5	78.7	16.767	4.4%
Wet Sample 2	1056.6		17.512	
Dry Sample 3	1401.3	88.7	16.890	2.1%
Wet Sample 3	1242.6		17.250	

Table 6-2 TSR and L^*_{RT} for NCDOT Field Specimens from Source 2

Moisture Conditioning	TSR (%)	L* Readings	L^*_{RT} Ratio
Dry Sample 1	57.0	15.917	12.2%
Wet Sample 1		17.853	
Dry Sample 2	60.0	16.570	9.8%
Wet Sample 2		18.200	

Table 6-3 TSR and L^*_{RT} for HMA 2 mixture prepared in Laboratory

Moisture Cond.	Median ITS Values (kPa)	TSR (%)	L^* Reading	L^*_{RT}	CD^*_{RT}
Dry	1247	94.0	19.343	1.4%	1.0%
Conditioned	1172		19.621		

Table 6-4 TSR and L^*_{RT} for HMA 3 mixture prepared in Laboratory

Moisture Cond.	**Median ITS Values (kPa)**	**TSR (%)**	**L* Reading**	L^*_{RT}	CD^*_{RT}
Dry	947	-	18.247	-	-
24 hr	764	80.7	19.005	4.2%	2.7%
36 hr	481	50.8	20.417	11.9%	7.7%
48 hr	301	31.8	21.846	19.7%	12.8%

Figure 6-2 shows a graph of the TSR ratio and the L^*_{RT} values for the field and laboratory specimens.

Equation 6-1 is a relationship to compute TSR ratio from L^*_{RT} using the results from Tables 6-1 to 6-4.

TSR ratio = 94.609 - 3.341 x (L^*_{RT}) Equation 6-1

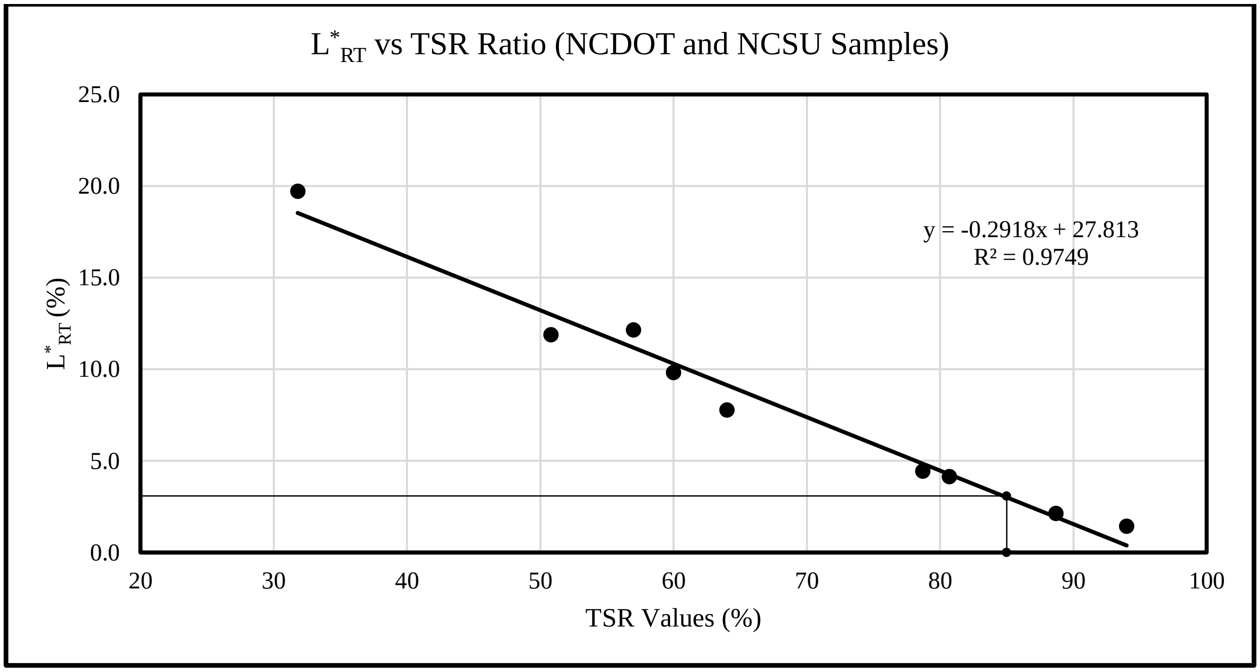


Figure 6-1 Plot between L^*_{RT} and TSR Ratio for the field and laboratory specimens

6.1 Estimating TSR value using the L^*_{RT} values

Equation 6-1 was used to estimate TSR values of mixtures from an independent laboratory. Six different mixtures prepared by an independent lab were used to verify the applicability of equation 6-1 in estimating TSR values from L^*_{RT} values. Indirect Tensile Strength test results were provided by the independent laboratory. L* values were measured on the fractured surfaces of the specimens using the colorimeter. L^*_{RT} values were computed for each mixture and the TSR values were estimated from L^*_{RT} values using equation 6-1. The TSR values, L^*_{RT} and estimated TSR values for all the mixtures are presented in Table 6-5.

Table 6-5 TSR, L^*_{RT}, estimated TSR values for mixtures prepared by an independent laboratory

Moisture Conditioning	**Measured TSR (%)**	**L* Readings**	**L^*_{RT} Ratio**	**Estimated TSR (%)**
Dry Sample 1	70.9	19.432	7.0%	71.2
Wet Sample 1		20.790		
Dry Sample 2	103	18.514	-0.1%	94.9
Wet Sample 2		18.500		
Dry Sample 3	91.9	19.380	1.1%	90.9
Wet Sample 3		19.591		
Dry Sample 4	94.1	19.097	0.9%	91.6
Wet Sample 4		19.274		
Dry Sample 5	97.2	19.121	0.5%	92.9
Wet Sample 5		19.224		
Dry Sample 6	56.7	20.554	12.5%	52.8
Wet Sample 6		23.132		

Figure 6-3 shows measured TSR values versus the estimated TSR values. A 45-degree line or a line of equality is also shown for reference. The plot shows that Equation 6-1 estimates the TSR well from L^*_{RT} values.

Equation 6-2 is an updated equation developed that includes the additional results from the independent laboratory mixtures to calculate TSR values from L^*_{RT} values.

$$\text{TSR Value} = 96.888 - 3.4927 \times (L^*_{RT}) \qquad \text{Equation 6-2}$$

Figure 6-4 shows the relationship for the combined data.

Using the graph between L^*_{RT} and the TSR values a threshold L^*_{RT} value can be calculated. In this study, a maximum threshold L^*_{RT} was calculated using the minimum TSR limit of 85% used by NCDOT. Using this relationship, the maximum threshold value for L^*_{RT} was calculated to be 3.1% if the minimum acceptable TSR value is 85%.

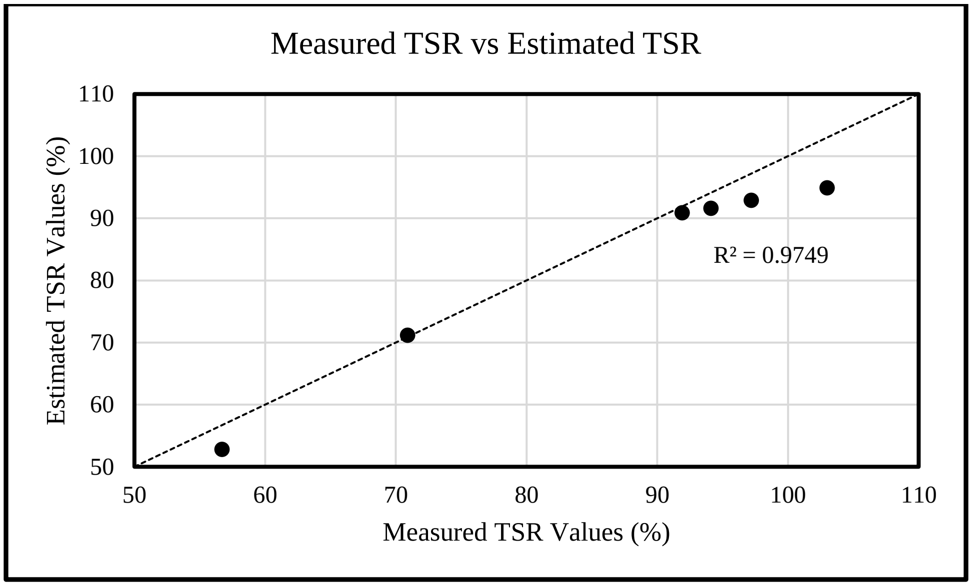


Figure 6-2 Plot between Measured TSR Values and Estimated TSR Values

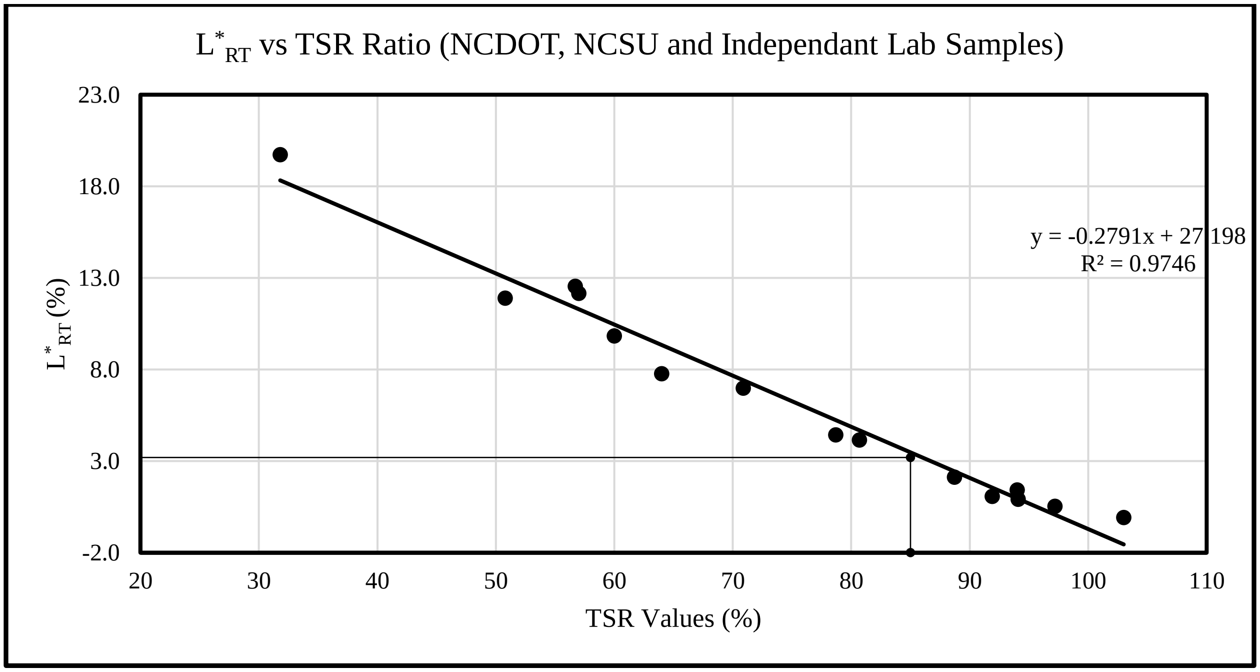


Figure 6-3 Plot between L^*_{RT} and TSR Ratio for the field, NCSU laboratory, and independent laboratory specimens

7. Impact Resonance Test

This section details the determination of the modulus ratio values using the impact resonance (IR) test on 1-inch thick specimens. These specimens were prepared at 9±0.5% air voids.

For the impact resonance test, a soft mat was used as a support for the asphalt disk to allow "free" vibration of the specimen. The response of the disk was measured using a high-frequency accelerometer which was coupled to the specimen bottom surface using a quick bonding adhesive through a hole in the foam. A light (6 oz.) hammer was used to induce acceleration. The response in the time domain is recorded using an oscilloscope. Then, Fast Fourier Transform (FFT) is used to find the resonance frequency of the specimens. The experimental setup is shown in Figure 7-1.

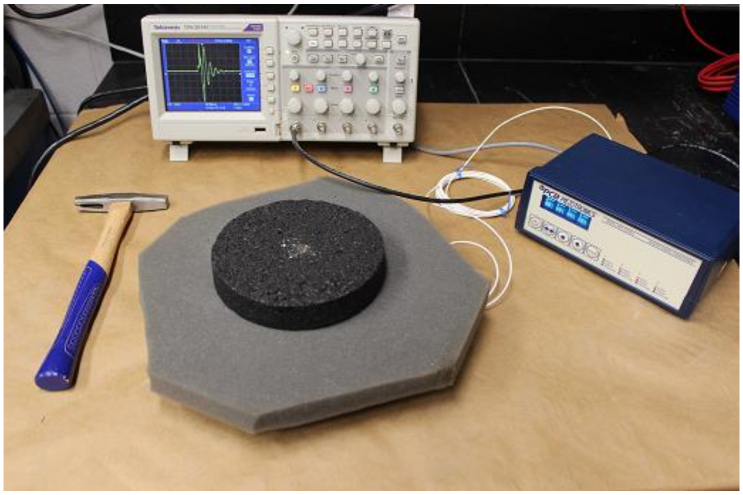


Figure 7-1 Impact Resonance Test setup

7.1 Impact Resonance Test vs TSR

Using the impact resonance test the elastic modulus value of asphalt concrete can be calculated without damaging the sample. By performing this test on a sample before and after moisture conditioning, it is possible to obtain the elastic modulus values of the sample before and after moisture conditioning. The moisture conditioning can induce damage inside of the specimen that may affect the elastic modulus of the specimen. The ratio of elastic modulus values before and after moisture conditioning can give an indication of the amount of damage in the specimen due to moisture conditioning.

