Identification of Enhanced Moisture Susceptibility Testing for Asphalt Pavements

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16. Abstract

The Tensile Strength Ratio (TSR) test is the most widely used test by state agencies based on a survey and specification review. The next most widely used test is the Hamburg Wheel-Track Test (HWTT). The survey also found there has been a move from the TSR test to the HWTT by state agencies over the last 10 years.

Limited TSR and HWTT testing for this proejct was inconclusive. Detachment or displacement of the binder from the aggregate was not visible on the TSR samples indicating other factors are affecting the tests. Potential factors could include PPA modified asphalt binder, dust, low AC content, porosity of the coarse aggregate, stripping of the fine aggregate, etc.

LCCA evaluation showed the use of antistrip additives had a small impact on the cost of rehabilitation activities, and therefore it is justified to require the use of antistrip additives when the moisture susceptibility potential of the aggregates is unknown or when it is known the aggregates are susceptible to moisture.

The following are the recommendations of the research team:

- *The TSR test may not be able to accurately capture the moisture susceptibility in the field. In addition, in Ohio, the correlation between contractor tested and ODOT tested TSR specimens for the same mix is low. The use of Supplement 1051 (AASHTO T 283) to determine moisture susceptibility should be discontinued.*
- *It is recommended ODOT move forward with implementation of the HWTT AASHTO T 324-22 test procedure using 15,000 as the SIP limiting criterion. The ratio between the stripping slope and creep slope should be 2.0 or greater for the SIP to be valid.*
- *In many cases, samples tested at 50°C exceeded 12.5 mm rutting limitations in fewer passes than the 15,000 SIP criteria. Therefore, a test temperature of 45°C is recommended.*
- *The LCCA evaluation showed the use of antistrip additives had a small impact on the cost of rehabilitation activities ($704 per lane mile), and therefore it is justified to require the use of antistrip additives when the moisture susceptibility potential of the aggregates is unknown or when it is known the aggregates are susceptible to moisture.*

17. Key Words
Asphalt concrete, moisture susceptibility, stripping, antistripping agents, tensile strength ratio, asphalt testing

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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Final Report

September 2023

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1 Project Background

Moisture damage is a major distress in asphalt pavements, characterized by the loss of adhesion between the asphalt and aggregate (stripping) and/or the loss of cohesion within the asphalt binder in the presence of water. There are a number of factors which influence moisture susceptibility of asphalt mixtures, including asphalt binder and aggregate characteristics, environmental factors, and stripping mechanisms such as displacement, detachment, spontaneous emulsification, build-up pore pressure, and hydraulic scouring [Lytton et al, 2005; Kanitpong and Bahia, 2005].

Over the years, efforts have been made to identify test procedures with appropriate moisture conditioning methods to quantify the potential of moisture susceptibility in asphalt mixtures. Some of the most commonly used test procedures include Modified Lottman Test (AASHTO T 283), Hamburg Wheel-Track Test (HWTT) (AASHTO T 324), and visual strip rating tests conducted on loose mix such as Boiling Test (ASTM D3625). Moisture conditioning methods include hot water bath, freeze-thaw conditioning, moisture-induced stress tester (MIST), and others. However, there is no agreement on how these various tests assess the probability moisture damage will occur. In addition, to reduce the effects of moisture damage, some state DOTs required the use of antistripping agents including liquid antistrip (LAS) additives and hydrated lime, but reliable laboratory tests are still needed to insure acceptable improvement in resistance to moisture damage is achieved.

The Ohio Department of Transportation (ODOT) has been proactive to address potential moisture susceptibility issues in asphalt mixtures by incorporating testing procedures during the mix design phase. However, multiple pavements in Ohio have shown stripping problems, particularly in areas where lower quality sources of aggregates are used and where tree canopies are prevalent. Therefore, there is a need to identify and/or refine mix test procedures which can provide results corresponding to in-place performance. In addition, ODOT needs guidance regarding the use of antistrip agents to determine if their use is a cost-effective solution to their current stripping problems.

This report consists of 6 sections and 11 appendices. The first three sections provide the background, research context and objectives of the research project. Section 4 discusses the research method. The appendices document all technical data, data analysis, and results for the project. The appendices are summarized in section 5. Finally, Section 6 provides the conclusions and recommendations.

2 Research Context

2.1 Moisture Susceptibility of Asphalt Mixtures

Moisture susceptibility of asphalt mixtures refers to the tendency for specific combinations of asphalt binders and aggregates to sustain damage or a loss in functionality due to the detrimental effects of moisture under repetitive traffic loading. Therefore, the compatibility between aggregate and asphalt binder source is critical to the prevention of moisture damage. There are two major causes of moisture damage within asphalt mixtures: (1) the loss of adhesive bonding between the asphalt binder or mastic and the aggregates, and (2) the loss of cohesion in the mastic due to the presence of moisture [Little and Jones, 2013].

Researchers have identified the following processes which contribute to the causes of moisture damage [Taylor and Khosla, 1983; Santucci, 2010; Sebaaly, et al., 2010]:

- *Detachment of the binder film from the aggregate without film rupture,*
- *Displacement of the binder film from the aggregate through film rupture,*
- *Spontaneous emulsification and formation of an inverted emulsion of water in binder,*
- *Pore pressure-induced damage due to repeated traffic loading,*
- *Hydraulic scour at the surface due to tire-pavement interaction*
- *pH instability of the contact water, which affects the binder-aggregate interface, and*
- *Environmental factors such as excessive rainfall, large temperature fluctuations, and freeze-thaw (F/T) conditions.*

2.2 Laboratory Characterization of Moisture Susceptibility

Over the last few decades, several moisture conditioning protocols and laboratory tests have been proposed to evaluate the moisture susceptibility of asphalt mixtures. In general, these protocols and test methods can be grouped into three categories: (1) tests on uncompacted loose mixtures, (2) tests which mechanically measure stiffness or tensile strength of asphalt mixtures before and after moisture conditioning to simulate field conditions, and (3) tests which utilize repetitive loading of compacted mixtures in the presence of water. Among these tests, Modified Lottman Test (also known as Tensile Strength Ratio (TSR)) and HWTT are most commonly used by state DOTs. The detailed procedures and parameters of these two tests are described in the next paragraphs.

The TSR test (AASHTO T 283) is the most common laboratory standard test to evaluate moisture susceptibility of asphalt mixtures. To perform the test, the indirect tensile (IDT) strength at 25°C (77°F) is determined for both dry specimens and for wet specimens which are moisture conditioned by following the modified Lottman procedure. As presented in Figure 1, the moisture conditioning procedure consists of partial vacuum saturation, one freeze-thaw cycle for 16 hours at -18°C (-0.4°F), and soaking in warm water for 24 hours at 60°C (140°F). The TSR is then determined as the ratio of the average IDT strength obtained from three moisture conditioned specimens to the average IDT strength of three dry control specimens. Asphalt mixtures with higher wet IDT strength and TSR values are expected to have better resistance to moisture damage.

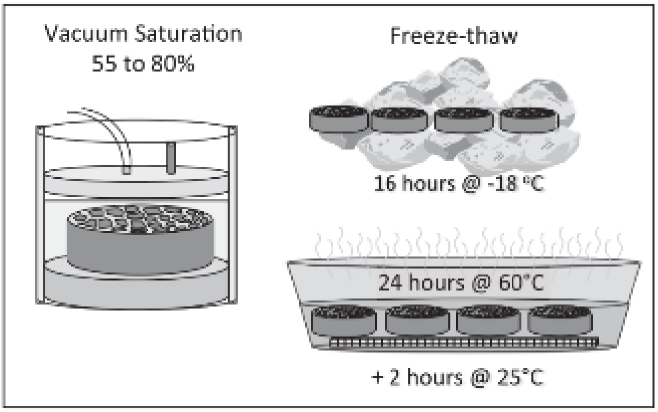


Figure 1 Schematic Modified Lottman Moisture Conditioning Procedure [Santucci, 2010]

The ODOT adopted a modified version of AASHTO T 283 as specified in Supplement 1051 which utilizes a higher saturation rate of 80-90% for Superpave mixes. In NCHRP project 9-13 Epps et. al. [2000] recommended states transitioning from Marshall to gyratory compacted sample during implementing of Superpave perform a structured laboratory program to validate the test procedure using gyratory samples and their aggregates and binders. Liang [2008] performed the recommended evaluation for ODOT. The following variables and their effect on dry tensile strength, conditioned tensile strength, and TSR were considered:

- *aggregate source – one limestone, one trap rock, and two gravel sources were used*
- *binder – one virgin (PG 64-22) and one polymer modified (PG 70-22) were used*
- *compaction method – Marshall and Superpave gyratory*
- *specimen size – 4 in (100 mm) for Marshall, 4 in (100 mm) and 6 in (150 mm) for Superpave gyratory*
- *aging method – none, 2, 4, and 15 hours for loose mix; 0 to 24 hours and 72 to 96 hours for compacted samples*
- *degree of saturation – 55%, 75%, and 90%*
- *freeze-thaw cycle – none and one freeze/thaw cycle*

Liang [2008] reported the following findings:

- *Loose mix aging was the most important factor affecting dry tensile and conditioned tensile strength. Source of aggregate and compaction method were also important. Saturation level was also important for conditioned tensile strength.*
- *Loose mix aging, saturation level, and compaction level were important factors affecting TSR values.*

Liang recommended a conditioning and testing procedure for 6 in (150 mm) Superpave gyratory specimen which would produce results similar to the 4 in (100 mm) Marshall specimen. Liang's study did not relate the test results to field performance.

2.3 Antistrip Agents

The most commonly used strategy to minimize moisture damage in asphalt pavements is using antistrip agents such as hydrated lime and LAS additives. Lime is widely used by transportation agencies to improve the resistance of asphalt mixtures to moisture damage; it can be added in powder form to dry or damp aggregate or as a slurry marination [Santucci, 2010]. The typical rate for hydrated lime is 1% by weight of the aggregate. A study at the Western Research Institute determined the addition of hydrated lime benefited the pavement in several ways: reduced asphalt age-hardening, increased high-temperature stiffness of unaged asphalt, increased tensile elongation of asphalt at low temperatures, and improved resistance to moisture damage. These benefits consequently resulted in increased durability, reduced rutting, improved fatigue resistance in aged pavements, and improved resistance to low-temperature transverse cracking [Petersen et al., 1987].

Most LAS additives are amine-based compounds designed to act as coupling agents to promote the adhesion at the binder-aggregate interface [Curtis et al., 1993]. LAS additives are typically added at a rate of 0.25% to 1% by weight of the binder. Although LAS additives are more convenient and generally less expensive, their effectiveness to reduce mixture susceptibility depends on the physicochemical properties of the asphalt binder and the aggregate, and the dosage of liquid antistrip agent used [Epps et al., 2003].

Sebaaly et al. [2010] compared the performance of fifteen mixtures using aggregates from five states and three treatments: no antistrip agent, 0.5% LAS additive, and 1% hydrated lime. TSR testing was conducted on samples conditioned to up to 15 freeze-thaw cycles. TSR results indicated both lime and LAS were found to improve resistance to moisture susceptibility, the untreated and LAS treated mixtures had significantly lower strength after several freeze-thaw cycles, while the hydrated lime treated mixtures were able to maintain high strength values for 15 cycles with all aggregate sources. A similar study was conducted by Watson et al. [2013] with mixtures treated with hydrated lime, LAS, and a warm-mix asphalt antistrip additive. The mixtures were subjected to multiple free-thaw cycles for up to 10 cycles. The results indicated the hydrated lime had the highest tensile strength and highest TSR values and was the only additive treatment to meet the minimum of 80% TSR for all freeze–thaw cycle combinations evaluated.

Amirkhanian et al. [2018] evaluated the performance of LAS additives of asphalt mixtures with hydrated lime, five LAS additives, six aggregate sources, and six RAP sources. Their test results showed hydrated lime-treated asphalt mixtures always met the TSR (≥ 85% and wet ITS (≥65 psi (450 kPa)) required criteria, while liquid LAS additive-treated asphalt mixtures of some aggregate types did not meet these requirements. The researchers recommended a minimum dosage of 0.7% LAS additives by weight of binder for those mixtures that did not meet the minimum required criteria.

In general, antistrip agents have demonstrated that they are effective in mitigating moisture susceptibility of asphalt mixtures, but their effectiveness depends on the source (type), dosage, and properties of the mixture components (asphalt and aggregates).

3 Objectives

The primary goals of this research were:

- *Provide recommendations, based on a literature search and limited lab testing, for refining ODOT's current moisture susceptibility test procedures, or recommend a new test procedure, which will better predict field performance.*
- *Determine the feasibility, cost, and risk of using antistripping agents with marginal or poor performing mixtures in lieu of laboratory testing for moisture susceptibility*

4 Method

To fulfill the objectives listed above, the following tasks were undertaken as part of this project:

1. *Conduct a literature review.*

A comprehensive literature search was conducted to identify laboratory test procedures used within the United States, as well as internationally, for identifying moisture susceptibility of asphalt mixtures and the use of antistrip agents to mitigate moisture susceptibility.

Taylor and Khosla [1983] and Brown et al. [2001] identified tests which had been developed to determine moisture susceptibility of asphalt mixtures. These tests were summarized into the following:

- *Static Immersion Tests (includes ASTM D1664, AASHTO T 182)*
- *Dynamic Immersion Tests*

- *Boiling Tests (includes ASTM D 3625)*
- *Chemical Immersion Test*
- *Quantitative Coating Evaluating Tests*
- *Abrasion Tests*
- *Simulated Traffic Tests*
- *Immersion-Mechanical Tests (includes ASTM D 1075, AASHTO T 165, AASHTO T 283)*
- *Nondestructive Tests*
- *Net Absorption Test (SHRP Project A-003B)*
- *Environmental Conditioning System (SHRP Project A-003A)*

The research team reviewed the literature to identify tests which are fundamentally sound and have the potential to predict field performance.

The literature search also focused on available antistripping agents, the effects of aggregate type and binder type on the effectiveness of the agents, cost, and reliability.
Search engines such as TRID, Google Scholar, and ScienceDirect were used to identify relevant publications. The team also searched the websites of Transport Canada, Austroads, PIARC, and SANRAL to identify commercially available test procedures for moisture susceptibility and antistrip agents in use in Canada, Australia, New Zealand, Europe, and South Africa.

2. *Survey of State Agencies.*

A survey was developed to help identify current and best practices across the United States. The survey included questions seeking information on:

- *The agency's experience with moisture damage on in-service pavements*
- *Moisture susceptibility tests and equipment used in mix design*
- *Criteria used to accept a mix design*
- *Corrective actions taken when samples fail test procedure*
- *Ability of test to predict field performance*
- *Results of any forensic evaluations/case studies of stripping in the field*
- *Use and effectiveness of antistrip agents*
- *Approval and evaluation of antistrip agents*

The survey questions are provided in Appendix H. Qualtrics survey software was used to deliver the survey and to compile and analyze survey results. The team made follow-up efforts such as phone calls and emails to collect the survey information from states with similar climate and aggregate types as Ohio.

3. *Review of Agencies Specifications for Moisture Susceptibility Tests and Use of Antistrip Agents.*

State DOT specifications for moisture susceptibility testing were requested from each agency through the survey, or they were obtained from state DOT websites. The research team reviewed these specifications with a focus on states with similar climates and aggregate types as those in Ohio. These specifications were compared and contrasted with ODOT's specification, and differences which could improve ODOT's specification were identified as well as alternative or complementary test procedures.

4. *Develop a List of Candidate Laboratory Tests for Moisture Susceptibility.*

The results of Tasks 1-3 were used to identify tests for further evaluation in Task 5. The Hamburg Wheel-Track Testing, AASHTO T-324, was chosen for comparison with the TSR test as modified by ODOT Supplement 1051.

5. Evaluate Candidate Laboratory Tests.

This task consisted of comparing the Hamburg Wheel-Track Testing to the current ODOT Supplement 1051. It included the following subtasks:

5.1 Identify Asphalt Mixes for Evaluation

The research team reviewed TSR tests results on file at ODOT, interviewed ODOT Central Lab, and Ohio and Georgia asphalt contractors to identify mixes and/or specific aggregate types and sources which have failed, performed marginally (i.e. TSR value is near the criteria), or performed exceptionally well in either laboratory tests or the field, or both.

5.2 Recreate Asphalt Mixes in Laboratory

The research team obtained JMFs, when available, for projects identified in Task 5.1. The team selected one poor performing, one marginally performing, and one exceptional performing mix to evaluate in the laboratory. To mimic the materials used in the plant produced mix as much as possible, recently placed mixes were emphasized. The research team collected material from the various asphalt producers and aggregate suppliers. Utilizing the JMFs, test samples were produced in the laboratory. The essential volumetric mix properties, i.e. maximum specific gravity, air voids, etc., were determined for a mix when not available on the JMF.

5.3 Conduct Laboratory Testing

The research team evaluated the two test procedures, the TSR and Hamburg Wheel Track Test (HWTT) for all mixes utilized in Task 5.2. Antistrip was not used for this testing. TSR was determined in accordance with ODOT Supplement 1051. The HWTT device was evaluated using AASHTO T-324. A test matrix is presented in Table 1.

Table 1 Laboratory Test Plan for Test Procedures

Mix Field Performance	**Test Procedure**		
	ODOT Supplement 1051 (gyratory sample)	**ODOT Supplement 1051 (Marshall sample)**	**AASHTO T-324**
Poor	X	X	X
Marginal	X	X	X
Exceptional	X	X	X

5.4 Evaluate Antistrip Additive

Three antistrip additives, lime and two liquid additives, were used on the poor performing and marginal performing mixes to determine the effect of the additives on test results. Table 2 presents the test matrix for this subtask. The two additives will be referred to as “additive A” and “additive B” in this report. The results were evaluated by the research team to determine if antistrip additives can be used in lieu of testing. The Table 1 ODOT Supplement 1051 gyratory samples served as control samples for the antistrip test plan shown in Table 2.

Table 2 Laboratory Test Plan for Antistrip Additives

Mix Field Performance	**Test Procedure**					
	ODOT Supplement 1051			**AASHTO T-324**		
	Lime	**Additive A**	**Additive B**	**Lime**	**Additive A**	**Additive B**

Poor	X	X	X	X	X	X
Marginal	X	X	X	X	X	X

6. *Conduct Cost Analysis of using Antistrip Additives.*

The potential impact of moisture damage, and antistrip usage on the cost of rehabilitation required to keep the pavement in serviceable condition for 35 years in Ohio was assessed using a simple life cycle cost analysis. The analysis relies on the net present value (NPV) of different scenario analyses. This performance period was selected based on the current analysis period specified in section 703.1 of the Ohio DOT Pavement Design Manual. The research team conducted a cost analysis relying on existing unit price of asphalt mixtures in Ohio, unit cost of antistripping agents, and the potential increase in the life span of mixtures susceptible to moisture damage (with the use of antistrip agents).

5 Research Findings

5.1 Key findings from the Literature Review and Survey

A comprehensive literature search was conducted, in which over 100 journal articles, technical reports, conference proceedings, and conference presentations were identified that pertained to laboratory testing to assess moisture susceptibility of asphalt mixtures, and the use of antistrip agents to mitigate moisture susceptibility in asphalt mixtures. There is a wide body of work related to moisture susceptibility of asphalt mixtures. The intent of this literature search was to help identify tests, conditioning methods, or combination of both, which show promise for improving the ODOT's ability to identify asphalt mixtures susceptible to moisture damage. A summary of the journal articles, conference proceedings ant technical reports is provided in the Appendix. Key findings related to the commonly utilized test methods for testing moisture susceptibility of asphalt mixtures are provided in the following subsections.

