RESEARCH & DEVELOPMENT

Quality Control of Field Asphalt Mixtures and Compatibility of Aggregates and Emulsions using Asphalt Compatibility Tester

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16. Abstract

The objectives of this project are to: (1) Establish a procedure to identify the optimum antistrip additive content for a given asphalt mixture and antistrip additive combination; (2) Evaluate the moisture damage resistance of plant-produced asphalt mixtures to establish a preliminary protocol for quality assurance and control; and (3) Develop an objective means to quantify emulsion-aggregate compatibility in lieu of the visual assessment procedure currently specified in NCDOT A-24 procedure. Laboratory-mixed, laboratory compacted mixtures were used to establish an antistrip dosage selection procedure for Boil test results coupled with Asphalt Compatibility Tester (ACT) color measurements.

Boil tests coupled with indices calculated from Asphalt Compatibility Tester (ACT) color measurements are correlated with Tensile Strength Ratio (TSR) test results. Limits for a moisture damage index calculated from Boil tests coupled with ACT measurements for laboratory-mixed samples to ensure a minimum TSR of 85 percent when using the NCDOT's modified AASHTO T 283 conditioning procedure were established that can be applied for antistrip dosage selection during asphalt mixture design. The limits could also be applied in lieu of TSR testing when there is a change in antistrip source or dosage if laboratory-mixed, laboratory-compacted samples are used. Furthermore, interlaboratory testing suggests Boil tests coupled with ACT measurements generally yield reproducible results. However, a relationship Boil test results coupled with ACT measurements are not correlated with the TSR results of plant-mixed asphalt mixtures and therefore, the limits cannot be extended to quality control and quality assurance testing of plant-produced asphalt mixtures. Five of the 11 plant-produced mixtures evaluated through TSR testing failed to meet the specified minimum limit of 85 percent when using the NCDOT's modified AASHTO T 283 conditioning procedure. Furthermore, six of the plant-produced mixtures failed to meet recommended TSR requirements when using the M.i.S.T. conditioning procedure. The NCDOT A-24 procedure coupled with ACT color measurements are effective in identifying poor compatibility in emulsion-aggregate blends, providing a potential means to remove the subjectivity of the current visual rating procedure. Criteria for identifying poor compatibility on the basis of ACT results were proposed. All field emulsion-aggregate blends evaluated that met these criteria also resulted in acceptable aggregate retention performance based on the Vialit test results of as-constructed chip seal samples. However, two aggregate-emulsion blends that failed to meet the criteria also resulted in acceptable Vialit aggregate retention test results, suggesting the preliminary limits may be overly stringent and require refinement.

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EXECUTIVE SUMMARY

The North Carolina Department of Transportation (NCDOT) currently uses the Tensile Strength Ratio (TSR) as the measure of the moisture damage resistance of asphalt mixtures. The NCDOT requires that contractors conduct TSR testing of laboratory-mixed, laboratory-compacted samples as part of mixture design to verify that minimum moisture damage resistance requirements are met. The NCDOT also requires TSR testing of plant-mixed, laboratory compacted samples within seven calendar days of the beginning of production each mixture design, when there is a change in antistrip additive source or dosage, and/or deemed necessary by the NCDOT as part of quality assurance and quality control (QA/QC) procedures. It would be advantageous if an alternative, more efficient test method could be employed for QA/QC of plant-produced mixtures and to establish the appropriate antistrip additive dosage during mixture design or when a change is made to the source of antistrip additive used. Recent NCDOT research projects (2014-04 and 2017-01) demonstrated promise for using the Boil test (ASTM D3625) coupled with color measurements to more efficiently assess adhesive moisture damage resistance of asphalt mixtures. However, the previous projects did not evaluate application of the Boil test to plant-produced asphalt mixtures. The use of color measurements is also potentially extensible to the evaluation of emulsion-aggregate compatibility. The NCDOT Materials and Tests Asphalt Procedure A-24 (herein after referred to as NCDOT A-24) is currently used to evaluate the compatibility of emulsion-aggregate blends using visual inspection of samples of emulsion and aggregate that are mixed and then rinsed. A limitation of this test method is that visual inspection is subjective. Correspondingly, the objectives of this project are to: (1) Establish a procedure to identify the optimum antistrip additive content for a given asphalt mixture and antistrip additive combination; (2) Evaluate the moisture damage resistance of plant-produced asphalt mixtures to establish a preliminary protocol for quality assurance and control, and (3) Develop an objective means to quantify emulsion-aggregate compatibility in lieu of the visual assessment procedure currently specified in NCDOT A-24 procedure.

Laboratory-mixed, laboratory compacted mixtures were used to establish an antistrip dosage selection procedure for Boil test results coupled with Asphalt Compatibility Tester (ACT) color measurements that ensure a minimum TSR of 85 percent is achieved when using the NCDOT's modified AASHTO T 283 moisture conditioning procedure. Indices calculated from Boil tests coupled with Asphalt Compatibility Tester (ACT) color measurements are correlated with Tensile Strength Ratio (TSR) test results. Limits for Boil tests coupled with ACT measurements for laboratory-mixed samples to ensure both a minimum TSR of 85 percent when using the NCDOT's modified AASHTO T 283 conditioning procedure and a minimum TSR of 80 percent when using the M.i.S.T. conditioning procedure were established that can be applied for antistrip dosage selection during asphalt mixture design. The limits could also be applied in lieu of TSR testing when there is a change in antistrip source or dosage if laboratory-mixed, laboratory-compacted samples are used.

Plant-produced mixtures were acquired and evaluated through TSR testing and Boil tests coupled with ACT measurements. Boil tests were conducted at both NCSU and NCDOT laboratories to evaluate the multilaboratory precision of the test. In addition, plant-produced, laboratory-compacted samples were prepared at NCSU's lab and subjected to TSR testing using both the NCDOT's modified AASHTO T 283 and M.i.S.T. conditioning procedures. An evaluation of the multilaboratory precision indicates that results of Boil tests coupled with ACT color measurements from different labs do not generally differ by more than 10 percent, showing promising

reproducibility. However, a relationship Boil test results coupled with ACT measurements are not correlated with the TSR results of plant-mixed asphalt mixtures and therefore, the limits cannot be extended to quality control and quality assurance testing of plant-produced asphalt mixtures. Five of the 11 plant-produced mixtures evaluated through TSR testing failed to meet the NCDOT's specified minimum limit of 85 percent when using the NCDOT's modified AASHTO T 283 moisture conditioning procedure. Four of these five mixtures also failed to meet the recommended minimum TSR limit of 80 percent when using M.i.S.T. conditioning. These findings suggests the evaluation of plant-produced asphalt mixture moisture damage resistance through quality assurance and control testing is important to avoid moisture damage prone pavements. Two mixtures that passed the TSR limit when using AASHTO T 283 conditioning failed to achieve a minimum TSR of 80 percent when the M.i.S.T. conditioning procedure was used, indicating the two moisture conditioning procedures can yield different inferences regarding the moisture damage resistance of plant-produced mixtures.

The compatibility of laboratory and field emulsion-aggregate blends was assessed through the NCDOT A-24 visual ratings and ACT measurements of the color of dry and rinsed samples produced according to the NCDOT A-24 procedure. The NCDOT A-24 procedure coupled with ACT color measurements are effective in identifying poor compatibility in emulsion-aggregate blends, providing a potential means to remove the subjectivity of the current visual rating procedure. Criteria for identifying poor compatibility on the basis of ACT results were proposed. All field emulsion-aggregate blends evaluated that met these criteria also resulted in acceptable aggregate retention performance based on the Vialit test results of as-constructed chip seal samples. However, two aggregate-emulsion blends that failed to meet the criteria also resulted in acceptable Vialit aggregate retention test results, suggesting the preliminary limits may be overly stringent and require refinement.

1. INTRODUCTION

1.1. Overview

1.1.1. Introduction

The North Carolina Department of Transportation (NCDOT) currently uses the Tensile Strength Ratio (TSR) as the measure of the moisture damage resistance of asphalt mixtures. The TSR is the ratio of the indirect tensile strengths of moisture conditioned relative to unconditioned asphalt mixture samples. The NCDOT specifies a modified AASHTO T 283 moisture conditioning procedure to induce moisture damage in asphalt mixture samples. The NCDOT requires that contractors conduct TSR testing of laboratory-mixed, laboratory-compacted samples as part of mixture design to verify that minimum moisture damage resistance requirements are met. The NCDOT also requires TSR testing of plant-mixed, laboratory compacted samples within seven calendar days of the beginning of production each mixture design, when there is a change in antistrip additive source or dosage, and/or deemed necessary by the NCDOT as part of quality assurance and quality control (QA/QC) procedures. The TSR is a time-consuming test and therefore, if an alternative and more efficient test method could be employed for QA/QC of plant-produced mixtures and to establish the appropriate antistrip additive dosage during mixture design or when a change is made to the source of antistrip additive used. Recent NCDOT research project (2014-04 and 2017-01) demonstrated promise for using the Boil test (ASTM D3625) coupled with color measurements to more efficiently assess adhesive moisture damage resistance of asphalt mixtures (Tayebali et al. 2017, Tayebali et al. 2019). However, the previous projects did not evaluate application of the Boil test to plant-produced asphalt mixtures.

The use of color measurements is also potentially extensible to the evaluation of emulsion-aggregate compatibility. The NCDOT Materials and Tests Asphalt Procedure A-24 (herein after referred to as NCDOT A-24) is currently used to evaluate the compatibility of emulsion-aggregate blends using visual inspection of samples of emulsion and aggregate that are mixed and then rinsed. A limitation of this test method is that visual inspection is subjective. Objective measurements of the color of emulsion-aggregate blends can potentially be used to quantify compatibility in lieu of the current visual inspection process.

1.1.2. Research Need Definition

Research is needed to evaluate if the Boil test coupled with color measurements can be used to select an antistrip dosage to ensure an adequate TSR value is met during mixture design. In addition, research is needed to evaluate if Boil tests coupled with color measurements can be applied to plant-produced asphalt mixtures for routing QA/QC to ensure that minimum TSR requirements are met. Furthermore, past research suggests that the modified AASHTO T 283 moisture conditioning procedure employed by the NCDOT simulates the adhesive but not the cohesive moisture damage resistance of asphalt mixtures. In contrast, the Moisture Induced Stress Tester (M.i.S.T) was developed to better simulate the both adhesive and cohesive moisture damage expected in the field using dynamically induced pore pressure (Tayebali et al. 2019). Thus, further research is needed to critically evaluate the ability of the Boil test and TSR test using the modified AASHTO T 283 procedure to reflect the more realistic moisture damage induced by the M.i.S.T. Additional research is warranted to evaluate if color measurements could be used in lieu of the visual inspection process currently specified in the NCDOT A-24 procedure to remove the subjectivity of assessing the compatibility of emulsion-aggregate blends.

1.1.3. Research Objectives

The objectives of this project are to:

1. Establish a procedure to identify the optimum antistrip additive content for a given asphalt mixture and antistrip additive combination.
2. Evaluate the moisture damage resistance of plant-produced asphalt mixtures to establish a preliminary protocol for quality assurance and control.
3. Develop an objective means to quantify emulsion-aggregate compatibility in lieu of the visual assessment procedure currently specified in NCDOT A-24 procedure.

1.2. Summary of the Literature

A summary of most relevant information garnered from a review of the literature is presented.

1.2.1. Moisture Damage Mechanisms in Asphalt Pavements

Asphalt mixture moisture damage is a major distress affecting the performance of pavements. Researchers have described the two main mechanisms involved in moisture damage of asphalt mixtures as the loss of adhesion (stripping) between asphalt and aggregate, and loss of cohesion within the asphalt binder (strength) (Hicks 1991, Cheng et al. 2003, Little et al. 2003, Hicks et al. 2003, Doyle and Howard 2013, Solaimanian et al. 2003). Hicks (1991) explained that the action of water at the asphalt-aggregate interface is the major cause of loss of adhesion. He also explains that the cohesive failure is induced by emulsification of the asphalt due to the action of the water, which weakens the bond between asphalt binder molecules.

1.2.2. Characterizing Moisture Damage of Asphalt Mixtures

State agencies generally require assessment of the moisture damage resistance of the design asphalt mixture as part of asphalt mixture design. West et al. (2018) conducted a survey of state agencies practices for moisture damage assessment, which are conveyed in Figure 1. Figure 1 shows that the majority of state agencies specify the TSR test with seven states specifying the Hamburg Wheel Tracking test. Two states (Arizona and Idaho) use the Immersion Compression Test (AASHTO T 165), one state (Arkansas) uses the Retained Stability test, and one state (Alaska) requires the Asphalt Film Residue test to evaluate the moisture damage resistance of asphalt mixtures.

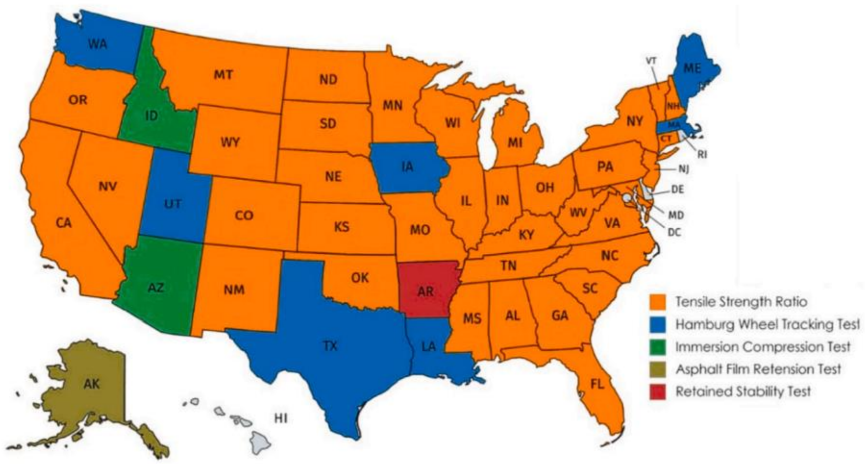


Figure 1. Test methods specified by state agencies to assess moisture damage resistance of asphalt mixtures (West et al. 2018).

The TSR test is specified in AASHTO T 283 and several modified versions of this procedure have also been developed (e.g., the NCDOT modified T 283 conditioning procedure). The TSR test method uses the ratio of the indirect tensile strength (ITS) of an asphalt mixture in a moisture saturated state relative to the ITS in a dry condition to quantify moisture damage resistance. Recent research indicates that the TSR test conditioning procedure primarily induces the adhesive failure mechanism in asphalt mixtures (LaCroix et al. 2016, Do et al. 2019). In the field, asphalt mixtures are subjected not only to the presence of moisture but also to the pumping action of moisture due to traffic loading. The pumping action is believed to affect the cohesive strength of the mixtures (LaCroix et al. 2016, Mallick et al. 2003, Mallick et al. 2019, Sulejmani et al. 2019). The AASHTO T 283 moisture conditioning procedure requires vacuum saturation of the specimens to ensure that 70 to 80 percent of the air voids are saturated. This conditioning procedure has two drawbacks: 1) the saturation level does not reflect in-situ field conditions where the moisture occupies the voids naturally depending on the porosity and the permeability (the void content and the interconnection of the voids) of the compacted mixture, and 2) the vacuum saturation may artificially impart internal damage to the compacted asphalt mixture specimens where the voids are not interconnected (LaCroix et al. 2016). Although this test induces damage due to moisture, there have been cases where moisture sensitive mixtures passed the TSR test but performed poor in the field (Epps et al. 2000, Harvey and Lu 2005, Schram and Williams 2012).

Jimenez (1974) studied the effect of pore water pressure and saturation on moisture damage in asphalt mixtures. The researcher found that the volume change due to cyclically varying water pressure provided a good indication of moisture damage. Due to the importance of pore water pressure and saturation, Mallick et al. (2003) developed a device with a pressure chamber that can generate hydrostatic pressure in the specimens when submerged in water inside the chamber. This is called the moisture-induced stress tester (M.i.S.T.) conditioning procedure. The M.i.S.T. procedure simulates the pumping action of moisture in-situ due to traffic loading and conditions asphalt mixtures more realistically. Several researchers found that this method enhances the identification of moisture-sensitivity in mixtures compared to the AASTHO T 283 procedure (LaCroix et al. 2016, Schram and Williams 2012, Pinkham et al. 2012). Recently, Tayebali et al. (2019) found that the M.i.S.T. is effective for quantifying cohesive moisture damage using sample volume change measurements and, in some cases, provides unique information about the moisture damage resistance of asphalt mixtures compared to the AASHTO T 283 conditioning procedure.