To determine if the ratios from impact resonance test correlated well with the TSR values, elastic modulus ratio (E/E_0) was calculated for five different mixtures – HMA 2, HMA 3 with 24, 36 and

48-hour conditioning, WMA with foaming technology, Crabtree Valley mix with antistrip additive and Crabtree Valley mix without antistrip additive. The elastic modulus ratio (E/E_0) is the ratio of elastic modulus value of conditioned sample to the elastic modulus value of the unconditioned sample. This elastic modulus ratio (%) was plotted against TSR values for all five mixtures. Figure 7-2 shows the plot between elastic modulus ratio and TSR values for these mixtures. There is also a 45-degree line (line of equality) for reference.

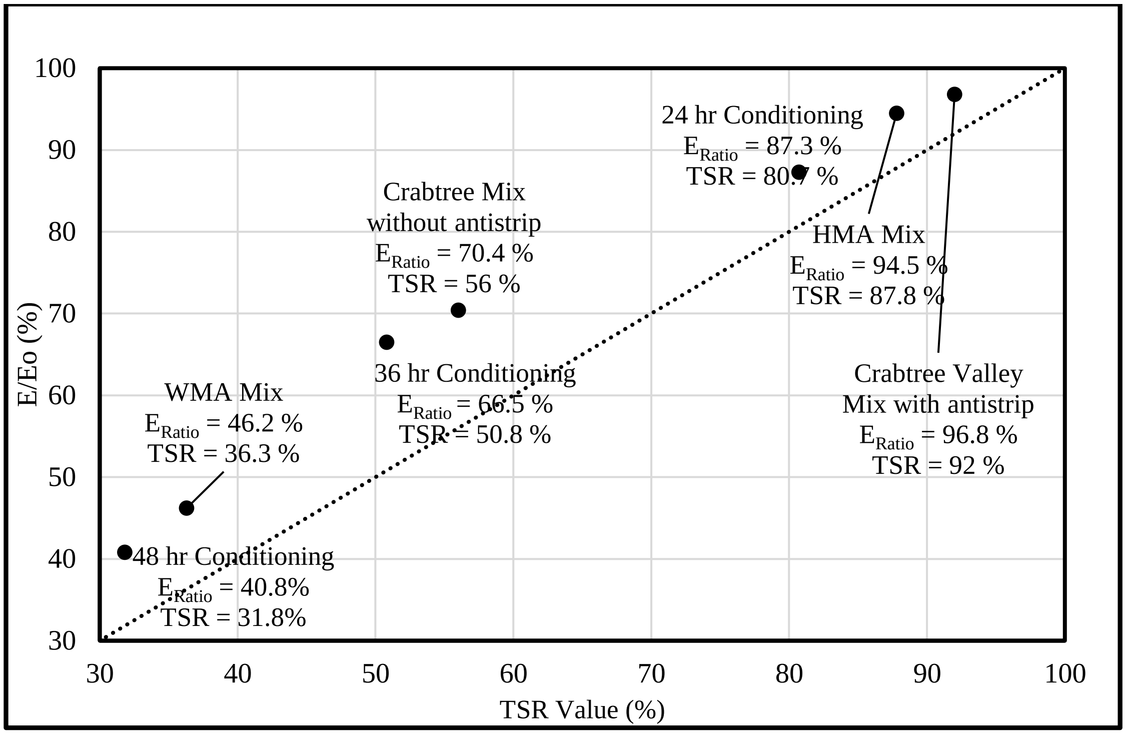


Figure 7-2 Relationship between elastic modulus ratio and TSR values

Figure 7-2 shows that the elastic modulus ratio and TSR values follow the same trend. Another important observation is that all the values are above the line of equality.

The elastic modulus ratio and TSR values for HMA 3 mix were plotted against the duration of moisture conditioning of the samples in Figure 7-3. This was done to check the sensitivity of elastic modulus ratio compared to TSR with an increase in moisture conditioning. From the plot, the sensitivity to the duration of moisture conditioning of elastic modulus ratio and TSR is similar. The difference in the values of elastic modulus ratio and TSR for each duration is evident in Figure 7-3 as the line of elastic modulus ratio is always above the TSR line.

The difference observed in Figures 7-2 and 3 can be due to the testing procedure to obtain the ratios. In impact resonance test, the damage in the specimen mostly occurs during the moisture conditioning process. In indirect tensile strength test (TSR test), the damage in the sample occurs during the moisture conditioning procedure as well as during testing. Because of this difference in testing, the damage during the indirect tensile strength test is more than the damage in the sample during the impact resonance test. Therefore, the elastic modulus ratio which comes from the impact resonance test will be higher that TSR value.

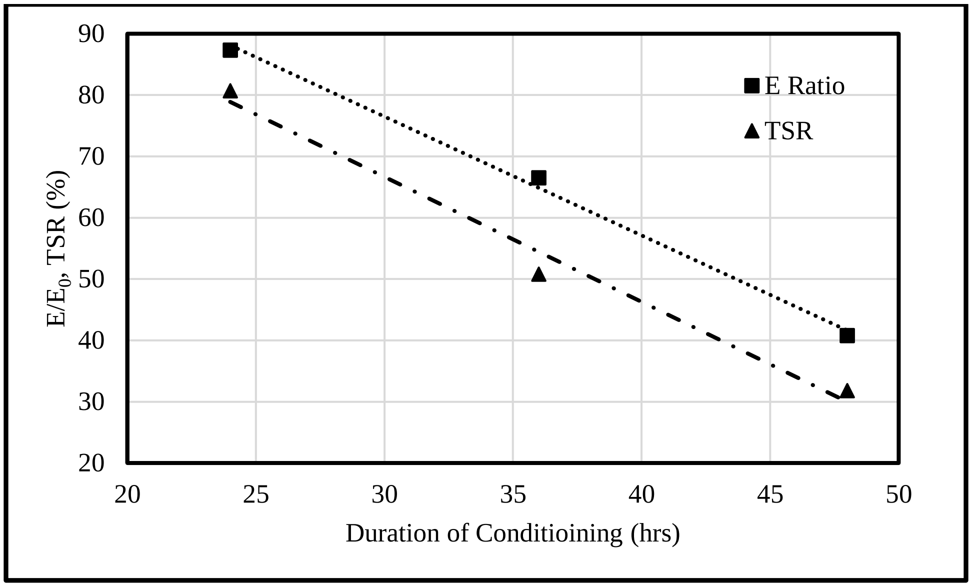
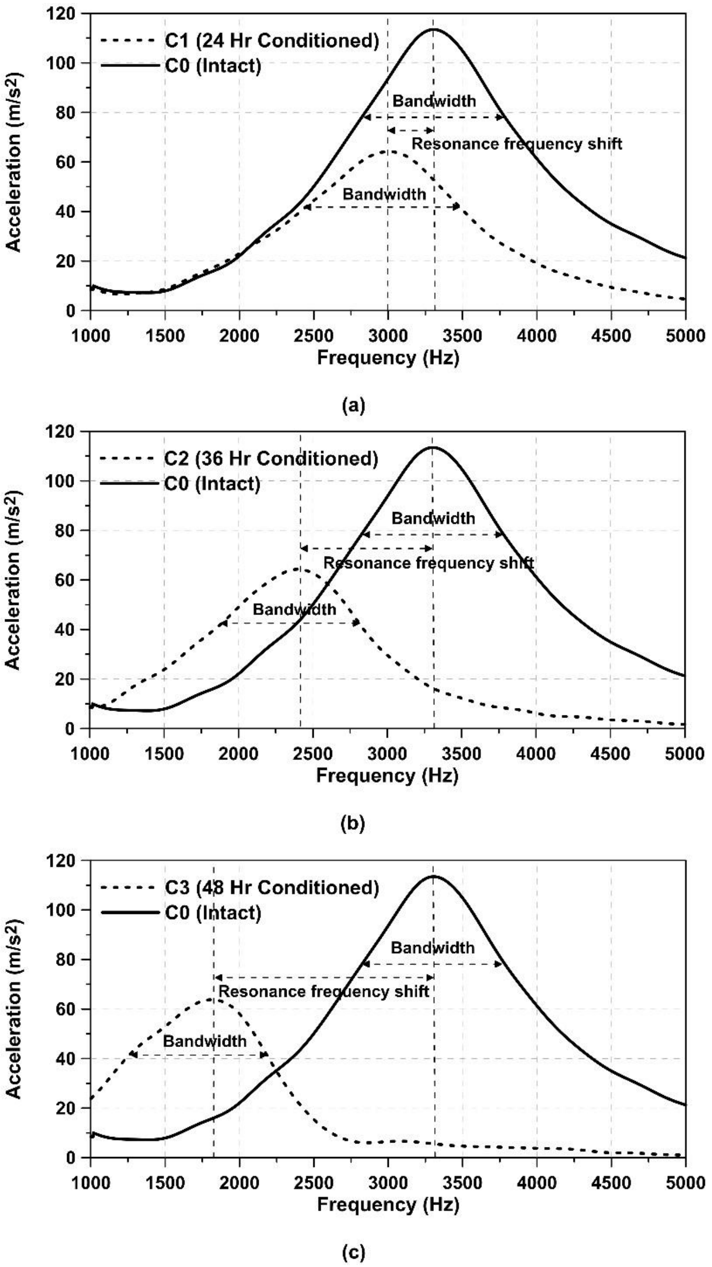


Figure 7-3 Plot of E/E_0 and TSR (%) versus the duration of moisture conditioning of the samples for HMA 3 mixture

7.2 Detecting moisture damage in HMA

In this section, the feasibility of the use of AFV method to quantify moisture damage in HMA specimens without anti-strip is studied. The TSR values for the same mixtures are compared with the results of AFV method. For this purpose, sixteen disk specimens (4 sets of four) were tested using AFV method and sixteen (4 sets of four) cylinder specimens were prepared and tested to obtain TSR values. The four sets included unconditioned samples (C0), 24-hour moisture conditioned (C1), 36-hour moisture conditioned (C2), and 48-hour moisture conditioned (C3). The frequency spectrums of one sample from C1, C2, and C3 are compared to that of a sample from C0 set. Clearly, in Figure 7-4, increasing the moisture conditioning duration increases the resonance frequency shift. Note that while Figure 7-4 illustrates the response of one sample in each graph, the illustrated responses are typical for all samples in the same set. In each graph, the shift in the resonance frequency is also illustrated.

Figure 7-5 illustrates the change in the resonance frequencies and calculated elastic modulus with respect to the conditioning duration for all sets. Both resonance frequency and dynamic elastic modulus decrease with conditioning duration showing the development of damage in the material. It should be noted that the resonant frequency is not significantly changed by the magnitude of the acceleration [21].