There are two major causes of moisture damage within asphalt mixtures (Little and Jones, 2003):

1. *The loss of adhesion bonding between the asphalt binder or mastic and the aggregates, and*
2. *The loss of cohesion in the mastic due to the presence of moisture*

Moisture damage is often a combination of processes which include (*Taylor and Khosla, 1983; Santucci, 2010; Sebaaly et al., 2010*):

- Detachment of the binder film from the aggregate without film rupture,
- Displacement of the binder film from the aggregate through film rupture,
- Spontaneous emulsification and formation of an inverted emulsion of water in binder,
- Pore pressure-induced damage due to repeated traffic loading,
- Hydraulic scour at the surface due to tire-pavement interaction pH instability of the contact water, which affects the binder-aggregate interface, and
- Environmental factors such as excessive rainfall, large temperature fluctuations, and freeze-thaw (F/T) conditions.

Laboratory tests to evaluate moisture susceptibility can be grouped into four categories:

1. Tests on uncompacted loose mix

2. Test that mechanically measure stiffness or tensile strength
3. Tests that utilize repetitive loading of compacted specimens
4. Other tests on uncompacted specimens

5.1.1 TSR

A survey by West et. al. (2018) found the TSR test is the most common laboratory standard test used by state DOTs to evaluate moisture susceptibility of asphalt mixtures. Asphalt mixtures with higher wet IDT strength and higher TSR values are expected to have a better resistance to moisture damage.

- Factors affecting tensile strength and TSR may include:
    - Liang (2008) found loose mix aging affects dry tensile, freeze/thaw tensile strength, and TSR, whereas Aschenbrener and McGennis (1993) found aging did not have an effect on the mixtures.
    - Results concerning saturation level were mixed: Liang (2008) found saturation level affects freeze/thaw tensile strength and TSR and recommended the saturation level be between 80-90%; Hanz et al. (2007) found all mixes exhibited losses in tensile strength due to moisture conditioning; whereas Epps et al. (2000) found the level of saturation had little effect on tensile strengths observed in freeze-thaw and no freeze-thaw; Solaimanian et al. (2010) and Zaniewski and Viswanathan (2006) reported no relationship between saturation level and TSR value; and NCHRP (2010) reported 70% to 80% saturation level may induce micro-cracks which contribute to test variability.
    - Compaction level (Liang, 2008).
    - Compaction method may influence TSR values. TSR values from 6" gyratory were greater than TSR values from 4" Marshall specimens (Zehr, 2002). The average tensile strength of 4" Marshall specimens was greater than the 6" gyratory compacted specimens (Zehr, 2002)
    - Plant produced mixtures had greater average tensile strength than lab produced mixtures (Zehr, 2002).
    - The results for freezing and thawing were also mixed. Sebaaly et al. (2001) found freeze and thaw had no significant effect on indirect tensile strength. Liang (2008) found a need to incorporate at least one freeze-thaw cycle to distinguish between mixes. Watson et al. (2013) investigated the use of 0, 1, 5, and 10 freeze-thaw cycles, and found 5 and 10 cycles were "significantly more discriminating than one freeze-thaw cycle alone". Aschenbrener and McGennis (1993) found freezing and saturation can distinguish between well performing and poorly performing mixtures.
- The correlation between field performance and laboratory test results were likewise mixed. Lottman (1982) and Tunnicliff and Root (1984) reported good correlation between performance in the field 5 years after construction and stripping found in the lab. Hanz et al. (2007) found the results of TSR testing appropriately differentiated between mixes with aggregate known to cause stripping and those with aggregate known to be resistant to moisture damage. Christensen et al. (2015) compared modified Lottman test results to field performance and found there were a significant percentage (50%) of false positives for moderately susceptible mixes but was reasonably accurate for mixes with low or high susceptibility. Aschenbrener and McGennis (1993) reported good, but not ideal, correlation between the modified Lottman and field performance. Sebaaly et al. (2001) found TSR values from cores

were consistent with field performance whereas TSR values from lab prepared samples were not. On the other hand, Zaniewski and Viswanathan (2006) concluded the T-283 test does not reliably reflect field performance. Stuart (1998) also found poor correlation between test on cores and field performance. Bahia and Ahmad (1999) found poor correlation between pavement distress rating and TSR tests. Dave et al. (2018) reported the modified Lottman and TSR criteria were unable to distinguish between poor, moderate, and well performing mixtures.
- Variability in the test results has also been reported. Aschenbrener and McGennis (1993) found TSR values had a range (max minus min) for a given mix between 6% and 37%

5.1.2 Hamburg Wheel Track Testing

The HWTT per AASHTO T 324 is a laboratory procedure which uses repetitive loading from a steel wheel in the presence of water and measures the rut depth induced in an asphalt mixture with increasing load cycles. To perform the test, two sets of cylindrical specimens are placed side by side, submerged in heated water, and subjected to approximately 52 passes of a steel wheel per minute.

- Rut depth versus load cycles can be divided into three phases
    1. Post-compaction: wheel load densifies the mixture
    2. Creep phase: constant rate of increase in rut depth with load cycle due to viscous flow of the asphalt mixture
    3. Stripping phase: bond between binder and aggregate starts degrading

Figure 2 presents a typical plot of the HWTT test result curve in terms of rut depth versus load cycles. The stripping inflection point (SIP) represents the number of load cycles on the HWTT curve at which a sudden increase in rut depth occurs, mainly as a result of the stripping of the asphalt binder from the aggregate; it is graphically represented at the intersection of the fitted lines that characterize the creep phase and the stripping phase. Rut depth and SIP are the parameters used to evaluate the mixture resistance to rutting and moisture damage, respectively. Asphalt mixtures with lower rut depths and higher SIP values are considered to have better performance in the HWTT.

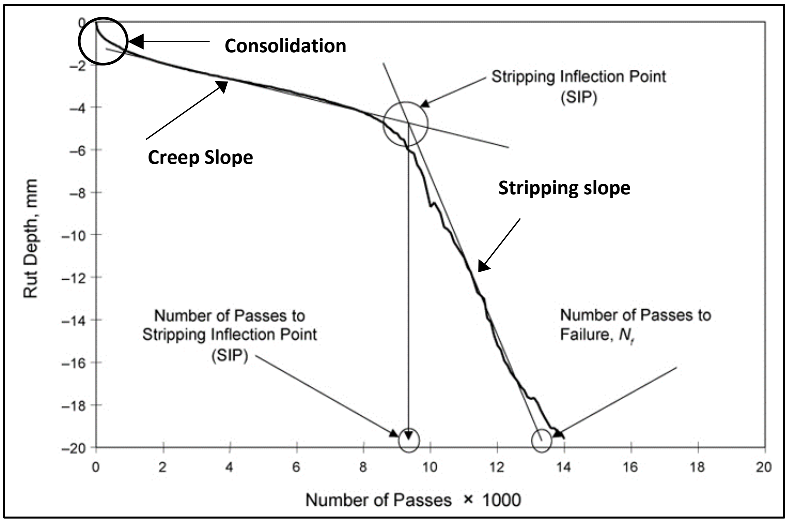


Figure 2 Typical Plot of HWTT Results [AASHTO, 2019]

- Aschenbrener (1995) reported the HWTT is sensitive to
    - Quality of aggregate
    - Asphalt binder stiffness
    - Length of short-term aging
    - Compaction temperature
- Aschenbrener (1995) reported an excellent correlation between SIP and stripping performance of several pavement sections. Lu, Harvey and Monismith (2007) reported a fair correlation with some false positive results. NCHRP project 9-49A found eight of 28 projects showed an SIP at less than 20,000 passes but no moisture related distress was found in the field for projects 2 to 10 years old. Yin et al. (2014) proposed an alternative parameter, stripping number (SN), obtained by fitting an exponential function to the data. The SN represents the maximum number of load cycles the mix can withstand before adhesion fraction between the asphalt and aggregate occurs.
- AASHTO T 324 does not specify a test temperature. Test temperatures in state DOTs specifications range for 45ºC to 50ºC. Izzo et al. (1999) observed inconsistent trends at 50°C suggesting, for mixes with AC-20 binder, this temperature was too extreme. Lu et al. (2007) found the test underestimated the performance for soft binders when a test temperature of 50°C was used.

5.1.3 Antistrip

The most commonly used strategy to minimize moisture damage in asphalt pavements is using antistrip agents such as hydrated lime and liquid antistrip (LAS) additives.

- *The Western Research Institute determined the addition of hydrated lime benefited the asphalt in several ways (Petersen et al., 1987):*
    - *Improved resistance to moisture damage*
    - *Reduced asphalt age hardening*
    - *Increased high-temperature stiffness*
    - *Increased tensile elongation of asphalt at low temperatures*
- *Sebaaly et al. (2010) compared three treatments: no antistrip, 0.5% LAS additive, and 1% hydrated lime. TSR testing was conducted on samples conditioned up to 15 freeze-thaw cycles. Both lime and LAS improved resistance to moisture susceptibility. However, LAS treated mixtures had significantly lower strength after several freeze-thaw cycles, whereas the lime treated mixtures were able to maintain high strength values for 15 cycles. Watson et al. (2013) conducted a similar study and found hydrated lime had the highest tensile strength and highest TSR value. Likewise, Amirkhanian et al. (2018) found lime treated mixtures always met the TSR (≥ 85%) and wet ITS (≥ 65 psi) criteria while LAS mixtures of some aggregates did not meet requirements.*
- *Aschenbrener (1995) found liquid antistrip improved the HWTT results for some aggregates. Lime improved the test results for all mixes tested. Izzo et al. (1999) also found lime provided the best performance.*

5.1.4 Economic analysis of Antistrip Additives in Asphalt Mixtures

Christensen et al. (2015) considered three aggregates in both a life cycle cost analysis (LCCA) cost benefit analysis (CBA); aggregates which were not susceptible to moisture damage (control), aggregates which were highly susceptible to moisture damage, and aggregates with moderate susceptible to moisture damage. Traffic growth rates and discount rates were considered. The results of their analysis, using a 24-year analysis period and a 2% discount rate are shown in Table 3. As presented in the table, the use of a moisture damage susceptible aggregate increased the annual cost of maintaining the roads. The use of antistrip significantly reduced that cost.

Table 3 Changes in EAUC ($/lane mile) Relative to Control (aggregate not susceptible to moisture damage) [Christensen et. al., 2015]

Moisture Susceptibility			High	High	Moderate	Moderate
Antistrip			No	Yes	No	Yes
Traffic (ADT)	Without User Cost	2,000	$12,840	$7,902	$7,209	$49
		5,000	$13,270	$8,137	$7,444	$49
		15,000	$13,614	$8,325	$7,632	$49
		50,000	$13,958	$8,516	$7,820	$49
	With User Cost	2,000	$13,157	$8,023	$7,330	$49
		5,000	$14,086	$8,444	$7,751	$49
		15,000	$14,849	$8,887	$8,194	$49
		50,000	$18,397	$10,531	$9,839	$49

The CBA performed by Christensen et al. (2015) considered the accuracy of the moisture susceptibility testing. They assumed the AASHTO T 283 test correctly identified moisture susceptibility 77% of the time for highly susceptible mixtures and 38% of the time for moderate susceptible mixtures. They also assumed mixtures not susceptible to moisture damage were correctly identified 94% of the time. Two cases were considered: conditional use of antistrip to pass the AASHTO T 283 test and mandatory use of antistrip in all mixtures. The researchers considered a 1.75” asphalt layer thickness and a lane width of 12 feet. The analysis found that testing and the use of antistrip had a benefit cost (B/C) ratio greater than one for both conditional and mandatory use of antistrip, meaning testing and antistrip usage are cost effective.

The potential savings in Pennsylvania based on the LCCA for realistic performance are shown in Table 4 as a function of the percentage of susceptible aggregates that assumed to be use in their mixes.

Table 4 Summary Results of LCCA Comparing Moisture Resistance Testing to No Testing [Christensen et. al., 2015]

Antistrip Usage		Cost Savings for Percentage of Susceptible Aggregates:		
		40	20	10
Without User Cost	Conditional on Test Results	$8,003,222	$3,958,155	$1,935,622
	Mandatory for All Mixes	$14,725,686	$7,183,226	$3,411,995
	Savings, Mandatory over Conditional	$6,722,464	$3,225,071	$1,476,374
	Savings, % of Total Cost	6.0	3.2	1.6
With User Cost	Conditional on Test Results	$9,199,60	$4,556,074	$2,234,581
	Mandatory for All Mixes	$16,728,406	$8,184,586	$3,912,675
	Savings, Mandatory over Conditional	$7,529,346	$3,628,511	$1,678,094
	Savings, % of Total Cost	5.9	3.2	1.6

As a result of their LCCA and CBA, Christensen et al. [2015] reported their following findings:

- The B/C ratio of antistrip usage in conjunction with high-saturation moisture resistance testing, i.e. AASHTO T 283, was found to be, under all scenarios much greater than one, indicating that antistrip usage and appropriate moisture resistance testing significantly lower the net life cycle cost of HMA pavements in Pennsylvania
- The B/C ratio of antistrip usage in conjunction with high-saturation (70 to 80%) moisture resistance testing was greater than one (again, much greater in most cases) for both conditional use of antistrip and mandatory use of antistrip, indicating that both approaches are very economical.
- Mandatory antistrip usage, in conjunction with high-saturation testing, i.e. AASHTO T 283, appears to always result in greater net savings compared to antistrip usage dependent on the results of moisture resistance testing because the failure of such testing to identify all susceptible mixes and the high cost associated with poor performance.

5.2 Key findings from the Survey of Other Agencies

A total of 33 (66%) DOTs and the District of Columbia responded to the survey. Based on these responses, the research team has the following observations:

- *The most used test procedure for moisture susceptibility is tensile strength ratio (TSR) in accordance with AASHTO T 283 or ASTM D 4867 or a modification thereof. This procedure is used by twenty-three of the responding agencies.*
- *The next most used procedure is the HWTT in accordance with AASHTO T 324. This procedure is used by nine of the responding agencies.*
- *Ten states perform multiple tests. The most common combination was TSR and boiling water test, used by five states, followed by TSR and the HWTT which was used by four states.*
- *Six of the eight agencies which have modified their procedure in the last 10 years replaced or supplemented TSR testing with HWTT*
- *Twenty-nine agencies provided acceptance criteria for the TSR test. Minimum TSR values ranged from 70% to 85%. Four of the agencies also had a tensile strength requirement. The minimum tensile strength requirement ranged from 60 psi (415 kPa) to 100 psi (690 kPa)*
- *Seven agencies have established acceptance criteria for the HWTT. The number of passes varied based on mix type, binder grade or truck traffic (ESAL) level. Four of the agencies included a minimum number of passes before the stripping inflection point (SIP) can occur in their acceptance criteria.*
- *Seventeen agencies indicated lab testing and mix acceptance criteria reduced the occurrence of moisture damage, two agencies indicated lab testing and mix acceptance criteria did not reduce the occurance of moisture damage, and eleven agencies were unsure. The percent of agencies who indicated lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage was higher for agenies who perform multiple test or the HWTT than for the agencies who only perform the TSR test.*
- *The agencies rely heavily on the contractor to prepare, and in many cases test, specimens.*
- *Half of the responding agencies have encountered instances where mixtures have passed laboratory testing but performed poorly in the field with regard to moisture damage. However, no trend was observed between agencies reporting this situation and the test method used.*

- *Almost all, twenty-nine, of the responding agencies allow or require the use of antistrip agents.*
- *Of the agencies requiring antistrip agents, about a third indicated antistrip eliminated moisture susceptibility problems, slightly more than a third indicated antistrip did not eliminate moisture susceptibility problems, and slighly less than a third were unsure.*

5.3 Key findings from the Review of Other State Specifications

To complement the information gathered from the survey, the National Asphalt Pavement Association's Balanced Mix Design Resource Guide (NAPA, 2022) website was utilized, as well as the websites of the state highway agencies which had not completed the survey, and international transportation agencies were searched for moisture susceptible test specifications.

HWTT specifications were located for six additional states. Of those specifications reviewed, required passes of the load ranged from 10,000 passes to 20,000 passes. Maximum permitted rut depth ranged from 6 mm to 13.5 mm. Acceptance criteria for the minimum number of passes before a SIP ranged from 8,000 to 15,000 passes. Test temperatures ranged from 45° C to 50° C.

TSR testing specifications were located for an additional 15 states and the European Union and Austroads. Minimum TSR values ranged from 70% to 80%. Two states had an additional minimum tensile strength requirement. California had a minimum wet tensile strength of 70 psi (485 kPa) and minimum dry tensile strength of 100 psi (690 kPA). Nevada had a minimum dry tensile strength requirement of 58 psi (400 kPa) for their 9.5 mm mix, 65 psi (450 kPa) for their 19 mm mix not using a PG76-22 binder and 100 psi (690 kPa) for their 19 mm mixes using a PG76-22 binder.

Additional test methods used included the boil test (four states, one Canadian province, and the European Union), retained Marshall stability test (two Canadian provinces), static immersion (one Canadian province) and the rolling bottle test (European Union).

5.4 Key findings from the Laboratory testing

All samples were prepared by Ohio University's Ohio Research Institute for Transportation and the Environment (ORITE), at their facility in Lancaster, Ohio. TSR testing was performed at ORITE. While HWTT was performed on an APA Jr. equipment at ORITE and on the Cox & Sons equipment HWTT at NCAT in Auburn, Alabama using samples prepared by ORITE.

Based on TSR test results with and without additives, the moisture resistance of the granite would be expected to be good. As shown in Table 5, all granite samples met ODOT's acceptance criteria for TSR of 80% or higher (70% or higher for Marshall samples). All additives improved the TSR value with additive B providing the most improvement, followed by the lime, then additive A. There were no signs of stripping of the binder from the aggregate in any of the samples.

Table 5 TSR Test Results

Aggregate Type	Additive	TSR (gyratory)	TSR (Marshall)
Granite	none	passed	passed
	A	passed	
	B	passed	
	lime	passed	
Gravel	none	passed	passed
	A	failed	
	B	failed	
	lime	failed	
Limestone	none	failed	failed

Based on TSR test results, the moisture resistance of the gravel would be expected to be marginal, with some samples passing and some failing. As shown in Table 5, the gravel gyratory and Marshall samples with no additives were the only samples to pass ODOT's acceptance criteria. The results, in order of increasing TSR values, were the samples containing additive A, lime, and additive B. The sample with additive B had a TSR of 79.7%, which was slightly below the acceptance level of 80%. Some of the coarse aggregate in all samples showed a thin coating of binder. All mixtures, with the exception of the mixture containing lime, were given a rating of "1" for visual stripping. The mixture with the lime additive was given a visual rating of "1 to 2" for stripping. Coarse aggregate with a thin binder coating was also observed in the control samples.

Based on TSR test results, the moisture resistance of limestone would be expected to be poor. As shown in Table 5, both the gyratory and Marshall samples containing limestone aggregate did not meet the ODOT criteria. Other than one sample with a thinly coated aggregate, there were no signs of stripping of the binder from the aggregate in any of the samples.

Two of the mixes, one granite and one limestone, used in the testing were based on JMFs approved for construction. The approved JMFs included TSR testing.

The contractor's JMF was available for the 19 mm mix with granite aggregate and 1% lime approved for use in Georgia. This mix used a PG 67-22 binder rather than the PG 64-28 binder used for the lab testing on this project. The detailed TSR test data were not provided but the average conditioned strength reported on the JMF was 802.3 kPa (116.3 psi), approximately 14% higher than the 704.6 kPa (102.2 psi) measured on the similar mix design for this project, and the average control strength was 876.1 kPa (127.1 psi), 44% higher than the 609.5 kPa (88.4 psi) measured on this project, resulting in a TSR of 91.5%, 21% lower than the 115.7% measured on this project. Regardless of the differences, the IDT and TSR values measured by ORITE and the contractor met or exceeded ODOT and GDOT criteria.

