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Reference

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ABSTRACT

Asphalt materials experience substantial amounts of environmental damage throughout their lives as surface layers in pavements. One of the most prominent forms of environmental damage, moisture-induced damage, is caused by the weakening of internal bonds of the material because of the presence of moisture in the voids of asphalt mixtures and is a common problem for asphalt pavements in wet climates. Moisture-induced damage is typically accounted for during asphalt mixture design by conducting performance tests to ensure the material is not susceptible to severe damage from moisture, although many of these methods have seen mixed amounts of success historically. The main objective of this study is to evaluate the ability of multiple asphalt mixture moisture susceptibility tests to identify good and poor performing mixtures with respect to moisture-induced damage to replace current mix design testing requirements. Ten plant-produced hot mix asphalt materials with established good and poor field moisture performance were subjected to various moisture susceptibility test methods. The results from these procedures are assessed to determine which procedure is most effective and practical as a moisture susceptibility test for routine usage during asphalt mixture design for transportation agencies. Results from this study suggest that performance tests with stiffness-based measurements, such as dynamic modulus paired with moisture conditioning and the saturated aging tensile stiffness procedure, show better correlation to field performance than traditional test methods such as AASHTO T-283, *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage*, and that the Hamburg wheel tracker test is the most effective and practical test method to reliably identify mixtures prone to experiencing moisture-induced damage.

Keywords

moisture-induced damage, moisture susceptibility, dynamic modulus, Hamburg wheel tracker, performance testing, hot mix asphalt, tensile strength ratio

Introduction

Over their service life, asphalt pavements experience significant amounts of deterioration and damage from external forces, such as traffic loading and environmental conditions. Although the focus of many asphalt material specifications is on the prevention of rutting and cracking, the two major distresses in asphalt pavements, there are many other distresses that material specifications need to address to ensure asphalt pavement performance. One of these distresses is moisture-induced damage, which is a constant, prevalent, and challenging distress for asphalt pavements in wet weather climates.

Moisture-induced damage, typically caused by a reduction in strength of the internal adhesive and/cohesive bonds of the material, occurs when the integrity of an asphalt mixture is compromised because of the presence of external moisture within the material. When external moisture enters an asphalt material through permeable voids present in the mixture, the moisture can begin to weaken the internal bonds of the material. This occurs through both chemical (reactions between water and aggregate surface and binder) and physical (pore pressure–induced stresses) means. Once these internal material bonds have been sufficiently weakened, the formation of distresses in the asphalt mixture will occur rapidly.

When considering moisture-induced damage, the most common distress manifests as stripping and raveling in the asphalt layers. Stripping is typically the first to occur and happens when the binder de-bonds from the aggregates and is washed away, exposing the aggregate faces. Raveling, which typically follows stripping, occurs when the internal material bonds have been weakened enough so that the aggregates begin to dislodge from the material. In addition to stripping and raveling, moisture-induced damage can also weaken the material in a general sense, leading to accelerated formation of other distresses such as rutting and cracking. A mixture's ability to maintain the strength of its internal adhesive and cohesive bonds and resist moisture-induced damage is critical in ensuring the long-term durability of the asphalt mixture.

Because of the complex nature of asphalt mixtures, the materials they are composed of, and the complicated and mixed mechanisms of moisture-induced damage, moisture-induced damage is a challenging problem to understand and address from a mixture design perspective. Many factors of asphalt mixtures have been shown to contribute to how likely a mixture is to experience moisture-induced damage, which include, but are not limited to, aggregate mineralogy, aggregate absorption and permeability, binder mechanical and chemical properties, volumetrics of the mixture design, etc.[1–3] All of these factors contribute to the extent to which an asphalt mixture is prone to experiencing moisture-induced damage, which is defined as the moisture susceptibility of the mixture.

Although it is apparent that non-moisture-susceptible materials are preferred for pavement construction, determining the extent of moisture susceptibility of a mixture may be difficult. Historically, the most common approach to evaluating moisture susceptibility of asphalt materials has been through performance testing. The main advantage of performance testing, compared with individual material property requirements, is that it removes much of the complexity of assessing moisture susceptibility by testing the final mixture. Regardless of the individual properties of the components of the mixture, as long as the mix can pass certain requirements deemed acceptable of the performance test, it is expected to perform well in the field. In the context of performance testing to assess the potential impacts of moisture-induced damage on asphalt materials, these tests are known as moisture susceptibility test methods.

A number of visual rating-based testing procedures have been used for testing moisture susceptibility, such as the boiling water test (ASTM D3625M-12, *Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water*) and the Texas boiling water test.[4,5] The concept behind these visual-based test methods is that the material is subjected to some form of accelerated, simulative conditioning and the determination of moisture susceptibility is made based off of visual changes in the material. Although these methods provided a basis to assess the moisture susceptibility of asphalt mixtures, tests on loose mixes have been criticized for high variability, low consistency with multioperator settings, not testing compacted mixtures, and only considering moisture-induced adhesive failure.[2,6]

As an evolution to visual-based loose mixture tests, laboratory moisture susceptibility performance tests on compacted asphalt specimens became the preferred method to evaluate a material's moisture susceptibility during mixture design because these tests are more simulative in nature. These tests typically combine some form of moisture conditioning, meant to simulate moisture damage experienced by asphalt pavements in the field, and a mechanical test method that is used to assess the material's reduction in mechanical properties that is due to moisture conditioning. Another approach is where moisture conditioning and testing for material property occurs simultaneously, such as the Hamburg wheel tracker (HWT) test (AASHTO T324-17, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*).[7] These methods, as well as others used in this research, are described in more detail in subsequent sections of this article.

Although laboratory moisture susceptibility testing has been used with success in the past, many of the current methods have recently been widely criticized. In the New England region and in the United States in general, the majority of state transportation agencies require the use of ASTM D4867M-09, *Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures*/AASHTO T283-14, *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage*, to assess the moisture susceptibility of asphalt mixtures.[8–11] This method, more than others, has received a substantial amount of criticism relating to its ability to reliably predict field performance.[6,12–14] This lack of reliability has led many agencies to investigate alternate testing methods (e.g., Maine Department of Transportation (DOT), Louisiana DOT) or to drop the moisture susceptibility requirements all together (e.g., Rhode Island DOT). Ultimately, an effective laboratory moisture susceptibility test method is needed to reliably, accurately, and repeatedly identify susceptible mixtures during the mixture design period.

Considering the many challenges agencies currently face with predicting moisture susceptibility and performing reliable moisture susceptibility testing, the primary objective of this research is to evaluate and compare a series of moisture susceptibility test methods in terms of their ability to be a reliable and repeatable test for routine use in asphalt mixture design. This comparison between methods was on the basis of the test's ability to distinguish materials that have had historically good and poor field performance in terms of moisture resistance in the New England region.

To realize this objective, material sampling and testing plans were developed on the basis of historic asphalt mixture performances, sampled mixtures were evaluated using a range of laboratory moisture susceptibility test methods, and results were evaluated to develop recommendations. The subsequent sections of this article describe the materials and test methodologies, present testing results and discussion, and summarize the findings.