(a)

(b)

(c)

Figure 7-4 Comparison between reference sample (C0) and damaged samples after a) 24 hours (C1), b) 36 hours (C2), and c) 48 hours (C3)

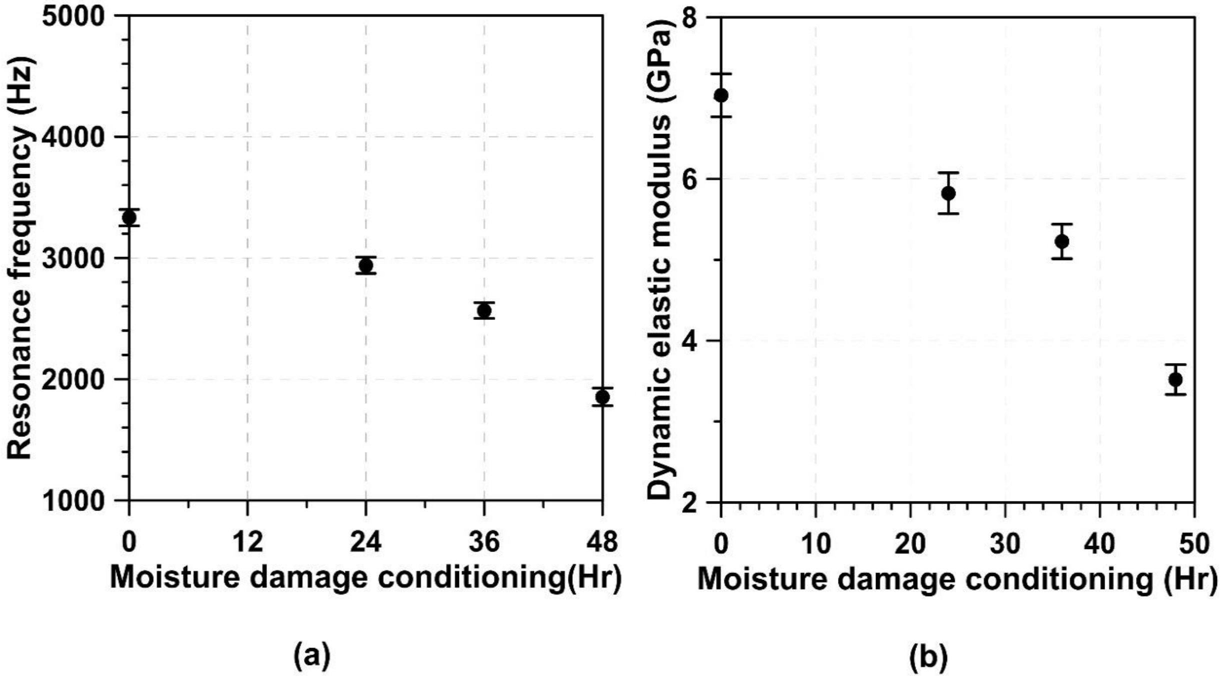


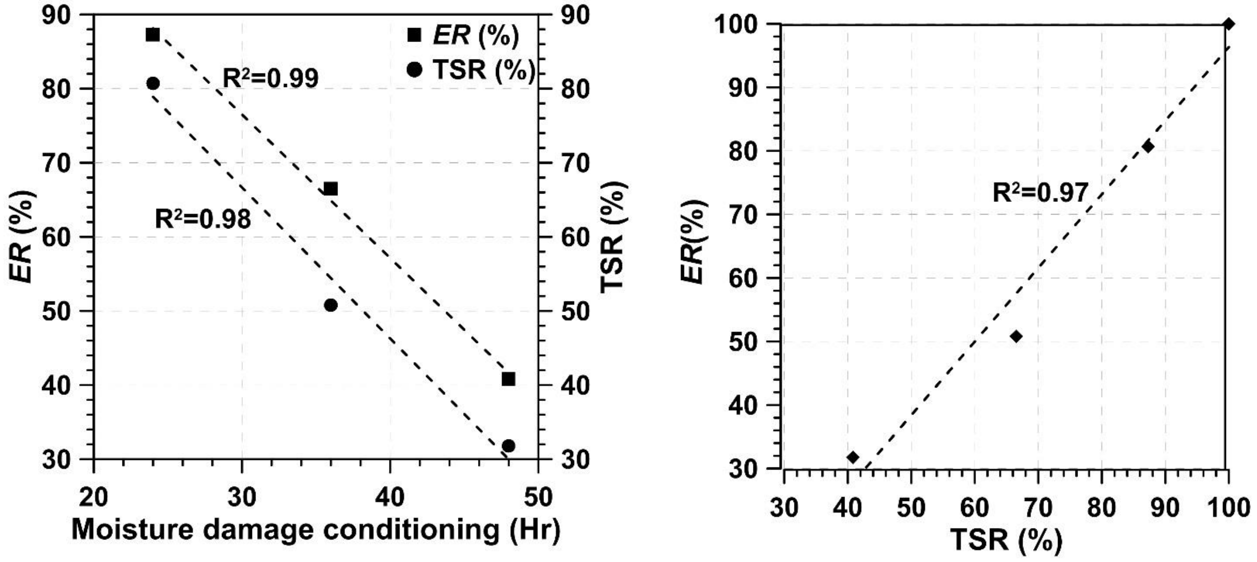
Figure 7-5 a) Resonance frequency of intact and conditioned disk specimens computed by LIRA method. b) Dynamic elastic modulus of intact and conditioned disk specimens computed by LIRA

The ITS and TSR values for all specimen sets are reported in Table 7-1. Clearly, in Table 7-1, both TSR and ITS values decrease with increasing duration of moisture conditioning.

Table 7-1 Tensile Strength Values for HMA Mixtures

Moisture Conditioning	ITS Values (kPa)	Standard Deviation	TSR (%)
Dry (C0)	947	18.91	100
24 hr (C1)	764	19.31	80.7
36 hr (C2)	481	27.42	50.8
48 hr (C3)	301	7.52	31.7

In Figure 7-6a, both TSR values and ER values (elastic modulus ratios) are plotted against conditioning duration. While the results, in Figure 7-6a, indicate that the *ER* is smaller than TSR for all conditioning durations, it should be noted that the computed *ER* based on AFV method is fundamentally different from TSR, however, both are ratios between the damaged and undamaged state of the material. The *ER* parameter from the AFV method, in Figure 7-6a, provides the change in elastic modulus or resonance frequency, while TSR provides an indirect measurement of the change in indirect tensile strength values. While it can be shown that, based on theoretical calculations, for homogenous linear elastic materials the tensile strength and elastic modulus are related, they are fundamentally different parameters. This is especially true for heterogeneous nonlinear viscoelastic materials such as asphalt concrete. Therefore, the results in Figure 7-6a should not be interpreted as lower damage detection by AFV technique and should be interpreted as observations on a direct linear correlation between TSR results and *ER*. In Figure 7-6b, the ER values are plotted against TSR values (from Table 7-1). A linear relationship exists between ER and TSR values.



(a)

(b)

Figure 7-6 a) ER and TSR ratio at different moisture damage conditioning levels and b) Comparing ER and TSR ratio

Here, the effect of specimens prepared with different mixtures is investigated. For this purpose, a total of eight WMA and eight HMA cylinder specimens were used in TSR testing: four control and four conditioned specimens for each material. Similarly, eight disks of WMA and eight disks of HMA were tested using AFV method.

Figure 7-7a shows the *ER* values for each material against TSR values. Figure 7-7a shows a direct linear correlation between TSR results and *ER* for both WMA and HMA. Figure 7-7b shows the actual elastic modulus values of both materials (average of four specimens). According to Figure 7-7b, AFV shows lower frequency shift and damage for WMA as compared to HMA. Therefore, it is concluded that AFV can differentiate between two different specimen mixtures as a new method for moisture damage evaluation.

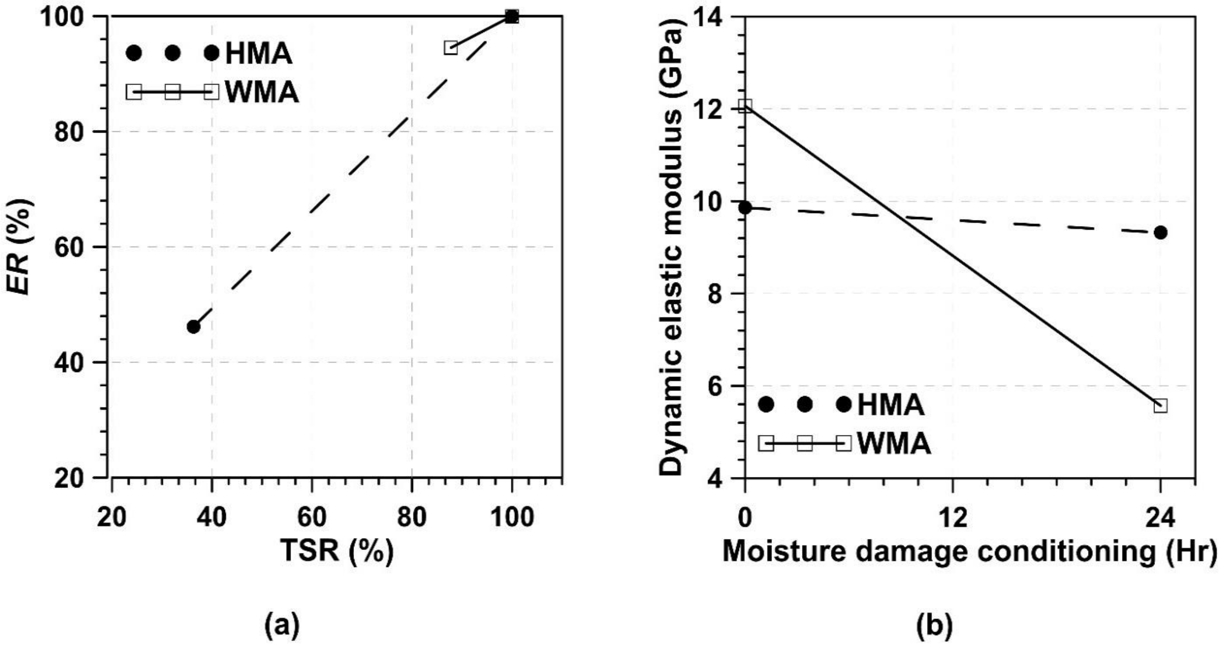


Figure 7-7 a) *ER* and TSR ratio of HMA and WMA after 24 hours of moisture conditioning and b) Comparing of dynamic elastic modulus changes for both HMA and WMA

7.3 Effect of temperature and aging

Asphalt concrete materials as viscoelastic materials are highly sensitive to the temperature changes. Therefore, it is necessary to evaluate the sensitivity of AFV test to detect the effect of temperature on material properties. For this purpose, four HMA specimens were tested at different temperatures.

The effect of temperature on the AFV measurements is shown in Figure 7-8 where measurements were taken at three temperatures of 0 ± 0.5^o, 23 ± 1^o, and 30 ± 1^o C. Figure 7-8a and b illustrate the measured resonance frequency and the calculated dynamic elastic modulus against temperature, respectively. The error bars in Figure 7-8 indicate standard deviation for four specimens. As expected by increasing temperature the dynamic elastic modulus of the material decreases. The results in Figure 7-8 clearly illustrate the capability of the AFV test method to capture the effect of temperature.

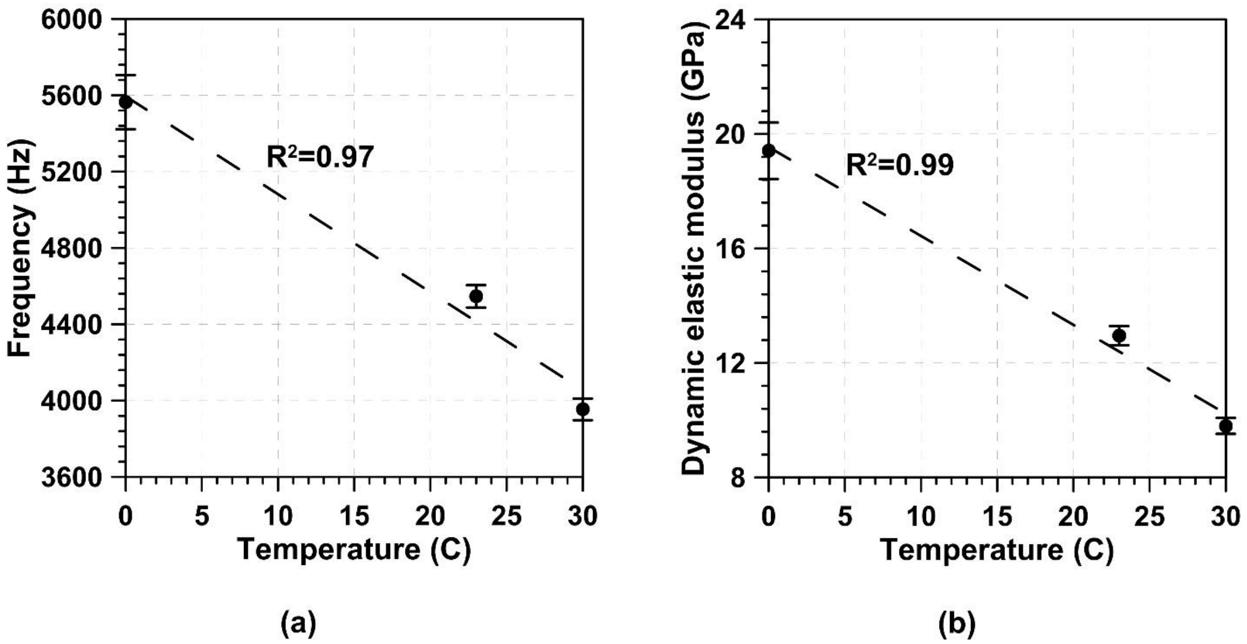


Figure 7-8 Effect of temperature on measured a) the measured resonance frequency, b) the measured dynamic elastic modulus

Asphalt concrete mixtures age with time due to various environmental conditions. The main reason for aging is oxidation of the asphalt binder in asphalt concrete due to the oxygen present in the air. Therefore, it is necessary to evaluate the sensitivity of AFV method in detecting the effect of aging on specimen's properties. Four HMA asphalt disk specimens were tested for the effect of aging. For this purpose, the samples were stored at room temperature and measurements were performed on the samples as a function of time. The effect of aging on the AFV measurements is shown in Figure 7-9 where measurements have been taken immediately after preparation, and after 3, 7, 30, 60, 90 and 120 days. Figure 7-9a and b illustrate the resonance frequency and calculated dynamic elastic modulus at different ages, respectively. The measurements show that the material becomes "stiffer" with aging. This observation indicates that AFV is sensitive enough to capture the effect of aging of asphalt concrete disks.