The contractor's detailed TSR test data were available for the limestone mix. The JMF TSR test results are shown in Figure 27. The binder grade, PG 64-28, was the same for both mixtures. When compared to the results of the evaluation of the same mix on this project, the dimension, weight and volume data are very similar. The major difference in the tests are the conditioned strength average and the average dry strengths. The conditioned strength average reported in the JMF was 597.8 kPa (86.7 psi) while the measured value found in this study was 45% lower at 330.9 kPa (48.0 psi). The average dry strength reported in the JMF was 683.3 kPa (99.1 psi) compared to 551.6 kPa (80.0 psi) for the lab test, which was 19% lower than the JMF. The TSR value reported in the JMF was 87.5%, which passes ODOT criteria. The lab testing in this study resulted in a TSR value of 60.0%, which is 31% lower and does not pass the ODOT criteria.

In summary,

- *Based on TSR values*
    - *The granite mixtures would be resistant to moisture damage*
    - *The gravel mixtures are marginally resistant to moisture damage*
    - *The limestone mixtures are not resistant to moisture damage*
- *Based on the visual observation of the conditioned TSR samples after testing, only the gravel mixtures showed signs of stripping, i.e. thinning of the binder coating on coarse aggregate.*
- *The use of lime or liquid additives*
    - *Improved the TSR values for mixtures using granite aggregates and compacted with the gyratory compactor.*
    - *Did not improve the TSR values for mixtures using gravel aggregate*
- *There were two mixtures for which TSR test data for the same aggregate, different binder, were available from the producer's laboratory.*
    - *The granite with lime treatment JMF passed the TSR criteria during acceptance as did the sample tested for this project.*
    - *The limestone JMF passed the TSR criteria during acceptance whereas the sample tested for this project failed.*

The Pavement Technology Inc.'s (PTI's) operating software generates an Excel spreadsheet at the end of testing containing raw data, a summary plot, and an estimate of the SIP value. An example of the summary plot with SIP values are shown for all tests in Appendix J. Initial tests were conducted on granite samples. None of these samples showed a significant break in the slope of the rutting curve which indicates the samples are not stripping. However, the software supplied with the APA Jr. assigned an SIP value. During conversations with PTI, they indicated negative values and extremely high values indicate there is no SIP. During the last test of the granite tests, granite with additive A, the motor on the APA Jr. failed after 9,000 passes. During the motor replacement, routine service and calibration was also performed by PTI, including an upgrade to the operating software. After service, two more sets of tests were performed on mixes with granite aggregate, one with additive A on one side and additive B on the other; the second with no additive on one side and lime additive on the other. These results are shown in Figures 52 and 53. Following a second failure of the APA Jr.'s motor, the maximum allowable rutting was set to 12.5 mm, the maximum recommended by the manufacturer and typically specified by state DOTs, for the testing of the specimens containing gravel and limestone aggregates.

Although the break in slope was not prominent in all plots shown in Appendix J, the shape of some of the curves were sufficient to manually calculate the SIP using the procedure in AASHTO T 324, in which linear regression is used to fit a line to the creep curve and the stripping curve. The value of the number of passes at the intersection of the two lines is the SIP. The SIP values calculated by the PTI software, as well as the SIP values calculated manually, are shown in Table 28.

Control samples for the granite, gravel and limestone aggregates as well as samples with lime additive and additive B were mixed and compacted at the ORITE laboratory and shipped to NCAT for testing on a Cox & Sons Hamburg Wheel Tester. The results are presented in Appendix K and summarized in Table 29. The granite samples, with and without additives, performed poorly, all samples except one of the samples treated with lime failed an acceptance criterion of no SIP in less than 15,000 load applications. The gravel samples performed moderately, the samples with additive B and one of the samples treated with lime failed an acceptance criteria of no SIP in less than 15,000 load applications while the control samples and the other sample treated with lime passed. Both samples with limestone aggregate failed an acceptance criterion of no SIP in less than 15,000 load applications.

Iowa DOT uses the ratio between the stripping slope and the creep slope to validate the SIP number (Schram et. al., 2012). The SIP number is considered valid if the ratio is 2.0 or greater. Schram reported stripping behavior was not observed in the field in sections with a ratio less than 1.0, even though a SIP number can be calculated. Under the current Iowa DOT specification, if the ratio of slopes is less than 2.0, the SIP is considered invalid and the mix is considered passing. An evaluation of the validity of the calculated SIP based on the Iowa criteria is also shown in Tables 28 and 29 and summarized in Table 6.

Two failure criteria are shown in Table 6. The first is a SIP less than 15,000, the value commonly used by agencies responding to the survey. The second is a SIP less than 15,000 and a stripping slope to creep slope ratio greater than or equal to 2.0, a criteria used by Iowa DOT to validate the SIP criteria. The table shows whether the sample passed based on the SIP calculated with the APA Jr software, a manual calculation of the SIP as detailed above, and the SIP calculated by the NCAT Cox & Son software. Using the SIP criterion alone, the granite and gravel samples were marginal, with some samples passing and some failing. The limestone samples failed. Using the SIP criterion and accounting for whether the SIP was valide based on the Iowa DOT slope ratio, almost all the granite and gravel samples passed, while the limestone samples failed.

Table 6 HWTT Test Results

Aggregate Type	Additive	Fail Criteria				
		SIP < 15,000			stripping line slope/creep line slope ≥ 2.0	
		APA jr	manual	NCAT	manual	NCAT
Granite	none	passed	passed	failed	passed	passed
		passed	passed	failed	passed	passed
		failed	failed		passed	
	A	failed	passed		passed	
		failed	passed		passed	
		failed	passed		failed	
	B	passed	passed	failed	passed	passed
		passed	passed	failed	passed	passed
		passed	failed		failed	
	lime	failed	passed	passed	passed	passed
		failed	passed	failed	passed	passed
		passed	failed		passed	
gravel	none	failed	failed	passed	passed	passed
		failed	passed	passed	passed	passed
	A	failed	failed		passed	
		failed	failed		passed	
	B	failed	passed	failed	passed	passed
		failed	failed	failed	passed	passed
	lime	failed	failed	failed	passed	failed
		failed	failed	passed	passed	passed
Limestone	none	failed	failed	failed	failed	failed
		failed	failed	failed	failed	failed

The following are observations based on the HWTT laboratory testing using a no “SIP in less than 15,000 load application” criterion to define a moisture susceptible mix:

- *Based on HWTT, the granite mix would be expected to have*
    - *Marginal performance when tested on the APA Jr and analyzed with the APA Jr software. Only the mixture using additive B would pass the criterion.*
    - *Marginal performance when tested on the APA Jr and analyzed manually. Only the mixture using additive A would pass the criterion*
    - *Poor performance when tested with the Cox & Sons and analyzed with the Cox & Sons software. All samples of the granite mix tested on the Cox & Sons failed the SIP criterion (and all SIPs are considered valid), except one of the two samples mixed with hydrated lime.*
- *Based on HWTT, the gravel mix would be expected to have*
    - *Poor performance when tested on the APA Jr and analyzed with the APA Jr software. All samples failed the criterion.*
    - *Poor performance when tested on the APA Jr and analyzed manually. All samples failed the criterion.*
    - *Marginal performance when tested with the Cox & Sons and analyzed with the Cox & Sons software. Only the control passed the criteria.*
- *Based on HWTT, the limestone mix would be expected to have*
    - *Poor performance when tested on the APA Jr and analyzed with the APA Jr software. All samples failed the criterion.*

    - *Poor performance when tested on the APA Jr and analyzed manually. All samples failed the criterion.*
    - *Poor performance when tested with the Cox and analyzed with the Cox software. All samples failed the criterion.*

The results from the laboratory testing do not reflect the typical performance expected for the aggregate types selected based on the historic performance of that aggregate type.

Taylor and Khosla [1983], Santucci [2010], and Sebaaly [2010] identified the following seven processes which contribute to the causes of moisture damage.

- *Detachment of the binder film from the aggregate without film rupture,*
- *Displacement of the binder film from the aggregate through film rupture,*
- *Spontaneous emulsification and formation of an inverted emulsion of water in binder,*
- *Pore pressure-induced damage due to repeated traffic loading,*
- *Hydraulic scour at the surface due to tire-pavement interaction*
- *pH instability of the contact water, which affects the binder-aggregate interface, and*
- *Environmental factors such as excessive rainfall, large temperature fluctuations, and freeze-thaw (F/T) conditions.*

When designing the experiment the aggregate sources were selected based on aggregate type since performance data for individual quarries was not available for Ohio sources. It was expected the granite would be the most susceptible to moisture damage, the gravel marginally susceptible to moisture damage, and the limestone the least susceptible to moisture damage as determined by TSR. However, as shown above, the results for this project did not follow the expected trend. The results of the TSR and HWTT are typically explained by the first two factors and the last factor, i.e. detachment or displacement of the binder film from the aggregate as a result of being subjected to moisture and freeze/thaw conditions in the case of TSR or high temperature and moisture in the case of the HWTT.

The examination of the TSR samples found little evidence of detachment or displacement of the binder from the aggregate, with the exception of some thinning of the asphalt coating on some of the aggregates in the samples containing gravel aggregates. However, this condition was observed on the unconditioned samples also. In addition, the ineffectiveness of the additives indicates other factors are affecting the outcome of the testing.

As discussed previously, TSR samples tested by the contractors as part of the JMF development for the granite with lime and the limestone mix passed the TSR criteria. The only difference between the JMF samples and the samples compacted in the lab was the binder. The binder used on this project was modified with polyphosphoric acid (PPA) to obtain a PG 64-28 grading. Research has shown PPA can affect the moisture damage resistance of a mix [TRB, 2012]. Buncher and D'Angelo report PPA could improve the moisture resistance of mixes using acidic aggregate, such as granite [TRB, 2012]. Arnold, Youtcheff, and Needham [TRB 2012] have also shown PPA modified binders my increase stripping potential, although the research shows lime should mitigate the potential for moisture damage whereas the ability for liquid additives to mitigate the potential for moisture damage is aggregate/binder specific.

In addition, other factors have been identified which may influence the test results including dust, binder content, porosity, etc. (NCHRP, 2010). HWTT is also sensitive to binder grade and test temperature. The porosity may explain the performance of the mixture with limestone. During TSR testing, these samples were easily saturated with a low vacuum applied for a short period of time while the granite and gravel samples required a high vacuum applied multiple times for a long period of time to achieve the target saturation.

Finally, test variability as high as 25% has been reported for the TSR test in the literature (Schram, 2012). When contractors in Ohio conduct the TSR test, additional samples are compacted and submitted to ODOT for verification testing. The data for calendar years 2020 and 2021 were provided to the researcher. Tests with comments indicating issues were removed from the dataset. The contractors' results, ODOT's results, and whether the sample passed or failed the test based on ODOT's results are presented in Appendix L. A plot of the data is shown in Figure 3. A linear regression, forced through the origin, has an R^2 of 0.24, indicating very little correlation between contractor's test results and ODOT's results. The contractor's TSR value varied as much as 36% from ODOT's value. NCHRP (2010) reported 70% to 80% saturation level may induce micro-cracks which contribute to test variability. Unlike the TSR test, the literature does not report the HWTT to be a highly variability test procedure.

Figure 3 Contractor's and ODOT's TSR Test Data, Calendar Years 2020 and 2021

5.5 Key findings from the Cost Analysis

A life cycle cost analysis (LCCA) was conducted to assess the potential impact of moisture damage, and antistrip usage on the cost of rehabilitation activities needed to keep asphalt pavements in serviceable condition for 35 years in Ohio. This performance period is based on the current analysis period specified in section 703.1 of the Ohio DOT Pavement Design Manual.

The study evaluated three different scenarios:

- Scenario 1-Moisture resistant (control) mixes
- Scenario 2-Moderate stripping potential mixes without antistrip additives
- Scenario 3- Moderate stripping potential mixes with antistrip additives

The LCCA indicated the use of moisture susceptible aggregates significantly increases the cost of rehabilitation activities required to keep the pavements in good condition. The analysis showed an increase in maintenance cost of $19,066 per lane mile when susceptible aggregates are used instead of moisture resistant aggregates as a result of the reduced service life. The evaluation also showed the use of antistrip additives had a small impact in the cost of rehabilitation activities ($704 per lane mile), and therefore it is justified to require the use of antistrip additives when the moisture susceptibility potential of the aggregates is unknown or when it is known that the aggregates are susceptible to moisture.

It is important to point out this evaluation is very limited, and it was based on the assumption that antistrip additives will provide satisfactory moisture susceptibility performance. However, actual field performance data of mixes with susceptible aggregate are needed to verify that the improved performance presented in this analysis can be achieved.

6 Conclusions and Recommendations

The objectives of this research were to (1) provide recommendations, based on a literature search and limited laboratory testing, for refining ODOT's current moisture susceptibility test procedures, or recommend a new test procedure, which will better predict field performance and (2) determine the feasibility, cost, and risk of using antistripping agents with marginal or poor performing mixtures in lieu of laboratory testing for moisture susceptibility.

This research consisted of five tasks; (1) conduct a literature search to identify laboratory test procedures used within the United States, as well as internationally, for identifying moisture susceptibility of asphalt mixtures and the use of antistrip agents to mitigate moisture susceptibility (2) survey state DOTs to identify current and best practices across the United States (3) review state DOT specifications for moisture susceptibility testing requested from each agency through the survey, or obtained from state DOT websites, (4) recommend and evaluate candidate a test procedure and antistrip additives, and (5) conduct an economic analysis to determine the feasibility, cost, and risk of using antistripping agents with marginal or poor performing mixtures in lieu of laboratory testing for moisture susceptibility

The literature search identified over 22 tests which have been developed to determine the moisture susceptibility of asphalt mixtures based on testing of uncompacted or compacted mixtures. The modified Lottman, also known as the TSR test (AASHTO T 283), developed in the early 1980's, was the most widely used test used by state agencies based on the survey and specification review. The AASHTO T 283 test is a complicated and time-consuming. The literature reported the reliability of the TSR test in predicting the moisture resistance performance in the field was mixed, with early research reporting a good correlation but later research reporting poor correlation. An analysis of between lab results measured by contractors and by ODOT using contractor compacted specimens found a very weak correlation (R^2= 0.24).

The next most widely used test was the HWTT. The survey found there has been a move by state DOTs from the TSR to the HWTT over the last 10 years, the benefit being the HWTT can be completed in a much shorter time period and can be used to evaluate both moisture susceptibility and rutting resistance. The percent of agencies who indicated lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage was higher for agenies who perform multiple test or the HWTT than for the agencies who only perform the TSR test.

Limited TSR and HWTT lab testing was performed in this study using granite, gravel and limestone aggregate. The granite and gravel aggregate was also tested with lime additive and two liquid antistrip additives. The lab testing was inconclusive. Field performance of the mixes was not available to confirm the results. Detachment or displacement of the binder from the aggregate was not visible upon close examination of the TSR samples indicating other factors are affecting the tests. Potential factors could include PPA in the asphalt binder, dust, low AC content, porosity of the coarse aggregate, stripping of the fine aggregate, etc.

With regard to the use of antistrip, Christensen et. al. [2015] found the benefit/cost ratio was greater than 1 for the use of antistrip in the state of Pennsylvania. The literature search found lime, in addition to providing resistance to moisture, also reduced age hardening, increases high temperatue stiffness, and increases tensile elongation at low temperatures. LCCA evaluation by the research team showed the use of antistrip additives had a small impact in the cost of rehabilitation activities ($704 per lane mile), and therefore it is justified to require the use of antistrip additives when the moisture susceptibility potential of the aggregates is unknown or when it is known the aggregates are susceptible to moisture. The evaluation was very limited, based on the assumption antistrip additives will provide satisfactory moisture susceptibility performance. Actual field performance data of mixes with susceptible aggregate are needed to verify the improved performance presented in the analysis can be achieved.

The following are the recommendations of the research team:

- *Based on the literature search and state DOT responses to the survey, the TSR test may not be able to accurately capture the moisture susceptibility in the field. In addition, in Ohio, the correlation between contractor tested and ODOT tested TSR specimens for the same mix is low. Nothing was discovered in the literature search or other state specifications which would improve the current ODOT Supplement's procedure. As a result, the use of Supplement 1051 (AASHTO T 283) to determine moisture susceptibility should be discontinued.*
- *The percent of state DOTs who indicated lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage was higher for agenies who perform multiple test or the HWTT, than for the agencies who only perform the TSR test. Therefore, it is recommended ODOT move forward with implementation of the HWTT AASHTO T 324-22 test procedure using 15,000 as the SIP limiting criteria.*
- *Based on the survey response and the review of state DOT specifications, the range of test temperature used for the HWTT for PG 64 and above ranged from 45°C to 50°C. The predominate temperature of 50°C was used for this project. However, samples tested at 50°C exceeded 12.5 mm rutting limitations in fewer passes than the 15,000 SIP criteria. Therefore, the lower test temperature of 45°C is recommended.*

- *The LCCA evaluation showed the use of antistrip additives had a small impact in the cost of rehabilitation activities ($704 per lane mile), and therefore it is justified to require the use of antistrip additives when the moisture susceptibility potential of the aggregates is unknown or when it is known the aggregates are susceptible to moisture.*

7 Appendix A: Literature Review

7.1 Introduction

A comprehensive literature search was conducted, in which over 100 journal articles, technical reports, conference proceedings, and conference presentations were identified that pertained to laboratory testing to assess moisture susceptibility of asphalt mixtures, and the use of antistrip agents to mitigate moisture susceptibility in asphalt mixtures. There is a wide body of work related to moisture susceptibility of asphalt mixtures. The intent of this literature search is to help identify tests, conditioning methods, or combination of both, which show promise for improving the ODOT's ability to identify asphalt mixtures susceptible to moisture damage. A summary of the journal articles, conference proceedings and technical reports is provided in the Appendix. Key findings related to the commonly utilized test methods for testing moisture susceptibility of asphalt mixtures are provided herein, as well.

7.2 Moisture Susceptibility of Asphalt Mixtures

Moisture damage has been defined by Little and Jones (*2003*) as "the loss of strength and durability in asphalt mixtures due to the effects of moisture." Moisture susceptibility of asphalt mixtures refers to the tendency for specific combinations of asphalt binders and aggregates to sustain damage or a loss in functionality due to the detrimental effects of moisture under repetitive traffic loading. As moisture penetrates the mastic, it weakens and makes it more susceptible to moisture under cyclic loading (*1*). Little and Jones (*2003*) also stated moisture damage can occur due to the loss of bond between asphalt cement or the mastic (asphalt cement and mineral filler) and the aggregate.

There are two major causes of moisture damage within asphalt mixtures: (1) the loss of adhesive bonding between the asphalt binder or mastic and the aggregates, and (2) the loss of cohesion in the mastic due to the presence of moisture (Little and Jones, *2003*). Researchers have identified the processes listed below which contribute to the causes of moisture damage (*Taylor and Khosla, 1983; Santucci, 2010; Sebaaly et al., 2010*). While Little and Jones (*2003*) identified these and other processes which contribute to moisture damage, they concluded moisture damage is often the result of a combination of processes:

- Detachment of the binder film from the aggregate without film rupture,
- Displacement of the binder film from the aggregate through film rupture,
- Spontaneous emulsification and formation of an inverted emulsion of water in binder,
- Pore pressure-induced damage due to repeated traffic loading,
- Hydraulic scour at the surface due to tire-pavement interaction
- pH instability of the contact water, which affects the binder-aggregate interface, and
- Environmental factors such as excessive rainfall, large temperature fluctuations, and freeze-thaw (F/T) conditions.

