TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle
   Development of a Moisture Sensitivity Test for Asphalt Mixtures

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5. Report No.
   FHWA/LA.25/712

6. Report Date
   June 2025

7. Performing Organization Code
   LTRC Project Number: 19-2B
   SIO Number: DOTLT1000275

8. Type of Report and Period Covered
   Final Report
   5/2019-06/2024

9. No. of Pages
   98

10. Supplementary Notes
   Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration.

11. Distribution Statement
   Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

12. Key Words
   Moisture damage; moisture conditioning; Moisture-induced Stress Tester; freeze-thaw cycles; Semi-Circular Bend; Jd-ratio; Hamburg Wheel-Tracking; Modified Lottman; amine-based anti-stripping; chemical WMA additives

13. Abstract
   Moisture-induced damage in asphalt pavements poses a significant concern for road agencies, affecting both long-term performance and driving safety. Most road agencies have relied on the Modified Lottman (ML) test, following the AASHTO T 283 standard, to assess the moisture susceptibility of asphalt mixtures. However, researchers have questioned the reliability of this test and its ability to accurately simulate moisture damage in the field. Although the Hamburg Wheel-Tracking (HWT) test, following the AASHTO T 324 standard, shows more reliability, it also has limitations. The “pass/fail” criteria based solely on rutting depth may not fully capture the complex

nature of moisture-induced damage in the field. Further, the ability of the HWT test to simulate field moisture damage conditions and predict moisture sensitivity for a wide range of mixtures is limited.

The primary objective of this study was to develop a reliable moisture susceptibility test procedure that consistently evaluates the resistance of asphalt mixtures to moisture-induced damage. To fulfill this objective, 13 asphalt mixtures were prepared using two binder types (unmodified PG 67-22 and polymer-modified PG 70-22), three aggregate types (limestone, crushed gravel, and semi-crushed gravel), and two anti-strip additives (amine-based and chemical WMA). The mixtures were subjected to five conditioning levels: control, a single freeze-and-thaw cycle (FT-1), a triple freeze-and-thaw cycle (FT-3), Moisture-induced Stress Tester for 3500 cycles (MiST 3500), and MiST for 7000 cycles (MiST 7000). The Semi-Circular Bend (SCB) test was also conducted on the studied mixtures. Results indicated that moisture conditioning increased binder stiffness but did not necessarily improve moisture resistance in mixtures. Polymer-modified binders exhibited better moisture damage resistance than unmodified binders. Limestone aggregates generally showed better performance than gravel aggregates. The HWT test effectively captured moisture damage resistance in asphalt mixtures, while the ML test showed limitations in effectively measuring moisture damage resistance. The amine-based anti-stripping additive was able to enhance the asphalt mixtures' resistance to moisture damage; however, the chemical WMA showed an insignificant effect. The SCB J_d-ratio parameter was found to be a promising alternative to HWT rut depth. The MiST conditioning protocol effectively simulated field conditions.

Based on the findings of the study, it is recommended to incorporate a moisture conditioning protocol into the AASHTO T 324 standard to better assess moisture susceptibility. Additionally, further research using atomic force microscopy is suggested to understand the moisture damage mechanisms. The potential negative impact of anti-strip additives on rutting resistance should be considered during mixture design, and field studies are recommended to validate laboratory findings.

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Development of a Moisture Sensitivity Test for Asphalt Mixtures in Louisiana

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LTRC Project No. 19-2B
SIO No. DOTLT1000275

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

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June 2025

Abstract

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The primary objective of this study was to develop a reliable moisture susceptibility test procedure that consistently evaluates the resistance of asphalt mixtures to moisture-induced damage. To fulfill this objective, 13 asphalt mixtures were prepared using two binder types (unmodified PG 67-22 and polymer-modified PG 70-22), three aggregate types (limestone, crushed gravel, and semi-crushed gravel), and two anti-strip additives (amine-based and chemical WMA). The mixtures were subjected to five conditioning levels: control, a single freeze-and-thaw cycle (FT-1), a triple freeze-and-thaw cycle (FT-3), Moisture-induced Stress Tester for 3500 cycles (MiST 3500), and MiST for 7000 cycles (MiST 7000). The Semi-Circular Bend (SCB) test was also conducted on the studied mixtures. Results indicated that moisture conditioning increased binder stiffness but did not necessarily improve moisture resistance in mixtures. Polymer-modified binders exhibited better moisture damage resistance than unmodified binders. Limestone aggregates generally showed better performance than gravel aggregates. The HWT test effectively captured moisture damage resistance in asphalt mixtures, while the ML test showed limitations in effectively measuring moisture damage resistance. The amine-based anti-stripping additive was able to enhance the asphalt mixtures’ resistance to moisture damage; however, the chemical WMA showed an insignificant effect. The SCB J_d-ratio parameter was found to be a promising alternative to the HWT rut depth. The MiST conditioning protocol effectively simulated field conditions.

Based on the findings of the study, it is recommended to incorporate a moisture conditioning protocol into the AASHTO T 324 standard to better assess moisture susceptibility. Additionally, further research using atomic force microscopy is suggested to understand the

moisture damage mechanisms. The potential negative impact of anti-strip additives on rutting resistance should be considered during mixture design, and field studies are recommended to validate laboratory findings.

Acknowledgements

The authors would like to express their appreciation to the Federal Highway Administration (FHWA), Louisiana Department of Transportation and Development (DOTD), and Louisiana Transportation Research Center (LTRC) for their support for this project. Additionally, the research team acknowledges the Project Review Committee (PRC) members for the valuable feedback provided for the completion of this report.

Implementation Statement

This report recommends reliable and consistent moisture conditioning and testing protocols for consideration and implementation in the Louisiana Standard Specifications for Roads and Bridges. Adopting these recommended moisture damage conditioning and testing methods will enhance the durability, resilience, and long-term performance of Louisiana's asphalt pavements.

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Introduction

Moisture damage significantly impacts the overall performance of asphalt pavements. The presence of moisture in asphalt pavements can lead to stripping and durability issues. Further, moisture-induced damage can have detrimental effects on long-term mechanical performance and user safety. Despite being a long-standing issue, many aspects of moisture damage in asphalt pavements remain unclear. As a result, current characterization methods often fail to reliably predict moisture susceptibility in the field [1, 2]. Numerous studies have suggested that addressing moisture damage primarily requires adequate mixture and pavement design procedures and proper construction practices [3, 4, 5].

A 2002 Colorado Department of Transportation survey revealed that 87% of highway agencies in North America had adopted the Modified Lottman (ML) and Hamburg Wheel-Tracking (HWT) tests to evaluate moisture susceptibility for asphalt mixture design and acceptance. However, moisture damage issues persist and have even intensified in recent years. This phenomenon can be attributed to various factors, including the use of unconventional asphalt modifiers (e.g., recycled engine oil bottoms, asphalt binder rejuvenators, crumb rubber, etc.), recycled materials, alternative mixture production techniques (e.g., warm-mix asphalt), and more frequent extreme weather events (e.g., heavier rainfall, colder winters, hotter summers, etc.) [6, 7, 8, 9].

Over the years, researchers have incorporated laboratory moisture conditioning protocols to simulate field conditions, such as the freeze-thaw conditioning procedure (AASHTO T 283) [8] and the Moisture-induced Stress Tester (MiST) (ASTM D 7870) [10]. The inclusion of these conditioning protocols before laboratory tests has led to improved prediction of asphalt mixtures' moisture susceptibility. Before adopting the 2016 specifications document, the Louisiana Department of Transportation and Development (DOTD) evaluated the moisture damage susceptibility of asphalt mixtures by conducting the Modified Lottman (ML) test, following [3] the AASHTO T 283 standard. While the ML test is widely used, many researchers [11, 12, 13, 14] argue that the tensile strength ratio (TSR) is not a consistent and reliable indicator of moisture sensitivity. The ML test lacks repeatability due to its sensitivity to air void distribution and saturation levels. Additionally, the moisture conditioning procedure of the ML test has been criticized for its impracticality and inability to accurately simulate field moisture damage [15, 16, 17]. Recently, AASHTO T 324 was included in the 2018 Louisiana Standard Specifications for Roads and Bridges to complement the shortcomings of the AASHTO T 283 test method. However, the accuracy of the "pass/fail" criteria of the HWT test results in predicting the moisture susceptibility of typical Louisiana asphalt mixtures is limited. This study aimed to conduct a comprehensive evaluation of current moisture damage test procedures and establish a reliable test procedure that combines a state-of-the-art moisture conditioning method with a suitable mechanical test.

Literature Review

Asphalt pavements are subjected to a variety of environmental stresses and traffic loads throughout their service life, which can significantly impact their durability and overall cost-effectiveness [1]. Moisture infiltration into asphalt pavements is inevitable, occurring through various pathways, including cracks, interconnected air voids, pavement edges, and rising groundwater levels [5]. Once moisture infiltrates the pavement, it can compromise its structural integrity by generating cyclic hydraulic pressure within the voids, particularly under repeated traffic loading or freeze-thaw cycles. The resulting damage can manifest as adhesive failure, cohesive failure, or a combination of both [13]. Adhesive failure involves the separation of the asphalt binder film from the aggregate surface, commonly known as stripping. Cohesive failure, on the other hand, entails a loss of stiffness in the asphalt mixture due to reduced cohesion within the binder matrix [3].

Induced moisture weakens the bond strength between the components of the mixture and reduces the overall stiffness, which further leads to distresses such as fatigue cracking, rutting, stripping, and raveling [1]. Saturated surface layers of asphalt pavements are particularly susceptible to rutting, as shear stress accumulates at the surface due to traffic loading. Further, a loss of cohesion within the asphalt mixture can lead to top-down cracking. Base layers, which retain moisture for longer periods due to slower evaporation rates, are more prone to disintegration, ultimately initiating bottom-up fatigue cracking in the overlying asphalt layers.

Moisture-induced distresses, such as stripping, raveling, cracking, and rutting have been observed in asphalt pavements since the advent of asphalt paving technology [1, 2] . Over time, various laboratory testing methods, both qualitative and quantitative, have been developed to assess moisture damage in asphalt mixtures. Qualitative methods evaluate moisture susceptibility by subjectively assessing the potential for stripping in moisture-induced mixtures, utilizing laboratory tests such as the boiling water test (ASTM D 3625), static immersion test (AASHTO T 182), etc. [4, 6]. Quantitative methods, on the other hand, measure a numerical value for a specified parameter (e.g., indirect tensile strength before and after moisture conditioning) used in characterizing moisture damage. Examples of quantitative test methods include the immersion-compression test (AASHTO T 165), Modified Lottman test (AASHTO T 283), and Hamburg Wheel-Tracking test (AASHTO T

324) [7, 8, 18]. Generally, quantitative tests are considered more reliable for assessing or predicting moisture susceptibility compared to qualitative methods [5].

Failures in asphalt pavements can be categorized into two primary types: stability-related and durability-related. Stability-related failures are primarily associated with design and displacement issues under normal loading conditions. In contrast, durability-related failures are influenced by factors such as pavement age and environmental conditions [2, 12]. Moisture damage falls under the category of durability-related failure and typically manifests as softening and stripping [3]. Stripping involves the breakdown of the bond between the asphalt binder and aggregate surface due to moisture intrusion. Softening results from a loss of cohesion within the binder film or matrix, leading to reduced strength and stiffness of the asphalt mixture [3]. The combined effects of repeated traffic loading and freeze-thaw cycles under saturated conditions create cyclic hydraulic pressure within asphalt pavements, often resulting in premature failure; see Figure 1 [2]. This accumulated moisture damage can manifest in distresses such as stripping, premature rutting, raveling, and cracking; see Figure 2 [2].

Figure 1. Premature failure in asphalt pavements: (a) rutting and (b) fatigue cracking [2]

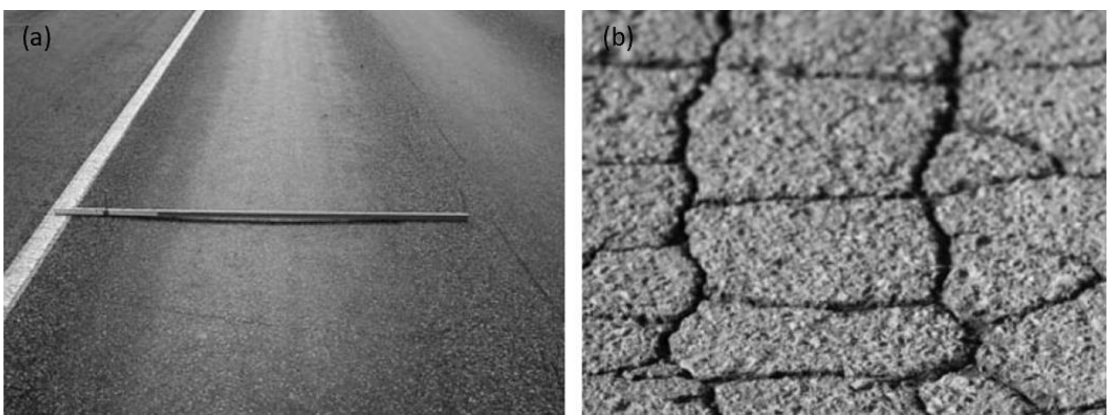
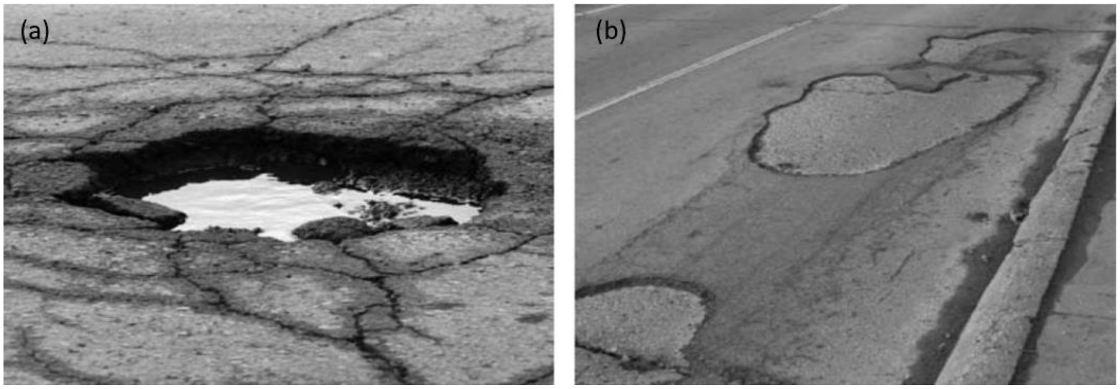


Figure 2. Moisture induced distresses: (a) potholes and (b) delamation [2]



The moisture damage or failure mechanisms that result in distresses such as stripping, raveling, cracking, and rutting are typically characterized as adhesive and cohesive failure mechanisms [19]. Understanding the adhesive and cohesive failure mechanisms of asphalt mixtures is critical for the effective characterization of moisture damage in asphalt mixtures. These mechanisms are further categorized into three types: mechanical, chemical, and thermodynamic [5]. Mechanical bonding relies on the ability of the binder to hold the aggregate particles together in the mixtures, influenced by aggregate surface characteristics and asphalt binder tensile strength. Chemical bonding is influenced by the surface charge and pH of mixture components, while thermodynamic bonding depends on the asphalt binder's viscosity and surface tension, which together affect its ability to wet and coat aggregate surfaces [12].

Researchers have emphasized the impact of environmental conditions on these failure mechanisms, highlighting variations in stripping mechanisms across different climates [1, 20]. Moisture damage in asphalt pavements can stem from construction-related issues such as poor pavement drainage, insufficient compaction, excessive dust coating on aggregate, inadequate aggregate drying, and the presence of weak or friable aggregate [5]. Moisture can disrupt adhesion and cohesion through various mechanisms, as detailed below:

Detachment. Asphalt binder can separate from aggregate through two primary mechanisms: physical detachment and chemical detachment. In physical detachment, interstitial pore moisture fills void spaces between the binder and aggregate, creating a physical barrier that weakens the bond. In chemical detachment, water molecules infiltrate the asphalt binder film, chemically weakening the interfacial bond between the binder and aggregate, especially for hydrophilic aggregates. The presence of bond energy, specifically surface free energy, plays a critical role in resisting detachment. Higher bond energy strengthens the adhesion between the binder and aggregate, reducing the likelihood of detachment. However, the presence of moisture diminishes the surface energy by preferentially interacting with the aggregate due to stronger polar forces [5, 13].

The reduction in surface energy significantly increases the susceptibility of asphalt pavements to moisture-related distresses, particularly stripping. In moist conditions, the weakened bond between the binder and aggregates makes it easier for water to infiltrate the pavement structure, leading to accelerated deterioration. Additionally, variations in environmental factors such as temperature and humidity can further influence surface energy. For example, in colder climates, the expansion of water during freezing can exacerbate the separation between the binder and aggregates, leading to increased distress. Similarly, in areas with high rainfall or humidity, constant moisture exposure can continuously weaken the bond, increasing the risk of distress.

Further, the composition of the asphalt binder and aggregates can also impact the effectiveness of the surface energy. Different types of binders and aggregates exhibit varying levels of compatibility, which can affect the strength and durability of the pavement structure. Therefore, the proper selection of materials and construction techniques is critical in mitigating moisture-induced distress and ensuring the long-term performance of asphalt pavements.

Displacement. The presence of moisture within asphalt pavements can cause the asphalt binder to physically dislodge from the aggregate surface. This occurs as moisture permeates the pavement structure and reaches the aggregate surface. The moisture disrupts the binder coating, leading to separation from the aggregate [12, 13]. This displacement significantly contributes to the deterioration of asphalt pavements. The weakened bond between the binder and aggregates makes it easier for the binder to detach, compromising the structural integrity of the pavement and increasing the susceptibility of the asphalt pavement to other distresses, such as stripping and raveling. Moreover, the extent of displacement can vary depending on factors such as pavement composition, environmental conditions, and traffic loading. For example, in areas with poor drainage or high precipitation rates, the continuous presence of moisture can exacerbate displacement, accelerating pavement deterioration. Similarly, heavy traffic loads can further intensify displacement by exerting additional stress on the weakened binder-aggregate bond. Addressing displacement requires comprehensive pavement management strategies that prioritize proper drainage, effective pavement design, and timely maintenance practices. By mitigating the effects of moisture-induced displacement, authorities can enhance the longevity and performance of asphalt pavements, ultimately reducing life cycle costs and minimizing disruptions to road users.

Spontaneous Emulsifications. This phenomenon occurs when moisture interacts with the asphalt binder, resulting in a decrease in its tenacity. The presence of heavy traffic loads, particularly under saturated conditions, is primarily responsible for triggering this process [5, 13].

Film Rupture. Film rupture manifests as fissures developing at the edges and corners of aggregates under the stress of traffic loading. Once these fissures form, moisture can infiltrate, initiating the process of stripping [5, 14, 15, 16].

Pore Pressure. The movement of traffic compresses void spaces within the pavement, trapping water inside these voids. Over time, the ongoing traffic activity can build up significant pore pressure within these voids, ultimately leading to the stripping of the asphalt binder from the aggregate surface [13, 20, 17].

Hydraulic Scouring. When vehicles travel over saturated asphalt pavements, infiltrated water builds up excessive pore pressure ahead of the tires. This pressurized water is then forced out from behind the tires. Further, the high-pressure flow of water can strip the asphalt binder away from the underlying aggregates. The scouring effect is worsened by the presence of dust or abrasive materials on the road surface. [21, 22].

Factors Affecting Moisture Susceptibility

A 2002 survey conducted by the Federal Highway Administration (FHWA) as part of the "Rehabilitation Techniques for Stripped Asphalt Pavements" project found that the severity of moisture damage in asphalt mixtures is influenced by various factors, including environmental conditions, aggregate properties, asphalt binder quality, and mixture properties [23]. The study demonstrated that aggregate and mixture properties, such as aggregate shape and mixture density, significantly influence the moisture damage resistance of asphalt mixtures. The factors influencing the moisture damage resistance of asphalt mixtures, as determined by previous researchers, are discussed below.

Environmental Conditions

The FHWA divides the United States into four climatic regions: Dry Freeze, Wet Freeze, Dry-Non Freeze, and Wet-Non-Freeze; see Figure 3.

Figure 3. Four climatic regions based on FHWA [24]

Climate Zone	Annual Rainfall (Inch)	Freezing Index (°F-Days)
Wet Non-Freeze	> 28	< 100
Wet Freeze	> 28	> 100
Dry Non-Freeze	< 28	< 100
Dry Freeze	< 28	> 100

Note: 1 inch = 2.54 cm;
Temperature (unit in °F) = Temperature (unit in °C) × 1.8 + 32.

Regions with high annual rainfall are expected to exhibit higher moisture damage and stripping [24, 25, 26]. Thermal cracking in asphalt pavements is primarily related to environmental loading. It is more prevalent in areas with small seasonal temperature differences (Dry Non-Freeze) and large diurnal temperature differences (Dry Freeze) [27, 28, 25]. In contrast, fatigue cracking is more common in Wet-Freeze and Wet Non-Freeze areas. The change in asphalt binder stiffness due to the combined effects of environment and traffic loading hampers the ability of the asphalt pavements to resist fatigue cracking. Additionally, high average annual rainfall can saturate the pavement layers, further weakening the support structure and accelerating fatigue cracking [17].

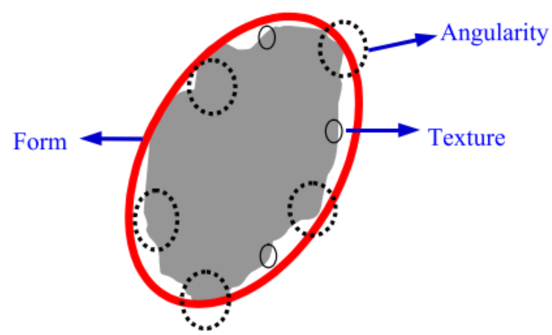
Asphalt Binder Properties

Understanding the physical and chemical properties of asphalt binders is critical for assessing the characteristics of asphalt mixtures in the presence of moisture. Studies have established a correlation between asphalt binder film thickness and the type of failure observed (cohesive or adhesive) in asphalt mixtures [24, 29, 25]. Thinner asphalt binder films tend to have higher cohesive tensile strength compared to adhesive tensile strength [30]. Modified asphalt binders have shown promise in improving the performance of asphalt mixtures. Elastomer-modified asphalt binders have been associated with improvements in fatigue and rutting resistance, while plastomer-modified asphalt binders have primarily shown enhancements in rutting resistance. Notably, elastomer-modified asphalt has demonstrated increased resistance to moisture damage in asphalt mixtures [30, 31, 32, 33].