Another simple test method to evaluate moisture sensitivity of asphalt mixtures is the Boil test (ASTM D3625). This is a quick and easy test to determine the loss of adhesion (or stripping) in asphalt mixtures. The drawback of the standardized test method is that it relies on subjective, visual assessment of samples to infer moisture damage. However, color measurements and digital image processing provide alternative tools to objectively quantify stripping in asphalt mixture samples (Lee et al. 2013, Amelian et al. 2014, Tayebali et al. 2017, Tayebali et al. 2018, Tayebali et al. 2019). Tayebali et al. (2019) successfully used color-measuring devices, including a colorimeter and the Asphalt Compatibility Tester (ACT) to objectively quantify the extent of stripping induced in the Boil test. The results of the laboratory-mixed Boil test coupled with color measurements were found to be correlated with laboratory-mixed, laboratory-compacted mixture TSR test results obtained using the NCDOT's modified AASHTO T 283 moisture conditioning procedure. Tayebali et al. (2019) further demonstrated that the results of Boil tests coupled with color measurements are sensitive to the antistrip type and content, suggesting promise for use in establishing additive dosages. Researchers have also explored the viability of evaluating moisture damage in asphalt mixture using nondestructive testing as an alternative to the conventional procedures (Rashetnia et al. 2020, Tayebali et al. 2019, Yadav et al. 2021). Impact resonance measurements of the modulus of moisture-conditioned and dry asphalt mixture samples have shown promise for capturing the moisture damage in asphalt mixtures (Tayebali et al. 2019, Yadav et al. 2021).

1.2.3. Characterizing Emulsion-Aggregate Compatibility

Chip seals are a cost-effective pavement preservation strategy. Chip seals improve skid resistance and reduces the rate of deterioration of the underlying pavement by filling existing cracks and limiting both water and oxygen intrusion. Aggregate loss, also referred to as raveling, is a primary distress in chip seals that can cause windshield damage and diminish skid resistance (Gransberg and James 2005). During the construction of chip seals, asphalt emulsion is first sprayed onto the existing pavement. Then, a single layer of uniformly graded aggregate is spread on top of asphalt film and rolled. The compatibility of the asphalt emulsion and aggregate affects the bond that develops between the aggregate and the residual binder in a chip seal (Adams et al. 2017). Consequently, compatibility plays a significant role on aggregate retention.

Several standard test methods exist to quantify compatibility and aggregate loss performance. AASHTO T 59, ASTM D244, and the NCDOT A-24 procedure all involve similar procedures for compatibility assessment. In each procedure, a sample of aggregate and emulsion is mixed and rinsed. In all the three methods, the compatibility of the rinsed sample is reported as “good”, “fair”, or “poor” based on visual inspection of asphalt coating the aggregate surface area. A rating of “good” refers to aggregates fully coated with asphalt emulsion except some pinpoints and sharp edges, a rating of “fair” is given if the more surface area of aggregate is coated than uncoated, and a rating of “poor” is given if more surface area of aggregate is uncoated than coated. The existing test methods that rely on visual inferences are subjective and may suffer from operator bias. Color measurements, like those employed by Tayebali et al. (2019) to quantify stripping in asphalt mixtures, offer an opportunity to remove the subjectivity of the NCDOT A-24 procedure.

Performance-based test methods have also been applied to quantify aggregate loss resistance of chip seals but are generally more cumbersome than the NCDOT A-24 procedure. The sweep test specified in ASTM D 7000 has been widely applied to quantify raveling resistance of chip seals (Shuler et al. 2011, Rahman et al. 2012, Guirguis and Buss 2019). The sweep test imparts sweeping to chip seal samples using a rotating stiff-bristled brush affixed to a Hobart Mixer. An alternative test that has been employed is the Vialit test, specified in British Standard EN 1227-3, in which chip seal raveling resistance is measured using impact applied to an inverted chip seal sample affixed to a plate (Aktas et al. 2013). Adams et al. (2017) investigated different test method to evaluate early, late, and wet raveling found that the Vialit test was the most sensitive to the compatibility between emulsion and aggregate. Hanz et al. (2012) investigated the feasibility of using the Asphalt Bond Strength (ABS) test to evaluate and quantify adhesion of the emulsion to aggregate surfaces. The ABS test uses the Pneumatic Adhesion Tensile Testing Instrument (PATTI) device for quantifying adhesion of asphalt to aggregate is specified in AASHTO T 361. The sweep and Vialit tests may adequately capture emulsion-aggregate compatibility but require the preparation and curing of chip seal samples, which may be impractical for routine field use. Adams et al. (2017) found a moderately strong correlation between ABS test results and the Vialit test but noted the use of AASHTO T 361 is more challenging because it requires the preparation of large aggregate substrates, rendering it also impractical for routine use.

1.2.4. Summary of Knowledge Gaps and Applications

The literature demonstrates a variety of method have been established to characterize the moisture damage resistance of asphalt mixtures and compatibility of emulsion-aggregate blends. The most widely employed test method for moisture damage assessment of asphalt mixtures is the TSR, using the AASHTO T 283 conditioning procedure to induce moisture damage. This procedure has several limitations, namely (1) it may fail to simulate the cohesive moisture damage in the field, and (2) it is time consuming which is prohibitive for routine QA/QC testing. The M.i.S.T device offers a means to simulate both the cohesive and adhesive moisture damage expected in pavements but does not alleviate the time requirements of the TSR test. The Boil test coupled with colored measurements offers a means to efficiently quantify adhesive moisture damage resistance of asphalt mixtures and thus, may be a possible alternative to TSR testing for establishing antistrip additive dosages and performing QA/QC of field mixtures. However, further research is needed to establish criteria for antistrip additive dosage selection to ensure minimum TSR requirements are met and to evaluate the ability of Boil testing of plant-produced to capture the moisture damage resistance of asphalt mixtures using comparative TSR testing. Color measurements offer an opportunity to remove the subjectivity of the NCDOT A-24 procedure used to evaluate the compatibility of asphalt emulsions. However, research is needed to evaluate the viability of using color measurements to quantify the compatibility of emulsion-aggregate blends and critically evaluate the ability of the measurements to reflect aggregate retention performance in chip seals.

1.3. Organization of the Report

This report is composed of seven primary sections. Section 1 presents the needs, objectives, and summarizes the most relevant literature. Section 2 describes the research methodology to establish a procedure to identify the optimum antistrip additive content and the corresponding results. Section 3 describes the research methodology employed to evaluate the moisture damage resistance of plant-produced asphalt mixtures and the corresponding results. Section 4 presents the methodology and results to develop an objective means to quantify emulsion-aggregate compatibility in lieu of the visual assessment procedure currently specified in the NCDOT A-24 procedure. Section 5 summarizes the conclusions and recommendations. Section 6 provides an implementation and technology plan and Section 7 provides the full bibliographic information for the references cited within the report. Appendix A presents the impact resonance test results.

2. ESTABLISHMENT OF AN ANTISTRIP ADDITIVE DOSAGE SELECTION PROCEDURE

2.1. Overview

Laboratory-mixed, laboratory compacted mixtures were evaluated using both Boil tests and TSR tests to establish an antistrip dosage selection procedure. The results were used to establish a limit for Boil test results coupled with ACT color measurements that ensure a minimum TSR of 85 percent is achieved when using the NCDOT's modified AASHTO T 283 moisture conditioning procedure.

2.2. Methodology

2.2.1. Materials

Three NCDOT-approved mixtures were evaluated that are detailed in Table 1. The component materials for the three mixtures were acquired to produce laboratory-mixed, laboratory-compacted samples for evaluation. The three mixtures are sourced from the different geologic regions in NC to encompass a range of aggregate mineralogies: one from the piedmont region (P), one from the mountains (M), and one from the coastal (C) region of North Carolina. Four different antistrip additives commonly used in North Carolina were also acquired, designated A, B, C, D to preserve supplier anonymity. Each asphalt mixture was prepared in combination with each antistrip additive at additive contents of 0, 0.25, 0.5, and 1 percent (by weight of virgin binder). Within the results, the mixtures are identified by the aggregate source-antistrip additive-additive content. For example, P-B-0.25 indicates the mixture sourced from the Piedmont region prepared with antistrip additive B using a content of 0.25 percent.

Table 1. Laboratory-mixed, Laboratory-compacted Mixtures Evaluated

Mix Designation	Mix Type	Aggregate Mineralogy	RAP Content (%)	RBR (%)	VMA (%)
P	RS9.5C	Granite	30	29	16.5
M	RS9.5C	Granite/Mica	30	25	15.9
C	RS9.5C	Limestone	20	14	18.6

2.2.2. Experimental Methods

Boil tests were conducted on asphalt mixtures prepared at each antistrip dosage content and TSR testing was conducted at an additive dosage of 0.25 percent only. The TSR tests were conducted following both AASHTO T 283 and MIST moisture conditioning procedures.

2.2.2.1. Boil Tests Coupled with Color Measurements

Boil tests were conducted on laboratory-mixed samples according to ASTM D3625 with a few exceptions. According to ASTM D3625, the loose asphalt mixture is boiled in distilled water for 10 minutes. The boiling of asphalt mixtures leads to the stripping of asphalt from the aggregate if there is poor adhesion. The stripping in the mixture leads to exposed aggregates and result in a noticeable color change compared to the unboiled mixture. This color change can be visually compared to standard charts to estimate the amount of stripping. In this study, the loose asphalt mixture was boiled for 30 minutes instead of the standard 10 minutes, which was expected to achieve more uniform heating of the sample. Also, two different color measuring devices, the

Chroma Meter CR400 and Asphalt Compatibility Tester (ACT), were used to quantify stripping objectively in place of visual assessment. Color measurements were made on the source aggregate, unboiled loose mixture, and boiled loose mixture samples.

The Chroma Meter CR400 is a colorimeter manufactured by Konica Minolta and is shown in Figure 2. A standard light source is emitted from the CR400 device onto the target object and the reflection from the material is used to measure the L* of the object. The L* is a luminosity index that measures lightness versus darkness of an object. The range of possible L* values spans from 0 to 100 with darker colors yielding lower values.

Figure 2. Chroma Meter CR 400 (Source: Konica Minolta Website).

The ACT was developed specifically for the asphalt industry by Instrotek, Inc. Figure 3 shows the ACT device. The image on the right side of Figure 3 shows the ACT chamber where the aggregate-emulsion mixture sample is placed in a circular mold. The light source (one with the handle on top) is used to take L* readings on the sample lightness. The ACT also emits a standard light source similar to CR400 and reflection from the material is used to measure the color. The ACT uses a blue Light-Emitting Diode (LED) as its light emitting source. Because this device was developed specifically for the asphalt industry, it is easier to use than the CR400, with programmable features and the built-in chamber for placing asphalt samples and removing the influence of external light sources.

Figure 3. Asphalt Compatibility Tester (ACT) Device by Instrotek Inc.

For each asphalt mixture, four, 450 g loose mix samples were prepared. Two samples were boiled whereas two samples remained unboiled. The ACT and CR400 device were used to take reading on both on both the boiled and unboiled samples. For each sample, three ACT reading were taken on both top and bottom surface and averaged. The Boil test setup is shown in Figure 4. ACT and CR400 readings of the aggregates for each mixture were also obtained.

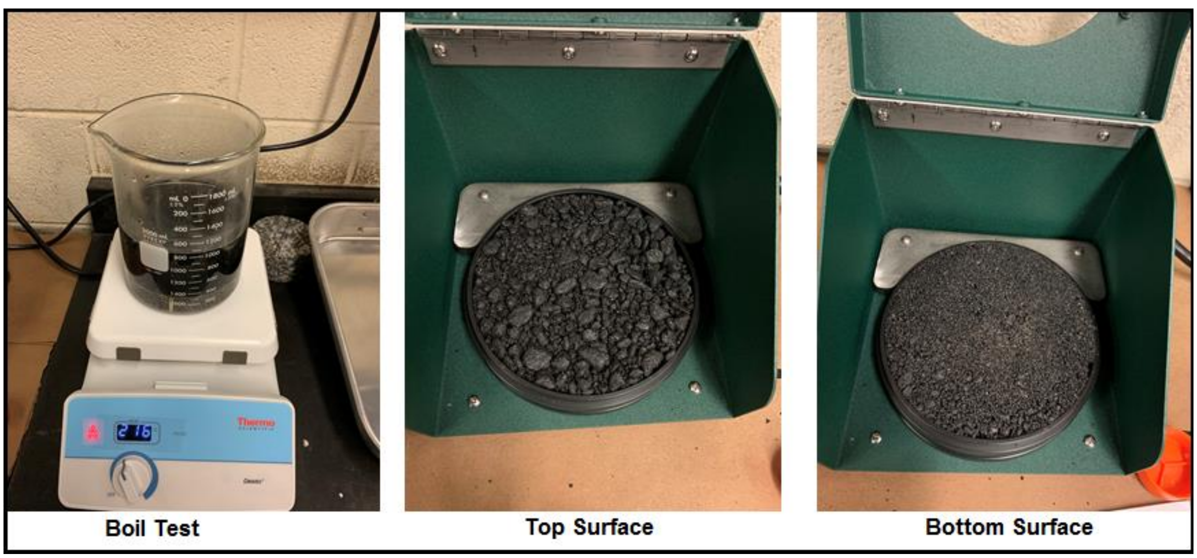


Figure 4. Boil test set up and image of top and bottom surfaces of loose mix in the ACT pan.

Consistent with Tayebali et al., the L* values of aggregate (Aggregate L*), unboiled loose asphalt mixture (Unboiled L*), and boiled loose asphalt mixture (Boiled L*) were used to quantify stripping through LD^*_{RB}, defined in Equation 1.

$$LD^{*}_{RB} = \frac{(Boiled\ L^{*} - Unboiled\ L^{*}) \times 100}{Aggregate\ L^{*} - Unboiled\ L^{*}} \tag{1}$$

2.2.2.2. Tensile Strength Ratio Tests

Laboratory-mixed, laboratory-compacted samples were also prepared for TSR testing. TSR testing was conducted using two moisture conditioning procedures, the modified AASHTO T 283 procedure used by the NCDOT and the MIST (ASTM D7870). The TSR is the ratio of the median tensile strength of conditioned specimens to dry specimens, as defined in Equation 2. The indirect tensile strength values needed to calculate the TSR ratio were obtained by conducted the Indirect Tensile (IDT) Strength Test on dry and moisture conditioned specimens (ASTM D6931). The IDT tests are conducted on four unconditioned specimens and four moisture conditioned specimens (for a given moisture conditioning procedure).

$$Tensile\ Strength\ Ratio\left(TSR\right) = \frac{S_2}{S_1} X\ 100 \tag{2}$$

where S_1 = median tensile strength of dry specimens; and S_2 = median tensile strength of conditioned specimens

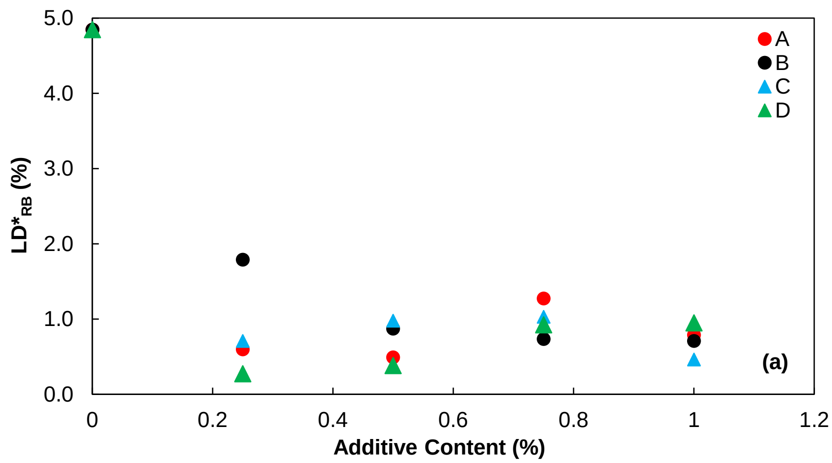
In the modified AASHTO T 283 procedure employed herein, the specimens were vacuum saturated between 70 to 80 percent and then placed in a hot water bath at 60°C for 24.0 ± 1.0 hours. The NCDOT does not require the freeze-thaw cycles during the conditioning procedure so none were used herein.

The MIST simulates the hydraulic stresses due to traffic loading over moisture-saturated asphalt concrete. The MIST device shown in Figure 5 includes a chamber that is filled with water and hydraulic pressure (pumping action) is generated to induce stress. The moisture conditioning procedure includes two cycles: an adhesion cycle and the cohesion cycle. First, the adhesion cycle is conducted wherein the specimens are placed in the chamber filled with hot water at 60°C for 20 hours. Next, the cohesion cycle is conducted where the specimens remain in the hot water chamber at 60°C and are subjected to 3,500 cycles of 270 kPa (40 psi) hydrostatic pressure at a rate of 3.5 seconds per pressure cycle. In the MIST conditioning, the specimens are not saturated before placing them in the water chamber but rather saturated through the peripheral and interconnected voids during the conditioning procedure. This method of saturating the specimens ensures that they are saturated in a natural way and not in a forced way as in the AASHTO T 283 procedure where the specimens are required to have a saturation between 70 to 80 percent regardless of the surface air voids and the interconnectivity of the voids for the specimens.

Figure 5. M.i.S.T. device (Instrotek Inc.).

2.3. Results

The LD^*_{RB} results from the Boil test coupled with ACT device measurements as a function of the antistrip additive type and content are shown in Figure 6. Note that similar trends are observed for the CR400 measurements. The expected trend of a decrease in LD^*_{RB} values with the increase in antistrip additive content was generally observed for asphalt mixtures prepared from the three aggregate sources. A general trend of a decrease in LD^*_{RB} values is observed for asphalt mixtures with no additive to 0.25 percent additive content for each antistrip additive and aggregate source with the exception of aggregate source M and additive B which appears to be an outlier. However, there is no significant reduction in LD^*_{RB} values when increasing the additive content beyond 0.25 percent in many cases. The Boil test results indicate some sensitivity in the test results to the additive type for a given aggregate source.