7.3 Laboratory Characterization of Moisture Susceptibility

Over the last few decades, several moisture conditioning protocols and laboratory tests have been proposed to evaluate the moisture susceptibility of asphalt mixtures. In general, these protocols and test methods can be grouped into four categories: (1) tests on uncompacted loose mixtures, (2) tests that mechanically measure stiffness or tensile strength of asphalt mixtures before and after moisture conditioning to simulate field conditions, (3) tests that utilize repetitive loading of compacted mixtures in the presence of water and (4) other tests on compacted specimens.

The literature search revealed the following laboratory tests have been used to assess the moisture susceptibility of asphalt mixtures:

- Tests on uncompacted loose mixtures:
    - Boiling Tests (includes ASTM D 3625)
    - Static Immersion Tests (includes ASTM D1664, AASHTO T 182)
    - Dynamic Immersion Tests
    - Rolling Bottle Test
    - Pull-off tensile strength test
    - Surface Energy
    - Tack factor
    - Methylene Blue Test (ISSA TB 145)
    - Net Absorption Test (SHRP Project A-003B)
- Tests that mechanically measure stiffness or tensile strength
    - Lottman/Modified Lottman Test (AASHTO T 283, ASTM D4867)
    - Resilient Modulus
    - Dynamic Modulus Test
    - Fracture Energy Test/DCT (ASTM D7313)
    - Marshall Stability/Retained stability test
- Tests that utilized repetitive loading of compacted specimens
    - Hamburg Wheel Track Test (HWTT) (AASHTO T 324)
    - Loaded Wheel Test or Asphalt Pavement Analyzer (APA)
    - Flow Number
    - Push-pull (compression-tension) test
    - Rotary Wheel Tester
- Other tests on compacted specimens
    - X-Ray CT Imaging
    - Freeze Thaw Pedestal Test (AASHTO T 165 or ASTM D1075)
    - Uni-axial Compression Test
    - Static Creep test

Figure 4 shows which tests states use to assess moisture damage of asphalt pavements, as of 2018. As shown, the largest proportion of states use tensile strength ratio (TSR), followed by the Hamburg Wheel Tracking Test. As shown in the figure below, states surrounding Ohio utilized the TSR test to evaluate the susceptibility to moisture damage.

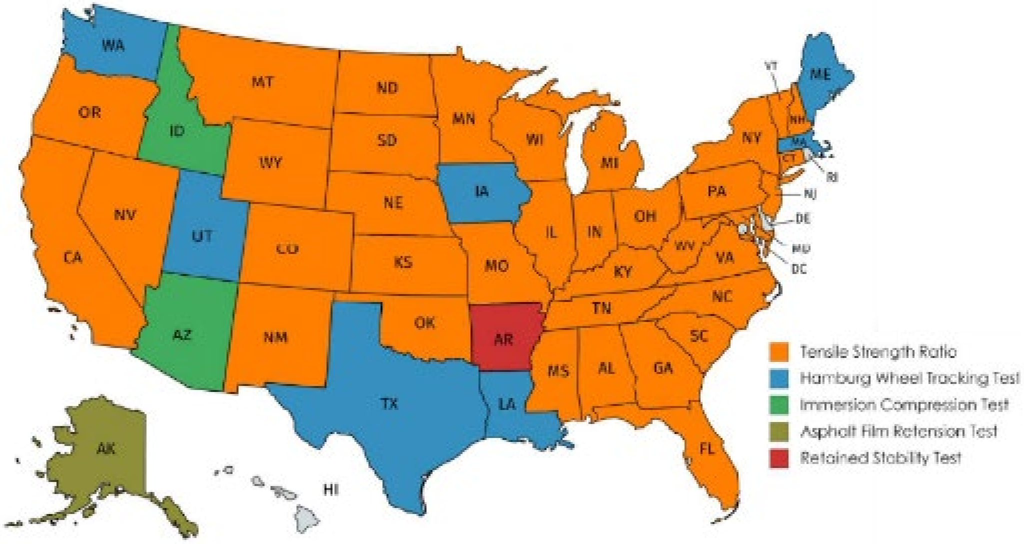


Figure 4 U.S. Map of Current Use of Moisture Damage Tests [West et. al., 2018]

Among the tests identified in literature, Modified Lottman Test (also known as Tensile Strength Ratio [TSR]) and HWTT are most commonly used by state agencies. The detailed procedures and parameters of these two tests are described in the following subsections.

7.4 Tensile Strength Ratio

The TSR test (AASHTO T 283, or ASTM D4867) is the most common laboratory standard test to evaluate moisture susceptibility of asphalt mixtures. To perform the test, the indirect tensile (IDT) strength at 25°C is determined for dry specimens, and for wet specimens that are moisture conditioned by following the modified Lottman procedure. As presented in Figure 5, the moisture conditioning procedure consists of partial vacuum saturation, one freeze-thaw cycle for 16 hours at -18°C, and soaking in warm water for 24 hours at 60°C. The TSR is then determined as the ratio of the average IDT strength obtained from three moisture conditioned specimens to the average IDT strength of three dry control specimens. Asphalt mixtures with higher wet IDT strength and TSR values are expected to have better resistance to moisture damage. It should be noted there are two notable differences in the AASHTO T 283 and ASTM D 4867 specifications. First, the freeze-thaw cycle is optional in the ASTM specification and mandatory in AASHTO T 283. Second, the target saturation level is 55% to 80% in ASTM D 4867 and is 70% to 80% in AASHTO T 283.

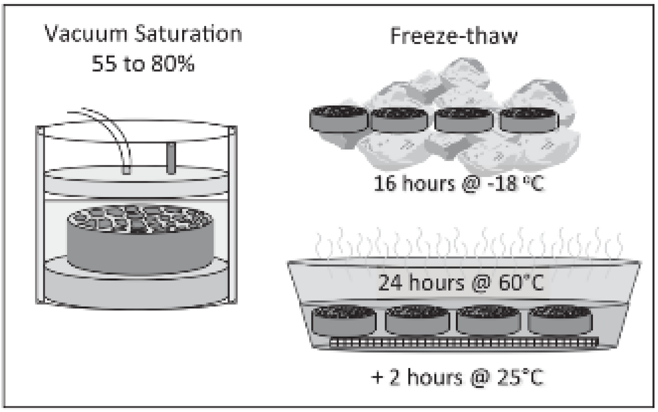


Figure 5 Schematic Modified Lottman Moisture Conditioning Procedure [Santucci, 2010]

The AASHTO T 283 has undergone several revisions. As noted by Zaniewski and Viswanathan (2006), the specification was updated in 2003 to include a mandatory freeze-thaw cycle, while the previous (1989) version included only partial saturation and optional freeze-thaw cycle.

The ODOT adopted a modified version of AASHTO T 283 as specified in Supplement 1051. In NCHRP project 9-13 Epps et al. *(2000)* recommended states transitioning from Marshall to gyratory compacted samples during implementation of Superpave perform a structured laboratory program to validate the test procedure using gyratory samples and their aggregates and binders. Liang *(2008)* performed the recommended evaluation for ODOT. The following variables and their effect on dry tensile strength, conditioned tensile strength and TSR were considered:

- aggregate source - one limestone, one trap rock, and two gravel sources were used
- binder – one virgin (PG 64-22) and one polymer modified (PG 70-22) were used
- compaction method – Marshall and gyratory
- specimen size – 4” for Marshall, 4” and 6” for gyratory
- aging method – none, 2, 4, and 15 hours for loose mix; 0 to 24 hours and 72 to 96 hours for compacted samples
- degree of saturation – 55, 75, and 90%
- freeze-thaw cycle – none and one freeze/thaw cycle

Liang *(2008)* reported the following findings:

- Loose mix aging was the most important factor to affect dry tensile and freeze/thaw tensile strength. Source of aggregate and compaction method were also important. Saturation level was also important for freeze/thaw tensile strength.
- Loose mix aging, saturation level, and compaction level were important factors affecting TSR values.

Liang recommended a conditioning and testing procedure for 6” gyratory specimens which would produce results similar to the 4” Marshall specimen. Liang’s study did not relate the test results to field performance. Illinois DOT also conducted a study to aid in transitioning from 4” Marshall specimens to 6” gyratory specimens. Zehr (2002) found TSR values from 6” gyratory compacted specimens were larger than 4” Marshall specimens, and recommended the criteria, at that time, of 0.75 for Marshall-compacted specimens but increased to 0.85 for 6” gyratory compacted specimens. Zehr (2002) also reported the average tensile strength of the 4” diameter Marshall specimens was greater than the 6” gyratory compacted specimens, and plant-produced mixtures had greater average tensile strength than lab-produced mixtures. In addition to increasing the TSR criterion, Zehr also recommended Illinois DOT consider a minimum tensile strength of 60 psi.

While a freeze-thaw cycle is included in the AASHTO T 283 specification and optional in the ASTM D4867, literature indicates various conditioning methods have been explored. Aschenbrener and McGennis (1993) explored five conditioning means: freeze, no freeze, 30-minute saturation, short term, and no short-term aging. The findings from the report indicated that freezing and saturation can accurately distinguish between well performing and poorly performing mixes. Aging however, did not have any distinguishing effect on mixes. Christensen et al. (2015) examined the efficiency of saturation at high and low rates concluding that low saturation rates are unable to distinguish even a single poorly performing mix.

Behiry (2013) explored five degrees of saturation (0%, 10%, 25%, 50%, and 80%). Behiry also explored the use of fresh water and sea water for soaking the samples at 1, 3, 7, and 14 days, as well as varying specimen air voids: 1.5%, 4% and 6%. He found as air voids increase, indirect tensile strength (ITS) decreases, and similarly as the condition period increases, ITS decreases. As the condition period increased, it was found TSR values decrease, and the rate of decrease was greater at higher air voids. He reported ITS values decreased by 19 to 40% with the increase in saturation level from 50 to 80%. Behiry used a TSR 0.80 criterion and reported for the following conditions all mixtures were considered moisture resistant:

- at 1.5% air voids
- at condition period of 1 day
- at conditioning period of 3 days for fresh water

Epps et al. (2000) investigated the effect of conditioning by saturation and by freeze thaw and found the level of saturation had little effect on tensile strengths observed in freeze-thaw and no freeze-thaw scenarios. Mixes examined in a study by Solaimanian et al. (2010) revealed no relationship between saturation level and TSR ratio. A report by (NCHRP et al., 2010) indicated the standard 70-80% saturation level for conditioning may induce micro-cracks which contributes to the test variability noticed by researchers. Liang's (2008) study emphasized that saturation level is crucial to the TSR value recorded recommending that level be maintained between 80-90%. The current AASHTO T 283 and ASTM specifications state specimens saturated more than 80% have been damaged and must be discarded.

The AASHTO T 283 specification was updated in 2003 to include a mandatory freeze-thaw cycle. Zaniewski and Viswanathan (2006) examined the application of the 2003 AASHTO T 283 specification for West Virginia mixes, although a moisture sensitivity problem was not believed to exist in the state. The authors conducted indirect tensile strength testing following no conditioning, saturation only, and saturation and one freeze-thaw cycle. They concluded it was not a reliable test method for moisture sensitivity. Furthermore, Zaniewski and Viswanathan (2006) reported their results were consistent with Epps et al. (2000) in that there was 1) a lack of sensitivity relative to the saturation level; 2) samples subjected to saturation only had results similar to samples saturated and subjected to one freeze-thaw cycle; and 3) TSR was not found to reliably reflect field performance.

Dave et al. (2018) noted a consistent trend of stronger ITS values for both conditioned and unconditioned samples when examining well performing materials. In contrast, Sebaaly et al.

(2001) noted that moisture conditioning (freeze-thaw and no freeze-thaw) had no significant effect on Indirect Tensile Strength and Resilient Modulus.

Liang (2008) noted the need to incorporate at least one freeze-thaw cycle to help distinguish between mixes. Whereas Abuawad et al. (2014) conditioned samples by five freeze-thaw cycles, Mallick et al. (2005) suggested that a minimum of six freeze-thaw cycles be completed for effectively discriminating between mixes. Watson et al. (2013) investigated the use of 0, 1, 5, and 10 freeze-thaw cycles, and found 5 and 10 cycles were "significantly more discriminating than one freeze-thaw cycle alone."

Hanz et al. (2007) modified the ASTM D4867 method to evaluate both fracture energy and indirect tensile strength testing for assessing moisture susceptibility of asphalt mixtures. After long-term aging, six specimens for each mix were compacted and conditioned by vacuum saturation to 55-85%. Three of the specimens were conditioned in a water bath at 60C (140F) for 24 hours. All 6 specimens were cut into discs 50.8 mm (2 inches) thick. Once specimens were dry, linear variable transducers (LVDTs) were mounted to the samples and conditioned in the environmental chamber of the machine at the test temperature for 2 hours prior to testing by indirect tension at 10C. Tensile strength ratio was calculated as the average conditioned tensile strength to the average unconditioned tensile strength. Hanz et al. (2007) found all mixes exhibited losses in tensile strength due to moisture conditioning. Additionally, they found results appropriately differentiated between mixes with aggregate known to cause stripping and those mixes which used aggregate known to be resistant to moisture damage.

While early studies suggested a good correlation between Lottman testing and field performance, most studies found TSR was inconsistent at predicting field performance. Lottman (1982) reported good correlation between performance in the field 5 years after construction and stripping found in the laboratory. Tunnicliff and Root (1984) reported performance in the field for 16 of 19 sections was as expected based on results of Lottman testing in the laboratory and the use of antistripping agents. Aschenbrenner and McGennis (1993) concluded the modified Lottman test had reasonably good correlation with field performance, although it was not ideal. They also reported swell in samples that were highly susceptible to moisture damage, and which had been saturated for 30 minutes. They found as swell increased, the TSR values decreased, and field performance decreased. Stuart (1998) conducted tests based on core samples taken from the field and noted a poor correlation between tests and field performance. Bahia and Ahmad (1999) compared TSR results to pavement distress index (PDI) numbers in Wisconsin and concluded no relationship exists between PDI, and TSR values in the mixture designs or TSR on recovered field samples. Results from Sebaaly et al. (2001) noted that TSR values from core samples obtained in the field were consistent with field performance. However, Sebaaly et al. (2001) pointed out that laboratory prepared samples were inconsistent in observance with field performance. In a report by Christensen et al. (2015), for samples with a high saturation level of 70-80%, there was still a significant percentage (50%) of false positives with respect to field performance of moderately susceptible mixes. Furthermore, Christensen et al. (2015) reported the modified Lottman test was reasonably accurate in terms of discriminating between mixes with low and high susceptibility to moisture damage and had poor accuracy in terms of identifying mixes with moderate susceptibility. Dave et al. (2018) reported the Modified Lottman test and TSR criteria were unable to distinguish between poorly, moderate and well performing mixtures.

The minimum TSR criteria used by Aschenbrener and McGennis (1993) and Stuart (1998) was 80%, consistent with the standard range of 70 – 80%. However, Aschenbrener and McGennis (1993) recommended a value of 85% be considered to ensure mixtures with marginal performance would be rejected. Hanz et al. (2007) reported TSR values had ranges (maximum minus minimum TSR value) for a given mix between 6% and 37%. Due to this spread in the TSR data, the researchers concluded, in following Wisconsin's procedure at the time, there is some "uncertainty that a mix with an average TSR greater than 0.7 is moisture resistant." Therefore, they adapted the ASTM D4867 between lab precision and compared the standard deviation of all TSR measurements for a given mix to the 8% threshold. Those that had a standard deviation less than 8% were then compared to Wisconsin DOT's criterion of 0.70 (and 0.75 for mixes using antistrip) used to identify mixes resistant to moisture damage.

7.5 Hamburg Wheel Tracking Test

The HWTT per AASHTO T 324 is a laboratory procedure that uses repetitive loading in the presence of water and measures the rut depth induced in an asphalt mixture with increasing load cycles. To perform the test, two sets of cylindrical specimens are placed side by side, submerged in water, and subjected to approximately 52 passes of a steel wheel per minute. During testing, rut depths at different positions along the specimens are recorded with each load cycle. Figure 6 presents a typical plot of the HWTT test result curve in terms of rut depth versus load cycles. As shown, the curve can be divided into three main phases including post-compaction phase, creep phase, and stripping phase. The post-compaction phase consists of the consolidation of the specimen that occurs as the wheel load densifies the mixture and the air voids decrease significantly. This phase usually occurs within the first 1,000 load cycles. The creep phase is represented by an approximately constant rate of increase in rut depth with load cycle. The rut depth accumulated in this phase is primarily due to the viscous flow of the asphalt mixture. The stripping phase starts once the bond between the asphalt binder and the aggregate starts degrading, causing visible damage such as stripping or raveling with additional load cycles. The stripping inflection point (SIP) represents the number of load cycles on the HWTT curve at which a sudden increase in rut depth occurs, mainly as a result of the stripping of the asphalt binder from the aggregate; it is graphically represented at the intersection of the fitted lines that characterize the creep phase and the stripping phase. Rut depth and SIP are the parameters used to evaluate the mixture resistance to rutting and moisture damage, respectively. Asphalt mixtures with lower rut depths and higher SIP values and are considered to have better performance in the HWTT.

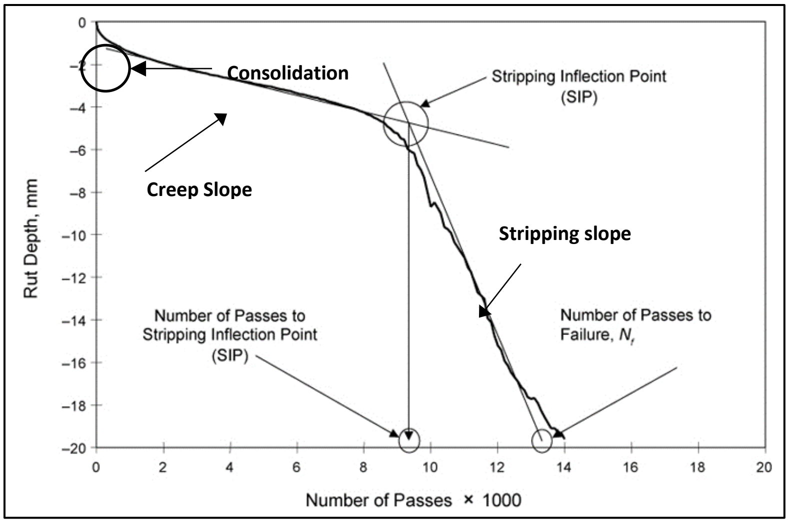


Figure 6 Typical Plot of HWTT Results [AASHTO, 2019]

Research conducted in the mid-90s showed the HWTT was sensitive to the quality of aggregates, asphalt binder stiffness, length of short-term aging, crude oil source, type of antistrip treatment (liquid vs. hydrated lime), and compaction temperature (Aschenbrener, 1995). The study showed excellent correlation between the stripping inflection point, and the known varying stripping performance of several pavement sections. Regarding the use of antistrip agents, the study showed that liquid antistrip (LAS) additives improved the HWTT results with some aggregates but not with other aggregates. On the other hand, hydrated lime improved the test results of all the mixes tested.

Izzo et al. (1999) evaluated asphalt mixtures with and without antistrip additives with the HWTT. All the mixes contained an AC-20 binder that was commonly used in Texas. The researchers indicated that for tests conducted at 40°C, the mixtures with hydrated lime had the best performance, followed by those that contained LAS additive, and the worst performance was observed for mixtures with no modifications. Inconsistent trends were observed at 50°C suggesting that for mixes with AC-20 binder this temperature was too extreme.