Aggregate Shape Characteristics

The structure and properties of aggregates in a mixture significantly influence the mechanical bond between the asphalt binder and aggregates. Key aggregate characteristics, such as surface area and porosity, influence mechanical interlocking within the mixture, minimizing excessive deformation and moisture damage [24, 32, 33, 34]. Aggregate texture reflects the surface characteristics of aggregate particles, which describes the roughness or smoothness of the aggregate surface. Aggregate angularity, on the other hand, refers to the shape of the aggregate, ranging from round to angular. Increasing angularity leads to a larger surface area, potentially increasing the overall bond energy [34]. However, highly angular aggregates may puncture the asphalt binder film, allowing moisture to penetrate onto aggregate surfaces. Figure 4 shows the differences between aggregate angularity, texture, and form.

Figure 4. Schematic of aggregate shape: angularity, form, and texture [13]



Masad et al. conducted a study to investigate how aggregate properties influence the moisture damage resistance of asphalt mixtures. They examined asphalt mixtures prepared with three different aggregates: limestone, granite, and gravel. The results showed that granite aggregate exhibited the highest levels of texture and angularity, followed by limestone, while gravel had the lowest. The researchers then subjected these asphalt mixtures to testing under various conditions using the Asphalt Pavement Analyzer (APA), Hamburg Wheel-Tracking (HWT) device, and Dynamic Modulus (DM) test. Their findings indicated that asphalt mixtures containing granite and limestone performed better than those with gravel aggregates in both dry and wet conditions, primarily due to their higher angularity [29].

Mixture Properties and Tools for Evaluating Moisture Damage Resistance

The susceptibility of asphalt pavements to moisture damage largely depends on how easily and to what extent moisture can infiltrate the mixture, which is influenced by the air void content and permeability of the asphalt mixture. Generally, denser-graded asphalt mixtures are less susceptible to moisture damage compared to poorly graded or gap-graded mixtures [35]. Researchers have investigated the relationship between the moisture susceptibility of asphalt mixtures, void structure, and pore pressure. These researchers employed various gradations to represent different air void distributions, compacting the asphalt mixtures to achieve a target of 7% air voids before testing them using the Modified Lottman test [36, 31]. The study also explored the concept of the pessimum size, which refers to the average diameter of aggregate particles where moisture damage is most severe. At this critical air void size, moisture infiltration is high, while drainage is restricted, resulting in significant moisture damage [29].

A recent survey revealed that 94% of state highway agencies in the U.S. require at least one test method to evaluate the moisture sensitivity of asphalt mixtures in their mix design specifications [37]. Among the preferred tests for assessing moisture damage are the Modified Lottman (ML) and the Hamburg Wheel-Tracking (HWT) tests, which are used by approximately 85% of agencies [37]. The Modified Lottman test, which assesses moisture damage by analyzing the Tensile Strength Ratio (TSR) of conditioned to unconditioned asphalt mixture specimens, is particularly popular and widely utilized [23, 27, 37]. A previous study utilized the Modified Lottman test to evaluate the moisture susceptibility of five different asphalt mixtures obtained from various states. The researchers observed an inconsistent correlation between the TSR values obtained from laboratory testing and the actual field performance [5].

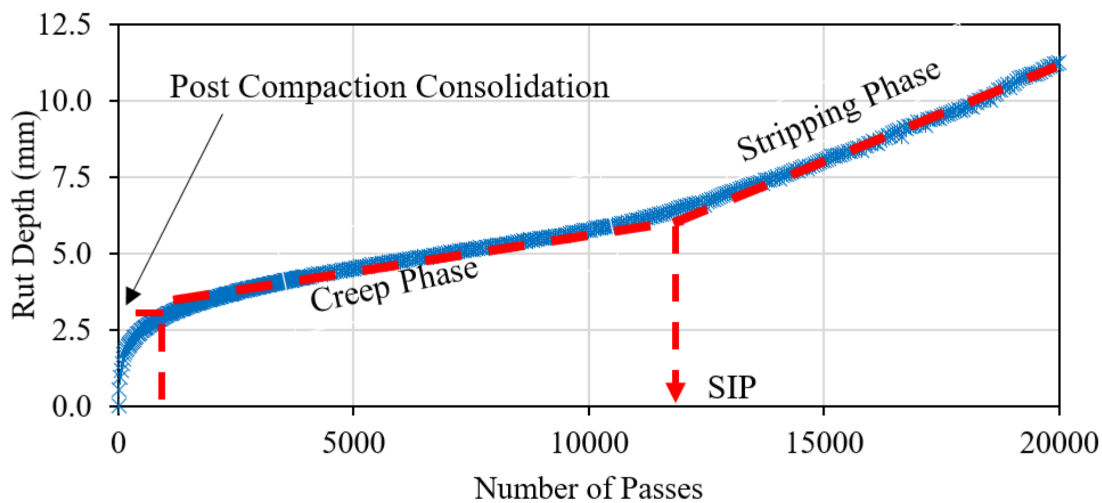
Additionally, research has underscored the importance of investigating the repeatability of the Modified Lottman test, particularly concerning its sensitivity to variations in air void distribution and saturation levels [21, 27]. Over the years, numerous researchers have investigated the ability of the Modified Lottman test to ascertain the moisture sensitivity of asphalt mixtures. A study by the Montana Department of Transportation evaluated five different asphalt mixtures of known field performance using the Modified Lottman test and did not find a satisfactory correlation with observed laboratory performance [19]. In 2002, Kandhal and Rickards recommended the use of a cyclic loading test for moisture damage evaluation, as it can simulate the pumping action of traffic [38]. Further, a NCHRP study in 2010 [39] conducted an inter-laboratory study to investigate the precision estimates of the test and reported several shortcomings of the test method by analyzing the specimens via X-ray tomography images. The researchers highlighted the variability of the test results, which may arise from the variable void structure, specimen geometry, and compaction method used for preparation of the specimens. Moreover, Kandhal and Rickards recommended a higher level of saturation (> 90%) or the inclusion of multiple freeze-thaw cycles for creating a stripping effect [38]. In a subsequent study, Apeagyei et al. [36] stated that the use of plane stress analysis in calculating the tensile strength of the asphalt mixtures may cause erroneous results. The researchers reported that the presence of excessive moisture damage could lead to substantial plastic deformation or punching shear and redistribution of stresses under the loading strip, which can further account for inconsistent test results [36].

The Hamburg Wheel-Tracking (HWT) test emerges as the second most widely used method for evaluating moisture sensitivity in asphalt mixtures, adopted by approximately 16% of U.S. states [40]. HWT operates as a controlled laboratory test for rut depth, employing loaded wheels to apply dynamic loads on asphalt mixture specimens, replicating the traffic-induced stresses experienced by asphalt pavements [1, 21].

Originally developed by Helmut-Wind Incorporated of Hamburg in the 1970s, the HWT device was initially intended for assessing the rutting performance of asphalt mixtures by rolling a steel wheel across specimens submerged in hot water [41]. Its introduction to the United States in the 1990s saw a surge in its popularity because of its ability to correlate laboratory moisture sensitivity measurements with field moisture damage performance [26, 42].Currently, states such as Louisiana, Iowa, Maine, Massachusetts, Texas, Utah, Washington, and California utilize the HWT test to evaluate moisture sensitivity. The assessment of moisture sensitivity through the HWT test is based on a “pass/fail” criteria using a range of parameters. This method has proven valuable in gauging the potential moisture damage susceptibility of asphalt mixtures under simulated conditions, aiding in the enhancement of pavement performance and longevity.

Figure 5 illustrates typical HWT test results. Key parameters derived from the HWT test include post-compaction consolidation, creep slope, stripping slope, maximum rut depth (12.5 mm), passes at maximum rut depth, and stripping inflection point (SIP) [21, 28]. Post-compaction consolidation is the rut depth at 1,000 passes. Creep slope characterizes the inverse of deformation rate in the creep phase of rut depth versus number of wheel passes plot; see Figure 5. The creep phase begins after the post-compaction consolidation phase and ends before stripping occurs. There is a steady increase in deformation in the creep phase due to viscous flow [43]. Stripping slope is the inverse of the deformation rate at points where rut depth increases rapidly as moisture damage occurs. A mixture with a larger stripping slope value is more susceptible to moisture damage. The ratio of the creep slope to the stripping slope has been used to characterize moisture sensitivity of asphalt mixtures in some states [23, 43]. The SIP denotes the number of passes at the intersection of creep slope and stripping slope, serving as an indicator of moisture damage initiation in a mixture [23]. Researchers have established a strong correlation between laboratory-measured SIP and field moisture damage performance [44]. Table 1 presents a summary of HWT moisture sensitivity specifications required by different state agencies [45].

Figure 5. Typical HWT test results



Despite the ability of the HWT test to relate laboratory results to field moisture sensitivity performance, the accuracy of the "pass/fail" criteria for screening mixtures is limited [41, 44, 45, 46]. Further, researchers have questioned the capability of the HWT test to simulate field exposure conditions and reliably predict the moisture sensitivity of a wide range of asphalt mixtures [40]. Among state DOTs that currently specify the HWT test for mix design and/or quality assurance testing, none consider moisture conditioning protocols aside from testing under submerged conditions, as specified in AASHTO T 324. Therefore, there is a need to perform an evaluation of the HWT test by considering moisture conditioning protocols to screen a wide range of moisture sensitive asphalt mixtures.

Table 1. Moisture sensitivity specifications for HWT test

State	Test Standard	% AV	Test Temperature and Condition	Moisture Sensitivity Criteria: Max. Rut Depth (mm)	No. of Passes for Max. Rut Depth	SIP, Min
Cal.	AASHTO T 324	7±0.5%	PG 58: 45°C, W	12.5	PG 58/<: 10000	PG 58/64: 10000
			PG 64: 50°C, W		PG 64: 15000	PG 70: 12500
			PG 70/>: 55°C, W		PG 70: 20000	PG 76/>: 15000
					PG 76/>: 25000	
Iowa	AASHTO T 324	7±1.0%	PG 52/58: 40°C, W	20.0	20000	TDS: 10000
			PG 64/>: 50°C, W			TDV/H: 14000[c]
La.	AASHTO T 324	7±0.5%	50°C, W	TL1: 10	20000	N/A
				TL2: 6		
Maine	AASHTO T 324	7±0.5%	45°C, W	12.5	20000	15000
Mass.	AASHTO T 324	7±0.5%	50°C, W	12.5	20000	TL1: 10000
						TL2/3: 15000
Texas	Tex-242-F	7±1.0%	50°C, W	12.5	PG 64/<: 10000	N/A
					PG 70: 15000	
					PG 76/>: 20000	
Utah	AASHTO T 324	7±1.0%	PG 58/<: 46°C, W	10.0	75/< Gyr.: 10000	N/A
			PG 64: 50°C, W		75/> Gyr.: 20000	
			PG 76/>: 54°C, W			
Wash.	AASHTO T 324	7±0.5%	50°C, W	10.0	<0.3m ESALs: 10000	20000
					0.3 to > 3m ESALs: 12500	
					>3m ESALs: 15000	

Max: maximum; Min: minimum; %AV: percent air void content; Cal.: California; La.: Louisiana; Mass.: Massachusetts, Wash: Washington; W: wet; TL1: traffic level 1; TL2: traffic level 2; PG: performance grade; /: or; /<: or lower; /<: or higher; Gyr.: gyrations; m: million; ESALs: equivalent standard axel loads; TDS: traffic designation S; TDV/H: traffic designation V or H; N/A: not applicable.

Over time, researchers have integrated laboratory moisture conditioning protocols to replicate field conditions, including freeze-thaw conditioning procedures according to AASHTO T 283 [8] and the use of the Moisture-induced Stress Tester (MiST) outlined in ASTM D7870 [10]. Incorporating these conditioning protocols prior to laboratory testing has yielded improved predictions of moisture-susceptible asphalt mixtures [28]. Despite extensive research efforts, moisture-induced distress remains a persistent challenge in the U.S. and around the globe [27]. Studies have revealed that existing test protocols for assessing moisture sensitivity have limitations in effectively distinguishing between moisture-sensitive and moisture-resistant asphalt mixtures. Therefore, there is a pressing need for a straightforward performance test that can consistently provide a mechanistic evaluation of moisture damage in asphalt mixtures.

Over the years, the Semi-Circular Bend (SCB) test has served as a reliable method for characterizing intermediate temperature cracking in asphalt mixtures, consistently correlating laboratory cracking potential with field performance [47, 48]. Recent studies have highlighted the SCB test's prominence among other cracking test protocols due to its straightforward specimen preparation, sensitivity to mix design variables, and swift testing procedures [49, 50, 51, 52]. Conducted as a three-point bending test on a notched semi-circular asphalt mixture specimen, SCB test results are analyzed using fracture mechanics principles [53]. The pre-notching or crack initiation process in the SCB test is grounded on the concept that the energy stored at the fracture zone, near the crack, equals the energy required to create new surfaces. The SCB test geometry and the critical strain energy (J_c) approach was introduced in paving technology to characterize asphalt mixtures' resistance to fracture [30]. Kim et al. [31] evaluated the potential of the SCB test to relate laboratory cracking performance to field cracking performance. The study utilized 13 plant loose mixtures and evaluated the J_c corresponding to each mixture using a semi-circular specimen of 150 mm diameter by 57 mm thick at three different notch depths of 25.4, 31.8, and 38.0 mm. The researchers found that the parameter J_c obtained from the SCB test correlates well, at approximately 73%, with the field cracking performance of the asphalt mixtures obtained from the Louisiana Pavement Management System (PMS). Ali utilized the SCB critical strain energy release rate (J_c) parameter to assess moisture damage in asphalt mixtures by conditioning specimens in the Moisture-induced Stress Tester (MiST). Observations revealed a decrease in J_c as specimens were subjected to moisture conditioning in the MiST [30]. Despite the SCB's capability to link laboratory cracking potential with field performance, limited research has explored its potential application in evaluating moisture damage in asphalt mixtures. Further investigation into this aspect could provide valuable insights into enhancing asphalt mixture performance under various environmental conditions.

Anti-strip additives are typically incorporated into asphalt mixtures prepared with moisture-susceptible aggregates to improve the adhesive bond between the asphalt binder and aggregate in the mixture [54].

Effects of Mixture Additives on Moisture Damage

The idea of incorporating anti-stripping agents in asphalt mixtures is not new. For some time, researchers have been using different types of anti-stripping agents to improve resistance to moisture damage [55]. Hurley and Prowell incorporated Evotherm to evaluate the resistance to moisture damage of mixtures fabricated with PG 76-22 binder [56]. They observed that increasing the moisture conditioning level resulted in a reduction in tensile strength and resistance to moisture damage of such mixtures. Elseifi et al. [32] also demonstrated similar results, where the addition of Evotherm at 0.6% binder content enhanced the anti-stripping resistance using a dense-graded asphalt mix design with a Nominal Maximum Aggregate Size (NMAS) of 19 mm. Evotherm contains surfactants, dispersants, and reactive polymers that interact with asphalt to change its rheological properties [57]. Nazzal et al. [58] examined the effect of various additives on the moisture resistance of asphalt binders and correlated them with the mechanical performance of the mixtures. The atomic force microscopy of asphalt binders containing Evotherm additives added at 0.5% by weight of binder indicated a similar trend as that reported by Elseifi et al. [32]. Polymer additives were also found to significantly minimize moisture damage in asphalt mixtures. Further, asphalt binder adhesive forces were found to be more susceptible to moisture damage than adhesive forces [37]. Jattak et al. [33] incorporated unmodified 60/70 penetration grade bitumen with Evotherm 3G as a warm mix additive. The researchers reported that surfactant agents were effective in promoting wetting and better adhesion between asphalt binder and aggregate particles, resulting in higher tensile strength compared to control mixtures [33, 59, 60].

The presence of ester functional groups in Evotherm leads to an exchange between molecules, forming new ester bonds that modify the chemical structure of asphalt [61, 55]. A study conducted by Kusam et al. [59] indicated that increased resistance to moisture damage due to the presence of such groups in Evotherm-modified asphalt led to a stronger bond formation that satisfied the minimum TSR requirement for moisture damage resistance. Xu et al. [61] reported that Evotherm-modified warm mix asphalt exhibited better resistance to moisture damage and enhanced fatigue performance than HMA. By acting as a surface-active agent, Evotherm induces a low internal friction of asphalt binder that also results in improved mixing and compaction at low temperatures [62]. Lee et al. [55] evaluated the moisture susceptibility of Evotherm-modified mixtures using the Hamburg Wheel-Tracking (HWT) test coupled with digital image analysis. The stripping inflection point and corresponding rut depth values indicated better resistance against moisture damage in the Evotherm-modified mixtures compared to conventional HMA.

Amine-based liquid anti-stripping contains chemical compounds that interact with asphalt binder. These interactions modify the rheological properties of asphalt binder by increasing film thickness and improving its adhesion to aggregate particles. This results in an enhanced resistance to moisture damage [34]. Studies conducted by the Georgia Department of Transportation revealed the resistance to moisture damage of asphalt mixtures containing amine-based additive but hinted at a reduction in resistance to moisture damage with increased conditioning levels. In another study conducted by Gholam et al. [63], it was established that amine-based additive significantly influenced moisture damage resistance.

The mechanism by which hydrated lime reduces moisture damage susceptibility in asphalt mixtures involves a chemical interaction with the asphalt binder. This interaction, often referred to as lime stiffening, is enhanced by the presence of smaller-sized lime particles, which improve binder viscosity [31, 58]. Further, hydrated lime fills voids between aggregate particles, increasing the overall packing density of the mixture and reducing its permeability. This reduced permeability makes the mixture more resistant to moisture intrusion, ultimately leading to decreased moisture damage. Mohammad et al. [64] conducted a mechanistic evaluation of hot mix asphalt containing hydrated lime and reported an enhanced resistance to high-temperature permanent deformation and fatigue life. Additionally, Huang et al. [65] found that long-term aging does not significantly affect the rate of hardening and embrittlement in hydrated lime-modified asphalt mixtures. As a filler, hydrated lime reduces micro-cracking damage and promotes micro-damage healing through viscoelastic and plastic flow at a wide range of temperatures. Elastoplastic behavior under thermal-mechanical loading, coupled with uni- and triaxial tests, indicates enhanced resistance to plastic deformation at high temperatures and increased rigidity, as evidenced by resilient modulus [66]. Conventional techniques for mitigating moisture damage in asphalt mixtures require the incorporation of specific additives into the mixture. However, the mechanisms of bond formation and performance vary among different additives or modifiers.

The literature review highlights the need for the further refinement of testing protocols to ensure consistent and reliable assessment of moisture damage susceptibility. Moisture-induced distress in pavements is a complex issue influenced by numerous factors beyond testing procedures, including mixture design, production practices, construction methods, climatic variations, and other factors [29]. Understanding and addressing these diverse influences is critical for developing comprehensive strategies to mitigate moisture-related deterioration and extend pavement service life. The intricate relationship between asphalt mixture design factors and moisture damage susceptibility underscores the complexity of pavement performance. Factors such as asphalt binder and aggregate chemistry, aggregate absorption and texture, air void content, mixture additives, and aggregate particle distribution all contribute to the overall response of asphalt pavements to moisture-induced distress [29, 31]. By exploring these factors in greater detail and refining testing methodologies, researchers and practitioners can enhance the understanding of moisture damage mechanisms and develop more effective strategies to improve pavement performance and longevity.

Objective

The objective of this study was to develop a reliable test procedure to consistently assess the resistance of asphalt mixtures to moisture-induced damage. Specific objectives included:

- Identifying candidate laboratory test methods that can be used for asphalt mixtures' moisture susceptibility evaluation;
- Identifying available moisture conditioning procedures for asphalt mixtures;
- Evaluating current and candidate moisture susceptibility test methods with typical Louisiana asphalt mixtures;
- Establishing a laboratory test protocol that combines a state-of-the-art moisture conditioning method and an advanced mechanical test method; and
- Validating the proposed moisture conditioning protocols and test methods using asphalt mixtures containing anti-strip additives.