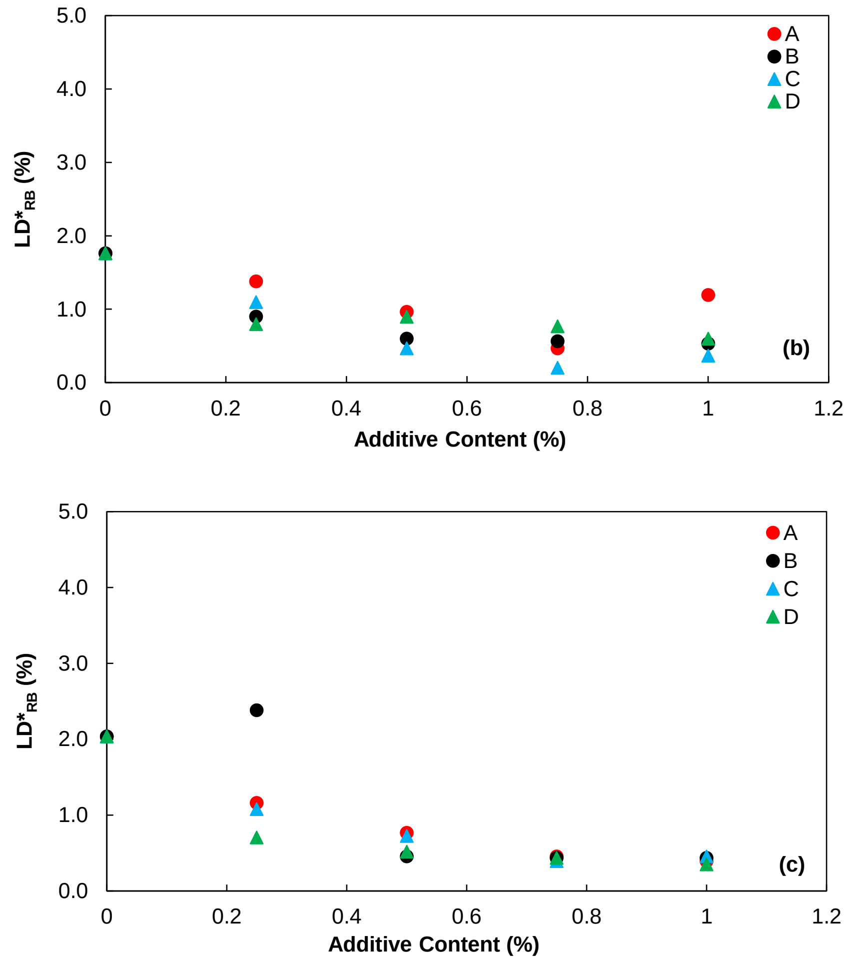


Figure 6. L^*_{RB} (%) versus antistrip additive content (%) (a) aggregate P mixtures, (b) aggregate M mixtures, and (c) aggregate C mixtures.

Based on the results shown in Figure 6, TSR testing was conducted with each aggregate-additive combination at an antistrip additive dosage of 0.25 percent. Figure 7 and Figure 8 show the resultant correlations between LD^*_{RB} values from the ACT and TSR values obtained from the AASHTO T 283 and M.i.S.T. conditioning procedures, respectively. In both cases, relatively high correlations are observed, indicating that the Boil test results are generally a good predictor of TSR values from both the AASHTO T 283 (R^2 = 0.81) and M.i.S.T. (R^2 = 0.79) conditioning procedures. Figure 9 and Figure 10 show the correlations between LD^*_{RB} values from the CR400 and TSR values obtained from the AASHTO T 283 and M.i.S.T. conditioning procedures, respectively. A high correlation between the CR400 LD^*_{RB} values and TSR values is evident when the AASHTO T 283 conditioning procedure is used (R^2 = 0.92) whereas a more moderate correlation is observed when the M.i.S.T. conditioning procedure is used (R^2 = 0.68). This matches general expectations based on the literature, which suggests both AASHTO T 283 and the Boil test primarily induce adhesive moisture damage whereas the M.i.S.T. also induces cohesive moisture damage.

Given the practical advantages of the ACT device, a maximum LD^*_{RB} value for Boil tests coupled with ACT readings was established for use in establishing antistrip additive dosages to ensure a minimum TSR of 85 percent is achieved when using the NCDOT's modified AASHTO T 283 conditioning procedure. To establish a maximum limit on LD^*_{RB} to ensure a TSR of 85 percent is achieved, the 95 percent confidence interval for the relationship between the TSR and L^*_{RB} was defined. The lower bound of the confidence interval was used to identify the LD^*_{RB} value that will yield a minimum TSR of 85 percent with 95 percent confidence, as shown by the arrows on Figure 7. Based on rounding conservatively, this yields a maximum LD^*_{RB} limit of 2.0 percent. Thus, it is recommended that Boil testing coupled with ACT measurements can be perform used to ensure adequate antistrip dosage is selected such that LD^*_{RB} falls below 2.0 percent.

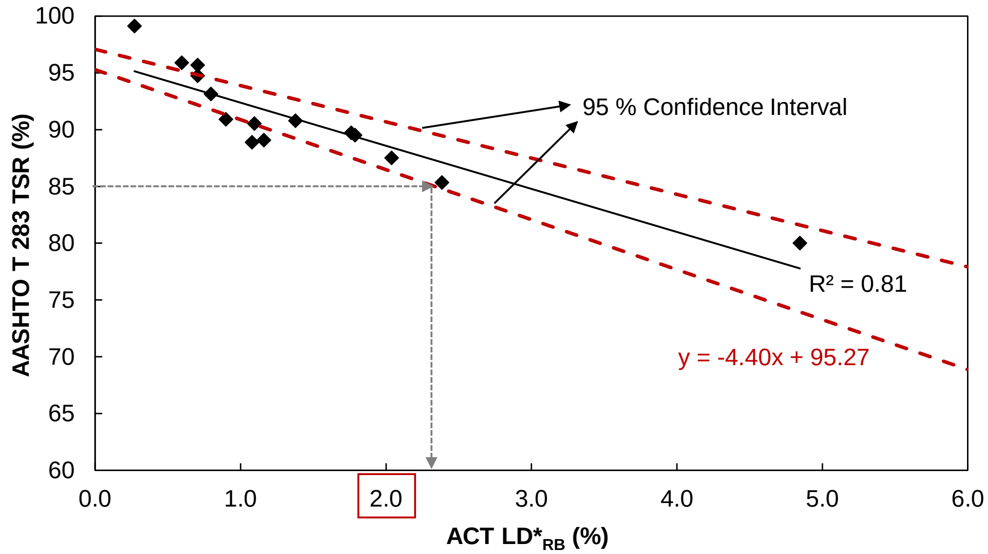


Figure 7. Relationship between TSR values from the AASHTO T 283 conditioning procedure and LD^*_{RB} values from ACT measurements coupled with the Boil test.

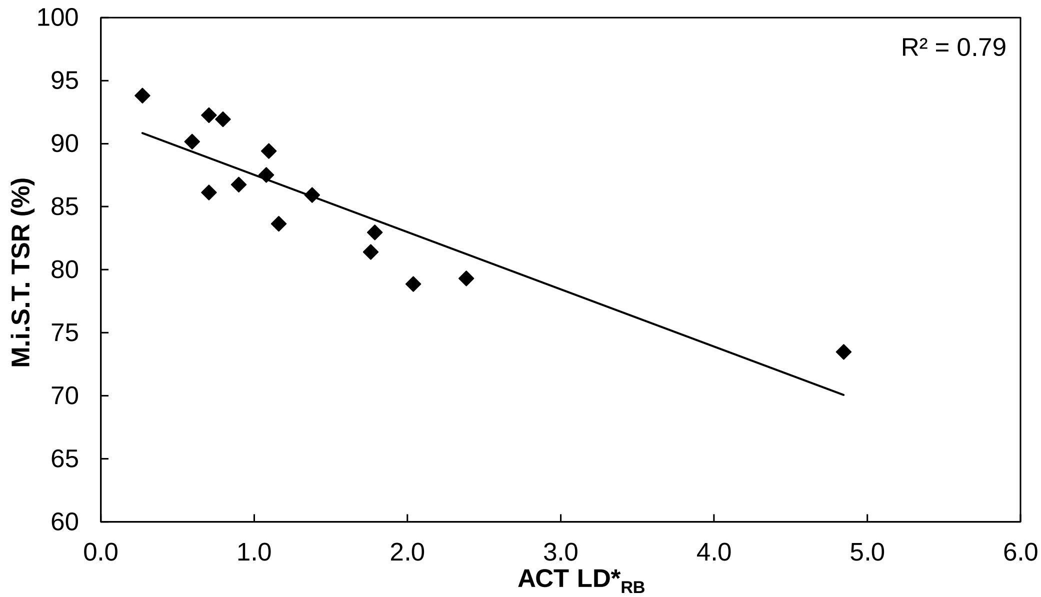


Figure 8. Relationship between TSR values from the M.i.S.T. conditioning procedure and LD^*_{RB} values from ACT measurements coupled with the Boil test.

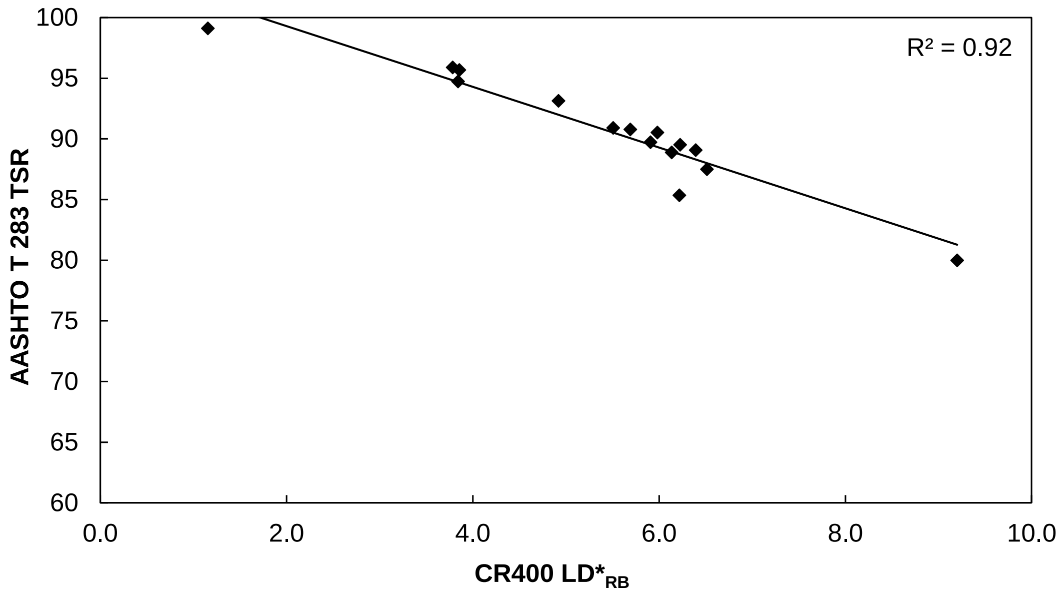


Figure 9. Relationship between TSR values from the AASHTO T 283 conditioning procedure and LD^*_{RB} values from CR400 measurements coupled with the Boil test.

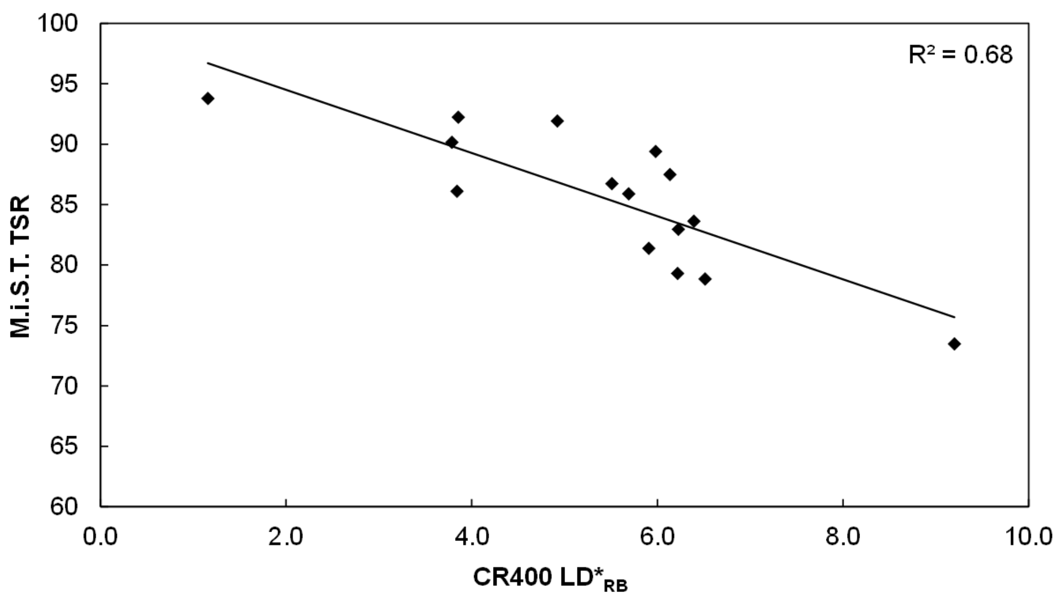


Figure 10. Relationship between TSR values from the M.i.S.T. conditioning procedure and LD^*_{RB} values from CR400 measurements coupled with the Boil test.

To evaluate the proposed L^*_{RD} maximum limit of two percent, the asphalt mixtures tested at the 0.25 percent antistrip dosage content were evaluated based on this pass/fail criterion as well as TSR criteria. TSR criteria included a minimum limit of 85 percent for the AASHTO T 283 conditioning procedure in line with the NCDOT's current specifications and a minimum limit of 80 percent for the M.i.S.T. conditioning procedure based on recommendations from LaCroix et al. (2016). Table 2 shows the pass/fail determinations from the TSR and LD^*_{RB} results. In all but one case (C-0), the three criterion yield equivalent conclusions in terms of passing or failing moisture susceptibility limits. In this case, the AASHTO T 283 TSR results and LD*$_{RB}$ results were in agreement but differed from the M.i.S.T. TSR results.

Table 2. Pass/Fail Evaluation of the Mixtures based on TSR and Proposed ACT LD*$_{RB}$ Criteria

Mixture Designation	TSR Value (%)				ACT LD*$_{RB}$	Pass/fail max 2
	T 283	Pass/fail min 85	M.i.S.T	Pass/ fail min 80		
P-0	80.0	Fail	73.5	Fail	4.8	Fail
P-A-0.25	95.9	Pass	90.2	Pass	0.6	Pass
P-B-0.25	89.5	Pass	83.0	Pass	1.8	Pass
P-C-0.25	95.7	Pass	92.2	Pass	0.7	Pass
P-D-0.25	99.1	Pass	93.8	Pass	0.3	Pass
M-0	89.7	Pass	81.4	Pass	1.8	Pass
M-A-0.25	90.8	Pass	85.9	Pass	1.4	Pass
M-B-0.25	90.9	Pass	86.7	Pass	0.9	Pass
M-C-0.25	90.5	Pass	89.4	Pass	1.1	Pass
M-D-0.25	93.1	Pass	91.9	Pass	0.8	Pass
C-0	87.5	Pass	78.9	Fail	2.0	Pass
C-A-0.25	89.1	Pass	83.6	Pass	1.2	Pass
C-B-0.25	85.3	Fail	79.3	Fail	2.4	Fail
C-C-0.25	88.9	Pass	87.5	Pass	1.1	Pass
C-D-0.25	94.7	Pass	86.1	Pass	0.7	Pass

2.4. Summary of Findings

The results of laboratory-mixed samples demonstrate that LD*$_{RB}$ values determined using color measurements obtained using either the ACT or CR 400 in conjunction with the Boil tests provide a reasonable measure of moisture damage as determined via TSR tests conducted using the AASHTO T 283 and M.i.S.T. conditioning procedures. An LD*$_{RB}$ limit of 2.0 was established for ACT results can be applied to yield a minimum TSR value of 0.85 (as specified by the NCDOT) when using the AASHTO T 283 procedure that also generally yields a minimum TSR value of 0.80 when using the M.i.S.T. conditioning procedure which is the recommended minimum limit in the literature (LaCroix et al. 2016). This specification criteria can be applied to Boil tests coupled with ACT color measurements to guide optimum antistrip dosage selection in mixture design prior to performing the required TSR test. The criteria could also potentially be applied in lieu of TSR testing when there is a change in antistrip source or dosage if laboratory-mixed, laboratory-compacted samples are used.

3. Evaluation of the Moisture Damage Resistance of Plant-Produced Asphalt Mixtures

3.1. Overview

Plant-produced mixtures were acquired and evaluated through TSR testing and Boil tests coupled with ACT measurements. Boil tests were conducted at both NCSU and NCDOT laboratories to evaluate the multilaboratory precision of the test. In addition, plant-produced, laboratory-compacted samples were prepared at NCSU's lab and subjected to TSR testing using both the NCDOT's modified AASHTO T 283 and M.i.S.T. conditioning procedures. The collective results were used to evaluate if Boil tests coupled with ACT measurements can be used to assess the moisture-damage resistance of plant-produced mixtures.