Study Materials and Experimental Plan

To fulfill the objectives of this study, a set of asphalt mixtures were selected on the recommendations of local DOT materials engineers with extensive experience with the historic performance of the materials in their respective states. The goal of the mixture sampling was to incorporate a wide range of historic material performance with respect to moisture susceptibility as well as capturing a variety of material properties (volumetrics, additives, binder properties, etc.) from the sampled mixtures, which is intended to reflect the diverse range of asphalt mixtures produced during any given construction season. With these goals in mind, a total of 10 mixtures were selected from the New England region. Of these 10 mixtures, 3 were identified as historically having good performance, two were considered moderate, and five were considered historically poor performing. More detailed information on the materials can be found elsewhere.[11] **Table 1** shows an overview of select properties for the 10 mixtures.

All of the sampled mixtures were designed and constructed as surface layers. The primary reason for this choice is that the New England transportation agencies experienced the most moisture damage–related challenges

TABLE 1

Properties of study mixtures

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Mix Name	Performance	Aggregate Type	Binder Grade	Additive	NMAS (mm)
MEP1[11]	Poor	Limestone	64-28	No additive	12.5
MEP2[11]	Moderate	Limestone	64-28	Amine-based antistrip additive	12.5
MEP3	Poor	Granite	64-28	No additive	12.5
MEP4	Poor	Sandstone/limestone	64-28	No additive	12.5
MEG1	Good	Diorite	64-28	No additive	12.5
VTP1[22]	Poor	Quartzite	58-28	WMA/antistrip additive	9.5
VTP2[22]	Poor	Quartzite	58-28	No additive	9.5
VTG1	Good	Dolomite	70-28	WMA additive	12.5
CTP1	Moderate	Granite	64-22	Amine-based antistrip additive	12.5
NHG1	Good	Granite	64-28	No additive	12.5

Note: 1,2 Indicates that mixtures are produced at the same plant and have the same mix designs, where the only difference is the presence of an additive.

with surface mixtures in recent years. Surface mixtures are generally believed to experience more moisture-induced damage because of greater exposure to precipitation, inundation, and traffic-induced stresses. All 10 mixtures were produced as hot mix asphalt surface course mixtures in New England. Although some of the mixtures used warm-mix additives, these were only used as compaction aides as production and compaction temperatures were within normal ranges for hot mixtures.

The materials evaluated for this study were sampled as loose mixtures from the production plant. Although current specifications do not specifically address storage conditions of loose mixtures, the material used in this study was stored between one to three months in sealed containers in a climate-controlled space. To produce testing specimens, the loose mix was reheated and compacted in a gyratory compactor per ASTM D6925-15, *Standard Test Method for Preparation and Determination of the Relative Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor.*[15] The gyratory specimens were then cored or cut to their final testing geometry, and the air voids of the specimens were measured using ASTM D6752-18, *Standard Test Method for Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method.*[16] All testing specimens measured 7 ± 0.5 % air voids in their final testing geometry. No short- or long-term laboratory aging was conducted, which is consistent with AASHTO T-283/ASTM D4867-09.

LABORATORY TESTING METHODOLOGY

Laboratory moisture susceptibility evaluation methods typically combine some form of moisture conditioning with a mechanical test method (either occurring separately or simultaneously). The test and conditioning methods employed in this study are described in the following section.

Indirect Tensile Strength/Modified Lottman Procedure

One of the test methods applied in this research was the modified Lottman procedure. This procedure, specified by ASTM D4867-09/AASHTO T-283, requires that two sets of specimens be made from each mixture. One set of these specimens is tested to determine the indirect tensile strength (ITS) of the material at 25°C. The other set is then conditioned by first vacuum saturating the specimens to a level between 70 and 80 %, subjecting the specimens to a freeze cycle at −18°C for a minimum of 16 h, and then placing the specimens in a 60°C water bath for 24 h. After conditioning, the samples are tested for ITS. The primary result from this testing is the tensile strength ratio (TSR) of the average conditioned strength to the average unconditioned strength. Typically, mixtures that achieve TSR values over 0.80 are considered good performers. In addition, some agencies will also require that minimum strength values are met, regardless of the TSR of the material.

ITS has been used extensively as a moisture susceptibility evaluation tool as it is a part of ASTM D4867-09/AASHTO T-283, which are what a majority of U.S. state transportation agencies use as the standard test for evaluating moisture susceptibility.[17] Although ITS has been a very popular method for determining moisture susceptibility, it has received criticism from a number of sources. Some examples include the fact that the test is nonfundamental in nature,[18] poor relationships between results and field conditions,[19] potential shear failures that are due to soft binders at room temperature, not being able to capture moisture damage seen from actions of traffic[20–22] or in regions of colder climates,[8] and the potential for false-positive or false-negative results.[23]

The moisture-induced stress tester (MiST; ASTM D7870-13, *Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure*) was utilized as an alternative moisture conditioning system.[24] The equipment consists of a chamber with a bladder that is able to apply pressure cycles to a saturated specimen, typically applying 3,500 cycles at 276 kPa where the water temperature is maintained at a specific temperature.[21,22,25,26] The conditioning process creates water pulses on the sample and simulates hydraulic scouring, which is considered a common moisture damage mechanism in asphalt pavements. In this study, the samples of mixes with PG 58-28 binder were conditioned at 58°C, whereas those with PG 64-28 or PG 70-28 binder were conditioned at 60°C.

The effect of pore water pressure and saturation on debonding of asphalt paving mixes was investigated by Jimenez[27] and Kiggundu and Roberts,[28] whereas the effect of permeability and vehicle speed on pore water pressure in pavements was investigated by a number of researchers.[29–32] In general, the need for equipment for generating cyclic pore pressure in HMA has been widely suggested by researchers to identify mixes with potential for moisture damage.

Similar to the Lottman/AASHTO T-283 procedure, MiST-conditioned specimens are tested for ITS. The primary result is the TSR between the MiST-conditioned specimens and the unconditioned specimens.

Dynamic Modulus

Dynamic modulus tests (AASHTO T342-11, *Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*) were conducted on three replicates of both unconditioned and MiST-conditioned specimens.[33] The test was conducted at three temperatures (4.4, 21.1, and 37.8°C) and six loading frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz). The data from these tests were then used to construct dynamic modulus master curves at a reference temperature of 21.1°C.

The master curves are compared visually and dynamic modulus stiffness ratios (DMR) are calculated at specific frequencies along the master curve to assess the moisture susceptibility of the mixtures. The DMR is calculated similar to TSR where the MiST conditioned stiffness is divided by the unconditioned stiffness.

In general, dynamic modulus has not commonly been used to assess the moisture susceptibility of asphalt mixtures. In the few instances where dynamic modulus has been used as a moisture susceptibility test method, the focus has been on the reduction in dynamic modulus when comparing conditioned specimens with unconditioned specimens, referred to as an E^* stiffness ratio.[34] Generally, dynamic modulus results have been able to consistently distinguish between materials with varying levels of moisture susceptibility, this effect being most prevalent at high testing temperatures and low frequencies.[35] Unlike ITS testing, which also uses a ratio-based evaluation criteria, at present there are no formal or proposed values of minimum dynamic modulus for moisture susceptibility evaluation.