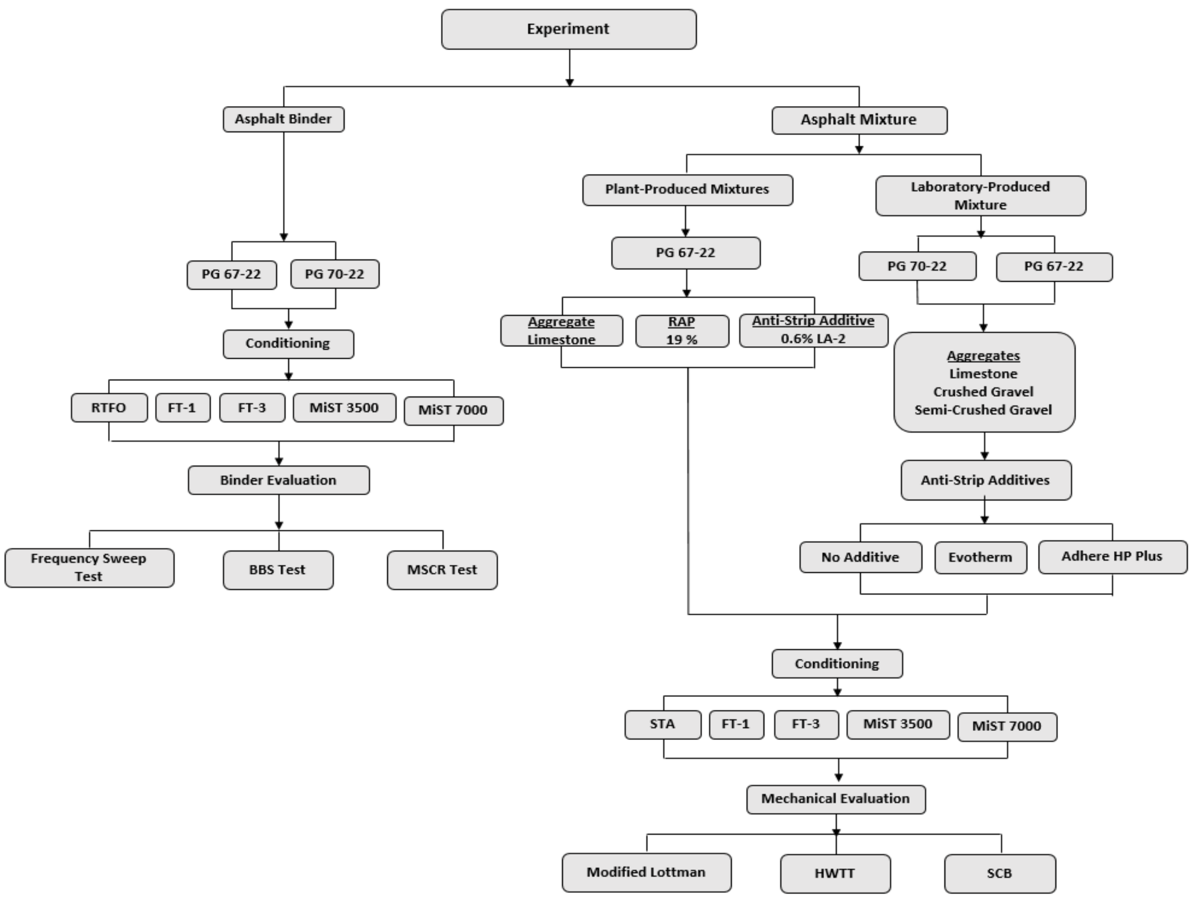
Scope

A total of 13 asphalt mixtures were prepared, including one plant-produced mixture and 12 laboratory-compacted mixtures. The study utilized two types of asphalt binders (unmodified PG 67-22 and polymer-modified PG 70-22) and three types of aggregates (limestone, crushed gravel, and semi-crushed gravel) with varying absorption levels. Further, two anti-strip additives (amine-based and chemical WMA) were incorporated into selected mixtures to assess their ability to mitigate moisture damage. To evaluate the impact of moisture conditioning, asphalt binders and mixtures were subjected to five different conditioning levels: control (no moisture conditioning applied), a single-freeze-and-thaw cycle (FT–1), a triple freeze-and-thaw cycle (FT–3), 3500 Moisture-induced Stress Tester cycles (MiST 3500), and 7000 MiST cycles (MiST 7000). The asphalt binders subjected to the five conditioning protocols were evaluated utilizing the frequency sweep test at multiple temperatures, the multiple stress creep recovery test, and the binder bond strength test. Loose asphalt mixture samples were first subjected to the boil test, as outlined in ASTM D 3625. The resulting samples were then evaluated using the asphalt compatibility tester (ACT). To assess the resistance of the asphalt mixtures to moisture-induced damage, the Modified Lottman (ML), Hamburg Wheel-Tracking (HWT), and Semi-Circular Bend (SCB) tests were utilized.

Methodology

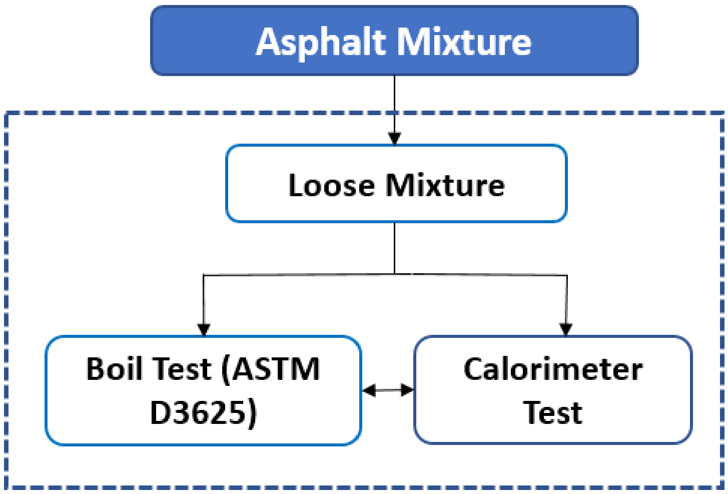
Figures 6 and 7 outline the experimental plan for the study. The detailed experimental plan is discussed below.

Figure 6. Experimental plan for asphalt binders and mixtures



RTFO: rolling thin film oven; FT-1: single freeze-thaw; FT-3: triple freeze-thaw; M-35: 3500 Moisture-induced Stress Tester cycles; M-70: 7000 Moisture-induced Stress Tester cycles; MSCR: multiple stress creep recovery test; RAP: recycled asphalt pavement; HWT: Hamburg Wheel-Tracking test.

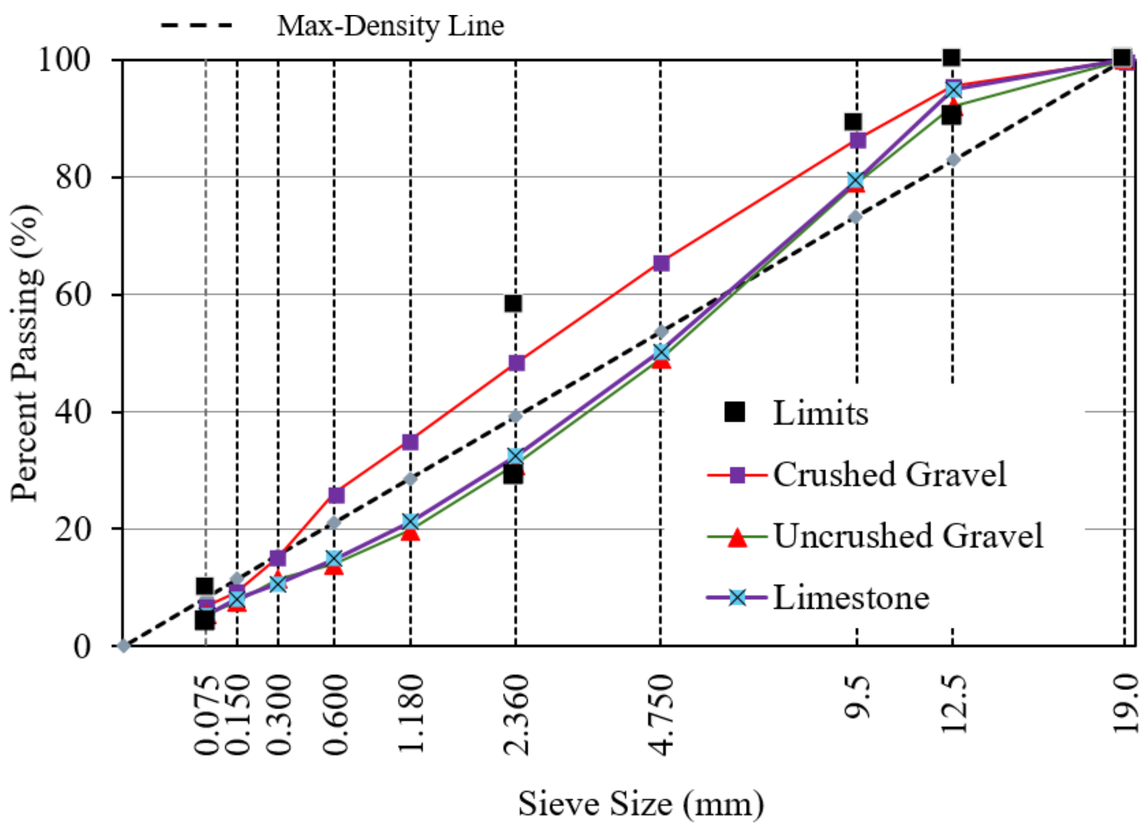
Figure 7. Experimental plan for loose mixture



Material Characterization

Two asphalt binder types, unmodified PG 67-22 and SBS-modified PG 70-22 meeting the Louisiana DOTD standard specification for asphalt binders, were selected [67]. Further, three aggregate types, limestone (absorption < 2%), crushed gravel (absorption > 2%, natural sand content > 15%), and a semi-crushed gravel (absorption > 2%, natural sand content > 15%) meeting specification for 12.5 mm NMAS were selected. It is noted that the semi-crushed gravel was selected such that all particles passing the No. 4 sieve (4.75 mm) were crushed, whereas those particles retained on the No. 4 sieve (50%) were smooth and round aggregates. Additionally, two anti-strip additives were selected from the Louisiana DOTD approved materials list, meeting the requirements of Section 1002.02.1 of the standard specification: Evotherm and amine-based. Figure 8 shows the gradation plots for the three aggregate types used in the study.

Figure 8. Mixture gradations



The second phase of the study included the validation of the moisture conditioning protocol by incorporating two different anti-stripping additives, amine-based and chemical WMA, using the Modified Lottman (ML) and Hamburg Wheel-Tracking (HWT) tests. The experimental plan detailed in Figure 6 depicts the assessment of moisture conditioning levels at FT-1, FT-3, and MiST 7000.

Asphalt Binder Experiment

Moisture Conditioning of Asphalt Binders

Five conditioning levels were evaluated in the asphalt binder experiment. The first conditioning level is the control, based on the short-term aging of asphalt binders following the AASHTO T 240 specification. RTFO-aged asphalt binder was heated to 160º C until it was sufficiently fluid and then poured into PAV pans to achieve a uniform thickness of 3.2

mm. The specimens in the PAV pans were then subjected to the remaining four conditioning levels; see Figure 9. The second and third conditioning levels included single- and triple-freeze-thaw conditioning, respectively, while the fourth and fifth conditioning levels were MiST 3500 (3500 Moisture-induced Stress Tester cycles) and MiST 7000 (7000 Moisture-induced Stress Tester cycles), respectively. Details of each conditioning cycle procedure are provided in the freeze-thaw and MiST conditioning sub-sections of the Asphalt Mixture Experiment section.

Figure 9. Freeze-thaw and MiST conditioning of asphalt binder samples

Asphalt Binder Characterization

Each asphalt binder specimen subjected to one of the five conditioning levels was then rheologically evaluated through multiple temperatures and frequencies, as well as the Multiple Stress Creep Recovery (MSCR) test. Additionally, adhesive bonds between asphalt binder samples and different aggregate substrates were evaluated using the binder bond strength (BBS) test. A minimum of three replicates were used in each test.

Frequency Sweep Test. The frequency sweep test was performed according to AASHTO T 315, "Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)." The test was performed at frequencies ranging from 0.1 to 100 rad/sec. and at multiple temperatures of 5°, 20°, and 35° C. The obtained test data was used to construct master curves for dynamic shear modulus (G^*) and phase angle (δ), from which the effect of moisture conditioning on asphalt binder rheological properties was determined.

Multiple Stress Creep Recovery (MSCR) Test. The Multiple Stress Creep Recovery (MSCR) test was conducted following the AASHTO T 350 specification, "Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)," to evaluate the elastic behavior of asphalt binders. This test method involves subjecting the binder to ten cycles of stress and recovery at two different stress levels (0.1 kPa and 3.2 kPa) using a Dynamic Shear Rheometer (DSR). Two key parameters are derived from the MSCR test to assess high-temperature performance: non-recoverable creep compliance (*Jnr*) and percent recovery. The *Jnr* parameter quantifies the permanent deformation of the binder under traffic load, with lower values indicating better resistance to rutting. Further, the percent recovery parameter measures the ability of the binder to recover its original shape after stress removal. Higher recovery percentages are generally preferred.

Asphalt Binder Bond Strength (BBS) Test. The asphalt binder bond strength (BBS) test was conducted according to AASHTO T 361, "Standard Method of Test for Determining Asphalt Binder Bond Strength by Means of the Binder Bond Strength (BBS) Test." In the BBS, asphalt binder samples were applied onto a pullout stub, which is firmly pressed onto a prepared surface of the aggregate substrate to establish an asphalt binder-aggregate bond. The strength of the asphalt binder-aggregate bond (pull-off tensile strength, POTS) was determined after dry and wet conditioning. The failure mode of each test is noted and the ratio of the wet-conditioned POTS to the dry-conditioned POTS recorded to represent the effect of moisture conditioning on the adhesive bond between the asphalt binder and the aggregate substrate.

Asphalt Mixture Experiment

Mixture Design

A total of 13 12.5 mm Superpave asphalt mixtures were designed, utilizing two levels of asphalt binders and three types of aggregates. A Level 2 design ($N_{initial}$ = 7, N_{design} = 65, N_{final} = 105 gyrations) was performed following AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)"; AASHTO M 323, "Standard Specification for Superpave Volumetric Mix Design"; and Section 502 of the 2016 Louisiana Standard Specifications for Roads and Bridges [67]. Specifically, the optimum asphalt cement content was determined based on volumetric properties (VTM = 2.5-4.5%, VMA ≥ 13.5%, VFA =

69-80%) and densification requirements (%G_{mm} at $N_{initial} \leq 90$, % G_{mm} at $N_{final} \leq 98$). Among the 13 asphalt binders studied, seven were used to develop effective moisture damage tests and conditioning protocols. The remaining six binders were used to assess the effectiveness of these protocols in evaluating various anti-strip additives.

Of the seven mixtures used to develop the moisture damage tests and conditioning protocols, six (M1-M6) were laboratory-produced and laboratory-compacted, while one (M7) was plant-produced and laboratory-compacted; see Table 2. M1, M2, and M3 consisted of unmodified PG 67-22 asphalt binder and limestone, crushed gravel, and semi-crushed gravel aggregates, respectively: see Table 3. M4, M5, and M6 included SBS-modified PG 70-22 asphalt binder and limestone, crushed gravel, and semi-crushed gravel aggregates, respectively; see Table 3. M7 was a plant produced mixture prepared with PG 67-22 and limestone aggregate. It is noted that M7 contained liquid anti-strip additive (Arr-Maz Products, Inc) at a dosage rate of 0.6% by weight of mixture, and 19% RAP material; see Table 2. Table 3 presents the volumetric properties of the mixtures employed to establish the effective moisture damage test and conditioning protocols for Louisiana mixtures.

Table 2. Properties of asphalt mixtures

Mix ID	Asphalt Binder Type	Aggregate ID	ASA	RAP	Moisture Sensitivity
M1	PG 67-22[1]	Limestone	N/A	N/A	Low
M2		Crushed Gravel	N/A	N/A	High
M3		Semi-Crushed Gravel	N/A	N/A	High
M4	PG 70-22[1]	Limestone	N/A	N/A	Low
M5		Crushed Gravel	N/A	N/A	High
M6		Semi-Crushed Gravel	N/A	N/A	High
M7	PG 67-22[1]	Limestone	0.6% (LA-2)	19%	Low

[1]: Meeting 2016 Louisiana DOTD specifications for Road and Bridges; RAP: recycled asphalt pavement content; N/A: not applicable; LA-2: liquid anti-strip additive; Low: low moisture susceptible aggregate (water absorption < 2%); High: high moisture susceptible aggregate (water absorption > 2%).

Table 3. Volumetric properties of asphalt mixtures

Property	Limestone (M1 and M4)	Crushed Gravel (M2 and M5)	Semi-Crushed Gravel (M3 and M6)	Limestone (M7)
NMAS	12.5 mm			
G_{mm}	2.502	2.383	2.361	2.479
AC (%)	4.9	4.7	5.6	5.1
% G_{mm} @ N_{ini}	88.1	89.2	87.9	88.9
%G_{mm} @ N_{max}	96.3	97.4	94.2	97.9
Air Voids (%)	4.0	3.8	3.5	3.7
VMA	14.0	13.9	13.9	13.9
VFA	71	74	75	74
Dust Ratio	0.9	1.0	1.1	1.1
Pbe (%)	4.5	5.1	5.0	4.4
Absorption (%)	1.6	2.3	2.3	0.8

A total of six asphalt mixtures were used to validate the effectiveness of the established moisture conditioning protocols in evaluating anti-strip additive-modified asphalt mixtures. Table 3 summarizes the properties of the mixtures issued in evaluating the anti-strip additives. Two different binder types, PG 67-22 and PG 70-22, were used with semi-crushed gravels. The mixtures were designed in accordance with the Louisiana DOTD criteria for Level 2 traffic with a nominal maximum aggregate size (NMAS) of 12.5 mm. Table 4 shows the volumetric properties of the mixtures used in evaluating the anti-strip additives.

Table 4. Volumetric properties of anti-strip additive mixtures

Semi-Crushed Gravel		
Property	**Results**	**Criteria**
G_{mm}	2.357	-
% AC	5.6	-
VTM	3.6	2.5-4.5%
VMA	13.7	> 13.5
VFA	72.5	69-80%
%G_{mm} ($N_{initial}$)	88.7	< 89%
%G_{mm} (N_{final})	97.9	< 98%
Absorption	2.01	-

Tests on Loose Asphalt Mixtures

Boil Test. The boil test was conducted according to ASTM D3625, "Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water" [4]. The test was performed to evaluate the resistance of asphalt film coating on the surface of aggregate particles to moisture damage after a short duration of boiling under water. Approximately 250 g of the mixture was added to boiling water for approximately 10 min. After 10 min. of boiling, the sample was measured for the percentage of aggregate surface that retains its asphalt binder coating by visual observation. The percentage of aggregates that lose its asphalt binder coating was recorded as a measure of the loss of adhesion in the uncompacted asphalt mixture due to moisture. For this study, the loose mixture was subjected to boiling durations of 30, 60, and 120 min., in addition to the standard 10 min. boiling duration, to assess progressive moisture damage in asphalt mixtures.

Asphalt Compatibility Tester (ACT). The ACT was conducted to measure the color change that occurs after subjecting loose asphalt mixture samples to the boil test (ASTM D 3625). The test was performed to evaluate the resistance of asphalt film coating on the surface of aggregate particles to moisture damage after a short duration of boiling under water. Asphalt mixture samples subjected to different boiling durations (e.g., 10, 30, 60, and 120 min.) in the boil test were measured for the percentage of aggregate surface that does not retain its asphalt binder coating in the ACT device. The ACT quantifies the change in the color of the asphalt mixture due to boiling by measuring the percent loss of asphalt binder before and after boiling. The percentage loss is the measure of the effect of the moisture conditioning (i.e., boiling in water) on the adhesive strength between the asphalt binder and the aggregates in the mixture.

Moisture Conditioning of Compacted Asphalt Mixtures

Five conditioning levels were considered in the asphalt mixture experiment. The first conditioning level is the control and comprised short-term aging of loose asphalt mixture samples according to AASHTO R 30, "Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)", prior to compaction in the gyratory compactor. The other four conditioning levels were performed on compacted asphalt mixture samples, as follows:

Freeze-Thaw Cycle Conditioning. The freeze-thaw cycles were performed according to AASHTO T 283, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to

Moisture-Induced Damage" [8]. For the second and third conditioning levels, RTFO-aged asphalt binders and compacted short-term aged asphalt mixture samples were subjected to one and three freeze-thaw conditioning cycles, respectively. For each conditioning level, asphalt mixture specimens were partially vacuum saturated between 70-80%. Vacuum-saturated specimens were covered tightly with plastic wrap and placed in a freezer at a temperature of -18º C for 16 hrs. Further, asphalt mixture specimens were removed from the freezer and placed in a water bath at 60º C for 24 hrs. Asphalt binder specimens were conditioned without vacuum saturation or utilizing plastic wraps. It is noted that for the three conditioning cycles, specimens were removed from water, tightly covered with plastic wrap, then placed back in the freezer to repeat freeze-thaw cycles two additional times. After conditioning, the specimens were removed from the 60ºC water bath and placed in another water bath at 25ºC before testing.

MiST Conditioning. The Moisture-induced Stress Tester (MiST) conditioning was performed according to ASTM 7870, "Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure" [10]. For the fourth and fifth conditioning levels, RTFO-aged and compacted asphalt mixture samples were conditioned at 3500 and 7000 cycles, respectively, in the MiST. Specimens were placed in the MiST, and the chamber was filled with water to the appropriate level. The specimens were kept in the machine at 60ºC for 20 hrs. to simulate adhesive failure in the mixture. Further, a pressure amplitude of 40 *psi* was applied for 3500 and 7000 cycles, respectively, for the fourth and fifth conditioning levels.

Mechanical Evaluation of Asphalt Mixture Samples

Modified Lottman (ML) Test. The Modified Lottman (ML) test was conducted in accordance with AASHTO T 283, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage." The procedure uses two sets of specimens compacted to 150 mm in diameter and 95 mm in thickness at 7.0±0.5% air void: 1) the control set without condition and 2) the conditioned set with partial vacuum saturation (70-80%) followed by a freeze-thaw cycle. A split tensile test at 25°C was performed on each sample, and the indirect tensile strength of the conditioned samples were compared to the control group to determine the tensile strength ratio (TSR), which measures the effect of moisture on the indirect tensile strength. A minimum TSR of 0.70 to 0.80 is often used as a standard criterion [3, 36].

Hamburg Wheel-Tracking (HWT) Test. The Hamburg Wheel-Tracking (HWT) test was conducted in accordance with AASHTO T 324, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)" [18]. This is considered a torture test. It produces damage by rolling a 703 N (158 lb.) steel wheel across the surface of 150 mm diameter by 60 mm thick cylindrical specimens that are submerged in 50°C water for 45 min. The test duration is 20,000 passes at a rate of 52 passes per min. Four specimens (two per wheel) were tested. Rut depth measurements were recorded at 11 locations across each cylindrical specimen until failure. The average rut depth at four middle locations and the rut depth at 20,000 cycles were recorded for analysis. Additionally, the stripping inflection point (SIP) was calculated as a measure of moisture damage. Sample failure is considered at either 20,000 passes or 25 mm rut depth, whichever occurred first.

Semi-Circular Bending (SCB) Test. The SCB test was performed per ASTM D 8044, "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures" [68]. This test was performed to characterize the fracture resistance of asphalt mixtures regarding the critical strain energy release rate or the critical J-integral (J_c). To determine J_c, specimens with three notch depths (25.4, 38.1, and 38 mm) were considered. A minimum of four replicates were tested for each notch depth at 25°C. The SCB specimens were loaded monotonically at a constant crosshead displacement of 0.5 mm/min. until failure. The load and deformation data were recorded continuously for the determination of J_c [68]. A higher J_c value is an indication of higher cracking resistance at intermediate-temperatures and vice versa.

In this study, a new parameter (*Jd*) was developed to quantify the effect of moisture damage (adhesive and cohesive) on the cracking resistance of the asphalt mixtures evaluated. Moisture damage in asphalt is a cumulative effect of reduction in strength and stiffness due to cohesive and adhesive failure [2]. Thus, the J_d parameter was proposed as part of this study to capture those effects (i.e., lower peak load and increased deformation). The J_d parameter is computed as follows:

$$J_d = -\left(\frac{1}{B}\right)\left(\frac{dU_d}{da}\right) \tag{1}$$

where,
J_d = critical strain energy per unit peak deformation (kJ/mm^3);
B = specimen thickness (mm);
a = notch depth (mm); and
U_d = peak strain energy per unit peak deformation (N.mm/mm).