3.2. Methodology

3.2.1. Materials

Plant-produced mixtures were sampled 28 times during the project period. The plant-produced mixtures evaluated are summarized in Table 3. In Table 3, M indicates that the mixture was sourced from the mountains region, P indicates the mixture was sourced from the piedmont region, and C indicates the mixture was sourced from the coastal region of North Carolina. The number directly following the letter indicates the mixture sampling number, labeled according to sequence in time for a given region and the last number indicates the laboratory that tested the mixture (where 1 indicates NCDOT and 2 indicates NCSU). Three NCDOT laboratories participated in testing, one in each of the three geologic regions. Subscripts within the mixture designations identify cases where a given JMF was sampled on more than one occasion; for example, P1 and P5 correspond to the same JMF sampled on two different dates. Boil testing was conducted on all study mixtures by NCDOT and NCSU laboratories. TSR testing, using the NCDOT's modified AASHTO T 283 moisture conditioning procedure and M.i.S.T. conditioning, was also conducted on a subset of the acquired mixtures at the NCSU laboratory only.

Table 3. Summary of the Plant-Produced Mixtures Evaluated

Designation	Mix type	Source Location	Date Mixture Produced	Testing Laboratory	Date Tested	TSR?
M11	RS 9.5B	M	8/17/2021	NCDOT	9/22/2021	
M21	RS 9.5B	M	9/21/2021	NCDOT	9/27/2021	
M22	RS 9.5B	M	9/21/2021	NCSU	10/7/2021	
M31[a]	RS 9.5D	M	9/9/2021	NCDOT	10/6/2021	
M32[a]	RS 9.5D	M	9/9/2021	NCSU	11/19/2021	
M41	RS 9.5C	M	10/13/2021	NCDOT	10/19/2021	
M42	RS 9.5C	M	10/13/2021	NCSU	11/23/2021	
M51	RS 9.5B	M	10/11/2021	NCDOT	10/14/2021	Y
M52	RS 9.5B	M	10/11/2021	NCSU	1/26/2022	
M61[a]	RS 9.5D	M	10/27/2021	NCDOT	10/29/2021	Y
M62[a]	RS 9.5D	M	10/27/2021	NCSU	1/26/2022	
M71	RS 9.5C	M	11/9/2021	NCDOT	11/17/2021	
M72	RS 9.5C	M	11/9/2021	NCSU	1/26/2022	

M81	S 4.75A	M	12/8/2021	NCDOT	12/15/2021	Y
M82	S 4.75A	M	12/8/2021	NCSU	1/28/2022	
P11[b]	RS 9.5B	P	8/26/2021	NCDOT	9/3/2021	
P12[b]	RS 9.5B	P	8/26/2021	NCSU	9/7/2021	
P21	S 9.5D	P	8/2/2021	NCDOT	9/17/2021	
P22	S 9.5D	P	8/2/2021	NCSU	9/21/2021	
P31	RS 9.5B	P	9/28/2021	NCDOT	10/1/2021	
P32	RS 9.5B	P	9/28/2021	NCSU	10/1/2021	
P41	RS 9.5C	P	9/28/2021	NCDOT	10/4/2021	
P42	RS 9.5C	P	9/28/2021	NCSU	11/24/2021	
P51[b]	RS 9.5B	P	9/27/2021	NCDOT	10/5/2021	
P52[b]	RS 9.5B	P	9/27/2021	NCSU	11/24/2021	
P61	RS 4.75A	P	10/14/2021	NCDOT	10/19/2021	Y
P62	RS 4.75A	P	10/14/2021	NCSU	1/28/2022	
P71	RS 9.5C	P	9/8/2021	NCDOT	11/19/2021	
P72	RS 9.5C	P	9/8/2021	NCSU	11/23/2021	
P81	RS 9.5C	P	11/15/2021	NCDOT	12/9/2021	
P82	RS 9.5C	P	11/15/2021	NCSU	1/27/2022	
C11[c]	RS 9.5C	C	8/6/2021	NCDOT	8/25/2021	
C12[c]	RS 9.5C	C	8/6/2021	NCSU	25-Aug	
C21[c]	RS 9.5C	C	8/25/2021	NCDOT	8/30/2021	
C22[c]	RS 9.5C	C	8/25/2021	NCSU	9/21/2021	
C31[c]	RS 9.5C	C	9/10/2021	NCDOT	9/14/2021	Y
C32[c]	RS 9.5C	C	9/10/2021	NCSU	9/21/2021	
C41[c]	RS 9.5C	C	9/13/2021	NCDOT	9/16/2021	
C42[c]	RS 9.5C	C	9/13/2021	NCSU	10/7/2021	
C51[c]	RS 9.5C	C	9/16/2021	NCDOT	9/21/2021	Y
C52[c]	RS 9.5C	C	9/16/2021	NCSU	10/7/2021	
C61	RS 9.5B	C	9/29/2021	NCDOT	9/30/2021	
C62	RS 9.5B	C	9/29/2021	NCSU	11/19/2021	
C71[d]	RS 9.5B	C	10/4/2021	NCDOT	10/5/2021	Y
C72[d]	RS 9.5B	C	10/4/2021	NCSU	11/19/2021	
C81[e]	RS 9.5C	C	10/19/2021	NCDOT	10/21/2021	Y
C82[e]	RS 9.5C	C	10/19/2021	NCSU	11/19/2021	
C91[d]	RS 9.5B	C	10/26/2021	NCDOT	10/27/2021	
C92[d]	RS 9.5B	C	10/26/2021	NCSU	11/17/2021	
C101[d]	RS 9.5B	C	11/2/2021	NCDOT	11/3/2021	Y
C102[d]	RS 9.5B	C	11/2/2021	NCSU	11/17/2021	
C111	RS 9.5B	C	11/29/2021	NCDOT	12/1/2021	Y
C112	RS 9.5B	C	11/29/2021	NCSU	1/28/2022	
C121[e]	RS 9.5C	C	12/16/2021	NCDOT	12/17/2021	Y
C122[e]	RS 9.5C	C	12/16/2021	NCSU	1/26/2022	

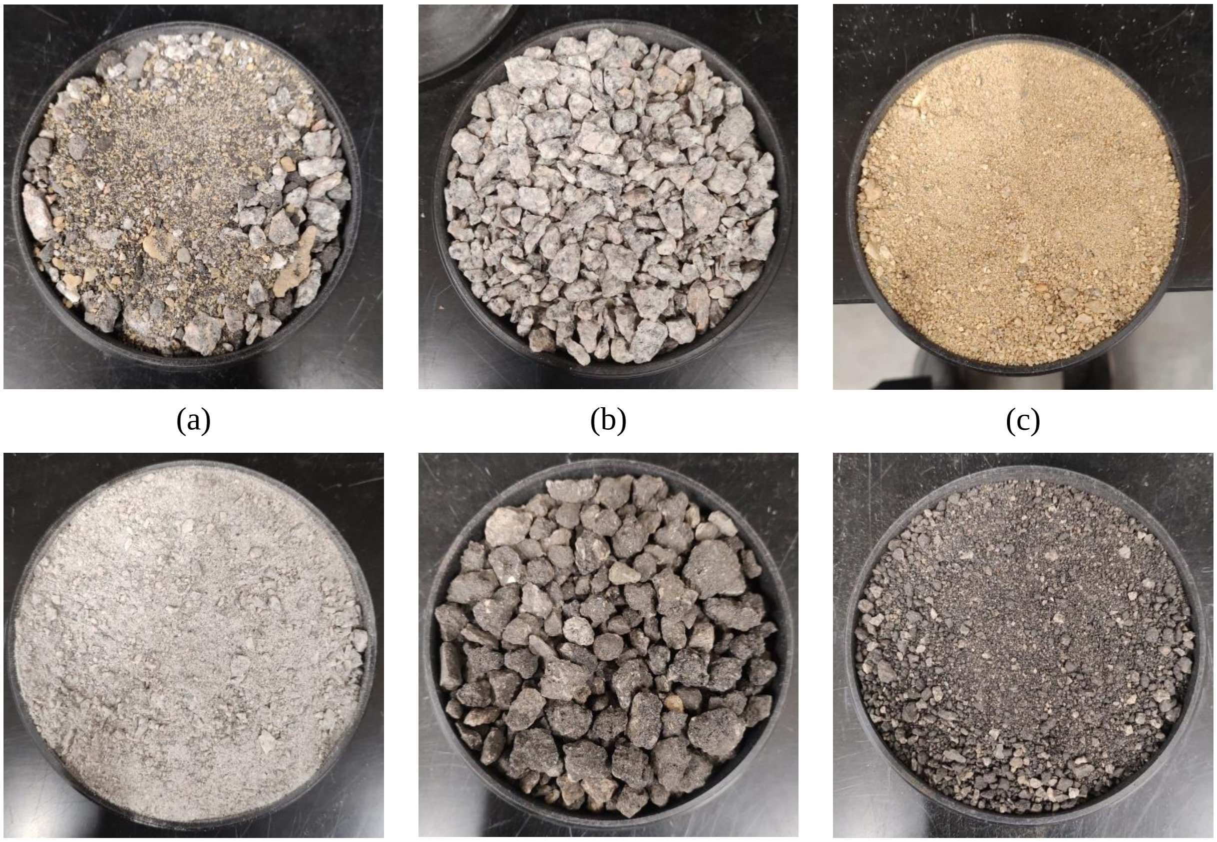
3.2.2. Experimental Methods

3.2.2.1. Boil Tests Coupled with Color Measurements

NCSU trained the participating NCDOT laboratories on how to conduct Boil tests coupled with ACT measurements and then both laboratories proceeded to conduct the tests on the acquired plant-produced mixtures. The Boil testing procedure followed the same approach detailed in Chapter 2. The color of the plant-produced mixtures was measured before and after boiling and used to calculate L^*_{RB}, defined in Equation (3). Note that Equation (3) differs from Equation (1) in that Equation (3) does not account for the color of the source aggregate and its influence on the inference of stripping from color measurements.

$$L^*_{RB} = \frac{Boiled\ L^* - Unboiled\ L^*}{Unboiled\ L^*} \times 100 \quad (3)$$

As will be shown in the results, L^*_{RB} was not found to correlate with the TSR of asphalt mixtures. Therefore, aggregates and RAP used in each JMF selected for TSR testing were acquired. The aggregate blend color was measured following two approaches: 1 – preparing a blend of the aggregate stockpiles according to the proportions by mass presented in JMF and then measuring the color of the blend, and 2 – measuring the color of the individual stockpiles and then calculating the blend aggregate L* using a weighted average based on the mass proportion of the aggregate stockpiles reported in the JMF. The latter is considered advantageous as it is less cumbersome to implement and the blend samples suffer segregation, leading to differences in color readings from the top and bottom of samples. Figure 11 shows the blend of the stockpiles and individual stockpiles of a mixture prior to testing.



(a) (b) (c) (d) (e) (f)

Figure 11. Blend of the stockpiles and individual stockpiles of a mixture in the ACT pan: (a) Blend of the stockpiles, (b) #78M coarse aggregate, (c) natural sand, (d) dry screenings, (e) RAP coarse, (f) RAP fine

3.2.2.2. Tensile Strength Ratio Tests

NCSU conducted TSR testing using both AASHTO T 283 and M.i.S.T. conditioning on selected plant-produced mixtures as detailed in Table 3. The general test procedures align with those detailed in Chapter 3.

3.2.2.3. Impact Resonance Tests

Impact Resonance (IR) testing was conducted on a subset of the plant-produced mixtures and complemented with several additional mixtures at NCSU following the procedure developed in NCDOT RP 2014-04 (Tayebali et al. 2017). IR tests were conducted on thin disk asphalt mixture specimens that were dry conditioned and moisture-conditioned using AASHTO T 283 and M.i.S.T. The results were used to calculate the ER ratio, which reflects the relative reduction in dynamic modulus from moisture conditioning and is calculated using the resonant frequency of the dry specimen and conditioned specimens. The results are provided in Appendix A.

3.3. Results

The L^*_{RB} results of the asphalt mixtures obtained using the ACT device are presented in Table 4. The differences between the L^*_{RB} results of the NCSU and NCDOT labs are also included in the table; generally, the percent difference values fall below 10 percent, indicating good reproducibility of the Boil test results coupled with the ACT. Note that the first mix result from the piedmont and mountain labs were discarded due to testing issues, and two mix results from the coastal region were discarded due to testing errors (C2 and C3). The correlation between the NCSU and NCDOT L^*_{RB} results is shown in Figure 12, indicating excellent agreement among the labs.

Table 4. ACT L^*_{RB} % Obtained from NCDOT and NCSU Labs for the Plant-produced Asphalt Mixtures

Mix Designation	ACT L^*_{RB} %		% Difference
	NCDOT Lab	NCSU Lab	
M2	5.17	5.54	7.3
M3	1.48	1.52	2.7
M4	4.17	4.06	2.6
M5	6.16	6.42	4.2
M6	6.92	6.84	1.3
M7	4.86	4.85	0.2
M8	0.60	0.60	0.0
P2	2.55	2.63	3.3
P3	4.01	4.12	2.8
P4	6.44	6.22	3.5
P5	3.56	3.53	0.8
P6	11.92	11.84	0.7
P7	10.93	10.20	6.7
P8	5.20	5.26	1.3
C1	7.87	7.37	6.3
C4	6.57	5.71	13.1
C5	4.78	4.42	7.7
C6	2.65	2.72	2.6
C7	1.82	1.91	5.1
C8	5.82	5.56	4.5
C9	4.03	4.15	3.2
C10	2.93	3.22	9.8
C11	1.69	1.61	5.1
C12	5.24	5.47	4.5

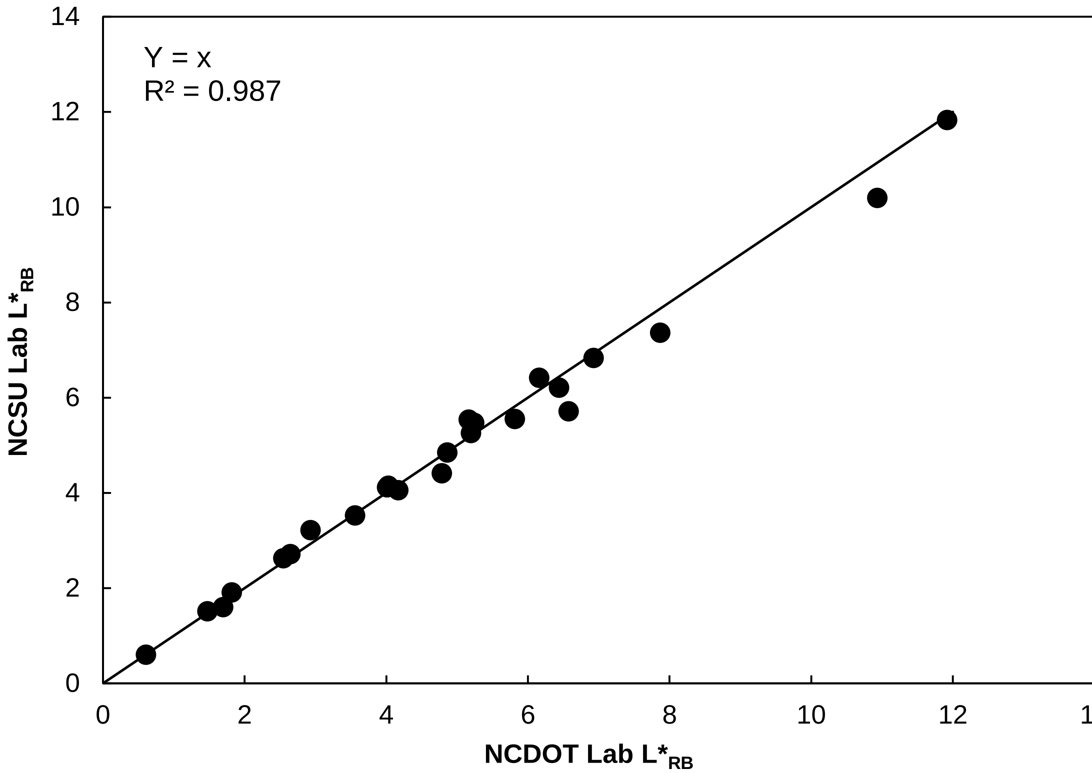


Figure 12. Comparison of NCSU and NCDOT L*$_{RB}$ (%) results for plant-produced asphalt mixtures

The TSR results of the plant-produced mixtures, all obtained by the NCSU research team, are shown in Table 5 for both the NCDOT's modified AASHTO T 283 and M.i.S.T. conditioning procedures. As expected, the TSR values from M.i.S.T. are lower than those from the AASHTO T 283 moisture conditioning procedure for a given mixture. Five of the cases (C5, C8, C11, C12, and M5) fail the NCDOT's specified minimum TSR of 85 percent when using AASHTO T 283 conditioning. As noted in Chapter 2, a specified TSR limit does not exist when using M.i.S.T moisture conditioning. However, a minimum limit of 80 percent is recommended in the literature (LaCroix et al. 2016). Six of the plant-produced mixtures evaluated fail this recommended limit.