The effectiveness of the HWTT to assess the moisture sensitivity of asphalt mixes was also evaluated using laboratory prepared samples and field cores by Lu et al. *(Lu, Harvey and Monismith, 2007)*. It was reported that the test procedure was able to identify the effect of antistrip additives but underestimated the performance of mixes with soft binders when a test temperature of 50°C was used. In addition, laboratory test results and field performance showed a fair correlation, but in some cases, the test procedure failed mixes that performed well in the field or yielded false positive results.

Project NCHRP 9-49A investigated the field performance of 28 hot mix asphalt (HMA) and warm mix asphalt (WMA) field projects with a service life ranging from 2 to 10 years (National Academy of Science, 2017). The researchers reported that although no moisture-related distress was found in the field for any of the projects, the HWTT was able to distinguish between mixtures with and without antistrip additives. Out of the eight projects that showed SIPs with less than 15,000 passes, seven projects did not use antistrip additives. These results also suggested that antistripping agents may be useful to prevent moisture damage, but it was recommended to continue monitoring these field projects for long-term moisture damage potential.

Iowa DOT uses the ratio between the stripping slope and the creep slope to validate the SIP number (Schram et. al., 2012). The SIP number is considered valid if the ratio is 2.0 or greater. Stripping behavior was not observed in sections with a ratio less than 1.0 even though an SIP number can be calculated.

An alternative HWTT parameter termed stripping number (SN) has been proposed by Yin et al. (2014). For this method, the HWTT results in terms of rut depth versus load cycle are first fitted by an exponential function composed of one part with negative curvature followed by another part with positive curvature. As presented in Figure 7, the critical point where the curvature changes is referred to as the stripping number (SN), and the load cycle where SN occurs (LC_{SN}) is proposed as a parameter to evaluate the moisture susceptibility before stripping. SN represents the maximum number of load cycles the mixtures can withstand before adhesive fracture between the asphalt and the aggregate occurs. Asphalt mixtures with higher LC_{SN} are considered to have better resistance to moisture damage. As compared to SIP, SN is less subjective because its determination is based on curve fitting of the entire rut depth curve instead of fitting two tangential lines for the creep phase and stripping phrase. This parameter has been used to assess the moisture susceptibility of asphalt mixtures (*Newcomb et al., 2015; Yin, et. al, 2020*).

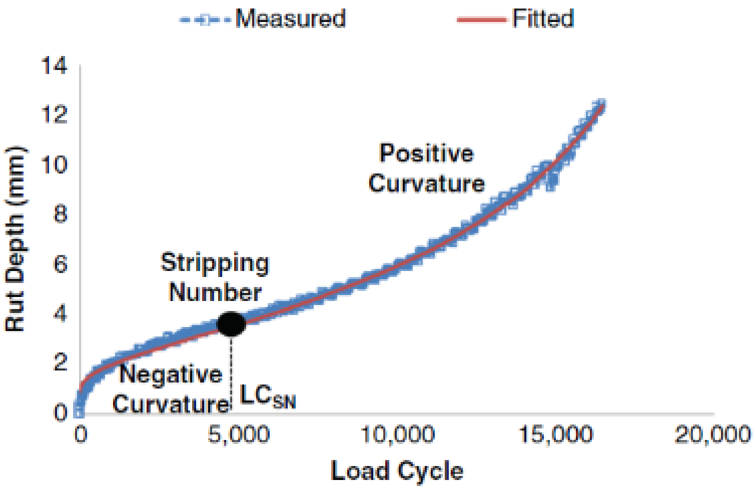


Figure 7 Alternative HWTT Stripping Number Parameter [Yin et. al., 2014]

7.6 HWTT States' Specifications on Moisture Susceptibility

Although HWTT is used as a rutting test in state specifications, several agencies have an additional minimum requirement for the moisture susceptibility parameter of stripping inflection point (SIP) (see Table 7 for an example) *(NAPA, 2022)*. AASHTO T 324 does not specify a test temperature to conduct the test, and states use a test temperature to reflect their local environmental conditions. As presented in Table 7 different test temperatures are currently being used by state DOTs. In addition, some agencies use the same temperature for all binder/mixtures, while others require the adjustment of test temperature based on the binder high temperature PG.

Table 7 Summary of HWTT Criteria used by State DOTs [NAPA, 2022]

States	Binder/Mixture Types	Test Temperature (°C)	Criteria
Iowa	PG 58-XX S and PG 52-XX S	40	Min. 10,000 passes SIP
	All other binder grades	50	Min.14,000 passes with no SIP
Maine	PG 64-28	45	Max. 12.5mm rut depth at 20,000 passes; Min. 15,000 passes SIP
	PG 64E-28	48	
	PG 70E-28	50	
Massachusetts	Traffic Level 1	45	Max. 12.5mm rut depth at 20,000 passes; Min. 10,000 passes SIP
	Traffic Level 2 and 3		Max. 12.5mm rut depth at 20,000 passes; Min. 15,000 passes SIP
Wisconsin	Binder designation level S	46	Max. 12.5mm rut depth at 10,000 passes; Min. 8,000 passes SIP
	Binder designation level H		Max. 12.5mm rut depth at 15,000 passes; Min. 8,000 passes SIP
	Binder designation level V and E		Max. 12.5mm rut depth at 20,000 passes; Min. 8,000 passes SIP
Washington	<0.3 M ESALs	50	Max. 10 mm rut depth at 20,000 passes; Min. 10,000 passes SIP
	0.3-3 M ESALs		Max. 10 mm rut depth at 20,000 passes; Min. 12,500 passes SIP
	>3 M ESALs		Max. 10 mm rut depth at 20,000 passes; Min. 15,000 passes SIP

7.7 Antistrip Agents

The most commonly used strategy to minimize moisture damage in asphalt pavements is using antistrip agents such as hydrated lime and LAS additives. Lime is widely used by transportation agencies to improve the resistance of asphalt mixtures to moisture damage; it can be added in power form to dry or damp aggregate or as a slurry margination *(Santucci, 2010)*. The typical rate for hydrated lime is 1% by weight of the aggregate. A study at the Western Research Institute determined the addition of hydrated lime benefited the pavement in several ways: reduced asphalt age-hardening, increased high-temperature stiffness of unaged asphalt, increased tensile elongation of asphalt at low temperatures, and improved resistance to moisture damage. These benefits consequently resulted in increased durability, reduced rutting, improved fatigue resistance in aged pavements, and improved resistance to low-temperature transverse cracking (*Petersen et al., 1987)*.

Most LAS additives are amine-based compounds designed to act as coupling agents to promote the adhesion at the binder-aggregate interface *(Curtis et al., 1993)*. LAS additives are typically added at a rate of 0.25 to 1% by weight of the binder. Although LAS additives are more convenient and generally less expensive, their effectiveness to reduce mixture susceptibility depends on the physicochemical properties of the asphalt binder and the aggregate, and the dosage of liquid antistrip agent used (*Epps et al., 2003)*.

Sebaaly et al. (*2010)* compared the performance of fifteen mixtures using aggregates from five states and three treatments: no antistrip agent, 0.5% LAS additive, and 1% hydrated lime. TSR testing was conducted on sample conditioned to up to 15 freeze-thaw cycles. TSR results indicated both lime and LAS were found to improve resistance to moisture susceptibility, the untreated and LAS treated mixtures had significantly lower strength after several freeze-thaw cycles, while the hydrated lime treated mixtures were able to maintain high strength values for 15 cycles with all aggregate sources. A similar study was conducted by Watson et al. (*2013*) with mixtures treated with hydrated lime, LAS, and a warm-mix asphalt antistrip additive. The mixtures were subjected to multiple free-thaw cycles for up to 10 cycles. The results indicated the hydrated lime had the highest tensile strength and highest TSR values and was the only additive treatment to meet the minimum of 80% TSR for all freeze-thaw cycle combinations evaluated.

Amirkhanian et al. *(2018*) evaluated the performance of LAS additives of asphalt mixtures with hydrated lime, five LAS additives, six aggregate sources, and six RAP sources. Their test results showed hydrated lime-treated asphalt mixtures always met the TSR (≥ 85% and wet ITS (≥ 65 psi) required criteria, while liquid LAS additive-treated asphalt mixtures of some aggregate types did not meet these requirements. The researchers recommended a minimum dosage of 0.7% LAS additives by weight of binder for those mixtures that did not meet the minimum required criteria.

In general, antistrip agents have demonstrated that they are effective in mitigating moisture susceptibility of asphalt mixtures, but their effectiveness depends on the source (type), dosage, and properties of the mixture components (asphalt and aggregates).

Christensen et al. [2015] investigated the economic benefits of testing asphalt mixtures for moisture susceptibility and the use of antistrip in asphalt mixtures in Pennsylvania. They performed a life cycle cost analysis (LCCA) using the guidelines in the PennDOT Pavement Policy Manual and performed a cost/benefit analysis (CBA) of testing for moisture susceptibility and the use of antistrip considering the ability of the AASHTO T 283 to correctly identify moisture susceptible mixtures.

Christensen et al. [2015] considered three aggregates in both the LCCA and the CBA; aggregates which are not susceptible to moisture damage (the control), aggregates which are highly susceptible to moisture damage, and aggregates with moderate susceptible to moisture damage. Two performance scenarios were considered; the "realistic" scenario which is the likely performance of the section, and the "optimistic" scenario, which is performance slightly better than the realistic scenario, which was used to evaluate the sensitivity of the analysis to performance. The LCCA considered mixtures with and without antistrip. Traffic growth rates and discount rates were also considered. The researchers determined the inclusion of antistrip in the mix increased equivalent annual uniform cost (EAUC) by $49 per mile. The results of their analysis, using a 24 year analysis period and a 2% discount rate are shown in Table 8 for the realistic case. As shown in the table, the use of a moisture damage susceptible aggregate increased the annual cost of maintaining the road. The use of antistrip significantly reduced that cost.

Table 8 Change in EAUC ($/lane mile) Relative to Control (aggregate not susceptible to moisture damage) [Christensen et. al., 2015]

Moisture Susceptibility			High	High	Moderate	Moderate
Antistrip			No	Yes	No	Yes
Traffic (ADT)	Without User Cost	2,000	$12,840	$7,902	$7,209	$49
		5,000	$13,270	$8,137	$7,444	$49
		15,000	$13,614	$8,325	$7,632	$49
		50,000	$13,958	$8,516	$7,820	$49
	With User Cost	2,000	$13,157	$8,023	$7,330	$49
		5,000	$14,086	$8,444	$7,751	$49
		15,000	$14,849	$8,887	$8,194	$49
		50,000	$18,397	$10,531	$9,839	$49

The CBA performed by Christensen et al. considered the accuracy of the moisture susceptibility testing. They assumed the AASHTO T 283 test correctly identified moisture susceptibility 77% of the time for highly susceptible mixtures and 38% of the time for moderate susceptible mixtures. They also assumed mixtures not susceptible to moisture damage were correctly identified 94% of the time. Two cases were considered; conditional use of antistrip to pass the AASHTO T 283 test and mandatory use of antistrip in all mixtures. The researchers considered a 1.75" asphalt layer thickness and a lane width of 12 feet. The analysis found the testing and use of antistrip had a benefit cost ratio greater than one for both conditional and mandatory use of antistrip, meaning testing and antistrip usage are cost effective. The potential savings in Pennsylvania based on the LCCA for realistic performance are shown in Table 9.

Table 9 Summary Results of LCCA Comparing Moisture Resistance Testing to No Testing [Christensen et. al.,2015]

Antistrip Usage		Cost Savings for Percentage of Susceptible Aggregates:		
		40	20	10
Without User Cost	Conditional on Test Results	$8,003,222	$3,958,155	$1,935,622
	Mandatory for All Mixes	$14,725,686	$7,183,226	$3,411,995
	Savings, Mandatory over Conditional	$6,722,464	$3,225,071	$1,476,374
	Savings, % of Total Cost	6.0	3.2	1.6
With User Cost	Conditional on Test Results	$9,199,60	$4,556,074	$2,234,581
	Mandatory for All Mixes	$16,728,406	$8,184,586	$3,912,675
	Savings, Mandatory over Conditional	$7,529,346	$3,628,511	$1,678,094
	Savings, % of Total Cost	5.9	3.2	1.6

As a result of the LCCA and CBA, Christensen et. al. [2015] findings include:

- The B/C ratio of antistrip usage in conjunction with high-saturation moisture resistance testing, i.e. AASHTO T 283, was found to be, under all scenarios much greater than one, indicating that antistrip usage and appropriate moisture resistance testing significantly lower the net life cycle cost of HMA pavements in Pennsylvania
- The B/C ratio of antistrip usage in conjunction with high-saturation (70 to 80%) moisture resistance testing was greater than one (again, much greater in most cases) for both conditional use of antistrip and mandatory use of antistrip, indicating that both approaches are very economical.
- Mandatory antistrip usage, in conjunction with high-saturation testing, i.e. AASHTO T 283, appears to always result in greater net savings compared to antistrip usage dependent on the results of moisture resistance testing because the failure of such testing to identify all susceptible mixes and the high cost associated with poor performance.

8 Appendix B: Survey Analysis and Review of State Specifications

8.1 Method

A survey was developed to identify current and best practices across the United States with regard to moisture susceptibility testing and the use of antistrip additives. After approval of the questions by the ODOT Technical Advisory Committee (TAC), the form shown in Appendix A was distributed November 8, 2021, to all 50 state Departments of Transportations (DOTs) by the ODOT through the AASHTO RAC listserv. The questionnaire could be completed either online through a link to a Qualtrics survey form or by completing a fillable pdf form attached to the ODOT email which could be mailed or emailed to the PI. The state DOTs were given a November 30, 2021 dead line to complete the survey. To increase the response, a reminder was sent by ODOT on November 22, 2021.

After collecting basic contact information, the online survey was comprised of sections which gathered information generally pertaining to the following topics:

- Section 1 –Test methods used to determine moisture susceptibility and their ability to predict field performance.
- Section 2 - The use of antistrip agents.

A total of 33 (66%) DOTs and the District of Columbia responded to the survey. One state, Washington, provided two responses. These were combined for the survey summary. Figure 8 shows the agencies which responded to the questionnaire, plotted on a map showing climatic zones.

Figure 8 Agencies Responding to Questionnaire

8.2 Responses

Responses to each question in the survey are summarized below.

Section 1: Questions on Moisture Susceptibility Testing (Questions 1-18)

Q1. Is moisture damage of the asphalt mixture one of your concerns regarding premature failure of pavements?

Moisture damage is a concern for 28 (82%) of the responding agencies, while 6 (18%) of the states indicated moisture damage is not a concern.

Q2. What are the distresses that you attribute to moisture damage?

Respondents were given the options of raveling, stripping, rutting, delamination/potholes, load related cracking, block cracking, transverse cracking, and other. The respondents were asked to select all that apply.

The distresses selected by each agency are provided in Figure 9. Stripping distress was selected by the most agencies, 32 (94%), followed by raveling selected by 30 (88%) agencies, delamination/potholes selected by 27 (79%) agencies, rutting selected by 12 (35%) agencies, load related cracking selected by 7 (21%) agencies, transverse cracking selected by 4 (12%) agencies, and block cracking selected by 2 (6%) agencies. One agency, Iowa DOT, identified "flushing of the stripped asphalt that migrates upward which can lead to rutting and friction loss" as another distress.

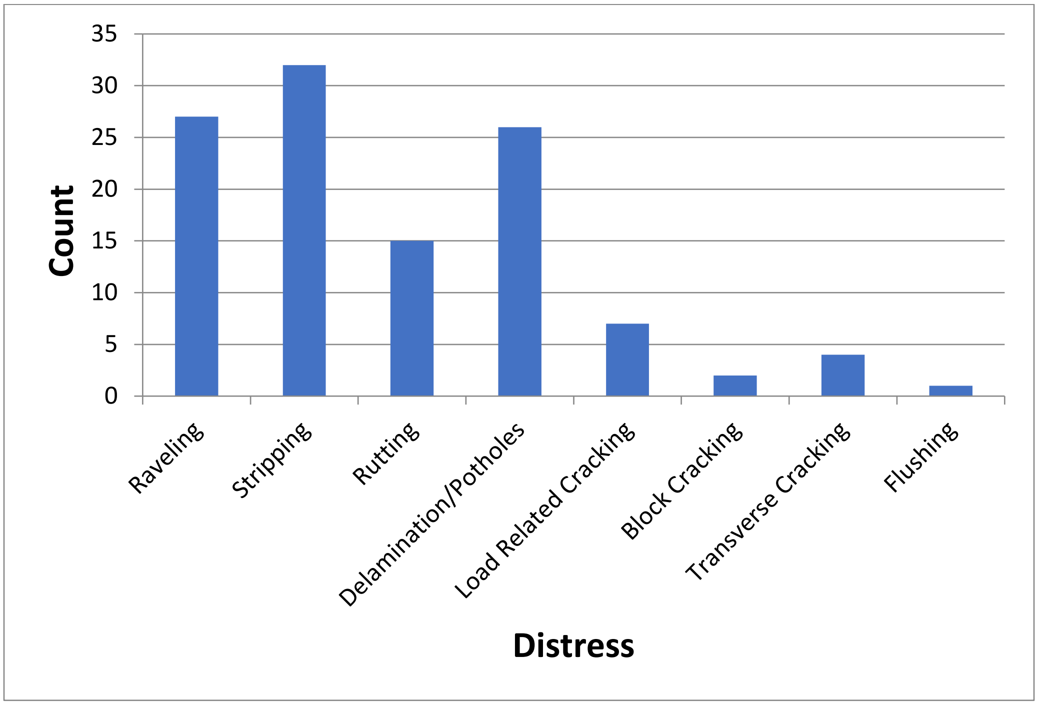


Figure 9 Question 2 What are the distresses that you attribute to moisture damage?

Q3. How early do the moisture damage problems typically occur in your pavements?

Respondents were given the options:

- *Do not have moisture damage problems*
- *0 to 2 years*

- *3 to 5 years*
- *6 to 8 years*
- *9 to 11 years*
- *12 to 14 years*
- *15 years or greater*

The responses are plotted in Figure 10. Eight (24%) of the responding agencies do not have moisture problems. One agency experiences moisture damage problems within 2 years, nine agencies experience moisture damage between 3 to 5 years, seven agencies experiences moisture damage between 6 to 8 years, five agencies experience moisture damage between 9 and 11 years, two agencies experiences moisture damage between 12 to 14 years and 3 agencies experiences moisture damage at 15 years or greater. Two agencies did not respond to the question. Three agencies selected two ranges. Georgia selected a range of 6 to 8 years but noted they "began requiring the use of hydrated lime in the early 1980's which has mostly eliminated the stripping susceptibility of it asphaltic concrete mixtures".

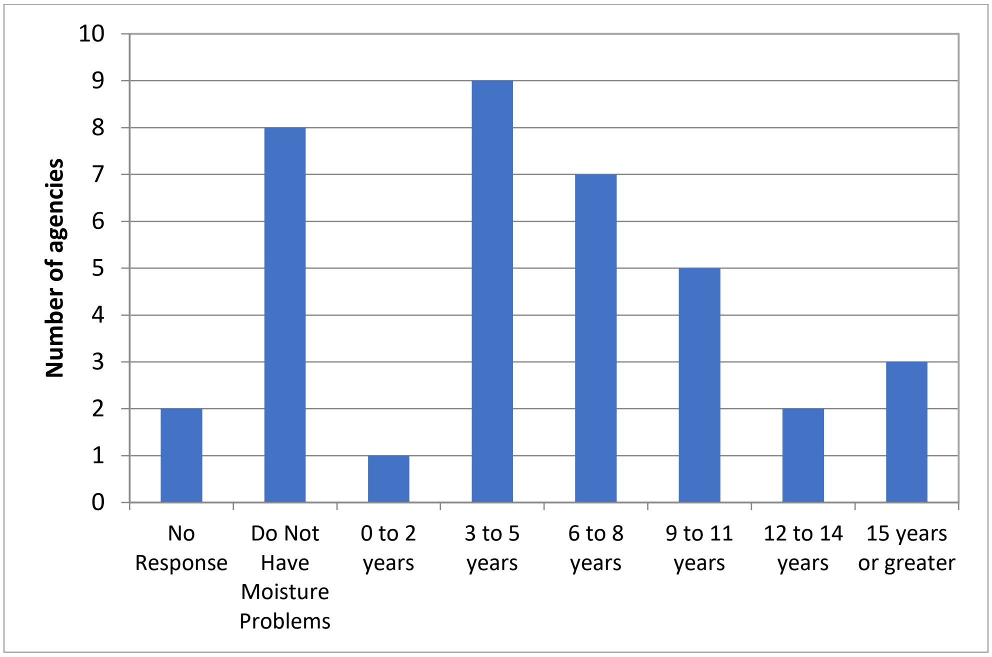


Figure 10 Question 3: How early do the moisture problems typically occur in your pavements?