Next, a J_d ratio was computed as follows:

$$J_d\,ratio = \frac{J_{d,\ conditioned}}{J_{d,\ dry}} \tag{2}$$

where,
$J_{d,\text{ conditioned}} = J_d$ for each conditioned specimen (FT-1, FT-3, M-3500, and M-7000); and
$J_{d,\text{ dry}} = J_d$ for control specimens.

A higher J_d value is desired for moisture damage resistant mixtures. It is noted that a preliminary minimum J_d ratio value of 90% was selected based on the analysis of SCB test data from asphalt mixtures with known moisture damage susceptibility.

Statistical Analysis

Test data from the asphalt binder and mixture experiments were analyzed statistically using the analysis of variance (ANOVA) procedure in the Statistical Analysis System (SAS) 9.4 program [69]. This analysis determined the significance of differences in moisture damage resistance among various asphalt binder types or mixtures (i.e., prepared with different binders, anti-strip additives, or aggregate types) subjected to the five conditioning levels evaluated in this study. A multiple comparison (Tukey test) with a 95% confidence level was performed on the mean test results to form statistical groupings. These groupings correspond to the average test results for each asphalt binder or mixture specimen type tested. Based on these groupings, the results of each specimen were categorized as A, B, C, and so on, with A representing the best performance (i.e., highest resistance to moisture damage) and subsequent letters indicating poorer performance (i.e., lower resistance to moisture damage). Multiple letter designations (A/B or A/B/C) indicate no statistically significant difference in performance between those groups. Additionally, error bars representing 95% confidence intervals from the mean were included in the figures presented in subsequent sections of the report.

Discussion of Results

This chapter presents an analysis of the results obtained from the asphalt binder and mixture experiments conducted in the study.

Impact of Conditioning on Asphalt Binder Properties and Mixture Performance as Measured by HWT Test

Asphalt binder and mixture experiments were conducted to assess the capability of the Hamburg Wheel-Tracking (HWT) test to evaluate the moisture susceptibility of asphalt mixtures subjected to various moisture conditioning protocols. Laboratory test data were collected and analyzed to evaluate the effects of:

- Asphalt binder type on the moisture damage of asphalt mixtures;
- Aggregate type on the moisture damage of asphalt mixtures; and
- Moisture conditioning protocols on the moisture damage of asphalt mixtures.

Asphalt Binder Experiment

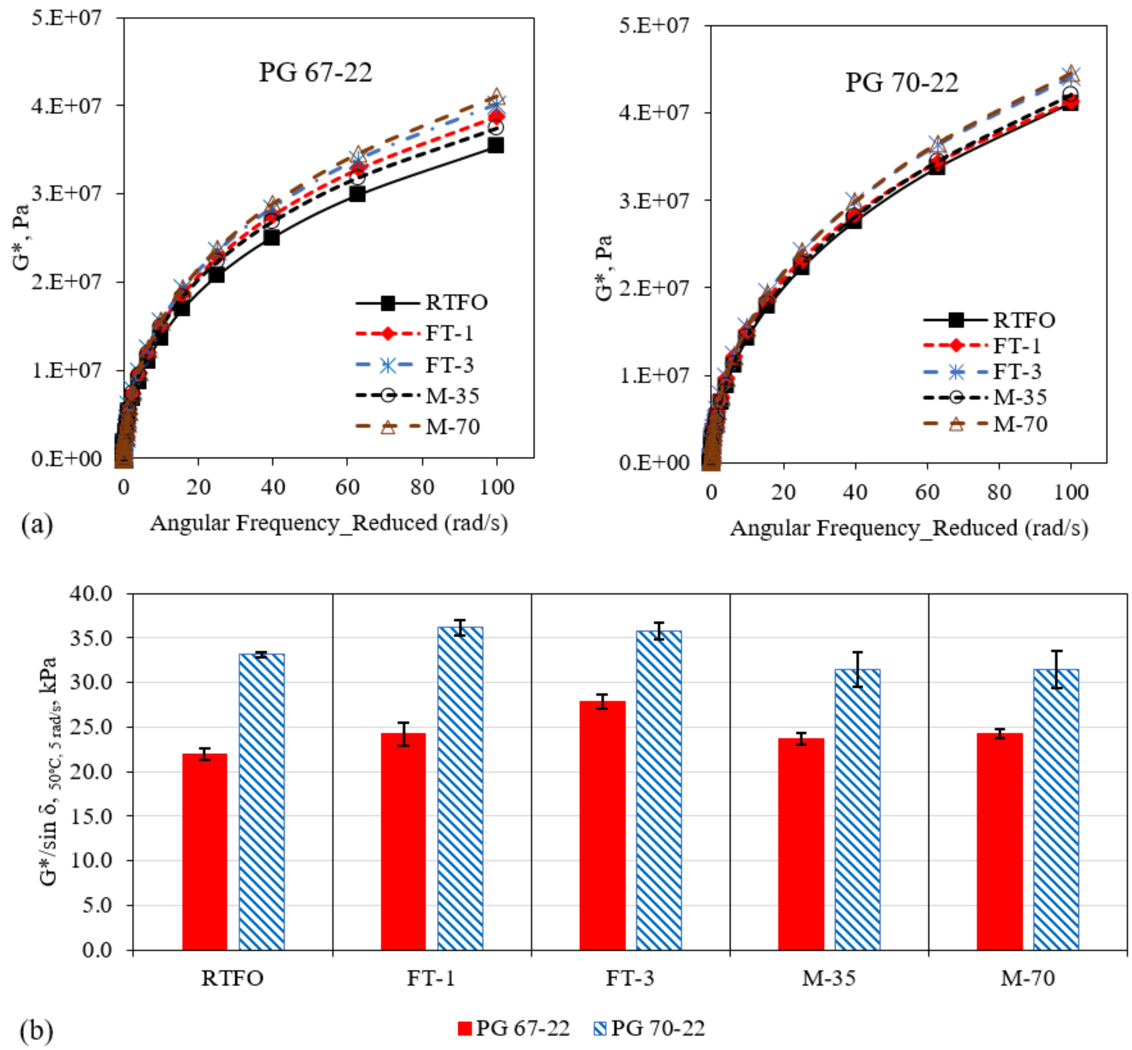
The results for the asphalt binder tests conducted on unconditioned and conditioned samples are presented in the following sections.

Frequency Sweep Test

Effect of conditioning on asphalt binder stiffness. Figure 10a presents frequency sweep master curves for the asphalt binders evaluated. For the two asphalt binders evaluated, freeze-thaw conditioning (FT-1 and FT-3) resulted in an increase in stiffness compared to the RTFO-conditioned asphalt binder. A similar increase from RTFO was observed for MiST-conditioned (M-3500 and M-7000) asphalt binder. However, PG 67-22 asphalt binder exhibited a higher increase in stiffness from RTFO for each conditioning level compared to PG 70-22 asphalt binder; see Figure 10a. It is noted that an increase in conditioning level (e.g., FT-1 to FT-3, M-35 or MiST 3500 to M-70 or MiST 7000) resulted in increased stiffness.

Figure 10b shows the rut factor ($G^*/\sin\delta$ at 50°C and 10 rad/sec.) values for the asphalt binders considered. For PG 67-22 binder, the rut factor values increased as the conditioning level progressed from RTFO to FT-1 and FT-3. However, a slight increase in the rut factor was observed due to MiST conditioning. For PG 70-22 asphalt binder, FT and MiST conditionings had a minimal effect on the rut factor values.

Figure 10. (a) Frequency sweep master curves (b) $G^*/Sin\delta$, 50°C, 10 rad/sec. for asphalt binders

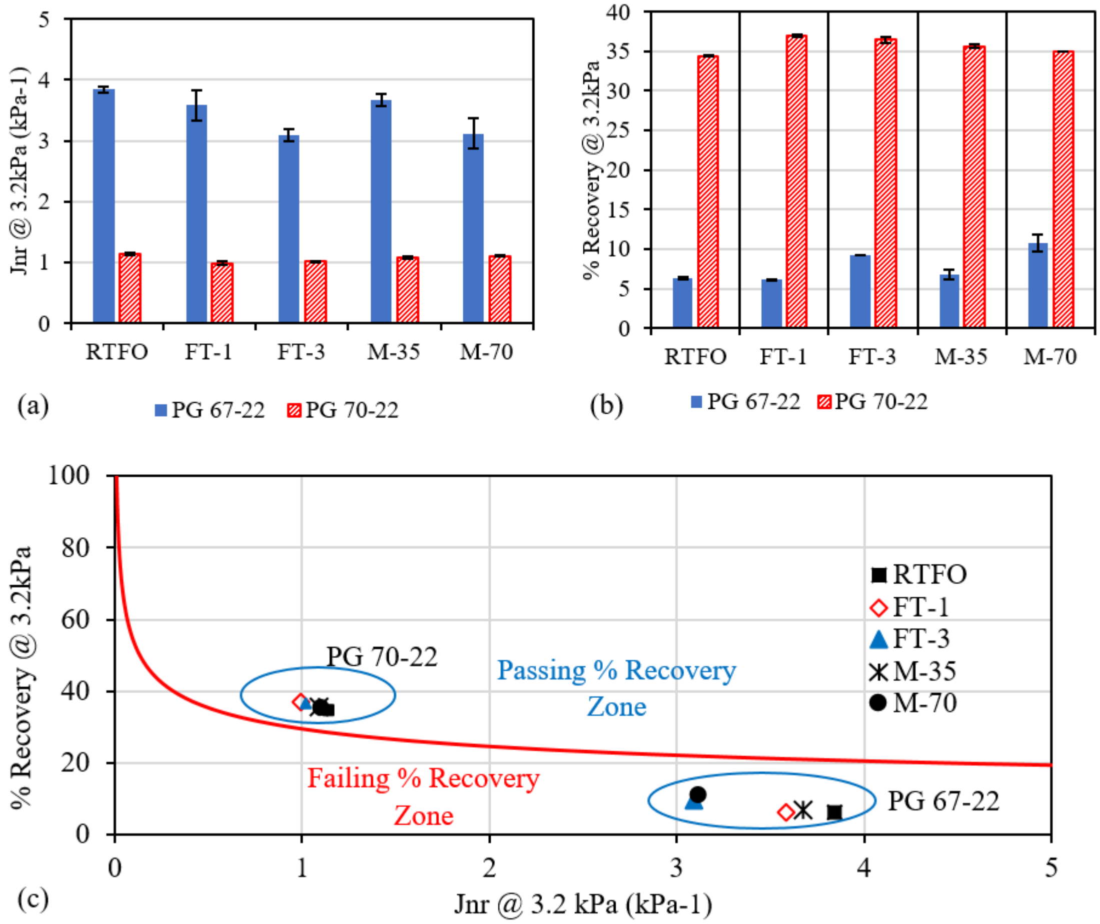


MSCR Test

Effect of conditioning on elastic response of asphalt binders. Figures 11a and 11b show the non-recoverable creep compliance (*Jnr*) and percent recovery (*R*) at a stress level of 3.2 kPa for the asphalt binders evaluated. For the asphalt binders evaluated, FT-1 and FT-3 conditioning resulted in a slight decrease in *Jnr* compared to RTFO-conditioned asphalt binder, as shown in Figures 11a and 11b. Additionally, these conditioning protocols (FT-1 and FT-3) resulted in a slight increase in *R* compared to RTFO-conditioned asphalt binder. A similar trend was observed for the M-35 (MiST 3500) and M-70 (MiST 7000) conditionings.

Figure 11c presents the elastic response curve for the asphalt binders evaluated. Two clusters were identified for each binder type: PG 70-22 in the passing zone, and PG 67-22 in the failed zone. For both clusters of asphalt binders shown in Figure 11c, freeze-thaw (FT-1 and FT-3) and MiST (M-35 and M-70) conditioning had no effect on the asphalt binder's ability to meet the delayed elastic response criteria.

Figure 11. (a) Non-recoverable creep compliance (b) percent recovery (c) elastic response curve for MSCR at 67° C



The MSCR test results were further analyzed to compute a new parameter, $J_{nrslope}$, to capture the stress-sensitive characteristics of the asphalt binder due to moisture conditioning. Stempihar et al. [70] developed this parameter to ensure that asphalt binders can withstand high stresses and temperatures in real-world applications. The $J_{nrslope}$ parameter has been shown to correlate well with incremental changes in field rut depth [70]. Lower $J_{nrslope}$ values are desirable, as they indicate better stress sensitivity. The parameter was calculated as follows:

$$J_{nrslope} = \frac{dJ_{nr}}{d\tau} \times 100 \tag{3}$$

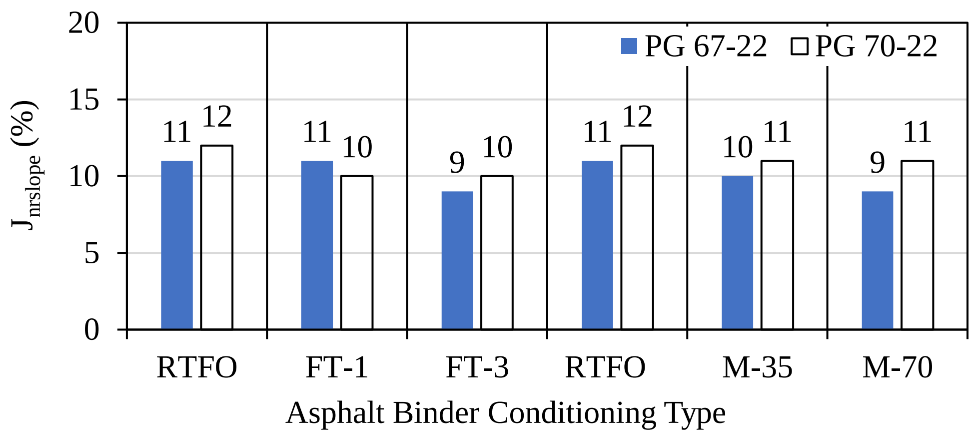
where,

dJ_{nr} = difference in J_{nr} values at 0.1 and 3.2 kPa stress levels; and

$d\tau$ = difference between higher (3.2 kPa) and lower stress levels (0.1 kPa).

Figure 12 presents the average $J_{nrslope}$ values for the PG 67-22 and PG 70-22 asphalt binders evaluated. Generally, freeze-thaw (FT-1 and FT-3) and MiST (M-35 and M-70) conditioning resulted in a slight reduction in stress sensitivity of both asphalt binders compared to the control RTFO asphalt binder. The slight reduction in the stress sensitivity associated with the freeze-thaw and MiST conditioning of asphalt binders may be attributed to the increased stiffness observed in frequency sweep test results reported in Figure 10.

Figure 12. Average *Jnr* slope values



Binder Bond Strength (BBS) Test

Figure 13 presents the average pull-off strength (BBS) values obtained from testing specimens prepared with various binder and aggregate types. These specimens were subjected to five different conditioning protocols. Additionally, Table 5 summarizes the observed failure types (cohesive, adhesive, or both) for each specimen. A detailed analysis of the data presented in Figure 13 and Table 5 is provided in the subsequent sections.

Figure 13. Average binder pull-off strength for (a) limestone and (b) gravel aggregates

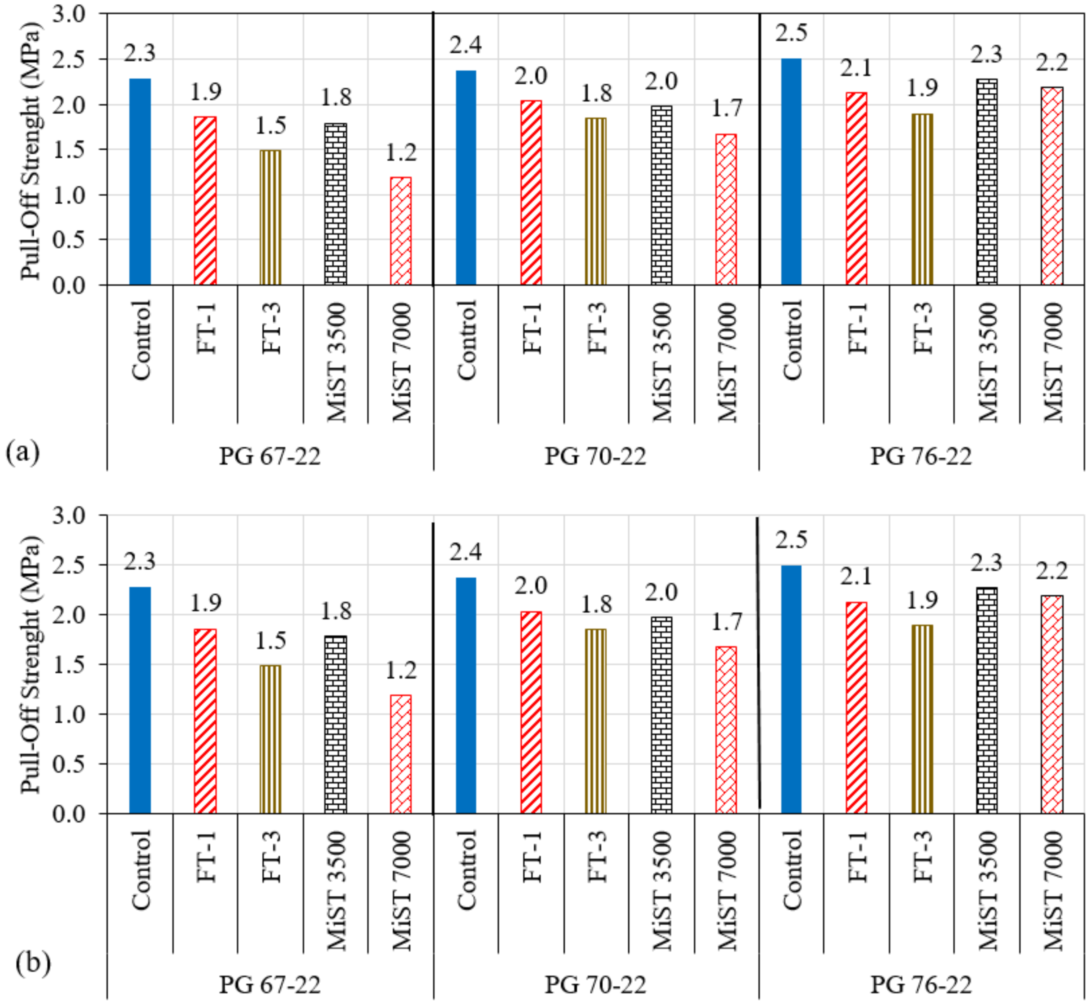


Table 5. Failure types observed in BBS test

Aggregate Type	Asphalt Binder Grade	Conditioning Level	Failure Type
Limestone	PG 67-22	Control	Cohesive
		FT-1	Cohesive
		FT-3	Cohesive + Adhesive
		MiST 3500	Cohesive
		MiST 7000	Cohesive + Adhesive
	PG 70-22	Control	Cohesive
		FT-1	Cohesive
		FT-3	Cohesive
		MiST 3500	Cohesive
		MiST 7000	Cohesive
	PG 76-22	Control	Cohesive
		FT-1	Cohesive
		FT-3	Cohesive
		MiST 3500	Cohesive
		MiST 7000	Cohesive
Gravel	PG 67-22	Control	Cohesive
		FT-1	Cohesive + Adhesive
		FT-3	Cohesive + Adhesive
		MiST 3500	Cohesive + Adhesive
		MiST 7000	Cohesive + Adhesive
	PG 70-22	Control	Cohesive
		FT-1	Cohesive
		FT-3	Cohesive + Adhesive
		MiST 3500	Cohesive + Adhesive
		MiST 7000	Cohesive + Adhesive
	PG 76-22	Control	Cohesive
		FT-1	Cohesive
		FT-3	Cohesive + Adhesive
		MiST 3500	Cohesive + Adhesive
		MiST 7000	Cohesive + Adhesive

Effect of aggregate type and binder grade on pull-off strength and failure type. The BBS values increased with increasing polymer modification level or binder grade from PG 67-22 to PG 76-22, indicating that polymer-modified binders exhibited better resistance to moisture damage. Additionally, the pull-off strength values were generally higher for limestone aggregate compared to gravel aggregate, suggesting improved resistance to moisture damage. This observation can be attributed to the higher silica (SiO_2) content in gravel aggregates, which makes them hydrophilic compared to hydrophobic limestone aggregates [13]. The failure type was predominantly cohesive across all binder grades. Further, the failure type was predominantly cohesive for limestone aggregates, confirming their superior adhesive properties and suggesting that the binder was the primary factor in determining moisture damage for these aggregates. In contrast, the failure type in gravel specimens was mixed, with both cohesive and cohesive+adhesive failures observed. This suggests that the aggregate type may have played a more significant role in the moisture-induced failure mechanism for gravel specimens.

Effect of conditioning level on pull-off strength and failure type. The control samples, which were not subjected to any conditioning, generally exhibited the highest BBS values and cohesive failure types. This observation indicates that moisture conditioning increased the potential for adhesive failure in asphalt mixtures. The MiST conditioning, which simulates exposure to traffic-induced pore pressure, resulted in a decrease in BBS values and an increase in the proportion of cohesive+adhesive failures. This observation suggests that the MiST device is capable of simulating moisture damage mechanisms typically observed in the field. Like the MiST conditioning, the freeze-thaw conditioning (FT-1 and FT-3) also caused a decrease in BBS values and an increase in the proportion of cohesive+adhesive failures. This suggests that repeated freeze-thaw cycles, commonly observed in the field, can weaken the bond between the aggregate and the binder, leading to moisture damage.

Asphalt Mixture Experiment

The results of the asphalt mixture tests conducted on unconditioned and conditioned loose and compacted samples are presented in the following sections.

Boil Test on Loose Asphalt Mixture Samples

Effect of asphalt binder type on percent AC loss. Table 6 illustrates the visually observed percentage of asphalt binder loss (% AC loss) in the asphalt mixtures subjected to the boil test (ASTM D 3625) for different durations. As expected, all asphalt mixtures showed an increase in stripping (% AC loss) with longer boiling times. Notably, asphalt mixtures incorporating PG 67-22 binder (M1 to M3) exhibited higher levels of stripping compared to those with PG 70-22 binder (M4 to M6) across all time intervals. This difference can be attributed to the use of SBS polymer-modified asphalt binder, known for its enhanced resistance to moisture damage. Additionally, M7 demonstrated less moisture damage compared to M1, possibly due to the incorporation of anti-strip additive in M7.