Table 5. Plant-produced Asphalt Mixture TSR Results

Mix Designation	Mix Type	TSR (%)	
		AASHTO T 283	M.i.S.T
C3	RS9.5C	88.8	82.9
C5	RS9.5C	78.9	76.6
C7	RS9.5B	88.8	69.8
C8	RS9.5C	71.1	69.8
C10	RS9.5B	96.7	82.9
C11	RS9.5B	83.5	80.8
C12	RS9.5C	74.8	71.5
M5	RS9.5B	79.8	64.6
M6	RS9.5D	85.4	83.8
M8	S4.75A	91.5	89.4
P6	RS4.75A	87.5	77.3

Figure 13 shows a comparison between the TSR results of the plant-produced mixtures obtained using M.i.S.T. and NCDOT's modified AASHTO T 283 moisture conditioning procedures. A poor correlation exists, indicating that the AASHTO T 283 procedure may fail to identify cases where plant-produced mixtures are prone to the cohesive moisture damage captured by the M.i.S.T. In general, most of the mixtures identified as performing poorly by the AASHTO T 283 procedure (i.e., failing to meet a minimum TSR of 85 percent under this moisture conditioning procedure) coincide with those that failed to meet the recommended minimum TSR limit for M.i.S.T. conditioning of 80 percent. However, one mixture (P6) met the AASHTO T 283 limit but not the recommended M.i.S.T. TSR limit.

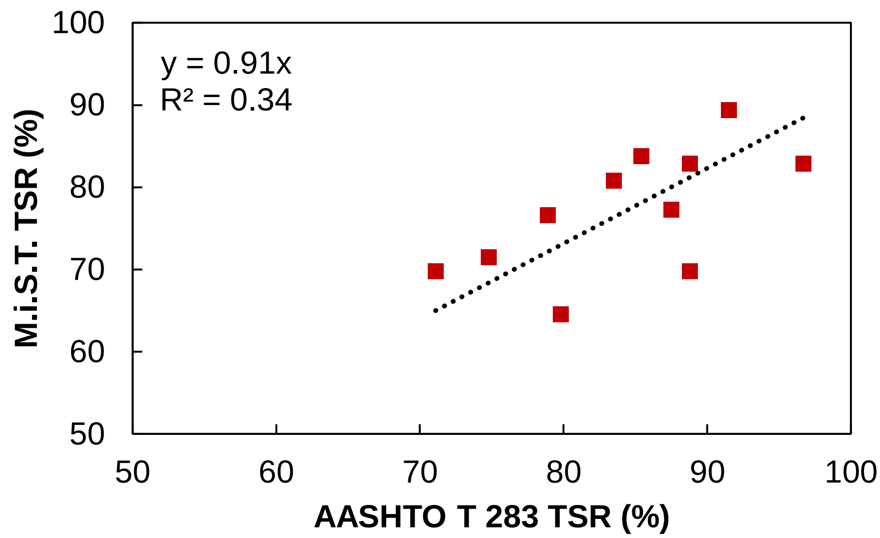


Figure 13. Comparison between TSR results of the plant-produced mixtures obtained using M.i.S.T. and AASHTO T 283 conditioning procedures

The comparison between the TSR results from the AASHTO T 283 moisture conditioning procedure and the L^*_{RB} results obtained from Boil tests coupled with the ACT are shown in Figure

14. The L^*_{RB} results shown were obtained at the NCSU lab. It is evident that no correlation exists between the two results. Similar findings are evident when comparing the ACT results from Boil tests and M.i.S.T. TSR results, as shown in Figure 15. The analysis of lab-produced mixtures indicates a strong correlation between LD^*_{RB} results from Boil tests coupled with ACT measurements and TSR values obtained using the AASHTO T 283 conditioning procedure as shown in Chapter 2. LD^*_{RB} includes consideration of the aggregate color (i.e., Aggregate L*) whereas L^*_{RB} does not. Thus, it was speculated that including the aggregate color when inferring the moisture damage from the Boil test is critical to accurately capturing moisture damage resistance. Consequently, the color of the aggregates used in the plant-produced mixtures was quantified by obtaining aggregate and RAP samples from the asphalt plants in which the plant-produced mixtures were sourced. Subsequently, LD^*_{RB} values were evaluated.

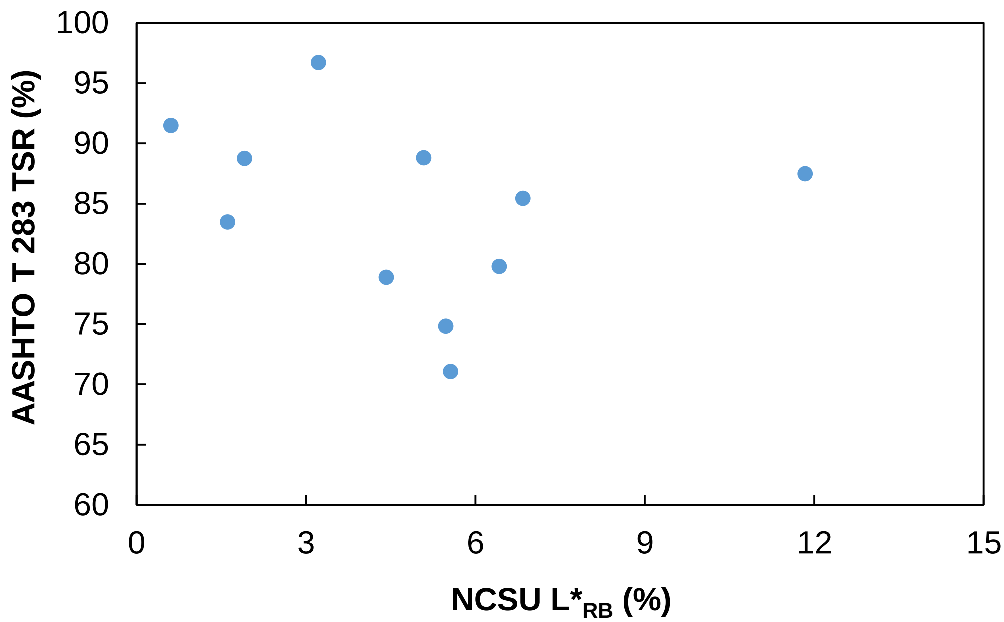


Figure 14. Comparison between TSR values obtained using AASHTO T 283 moisture conditioning and L^*_{RB} measurements at the NCSU lab

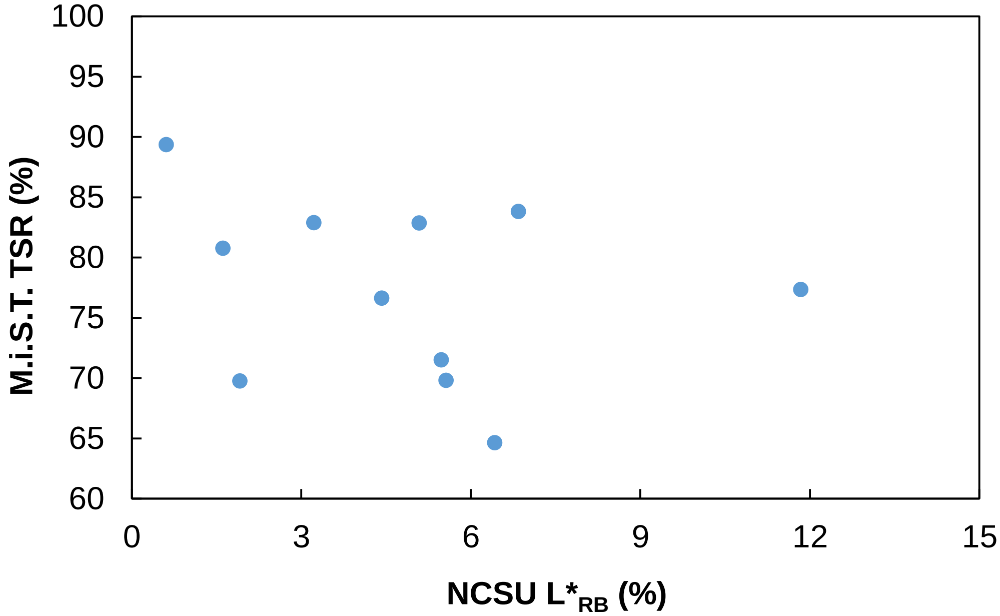


Figure 15. Comparison between TSR values obtained using M.i.S.T. moisture conditioning and L^*_{RB} measurements at the NCSU lab

Aggregate Color Assessment and Its Impact on the Correlation between Boil Test and TSR Test Results of Plant-Produced Mixtures

Two approaches were evaluated for obtaining the aggregate color of plant-produced mixtures: 1 – preparing a blend of the aggregate stockpiles according to the proportions by mass presented in JMF and then measuring the color of the blend, and 2 – measuring the color of the individual stockpiles and then calculating the aggregate blend color using a weighted average of the results, with weighting on the basis of the stockpile proportions by mass. The latter would be easier to implement since if a plant produces multiple JMFs, they could use measurements from individual stockpiles and then use the results to calculate the blended aggregate color for all JMFs based on the specified proportions. Otherwise, a blend of aggregate would need to be prepared and characterized for each JMF. If implemented, it is not envisioned that aggregate color measurements would be needed as often as other quality control measures since the color of aggregates is not expected to vary over short time scales. Table 6 shows the aggregate blend L* results when measured from a blend of the different aggregate stockpiles and when calculated from measurements of the individual stockpiles. Figure 16 presents the correlation between the two approaches. A relatively high correlation (R^2 = 0.89) falling close to the line of equality is observed, indicating that both approaches can be used to determine the baseline color of the mixture in the absence of virgin binder.

Table 6. Aggregate Blend Color based on Individual Stockpiles and Blend of Aggregate Stockpiles

Mix designation	Mix type	Aggregate L*	
		Individual stockpile	Blend
P3	RS9.5B	312.2	320.2
P2	S9.5D	511.2	544.0
C11	RS9.5B	303.5	303.4
P4	RS9.5C	407.4	361.1
C7	RS9.5B	337.0	354.1
C1	RS9.5C	345.3	355.6
M3	RS9.5D	471.1	507.4
M8	S4.75A	312.0	314.1
M5	RS9.5B	318.3	365.5
C8	RS9.5C	304.5	346.7
P6	RS4.75 A	448.2	512.4

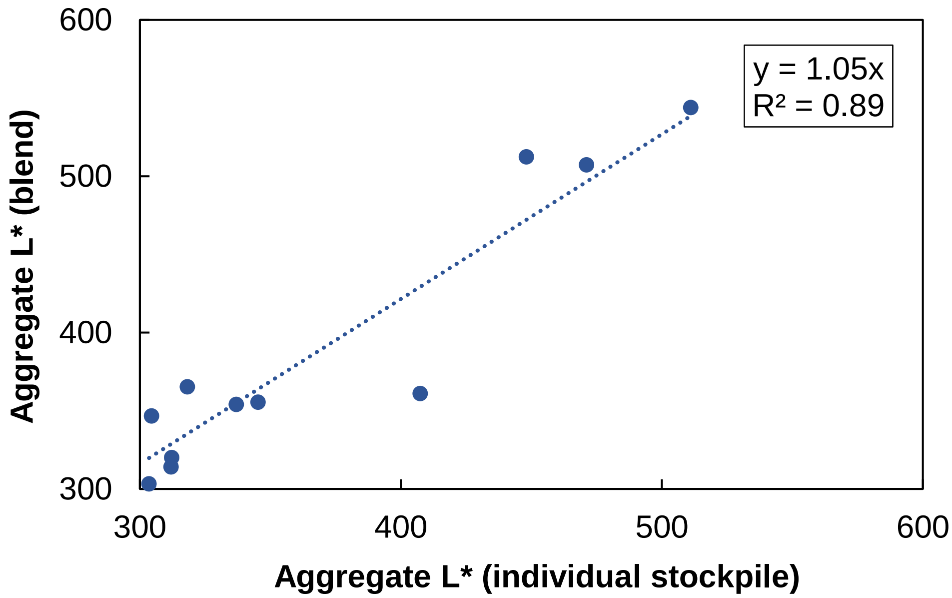


Figure 16. Comparison between aggregate color based on individual stockpiles and blend of aggregate stockpiles

The aggregate L* results (obtained via the weighted average of individual stockpile measurements approach) were coupled with the plant-produced asphalt mixture Boil test results to calculate LD^*_{RB} values. Table 7 summarizes the LD^*_{RB} results and TSR values for the asphalt mixtures evaluated in this project. The LD^*_{RB} values of the plant-produced mixtures span from 0.1 to 1.5. Recall, in Chapter 2 that a maximum LD^*_{RB} limit of 2.0 was recommend for antistrip additive dosage selection of laboratory-produced asphalt mixtures. Thus, all plant-produced mixture results fall below this limit despite five of the AASHTO T 283 TSR results failing the NCDOT's imposed minimum of 85 percent. The comparisons between LD^*_{RB} results and TSR results is shown in Figure 17 and Figure 18 for AASHTO T 283 and M.i.S.T moisture conditioning procedures, respectively. It is evident that no correlation exists between the Boil test and TSR results. Therefore, LD^*_{RB} does not appear suitable for evaluating the moisture susceptibility of plant-produced mixtures. Taking a closer look at Figure 17, three clusters of data points are evident. The cluster of points near LD*$_{RB}$ values of 1.0 correspond to C8, C12, and M5. C8 and C12 are the same JMF, produced at two times whereas M5 is a distinct JMF. Two of the three data points near LD*$_{RB}$ values of 0.7 correspond to C3 and C5, which are also the same JMF. The C8 versus C12 and C3 versus C5 cases show that plant produced mixture TSR values can vary for a given JMF, which was not captured using LD*$_{RB}$. It is unknown why the laboratory-produced samples exhibit a strong correlation between TSR and Boil test results whereas the plant-produced samples do not.

Table 7. LD*$_{RB}$ and TSR Results of the Plant-produced Asphalt Mixtures

Mix designation	Mix type	LD*$_{RB}$	TSR (%)	
			T 283	MIST
C3	RS9.5C	0.84	88.8	82.9
C5	RS9.5C	0.74	78.9	76.6
C7	RS9.5B	0.31	88.8	69.8
C8	RS9.5C	1.01	71.1	69.8
C10	RS9.5B	0.56	96.7	82.9
C11	RS9.5B	0.32	83.5	80.8
C12	RS9.5C	1.06	74.8	71.5
M5	RS9.5B	1.15	79.8	64.6
M6	RS9.5D	0.75	85.4	83.8
M8	S4.75A	0.11	91.5	89.4
P6	RS4.75 A	1.45	87.5	77.3

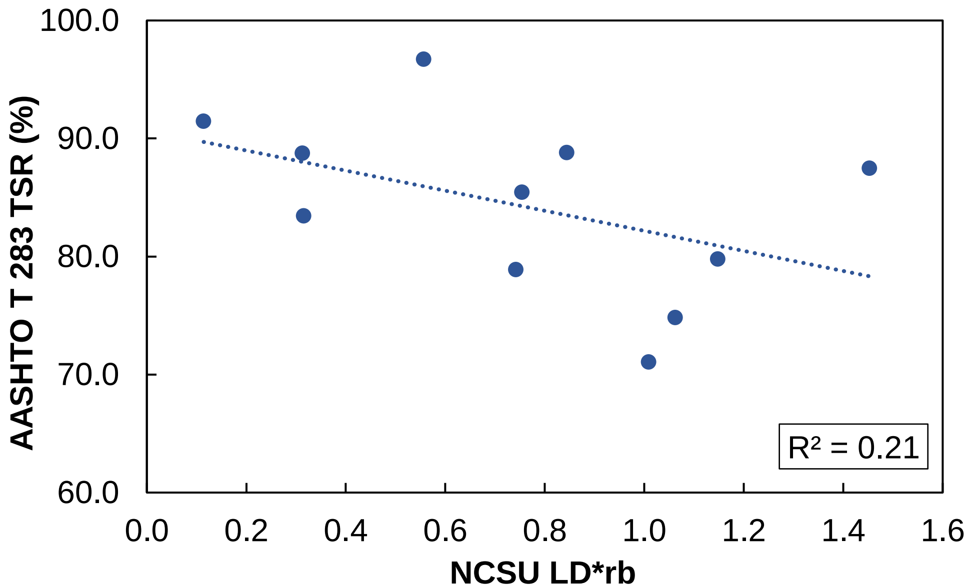


Figure 17. Comparison between TSR values obtained using AASHTO T 283 moisture conditioning and LD*$_{RB}$ measurements

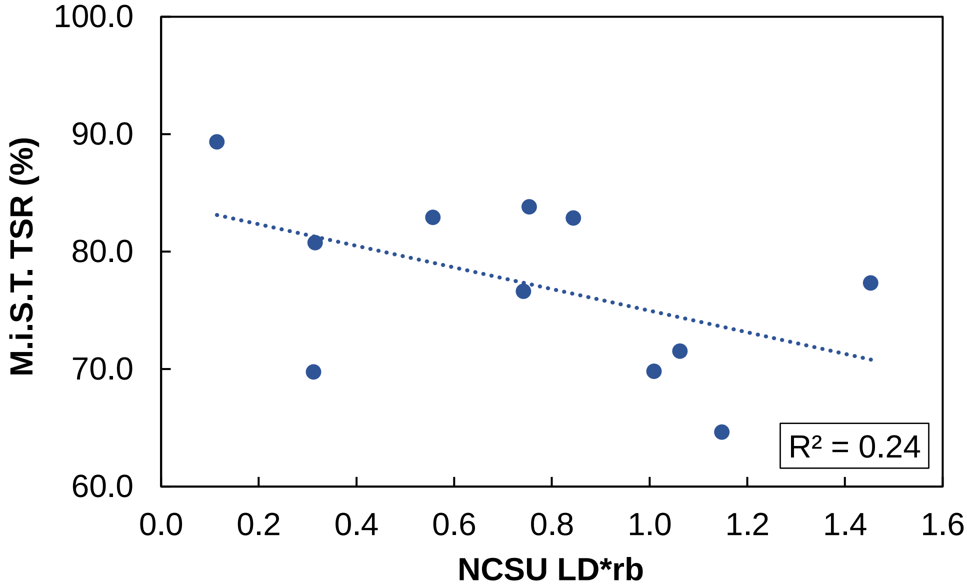


Figure 18. Comparison between TSR values obtained using M.i.S.T. moisture conditioning and LD*$_{RB}$ measurements

3.4. Summary of Findings

An evaluation of the multilaboratory precision of L*$_{RB}$ results indicates that results of Boil tests coupled with ACT color measurements from different labs do not generally differ by more than 10 percent, showing promising reproducibility. Furthermore, L* values of aggregate blends obtained directly from a blend of the aggregate stockpiles versus calculated using the weighted average of individual stockpile measurements are generally in good agreement. Based on this finding and the practical benefits (e.g., separate blends do not need to be prepared for JMFs that use the same stockpiles, negates segregation issues), the individual stockpile method is recommended for use when evaluating both laboratory- or plant-produced asphalt mixtures using Boil tests coupled color measurements.