Q4. What aggregate types are used in your asphalt mixtures, percent mixes with this aggregate type, does the aggregate type have a moisture damage history?

Question 4 asked the respondents to identify the types of aggregates used in their asphalt mixtures, estimate the percentage of mixtures containing this aggregate type, and whether the aggregate type had a history of moisture damage. The results are summarized in Table 10.

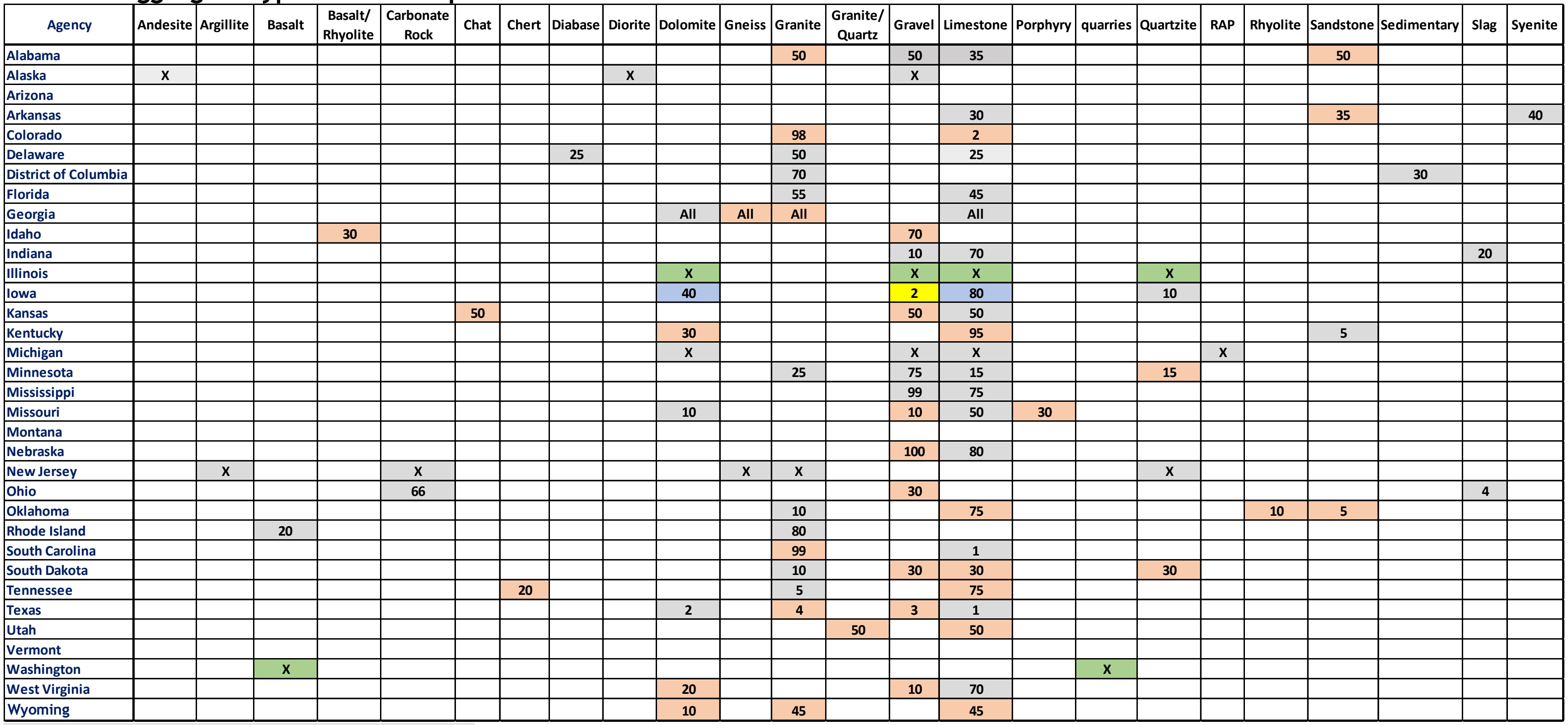
In the table of responses, the use of an aggregate types is indicated by an "X", "All", or a number. The number indicates the percentage of mixes in which the aggregate is used. An

"X" indicates the agency used that aggregate type but did not provide a percentage of mixtures in which the aggregate is used. The marked cells are color coded to indicate whether the aggregate had a moisture damage history, did not have a moisture damage history, had issues with binders, unsure if the aggregate had a moisture damage history, or did not respond to the moisture damage history question.

Q5. Which mixtures or aggregates do you test for moisture susceptibility?
Respondents were given the options:

- *Do not test asphalt mixtures for moisture susceptibility*
- *Test all asphalt mixtures or aggregates*
- *Test Mixtures with specific aggregate(s) type, specify type(s) tested*
- *Other (specify)*

Table 10 Aggregate types used in asphaltic mixtures



Agency	Andesite	Argillite	Basalt	Basalt/ Rhyolite	Carbonate Rock	Chat	Chert	Diabase	Diorite	Dolomite	Gneiss	Granite	Granite/ Quartz	Gravel	Limestone	Porphyry	quarries	Quartzite	RAP	Rhyolite	Sandstone	Sedimentary	Slag	Syenite
Alabama												50		50	35						50			
Alaska	X								X					X										
Arizona																								
Arkansas															30						35			40
Colorado												98			2									
Delaware								25				50			25									
District of Columbia												70										30		
Florida												55			45									
Georgia										All	All	All			All									
Idaho				30										70										
Indiana														10	70								20	
Illinois										X				X	X			X						
Iowa										40				2	80			10						
Kansas						50								50	50									
Kentucky										30					95						5			
Michigan										X				X	X				X					
Minnesota												25		75	15			15						
Mississippi														99	75									
Missouri										10				10	50	30								
Montana																								
Nebraska														100	80									
New Jersey		X			X						X	X						X						
Ohio					66									30									4	
Oklahoma												10			75					10	5			
Rhode Island			20									80												
South Carolina												99			1									
South Dakota												10		30	30			30						
Tennessee							20					5			75									
Texas										2		4		3	1									
Utah													50		50									
Vermont																								
Washington			X														X							
West Virginia										20				10	70									
Wyoming										10		45			45									

Shading key:

🟧	Moisture damage history
⬜	No moisture damage history
🟦	Not usually but issues with some binders
🟨	Unsure
🟩	No response with respect to moisture damage history

Three agencies (9%) do not test for moisture susceptibility, and were not asked to answer questions 5 through 18. A large majority of the agencies, 22 (65%) test all asphalt mixtures for moisture susceptibility. Three agencies (9%) test mixtures with specific aggregate types. The specific aggregate types are provided in Table 11. Six (18%) of the agencies selected “Other”. Their responses are also provided in Table 11.

Table 11 Specific Aggregate/mixtures and other responses to Question 5

Agency	Test Specific Aggregate	Other
Florida	Honduran and Jamaican aggregates (both are used rarely)	
Ohio	All 442 (Superpave) mixes and any other mix with coarse gravel, more than 25% natural sand, and more than 20% RAP with coarse gravel in it	
Vermont	Aggregates with granite or quartzite present require an antistripping additive. Most mixtures subjected to Hamburg Wheel Tracker Test (HWTT) as part of mix design approval.	
Arizona		Test only during mix design
Iowa		Moisture sensitivity evaluation using HWTT is required for (1) Interstate and Primary highways designed for Very High Traffic (VT) and (2) Mixtures for Interstate and Primary highways containing quartzite, granite, or other siliceous (not a limestone or dolomite) aggregate obtained by crushing from ledge rock in at least 40% of the total aggregate (virgin and recycled) or at least 25% of the plus No. 4.
Kentucky		Interstate and Parkway/High Traffic Base and Surface Courses are verified for moisture susceptibility.
Montana		Hydrated lime in mandated in all mixes for moisture damage purposes.
South Dakota		Test mixes that do not add hydrated lime at a minimum moisture content of 1.0% above the saturated surface dry condition of the aggregate
West Virginia		All Superpave Mixtures

Q6. What test(s) has your agency adopted for the purpose of screening asphalt mixtures for moisture susceptibility?

As shown in Figure 11, a majority of the testing agencies, 23 (74%), test for tensile strength ratio (TSR) in accordance with AASHTO T 283 or ASTM D 4867 or a modification thereof. The next most used procedure is the HWTT, AASHTO T 324, which was used by 9 (29%) of the responding agencies. Of the remaining states, Alaska performs an asphalt film retention test on loose mix asphalt which is described in the state test method ATM 414, Arizona performs a modified AASHTO T 167/ASTN D 1075 immersion compression test, and Arkansas determines the retained stability, the stability of 6 in (150 mm) gyratory samples conditioned in water divided by the stability of 6 in (150 mm) unconditioned gyratory samples, using a modification of AASHTO T 245.

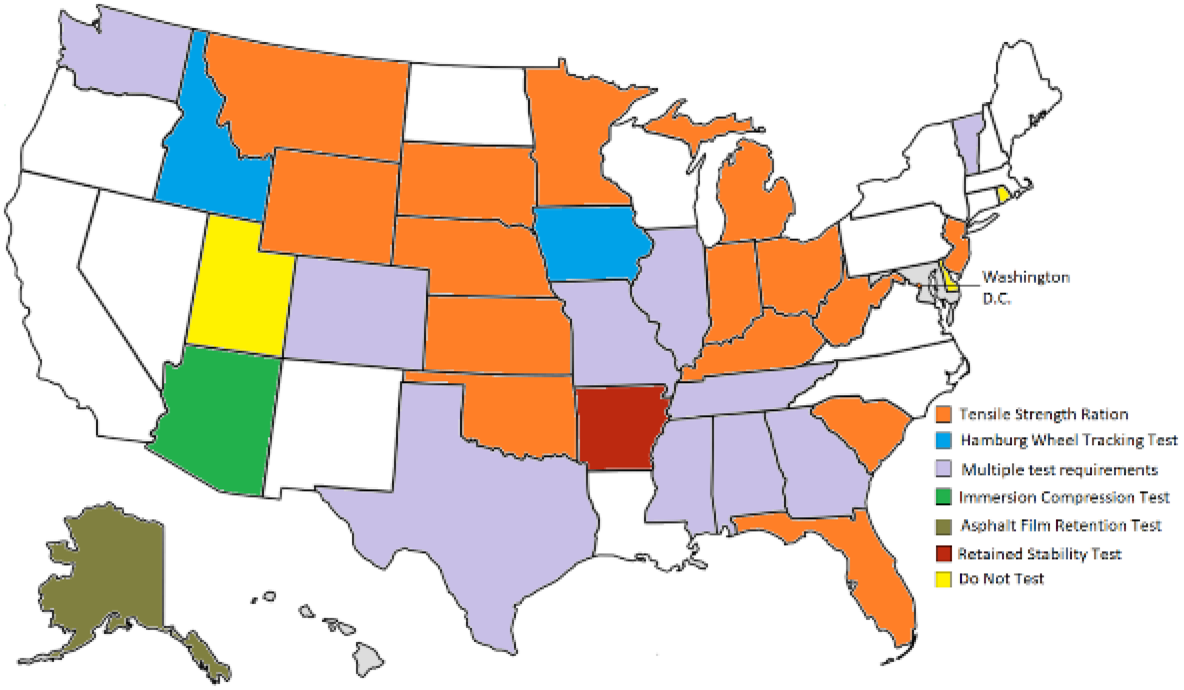


Figure 11 Moisture Susceptibility Test Method

Table 10 shows state DOTs which listed multiple tests for moisture susceptibility.

Table 12 Agencies with multiple moisture susceptibility testing requirements

Agency	Test Methods	Comments
Alabama	Tensile Strength Ratio (AASHTO T 283) and Boiling Water Test (ASTM D 3625)	
Colorado	Tensile Strength Ratio (AASHTO T 283) and HWTT (AASHTO T 324)	
Georgia	Tensile Strength Ratio (AASHTO T 283) and HWTT Wheel Tracking Test (AASHTO T 324)	GDT-56 Boil Test required for all open graded mixtures
Illinois	Tensile Strength Ratio (AASHTO T 283) and HWTT Wheel Tracking Test (AASHTO T 324)	HWTT is not typically used to determine moisture susceptibility
Mississippi	Tensile Strength Ratio (MT-63) and Boiling Water Test (MT-59)	
Missouri	Tensile Strength Ratio (AASHTO T 283) and HWTT Wheel Tracking Test (AASHTO T 324)	
Tennessee	Tensile Strength Ratio (AASHTO T 283) and Boiling Water Test (ASTM D 3625)	
Texas	HWTT Wheel Tracking Test (AASHTO T 324), Boiling Water Test (ASTM D 3625), and Methylene Blue Test	
Vermont	HWTT Wheel Tracking Test (AASHTO T 324) and Boiling Water Test (ASTM D 3625)	
Washington	HWTT Wheel Tracking Test (AASHTO T 324) and Indirect Tension Test (ASTM D 6931)	

Q7. Please specify your agency's mix acceptance criteria?

Twenty-four agencies provided TSR criteria which are presented in Table 13. Four agencies also had a minimum tensile strength requirement. Minimum TSR requirements ranged from 70% to 85%.

Eight agencies indicated they use the HWTT for moisture susceptibility. Their criteria are presented in Table 13 One state collects the data for informational purposes only. Six states reported a maximum rut criterion. Four states specified a minimum number of wheel passes permitted before the stripping inflection point (SIP) is observed.

Three states; Alaska, Arizona, and Arkansas, use a test other than TSR or HWTT to determine moisture susceptibility. The test method and criteria are presented in Table 14. Six states perform tests in addition to TSR and HWTT, primarily the boil test, these tests and criteria are also presented in Table 14.

Q8. Please provide your specifications/standard for your test procedure?

Agencies were asked to provide copies of their specifications. Responding agencies provided electronic copies (pdf or doc files) or a link to their specifications. This information was compiled and provided to ODOT in electronic format.

Table 13 Agency Criteria for TSR Test

Agency	Minimum Tensile Strength (psi (kPa))	Minimum TSR (%)	Notes
Alabama		80	
Colorado		70	
District of Columbia		80	Contractor shall develop a mix design in conformance with AASHTO R 35
Florida		80	
Georgia	60 (415)	80	
	100 (690)	70	
Idaho		80	Specification has been retired
Illinois	60 (415)	85	Non-polymer modified PG binders
	70 (485)	85	Polymer modified PG 64-28 and lower binders
	80 (550)	85	Polymer modified binders greater than PG 64-28
Indiana		80	
Kansas		80	
Kentucky		80	ASTM D4867
Michigan		80	
Minnesota		65	Less than 3 million ESAL
		70	Greater than 3 million ESAL
Mississippi		85	95% minimum interior face coating
Missouri		80	
Montana		70	
Nebraska		80	Plus visual rating
New Jersey		80	
Ohio		80	442 mixes (Superpave)
		70	All other mixes, if anti strip used, then minimum is 80
Oklahoma		80	Design samples
		75	Field samples
South Carolina	65 (450)	85	Design samples
	60 (415)	80	Field samples
South Dakota		80	ASTM D4867. S.D. class Q mixes
		70	ASTM D4867. S.D. class G mixes
Tennessee	80 (550)	80	Non-polymer modified
	100 (690)	80	Polymer modified
West Virginia		80	All Superpave mixes
Wyoming		75	

Table 14 Agency HWTT Wheel Tracking Test Criteria

Agency	Maximum Rut Depth (mm (in))	Passes	Notes
Colorado	4 (0.16)	10,000	
Georgia	12.5 (0.5)	15,000	4.75 mm (0.19 in) and 9.5 mm (0.37 in) mixes. No SIP within 15,000 passes. 50°C (122°F)
		20,000	12.5mm SP, 19mm SP, 25mm SP, all SMA and any mix using PG76-22. No SIP within 20,000 passes. 50°C
Idaho	10 (0.4)	15,000	No SIP within 15,000 passes.
Iowa		10,000	Minimum SIP, Standard traffic. If creep slope/stripping slope <2, SIP is invalid
		14,000	Minimum SIP, H&V traffic. If creep slope/stripping slope < 2, SIP is invalid
Missouri	12.5 (0.5)	20,000	Passes per AASHTO T 324
Texas	12.5 (0.5)	10,000	PG 64 or lower. 50°C (122°F)
		15,000	PG 70. 50°C (122°F)
		20,000	PG 76 or higher. 50°C (122°F)
Vermont			No criteria, results are for informational purposes
Washington	10 (0.4)	10,000	<0.3 ESAL, No SIP within 10,000 passes
		12,500	0.3 to 3.0 ESAL, No SIP within 12,500 passes
		15,000	>3.0 ESAL, No SIP within 15,000 passes

Q9. How do you accept moisture damage test results for mix design acceptance?

The purpose of this question was to determine who prepares the samples and perform the testing. The options provided were:

- *Contractor test results only (no agency verification)*
- *Contractor test results and agency verified with Contractor prepared specimens*
- *Contractor test results and agency verified with Agency prepared specimens*
- *Agency verification only*

As shown in Figure 12 a majority of the agencies, 14, rely on contractor test results with no agency verification. Twelve agencies also rely on contractor test results with five agencies verifying with contractor prepared samples and seven agencies verifying with agency prepared samples. Finally, seven agencies rely on agency prepared and tested samples.

Q10. Has lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage?

As shown in Figure 13, a little more than half of the agencies, 17 (57%), responding to this question indicated the lab testing and mix acceptance criteria has reduced the occurrence of moisture damage whereas a little more than a third, 11 (36%) agencies were unsure; and 2 (7%) agencies indicated the lab testing and mix acceptance criteria has not reduced the occurrence of moisture damage.

Eight of the ten states which perform multiple tests responded "yes", one responded "unsure", and one did not respond to this question. Eight of the seventeen states which only perform TSR testing responded "yes", seven responded "unsure", and two responded "no".

Finally, two of the three states that only perform HWTT testing responded "yes" and one responded "unsure".