Saturated Aging Tensile Stiffness

The saturated aging tensile stiffness (SATS) procedure uses a conditioning protocol that combines both oxidative aging and moisture conditioning into one procedure. Five specimens from each mix are initially tested for stiffness in indirect tensile mode at 20°C. Next, the specimens are vacuum saturated for 30 min at an absolute pressure of 33 kPa. The saturated specimens are then placed on a vertical rack inside a conditioning chamber (similar to a pressure aging vessel) where the intent is to have a wide range of saturation levels depending on the position of the specimen on the rack. Typical saturation values can be as low as 10 % and as high as 95 %. Because relatively softer surface mixtures (with low/high PG grade and high asphalt contents) were used in this study, the conditioning procedure was modified to use a temperature of 85°C under a pressure of 0.5 MPa for a duration of 24 hours on the basis of recommendations by Grenfell et al.[26] After conditioning, the percent saturation is determined for the specimens (referred to as retained saturation). The conditioned specimens are retested for stiffness, and the retained stiffness value is determined by finding the ratio in stiffness results between the conditioned and unconditioned specimens.

The SATS test is a test protocol originally developed to evaluate the moisture susceptibility and long-term durability of high-stiffness base course materials.[36,37] One of the unique aspects of SATS is that the protocol includes a conditioning procedure that combines both aging and moisture conditioning into a single process. Similar to the dynamic modulus method previously mentioned, the SATS test measures the change in stiffness of a material that is due to moisture and age conditioning. Strong correlations have been observed between stiffness reductions observed with SATS testing and field results.[38]

HWT

The last test procedure evaluated in this study was the HWT as specified in AASHTO T-324-17. This simulative test method rolls a weighted steel wheel back and forth over the asphalt specimens to mimic rutting damage in the field. The specimens are submerged in heated water to both control the temperature and introduce moisture damage to the material. Typical tests are conducted by applying 20,000 wheel passes where the rut depth at each pass is measured and recorded and where failure is defined as a 12.5-mm rut depth. Although the HWT test was originally developed as a rut test, it has also been employed as a moisture susceptibility test because the specimens are submerged.

The principal methods used to measure moisture damage from Hamburg results is the passes to failure and stripping inflection point (SIP). In the Hamburg test, passes to failure is defined as the number of wheel passes required to produce a 12.5-mm rut depth on the specimens. Similar to a rutting-based evaluation, materials subjected to a higher number of passes to failure are considered more moisture resistant. On the other hand, the SIP represents where the slope of the creep phase and stripping phase of the Hamburg data curve intersect, which gives an indication of both how quickly the material begins to experience stripping/moisture-induced damage as well as how quickly the material deteriorates once that moisture damage has occurred.

In the United States, the HWT has recently gained popularity as a moisture susceptibility test method for asphalt mixtures. Izzo and Tahmoressi compared six asphalt mixtures with and without antistripping additives and showed that the test is able to distinguish between the mixtures with and without additives.[39] Also, an evaluation of asphalt mixtures from 16 field projects through a range of moisture susceptibility tests was conducted by Schram and Williams.[40] The results from that study showed Hamburg results to have good correlation with stripping performance in the field. Recently, the National Cooperative Highway Research Program (NCHRP) 9-48 study employed the HWT to assess moisture susceptibility of various warm-mix technologies that recommended use of HWT (as an alternative to AASHTO T-283) for moisture susceptibility testing.[41] Generally, the SIP is used as a pass/fail parameter with a threshold value of around 10,000–15,000 passes.

In recent years, Yin et al. from the Texas Transportation Institute (TTI) developed more novel methods to evaluate moisture susceptibility using Hamburg data.[42] This method involves measuring two parameters, the first of which is called the stripping number, LC_{SN}. LC_{SN}, shown on a Hamburg data curve in figure 1, is calculated by first fitting equation (1) to the raw Hamburg data.

$$RD = p * \left[\ln\left(\frac{LC_{ult}}{LC}\right)\right]^{\frac{-1}{B}} \tag{1}$$

where:

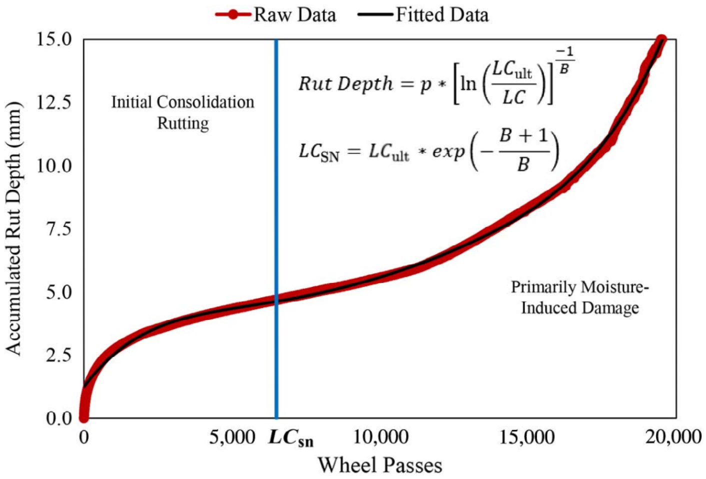
RD = rut depth,

LC = load cycles, and

B, p, LC_{ult} = fitting coefficients.

FIG. 1

Hamburg curve with LC_{SN} calculation.



The point of interest is the number of load cycles at which the accumulated rut depth begins to increase again after the creep phase of the test. This point is approximated by calculating the inflection point of equation (1). In its simplified form, this point can be directly calculated using equation (2).

$$LC_{SN} = LC_{ult} * \exp\left(-\frac{B+1}{B}\right) \tag{2}$$

where:

LC_{SN} = stripping number, and

B, LC_{ult} = fitting coefficients from equation (1).

The second parameter of the TTI method is known as the stripping life, LC_{ST}. LC_{ST} is calculated by first taking the LC_{SN} and zeroing the accumulated rut depth to that point. Equation (3) is fit to the data points occurring after the LC_{SN}. It should be noted that the definition of strain in this equation is the rut depth divided by the original height of the specimen.

$$\epsilon^{st} = \epsilon_0^{st} * \left(e^{\theta(LC - LC_{SN})} - 1\right) \tag{3}$$

where:

ϵ^{st} = stripping strain,

ϵ_0^{st} = initial stripping strain,

LC = load cycle,

LC_{SN} = stripping number, and

θ = fitting coefficient.

Once equation (3) has been fit, the LC_{ST} is calculated by determining the number of load cycles required to induce a certain amount of stripping strain in the material. The value proposed by Yin et al. is 0.20, which corresponds to a 12.5-mm deformation on a standard 62.5-mm-tall specimen. An example of LC_{ST} on a Hamburg curve is shown in figure 2.

The advantage of the two parameters proposed by Yin et al. is that they provide a more consistent means to evaluate moisture susceptibility compared with the relatively variable SIP. The stripping number captures how many load cycles are required for moisture to begin breaking down the bond between the aggregates and mastic. All accumulated rut depth before this is assumed to be caused by viscoplastic effects, whereas all rut depth increase after this point is assumed to be caused primarily by stripping damage, although viscoplastic effects are not

FIG. 2

Hamburg curve with LC_{ST} calculation.