Five of the 11 plant-produced mixtures evaluated through TSR testing failed to meet the NCDOT's specified minimum limit of 85 percent when using the NCDOT's modified AASHTO T 283 moisture conditioning procedure. Four of these five mixtures also failed to meet the recommended minimum TSR limit of 80 percent (LaCroix 2016) when using M.i.S.T. conditioning. These findings suggests the evaluation of plant-produced asphalt mixture moisture damage resistance through quality assurance and control testing is important to avoid moisture damage prone pavements. Two mixtures that passed the TSR limit when using AASHTO T 283 conditioning failed to achieve a minimum TSR of 80 percent when the M.i.S.T. conditioning procedure was used, indicating the two moisture conditioning procedures can yield different inferences regarding the moisture damage resistance of plant-produced mixtures.

The results demonstrated that neither L*$_{RB}$ or LD*$_{RB}$ values from Boil tests coupled with ACT color measurements correlate with TSR results of plant-produced mixtures, suggesting that Boil tests are ineffective for capturing the moisture damage resistance of plant-produced mixtures.

4. Evaluation of Aggregate-Emulsion Compatibility Using Color Measurements

4.1. Overview

The compatibility of laboratory and field emulsion-aggregate blends was assessed through the NCDOT A-24 visual ratings and ACT measurements of the color of dry and rinsed samples produced according to the NCDOT A-24 procedure. The results were used to identify tentative, objective color-based criteria to ensure good compatibility of emulsion-aggregate blends. Subsequently, the tentative criteria were compared to the aggregate retention performance of as-constructed chip seal samples measured via the Vialit test.

4.2. Methodology

4.2.1. Laboratory Samples

Three aggregate sources that encompass a broad range in mineralogies were acquired for compatibility testing in the laboratory, including granite, limestone, and lightweight. All of these aggregates were sourced from North Carolina. The granite and the lightweight aggregates are generally categorized as acidic and therefore carry a negative surface charge while the limestone is categorized as basic, carrying a positive surface charge. These aggregates were coupled with six emulsions, including three types and two sources. The emulsion manufacturers are designated “A” and “B” to preserve supplier anonymity. The emulsion types were CRS-2L, CRS-2, and SS-1h. In the emulsion designations, CRS stands for “cationic rapid setting,” 2 stands for “high viscosity emulsion,” L stands for “latex modified,” SS stands for “anionic slow setting,” 1 stands for “low viscosity emulsion,” and h stands for “hard base asphalt”. CRS-2L and CRS-2 are two typical asphalt emulsion types used in chip seals. Chip seals use rapid setting emulsions so the slow setting SS-1h is not a typical chip seal emulsion and therefore, was included in an effort to invoke poor compatibility. Similarly, all aggregates were evaluated in combination with each emulsion despite cases where this would not typically be done in practice (i.e., cationic emulsion in combination with limestone and anionic emulsion in combination with granite and lightweight) to evaluate if the measurements could be used to detect cases where poor compatibility was expected. In this study, the 78M aggregate gradation was used to prepare all laboratory aggregate-emulsion mixtures consistent with NCDOT A-24. Within the results, the laboratory emulsion-aggregate samples are identified by the aggregate (G = granite, L = limestone, LW = lightweight), followed by the emulsion supplier (A or B), and ending with the emulsion type. For example, G.A.CRS-2L is a blend of the granite with CRS-2L emulsion from supplier A.

4.2.2. Field Samples

In addition to the laboratory samples, materials were sampled from six chip seal field construction projects. The materials used in each construction site are provided in Table 8. Aggregate and emulsion were sampled from dump trucks and the emulsion distributor at the job site. In addition, samples of the constructed chip seals were acquired by following the procedure detailed in a previous NCDOT project final report (Kim et al. 2018). In summary, nine Vialit plates (8 in by 8 in) were placed on the existing pavement. After that, emulsion was sprayed on top of the Vialit plates and pavement followed by aggregate spreading and compaction, as part of the chip seal construction. The plates were extracted 15 minutes after compaction in order to prevent damage to the samples and to allow the water to evaporate from the emulsion. The field sampling procedure is depicted in Figure 19. For the construction sites where bottom and top layers were sampled, the samples were taken separately for each layer (i.e., Robeson County and Bladen County), using the same sampling procedure. After the construction of the bottom layer and extraction of the samples, nine Vialit plates were placed on top of the bottom layer and the samples of the top layer were extracted 15 minutes after compaction. Within the results, field samples are identified by the aggregate (G = granite, LW = lightweight), followed by the project county, followed by the emulsion type. For example, Stanly.G.CRS-2L corresponds to the first sample listed in Table 8.

Table 8. Summary of Chip Seal Field Samples

Project location	Layer	Aggregate	Emulsion type
Stanly County	Bottom	#78M granite	CRS-2L
Cumberland County	Bottom	#78M granite	CRS-2L
Robeson County	Bottom	#78M granite	CRS-2L
	Top	Lightweight	CRS-2L
Bladen County	Bottom	#78M granite	CRS-2L
	Top	Lightweight	CRS-2L
Scotland County	Top	#14 granite	CRS-2L
Forsyth county	Top	#14 granite	CRS-2L

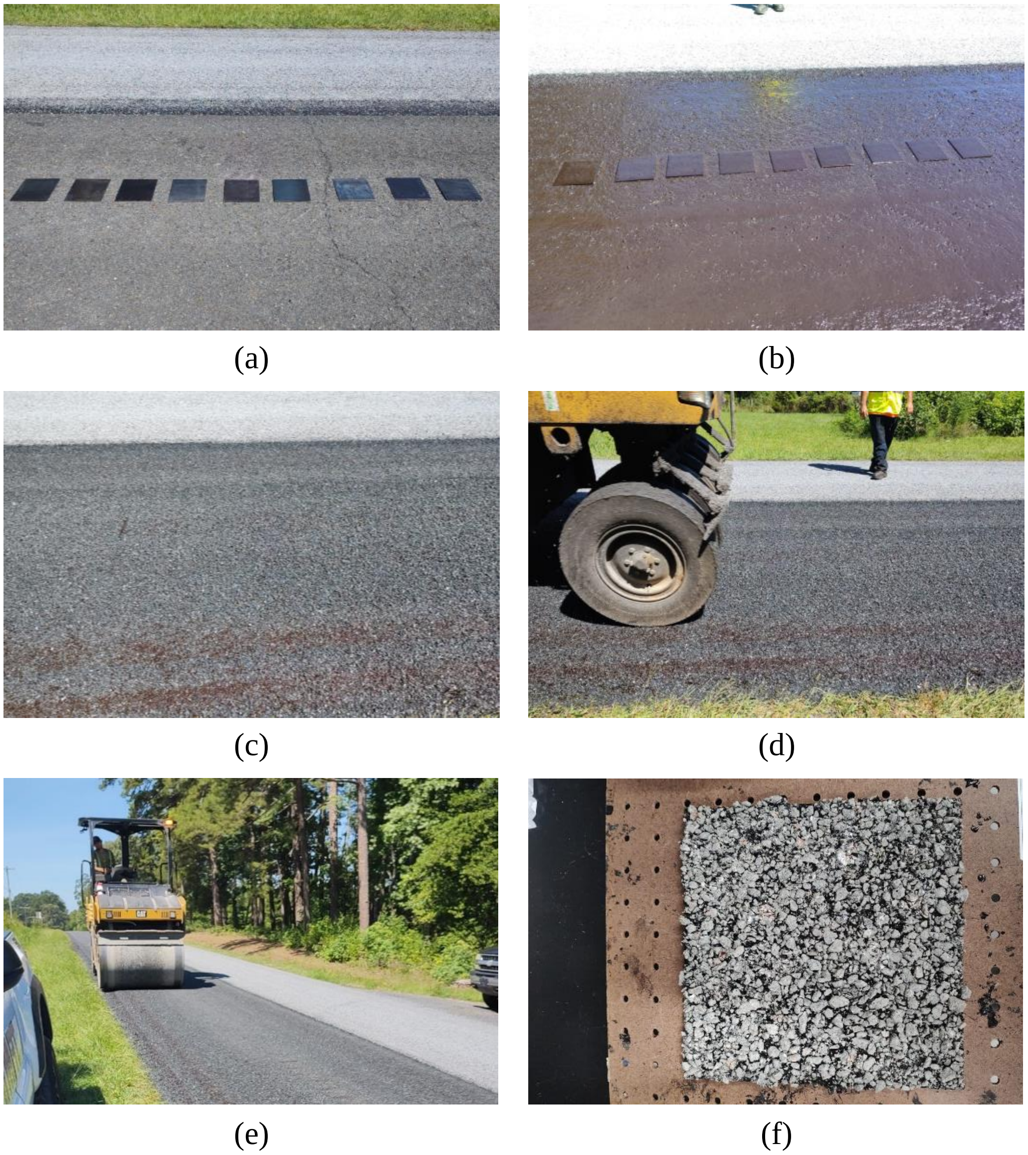


Figure 19. Field sampling procedure: (a) Vialit plates on the pavement, (b) emulsion spraying, (c) Aggregate spreading, (d) compacting with pneumatic roller, (e) compacting with roller, (f) extracted sample

4.2.3. Test Methods

NCDOT A-24 Compatibility Test with Color Measurements

Compatibility of emulsion-aggregate blends was assessed through a modified version of NCDOT A-24 coupled with color measurements. NCDOT A-24 is a modified version of AASHTO T 59. Aggregate-emulsion mixtures were prepared in general accordance with the NCDOT A-24 procedure. However, a larger sample size was required to allow for color measurements using the ACT device. For each aggregate-emulsion mixture sample, 930 g of air-dried aggregate (78M gradation for the lab samples and acquired aggregate samples for the field samples) was first mixed with 18 mL of water to dampen the aggregates. Then, 72 g of well-mixed emulsion was added to aggregates and the mixture was stirred with a large metal spoon until the aggregates were coated. As for the lightweight aggregate, a slight modification was made in the procedure. Instead of using

930 g of lightweight aggregate, the specific gravity of the lightweight and 78M gradation aggregates were obtained and the volume of the lightweight aggregate that would be equivalent to the volume of 930 g of 78M gradation aggregate was calculated. This slight modification was necessary because lightweight aggregate has a much lower density than 78M gradation aggregate, so it requires a high volume of lightweight aggregate to achieve 930 g, resulting in a larger surface area to be covered by emulsion and this might compromise the results. The excess emulsion was drained off and the mixture was stirred again. Then, half of the mixture was placed on an absorbent paper towel and the other half of the mixture was rinsed with water until the water ran clear. All samples were rinsed immediately after mixing the emulsion and aggregate. Following rinsing, samples were placed on a separate absorbent paper and left to cure and dry. Visual inspection was conducted once the rinsed mixtures were fully cured and dry and the compatibility was rated as “good” if only some pinpoints and sharp edges were exposed, “fair” if more coated than uncoated aggregate was present, and “poor” if more uncoated than coated aggregate was present. With the exception of the blends containing SS-1h emulsion, three different samples were prepared to evaluate the variability in test results. For the SS-1h emulsion-aggregate blends, three curing times prior to rinsing were used (immediately, one hour, and four hours) instead of replicates due to the slow setting nature of the SS-1h. While increasing the curing time resulted in less emulsion loss upon rinsing, it generally did not change the compatibility rating and therefore, only the results corresponding to immediate rinsing are presented within the report.

The ACT was used to evaluate the aggregate-emulsion compatibility of the samples produced both with and without rinsing. The ACT was used to obtain L* readings on both dry samples and rinsed samples after they were allowed to fully cure and dry. In addition, L* readings were taken on the aggregates. Visual ratings according to the NCDOT A-24 procedure were also recorded.

<u>Field Chip Seal Sample Testing</u>

The Vialit test was used to measure the raveling resistance of the as-constructed chip seal samples. The Vialit test is very simple and easy to be performed and is published as British Standard EN12272-3 (2003). In the Vialit test, the sample is first flipped 90° and the loose aggregate is brushed away using a soft brush. The sample is then weighed and conditioned for 2 hours at 25° C. After that, the sample is placed face down in the Vialit test apparatus. A steel ball (500 ± 5 g) is then released from its resting position so that it falls vertically 50 cm and strikes the back of the sample plate. The steel ball is dropped three times within 10 seconds for a valid test. The sample is reweighed after the drops are completed to determine the amount of percentage of aggregate lost during the test. In addition, the aggregate and emulsion application rates of the as-constructed chip seal samples were determined through ignition oven testing combined with the known water content of the emulsions acquired from the field projects.

4.3. Results

Figure 20 shows the comparison between L* dry (i.e., L* values of emulsion-aggregate blends that were not rinsed) and L* aggregate values (i.e., L* values of the aggregate blends) for the study materials. Figure 20 shows a much wider spread in the L* dry values of the limestone aggregate blends compared to the blends prepared with the other aggregate sources. The limestone aggregate also had the highest L* aggregate value of all aggregates evaluated. The high variation in L* dry values of the emulsion-aggregate blends containing limestone is attributed to their poor compatibility rather than their high L* aggregate. The limestone aggregate is basic and therefore, expected to be incompatible with cationic emulsions. Furthermore, all aggregates were expected to be incompatible with the SS-1h emulsions due to their slow setting characteristic.

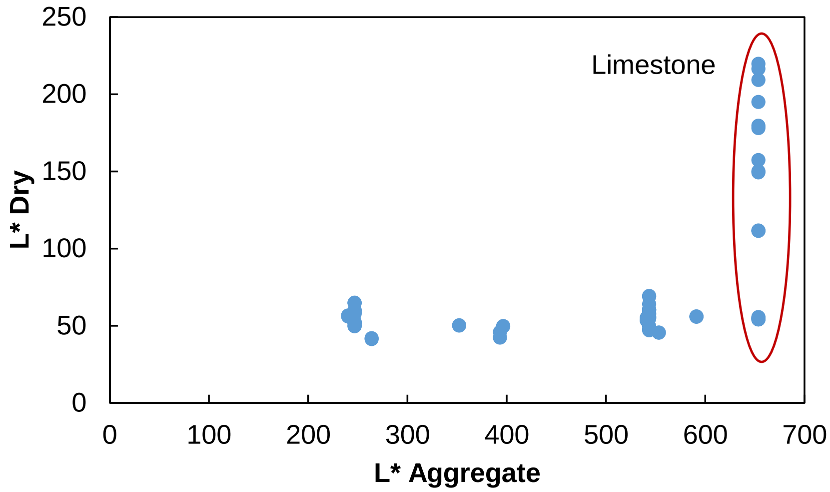


Figure 20. Comparison of L* Dry and L* Aggregate results for emulsion-aggregate blends

Figure 21 shows the comparison between L* Rinsed and L* Aggregate values where it is evident that there is no relationship between the two values. Initially, it was envisioned that the compatibility of emulsion-aggregate blends could be quantified using the ACT measurements using an equation akin to that for LD^*_{RB} (i.e., Equation 1), using the rinsed sample L* and dry sample L* values in place of boil L* and unboiled L* values, respectively. However, the absence of dependence of the L* Dry and L* Rinsed readings on the aggregate color suggests that the consideration of the aggregate color is unnecessary for quantifying emulsion-aggregate compatibility using color measurements. Furthermore, LD^*_{RB} values were found to be biased by the aggregate color, which is undesirable.