Effect of aggregate type on percent AC loss. Within the PG 67-22 asphalt mixture group, M2 and M3, with their high water absorption rates (> 2%), are classified as moisture-sensitive asphalt mixtures. In contrast, M1 incorporates limestone aggregates with low water absorption rates (< 2%). Additionally, M1 and M2 utilize aggregates with high angularity, while M3 uses a 50/50 mix of round and smooth aggregates. A clear trend in moisture resistance emerges, with limestone mixtures exhibiting greater moisture resistance than crushed gravel mixtures, which in turn demonstrates better resistance than semi-crushed gravel mixtures; see Table 6. This highlights the significant influence of moisture on the angularity and absorption characteristics of aggregates, ultimately impacting moisture resistance.

Table 6. Percent AC loss in asphalt mixtures after 10, 30, 60, and 120 min.

Mixture Type	10 min.	30 min.	60 min.	120 min.
M1	2	5	13	18
M2	2	5	17	21
M3	2	8	21	32
M4	2	2	4	7
M5	2	3	7	10
M6	2	3	7	11
M7	2	3	6	10

Asphalt Colorimeter Tester (ACT)

Effect of asphalt binder type on percent AC loss. Table 7 presents the Sample Ranking Index (SRI) determined using the Asphalt Compatibility Tester (ACT) for loose asphalt mixtures subjected to boiling for 10, 30, 60, and 120 min. While ASTM D 3625 visually identifies moisture damage in asphalt mixtures, ACT utilizes a colorimeter to quantify color changes occurring in the post-boiling mixtures. PG 67-22 asphalt mixtures (M1-M3) displayed higher SRI values compared to PG 70-22 asphalt mixtures prepared with similar aggregate types, indicating greater percent AC loss in the PG 67-22 mixtures. This observation is attributed to the utilization of SBS polymer-modified asphalt binder, which enhances moisture damage resistance. Further, M7 showed reduced moisture damage compared to M1 due to the incorporation of an anti-strip additive in M7.

Effect of aggregate type on percent AC loss. M2 and M3, prepared with high water absorption aggregates (> 2%), are more susceptible to moisture damage compared to M1, which uses low absorption aggregate (< 2%). Additionally, while M1 and M2 incorporate highly angular aggregates, M3 uses a 50/50 blend of round and smooth aggregates. These differences in aggregate properties contribute to varying levels of moisture susceptibility among the mixtures.

Further, the analysis indicates a clear trend in moisture resistance. Limestone-based mixtures exhibit the highest resistance, followed by crushed gravel mixtures, then semi-crushed gravel mixtures; see Table 7. This highlights the significant impact of aggregate properties, such as angularity and absorption, on the overall moisture resistance of asphalt mixtures. Understanding these factors is critical for developing optimal asphalt mixture designs to minimize moisture-related damage and improve long-term pavement performance.

Table 7. Sample ranking index of boiled asphalt mixtures for 10, 30, 60, and 120 min.

Mixture Type	10 min.	30 min.	60 min.	120 min.
M1	1.2	2.0	2.7	3.7
M2	1.2	2.3	3.5	4.9
M3	1.4	2.7	4.1	6.4
M4	0.7	1.3	1.4	1.4
M5	0.8	1.2	1.4	1.7
M6	0.8	1.5	1.5	1.7
M7	1.0	1.4	1.7	1.9

Hamburg Wheel-Tracking (HWT) Test

Effect of conditioning on moisture resistance: Figure 14 presents the HWT rut depth of the asphalt mixtures evaluated. Moisture-susceptible mixtures are expected to show higher rut depths in the HWT test. For each asphalt mixture evaluated, freeze-thaw (FT-1 and FT-3) and MiST (M-35 and M-70) conditioning resulted an in increase in rut depth compared to the control asphalt mixture. An increase in conditioning level (e.g., FT-1 to FT-3 and M-35 to M-70) resulted in a significant increase in rut depth. The increased rut depth observed in the HWT test contradicts the findings from the asphalt binder rheological test; see Figure 10. This discrepancy is attributed to the prevalence of adhesive failure within the mixtures, which is consistent with observations reported by other researchers [36, 71, 72]. Adhesive failure, primarily associated with the interface between the asphalt binder and the aggregate, is more pronounced in wet conditions, as evidenced by bitumen bond strength (BBS) tests. Conversely, cohesive failure, which is largely influenced by the properties of the asphalt binder itself, is less dominant in these cases [71, 72].

M2, M3, M5, and M6 were prepared with moisture-susceptible aggregates, per the Louisiana DOTD Standard Specification [67] Additionally, HWT test results for M2, M5, and M6 met the requirements of AASHTO T 324. However, after conditioning, an increase in rut depth measurements was observed, exceeding the specified limits. Conditioning levels applied to M3 had a significant impact on sample integrity, leading to damage; see Figure 14. This is likely due to the inclusion of 50% uncrushed material in M3.

Further, the incorporation of an anti-strip additive in M7 enhanced its moisture damage resistance compared to M1 across all conditioning levels. While M1, M4, and M7 were initially classified as moisture-resistant, subjecting them to increasing levels of freeze-thaw (FT-1 to FT-3) and moisture-induced stress cracking (M-35 and M-70) conditioning revealed their susceptibility to moisture damage. Consequently, it is essential to consider incorporating a moisture conditioning protocol into the AASHTO T 324 test to more accurately assess moisture damage resistance.

Figure 14. HWT test results—total rut depth for mixtures (a) M1-M3 and (b) M4-M7

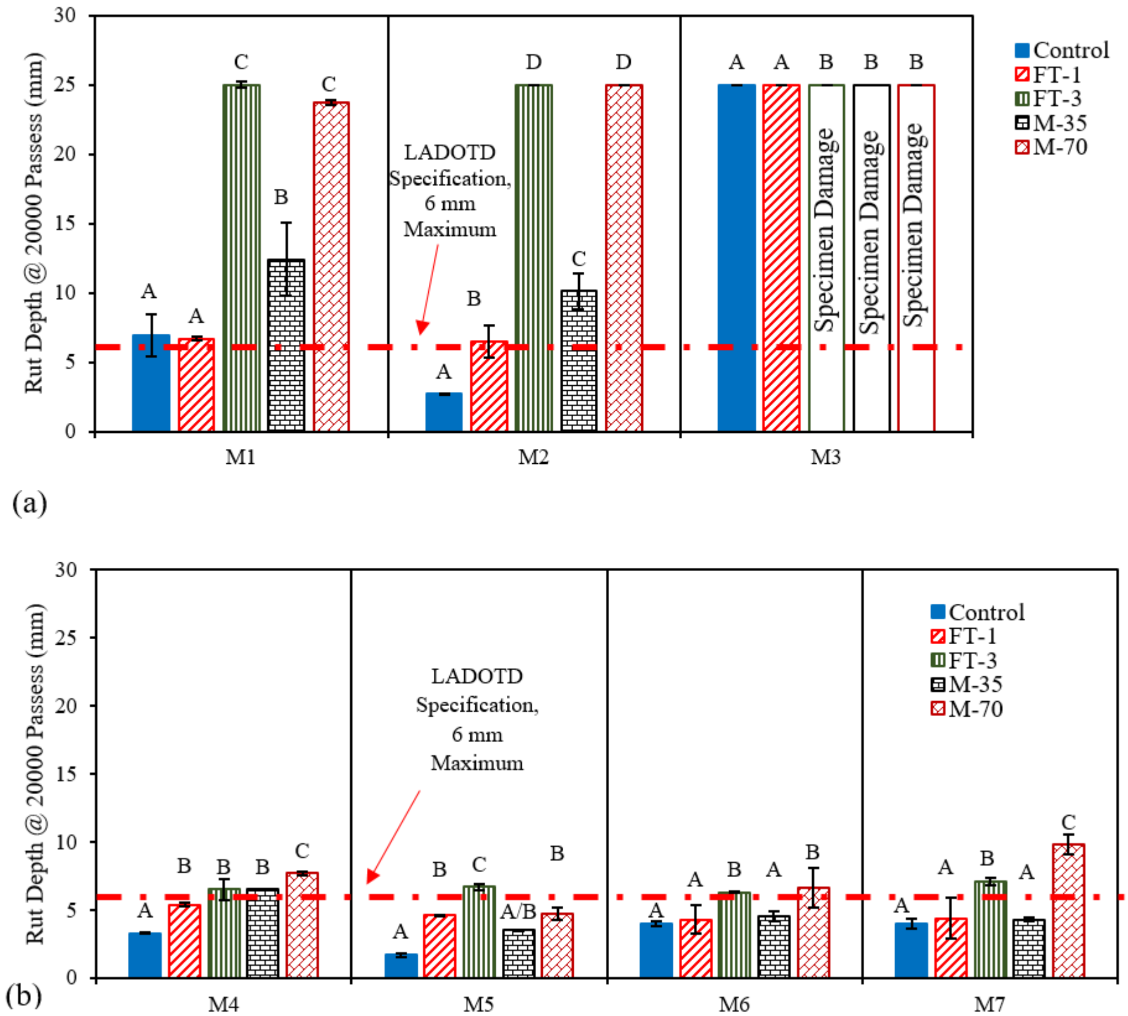


Figure 15 presents the SIP values of the mixtures evaluated in this study. Higher SIP values are desirable for moisture-resistant asphalt mixtures. Mixtures containing SBS polymer-modified PG 70-22 asphalt binder (M4, M5, M6) exhibited higher resistance to moisture damage, showing no signs of stripping damage. Conversely, mixtures prepared with unmodified PG 67-22 asphalt binder (M1, M2, M3, M7) showed a decrease in SIP values as the moisture conditioning level increased. This finding is consistent with field performance data reported by previous researchers [73, 74], which indicates that asphalt mixtures incorporating SBS polymer-modified binders exhibit enhanced resistance to moisture-induced damage.

Conditioning M2 at FT-3 and M-70 resulted in severe damage and rapid disintegration within a few wheel passes; see Figure 15. Consequently, the number of passes to failure was selected as the stripping inflection point for the FT-3 and M-70 conditioned M2; see Figure 16. For mixtures lacking a clearly defined stripping slope, relying solely on the total number of passes to total failure can be misleading. To mitigate this issue, SIP is deemed invalid whenever the ratio of the stripping slope to the creep slope is less than 2.0 [75].

Figure 15. HWT test results—stripping inflection point for mixtures (a) M1-M3 and (b) M4-M7

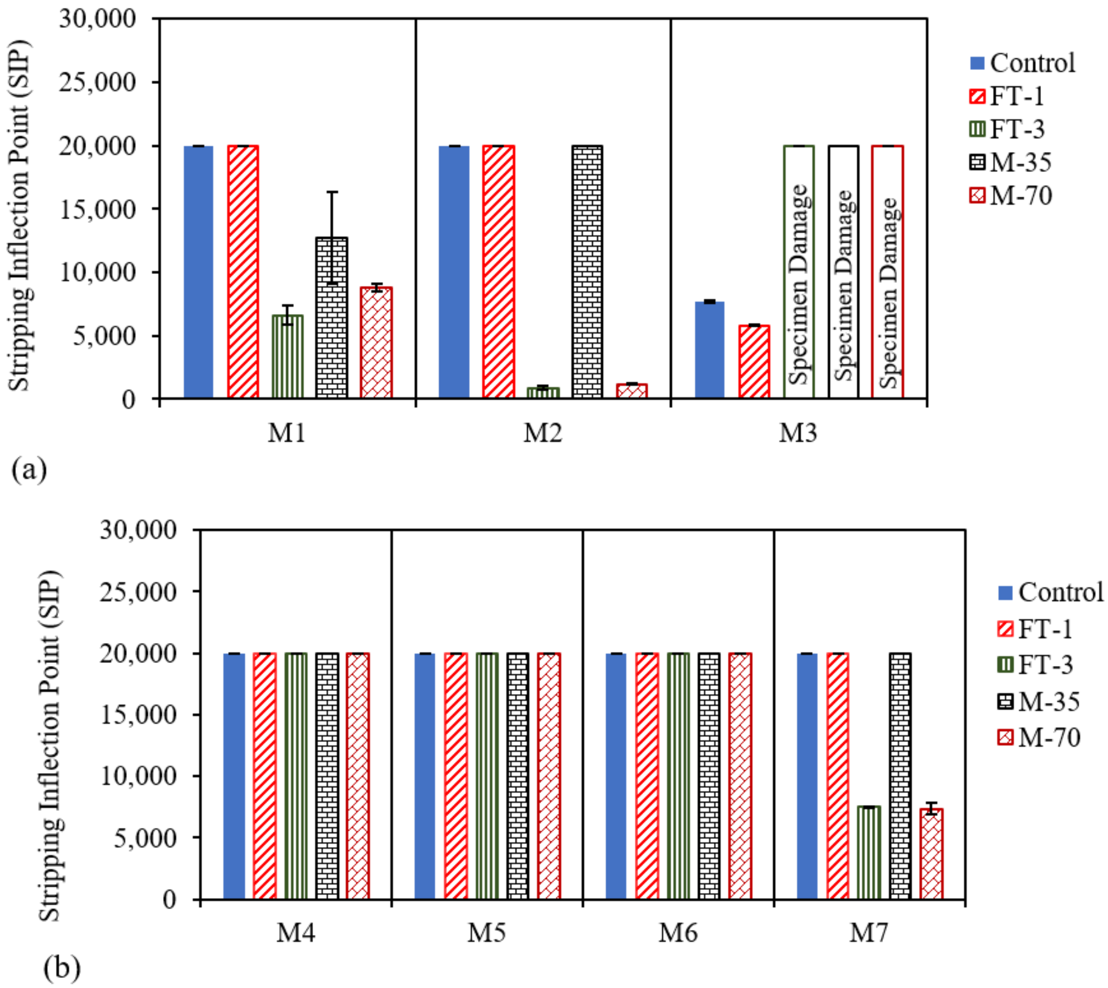


Figure 16. (a) HWT test results for M2 and (b) disintegrated conditioned specimens

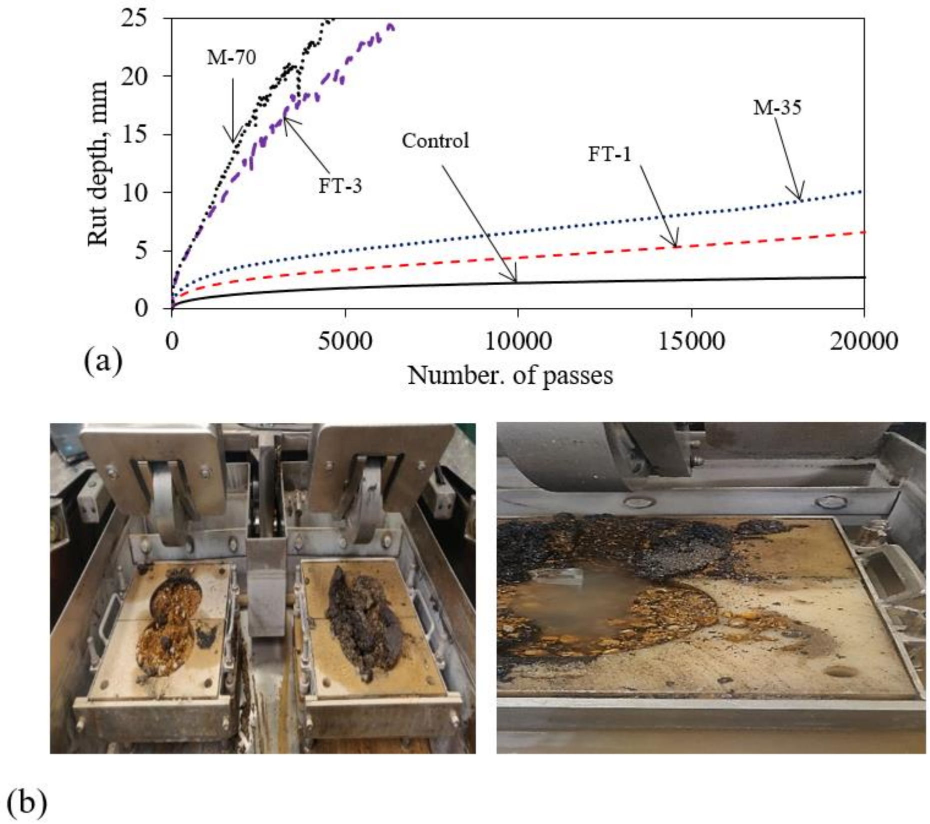


Figure 17 presents the HWT rut depths, separated into viscoplastic and stripping components of deformation, using a procedure developed by Yin et al. [93]. Among the mixtures evaluated, only M1 (FT-3, M-35, and M-70) and M7 (FT-3 and M-70) exhibited significant stripping deformations. Notably, M1 showed substantially higher stripping deformation compared to M7. Moreover, increasing the MiST conditioning severity from M-35 to M-70 resulted in an increase in both stripping and viscoplastic rut components for M1 and M7; see Figure 17b. This observation is consistent with previous research findings [20, 76, 77], which demonstrated that pore pressure buildup in asphalt mixtures can emulsify and soften asphalt binder films, leading to increased rutting and stripping. Yin et al.'s technique for analyzing rut depth data [78] could not separate the total rut depth into stripping and viscoplastic components for certain mixtures with high rut depths; see Figure 17. This limitation may be attributed to the sudden disintegration of these mixtures within a few wheel passes; see Figure 16.

Figure 17. Viscoplastic and stripping rut depth components for (a) M1-M3 and (b) M4-M7

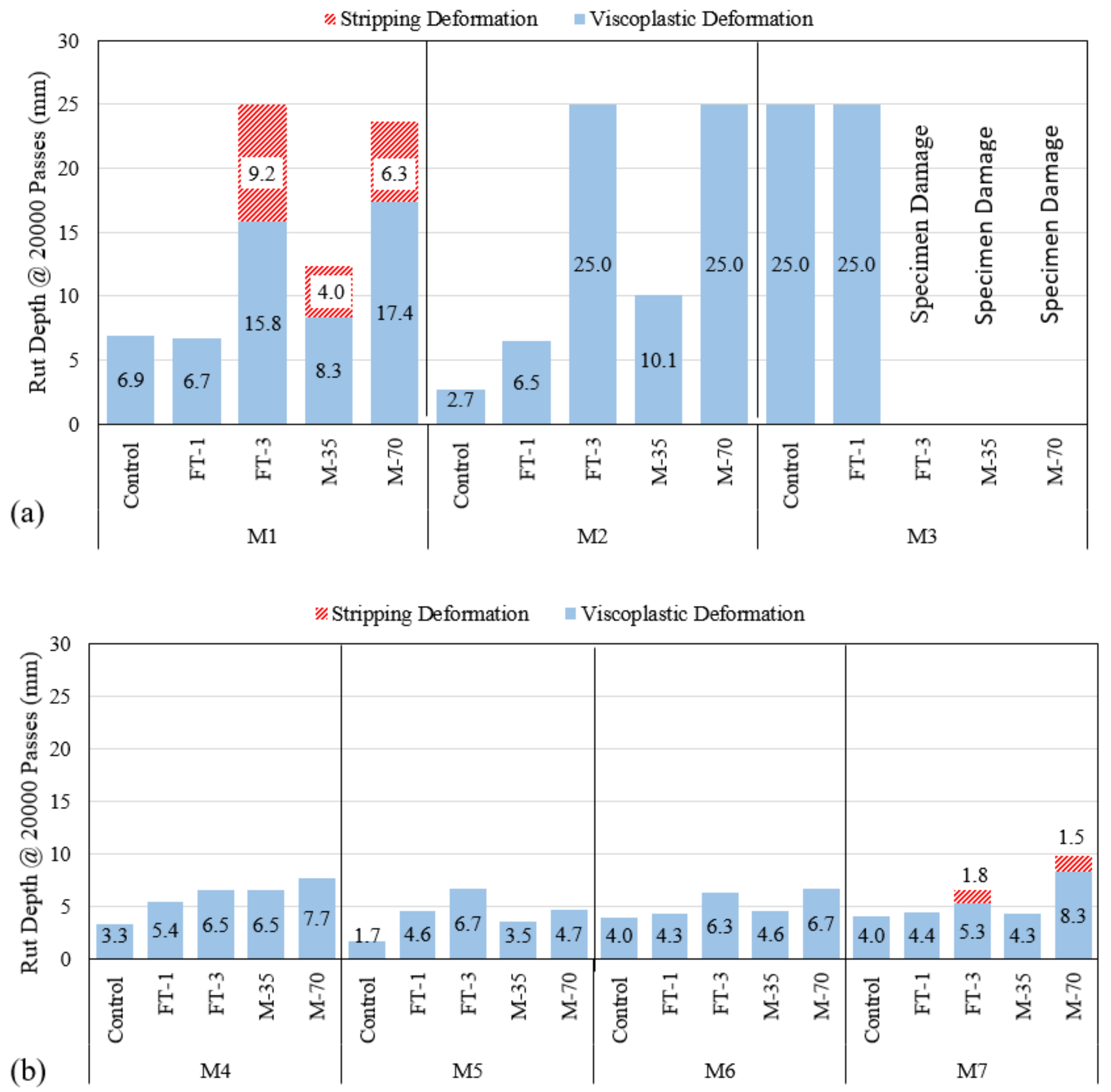


Table 8 provides an overview of computed parameters extracted from HWT test data utilized by several states, including California, Iowa, Louisiana, Massachusetts, Texas, Utah, and Washington. These parameters are summarized in Table 8, facilitating a comparative analysis across different state specifications. Conducting the HWT test in accordance with AASHTO T 324 on specimens subjected to moisture conditioning has proven to be effective in detecting moisture damage compared to the current protocol that lacks moisture conditioning. For example, the HWT test results obtained from M1, M2, M3, and M7, which underwent freeze-thaw (FT-3) and MiST (M-70) conditioning, did not meet the moisture damage criteria specified by respective states, as indicated in Table 8. However, these same mixtures demonstrated compliance with the specified state criteria when tested following the current AASHTO T 324 protocol. It is worth emphasizing that the utilization of SBS polymer-modified asphalt binder significantly enhances resistance to moisture damage, thus contributing to improved pavement performance.