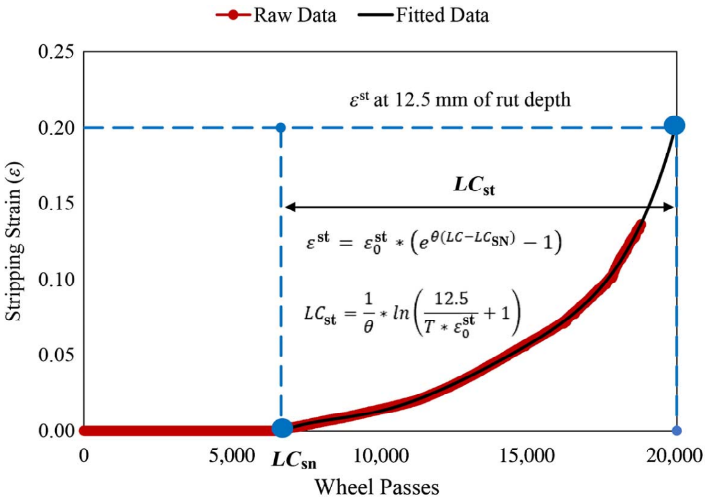


TABLE 2

Test and conditioning methods used in study

Mechanical Test Method	Modified Lottman Conditioning	MiST Conditioning
Indirect tensile strength	Yes	Yes
Dynamic modulus	No	Yes
SATS	Conditioning unique to SATS. Involves placing specimens in a moist PAV for 24 h at 85°C and 0.5 MPa	
Hamburg wheel tracker	No preconditioning used. Moisture damage simulated by conducting test under heated water	

ignored. The stripping life, on the other hand, describes how quickly the stripping damage evolves once stripping damage first occurs. These two parameters describe unique but equally important types of material behavior under moisture-induced stresses. To improve moisture resistance of a material, a high stripping number and stripping life are desired.

In this study, all Hamburg testing was performed at a temperature of 45°C on a dual wheel Instrotek SmarTracker wheel tracking device. Rut depths were measured by one sensor at four different points of the wheel's travel, where the maximum recorded rut depth at each pass was used for analysis. Although this is a general observation, the maximum rut depth was in the center of the testing specimen the majority of the time. The only time the end sensors would read as the maximum rut depth was typically during the beginning portion of the test. In these cases, the maximum rut depth switched to the center sensors at the beginning of the creep phase of the test. To evaluate moisture susceptibility of the mixtures used in this study, both the traditional and TTI analysis was conducted.

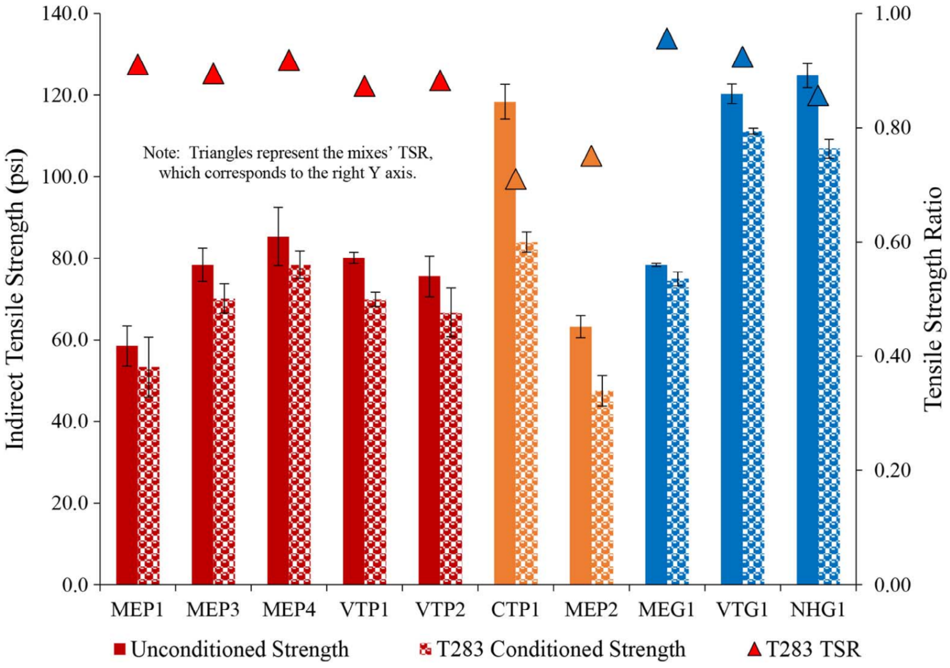
A summary of conditioning methods and mechanical tests used in this study is presented in **Table 2**.

Results and Discussion

ITS/MODIFIED LOTTMAN TESTING

Figure 3 shows the results from the modified Lottman procedure as specified by ASTM D4867/AASHTO T-283. For reference, saturation levels in the specimens were consistently measured between 73 and 78 % after the initial stage of conditioning, which is well within the specification limits. The plots shown display both the measured strength values as bars, which correspond to the left vertical axis, and the TSR values as points, corresponding to the right vertical axis. The error bars on each strength value represent the standard deviation of measured values.

FIG. 3 ITS with Lottman conditioning results.

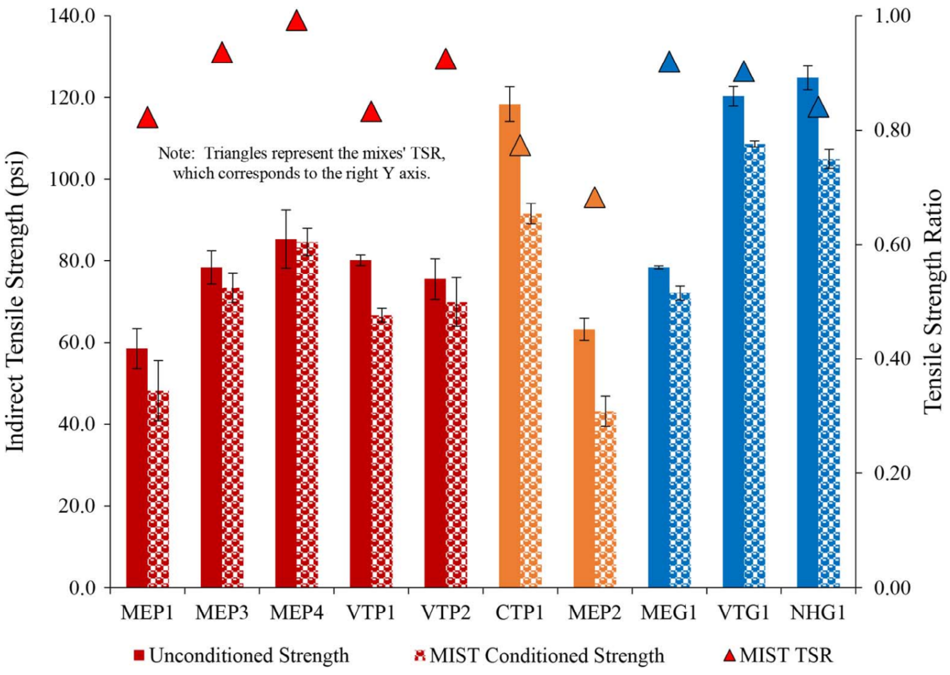


The color of the bars and points are tied to the historic performance of the material, wherein the darkest/leftmost bars represent poor mixtures (MEP1, MEP3, MEP4, VTP1, and VTP2), the lightest/center bars represent moderate (CTP1 and MEP2), and medium-shaded/rightmost bars represents good performers (MEG1, VTG1, and NHG1). Looking at the strength results alone, the good performing mixtures are generally stronger in both an unconditioned and moisture-conditioned state. Although these strength values show some distinction between the good, moderate, and poor mixtures, it is worth noting that the mixtures all have different binder grades. Binder grade has a significant impact on measured strength values as ITS is conducted at room temperature. Stiffer binders, which the good mixtures mostly use, will generally give higher strength values than mixtures with relatively soft binders, which is what most of the poor mixtures use.