Table 15 Agency Other Test Criteria

Agency	Test Method	Criteria	Notes
Alaska	Asphalt Film Retention	Minimum 90% of aggregates must be coated	
Arizona	Immersion Compression Test	Minimum retained strength of 60%, minimum wet strength of 150 psi (1030 kPa)	
Arkansas	Retained Stability	Minimum retained stability of 80%	
Idaho	Immersion Compression Test	Minimum retained strength of 85%	Specification has been retired
Mississippi	Boiling Water Test (MT-59)	95% minimum particle coating	
Tennessee	Boiling Water Test (ASTM D 3625)	No visible evidence of stripping	
Texas	Boiling Water Test (ASTM D 3625)	No visible stripping	
	Methylene Blue	<10%	Informational test on field sands to determine the clay affinity for water
Vermont	Boiling Water Test (ASTM D 3625)	95% retained coating	
Washington	IDT ASTM D6931	175 psi (1200 kPa) max	

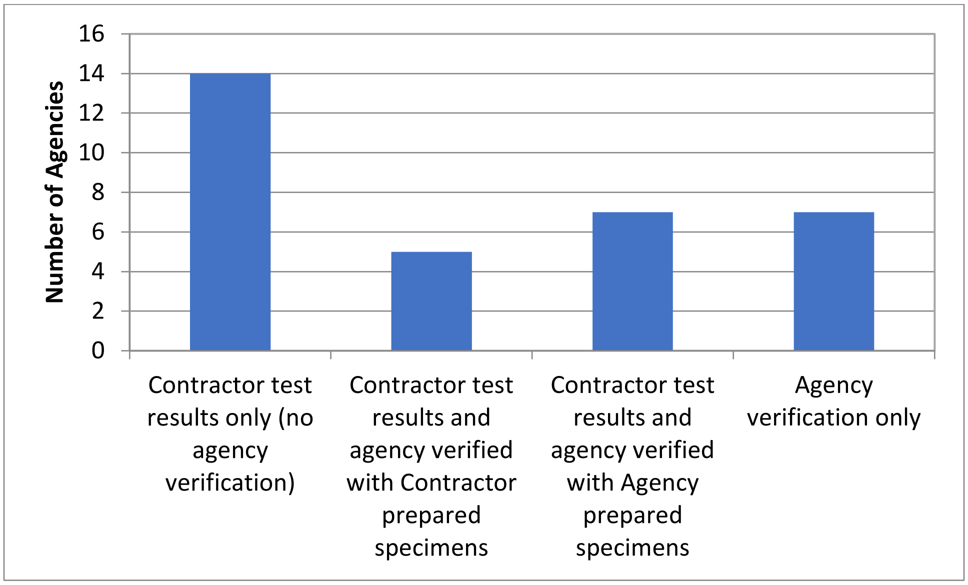


Figure 12 Question 9: How do you accept moisture damage test results for mix design acceptance?

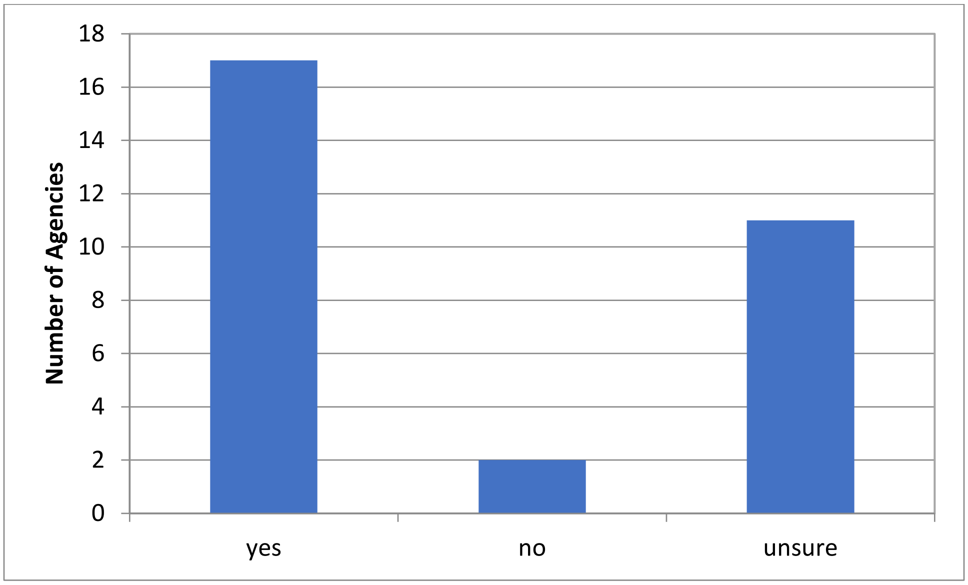


Figure 13 Question 10: Has lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage?

Q11 thru Q 14. Have you modified or changed the test method used to screen asphalt mixtures for moisture susceptibility in the last 10 years? What was the previously used procedure? Why was the procedure modified/changes? If research was used to support the change, please provide a reference.

Eight agencies have modified their moisture susceptibility testing procedures in the last 10 years. The modifications and reasons for the change are provided in Table 16. Seven of the eight agencies responding to this question have modified their test procedures to incorporate the HWTT.

Q15. What corrective measures do you recommend if the mix design fails the moisture damage test?

Respondents were given the options:

- ○ *Reject mixture*
- ○ *Add antistrip and retest*
- ○ *Add hydrated lime and retest*
- ○ *Add antistrip or hydrated lime and retest*
- ○ *Add antistrip or hydrated lime, no additional testing required*
- ○ *Other (please specify):*

As shown in Figure 14, an equal number of agencies, 11, recommend the mix be rejected or add antistrip or hydrated lime and retest if the mix fails the moisture damage test. Five agencies recommend antistrip be added and the mix retested, four agencies selected "other", one agency recommends hydrated lime be added and the mix retested, and one state recommends antistrip or hydrated lime be added and requires no additional testing. Comments from agencies selecting “other” are provided in Table 17.

Table 16 Agencies which have modified moisture susceptibility testing in the last 10 years

Agency	Current Procedure	What was the previously used procedure?	Why was the procedure modified/changed?	If research was used to support the change, please provide a reference
Arizona	Immersion Compression	Arizona 802h modified in 2017	The new procedure is less subjective	
Georgia	TSR and HWTT	Added AASHTO T 324 (HWTT)	AASHTO T 324 provides a rutting and moisture susceptibility test combined	
Idaho	HWTT	TSR and Immersion Compression	Had issues with internal QC that suggests our results were incomplete	
Illinois	TSR and HWTT	Have increased TSR criteria to 0.85 for gyratory compacted specimens from 0.75 for Marshall compacted specimens (More than 10 years ago around 2003)	The larger gyratory specimen TSR of 0.85 correlated close to 0.75 criteria for smaller Marshall specimens.	TSR Comparison of Four-inch Marshall-Compacted and Six-inch Gyratory-Compacted Specimens. Illinois Report No. 12003-02. December, 2002
Iowa	HWTT	AASHTO T-283 TSR	The new procedure better correlated with field performance and provides faster result	https://iowadot.gov/research/reports/Year/2012/fullreports/MIST%20Final%20Report_RB00_012.pdf
Texas	HWTT, Boiling Water Test, and Methylene Blue	HWTT recently added section about stripping and added pictures to identify. Meth blue is informational, but has recently been created to help diagnose stripping issues.	The updates to the procedures were to help explain rutting and stripping performance.	
Vermont	HWTT	AASHTO T 283 (the TSR test), along with an Agency specific one minute boil test during mix production that was tested on material retained on the No. 4 sieve.	The TSR test was found to be not representative of moisture susceptibility distresses in Vermont's climatic conditions and the HWTT was found to be more representative. The new procedure better correlated with field performance and provides faster results. There were concerns regarding the Agency’s one minute boil test not being able to account for material passing the No. 4 sieve.	https://www.newenglandtransportationconsortium.org/projects/15-3
Washington	HWTT	Modified Lottman	New procedure better correlated with field performance and provides faster results	

Q16. Has your agency developed correlations between laboratory measurements and moisture damage measured/observed in the field?

Only Iowa responded yes to this question. The respondent referenced Iowa DOT report no. RB00-012 by Scott Schram published in 2012 entitled "Ranking of HMA Moisture Sensitivity Tests in Iowa"

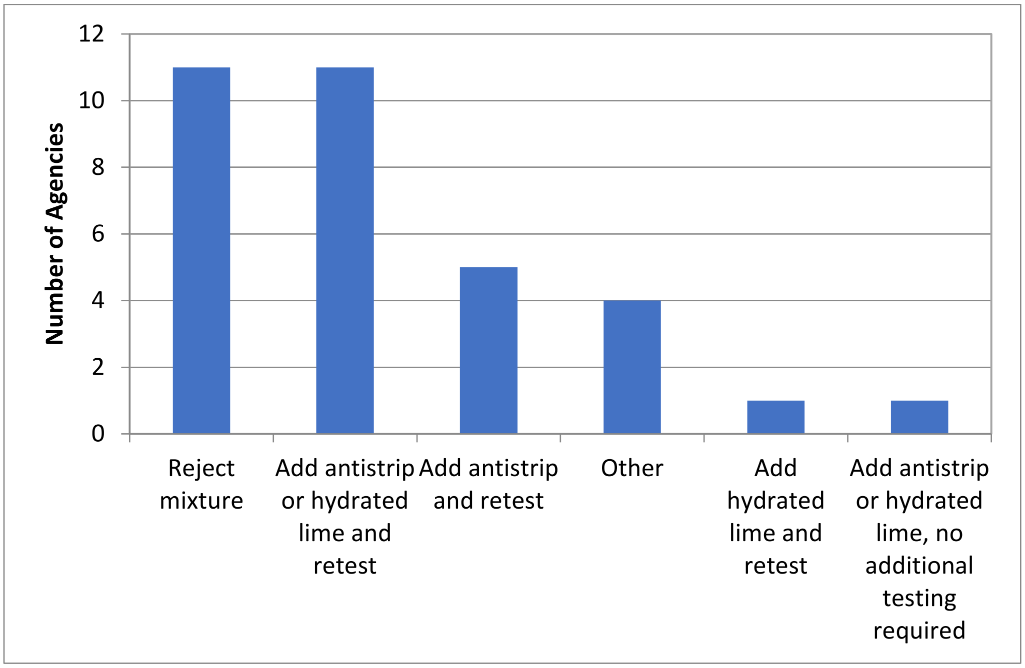


Figure 14 Question 15: What corrective measures do you recommend if the mix design fails the moisture damage test?

Table 17 Comments from agencies responding "other" to Question 15: What corrective measures do you recommend if the mix design fails the moisture damage test?

Agency	Recommended Corrective Action
Alaska	During mix design phase, add antistrip (and retest according ASTM 414) until coating criteria of 90% met.
Arizona	Run HWTT
District of Columbia	The required 0.2% Antistrip ensures no moisture damage problems. The region's stone products tend to fare well with respect to moisture damage.
Kansas	Typically add liquid additive, may make some aggregate or %RAP adjustments, may use binder source that performs better on modified Lottman test

Q17. Does your agency or the contractor perform moisture susceptibility testing during production to verify lab tests?

Thirteen (44%) agencies perform testing during production to verify lab tests while 17 (56%) do not.

Q18. As an agency, have you encountered instance(s) where an asphalt mixture has passed laboratory testing criteria but performs poorly in the field with regard to moisture damage?

The response was evenly distributed for this question with 15 (50%) agencies responding “yes” and 15 agencies responding “no”.

Section 2: Questions on Antistrip Agents (Questions 19-25)

Q19. What is your current practice with regard to the use of antistrip agents in asphalt mixtures?

Respondents were given the options:

- ○ *Do not use*
- ○ *Required*
- ○ *Allowed*

As shown in Figure 15, a total of 29 (88%) of the agencies either require or allow the use of antistrip agents with the response approximately evenly split between allowing the use and requiring the use. Only 4 (12%) of the agencies do not use antistrip agents.

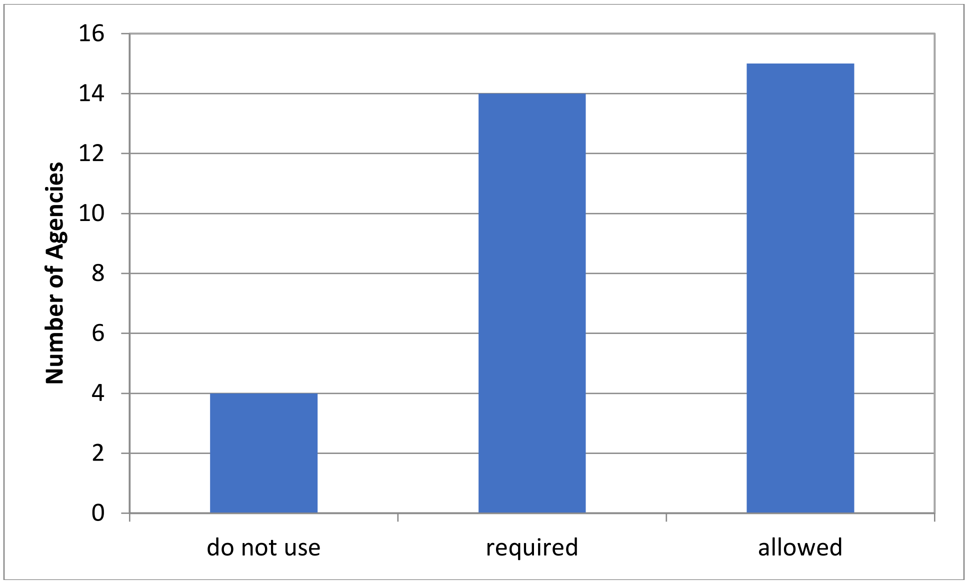


Figure 15 Question 19: What is your current practice with regard to the use of antistrip agents in asphalt mixtures?

Q20. How are antistrip agents specified?

Respondents were given the following options:

- ○ *Antistrip is required for all mixtures*
- ○ *Antistrip are required/allowed when using certain aggregates or mixtures (please list aggregates/mixtures where required/allowed*
- ○ *Antistrip is required/allowed to pass specific test requirement*
- ○ *Other (Please specify)*

As shown in **Figure 16**, 12 (41%) agencies require or allow the use of antistrip to pass specific test requirements, 10 (35%) of the agencies require antistrip for all mixtures, 5 (17%) require or allow the use of certain antistrip when using certain aggregates or mixtures, and 2 (7%) of the agencies selected "other". The comments from the agencies using antistrip when using certain aggregates or mixtures and agencies selecting "other" are provided in Table 18.

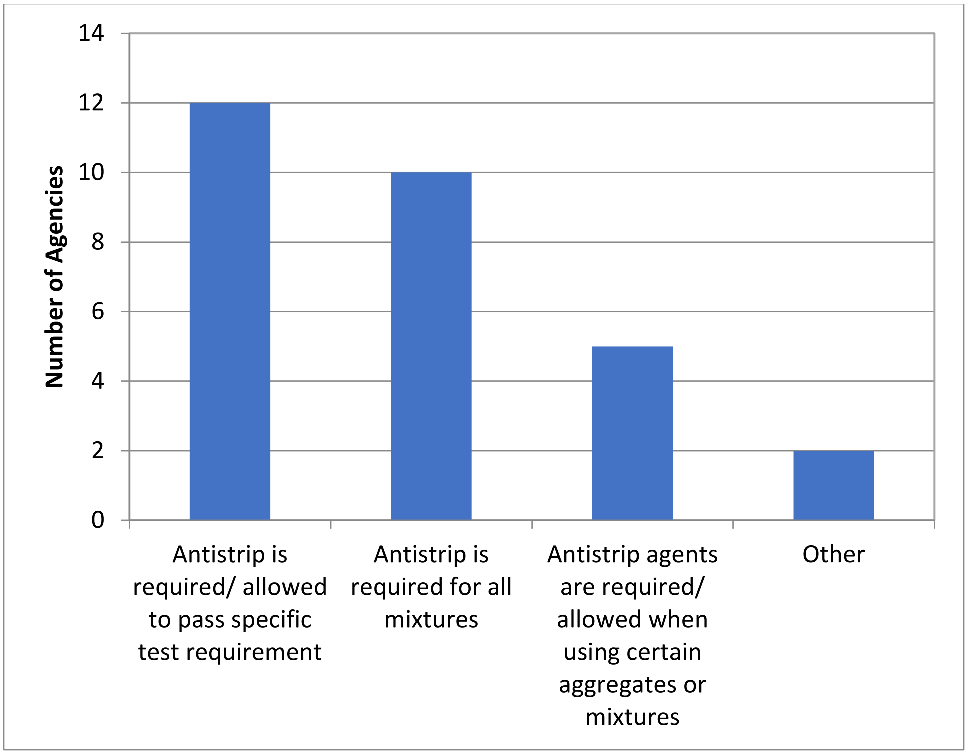


Figure 16 Question 14: How are antistrip agents specified?

Table 18 Selected agency's comments, Question 20

Agency	**Comments, Question 20**
District of Columbia	0.2% by weight of % binder of antistrip is required
Iowa	Mixtures for Interstate and Primary highways containing quartzite, granite, or other siliceous (not a limestone or dolomite) aggregate obtained by crushing from ledge rock in at least 40% of the total aggregate (virgin and recycled) or at least 25% of the plus No. 4.
Kansas	Required when the aggregate blend contains more than 25% RAP plus siliceous aggregates
Missouri	Allowed most mixtures
New Jersey	Allowed but not required
Vermont	Mixtures containing aggregates that originate from sources known to have granite and/or quartzite.
Washington	Antistrip is allowed if HMA mix design fails HWTT

Q21. If asphalt antistrips are required or allowed, what types are used.
Respondents could select any or all of the following options:

- ○ *Hydrated Lime*
- ○ *Liquid antistrip*
- ○ *Other (Please specify)*

As shown in Figure 17, the majority of the agencies, 16, allow the use of hydrated lime or liquid antistrip. Eight agencies use only liquid antistrip and four use only hydrated lime. Three states listed other antistrip agents used, these are provided in Table 19.

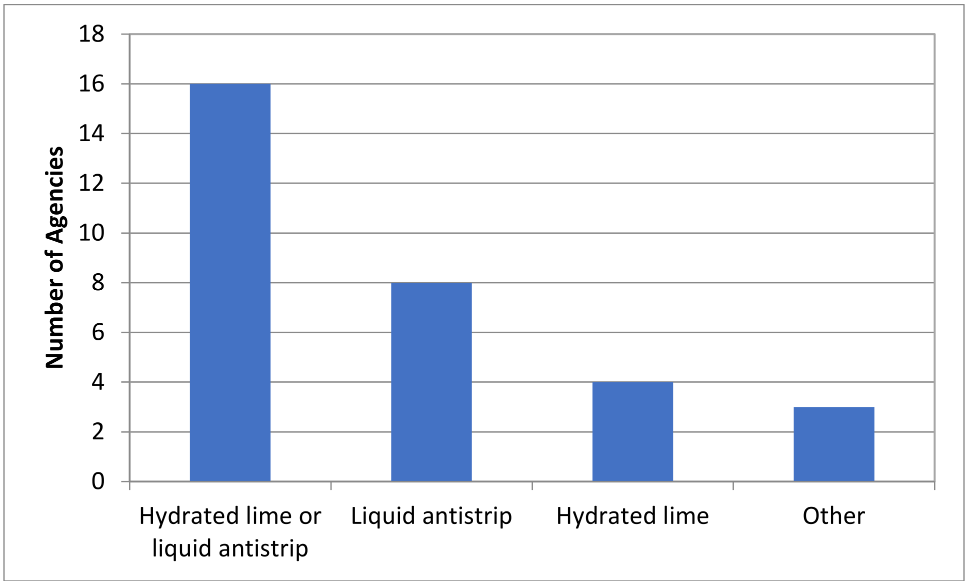


Figure 17 Type of antistrip used

Table 19 "Other" antistrip agents used

Agency	Antistrip Agent Used
Alaska	Amines based, Phosphate Ester based, Organo-Silane based
Iowa	Hydrated lime, liquid antistrip, polymer-based liquid aggregate treatments.
Tennessee	Contractor's option between liquid ASA and Lime; 99+% use liquid ASA.

Q22. Please explain how your agency determines the dosage of antistrip agents used.
Responses provided by the agencies are provided in Table 20. The responses fall into three basic categories (1) fixed percentage of the binder or aggregate, (2) based on the recommendation of the supplier or contractor, and (3) an amount sufficient to meet the moisture susceptibility test criteria.