Table 8. Summary of HWT results

State	Test Condition	M1		M2		M3		M4		M5		M6		M7	
		R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min
	T 324	P	P	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/FT-1	P	P	P	P	F	F	P	P	P	P	P	P	P	P
Cal.	T 324/FT-3	F	F	F	F	F	F	P	P	P	P	P	P	P	F
	T 324/M-35	P	P	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/M-70	F	F	F	F	F	F	P	P	P	P	P	P	P	F
	T 324	P	P	P	P	F	I	P	P	P	P	P	P	P	P
	T 324/FT-1	P	P	P	P	F	I	P	P	P	P	P	P	P	P
Iowa	T 324/FT-3	F	F	F	I	F	I	P	P	P	P	P	P	P	F
	T 324/M-35	P	F	P	P	F	I	P	P	P	P	P	P	P	P
	T 324/M-70	F	F	F	I	F	I	P	P	P	P	P	P	P	F
	T 324	F		P		F		P		P		P		P	
	T 324/FT-1	F		F		F		P		P		P		P	
La.	T 324/FT-3	F	N/A	F	N/A	F	N/A	F	N/A	F	N/A	P	N/A	F	N/A
	T 324/M-35	F		F		F		F		P		P		P	
	T 324/M-70	F		F		F		F		P		F		F	
	T 324	P	P	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/FT-1	P	P	P	P	F	F	P	P	P	P	P	P	P	P
Mass.	T 324/FT-3	F	F	F	F	F	F	P	P	P	P	P	P	P	F
	T 324/M-35	P	F	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/M-70	F	F	F	F	F	F	P	P	P	P	P	P	P	F
	T 324	P		P		F		P		P		P		P	
	T 324/FT-1	P		P		F		P		P		P		P	
Texas	T 324/FT-3	P	N/A	F	N/A	F	N/A	P	N/A	P	N/A	P	N/A	P	N/A
	T 324/M-35	P		P		F		P		P		P		P	
	T 324/M-70	F		F		F		P		P		P		P	

Cal.: California; La: Louisiana; Mass: Massachusetts ; Wash.: Washington; T 324: AASHTO T 324; /:And; FT-1: One freeze-thaw cycle; FT-3: Three freeze-thaw cycles; M-35: MiST 3500 cycles; M-70: MiST 7000 cycles; R, max: maximum rut depth at specified number of passes; SIP, min: minimum stripping inflection point; P: passes specification; F: failed specification; N/A: not applicable; I: invalid stripping inflection point value (92)

State	Test Condition	M1		M2		M3		M4		M5		M6		M7	
		R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min	R, max	SIP, min
Utah	T 324	P	N/A	P	N/A	F	N/A	P	N/A	P	N/A	P	N/A	P	N/A
	T 324/FT-1	P		P		F		P		P		P		P	
	T 324/FT-3	F		F		F		P		P		P		P	
	T 324/M-35	P		P		F		P		P		P		P	
	T 324/M-70	F		F		F		P		P		P		P	
Wash.	T 324	P	P	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/FT-1	P	P	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/FT-3	F	F	F	F	F	F	P	P	P	P	P	P	P	F
	T 324/M-35	P	F	P	P	F	F	P	P	P	P	P	P	P	P
	T 324/M-70	F	F	F	F	F	F	P	P	P	P	P	P	P	F

Cal.: California; La: Louisiana; Mass: Massachusetts ; Wash.: Washington; T 324: AASHTO T 324; /:And; FT-1: One freeze-thaw cycle; FT-3: Three freeze-thaw cycles; M-35: MiST 3500 cycles; M-70: MiST 7000 cycles; R, max: maximum rut depth at specified number of passes; SIP, min: minimum stripping inflection point; P: passes specification; F: failed specification; N/A: not applicable; I: invalid stripping inflection point value (92)

Evaluation of Different Moisture Conditioning and Testing Protocols for Asphalt Mixtures

Asphalt mixture mechanical test data were collected from samples subjected to five conditioning levels (control, FT-1, FT-3, M-35, and M-70) to:

- Evaluate the ability of different laboratory mechanical tests to capture moisture damage in asphalt mixtures; and
- Assess the impact of different moisture conditioning levels on the moisture damage of asphalt mixtures.

The laboratory mechanical tests considered in this study included the Modified Lottman (ML), Hamburg Wheel-Tracking (HWT), and Semi-Circular Bend (SCB) tests. The laboratory mechanical test data were subjected to statistical analysis, as described in the Methodology section of this report. Note that statistical analysis was performed only on HWT test results. However, Modified Lottman and SCB test results were analyzed based on their respective pass/fail thresholds (TSR ≥ 80% for Modified Lottman and *Jd* ratio ≥ 90% for SCB). Table 9 presents mean HWT, ML, and SCB test results along with their statistical groupings. It is noted that within each asphalt mixture (M1-M7) and conditioning type (FT, MiST), rows with letters A, B, and C represent statistically distinct groups from best to worst.

Table 9. Results for HWT, Modified Lottman and SCB tests

Mix ID	HWT Test Results						Specified Limit
	Freeze-Thaw Conditioning			MiST Conditioning			
	Control	FT-1	FT-3	Control	M-35	M-70	
	Average Rut Depth @ 20000 Passes, mm / Statistical Ranking						
M1	6.9 / A	6.7 / A	24.2 / B	6.9 / A	12.3 / B	24.4 / C	Rut depth > 6.0 mm (DOTD 2016)
M2	2.7 / A	6.5 / B	25.0 / C	2.7 / A	10.1 / B	25.0 / C	
M3	25.0 / A	25.0 / A	Damage	25.0 / A	Damage	Damage	
M4	3.3 / A	5.4 / B	6.5 / C	3.3 / A	6.5 / B	7.7 / C	
M5	1.7 / A	4.6 / B	6.7 / C	1.7/ A	3.5/ B	4.7 / C	
M6	3.9 / A	4.3 / A	6.3 / B	3.9 / A	4.6 / A	6.7 / B	
M7	4.0 / A	4.6 / A	7.1 / B	4.0 / A	4.3 / A	9.8 / B	
Mix ID	**Modified Lottman Test Results**						**Specified Limit**
	Freeze-Thaw Conditioning			**MiST Conditioning**			
	Control	**FT-1**	**FT-3**	**Control**	**M-35**	**M-70**	
	Average ITS, *psi* / TSR, %						
M1	122 /NA	120 / 98	112 / 92	122 /NA	94 / 77	100 / 82	TSR ≥ 80% (DOTD 2016)
M2	190 /NA	186 / 98	161 / 85	190 /NA	150 / 79	150 / 79	
M3	110 /NA	107 / 97	Damage	110 /NA	Damage	Damage	
M4	157 /NA	156 / 99	135 / 86	157 /NA	156 / 99	129 / 82	
M5	199 /NA	194 / 97	171 / 86	199 /NA	172 / 86	172 / 86	
M6	197 /NA	189 / 96	154 / 78	197 /NA	181 / 92	174 / 88	
M7	158 /NA	154 / 97	146 / 92	158 /NA	153 / 97	150 / 95	
Mix ID	**SCB Test Results**						**Specified Limit**
	Freeze-Thaw Conditioning			**MiST Conditioning**			
	Control	**FT-1**	**FT-3**	**Control**	**M-35**	**M-70**	
	Average J_d , kJ/mm^3 /J_d-ratio, %						
M1	0.36 /NA	0.32 / 89	0.24 / 67	0.36 /NA	0.27 / 75	0.20 / 56	J_d-ratio ≥ 90%
M2	0.45 /NA	0.42 / 93	0.35 / 78	0.45 /NA	Damage	Damage	
M3	0.37/ NA	0.25 / 68	Damage	0.37/ NA	Damage	Damage	
M4	0.38 /NA	0.36 / 95	0.31 / 82	0.38 /NA	0.32 / 84	0.27 / 71	
M5	0.46 /NA	0.43 / 93	0.40 / 87	0.46 /NA	0.39 / 85	0.36 / 78	
M6	0.38 /NA	0.36 / 95	0.20 / 53	0.38 /NA	0.31 / 82	0.19 / 50	
M7	0.41/ NA	0.39 / 95	0.34 / 83	0.41/ NA	0.39 / 95	0.36 / 88	

Note: NA = not applicable; ITS = indirect tensile strength; TSR = tensile strength ratio; *Jd* = critical strain energy per unit peak deformation (kJ/mm^3); Damage = specimen damaged during conditioning

HWT Test Results

The average coefficient of variation (CoV) for the mixtures evaluated (M1-M7) was 19%. Generally, freeze-thaw conditioning (FT-1 and FT-3) resulted in a significant increase in rut depth for the asphalt mixtures. Similarly, MiST conditioning (M-35 and M-70) resulted in increased rut depths compared to the control samples. Notably, more severe conditioning levels (FT-3 and M-70) resulted in significantly higher rut depths than less severe levels (FT-1 and M-35).

Further, mixtures containing unmodified PG 67-22 asphalt binder (M1-M3 and M7) exhibited a greater increase in rut depth from the control to each conditioning level compared to those containing SBS-modified PG 70-22 asphalt binder (M4-M6). These observations suggest that the HWT test can effectively capture incremental moisture damage associated with different moisture conditioning levels and the improved moisture damage resistance of mixtures containing SBS polymer-modified PG 70-22 asphalt binder. Additionally, the test was able to capture the improved moisture resistance of M7, which contained an anti-strip additive, compared to M1. It is noted that increased conditioning levels (FT-1 to FT-3 and Control to M-35 to M-70) in M3 resulted in extensive moisture damage, leading to the loss of specimen integrity before HWT testing. This observation is attributed to the use of 50% round and uncrushed gravel material in M3.

Modified Lottman Test Results

This test evaluates changes in indirect tensile strength (ITS) values due to moisture conditioning. Results are reported as tensile strength ratio (TSR), defined as the ratio of ITS values of moisture-conditioned samples to controlled samples. The average coefficient of variation (CoV) for ITS of M1-M3 and M7 was 11%, while that of M4-M6 was 8%. Conditioned specimens (FT and MiST) exhibited lower ITS values compared to their unconditioned counterparts. Generally, mixtures containing SBS polymer-modified PG 70-22 showed higher ITS values than those with PG 67-22. FT-1 conditioning did not significantly reduce ITS values compared to control mixtures. However, increasing freeze-thaw cycles (FT-1 to FT-3) significantly reduced ITS. Additionally, M-35 conditioning significantly reduced ITS values for most mixtures (M1-M3 and M5-M6).

Moisture conditioning severely damaged M2 (M-35 and M-70) and M3 (FT-1, M-35, and M-70), preventing further testing. This may be attributed to the use of highly absorptive aggregates (> 2%) and unmodified PG 67-22 in these mixtures. Like the HWT test results, the ML test effectively captured the improved moisture damage resistance of M7 with the anti-strip additive across all conditioning levels. It is noted that Louisiana DOTD specifies a minimum TSR value of 80%. Generally, the TSR parameter was not effective in capturing moisture susceptibility, except for the severely damaged M2 and M3. M2, M3, M5, and M6, each containing moisture-susceptible aggregates (> 2% absorption), were expected to exhibit TSR values below 80% after conditioning. Increasing conditioning levels (FT-1 to FT-3 and M-35 to M-70) did not reduce TSR values below 80% for M4, M5, and M7, while it did for M6 (M-70).

SCB Test Results

The SCB test data were analyzed as described in the Methodology section to compute the SCB J_d-ratio, a measure of the effect of moisture conditioning on the intermediate-temperature fracture resistance of asphalt mixtures. It is noted that a preliminary minimum J_d-ratio value of 90% was selected based on the analysis of SCB test data from asphalt mixtures with known moisture damage susceptibility [64, 34]. The average coefficient of variation (CoV) of SCB J_d values for M1-M3 and M7 was 18%, while that of M4-M6 was 20%. It is worth noting that conditioned asphalt mixtures (FT and MiST) exhibited lower SCB J_d values than their unconditioned counterparts. Additionally, increasing the conditioning level (FT-1 to FT-3 and M-35 to M-70) resulted in a progressive increase in moisture damage, as indicated by higher SCB J_d values. Further, asphalt mixtures containing SBS-modified PG 70-22 binder exhibited higher SCB J_d values compared to those with unmodified PG 67-22 binder.

The SCB J_d parameter effectively captured the improved moisture resistance associated with the use of an anti-strip additive in M7. Generally, the SCB J_d-ratio parameter successfully captured the progressive moisture damage associated with increased freeze-thaw and MiST conditioning levels; see Table 10.

Summary of Laboratory Mechanical Test Parameters

Table 10 summarizes laboratory mechanical test parameters (HWT rut depth, Modified Lottman TSR, and SCB J_d-ratio) and their corresponding minimum thresholds for characterizing moisture damage in asphalt mixtures. Generally, the HWT rut depth and J_d-ratio parameters consistently identified unmodified PG 67-22 asphalt mixtures subjected to the four conditioning levels (FT-1, FT-3, M-35, and M-70) as moisture susceptible (J_d-ratio < 90% and HWT rut depth > 6 mm), except for the anti-strip additive modified M7, which met the criteria at M-35 cycles. For SBS-modified PG 70-22 asphalt mixtures, the J_d-ratio and HWT rut depth parameters consistently identified mixtures subjected to higher levels of conditioning (FT-3 and M-70) as moisture susceptible. Additionally, the TSR parameter identified PG 67-22 mixtures subjected to 7000 MiST cycles as moisture susceptible, except for M1. Notably, the TSR parameter also identified the PG 70-22 asphalt mixture as moisture resistant, except for M6, which failed the TSR criteria at FT-3 cycles. Based on the analysis of the data in Table 10, incorporating an FT-1 or M-35 conditioning protocol into the HWT or SCB test can enhance the ability of these protocols to identify moisture-susceptible mixtures that may otherwise pass a conventional HWT test.

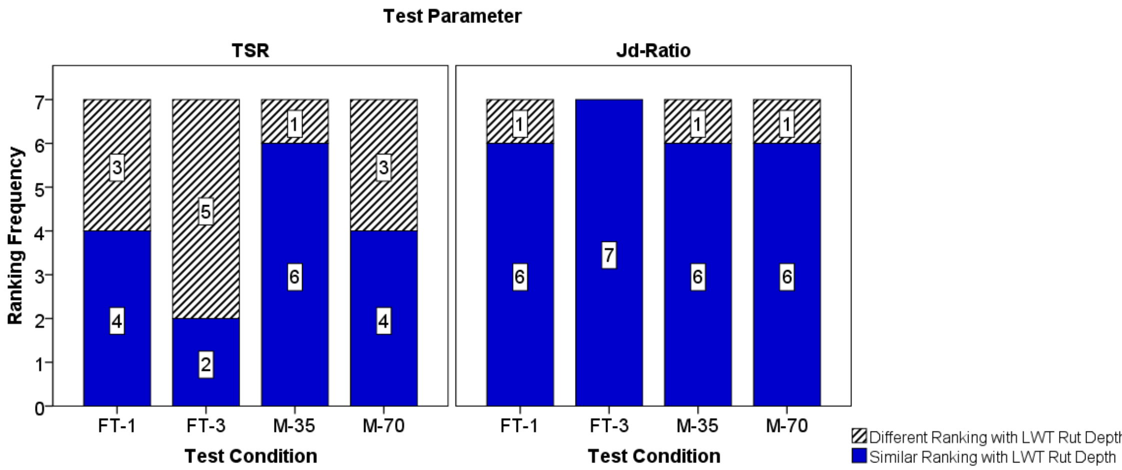
Table 10. Moisture damage test protocol and failure criteria

Mix ID	Test (Failure Criteria)	Control	FT-1	FT-3	M-35	M-70
M1	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Fail	Fail	Fail	Fail	Fail
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Pass	Fail	Pass
	SCB (J_d-ratio ≥ 90%)	NA	Fail	Fail	Fail	Fail
M2	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Pass	Fail	Fail	Fail	Fail
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Pass	Fail*	Fail*
	SCB (J_d-ratio ≥ 90%)	NA	Pass	Fail	Fail*	Fail*
M3	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Fail	Fail	Fail*	Fail*	Fail*
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Fail*	Fail*	Fail*
	SCB (J_d-ratio ≥ 90%)	NA	Fail	Fail*	Fail*	Fail*
M4	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Pass	Pass	Fail	Fail	Fail
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Pass	Pass	Pass
	SCB (J_d-ratio ≥ 90%)	NA	Pass	Fail	Fail	Fail
M5	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Pass	Pass	Fail	Pass	Pass
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Pass	Pass	Pass
	SCB (J_d-ratio ≥ 90%)	NA	Pass	Fail	Pass	Fail
M6	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Pass	Pass	Fail	Pass	Fail
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Fail	Pass	Pass
	SCB (J_d-ratio ≥ 90%)	NA	Pass	Fail	Fail	Fail
M7	HWT (Rut ≤ 6mm @ 20,000 passes)[a]	Pass	Pass	Fail	Pass	Fail
	Modified Lottman (TSR ≥ 80%)	NA	Pass	Pass	Pass	Fail
	SCB (J_d-ratio ≥ 90%)	NA	Pass	Fail	Pass	Fail

[a] DOTD specified minimum rut depth for Level 2 mixture; * Specimen damaged during conditioning; HWT = Hamburg Wheel-Tracking Test; TSR = tensile strength ratio; FT-1 = single freeze-thaw cycle; FT-3 = triple freeze-thaw cycle; M-35 = 3500 MiST cycles; M-70 = 7000 MiST cycles

Figure 18 compares the moisture susceptibility ranking capabilities of the SCB J_d-ratio and TSR parameters to the HWT rut depth parameter. These two parameters were compared to HWT rut depth to determine the frequency with which they exhibited similar or different moisture susceptibility rankings ("pass/fail") for the four conditioning levels (FT-1, FT-3, M-35, and M-70). Among the mixtures evaluated and conditioning levels considered, the SCB J_d-ratio exhibited similar rankings to HWT rut depth in 89% (25 of 28) of the comparisons. However, the TSR parameter showed similar rankings in only 57% (16 of 28) of the comparisons. This observation suggests that the SCB test may be a viable alternative to the HWT test for characterizing the moisture susceptibility of asphalt mixtures subjected to different conditioning levels.

Figure 18. Similarity of ranking between test protocols



Evaluating the Effectiveness of Anti-Strip Additives Using HWT and ML Tests

This section summarizes laboratory test data assessing the effectiveness of the HWT and ML tests in capturing the moisture damage resistance of asphalt mixtures containing various anti-strip additives and asphalt binder types. These mixtures were subjected to FT-3 and M-70 conditioning protocols. The asphalt mixtures were prepared using two asphalt binder types (unmodified PG 67-22 and SBS-modified PG 70-22) that meet Louisiana's Standard Specifications for Roads and Bridges [67], a single aggregate type (semi-crushed gravel), and three additive variations: no additive (control mixture), an amine-based liquid anti-strip additive (AM), and a chemical WMA.

The coefficient of variation (CoV), a measure of data variability, for HWT rut depth values ranged from 12-17%, with an average of 14%, for asphalt mixtures containing PG 67-22 binder and from 7-24%, with an average of 16%, for those containing PG 70-22 binder. Similarly, the CoV for ITS values ranged from 2-10%, with an average of 5%, for PG 67-22 mixtures and from 1-6%, with an average of 4%, for PG 70-22 mixtures. Further, the standard deviation, a measure of the level of test variability across test replicates, was recorded as error bars in the results presented in subsequent sections of this paper. The following sections examine the effects of different liquid anti-strip additives, moisture conditioning protocols, and asphalt binder types on the moisture damage resistance of asphalt mixtures using results obtained from the HWT and ML tests. For each test parameter measured, the average values were plotted on bar graphs, with standard deviation error bars representing the variability across test replicates.

Effect of Different Liquid Anti-Strip Additives

HWT Test Results

Figure 19 presents the HWT rut depth values at 20,000 passes for asphalt mixtures containing PG 67-22 asphalt binder and different additives. The unconditioned (UC) asphalt mixtures containing AM and WMAs showed a significant increase in rut depths compared to the control asphalt mixture without additive. Additionally, the unconditioned asphalt mixture containing the WMA exhibited stripping failure after 15,500 load passes. Asphalt mixtures containing NA and WMAs, when subjected to FT-3 conditioning, exhibited significantly higher rut depth values and earlier stripping failure (i.e., lower SIP values) compared to the asphalt mixture containing the AM additive. All asphalt mixtures subjected to MT 7000 moisture conditioning showed similarly high rut depth values and experienced stripping failure at 12,000, 10,000, and 8,000 passes for asphalt mixtures containing NA, AM, and WMAs, respectively. These observations suggest that moisture damage increased progressively from the unconditioned (UC) to the FT-3 and then to the MT 7000 conditioned specimens. Additionally, the use of the AM and WMAs in PG 67-22 asphalt mixtures had an insignificant impact on moisture damage resistance under both dry (UC) and FT-3 conditioning. It is noted that the use of the AM additive under FT-3 moisture conditioning resulted in reduced rutting and no stripping failure, implying its potential effectiveness in mitigating mild moisture damage.