When considering the TSR values from Lottman testing, the results become less clear. Comparing the good and poor materials, there is little differentiation in TSRs as shown in figure 3. Both sets of mixtures have TSR values ranging from 0.85 to 0.95 with their averages being within 0.01 of each other. The results suggest that these two groups of mixtures would both perform well in the field as they have retained more than 80 % of their strength, the pass/fail threshold set in AASHTO T283. Although this is known to be inaccurate considering the mixtures historic field performance, this is not particularly surprising as all of the mixes were designed using Superpave mix design specifications, which require the mixture to pass AASHTO T283 requirements. Interestingly, the moderate mixtures had the lowest TSR values, which were in the 70 % range.

The results from ITS testing paired with MiST conditioning are shown in figure 4. Interestingly, the results in this plot look very similar to those in figure 3. A similar trend of the good mixtures being stronger than both the moderate and poor mixtures is observed, as well as little distinction among the TSR values can be seen. A slightly wider range of 0.82 to 0.99 for TSR values among the good and poor performers exists, but the average TSR values for the two mixtures groups is again separated by very little. The same trend in which the mixtures performing moderately in field have the lowest TSR values (between 0.70 and 0.80 in this case) was observed with MiST conditioning. Both of these moderate mixes had amine-based antistrip additives in the binder. Note that unlike the freeze-thaw conditioning, SATS, or the HWT tests, the mixes with the different binders were conditioned at different temperatures in MiST, which could have affected the results.

FIG. 4 ITS with MiST-conditioning results.



One potential explanation for this observation of why neither method is able to show clear distinctions between historically good and poor materials is that standard ITS results may not completely capture the effects of moisture damage for the relatively soft mixtures (low PG grades and generally higher asphalt contents) used in this research. Because ITS is conducted at room temperature (typically 25°C), many soft mixtures are too ductile to exhibit a pure tensile failure during the ITS test. Instead, there is a substantial amount of creep and shear failure in the material close to the loading heads. The concept behind using ITS as a moisture susceptibility evaluation test is that it is directly stressing the internal adhesive and cohesive bonds within the material through splitting tensile stresses. On the other hand, the mechanisms behind the creep and shear failures are not directly stressing the areas that are expected to be sensitive to moisture-induced damage. Because soft materials are experiencing substantial amounts of shear and creep damage, it is likely that standard ITS cannot reliably capture the effects of moisture damage for these materials. Also, currently only the strength ratio aspect is the primary result from the ITS tests; other parameters, such as total dissipated energy as well as changes in testing temperature, could be better indicators of relative changes in the failure mechanism that are due to moisture damage.

It is worth noting when considering the effectiveness of ITS as a moisture susceptibility test method that the origin of its use was from the work done by Lottman where most of the testing was performed in conditions that are quite different than those in standard practice today.[43–46] Of note, the mixtures were not designed using Superpave specifications as the ones in this study were, the mixtures were significantly weaker (typical strength around 40–60 psi) than those used in this study, and, most notably, were tested at 55°F (12.8°C). In this work, findings from ITS testing at the lower temperature were found to have less variation and better correlation to field results, which isn't entirely surprising, especially when compared them with testing at room temperature, as lower testing temperatures are more conductive to causing the desired tensile failures previously mentioned. Ultimately, the original work to develop ITS as a moisture susceptibility test method was performed on significantly different materials and conditions as compared to what was done in this study, which is based on current practice and intends to evaluate the merits of test methods as they are currently performed. The results presented here should be considered in this context, rather than a blanket statement on ITS testing in all conditions.

DYNAMIC MODULUS

Figure 5 shows the dynamic modulus master curves for three of the study mixtures. This plot includes master curves for the mixtures in both an unconditioned (solid point) and MiST-conditioned (hollow point) state. Some general information about the three mixtures is shown in **Table 3**. It is worth noting that these three materials consist of one good performer (marked with circles on plots) and two poor performers, where one mixture includes an antistrip additive (marked with squares) and the other being the same mixture except it has no antistrip additive (marked with triangles). All of the master curves presented in this section are plotted on a log-log scale and were shifted to a reference temperature of 21.1°C.

Looking at the master curves in **figure 5**, it is apparent that all three mixtures experience a reduction in stiffness after MiST conditioning. This is most evident at lower frequencies, which represent slow traffic speeds or high pavement temperatures. The reduction in stiffness at high frequencies is less evident because of the log-log scale the data are being plotted on and the proximity of the points, but it is still noticeable for the two poor performing mixtures. Comparing the good and poor performing materials, the reduction of stiffness appears to be less for the good material as compared with both of the poor performing materials.

The dynamic modulus ratio (moisture conditioned modulus divided by unconditioned modulus) values at various frequencies along the master curve are shown in **figure 6**. The results in this plot support the visual observations made from **figure 5** where the materials experience a drop in stiffness across all frequencies after conditioning. This reduction in stiffness is much more pronounced at lower frequencies where the dynamic modulus ratio is as low as 0.71 for the good performer and 0.53 for the poor performer without the antistrip

FIG. 5 Dynamic modulus with MiST conditioning results.