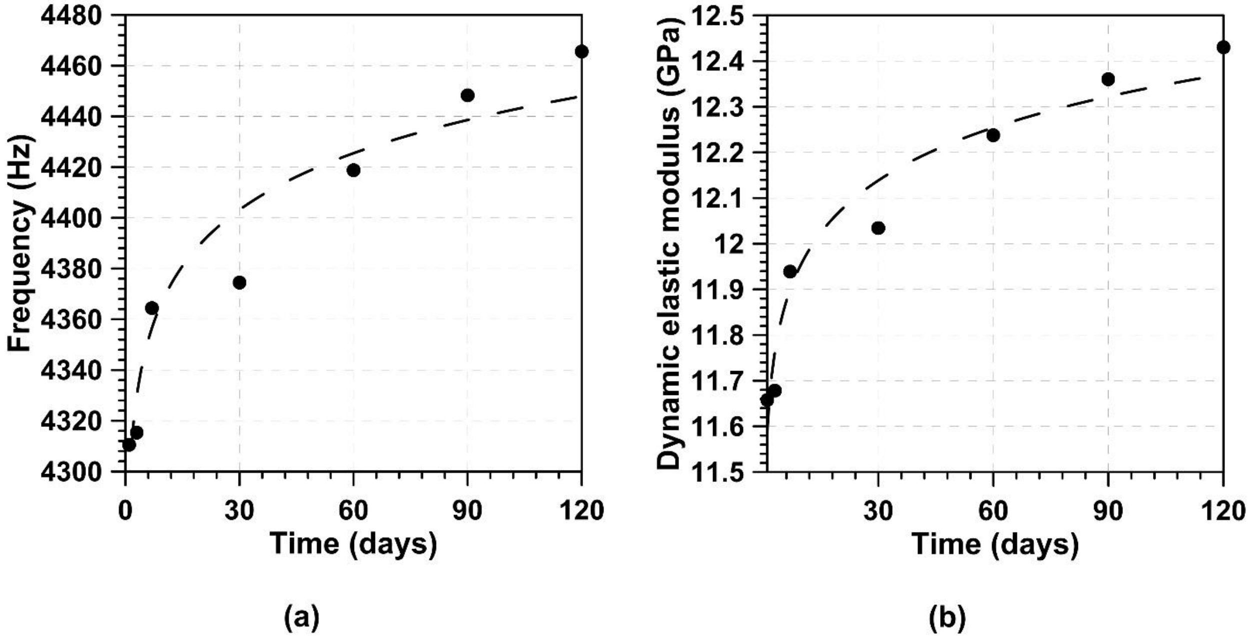


Figure 7-9 Effect of aging at room temperature measured using IRA method: (a) resonance frequency, (b) dynamic elastic modulus

8. E* Stiffness Ratio Test

In this section, details on the performance test based on dynamic modulus ratio of specimens that were specifically prepared to evaluate moisture damage are presented. These specimens were prepared at 7±0.5% air voids. The dynamic modulus values were determined for unconditioned and moisture-conditioned specimens using AASHTO T283 conditioning procedure.

Dynamic modulus is a fundamental material property used in various performance prediction models, such as the Mechanistic-Empirical Pavement Design Guide, to predict pavement distresses. It can also be used to directly compare the stiffness of different mixtures using the E* stiffness ratio (ESR) parameter. Dynamic modulus testing was performed using the Asphalt Mixture Performance Tester (AMPT) device.

8.1 Specimen Preparation and Conditioning

Specimens for ESR test were prepared per the procedure described in AASHTO TP 79-09, *"Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)"*. The specimens were initially compacted to a height of 178 mm with a diameter of 150 mm using the Superpave gyratory compactor and were cut and cored to dimensions of 150 ± 2.5 mm height and 100 ± 1 mm diameter for testing. The target air void content for ESR test was selected as 7 ± 0.5 % for the finished (cut and cored) specimens to ensure adequate saturation for testing in the moisture-conditioned (wet) state.

Conditioning of the mixtures during specimen preparation and testing was done as per the NCDOT modified AASHTO T-283 procedure. For preparing specimens for the saturated test, specimens were saturated using a vacuum to obtain 70-80% saturation. The saturated specimens were placed in a water bath at 60^{o}C for 24 hours.

Since the dynamic modulus test is a non-destructive test unlike the AASHTO T-283 Tensile Strength Ratio test, the same specimens were used for testing in both dry and wet conditions.

8.2 ESR Test Results

Table 8-1 shows the results of ESR test for all the mixtures. The dynamic modulus values shown in the table are averages of two specimens tested for each mix type. The dynamic moduli obtained from moisture-conditioned specimens are highlighted. The ESR ratio was calculated using the dynamic modulus values for the dry and wet specimens at 20^{o}C and 1 Hz frequency. These variables were used as they represent the service traffic and climatic conditions. Table 8-2 shows a comparison of TSR and average ESR values across all test temperatures for the nine mixtures.

The ESR value for HMA, FOAM, and Crabtree with LOF mixtures at 20^{o}C and 1 Hz frequency was greater than 85%. Crabtree without LOF was the only mixture that had an ESR value less than 85% at 20^{o}C and 1 Hz frequency. The Crabtree mixture without antistrip additive is known to be highly moisture sensitive. However, it should be noted that the ESR ratios are higher than the TSR results due to the mode of loading. The AMPT test is conducted in the compressive mode of loading and reflects the aggregate gradation and interlock; whereas, the TSR test is conducted in indirect tension mode of loading. Therefore, the ESR ratio may be a better indicator of the structural integrity of the pavement system at least for rutting and bearing capacity.

Table 8-1 E* Stiffness Ratio Test Results

Mix Type	Temp (ºC)	Specimen State	Dynamic Modulus (MPa)					
Frequency (Hz)			25	10	5	1	0.5	0.1
HMA	4	Dry	15,120	13,829	12,776	10,158	9,001	6,419
		Wet	14,377	13,098	12,069	9,554	8,459	6,032
	20	Dry	7,375	5,968	4,994	3,117	2,490	1,427
		Wet	6,928	5,610	4,698	2,937	2,344	1,331
	40	Dry	2,126	1,545	1,207	680	536	320
		Wet	1,998	1,444	1,119	612	472	265
FOAM	4	Dry	10,495	9,134	8,109	5,853	4,973	3,233
		Wet	9,469	8,169	7,208	5,134	4,342	2,799
	20	Dry	3,842	2,959	2,394	1,408	1,107	625
		Wet	3,336	2,558	2,065	1,211	951	536
	40	Dry	938	677	530	305	243	150
		Wet	805	581	453	259	205	125
Crabtree LOF	4	Dry	13,998	12,742	11,733	9,271	8,200	5,836
		Wet	13,677	12,368	11,324	8,815	7,745	5,435
	20	Dry	6,708	5,425	4,540	2,833	2,260	1,283
		Wet	6,277	5,043	4,205	2,631	2,115	1,246
	40	Dry	1,927	1,392	1,079	591	457	258
		Wet	1,817	1,342	1,066	630	508	320
Crabtree w/ LOF	4	Dry	15,255	14,067	13,090	10,621	9,507	6,952
		Wet	12,891	11,707	10,773	8,541	7,583	5,475
	20	Dry	7,910	6,494	5,490	3,491	2,799	1,593
		Wet	6,253	5,108	4,311	2,748	2,210	1,264
	40	Dry	2,391	1,729	1,338	722	553	304
		Wet	1,891	1,371	1,061	563	424	218

Table 8-2 Comparison of TSR and ESR Test Results

Mix Technology	LOF	TSR (%)	ESR (%)
HMA	Yes	87.8	94.2
FOAM	No	36.3	86
Crabtree	Yes	92	92.9
Crabtree	No	56	78.7

9. Pavement Performance Prediction

Dynamic modulus (|E*|) is an important parameter used in performance prediction models to predict pavement distresses over a specified design period. In this study, dynamic modulus testing was performed using the AMPT device per AASHTO TP 79-09, "Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)". Test details and specimen is described in section 8.

Dynamic modulus test was conducted on the mixtures at three temperatures: 4, 20 and 40°C and six frequencies: 25, 10, 5, 1, 0.5 and 0.1 Hz. The data obtained from the test were used to develop E* mastercurves at a reference temperature of 21°C (70°F) using a non-linear optimization procedure according to AASHTO PP 61-09, "Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)".

The data used to generate the mastercurves and the mastercurves are presented at the end of the report in the Appendix. This mastercurve data was used in AASHTOWare Pavement ME software to predict the performance of a typical pavement section with respect to two primary distresses, fatigue cracking and rutting.

9.1 Pavement Performance Prediction

The AASHTOWare Pavement ME software, which is based on Mechanistic-Empirical Pavement Design Guide (M-E PDG), was used to predict pavement performance in this study. A typical flexible pavement section for 9.5B mixtures as recommended by NCDOT was considered, and a weaker pavement section was used for evaluating the performance of the mixtures.

The pavement section used in this study is a three-layer flexible pavement consisting of an asphalt concrete layer, granular base course, and subgrade. Figure 9-1 shows the pavement section, including base and subgrade properties used in the analysis.

Traffic parameters, base and subgrade properties typically used for design of NCDOT traffic level B pavements were used as inputs for AASHTOWare analysis. The assumed pavement section was a four-lane highway with two lanes in each travel direction, having a two-way average annual daily truck traffic (AADTT) of 900, operating at 45 mph and increasing at an annual linear growth rate of 3%. Climatic data provided in the software for Raleigh-Durham Airport weather station was used.

A reliability of 90% was targeted for all distresses including fatigue (bottom-up and top-down), rutting (permanent deformation) and thermal cracking for all the analysis. Failure criteria were defined as 25% bottom-up cracking and 0.75 inches for total pavement rutting. Analysis runs were conducted using the E* data as Level 1 inputs for the topmost AC layer. Default Level 3 inputs were used for bottom two AC layers. Using a design life of 20 years for the pavement, months to failure was evaluated with respect to fatigue cracking and rutting for all nine mixtures.

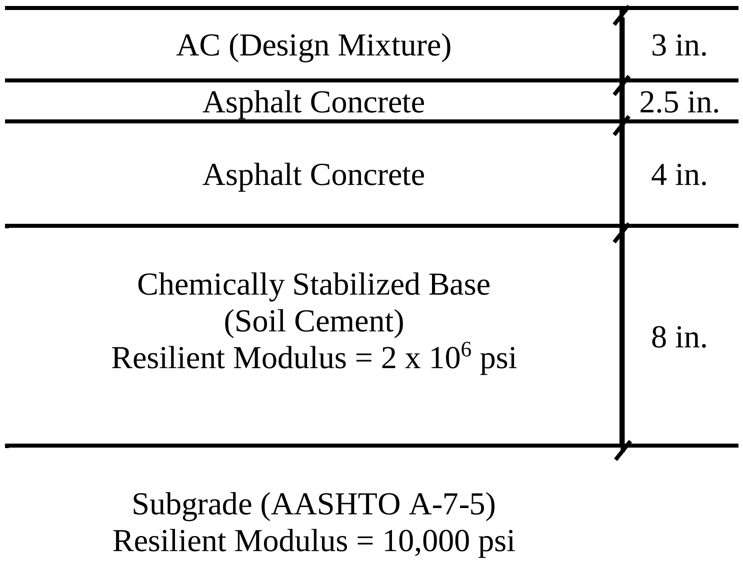


Figure 9-1 NCDOT Pavement Layer Structure for Performance Prediction

Table 9-1 shows the failure predictions as obtained from the analysis for the NCDOT pavement structure in the moisture-saturated state.

As can be seen from the failure predictions, none of the mixtures fail the target criteria for either fatigue or rutting even though the stiffness mastercurves used was for moisture conditioned mixtures. The amount of predicted permanent deformation in the total pavement varies slightly between HMA and both the Crabtree mixtures while the predicted permanent deformation for FOAM mixture was higher compared to the other three mixtures. The fatigue predictions are uniform for all the four mixtures.

Table 9-1 Fatigue and Rutting Failure Prediction for Typical 9.5B Pavement Structure (Conditioned)

Mix Type	Rutting (in.) Target: 0.75 in.	Fatigue (%) Target: 25%	Pass/Fail	Years to Failure
HMA	0.44	1.51	Pass	No Failure
FOAM	0.54	1.52	Fail	
Crabtree with LOF	0.45	1.51	Pass	No Failure
Crabtree no LOF	0.46	1.51	Pass	No Failure

To be able to observe trends in the performance of the mixtures, a weaker pavement structure with three layers as shown in Figure 9-2 was also analyzed.