Figure 19. HWT test results for asphalt mixtures containing PG 67-22 asphalt binder and different additives

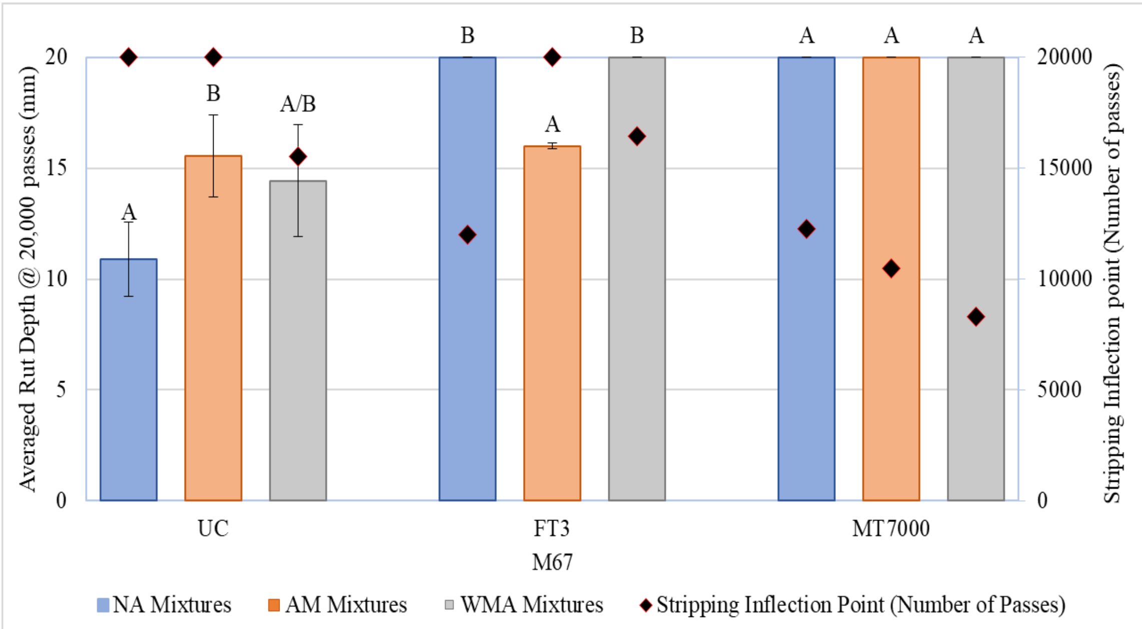
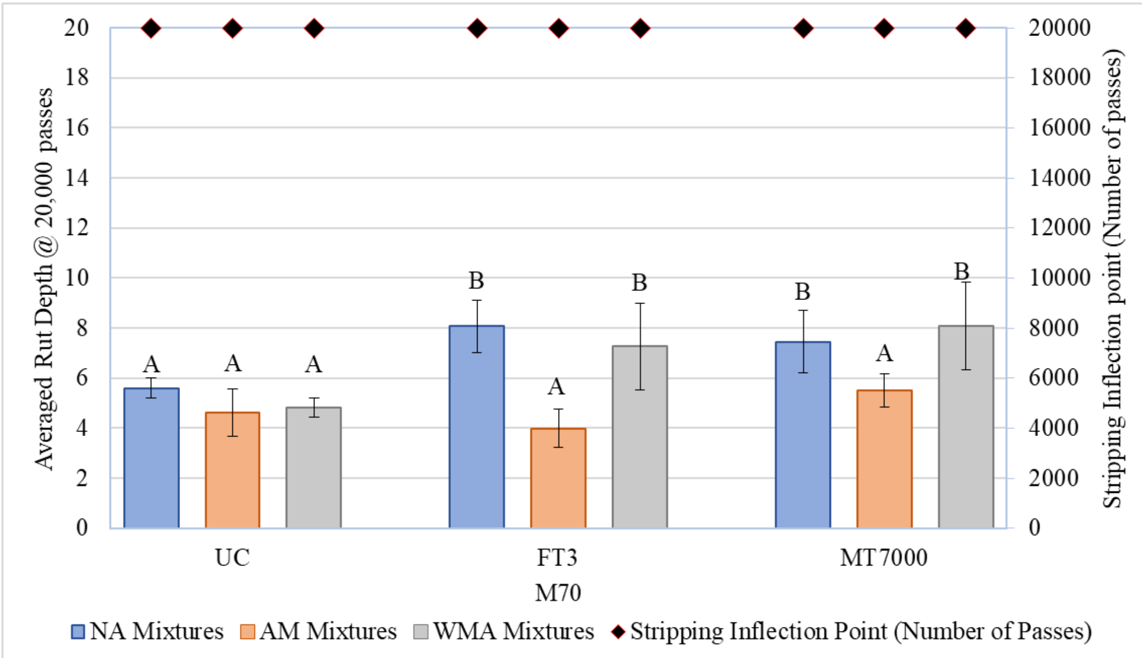


Figure 20 presents the HWT rut depth values at 20,000 passes for asphalt mixtures containing PG 70-22 asphalt binder and different additives. The UC asphalt mixtures showed similar HWT rut depth values, regardless of the anti-strip additive (UC, AM, and WMA) employed. However, PG 70-22 asphalt mixtures containing the AM additive exhibited significantly better rutting resistance (i.e., lower rut depth values) under FT-3 and MT 7000 conditioning compared to their corresponding UC and WMA asphalt mixtures. Notably, none of the PG 70-22 asphalt mixtures across all additives and conditioning levels experienced stripping failure. These observations suggest that incorporating AM additive into PG 70-22 asphalt mixtures significantly improved moisture damage resistance, while WMA had no such effect, corroborating previous research findings [59, 63].

Figure 20. HWT test results for asphalt mixtures containing PG 70-22 asphalt binder and different additives



ML Test Results

Figure 21 presents the ITS and TSR values obtained from the ML test for asphalt mixtures containing PG 67-22 asphalt binder and different additives. Under dry conditions, asphalt mixtures prepared with the three additives (NA, AM, and WMA) exhibited similar ITS values. After subjecting the test specimens to FT-3 conditioning, the asphalt mixture containing AM additive showed the highest ITS and TSR values compared to the NA and WMA asphalt mixtures. However, the NA and WMA asphalt mixtures showed equivalent moisture damage resistance after FT-3 conditioning. This observation suggests that asphalt mixtures containing the AM additive are more effective at minimizing moisture damage than those containing the WMA under freeze-thaw conditions. Following MT 7000 conditioning, all asphalt mixtures showed similar moisture damage performance, and all of the PG 67-22 asphalt mixtures exhibited significantly similar moisture damage resistance, as measured by the ITS values, suggesting that the effects of anti-strip additives become insignificant under severe moisture conditioning.

Figure 21. ML test results for asphalt mixtures containing PG 67-22 asphalt binder and different additives

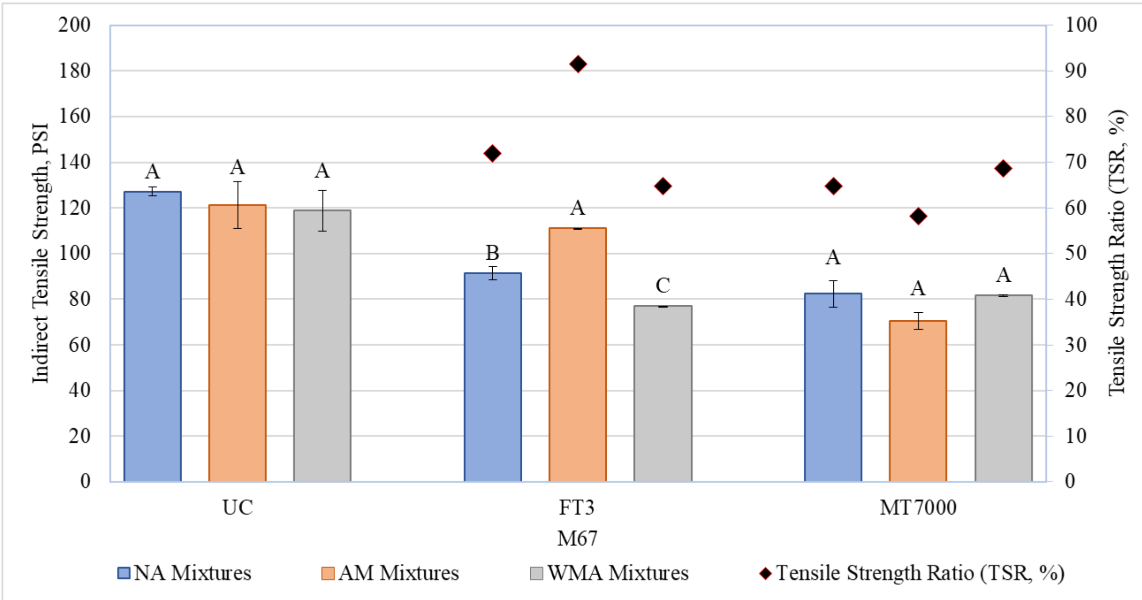
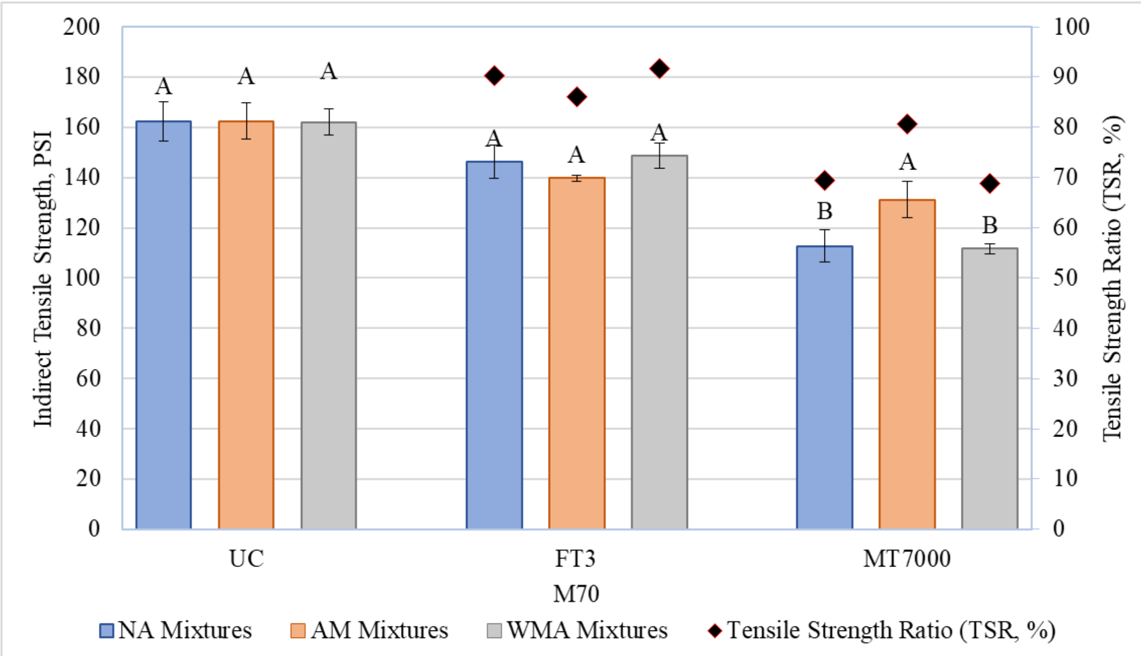


Figure 22 presents the ITS and TSR values obtained from ML tests conducted on the PG 70-22 asphalt mixtures prepared using different additives (NA, AM, and WMA). Under dry conditions, the three asphalt mixtures (NA, AM, and WMA) exhibited significantly similar ITS values. Similarly, asphalt mixtures subjected to FT-3 conditioning exhibited similar ITS values and TSR values above 80%, regardless of the additive type used. However, following MT 7000 conditioning, the asphalt mixture containing AM additive exhibited higher ITS and TSR values than the NA and AM asphalt mixtures. These observations imply that AM additive improved asphalt mixture resistance to moisture damage, while WMA promoted insignificant improvement.

Figure 22. ML test results for asphalt mixtures containing PG 70-22 asphalt binder and different additives



Effect of Moisture Conditioning Protocols

HWT Test Results

Figure 23 presents the HWT rut depth values at 20,000 passes for the PG 67-22 asphalt mixtures subjected to different moisture conditioning protocols. As expected, the FT-3 and MT 7000 conditioning of the NA asphalt mixtures significantly increased the rut depth compared to their unconditioned counterparts. Additionally, the two conditioned protocols induced stripping failure after 12,000 passes, whereas the unconditioned asphalt mixture showed no sign of stripping failure after 2,000 passes. MT 7000 conditioning of the AM asphalt mixtures significantly increased the rut depth compared to the UC and FT-3 conditioning. Further, MT 7000 conditioning induced stripping failure in the AM asphalt mixtures at 10,500 passes, whereas the UC and FT-3 conditioned AM asphalt mixtures exhibited no signs of stripping. This observation suggests that MT 7000 conditioning is more severe than FT-3 conditioning. For the WMA asphalt mixtures, stripping failure occurred at approximately 16,000 passes for both UC and FT-3 conditioned asphalt mixtures, while MT 7000 conditioning led to earlier stripping failure after only 8,300 passes. These findings confirm observations made in previous studies that the severity of moisture damage, as measured by the HWT test, increases with increasing conditioning levels from UC to FT-3 and then the MT 7000 [79].

Figure 23. HWT test results for asphalt mixtures containing PG 67-22 at different moisture conditioning protocols

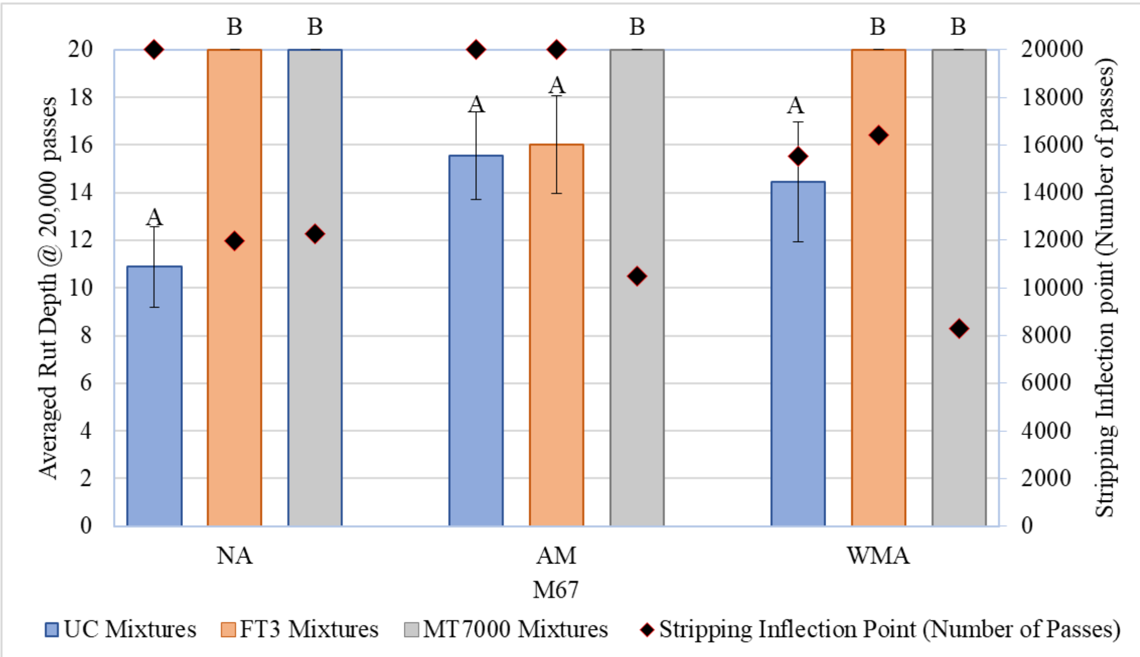
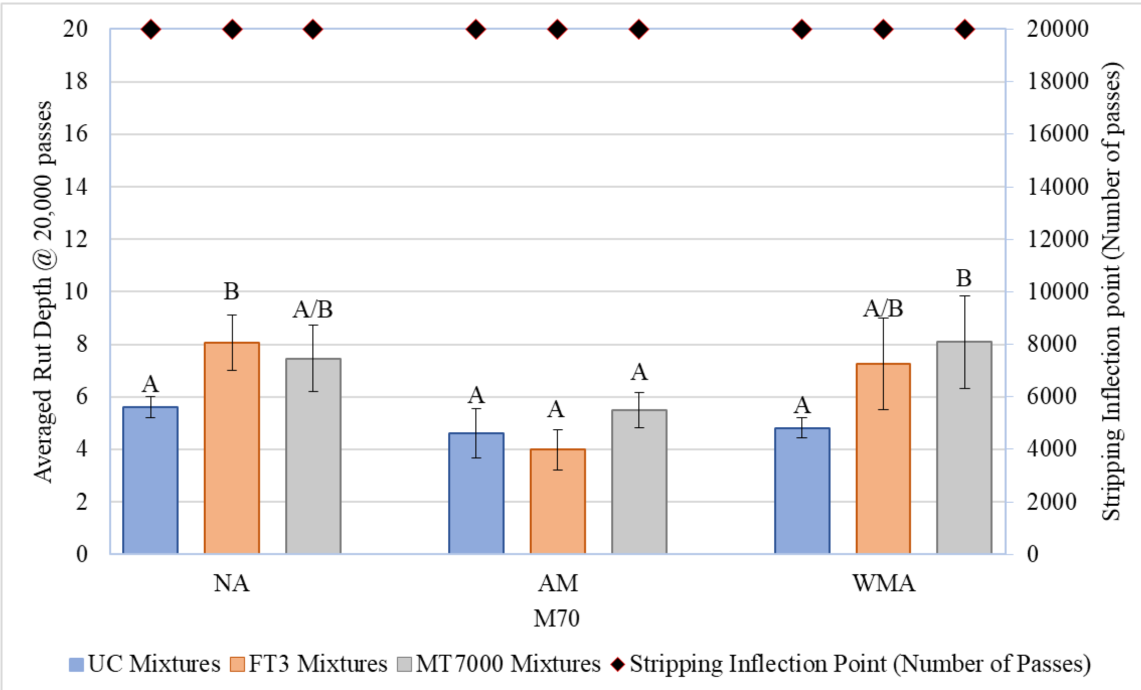


Figure 24 presents the HWT rut depth values at 20,000 passes for the PG 70-22 asphalt mixtures subjected to different moisture conditioning protocols. As expected, both FT-3 and MT 7000 conditioning significantly increased rut depth in additive-free (NA) asphalt mixtures compared to their unconditioned counterparts. Moisture conditioning of the AM asphalt mixture did not significantly influence the rut depth for the PG 70-22 asphalt mixtures. Further, under similar moisture conditioning protocols, the PG 70-22 asphalt mixtures containing AM additive exhibited lower rut depth values than their counterpart NA and WMA asphalt mixtures. Additionally, none of the PG 70-22 asphalt mixtures studied exhibited stripping failure. These observations further suggest that the AM additive effectively resisted moisture damage compared to the WMA.

Figure 24. HWT test results for asphalt mixtures containing PG 70-22 asphalt binder at different moisture conditioning protocols



ML Test Results

Figure 25 presents the ITS and TSR values obtained from the ML test conducted on PG 67-22 asphalt mixtures subjected to different moisture conditioning protocols. The MT 7000 and FT-3 conditioning of each of the PG 67-22 asphalt mixtures resulted in a significant decrease in the ITS and TSR values. These observations indicate that as the moisture conditioning severity of the PG 67-22 asphalt mixtures increased from UC to FT-3 to MT 7000, the ITS and TSR values decreased, rendering the asphalt mixtures more susceptible to moisture damage. It is worth noting that ITS values slightly decreased for unconditioned PG 67-22 mixtures when AM and WMA additives were incorporated. However, AM-modified PG 67-22 mixtures exhibited higher ITS and TSR values after FT-3 conditioning compared to their unconditioned counterpart. Additionally, WMA-modified PG 67-22 mixtures showed comparable ITS values but higher TSR values after MT 7000 conditioning compared to their unconditioned counterpart. These improvements in TSR values are counterintuitive and inconsistent with the results obtained from the HWT test; see Figure 24. This discrepancy could suggest that TSR may not be the most reliable indicator of moisture damage, as reported in previous studies [21, 27].

Figure 25. ML test results for asphalt mixtures containing PG 67-22 asphalt binder at different moisture conditioning protocols

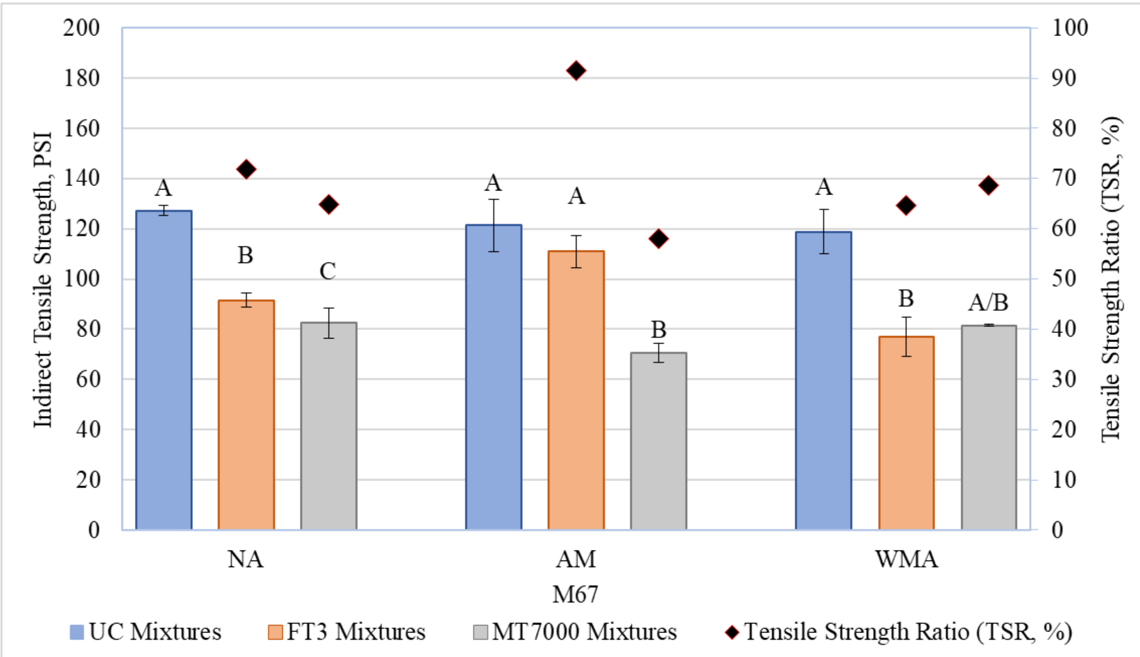
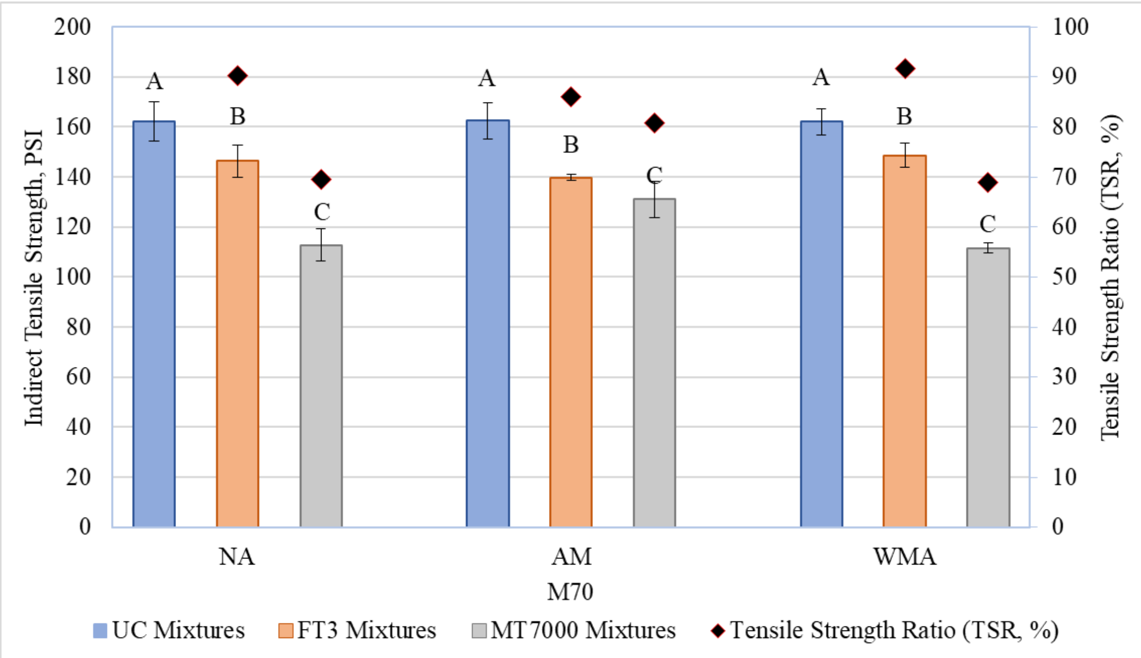


Figure 26 presents the ITS and TSR values for PG 70-22 asphalt mixtures subjected to different moisture conditioning protocols. Like the PG 67-22 asphalt mixtures, the MT 7000 and FT-3 conditioning of the PG 70-22 asphalt mixtures significantly decreased the ITS and TSR values. These observations are consistent with observations made in the PG 67-22 asphalt mixtures and findings from previous studies [79].