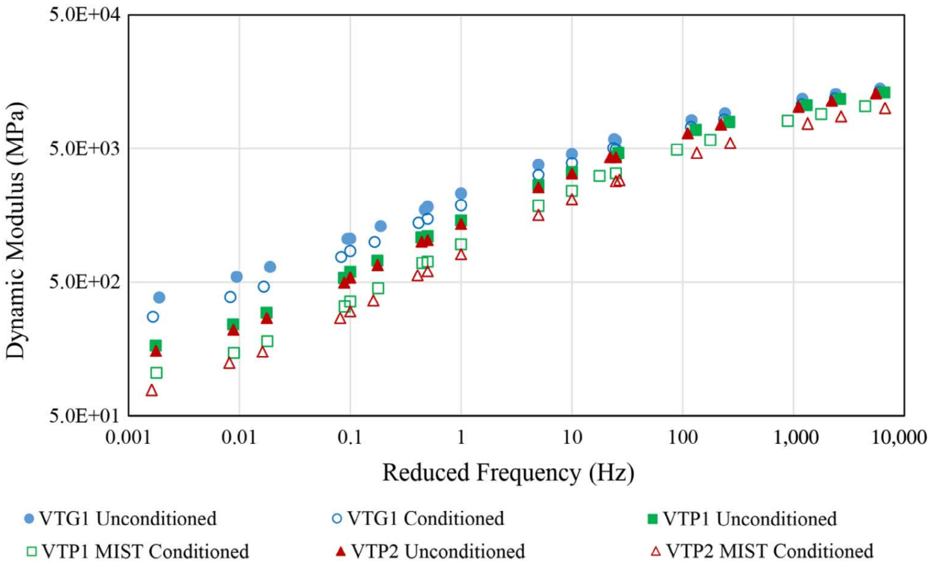
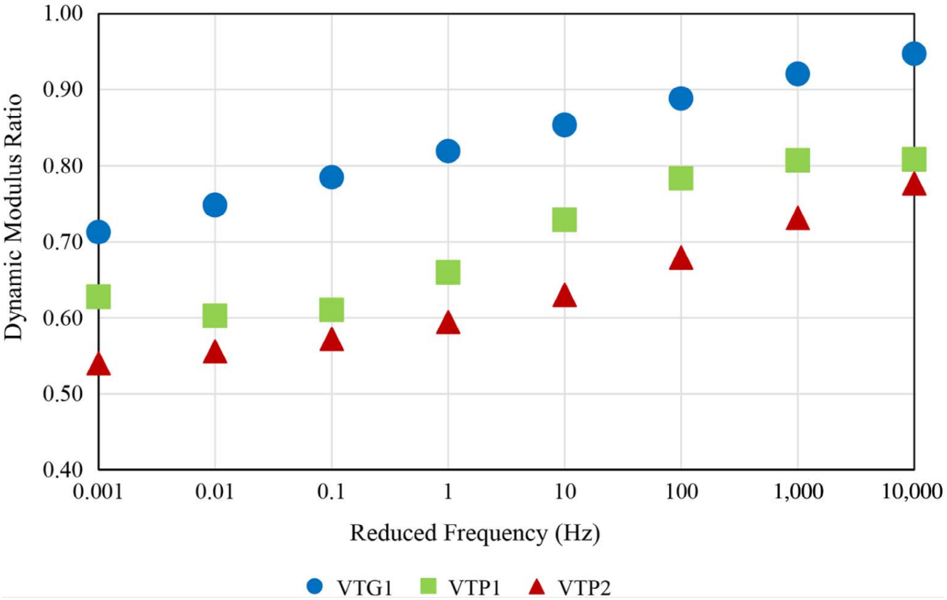


TABLE 3
Mixes tested with dynamic modulus and MiST conditioning AQ3

Mix Name	Performance	Aggregate Type	Binder Grade	Additive	NMAS (mm)
VTP1[a]	Poor	Granite	58-28	WMA/antistrip additive	9.5
VTP2[a]	Poor	Granite	58-28	No additive	9.5
VTG	Good	Dolomite	70-28	WMA additive	12.5

Note: NMAS, XXX; WMA, warm mix asphalt. [a] Indicates that mixtures are produced at the same plant, have the same volumetric properties, and the same gradations.

FIG. 6 Dynamic modulus ratio results.



additive. As the frequency increases, the dynamic modulus ratio steadily increases to values around 0.95 for the good performer and approximately 0.80 for both poor performers. These results suggest that asphalt mixtures are more affected by moisture conditioning at slower traffic speeds and higher temperatures. Under these conditions, the response of the aggregates remain the same (elastic) but that of the binder or the mastic changes to one more viscous in nature. Hence, it can be reasoned that the impact of moisture damage in this study was dominated by the binder and the mastic phase of mixtures.

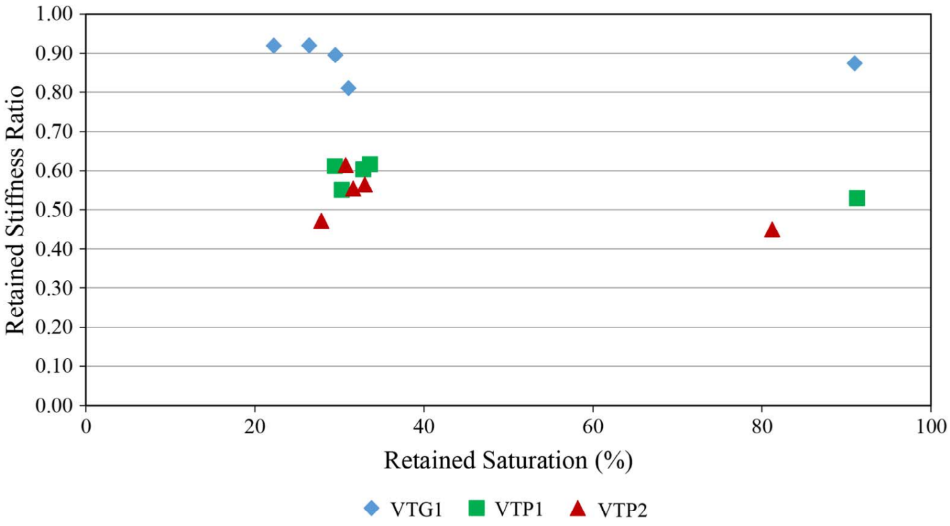
One reason dynamic modulus results may be more promising as compared with strength measures for moisture susceptibility is that dynamic modulus is able to capture a larger amount of specimen damage that is due to conditioning as compared to strength measurements. This is because dynamic modulus is a property measured on bulk specimen (response of whole specimen as opposed to localized region where failure might develop), allowing damage throughout the material (because of small defects from moisture conditioning) to be captured at the test level regardless of the location within the material. Also, the test is conducted at a range of frequencies and temperatures and thus is capable of detecting damages to the different components of the mix. ITS tests, on the other hand, focus on failure within one region of the material. This is especially apparent with strength tests that involve fracture, such as ITS, where the region of failure is highly controlled by the test geometry. In this case, it is likely that many regions of local damage (especially near the surface of the material) will not be fully captured by strength measurements as they are not along the failure plane.

SATS

Results from SATS testing are shown in the following section. The same three mixtures tested for dynamic modulus were tested with the SATS procedure.

Figure 7 shows the SATS results from the three mixtures. In terms of ranking the mixtures, the results show a clear difference between the good performing mixture and the two poor performing mixtures. As can be seen in figure 7, the good performing mixture's retained stiffness ratio always remained above 0.80, whereas the poor materials never retained more than 0.62 and dropped to a stiffness ratio as low as 0.45. It is worth noting that all three mixes pass the minimum 0.40 retained stiffness level recommendation by the UK Highway Agency, suggesting that the materials are sufficiently resistant to moisture-induced damage.

FIG. 7 SATS results.



The uniqueness of the SATS protocol, and why it was included in this research, is because the effects of both aging and moisture-induced damage are incorporated into the conditioning procedure, which provides a more realistic conditioning environment as compared with traditional conditioning. When considering pavements in the field, asphalt materials will experience both aging and moisture-induced damage concurrently rather than consecutively, as is typically done with laboratory procedures. Based on the results in this research, it appears that a combined approach holds promise in being an effective moisture susceptibility conditioning scheme.