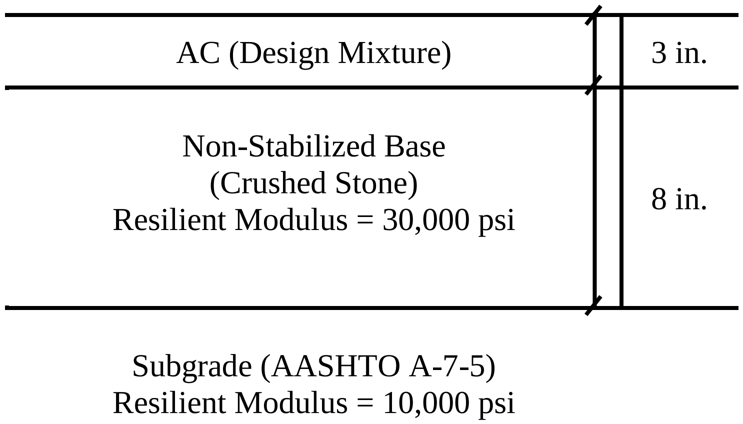


Figure 9-2 Weaker Pavement Layer Structure

The same inputs as used in the previous analysis were used and the rutting and fatigue failure criteria were evaluated. The results from AASHTOWare analysis with this structurally weaker pavement structure in the moisture-saturated state are shown in Table 9-2.

Table 9-2 Fatigue and Rutting Failure Prediction for a Weak Pavement Structure (Conditioned)

Mix Type	Rutting (in.) Target: 0.75 in.	Fatigue (%) Target: 25%	Pass/Fail	Years to Failure
HMA	0.80	27.20	Fail	14
FOAM	0.98	30.51	Fail	6
Crabtree with LOF	0.82	27.71	Fail	12
Crabtree no LOF	0.82	27.90	Fail	12

It may be observed that for the weaker pavement section, none of the mixtures are adequate when moisture conditioned and will not last the design life. Of importance is to note that the AASHTOWare software used with the dynamic modulus values evaluated using the AMPT (in the compressive mode of loading) is not able to differentiate the mixtures with and without antistrip additives even in the moisture conditioned state. It appears that the cohesive strength as measured in the compressive mode of loading in AMPT test overrides any adhesion weakness in the mixtures.

10. Summary, Conclusions, and Recommendation

In this research, two new methodologies were used to evaluate moisture sensitivity of asphalt-aggregate mixtures. The first approach used a commercially available colorimeter to quantify adhesive failure in asphalt concrete using the boil test. The second approach involved using the impact resonance (AFV) test to measure the adhesive and cohesive structural integrity of the compacted mixtures through evaluation of the intrinsic and fundamental stiffness measurement.

The colorimeter along with the boil test allows the control of adhesive failure between asphalt-aggregate due to moisture sensitivity of the mixtures even before a full-scale mixture design procedure is considered. The cohesive failure in a mixture that is predominantly based on the structural integrity of the compacted mixtures can be controlled by the AFV test. Separate or combined, these two tests are superior to the current TSR tests conducted using the AASHTO T283 test procedure currently followed in asphalt-aggregate mixture design.

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

1. The Boil Test with the use of colorimeter can be used as a preliminary quantifiable test to evaluate the compatibility between asphalt and aggregate.
2. Boil Test can be used to determine the amount of antistrip additive required, and even evaluate the most cost-effective antistrip additive that should be used.
3. If the TSR test is used as an acceptance or rejection criterion, then the damage ratio in the boil test should not exceed values of L^*_{RB} ratio of 10% or a CD^*_{RB} ratio of 5%.
4. The TSR value of a mixture can be estimated by measuring the damage ratio (L^*_{RT}) using a colorimeter on the fractured surface of a sample and should be more than 3.0.
5. Impact Resonance (AFV) test can be used to evaluate moisture sensitivity of asphalt concrete. This test measures both the adhesive and cohesive damage in mixtures including the structural integrating of the aggregate design structure (gradation) and is superior to the TSR test.

Based on the results of this study, a new NC asphalt-aggregate Mixture Design Procedure is proposed that is presented in Figure 10-1.

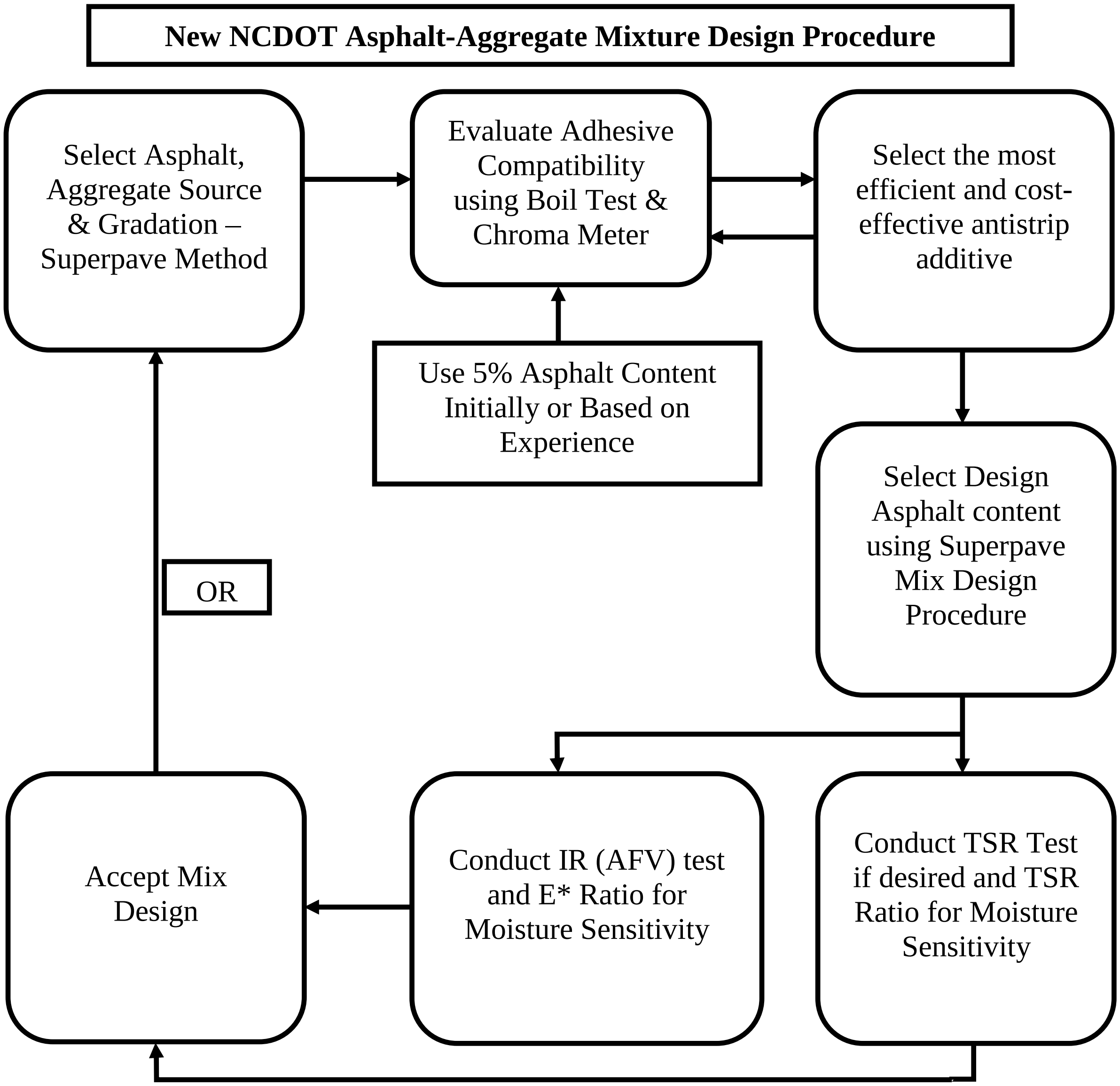


Figure 10-1 New NC Asphalt-Aggregate Mixture Design Procedure

Recommendations to NCDOT:

1. NCDOT needs to introduce the Boil Test as the first step in the design of asphalt-aggregate mixtures to control the adhesive failure due to moisture sensitivity rather than as a last step in the mix design process. The Boil Test takes a day whereas the TSR test takes 5-7 working days and that is a saving of 80% in time, resources, and manpower.
2. The Boil Test with the use of colorimeter can now be used to assess the effectiveness of antistrip additives including the cost benefits.

3. The impact resonance test (AFV) is a better indicator of cohesive failure in mixtures if the adhesive failure is controlled using the Boil Test. The impact resonance tests the complete structural integrity of the compacted mixtures compared to TSR test that only evaluates the tensile strength of the mixture. Therefore, NCDOT needs to consider replacing the TSR test with Impact Resonance test.
4. As a first step, NCDOT in their Job-Mix-Formula worksheet should require the value of L^*_{RB} to be less than equal to 10, and the L^*_{RT} value to be less than 3.
5. The methodology presented in this report can be used effectively by NCDOT for quality control/assurance for the field produced mixtures easily by using the Boil Test and colorimeter device to ascertain that the correct amount of antistrip additive is used.
6. The methodology identified herein can also be used easily with minimum effort to identify if the mixtures do contain antistrip additive.

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APPENDIX A – Material Characterization

PG 64-22 binder, granite aggregates and pond fines passing 75µm were used in this study. The aggregates were from two different quarries – Garner, NC and Crabtree, NC. Details about the materials used in the study are presented below. Two different anti-strip additives were used in this study to prepare the mixtures – LOF 6500 (0.75% by weight of binder) and a proprietary antistrip additive (varying percentages).

A.1 Aggregates

The aggregates were obtained from two different sources. The aggregates from Crabtree Quarry were highly moisture sensitive. The aggregates from the Garner Quarry were relatively less susceptible to moisture damage. The mixtures used in this study were designed for 9.5B (12.5 mm NMSA) surface course mixture. Three aggregates stockpiles were used for both the sources. The stockpile gradation and bulk specific gravity for these stockpiles specified in JMF were verified.

Representative samples from three stockpiles were used to verify the gradation of the aggregate stockpiles. ASTM C136-06, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates" [42] and ASTM C117-04, "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing" [43] procedures were used to do a washed sieve analysis on the dried representative samples to find out the gradation of the aggregate stockpiles.

The gradation of Manufactured Sand, Dry Screening and 78 M for the Garner aggregate source as determined are shown in the Tables A-1 to A-3. The gradation of Manufactured Sand, Dry Screening and 78 M for the Crabtree aggregate source as determined are shown in the Tables A-4 to A-6. Variability for the samples was low for all three stockpiles from both the aggregate sources. However, the overall gradation for the three stockpiles from the Garner quarry differed from that given in the JMF by a small extent. Thus, the gradation results as determined in the laboratory were used for preparing samples for further testing. For the Crabtree quarry materials, the JMF gradation was used. In addition to the three stockpiles, pond fines were used in the amount of 1.5% by weight of total aggregate that replaced the No. 200 passing virgin aggregates to increase the moisture susceptibility of the mixtures.

Table A-1 Gradation for Manufactured Sand for Garner Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100
3/8”	9.5 mm	100
No. 4	4.75 mm	100
No. 8	2.36 mm	93
No. 16	1.18 mm	73
No. 30	600 µm	49
No. 50	300 µm	24
No. 100	150 µm	8
No. 200	75 µm	3

Table A-2 Gradation for Dry Screenings for Garner Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100
3/8”	9.5 mm	100
No. 4	4.75 mm	97
No. 8	2.36 mm	77
No. 16	1.18 mm	59
No. 30	600 µm	44
No. 50	300 µm	30
No. 100	150 µm	19
No. 200	75 µm	12

Table A-3 Gradation for 78M Aggregates for Garner Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100
3/8”	9.5 mm	93
No. 4	4.75 mm	36
No. 8	2.36 mm	13
No. 16	1.18 mm	7
No. 30	600 µm	5
No. 50	300 µm	3
No. 100	150 µm	2
No. 200	75 µm	2

Table A-4 Gradation for Manufactured Sand for Crabtree Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100.0
3/8”	9.5 mm	100.0
No. 4	4.75 mm	100.0
No. 8	2.36 mm	85.0
No. 16	1.18 mm	66.0
No. 30	600 µm	49.0
No. 50	300 µm	30.0
No. 100	150 µm	11.4
No. 200	75 µm	3.3

Table A-5 Gradation for Dry Screenings for Crabtree Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100.0
3/8”	9.5 mm	100.0
No. 4	4.75 mm	100.0
No. 8	2.36 mm	80.0
No. 16	1.18 mm	52.0
No. 30	600 µm	37.0
No. 50	300 µm	28.0
No. 100	150 µm	19.0
No. 200	75 µm	10.9

Table A-6 Gradation for 78M Aggregates for Crabtree Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100.0
3/8”	9.5 mm	92.0
No. 4	4.75 mm	38.0
No. 8	2.36 mm	7.0
No. 16	1.18 mm	3.0
No. 30	600 µm	2.0
No. 50	300 µm	2.0
No. 100	150 µm	2.0
No. 200	75 µm	1.4

To calculate the bulk specific gravity of the aggregate gradation, the aggregates from each aggregate stockpile were divided into coarse and fine aggregates using the US Standard #4 sieve (4.75 mm). The bulk specific gravities of the coarse and fine aggregate portions were calculated separately and then a combined specific gravity was calculated using them. For pond fines, the bulk specific gravity provided by the quarry was used. The bulk specific gravity of the coarse aggregates was calculated per the procedure outlined in AASHTO T 85-14, “Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate”, [44] while the guidelines mentioned in AASHTO T 84-13, “Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate” [45] were used to calculate the bulk specific gravity of the fine aggregate portion. The combined specific gravity for an aggregate stockpile was calculated using the following equation.

$$\frac{100}{Gsb} = \frac{c}{G_c} + \frac{f}{G_f}$$

where, c = percentage of coarse aggregate of the total aggregate, f = percentage of fine aggregate, G_c = specific gravity of Coarse aggregate fraction, G_f = specific gravity of Fine aggregate fraction.