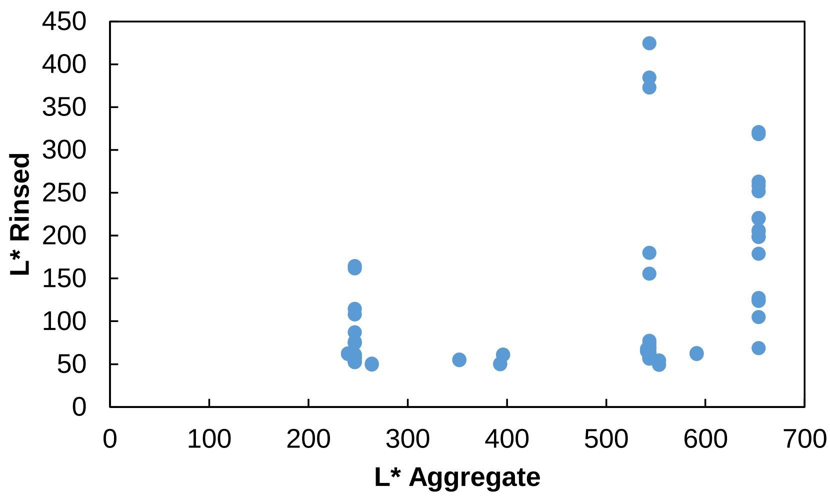


Figure 21. Comparison of L* Rinsed and L* Aggregate results for emulsion-aggregate blends

Correspondingly, two color-based measures were used to evaluate emulsion-aggregate compatibility: (1) L* Dry and (2) the percent change in L* from rinsing, defined in Equation 4. L* Dry is used to identify cases where poor emulsion-aggregate compatibility is evident even in the absence of rinsing whereas the change in L* from rinsing identifies cases where the rinsing process led to the loss of emulsion from aggregate surfaces. Table 9 summarizes the L* Dry and change in L* from rinsing results along with the visual ratings of each sample according to NCDOT A-24. Table 9 shows a wide range in results and also promising repeatability. The coefficients of variation (COVs) for L* Dry values are all below 6 percent whereas the change in L* from rinsing COVs are below 15 percent in all but three of the cases evaluated.

$$L*_{\%Change} = \frac{L*Rinsed - L*Dry}{L*Dry} \quad (4)$$

Table 9. Summary of the Compatibility Test Results

ID	L* Dry	L* COV	Change in L* from Rinsing	Change in L* from Rinsing COV	Visual Rating
LW.A.CRS-2L	64.9	0.15%	15.9%	6.9%	Poor
LW.A.SS-1h	49.8	NA	116.7%	NA	Poor
LW.A.CRS-2	51.6	0.11%	1.5%	12.5%	Good
G.A.CRS-2L	48.2	2.83%	30.5%	8.8%	Fair
G.A.SS-1h	60.4	NA	536.8%	NA	Poor
G.A.CRS-2	56.5	3.40%	24.9%	3.9%	Poor
L.A.CRS-2L	152.4	2.93%	30.4%	12.1%	Poor
L.A.SS-1h	54.1	NA	230.5%	NA	Poor
L.A.CRS-2	111.7	0.10%	12.1%	12.7%	Poor
LW.B.CRS-2L	52.4	0.19%	8.2%	4.7%	Good
LW.B.SS-1h	58.5	NA	181.2%	0.0%	Poor
LW.B.CRS-2	60.0	0.10%	1.7%	9.9%	Good
G.B.CRS-2L	55.4	0.58%	2.6%	14.0%	Good
G.B.SS-1h	69.4	NA	511.8%	NA	Poor
G.B.CRS-2	58.5	2.42%	3.1%	14.9%	Good
L.B.CRS-2L	184.3	5.09%	14.2%	8.9%	Poor
L.B.SS-1h	55.6	NA	477.0%	NA	Poor
L.B.CRS-2	215.3	2.47%	19.8%	17.8%	Poor
Bladen G.Field.CRS-2L	54.1	1.93%	22.2%	0.7%	Fair
Bladen LW.Field.CRS-2L	56.4	0.51%	10.0%	1.8%	Good
Forsyth G.Field.CRS-2L	56.0	0.21%	11.3%	3.8%	Good
Stanley G.Field.CRS-2L	44.2	5.93%	13.8%	56.9%	Good
Cumberland G.Field.CRS-2L	45.7	0.00%	13.3%	60.3%	Fair
Robeson G.Field.CRS-2L	50.3	0.28%	9.3%	2.7%	Good
Robeson LW.Field.CRS-2L	41.7	0.68%	20.3%	13.2%	Fair
Scotland G.Field.CRS-2L	49.8	0.14%	22.7%	3.9%	Poor

Figure 22 shows the comparison between the change in L* from rinsing and L* Dry values with delineation of test results on the basis of the visual rating. From Figure 22, it is clear that some emulsion-aggregate blends with poor compatibility have a high L* Dry, indicating poor coating of the aggregates prior to rinsing. Other blends with poor compatibility exhibit high percent changes in L* from rinsing, meaning a portion of the emulsion was removed upon rinsing.

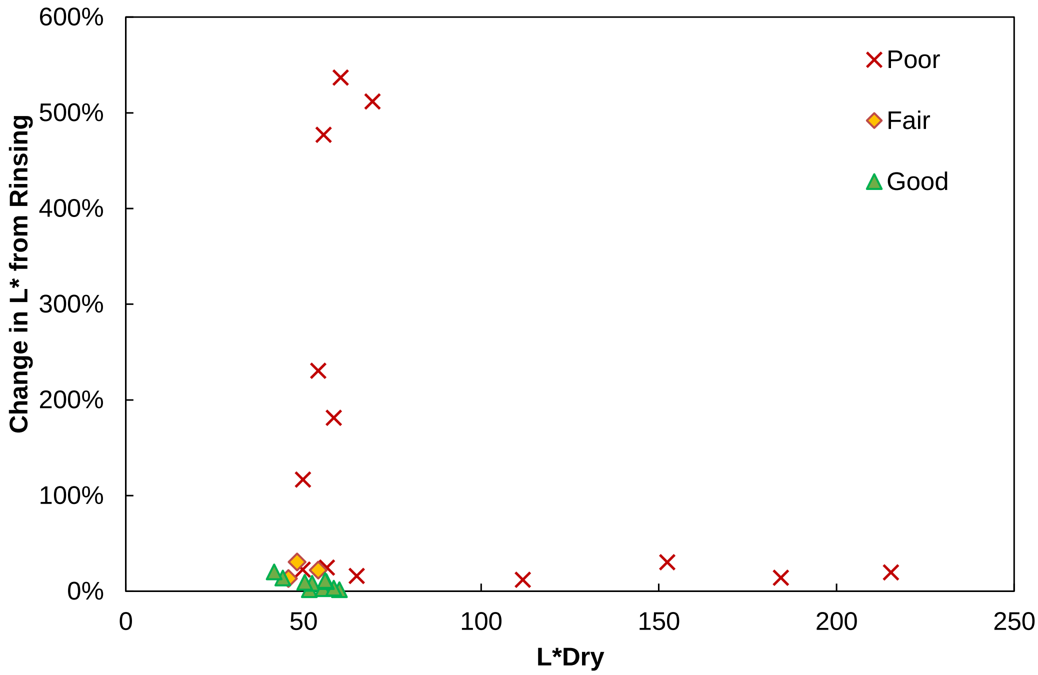


Figure 22. Comparison between the percentage change in L* from rinsing and L* dry values of the emulsion-aggregate blends

From Figure 23, it is apparent that the data points with high changes in L* from rinsing coincide with blends that contain SS-1h emulsions and blends with high L* Dry values coincide with blends containing limestone aggregate. Both SS-1h and limestone were included to test whether or not the NCDOT A-24 procedure combined with color measurements could identify cases known to result in poor compatibility, which is captured by the L* Dry and change in L* from rinsing results. The results show that maximum limits are needed for both L* Dry and the percent change in L* from rinsing to capture the compatibility of emulsion-aggregate blends.

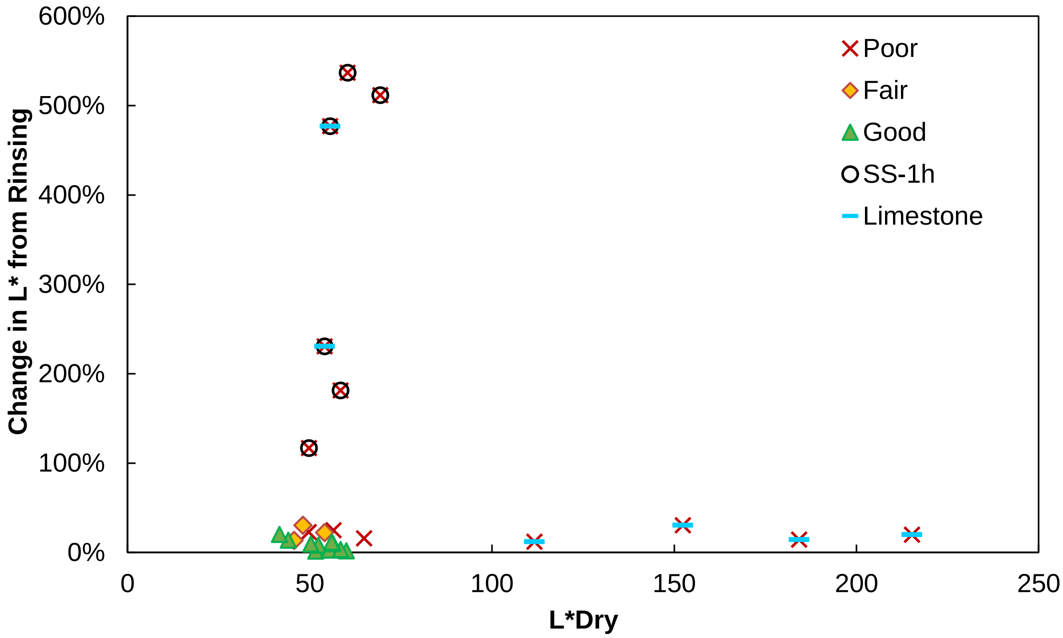


Figure 23. Comparison between the percentage change in L* from rinsing and L* dry values of the emulsion-aggregate blends with identification of the blends containing SS-1h emulsion and/or limestone aggregate

Figure 24 provides a further depiction of the emulsion-aggregate compatibility results after removing the SS-1h results which had extremely high change in L* from rinsing values. In Figure 24, the data are arranged in ascending order of change in L* from rinsing values where it is evident that emulsion-aggregate blends with good compatibility exhibit both low L* Dry values and low percent change in L* values from rinsing. Furthermore, as expected, the emulsion-aggregate blends with good compatibility do not include limestone aggregate.

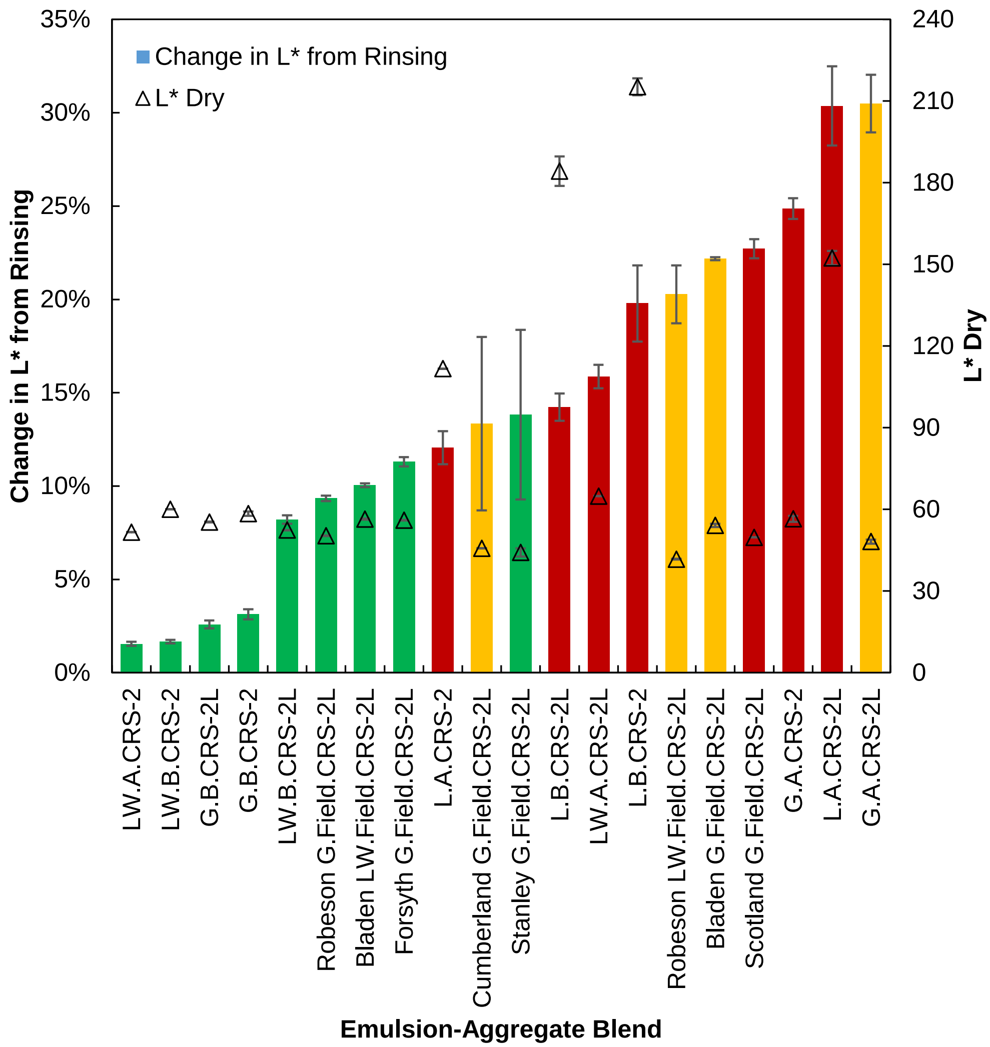


Figure 24. Percentage change in L* from rinsing and L* Dry results, delineated by blend (bar color indicates visual rating: green = good, yellow = fair, red = poor, error bars convey the standard error)

Figure 25 shows the comparison of the change in L* from rinsing and L* Dry results, without inclusion of the blends containing SS-1h emulsion with tentative limits for ACT results to ensure good emulsion-aggregate compatibility. The results reveal that cases where both the L* Dry is less than 65 and the change in L* from rinsing is less than 15 percent were identified as good compatibility from the visual ratings and thus, are recommended as preliminary thresholds for implementation or trial by the NCDOT.

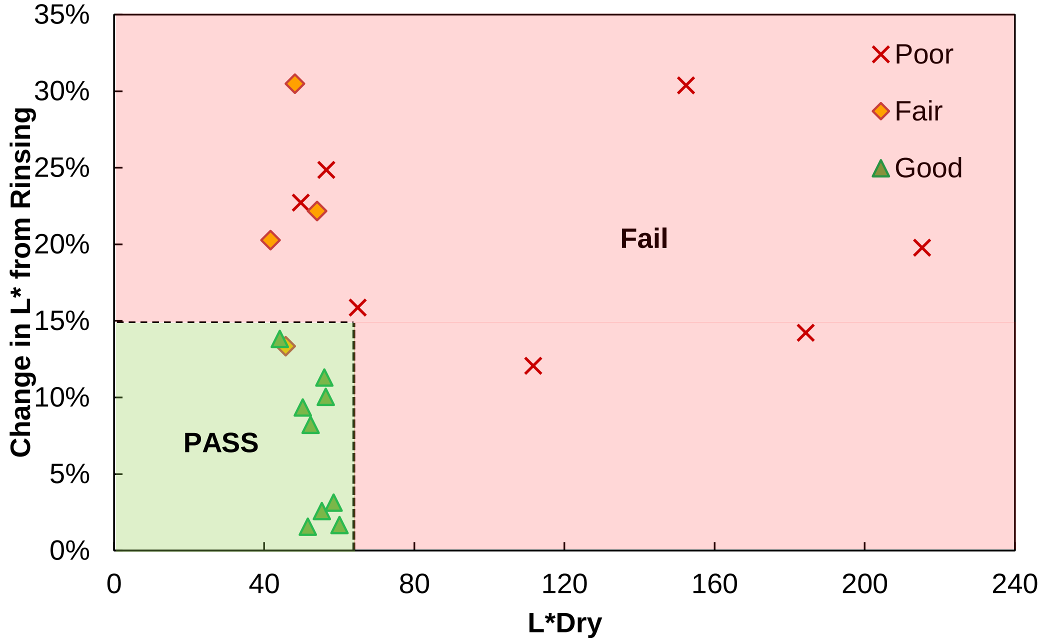


Figure 25. Proposed ACT criteria to evaluate emulsion compatibility

The chip seal samples acquired from the field projects were used to evaluate the tentative limits proposed in Figure 25. Table 10 shows a comparison between the target and measured EAR and AAR values for the acquired field samples, which indicates that in all projects the measured application rates fall below the targets. The reason for this is unknown. Samples were extracted 15 minutes after compaction and before sweeping so aggregate loss prior to sample extraction. It is noted that the EAR and AAR values impact the raveling resistance in a chip seal in addition to the compatibility between the emulsion and aggregate. Nevertheless, the Vialit test results were compared to the compatibility test results as a preliminary evaluation of the tentative limits for L* Dry and change in L* from rinsing.