HWT TEST

Results from the HWT test are shown in the following section. All 10 of the study mixtures are presented in this section and uses the same color convention as that in the ITS section, where the darkest shading/rightmost bars represent poor performance, lightest shading/middle bars represent moderate performance, and medium-shaded/rightmost bars represent good performance mixtures. Results from both traditional Hamburg analysis and the TTI method are presented and analyzed. For reference, representative Hamburg curves for each mix are shown in figure 8.

Figure 9 shows the results from traditional Hamburg analysis. This includes both the passes to failure, which corresponds to a rut depth of 12.5 mm, and the calculated SIP, wherein the error bars represent the maximum and minimum measured values. Looking at the passes to failure first, the results show that a majority of the poor mixtures failed within the standard 20,000 test passes. On the other hand, all of the moderate and good performing mixtures did not exceed the 12.5-mm rut depth accumulation during the test. Considering this, the rut depth could be a promising parameter as it is able to distinguish good and poor performing materials.

Although this parameter shows promise, it should be noted that the HWT test is run at a single temperature in this study. Rut depth can be somewhat misleading because a soft material could experience viscoplastic deformation at the high temperatures the Hamburg test is conducted at but no moisture-induced rut damage. This can be seen in limited cases in the results. Looking at the raw data curves in figure 8 for both MEG1 and VTP1, it can be seen that MEG1 experiences significantly more rut depth accumulation, although neither material shows obvious accumulation of moisture-induced damage (which would be seen as a significant increase in rut depth accumulation). This is likely due to the fact that MEG1 is a softer material as compared with VTP1 per dynamic modulus measurements on the materials.[7] Challenges like this support the use of parameters that ignore rut depth, such as SIP.

FIG. 8 Representative Hamburg data curves.

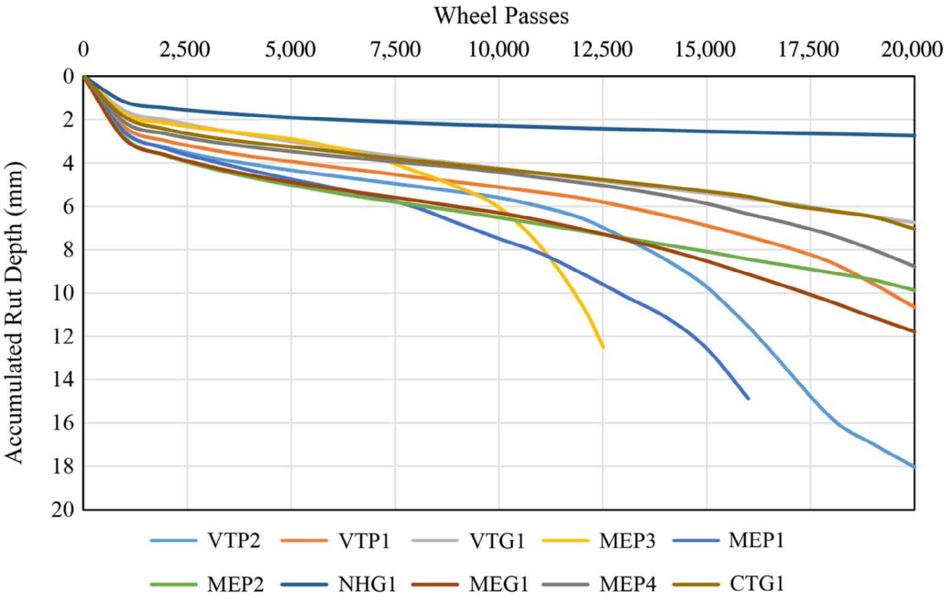
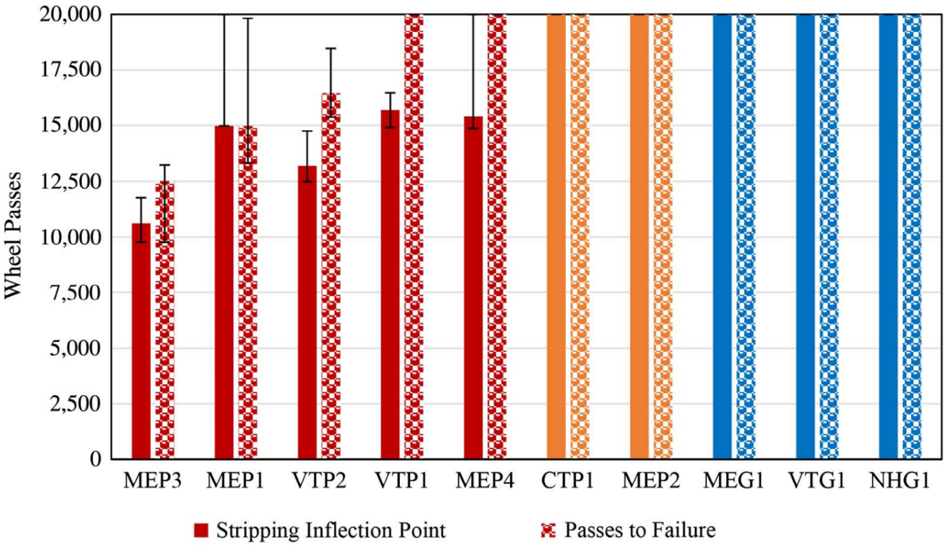


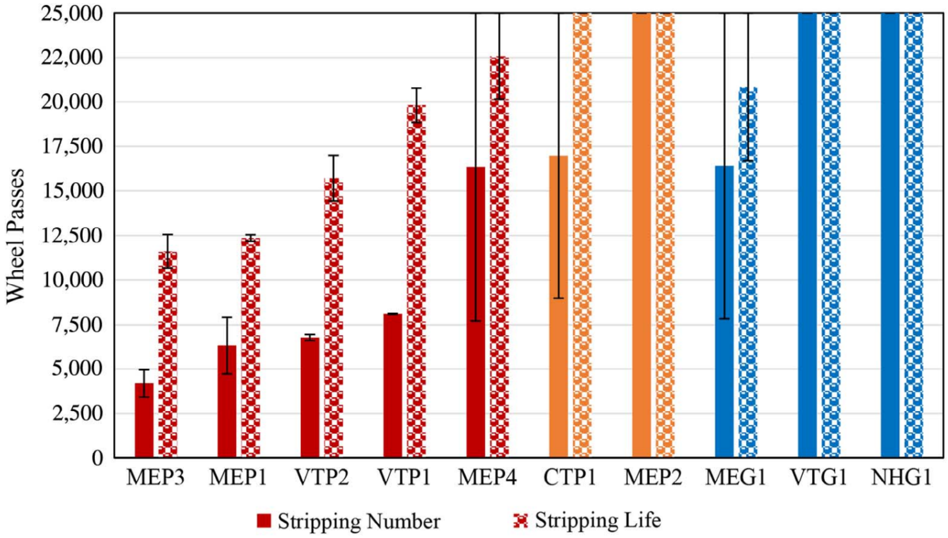
FIG. 9 Traditional Hamburg results.