The bulk specific gravity for the total aggregates was calculated using the blend ratio of the stockpiles and their corresponding bulk specific gravities. The blend ratio was calculated using all the three aggregate stockpiles in addition to the pond fines. The bulk specific gravity of the aggregates from Garner Quarry came out to be 2.640 and for the aggregates from Crabtree Quarry came out to be 2.664

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

Use of an antistrip additive, 0.75% by weight of binder was recommended in the JMF for all mixtures. The anti- strip additive used in this study was AD-here® LOF 6500, manufactured by ArrMaz Custom Chemicals. Additionally, a proprietary antistrip additive was also used for the boil test.

A.3 Colorimeter

In this research study, a commonly available colorimeter device (also known as “Chroma Meter”) – CR400 (Konica Minolta) shown in Figure 2-1 was used. There are many other similar devices manufactured and sold by other companies that could also be used effectively. An ASTM standard ASTM E284-13b [46] – Standard Terminology of Appearance exists and was used to define color.

Color perception, simultaneous contrast and chameleon effect, are the three main effects that "deceive" the color perception, based on hue, background on which the sample is placed on, and the light source under which the sample is being observed. Due to these reasons, the human eye can view the same color differently under different conditions, and hence leads to the qualitative subjective interpretation of boil and other tests.

The use of colorimeter eliminates this human bias in color perception. In the colorimeter test, the background, hue and the light source is controlled. A standard light source that is emitted from the colorimeter device is used while measuring the color of the specimen. The background color effect is eliminated by placing the colorimeter's measuring orifice on the specimen such that the sample or the specimen is completely enclosed within the orifice of the colorimeter device.

ASTM E284-13b Standard elaborates several ways under the heading of "Chroma" to measure and analyze the colors. In this study, the most widely used CIE L*, a*, and b* method was used where the color is plotted on a graph with L*, a*, and b* as their axes. The L* axis determines the color index on light to dark axis; a* determines the redness to greenness index, and b* determines the blueness to yellowness index. The measurements are with respect to a standard white color. Before the use of the colorimeter for measurements, the device is calibrated using a standard white color calibration plate provided with the colorimeter.

Additional accessories may be required to protect the light from escaping the device while taking readings on uneven samples. This is because some samples such as broken half of TSR samples will not likely have a uniform surface. Although, the comparison (color readings) can be done based on different color measurement scales or combination with respect to L*, a*, and b* readings; in this study, the results are analyzed and presented based on only the L* readings that measure color index based on gray scale. However, when colored aggregates or the asphalt cement is used, a more complex approach can be used that include a* and b* colorimeter parameters (ASTM E284-13b).

APPENDIX B – Superpave Mixdesign

This section describes the Superpave mix design method of the four mixtures used in this study. The optimum asphalt content given in the JMF was used for prepared specimens with aggregates from Garner Quarry and Crabtree Quarry using the Superpave mix design method. The volumetric properties were verified for the corresponding FOAM mixture for the mix produced using aggregates from Garner Quarry.

B.1 Mixture Design

B.1.1 Aggregates

All the mixtures were designed as Asphalt Concrete Surface Course, type NCDOT RS 9.5B mixtures. The design aggregate gradation was provided in the JMF for mixtures and is shown in Figure B-1. A blend ratio for the three aggregate stockpiles and the pond fines was calculated such that the resultant gradation was close to the target gradation and within all the control points.

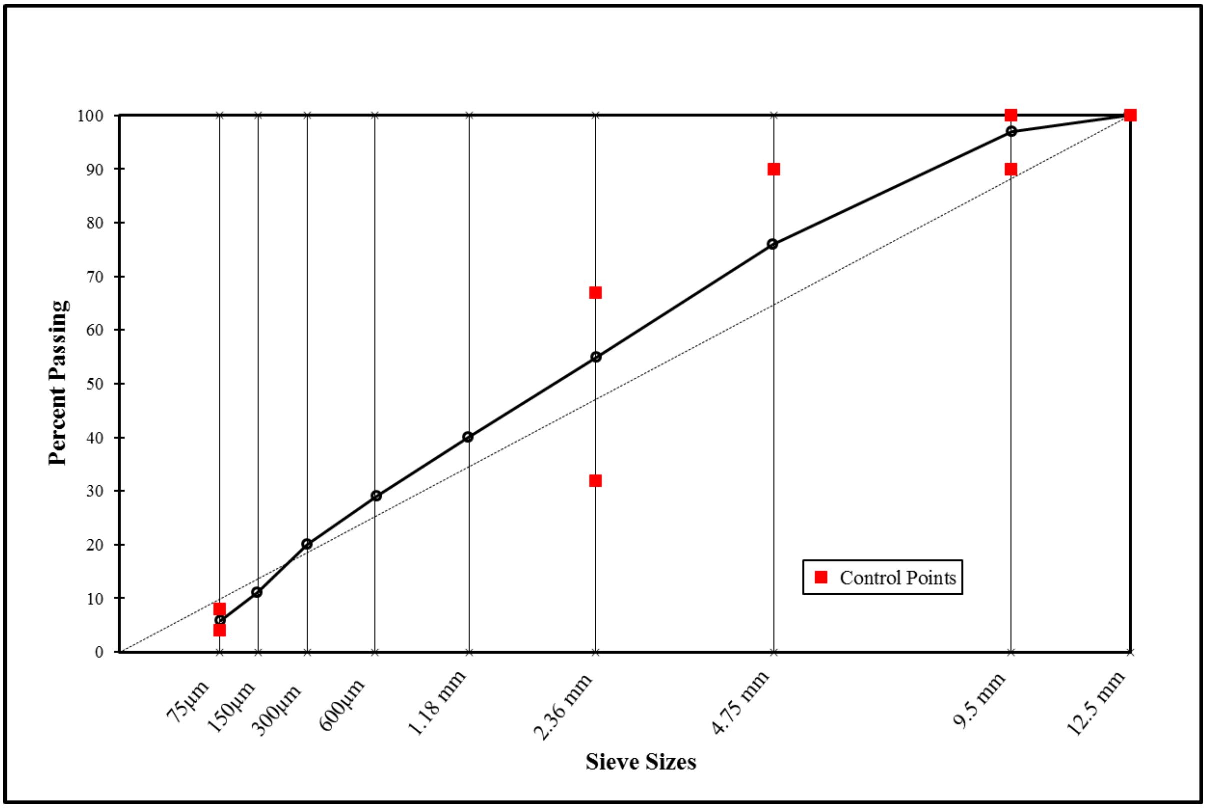

Figure B-1 Design aggregate gradation for the mixtures

B.1.2 Asphalt Binder

The mixing and compaction temperatures for the hot mix asphalt were provided by NCDOT for the 9.5 B mix. The mixing and compaction temperatures for PG 64-22 were 163°C (325°F) and 149°C (300°F), respectively.

Per NCHRP Report 714 [47], mixing and compaction temperatures of WMA mixtures cannot be calculated based on rotational viscosity test results and hence the temperatures reported by the manufacturers are suggested to be used. Since mixtures produced the PTI Foamer have mixing and compaction values around 135°C (275°F) and 120°C (248°F) respectively; these values were selected as the mixing and compaction temperatures in this study.

5.1.3 Air Void Calculation

The theoretical maximum specific gravity (G_{mm}) was calculated according to AASTO T 209 - 05, "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot-Mix Asphalt Paving Mixtures" [48]. Two loose mixtures were tested according to this procedure to find out the G_{mm} of the mix. AASHTO TP 69-04, "Standard Method of Test for Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method," [49] was used to calculate the bulk specific gravity (G_{mb}) of the compacted asphalt mixture specimens. CoreLok® device manufactured by InstroTek Inc. was used to vacuum seal the compacted asphalt mixtures for measuring the bulk specific gravity.

The percentage air voids were calculated using the calculated G_{mm} and G_{mb} values as per the following equation.

$$\% \, Air \, Voids = \frac{G_{mm} - G_{mb}}{G_{mm}}$$

The G_{mm}, G_{mb}, and the percent air void values for the mixtures with their asphalt content are given in Table B-1.

Table B-1 Air void content, G_{mb}, and G_{mm} for the mixtures

Mixture Type	Average G_{mm}	Measured G_{mb}	Air void content	Optimum Asphalt Content
HMA	2.425	2.330	3.9	6.0
FOAM	2.410	2.316	3.9	6.0
Crabtree w/LOF	2.430	2.331	4.1	6.4
Crabtree w/o LOF	2.430	2.326	4.3	6.4

B.1.4 Volumetric Properties

Volumetric properties required for the Superpave mix design were calculated for the HMA using the asphalt content as per the NCDOT QMS Manual. The calculated properties were checked with the design requirements specified in Superpave. The design limits for volumetric properties were chosen based on the design traffic level of 0.3 to 3 million ESALs as specified in the JMF. All volumetric properties were within the limits. Per NCHRP Report 691 [50], the mix design process for WMA mixtures is same as that of HMA mixtures. Therefore, the volumetric properties requirements for WMA are same as that of HMA. The volumetric properties of all the four mixtures were within the design limits.

The volumetric properties of all the mixtures are summarized in Table B-2.

Table B-2 Summary of Volumetric Properties

Mix Properties at N_{design}	**Asphalt Concrete Mix Technology**				**Volumetric Requirements**
	HMA	FOAM	Crabtree w/LOF	Crabtree no LOF	
G_{mb} @ N_{design}	2.330	2.316	2.331	2.326	
Max. Specific Gravity, G_{mm}	2.425	2.410	2.430	2.430	
% VTM	3.9	3.9	4.1	4.3	4.0 ± 0.5
% VMA	17.0	17.5	18.45	18.28	> 15.0%
% VFA	64.8	65.8	76.80	77.92	65-78%
% G_{mm} at N_{ini} (7)	89.5	89.5	89.2	88.1	≤ 89.0%
% G_{mm} at N_{des} (65)	96.1	96.1	96	96.2	96%

APPENDIX C – THEORY FOR DIFFERENT TESTS

C.1 TSR TEST

C.1.1 Specimen Preparation

The TSR test requires two sets of specimens for every mixture. One set was tested dry, while the other set was saturated before testing. Five specimens were prepared for each set and hence 10 specimens were prepared for each mixture. 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 that was used for mix design and the optimum asphalt content using the Superpave mix design.

As per standard specifications, the loose mixtures were prepared at their respective mixing temperatures (163°C for HMA and 136°C for WMA). After mixing, the mixtures were heated for 2 hours to their respective compaction temperatures (149 °C for HMA and 120 °C for WMA) and then compacted to a height of 95 ± 5 mm using the Superpave gyratory compactor.

C.1.2 Test Procedure

Two specimens whose air voids had the most deviation from the targeted value of 7.0% were eliminated from the 10 specimens for each mixture. The 8 specimens for each mixture were divided randomly into two sets of 4 specimens each. One set was kept dry and tested at room temperature i.e. 25 °C (77 °F), while the other set was moisture conditioned before testing. As per the NCDOT specifications, 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).

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%.

C.1.3 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.

Tables 6-2 to 6-8 show the TSR test results for all the mixtures.

C.2 Impact Resonance Test

In this study, a circular disk geometry was used. This geometry enables direct estimation of dynamic elastic modulus based on the measured resonance frequency (*f*) from the impact testing and termed as axisymmetric flexural vibration (AFV) test and using equation C-1 [21, 22].

$$E_d = 2(1+\upsilon)\rho\left(\frac{\pi f d}{\Omega_o}\right)^2 \qquad \text{Equation C-1}$$

where ν is the Poisson's ratio, *d* is the circular disk diameter, ρ is the mass density of the disk, and Ω_o is the dimensionless resonance frequency parameter (resonance frequency parameter hereafter).

The resonance frequency parameter (Ω_o) is estimated for a given geometry using the axisymmetric flexural vibration of thick free circular plate equations [20]. This solution algorithm to compute Ω_o is identical to the solution proposed by Huchinson [20] and the solution used by Leming [21]. Using this algorithm, the value of Ω_o was computed for a wide range of geometries.