Figure 26. ML test results for asphalt mixtures containing PG 70-22 asphalt binder at different moisture conditioning protocols

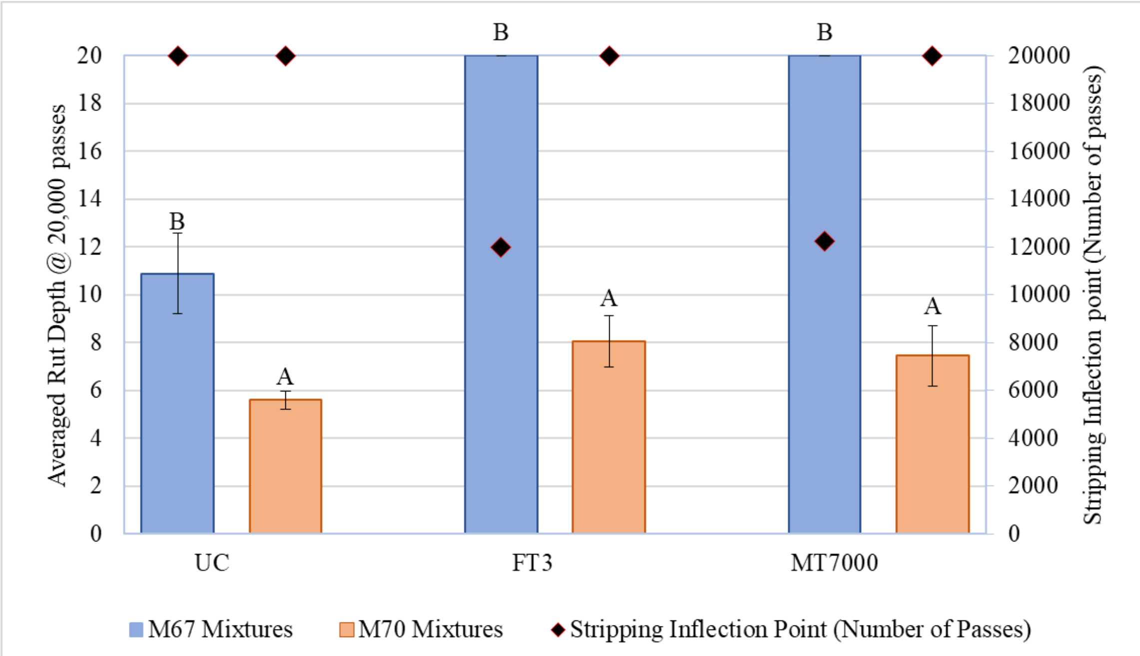


Effect of Different Asphalt Binder Types

HWT Test Results

Figure 27 presents the HWT rut depth values at 20,000 passes for the control PG 67-22 and PG 70-22 asphalt mixtures subjected to different moisture conditioning protocols. While no stripping failure was observed in asphalt mixtures containing PG 70-22 binder, asphalt mixtures containing PG 67-22 binder experienced stripping failure after 12,000 passes after being subjected to FT-3 and MT 7000 conditioning protocols. These observations suggest that SBS modification of asphalt mixtures has the potential to enhance moisture damage resistance.

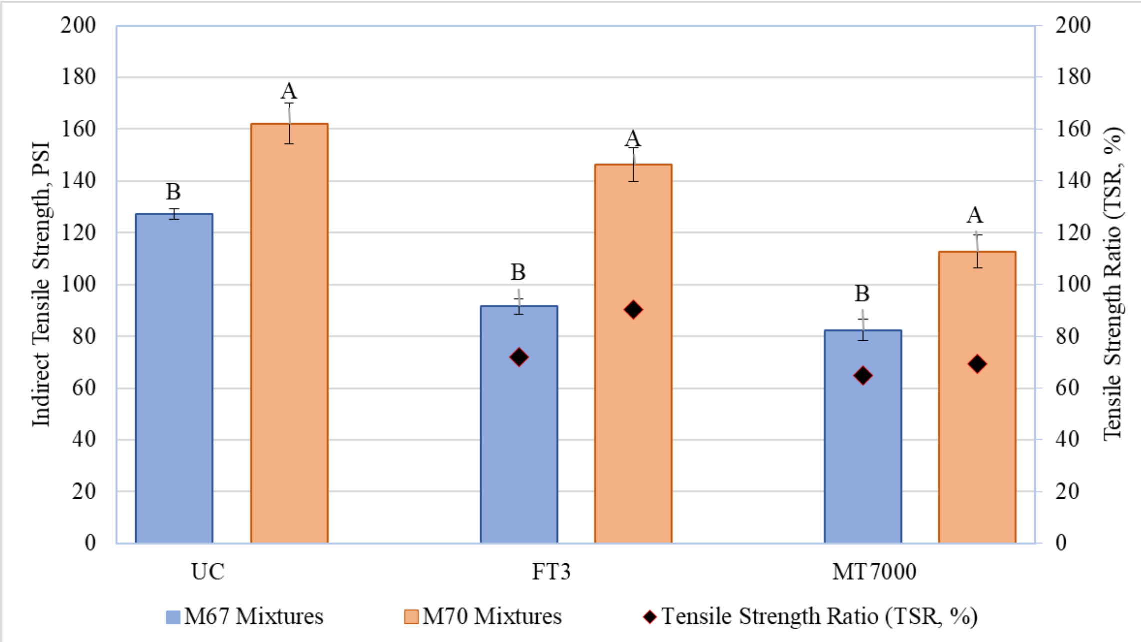
Figure 27. HWT test results for asphalt mixtures containing different asphalt binders



ML Test Results

Figure 28 presents the ITS and TSR values obtained from the ML test conducted on the PG 67-22 and PG 70-22 asphalt mixtures under FT-3 and MT 7000 moisture conditioning. The ITS and TSR values for all the asphalt mixtures containing PG 70-22 were higher than those containing PG 70-22 asphalt binder. This observation is attributable to the improved moisture resistance resulting from the SBS modification of the PG 70-22 asphalt binder.

Figure 28. ML test results for asphalt mixtures containing different asphalt binders



Summary of Laboratory Mechanical Test Parameters

Table 11 shows a summary of laboratory mechanical test parameters (HWT rut depth and TSR) and their corresponding thresholds for characterizing moisture damage resistance in asphalt mixtures. Asphalt mixtures meeting the criteria are classified as "pass," whereas asphalt mixtures that failed to meet the criteria are classified as "fail." Asphalt mixtures containing PG 67-22 asphalt binder failed to meet both HWT and TSR parameters' criteria, except for one asphalt mixture containing AM additive and subjected to FT-3 conditioning that passed the TSR criteria. By contrast, asphalt mixtures containing PG 70-22 asphalt binder passed the HWT and TSR parameters' criteria, with the exception of the asphalt mixtures containing additives (NA and WMA) and subjected to MT 7000 conditioning, which failed to meet the TSR criteria. These findings demonstrate that asphalt mixtures containing PG 70-22 asphalt binder exhibit better resistance to moisture damage than those containing PG 67-22 asphalt binder, even with the addition of anti-strip additives. Asphalt mixtures containing the AM additive exhibited higher resistance to moisture damage compared to those containing NA and WMAs. Asphalt mixtures containing NA and WMA additives achieved comparable moisture damage resistance. Additionally, the MT 7000 conditioning protocol induced more severe moisture damage than the FT-3 conditioning protocol. Further, the HWT test results were generally found to be consistent with the ML test results

Table 11. Summary of mixture test results and performance criteria

Mix ID	Test (Performance Pass Criteria)	UC	FT-3	MT-7000
M67NA	HWT (rut depth <= 10mm @ 20,000 passes)	Fail	Fail	Fail
	ML (TSR >= 80%)	NA	Fail	Fail
M67AM	HWT (rut depth <= 10mm @ 20,000 passes)	Fail	Fail	Fail
	ML (TSR >= 80%)	NA	Pass	Fail
M67WMA	HWT (rut depth <= 10mm @ 20,000 passes)	Fail	Fail	Fail
	ML (TSR >= 80%)	NA	Fail	Fail
M70NA	HWT (rut depth <= 10mm @ 20,000 passes)	Pass	Pass	Pass
	ML (TSR >= 80%)	NA	Pass	Fail
M70AM	HWT (rut depth <= 10mm @ 20,000 passes)	Pass	Pass	Pass
	ML (TSR >= 80%)	NA	Pass	Pass
M70WMA	HWT (rut depth <= 10mm @ 20,000 passes)	Pass	Pass	Pass
	ML (TSR >= 80%)	NA	Pass	Fail

UC: unconditioned asphalt mixtures; FT-3: three freeze-thaw cycles conditioning protocols for asphalt mixtures; MT7000: 7000 cycles of Moisture-induced Stress Tester conditioning protocol for asphalt mixtures; M67: asphalt mixtures containing PG 67-22 asphalt binder; M70: asphalt mixtures containing PG 70-22 asphalt binder; NA: not additive; AM: amine-based liquid anti-strip additive; WMA: chemical warm mix additive; NA: not applicable.

Conclusions

The objective of this study was to develop a reliable test procedure to consistently assess the moisture-induced damage resistance of asphalt mixtures. To fulfill the objectives of this study, 13 asphalt mixtures were prepared, including one plant-produced mixture and 12 laboratory-compacted mixtures. Two asphalt binder types (unmodified PG 67-22 and polymer-modified PG 70-22) and three aggregate types (limestone, crushed gravel, and semi-crushed gravel) with varying water absorption levels were utilized. Additionally, two anti-strip additives (amine-baesd and chemical WMA) were incorporated into selected mixtures to assess their ability to mitigate moisture damage. To evaluate the impact of moisture conditioning, asphalt binders and mixtures were subjected to five conditioning levels: control, a single freeze-and-thaw cycle (FT-1), a triple freeze-and-thaw cycle (FT-3), 3500 Moisture-induced Stress Tester cycles (MiST 3500), and 7000 Moisture-induced Stress Tester cycles (MiST 7000). Asphalt binders were evaluated using frequency sweep, Multiple Stress Creep Recovery (MSCR), and binder bond strength (BBS) tests. Loose asphalt mixture samples were subjected to the boil test, then evaluated using the Asphalt Compatibility Tester (ACT). To assess mixtures' moisture damage resistance, the Modified Lottman (ML), Hamburg Wheel-Tracking (HWT), and Semi-Circular Bend (SCB) tests were utilized.

Freeze-thaw and MiST conditioning increased binder stiffness compared to RTFO-aged binders. Both PG 67-22 and PG 70-22 asphalt binders experienced a slight reduction in stress sensitivity due to increased stiffness from moisture conditioning. Overall, the results suggest that the aggregate type, binder grade, and conditioning level all have a significant impact on the failure type (adhesive or cohesive) of the BBS test specimens. Limestone aggregates generally exhibited higher BBS values with cohesive failure, while gravel aggregate showed lower BBS values with mixed failure types. Polymer-modified binders exhibited higher BBS values, and conditioning can significantly reduce the BBS value and increase susceptibility to adhesive failure.

For the mixtures, freeze-thaw and MiST conditioning levels increased rut depth compared to the control condition. These conditioning levels were effective in exposing moisture-sensitive mixtures that initially complied with Louisiana DOTD specifications, per AASHTO T 324. Therefore, incorporating a moisture conditioning protocol into AASHTO T 324 is recommended to better assess moisture susceptibility. Regarding the impact of polymer modification on moisture damage resistance, SBS polymer-modified PG 70-22 asphalt mixtures exhibited lower rut depth and higher ITS values without stripping damage, while unmodified PG 67-22 asphalt binder showed higher rut depth and reduced ITS values, as well as stripping damage, with increasing moisture conditioning. The HWT rut depth and SCB J_d-ratio parameters effectively captured changes in moisture damage associated with progressive conditioning levels and improved the moisture damage resistance of mixtures containing SBS polymer-modified PG 70-22 asphalt binder and anti-strip additives. The following sections present specific observations made from this study.

Impact of Conditioning on Asphalt Binder Properties and Mixture Performance as Measured by HWT Test

- Generally, rut factor values for unmodified PG 67-22 asphalt binders increased with an increased level of freeze-thaw and MiST conditioning.
- Freeze-thaw and MiST conditioning had no effect on the rut factor of SBS-modified PG 70-22 asphalt binders.
- PG 67-22 asphalt binder exhibited a higher increase in stiffness from RTFO for each conditioning level compared to PG 70-22 asphalt binder.
- Freeze-thaw (FT-1 and FT-3) and MiST (M-35 and M-70) conditioning resulted in a minimal *Jnr* decrease and *R* increase compared to RTFO-conditioned asphalt binder.
- Two clusters for each binder type were identified in the MSCR elastic response curve: PG 70-22 in the passing zone, and PG 67-22 in the failed zone. For the two clusters of asphalt binders in Figure 5c, freeze-thaw (FT-1 and FT-3) and MiST (MiST 3500 and MiST 7000) conditioning had no effect on the capability of the asphalt binder to meet the delayed elastic response criteria.
- Polymer-modified binders (PG 76-22 and PG 70-22) exhibited higher pull-off strength (BBS) values than unmodified binders (PG 67-22).
- Limestone aggregates exhibited higher pull-off strength and predominantly cohesive failure compared to gravel aggregates, indicating better moisture damage resistance.
- Moisture conditioning (MIST and freeze-thaw) decreased pull-off strength and increased the proportion of adhesive failures, indicating increased potential for moisture-induced damage.
- MIST conditioning effectively simulated moisture damage mechanisms observed in the field.

- An increase in conditioning level (e.g., FT-1 to FT-3, M-35 to M-70) resulted in a significant increase in rut depth.
- The addition of anti-strip additive in M7 improved the moisture damage resistance compared to M1 at all conditioning levels evaluated.
- Progressive increase in MiST conditioning from 3500 to 7000 cycles yielded an increase in the stripping and viscoplastic rut components for M1 and M7.
- For certain mixtures with higher rut depths, total rut depth could not be separated into stripping and viscoplastic components due to the sudden disintegration of these mixtures within a few cycles of wheel passes.

Evaluation of Different Moisture Conditioning and Testing Protocols for Asphalt Mixtures

- TSR parameter was not effective in capturing the moisture susceptibility of asphalt mixtures subjected to different conditioning levels, with the exceptions of M2 (M-35, M-70) and M3 (FT-1, M-35, M-70), which were damaged during conditioning.
- An increase in conditioning level (e.g., FT-1 to FT-3, M-35 to M-70) resulted in a decrease in moisture resistance as measured by the SCB J_d and HWT rut depth of asphalt mixtures evaluated.
- Generally, the TSR parameter did not correlate with the other laboratory performance ratios evaluated.

Evaluating the Effectiveness of Anti-Strip Additives Using HWT and ML Tests

- The HWT and ML tests demonstrated their ability to evaluate and capture the moisture damage susceptibility of asphalt mixtures containing different anti-strip additives and subjected to different conditioning protocols. Additionally, the HWT test was able to evaluate asphalt mixtures' resistance to rutting, and the ML test was able to distinguish asphalt mixtures' tensile strength.

- Asphalt mixtures containing PG 70-22 asphalt binder exhibited superior moisture damage performance compared to those containing unmodified PG 67-22 asphalt binder, even when anti-strip additives were used.
- The AM additive enhanced the asphalt mixture's resistance to moisture damage compared to the control mixture without additives. However, the asphalt mixture containing WMA showed comparable moisture damage resistance to the control mixture.
- The MT-7000 moisture conditioning protocol induced more severe moisture damage to the asphalt mixtures evaluated compared to the FT-3 conditioning protocol.

Recommendations

Based on the findings of this study, the following recommendations are made:

- **Moisture Conditioning.** Since increased binder stiffness associated with moisture conditioning did not necessarily translate to improved moisture resistance in the conditioned asphalt mixtures, agencies should rely on asphalt binder and mixture conditioning to accurately assess moisture susceptibility. An appropriate conditioning protocol (FT-3, MiST 3500, or MiST 7000) should be included in the AASHTO T 324 protocol to better assess moisture susceptibility.
- **Test Methods.** The SCB J_d-ratio parameter, determined from the SCB test, is recommended as an alternative to HWT rut depth for moisture damage evaluation. To further understand the failure mechanisms, the atomic force microscopy test is recommended to estimate the extent of cohesive and adhesive failure in mixtures due to moisture damage.
- **Anti-Strip Additives.** The increase in rut depth associated with AM and WMA additives, as measured in the HWT test, is concerning. Agencies should assess the potential negative impact of these anti-strip additives on rutting resistance during the mixture design stage before incorporating them into mixtures. Given the widespread use of anti-strip additives in Louisiana, field studies are recommended to validate their potential positive and negative impacts.

Acronyms, Abbreviations, and Symbols

Term	**Description**
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Content
ASTM	American Society for Testing and Materials
BBR	Bending Beam Rheometer
BC	Binder Course
°C	degree(s) Celsius
cm	centimeter(s)
DOTD	Louisiana Department of Transportation and Development
°F	degree(s) Fahrenheit
FHWA	Federal Highway Administration
ft.	foot (feet)
G_{mm}	Theoretical maximum specific gravity
HMA	Hot Mix Asphalt
HWT	Hamburg Wheel-Tracking
Hz	Hertz
IDT|E*|	Indirect Tensile Dynamic Modulus
in.	inch(es)
J_c	Critical Strain Energy Release Rate
JMF	Job mix formula
kJ	Kilojoule
kPa	Kilopascal
ksi	Kilopound force per square inch
lb.	pound(s)
LTRC	Louisiana Transportation Research Center
m	meter(s)
MTV	Material Transfer Vehicle
mm	millimeter(s)
mm/min.	millimeter(s) per minute

Term	**Description**
N	Newton
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
Pa	Pascal
PAV	Pressure Aging Vessel
PG	Performance Grade
PQI	Pavement Quality Indicator
RAP	Reclaimed Asphalt Pavement
RTFO	Rolling Thin-Film Oven
SCB	Semi-Circular Bend
TSR	Tensile strength ratio
WC	Wearing Course

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Appendix

Table 12. Job mix formula for asphalt mixtures M1 to M7

Properties	M1	M2	M3	M4	M5	M6	M7	DOTD Specs
%G_{mm} at N_{ini}	88.1	89.2	87.9	88.1	89.2	87.9	88.9	≤ 90
%G_{mm} at N_{max}	96.3	97.4	94.2	96.3	97.4	94.2	97.9	≤ 98
Air Voids %	4.0	3.8	3.5	4.0	3.8	3.5	3.7	2.5 - 4.5
VMA %	14.0	13.9	13.9	14.0	13.9	13.9	13.9	≥ 13.5
VFA %	71	74	75	71	74	75	74	69 -80
AC %	4.9	5.7	5.6	4.9	5.7	5.6	5.1	-
Sieve Size, % Passing	Gradation							
19.0 mm	100	100	100	100	100	100	100	100
12.5 mm	95	95	92	95	95	92	93	90 -100
9.5 mm	79	88	79	79	88	79	82	≤89
4.75 mm	50	65	49	50	65	49	49	
2.36 mm	32	46	31	32	46	31	36	29-58
1.18 mm	21	35	20	21	35	20	28	
0.600 mm	15	28	14	15	28	14	22	
0.300 mm	11	16	12	11	16	12	14	
0.150 mm	8	9	8	8	9	8	7	
0.075 mm	5	6	6	5	6	6	5	4.0 -10.0

N_i: initial number of gyrations; N_f – final Number of gyrations; %*Gmm* - % maximum specific gravity of the asphalt mix; AV, VMA, VFA – air voids, voids in mineral aggregates, voids filled with asphalt.

Table 13. Job mix formula for anti-strip modified mixtures

Asphalt Mixture Designation*		M67NA	M67AM	M67WMA	M70NA	M70AM	M70WMA	DOTD (*27*)
Asphalt binder type		PG 67-22			PG 70-22			N/A
Total AC content, %		5.6			5.6			N/A
Aggregate blend	**Gravel #57, %**	86%			86%			N/A
	Coarse Sand, %	2.0			2.0			N/A
	Fine Sand, %	12.0			12.0			N/A
Anti-strip Additives	**AM, %**	N/A	0.6	N/A	N/A	0.6	N/A	N/A
	WMA, %	N/A	N/A	0.25	N/A	N/A	0.25	N/A
Design volumetric properties	**%G_{mm}, Ni**	88.7	90.0	89.9	88.7	90.0	89.9	≤ 91
	%G_{mm}, Nf	97.9	97.9	97.7	97.9	97.9	97.7	≤ 98
	AV, %	3.6	3.4	3.5	3.6	3.4	3.5	2.5-4.5
	VMA, %	13.7	13.6	13.9	13.7	13.6	13.9	≥ 13.5
	VFA, %	72.5	75.2	74.7	72.5	75.2	74.7	72-80
Effective AC Content, %		4.5	4.5	4.5	4.5	4.5	4.5	N/A
D:B		1.2	1.2	1.2	1.2	1.2	1.2	0.6-1.6

*M67: asphalt mixture contain unmodified PG 67-22 asphalt binder; M70: asphalt mixture contains SBS-modified PG 70-22 asphalt binder; AC: asphalt cement; NA – no additives, AM – amine-based liquid anti-strip additive, WMA – chemical warm mix additive; N_i: initial number of gyrations; N_f – final number of gyrations; %*Gmm* - % maximum specific gravity of the asphalt mix; AV, VMA, VFA – air voids, voids in mineral aggregates, voids filled with asphalt; D:B – dust to binder ratio, N/A: not available