Looking at the SIP values, shown with solid bars in **figure 9**, it is apparent that all of the poor performing mixtures experienced a SIP before the test concluded. As with the rut depth results, any bar shown as 20,000 passes for SIP indicates that no striping inflection point occurred during the test. Comparing the good and poor performing mixtures, it is apparent that the SIP does an excellent job at distinguishing the two types of materials. The poor mixtures never exceed 16,000 passes before experiencing a SIP where none of the good mixtures experienced a SIP.

Figure 10 shows the Hamburg results using the TTI analysis. It should be noted that, similar to the traditional results, a value of 25,000 passes for either parameter means that they did not occur within the tested number of load repetitions, which indicates excellent performance. The first parameter calculated is the stripping

FIG. 10 Hamburg results with TTI parameters.



number, which represents how quickly a material begins experiencing moisture-induced damage. Looking at the results, there is a clear distinction between the poor and good performing mixtures. Most of the poor mixtures, with the exception of MEP4, began stripping before 8,000 wheel passes. On the other hand, the good performing mixtures only had one mixture that begin stripping (at 13,000 passes), whereas the other two had no measurable stripping point. The moderate materials behaved, as one would expect, somewhere between the poor and good performing mixtures. Similar to the previous plot, this includes error bars that represent the maximum and minimum measured values.

The calculated stripping life, which represents how quickly striping damage progresses in the material, shows a similar trend where the poor materials consistently perform worse than both the moderate and good materials. As shown in figure 10, the average stripping life of the poor materials is substantially lower than that of both of the other two material groups. The only exception to this general trend is MEG1, which has a lower stripping life than a few of the poor and moderate mixtures. Interestingly, other than one or two exceptions, the ranking according to the postconditioned tensile strengths are similar to those of the rankings from the Hamburg test. This observation provides some support to the concept of using the postconditioned tensile strength rather than the TSR, if the ITS method is utilized at all.

Overall, the results from the Hamburg testing are very promising considering the main goal of this research. All four of the parameters used in this section show clear distinction between good and poor performing materials, and some are even able to distinguish the moderate materials as well. In addition, both methods are able to identify differences with and without antistrip additives. Comparing the two analysis methods, it appears that the TTI method shows larger distinctions between the materials in terms of results for the materials used in this study.

One of the main drawbacks of using the HWT test is that it is a simulative test. Although other tests focus on use of engineering or fundamental mechanical properties, Hamburg is an empirical measure with loading conditions that are simulative of traffic loads on saturated asphalt mixtures. Although this is not ideal for mechanistic analysis, the simulative nature of HWT gives it the unique ability of capturing distress mechanisms that are not currently simulated in mechanistic analyses. The Hamburg test is able to simulate the effects of both moisture inundation when the specimens are submerged in heated water as well as the effects of pore pressure damage from the action of the wheel. Considering this, it should be mentioned that the test could be overly harsh for fine-graded mixes that are used in relatively thin lifts on the surface.

Summary, Conclusions, and Recommendations

The primary goal of the research presented in this article is to compare a series of asphalt mixture moisture susceptibility test methods in terms of their ability to be a reliable test method for routine use during mixture design. Using methods that have shown promising results in previous studies, a series of historically good and poor performing mixtures were evaluated to achieve this goal. Results were analyzed to determine which tests are able to distinguish historically good and poor performing mixtures on a consistent and reliable basis. It is important to note that all of the materials used in this study were designed for, and produced in, the New England region of the United States. The findings from this study may not be applicable for regions with significantly different climates, particularly hot climates where relatively stiff mixtures are needed. On the basis of the findings presented in this thesis, a number of conclusions can be drawn.

- ITS ratios, regardless of whether modified Lottman or MiST conditioning was used, were unable to distinguish the performance of good and poor performing mixtures. Little difference was observed between the average TSRs of the poor and good mixtures as well. This confirms findings from other similar work and supports the motivation for this study.
- Postconditioned ITS values were able to distinguish good and poor performing mixtures. The results consistently showed that good materials were stronger in both unconditioned and conditioned (Lottman and MiST) states as compared with their poor performing counterparts. Although this finding is promising, it should be understood that this trend may be caused by higher high-temperature binder grades (which behave more stiffly at room temperature in general) that the good performing mixtures contained.
- Results obtained from dynamic modulus paired with MiST conditioning were promising considering the main goal of this research. The ratio of dynamic modulus values after conditioning for the good performing material clearly and consistently retained more initial stiffness compared with both poor performing materials.
- After conditioning, the materials consistently experienced a reduction in modulus and from dynamic modulus testing, particularly at the low frequencies. This trend indicates that moisture-susceptible materials may be particularly prone to rutting problems after being exposed to moisture-induced damage. Also, for the evaluation of moisture susceptibility, it could be sufficient to conduct dynamic modulus tests at lower frequencies only.
- SATS results were very similar to dynamic modulus results overall. The test was able to clearly distinguish the good and poor performing materials in terms of their respective retained stiffness values.
- HWT test results were very promising considering the main goals of this study. Whether traditional or TTI analysis was used to determine suitable moisture stripping performance parameters, clear and consistent differences were observed between poor and good performing materials. In many cases, the good materials never reached failure during the entire Hamburg test while most, if not all, of the poor materials failed. The average results among the different material groups also support these conclusions.
- When comparing traditional and TTI Hamburg analysis, both methods were able to distinguish good and poor materials. In general, the TTI analysis showed larger differences in results (in terms of magnitude) but this difference was not substantial.

Overall, the results presented in this research suggest that dynamic modulus in conjunction with MiST conditioning, SATS, and the HWT hold promise as a routine moisture susceptibility test during mixture design. When considering their ability to distinguish the effect of treatments and practical limitations, the HWT holds the most promise out of these three tests based on the materials evaluated in this study. Results from the Hamburg consistently showed clear distinction between good and poor materials as well as materials with and without antistripping additives. It is recommended that transportation agencies experiencing moisture damage in the field with materials passing mixture design requirements should investigate the feasibility of adopting and specifying the HWT test. Both traditional analysis and TTI analysis hold promise, although there is much more technical literature and existing specifications using SIP, so this may be the more practical approach currently.

Although the research presented here provides a starting point for determining an effective, practical replacement for current moisture susceptibility testing, further work is needed to gain a comprehensive understanding of the problem. Considering that the HWT showed the most promise as a procedure for routine usage during mixture design, verification work would be needed. Specifically, the connection between laboratory results and field performance seen in this research would need to be investigated. Ideally, Hamburg results could be compared to quantitative field results (such as a measured amount of surface stripping or some other form of reliable, in situ moisture damage) to confirm the findings of this research as well as ensure the laboratory results do not produce false-positive results. Such a verification would provide more confidence in the recommendations of this research for the agencies considering adopting the Hamburg test. Also, use of a performance-related approach should be explored further, whereby reduction in pavement service lives because of increased moisture susceptibility of mixtures should be incorporated in mix design and mix acceptance processes. A combined MiST conditioning with complex modulus testing approach could help in exploring the pavement life–based analysis. The option of using parameters other than the strength could be explored from ITS tests as well.

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