Figure C-1 schematically illustrates frequency spectrum for an intact and a damaged asphalt disk specimen. With increasing damage, the reduction of the resonance frequency (*f*) is clear. This reduction in resonance frequency, in equation C-1, translates to a reduction of the dynamic elastic modulus.

From equation C-1 it is evident that the elastic modulus is proportional to the square of frequency (*f*), and so the relative reduction in elastic modulus can be calculated using equation C-2.

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

where E_d^c and f^c are dynamic elastic modulus and the resonance frequency of conditioned disk specimen and E_d^0 and f^0 are dynamic elastic modulus and the resonance frequency of intact specimen. The ratio (ER) form equation C-2 can be used to compare the results of the impact resonance test method with the TSR results.

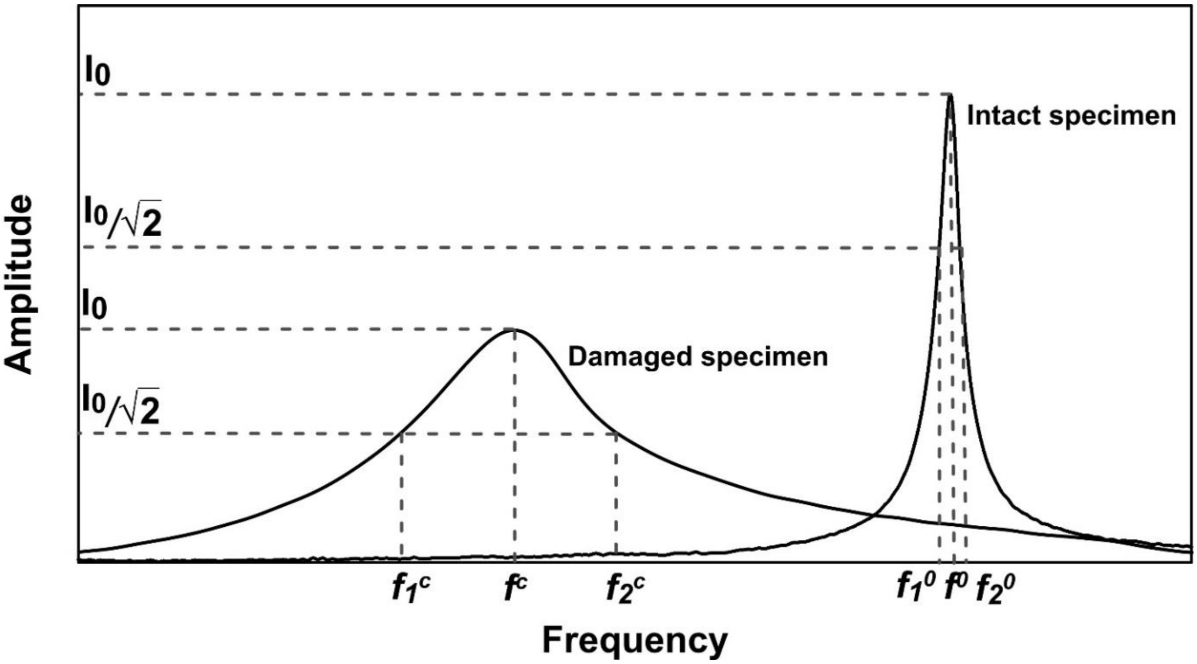

Figure C-1 Schematic illustration of resonance frequency and *Q* factor change by increasing damage in specimen

Resonance frequency parameter (Ω_o) is estimated by solving equation C-4. This equation describes the axisymmetric flexural vibration of a thick circular plate [20].

$$K\left(\psi'+\frac{\psi}{r}+\omega''+\frac{\omega'}{r}\right)+\Omega^2\omega=0 \quad \text{Equation C-3}$$

$$\frac{2}{1-\upsilon}\left(\psi''+\frac{\psi'}{r}-\frac{\psi}{r^2}\right)-\frac{3K\left(\psi+\omega'\right)}{h^2}+\Omega^2\psi=0 \quad \text{Equation C-4}$$

where r, ω and ψ are, respectively, dimensionless radial coordinate, dimensionless axial displacement, and dimensionless radial displacement of the disk; h is the thickness to diameter ratio of the disk; K is the shear coefficient of the disk; Ω is the dimensionless frequency parameter, and primes indicate the differentiation with respect to r.

Figure C-2 shows the solution for resonance frequency parameter (Ω_o) for different diameters and for Poisson's ratios of 0.25 and 0.35.

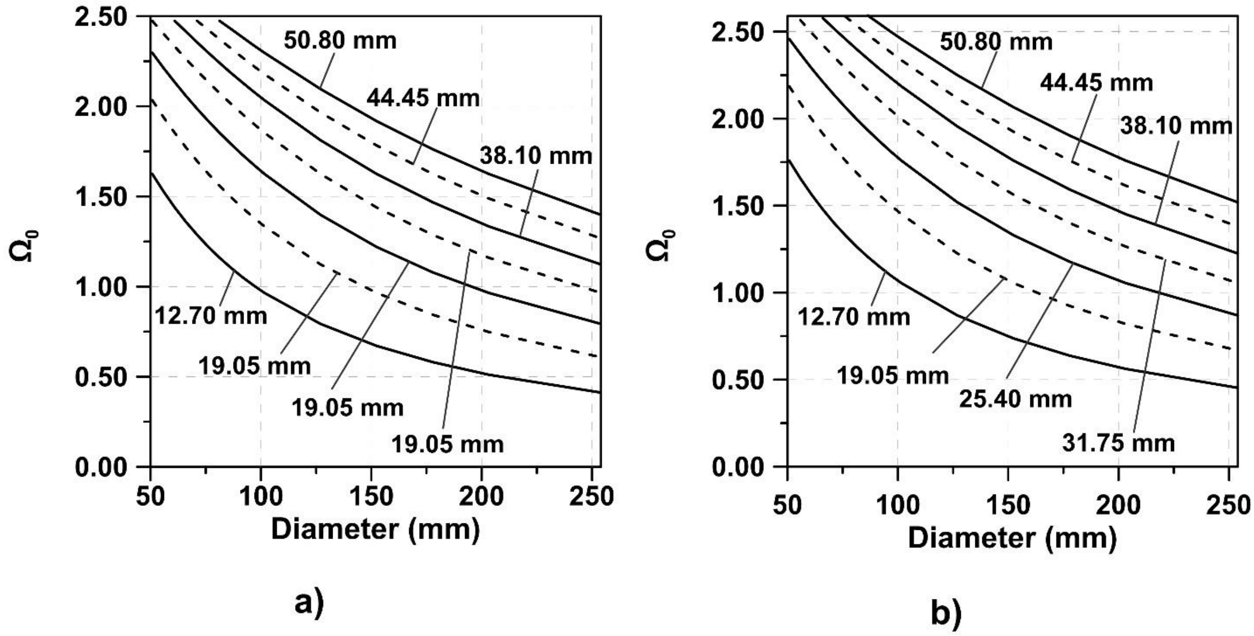

Figure C-2 Computed resonance frequency parameter of most available disks for a) ν = 0.25 and b) ν = 0.35

C.2.1 Validation of AFV Technique

The AFV technique, in principle, is applicable to a wide range of materials. However, it is important to ensure that the test setup is error free and potential nonlinearities of equipment and test setup does not affect the results adversely. A rather simple validation method of the test setup is performing measurements linear elastic materials such as aluminum. In this section, therefore, measurements are performed on a circular aluminum disk with an elastic modulus of approximately 76 GPa, 2.5 cm thickness, 10.2 cm diameter, and Poisson ratio of 0.33.

Five impacts with different intensities were used to accelerate the disk. The response of the disk was recorded in the time domain using an oscilloscope. Figure C-3b shows one of the time domain signals from an accelerometer. Figure C-3c illustrates the frequency domain response of the aluminum disk obtained using FFT for multiple impacts. It is noted that all the impacts result in the same resonance frequency (approximately 17.6 kHz), indicating that the value of resonance frequency in independent of the impact intensity (i.e., the test setup is linear). The resonance frequencies were used to calculate the elastic modulus of the aluminum disk using equation C-1 and are plotted in Figure C-3a. The proposed method estimated approximately 76 GPa elastic modulus for all impacts which is close to the actual elastic modulus of the material.

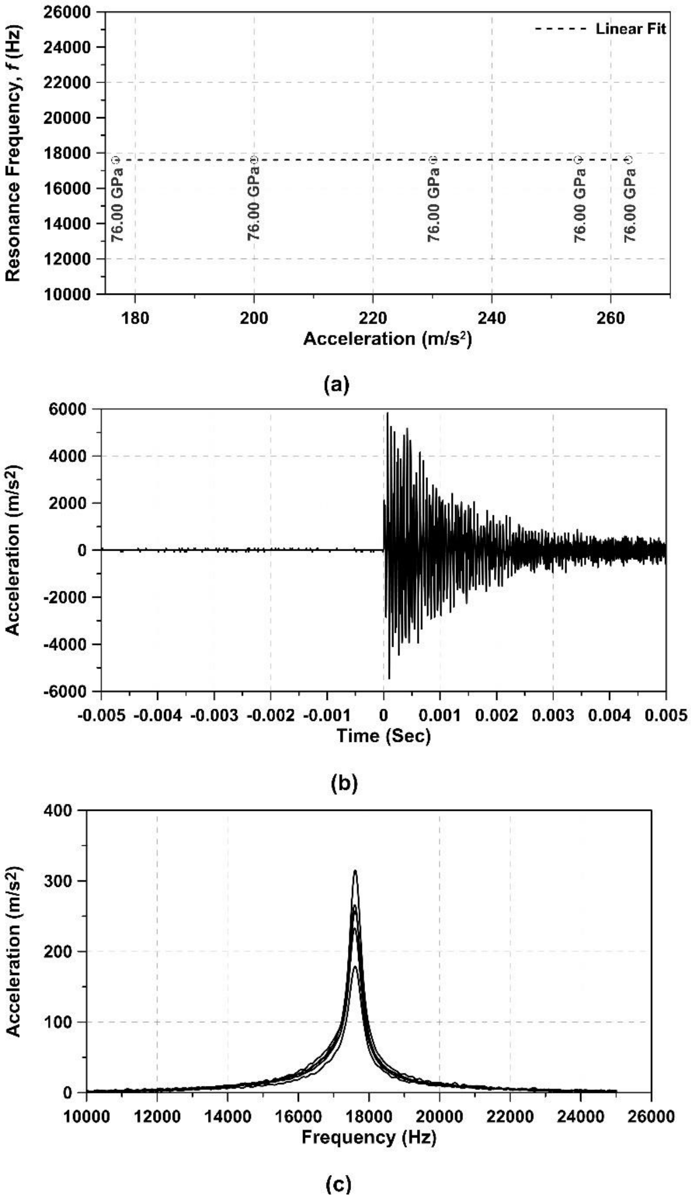

Figure C-3 a) Computed elastic modulus of the disks with respect to the resonance frequency and acceleration magnitudes of the impacts. b) Vibration signal of an impact recorded by oscilloscope c) Frequency spectrum of all impacts

C.3 Asphalt Mixture Performance Tester (AMPT)

The AMPT device is a computer-controlled hydraulic test system capable of applying cyclic loading on cylindrical asphalt concrete specimens over a range of test temperatures and loading frequencies. The device measures the dynamic modulus, E* which is a ratio of the amplitude of cyclic stress applied to the amplitude of cyclic strain at each test temperature and frequency as well as the phase angle, φ. Figure C-4 shows a sinusoidal loading cycle applied using the AMPT device, where E* is calculated using Equation C-5:

$$E^* = \frac{\sigma_0}{\epsilon_0} \qquad \text{Equation C-5}$$

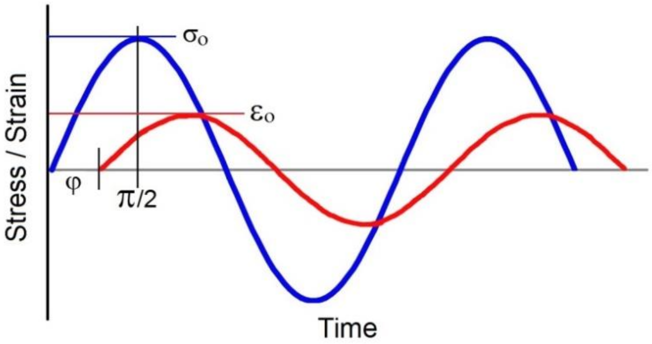

Figure C-4 Schematic Diagram of Stress and Strain in Asphalt Concrete

Test specimens for measurement of E* using the AMPT are fabricated to dimensions of 100 mm diameter and 150 mm height. Specimens in the Superpave gyratory were first compacted to a height of 178 mm and diameter of 150 mm, and then cored and sawed to the required dimensions for testing as per AASHTO TP 79.