Table 10. Comparison between Target and Measured Application Rates

Project location	Layer	Aggregate	Target EAR (gal/yd^2)	Measured EAR (gal/yd^2)	Target AAR (lb/yd^2)	Measured AAR (lb/yd^2)
Bladen County	Bottom	#78M Granite	0.30	0.24	16.3	10.2
	Top	Lightweight	0.25	0.22	8.0	5.1
Forsyth county	Top	#14 Granite	0.25	0.15	9.0	7.0
Stanly County	Bottom	#78M Granite	0.30	0.20	18.0	11.6
Cumberland County	Bottom	#78M Granite	0.30	0.20	16.3	11.1
Robeson County	Bottom	#78M Granite	0.30	0.25	16.3	12.6
	Top	Lightweight	0.25	0.21	8.0	7.8
Scotland County	Top	#14 Granite	0.25	0.18	9.0	6.9

Table 11 shows the ACT and visual rating results from the compatibility tests along with the Vialit test results. The ACT rating is pass if both the L* Dry is less than 65 and the change in L* from rinsing is less than 15 percent. The entries in Table 11 are color coded based on whether the value passed or failed limits. In the case of the Vialit test results, a maximum limit of 10 percent was used based on past research (Im 2013). Table 11 shows that the ACT and visual rating criteria are generally in good agreement. One of the visual ratings of fair resulted in passing ACT results whereas the others resulted in failure based on the ACT criteria. Three of the field projects failed the ACT rating criteria. However, only one of those cases resulted in a Vialit aggregate loss test result that exceeded 10 percent. This suggests that the tentative ACT rating criteria may be overly stringent. Further field evaluation is recommended to evaluate and refine the tentative limits. It is also noted that the relatively high EAR:AAR ratios resulting from the measured values compared to those calculated from the target rates may have caused the acceptable aggregate loss despite marginal compatibility.

Table 11. Summary of Compatibility Ratings

ID	L* Dry	Change in L* from Rinsing	Visual Rating	ACT Rating	Vialit Aggregate Loss
LW.A.CRS-2L	64.9	15.9%	Poor	Fail	NA
LW.A.SS-1h	49.8	116.7%	Poor	Fail	
LW.A.CRS-2	51.6	1.5%	Good	Pass	
G.A.CRS-2L	48.2	30.5%	Fair	Fail	
G.A.SS-1h	60.4	536.8%	Poor	Fail	
G.A.CRS-2	56.5	24.9%	Poor	Fail	
L.A.CRS-2L	152.4	30.4%	Poor	Fail	
L.A.SS-1h	54.1	230.5%	Poor	Fail	
L.A.CRS-2	111.7	12.1%	Poor	Fail	
LW.B.CRS-2L	52.4	8.2%	Good	Pass	
LW.B.SS-1h	58.5	181.2%	Poor	Fail	
LW.B.CRS-2	60.0	1.7%	Good	Pass	
G.B.CRS-2L	55.4	2.6%	Good	Pass	
G.B.SS-1h	69.4	511.8%	Poor	Fail	
G.B.CRS-2	58.5	3.1%	Good	Pass	
L.B.CRS-2L	184.3	14.2%	Poor	Fail	
L.B.SS-1h	55.6	477.0%	Poor	Fail	
L.B.CRS-2	215.3	19.8%	Poor	Fail	
Bladen G.Field.CRS-2L	54.1	22.2%	Fair	Fail	8.7%
Bladen LW.Field.CRS-2L	56.4	10.0%	Good	Pass	3.8%
Forsyth G.Field.CRS-2L	56.0	11.3%	Good	Pass	7.8%
Stanley G.Field.CRS-2L	44.2	13.8%	Good	Pass	2.3%
Cumberland G.Field.CRS-2L	45.7	13.3%	Fair	Pass	6.6%
Robeson G.Field.CRS-2L	50.3	9.3%	Good	Pass	9.0%
Robeson LW.Field.CRS-2L	41.7	20.3%	Fair	Fail	12.5% (Fail)
Scotland G.Field.CRS-2L	49.8	22.7%	Poor	Fail	6.1%

4.4. Summary of Findings

The NCDOT A-24 procedure coupled with L* measurements from the ACT are effective in identifying poor compatibility in emulsion-aggregate blends, providing a potential means to remove the subjectivity of the current visual rating procedure. Based on the results, emulsion-aggregate blends exhibit good visual compatibility ratings when the L* of emulsion-aggregate blends prepared without rinsing falls below 65 and the percent change in L* of emulsion aggregate blends from rinsing falls below 15. All field emulsion-aggregate blends that met these criteria also resulted in acceptable aggregate retention performance based on the Vialit test results of as-constructed chip seal samples. However, two aggregate-emulsion blends that failed to meet the L* criteria also resulted in acceptable Vialit test results, suggesting the preliminary limits may be overly stringent. Further evaluation of the relationship between compatibility test results and field chip seal raveling resistance is recommended to assess and refine the tentative L* limits.

5. Conclusions and Recommendations

The following conclusions and recommendations are drawn from the results of this study:

1. The LD^*_{RB} values of laboratory-mixed samples determined using color measurements obtained using either the ACT or CR 400 in conjunction with the Boil test provide a reasonable measure of moisture damage as determined via TSR tests conducted using the NCDOT's modified AASHTO T 283 and M.i.S.T. conditioning procedures. A maximum LD^*_{RB} limit of 2.0 applied to ACT results yields a minimum TSR value of 0.85 when using the NCDOT's modified AASHTO T 283 procedure. This specification criteria can be applied to Boil tests coupled with ACT color measurements to guide optimum antistrip dosage selection in mixture design prior to performing the required TSR test. The criteria could also be used in lieu of TSR testing when there is a change in antistrip additive source or dosage if tests are conducted on laboratory-mixed, laboratory-compacted samples.
2. An evaluation of the multilaboratory precision of L^*_{RB} results indicates that results of Boil tests coupled with ACT color measurements from different labs do not generally differ by more than 10 percent, showing promising reproducibility.
3. The L* values of aggregate blends obtained directly from a blend of the aggregate stockpiles versus calculated using the weighted average of individual stockpile measurements are generally in good agreement. Based on this finding and the practical benefits (e.g., separate blends do not need to be prepared for JMFs that use the same stockpiles, negates segregation issues), the individual stockpile method is recommended for use when evaluating asphalt mixtures using Boil tests coupled with ACT measurements.
4. Five of the 11 plant-produced mixtures evaluated through TSR testing failed to meet the NCDOT's specified minimum limit of 85 percent when using the NCDOT's modified AASHTO T 283 moisture conditioning procedure. Four of these mixture also failed to meet the recommended minimum TSR limit of 80 percent when using M.i.S.T. conditioning. Two additional mixtures failed to meet this M.i.S.T. TSR limit. These findings suggests the evaluation of plant-produced asphalt mixture moisture damage resistance through quality assurance and control testing is important to avoid moisture damage prone pavements.
5. The results demonstrated that neither L^*_{RB} or LD^*_{RB} values from Boil tests coupled with ACT color measurements correlate with TSR results of plant-produced mixtures, suggesting that Boil tests are ineffective for capturing the moisture damage resistance of plant-produced mixtures.
6. The NCDOT A-24 procedure coupled with L* measurements from the ACT are effective in identifying poor compatibility in emulsion-aggregate blends, providing a potential means to remove the subjectivity of the current visual rating procedure.
7. Emulsion-aggregate blends exhibit good visual compatibility ratings when the L* of emulsion-aggregate blends prepared without rinsing falls below 65 and the percent change in L* of emulsion aggregate blends from rinsing falls below 15. All field emulsion-aggregate blends that met these criteria also resulted in acceptable aggregate retention performance based on the Vialit test results of as-constructed chip seal samples.
8. Two aggregate-emulsion blends that failed to meet the L* criteria noted above resulted in acceptable Vialit test results, suggesting the preliminary limits may be overly stringent. Further evaluation of the relationship between compatibility test results and field chip seal raveling resistance is recommended to assess and refine the tentative L* limits.

6. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The Materials and Tests Unit of the NCDOT are the primary users of the outcomes of this research. The NCDOT can adopting Boil testing of laboratory-mixed, laboratory-compacted samples coupled with ACT measurements to guide optimum antistrip dosage selection in mixture design prior to performing the required TSR test. The NCDOT could also specify Boil testing of laboratory-mixed, laboratory-compacted samples in lieu of TSR testing when there is a change in antistrip additive source or dosage. However, the test is not applicable to plant-produced mixtures. The NCDOT can also consider implementing ACT measurements of dry and rinsed emulsion-aggregate blends as part of NCDOT A-24 in lieu of the current visual inspection procedure. Tentative acceptance limits for ACT results of both Boil test samples and NCDOT A-24 emulsion-aggregate blend samples were proposed based on the results of this research but should be critical evaluated and refined, if needed, based on future research and/or experience.

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APPENDIX A

IR testing was conducted on a subset of the plant-produced mixtures detailed in Chapter 3 along with three additional mixtures (denoted LC1, LM1, and LM2 within the results; the C and M indicate the mixture was sourced from the coastal or mountain region, respectively). The IR test is a vibration-based nondestructive test method used to determine material properties. The excitation is induced by striking a steel ball onto the specimen and accelerometer attached to the specimen records the signal using a data acquisition system. Herein, the IR tests were conducted on thin disk asphalt mixture specimens Standard TSR specimens with 95-mm height and 150-mm diameter were fabricated for IR testing. One set of specimens remain dry, a second set was subjected to AASHTO T 283 conditioning, and third set was subjected to M.i.S.T. conditioning. After conditioning, the specimens were sliced into thin disks approximately one-inch thickness. The impact was induced by 16-mm steel dropping from a height of 20 cm at the center of the specimen and the accelerometer was attached to the bottom center of the specimen to record the signal. An example result is shown in Figure 26. The recorded data are in the time domain, which further converted to frequency domain using the Fast Fourier Transform (FFT) function in MATLAB. The location of the peak in the frequency spectrum gives the value of the resonant frequency.

The resonant frequency was obtained from the frequency spectrum and the half-power bandwidth method was used to calculate the damping factor. The frequency spectrum and the half power bandwidth method is shown schematically in Figure 27. The damping factor was then further used to calculate the natural frequency.

The dynamic modulus calculated from the IR test is proportional to the square of ratio of natural frequency and frequency parameter as shown in Equation 5.

$$E_d \propto \left(\frac{f_n}{\Omega_o} \right)^2 \quad (5)$$

where f_n is the natural frequency, and Ω_o is the frequency parameter, which depends on the thickness and diameter of the specimen.

The ER ratio or the relative reduction in dynamic modulus due to moisture damage is calculated as the ratio of the f_n/Ω_o values of the moisture-conditioned specimen to dry specimen.

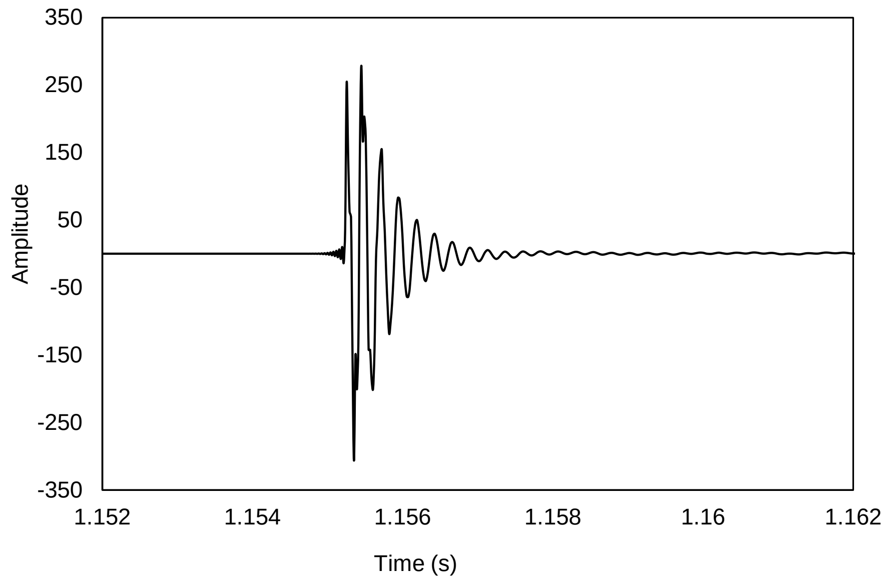

Figure 26. IR test data in time domain

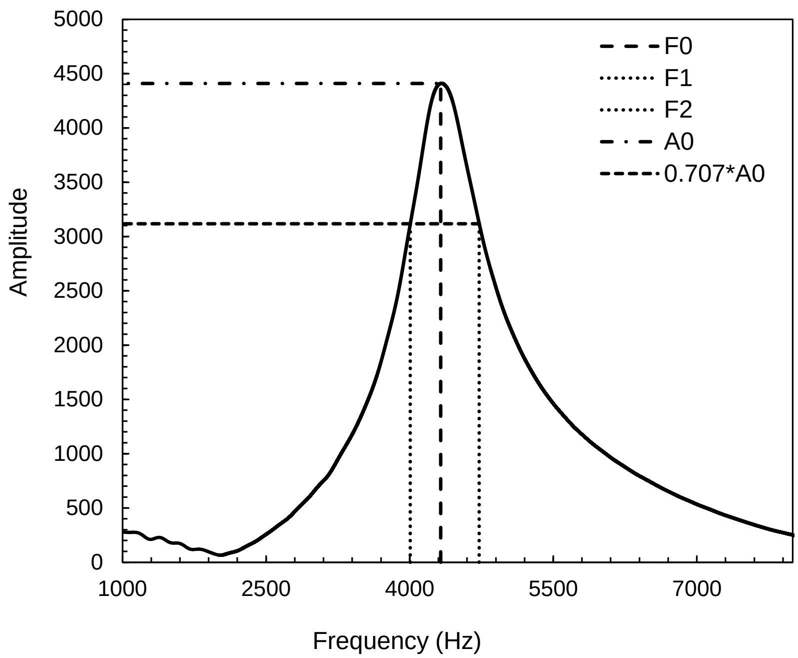

Figure 27. Frequency spectrum and half-power bandwidth method

The comparison of ER ratio and TSR results is presented in Table 12 and Figure 28 where a moderate relationship between the two measures is evident (R^2 = 0.65), suggesting some potential for using the ER ratio as a non destructive measure of moisture damage resistance of asphalt mixtures.

Table 12. Comparison of ER and TSR Results

Mix ID	ER Ratio (%)		TSR (%)	
	AASHTO T 283	M.i.S.T.	AASHTO T 283	M.i.S.T.
LC1	95.5	84.0	93.7	82.4
C3	90.6	80.8	88.8	82.9
LM1	94.9	84.5	95.3	86.9
LM2	94.1	90.4	98.5	92.8
C5	85.8	83.6	78.9	76.6
C7	95.1	73.5	88.8	69.8
C10	90.1	87.4	96.7	82.9
C11	91.6	75.7	83.5	80.8

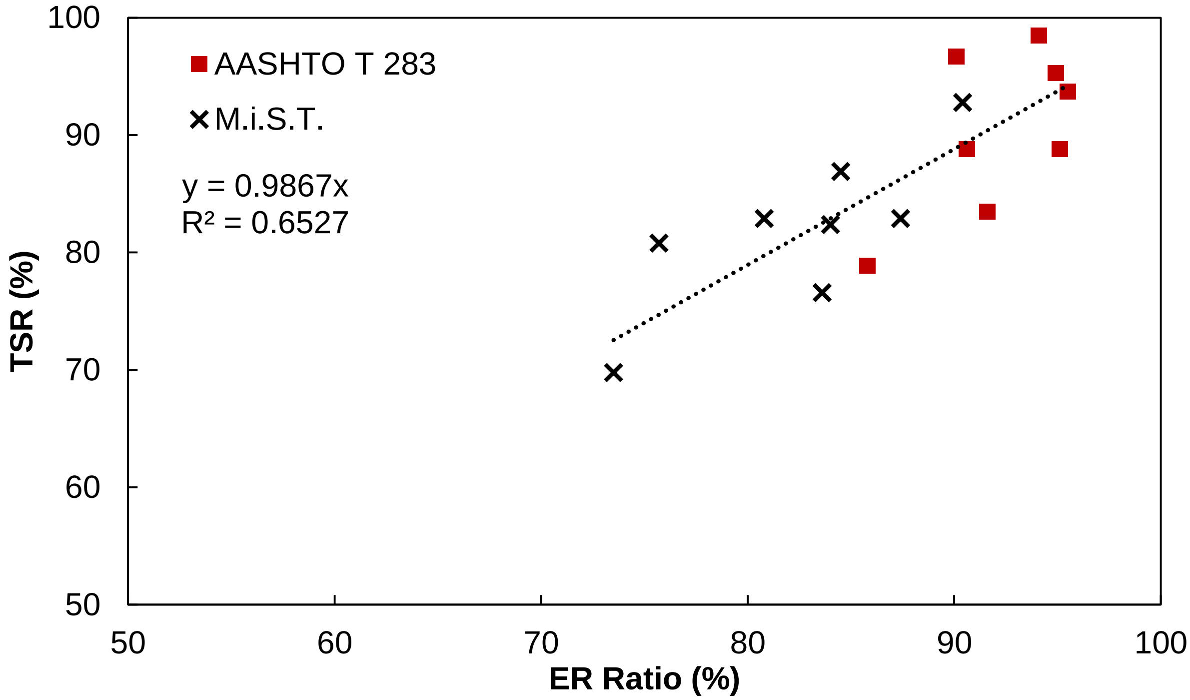

Figure 28. Relationship between TSR and ER results