The AMPT applies cyclic loading using a hydraulic actuator in a stress-controlled mode such that the axial strain in the specimen does not exceed a predetermined value. The axial strain is measured by placing linear variable displacement transducers (LVDTs) along the vertical length of the specimen. Three LVDTs are mounted onto the specimen using brass targets so that they measure displacements over a gauge length of 70 mm, which in turn is used to calculate the axial strain. The strain amplitude is reported as the average of the four LVDTs.

C.3.1 ESR Test Description

Moisture susceptibility of the asphalt mixtures was evaluated using the AASHTO T-283 Tensile Strength Ratio (TSR) test, as described in Section 4. Research studies have shown that WMA produced using moisture-inducing technology such as zeolites and foamed asphalt perform poorly when subjected to the TSR test. Recently, researchers have tried using E* stiffness ratio (ESR) test evaluate moisture susceptibility [54, 55].

The ESR test is conducted on conditioned and unconditioned subsets of specimens, which are subjected to AASHTO T283 test procedure. ESR is defined as the ratio of average dynamic modulus of conditioned (wet) specimens to the average dynamic modulus of unconditioned (dry) specimens. Since dynamic modulus measured using the AMPT is measured at three temperatures and three frequencies for each specimen, ESR values are reported as averages for each test temperature.

$$ESR = \frac{Average\ |E^{*}| of\ wet\ specimens\ at\ a\ test\ temperature\ and\ frequency}{Average\ |E^{*}| of\ dry\ specimens\ at\ a\ test\ temperature\ and\ frequency}$$

Appendix D - Boil Test Procedure

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

1. Prepare a 450 gram of loose asphalt concrete mixture and divide it into two equal parts using the quartering method. Boil one-half of the loose asphalt concrete mixture as per the boil test procedure mentioned. Keep the other half 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 190ºC. Heat for 30 minutes at 190ºC.

4. Simultaneously heat the asphalt mixture to 85ºC.

5. Heat a hot plate to 190ºC (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. Increase the temperature to 220ºC and 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. Keep stirring every 2-3 minutes using a glass rod and keep removing the asphalt accumulated on the surface of the water using a clean cloth or paper towel. Stir the water using a glass rod to maintain the water temperature since a hot plate is being used. The water should be stirred carefully such the asphalt mixture is not disturbed. Remove the accumulated asphalt regularly to avoid settling down of the stripped asphalt.

9. The standard boiling time is 10 minutes ± 15 seconds.

10. 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.

11. 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.

12. 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.

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

14. 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.

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

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

APPENDIX E – MASTERCURVES

Table C-1 Dynamic Modulus Test Results - 7 Percent Air Voids (Unconditioned)

Mix Type	Temp (°C)	Dynamic Modulus (MPa)					
Frequency (Hz)		25	10	5	1	0.5	0.1
HMA	4	15,120	13,829	12,776	10,158	9,001	6,419
	20	7,375	5,968	4,994	3,117	2,490	1,427
	40	2,126	1,545	1,207	680	536	320
FOAM	4	10,495	9,134	8,109	5,853	4,973	3,233
	20	3,842	2,959	2,394	1,408	1,107	625
	40	938	677	530	305	243	150
Crabtree with LOF	4	13,998	12,742	11,733	9,271	8,200	5,836
	20	6,708	5,425	4,540	2,833	2,260	1,283
	40	1,927	1,392	1,079	591	457	258
Crabtree w.o. LOF	4	15,255	14,067	13,090	10,621	9,507	6,952
	20	7,910	6,494	5,490	3,491	2,799	1,593
	40	2,391	1,729	1,338	722	553	304

Table C-2 Dynamic Modulus Test Results - 7 Percent Air Voids (Conditioned)

Mix Type	Temp (°C)	Dynamic Modulus (MPa)					
Frequency (Hz)		25	10	5	1	0.5	0.1
HMA	4	14,377	13,098	12,069	9,554	8,459	6,032
	20	6,928	5,610	4,698	2,937	2,344	1,331
	40	1,998	1,444	1,119	612	472	265
FOAM	4	9,469	8,169	7,208	5,134	4,342	2,799
	20	3,336	2,558	2,065	1,211	951	536
	40	805	581	453	259	205	125
Crabtree with LOF	4	13,677	12,368	11,324	8,815	7,745	5,435
	20	6,277	5,043	4,205	2,631	2,115	1,246
	40	1,817	1,342	1,066	630	508	320
Crabtree w.o. LOF	4	12,891	11,707	10,773	8,541	7,583	5,475
	20	6,253	5,108	4,311	2,748	2,210	1,264
	40	1,891	1,371	1,061	563	424	218

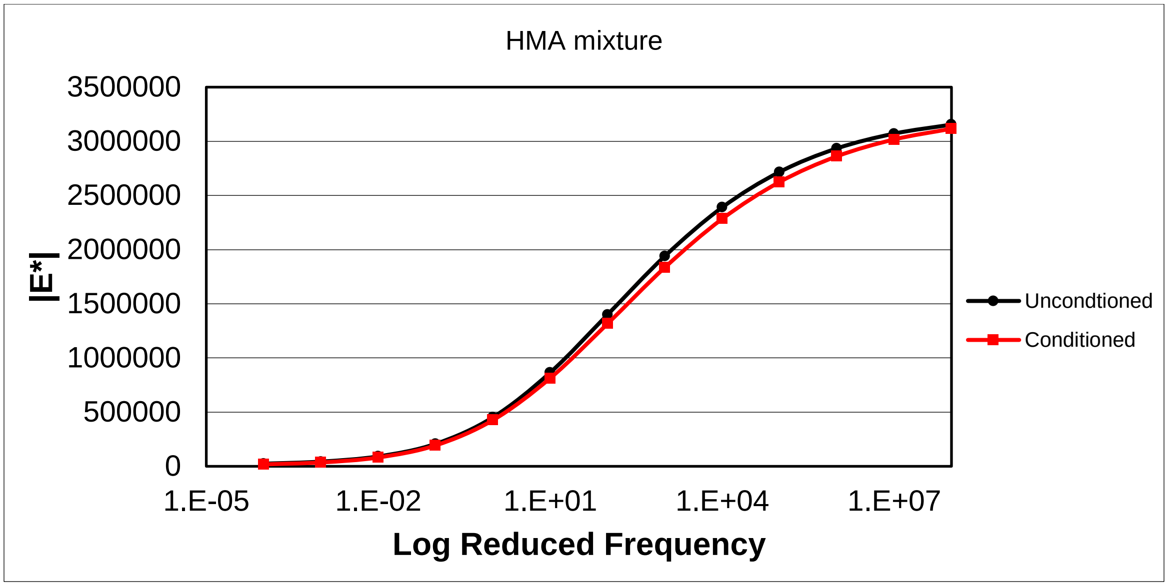

Figure C-1 Mastercurve for HMA mixture

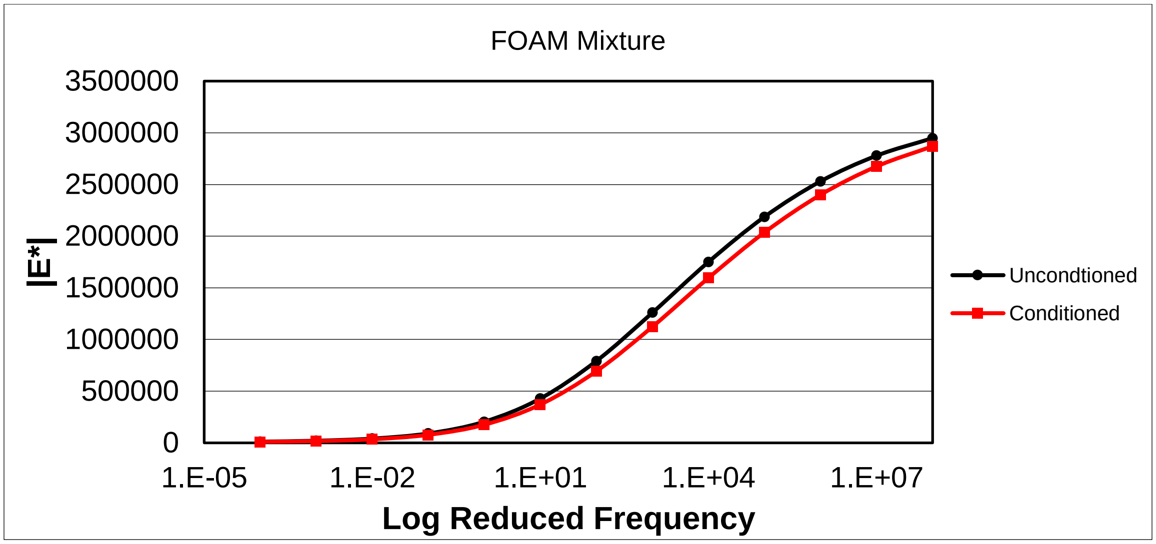

Figure C-2 Mastercurve for FOAM mixture

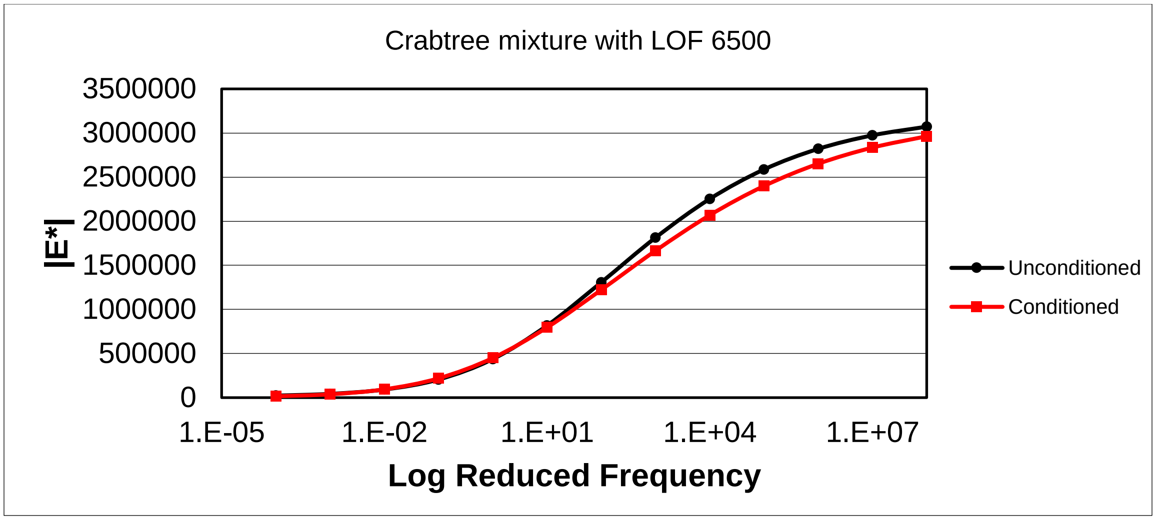

Figure C-3 Mastercurve for Crabtree mixture with LOF 6500

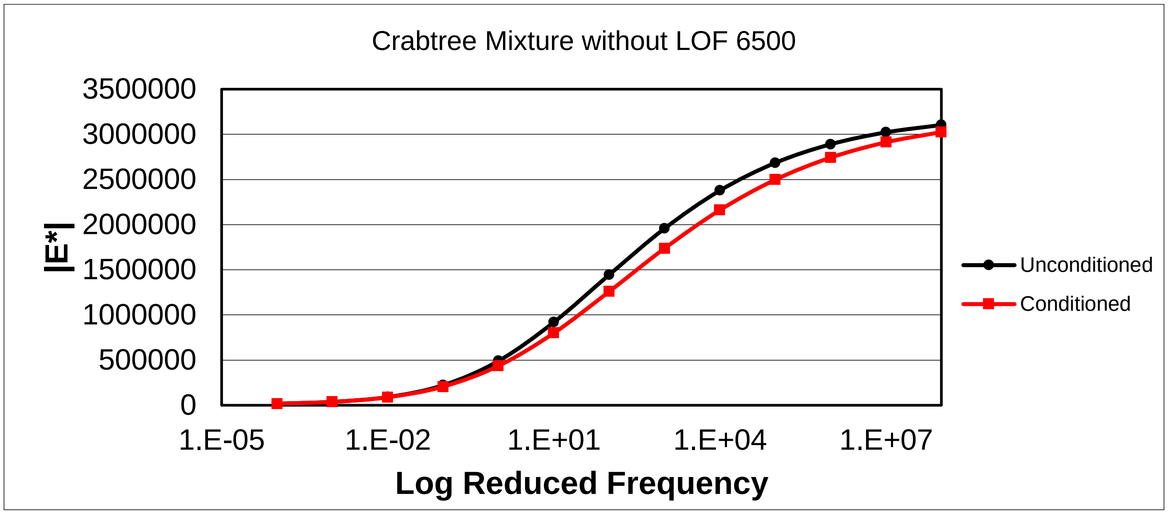

Figure C-4 Mastercurve for Crabtree mixture without LOF 6500