Q23. Does your agency have a list of approved antistrip agents?
The responses to this question are shown in Table 20. Fifteen agencies answered “yes” and provided electronic copies (pdf or doc files) or a link to their list. This information will be compiled and provided to ODOT in electronic format.

Q24. If antistrip agents are required, has your agency eliminated moisture susceptibility problems?
Respondents were given the option of responding “yes”, “no”, or “unsure”. As shown in Figure 18, of the 24 agencies that responded to this question, 8 (33%) replied no, 10 (42%) replied yes, and 6 (25%) replied unsure.

Table 20 Antistrip dosage rate determination

Agency	Q20 Please explain how your agency determines the dosage of asphalt antistrip used	Q21 Does your agency have a list of approved antistrip
Alabama	Agency verification only	Yes
Alaska	Refer to Section 401-2.02 of https://dot.alaska.gov/stwddes/dcsspecs/assets/pdf/hwyspecs/sshc2020.pdf	No
Arkansas	Dosage according to manufacturer's recommendation, but a minimum of 0.25% by weight of asphalt binder.	Yes
Colorado	1% hydrated lime is required for all asphalt mixes	Yes
District of Columbia	0.2% antistrip by weight of % binder.	No
Florida	0.5% except for the rare instance where a supplier will get it approved at a lower dose.	Yes
Georgia	Hydrated lime added at 1% of virgin aggregate percent and 0.5% of RAP percent. Will never be less than 0.9%	Yes
Idaho	Typically start at 0.5% by weight of liquid binder, at the discretion of the mix designer	Yes
Illinois	Liquid Antistrip – Generally 0.5% by weight of Asphalt Binder (although this can vary by specific product). Hydrated Lime - Generally 1.0% by weight of total dry aggregate	No
Indiana	No response	No
Iowa	The contractor shall test the mixture at a minimum of three different dosages of the antistrip additive to determine the effectiveness and optimum rate of addition to the mix. The dosages tested shall cover the range of dosages recommended by the supplier of the antistrip additive or, in the case of hydrated lime, at dosages agreed to by the District Materials Engineer (DME). The Contractor shall include the data from the moisture susceptibility testing in the electronic file and submit the file to the DME. The DME will evaluate the data and select an optimum dosage of antistrip additive based on effectiveness and economic evaluation.	Yes
Kansas	Minimum dosage rate of 0.01% by weight of virgin binder for every 1% RAP plus natural sand, higher dosage is an option to achieve 80% TSR minimum	Have a list but not published
Kentucky	Based on the manufacturer's recommendation.	Yes
Michigan	The amount necessary to meet a minimum of 80% on AASHTO T283	No
Minnesota	Contractor uses manufacturer's recommendations.	No
Mississippi	All asphalt mixtures regardless of aggregates type require 1% by weight hydrated lime.	No
Missouri	Construction Designed	Yes
Nebraska	Fixed dosage for particular mix types	Yes
New Jersey	Determined by the contractor.	No
Ohio	There is a min and a max dosage depending on whether it's liquid or hydrated lime. Final dosage is determined by contractor.	No
Oklahoma	Supplier recommendations	Yes
South Carolina	Minimum 0.7%, 0.5% if WMA additive (2:1 products like evotherm in 2022)	Yes
South Dakota	Add hydrated lime at a minimum moisture content of 1.0% above the saturated surface dry condition of the aggregate	Hydrated Lime
Tennessee	By Spec must use ASA between 0.3% to 0.5% by weight of binder. Contract mix	Yes

Agency	Q20 Please explain how your agency determines the dosage of asphalt antistrip used	Q21 Does your agency have a list of approved antistrip
	designer is responsible for designing mix to meet TSR and boil test requirements inside that also meet the dosage requirements.	
Texas	Ultimately, the mixture must pass the HWTT with little to no stripping.	No
Utah	UDOT determined 1.0% hydrated lime (by weight of the dry virgin aggregates) applied as a lime slurry through a pugmill was adequate protection against moisture damage as measured with the Lottman Test, AASHTO T 283. We have 30 years of excellent pavement performance against stripping that supports this as well. Before we did this, moisture damage and rutting possibly related to stripping was our number one distress.	No
Vermont	Dosage rates of antistrip agents are as recommended by the agent manufacturer.	No
Washington	Contractor determines and submit HMA mix design for testing by agency. Must pass the HWTT and IDT requirements	Yes
West Virginia	Dosage determined by designer/producer. If liquid additive, must follow manufacturer's recommendations.	N/A
Wyoming	1% - 1.5% lime as determined by location in state based off of history from pits. 0.75% antistrip agent added by special provisions.	No

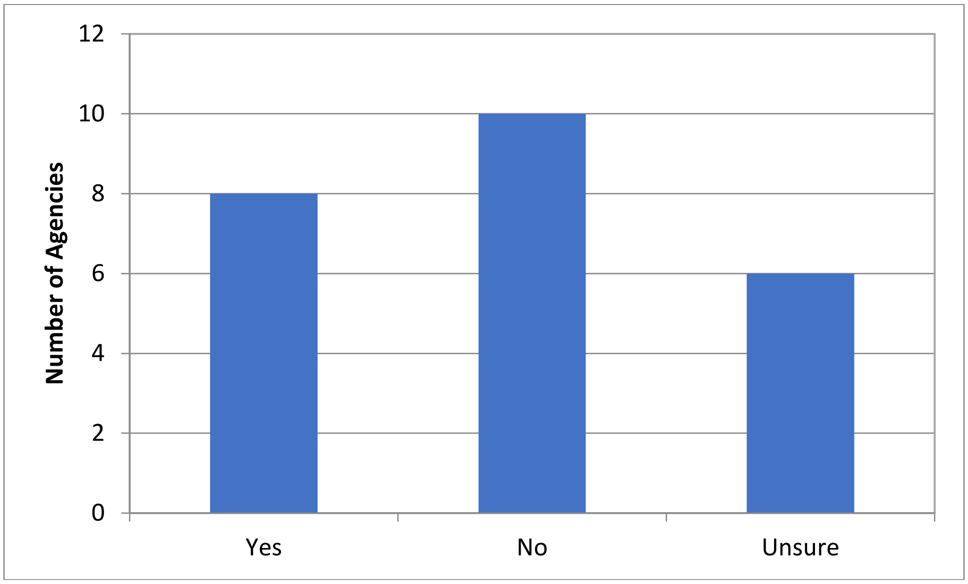


Figure 18 Question 24: If antistrip agents are required, has your agency eliminated moisture susceptibility problems?

Q25. If you would like, you may provide any additional information or comments related to your moisture susceptibility tests and/or use of antistrip agents which may be useful to the researchers?

The following agencies provided these comments:

- *Alaska: In the remote past, we were told that our agency has used the T283 test at the mix design phase, mainly for research purposes. In many cases, mixes that passed the T283 lab test did not perform as expected in the field in terms of moisture susceptibility. Some people called the test a "random number generator". It was abandoned since then.*
- *Nebraska: When we allowed any antistrip, we had problems. We only allow high end amine based antistripping agents that do not significantly lower the tensile strength of the mix.*
- *Ohio: May look at using NTPEP for approving liquid antistrip agents*
- *Rhode Island: The only time we observed stripping in RI was on a 100 foot (30.5 m) OGFC test section made without antistrip.*
- *Tennessee: TDOT pays for ASA outside of the bid. Contractors present their invoices for ASA and TDOT pays the amount up to the cap of $15/gal ($4/l). This was done as a way to prevent a 'race to the bottom' on ASA selection and encourage the right ASA and dosage be utilized for the particular mix. TDOT is working on possible adoption of the HWTT in some capacity for mix approval. The research isn't final yet but we are moving that direction.*
- *Utah: When we first implemented the use of hydrated lime back in the early 1990s we used the Lottman Test to see how we were doing. We consistently passed the test and after about 10 years determined that we didn't need to run the Lottman Test anymore. We simply require 1.0% hydrated lime in all our asphalt mixtures. We do have some aggregates that can pass the Lottman Test without lime, however, they perform even better with the lime so we believe we are still getting the value from using it in those mixes as well. With the high cost of stripping, we determined that the use of lime in all our mixtures was good insurance.*
- *Washington: Most moisture susceptibility issues WSDOT encounters are from trapping moisture in the pavement structure, mainly via an open graded mix trapped under a dense graded mix. We typically do not encounter moisture issues from a mix design.*
- *Wyoming: While testing in the lab is crucial, it is all meaningless if the contractor does not add the antistrip to the material under construction. This has caused our biggest failures with regards to moisture.*

8.3 Survey Results Summary

A total of 33 (66%) DOTs and the District of Columbia responded to the survey. Based on these responses, the research team has the following observations:

- *The most used test procedure for moisture susceptibility is tensile strength ratio (TSR) in accordance with AASHTO T 283 or ASTM D 4867 or a modification thereof. This procedure is used by twenty-three of the responding agencies.*
- *The next most used procedure is the HWTT in accordance with AASHTO T 324. This procedure is used by nine of the responding agencies.*
- *Ten states perform multiple tests. The most common combination was TSR and boiling water test, used by five states, followed by TSR and the HWTT which was used by four states.*
- *Six of the eight agencies which have modified their procedure in the last 10 years replaced or supplemented TSR testing with HWTT*

- *Twenty-nine agencies provided acceptance criteria for the TSR test. Minimum TSR values ranged from 70% to 85%. Four of the agencies also had a tensile strength requirement. The minimum tensile strength requirement ranged from 60 psi (415 kPa) to 100 psi (690 kPa)*
- *Seven agencies have established acceptance criteria for the HWTT. The number of passes varied based on mix type, binder grade or truck traffic (ESAL) level. Four of the agencies included a minimum number of passes before the stripping inflection point (SIP) can occur in their acceptance criteria.*
- *Seventeen agencies indicated lab testing and mix acceptance criteria reduced the occurrence of moisture damage, two agencies indicated lab testing and mix acceptance criteria did not reduce the occurance of moisture damage, and eleven agencies were unsure. The percent of agencies who indicated lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage was higher for agenies who perform multiple test or the HWTT than for the agencies who only perform the TSR test.*
- *The agencies rely heavily on the contractor to prepare, and in many cases test, specimens.*
- *Half of the responding agencies have encountered instances where mixtures have passed laboratory testing but performed poorly in the field with regard to moisture damage. However, no trend was observed between agencies reporting this situation and the test method used.*
- *Almost all, twenty-nine, of the responding agencies allow or require the use of antistrip agents.*
- *Of the agencies requiring antistrip agents, about a third indicated antistrip eliminated moisture susceptibility problems, slightly more than a third indicated antistrip did not eliminate moisture susceptibility problems, and slighly less than a third were unsure.*

9 Appendix C: Review of Agency Specifications

`To complement the information gathered from the survey, the NAPA website https://www.asphaltpavement.org/expertise/engineering/resources/bmd-resource-guide/implementation-efforts and the website of state highway agencies which had not completed the survey, as well as international transportation agencies were search for moisture susceptible test specifications. Shown in Table 21 are the specifications for various state agencies for the HWT along with the reference for the source of the information.

As shown in Table 21, Hamburg wheel track testing specifications were located for six additional states. Required passes of the load ranged from 10,000 passes to 20,000 passes. Maximum permitted rut depth ranged from 6 mm to 13.5 mm. Acceptance criteria for the minimum number of passes before a SIP ranged from 8,000 to 15,000 passes. Test temperatures ranged from 45^o C to 50^o C.

TSR testing specifications were located for an additional 15 additional states and the European Union and Austroads, see Table 22. Minimum TSR values ranged from 70% to 80%. Two states had an additional minimum tensile strength requirement. California had a minimum wet tensile strength of 70 psi (485 kPa) and 100 psi (690 kPA) dry tensile strength whereas Nevada had minimum dry tensile strength requirement of 58 psi (400 kPa) for their 9.5 mm mix, 65 psi (450 kPa) for their 19 mm mix no using a PG76-22 binder and 100 psi (690 kPa) for their 19 mm mixes using a PG76-22 binder.

Additional test methods used, Table 23, include the boil test (four states, one Canadian province, and the European Union), retained Marshall stability test (two Canadian provinces), static immersion (one Canadian province) and the rolling bottle test (European Union).

Specifications for lime and/or liquid additives was identified for 17 states and are presented in Table 24. Eight of the states allowed either liquid additive or lime, four states only allowed liquid additives, one state only allowed lime, and no provisions for antistrip could be found in their specifications for three states.

Table 21 Agency HWTT Criteria

Agency	Maximum Rut Depth	Passes	Notes	References
California*	0.5 in (12.5 mm)	10,000	PG 58 and PG 64: no SIP within 10,000 passes	2018 Standard Specifications, State of California, Section 39 Hot Mix Asphalt (50°C (122°F))
		12,500	PG 70: no SIP within 12,500 passes	
		15,000	PG 76 or higher: no SIP within 15,000 passes	
Louisiana*	10 mm (0.4 in)	10,000	Level 1 wearing course, binder course, and ATB mixtures (at 50°C (122°F))	2016 Standard Specifications for Roads and Bridges, Item 502 (45°C (113°F))
	6 mm (0.25 in)	20,000	Level 2 wearing and binder course and SMA mixtures (at 50°C (122°F))	
	12 mm (0.47 in)	20,000	Base course (at 50°C (122°F))	
Maine*	12.5 mm (0.5 in)	20,000	PG 64-28 (at 45°C (113°F)) no SIP within 15,000 passes	NAPA web site
		20,000	PG 64E-28 (at 48°C (118°F)) no SIP within 15,000 passes	
		20,000	PG 70E-28 (at 50°C (122°F)) no SIP within 15,000 passes	
Massachusetts*	0.5 in (12.5 mm)	20,000	< 0.3 million ESAL: No SIP within 10,000 passes	All HMA mixtures. Section M3, 2021 Standard Specifications
		20,000	≥ ESAL: No SIP within 15,000 passes	
New Mexico*			Plan to use for moisture susceptibility, currently establishing criteria	Email communication with Kelly Montoya, NMDOT
Wisconsin*	0.50 in (13.5 mm)	10,000	PG58-XX, No SIP within 8,000 passes	NAPA web site (46°C (115°F))
		15,000	PG64-XX, No SIP within 8,000 passes	
		20,000	PG70-XX, No SIP within 8,000 passes	
		20,000	PG76-XX, No SIP within 8,000 passes	

Table 22 Agency TSR test criteria

Agency	Minimum Tensile Strength (psi (kPa))	Minimum TSR (%)	Notes	References
California*	70 (485 kPa)		Minimum wet tensile strength	2018 Standard Specifications, State of California, Section 39 Hot Mix Asphalt
	100 (690 kPa)		Minimum dry tensile strength	
Connecticut		80	Superpave mix, minimal observed stripping	2020 Connecticut Standard Specifications for Roads, Bridges, Facilities and Incidental Construction, Section M.04.02
Louisiana*		80	ASTM D4867, may be used in lieu of HWTT for minor mixes	2016 Application of QA specifications for Asphalt Concrete Mixtures
Maine*		80	AASHTO R 35	
Massachusetts*		80	Required for OGFC, Engineer may require for other HMA	Section M3, 2021 Standard Specifications
Nevada	58 (400 kPa)	70	Unconditioned, Type 3 (9.5 mm) mixtures	2014 Standard Specifications for Road and Bridge Construction, Section 401
	65 (450 kPa)		Unconditioned, Type 2 (19 mm) and 2C mixtures except PG 76-22NV or PG 76-22NVTR asphalt	
	100 (690 kPa)		Unconditioned, Type 2 (19mm) and 2C mixtures with PG 76-22NV or PG 76-22NVTR asphalt	
New Hampshire		80	AASHTO R 35	2016 Standard Specifications for Road and Bridge Construction, Section 401
New Mexico*		85	HMA/SMA	Email communication with Kelly Montoya, NMDOT
		80	OGFC	
New York		80		2019 Materials Method MM5.16
North Carolina		80	Type S4.75A and B25.0 mixes	2020 Asphalt Quality Management System
		85	Mixes other than Type S4.75A and B25.0	
North Dakota		70	Prepare specimens at 7.0% ± 1% air	2020 Standard Specifications for Road and Bridge Construction
Oregon		80	JMF	Oregon Standard Specifications for Construction, Section 745.13
		70	Production	Oregon Standard Specifications for

Agency	Minimum Tensile Strength (psi (kPa))	Minimum TSR (%)	Notes	References
				Construction, Section 745.16
Pennsylvania*		80	Superpave/SMA	Bulletin 27, Chapter 2A
Virginia		80	HMA, design and production; SMA	2020 Road and Bridges Specifications, Section 211
Wisconsin*		75	With no antistrip additive HMA/SMA	2022 Standard Specifications, Section 460
		80	With antistrip additive HMA/SMA	
European Union			Method A uses the indirect tensile strength: ITSR	EN 12697-12 Determination of the water sensitivity of bituminous specimens
			Method B uses the compression strength: i/C	
			Method C defines the bonding value 1 hour after mixing. Bonding value is amount of fines and bitumen which come loose from 1000g (2.2 lb) sample when mixed with 1,500 ml (51 fl oz) of water	
Austroads			Adapted from ASTM D 4867-92 and AASHTO T 283-85	AG:PT/T232 Stripping Potential of Asphalt – Tensile Strength Ratio

Table 23 Criteria for Other tests

Agency	Minimum percent of aggregate coated	Notes	References
Louisiana*	90%	For approval of antistrip	2016 Standard Specifications for Roads and Bridges, Item 1002
Maryland	95%	Performance graded asphalt binders and asphalt mixes. If less than 95% use antistrip additive per manufacturer's recommendation	Section 904, 2021 Standard Specifications for Construction and Materials.
New Mexico*	85%	HMA/SMA	Email communication with Kelly Montoya, NMDOT
	80%	OGFC	
European Union		Bottle rolling machine. "…simple but subjective test suitable for routine testing"	EN 12697-11 Determination of the affinity between aggregate and bitumen
		Static test "…simple, though subjective test that is generally less precise, but can cope with high PSV-aggregates"	
		Boiling water test "…objective test and has high precision"	
Pennsylvania*	95%	Perform ASTM D 3625 if visual stripping is estimated to be 5% or greater on the T 283 specimen	Bulletin 27, chapter 2A
Ontario MOT		Percent retained stability of Marshall specimens	Test Method LS-283 Resistance to Stripping of Asphalt Cement in Bituminous Mixture by Marshall Immersion
Ontario MOT	65%	24 hour soak	LS-285 Stripping by Static Immersion
Saskatchewan		Retained Marshall Stability	STP 204-22

Hawaii: unable to find any information in the Hawaii 2005 Standard Specifications, Item 401, Hot Mix Asphalt Pavement, locals have included T 182 95% minimum

Maryland: Performance Graded asphalt binders and asphalt mixes, section 904, 2021 Standard Specifications for Construction and Materials. boil test, 95% minimum. If less than 95%, use a heat stable antistrip additive (minimum manufacturer's recommended amount, retest.

Table 24 Agency antistrip specification criteria

Agency	Required?	type	Notes	Reference	Approved list (Yes or No)
California	To pass test	Lime or liquid		2018 Standard Specifications, State of California, Section 39 Hot Mix Asphalt	
Connecticut	Specific case	Lime or liquid	1% added to Superpave mixtures with crushed recycled container glass	2020 Connecticut Standard Specifications for Roads, Bridges, Facilities and Incidental Construction, Section M.04.02	
Hawaii			No provisions for antistrip found in State DOT Specifications		
Louisiana	To pass test	Liquid or lime	Liquid Minimum 0.6% by weight of asphalt. Lime 1.5% minimum	2016 Standard Specifications for Roads and Bridges, Section 1002	Yes
Maine		Liquid	Minimum 0.50% by weight of binder	Bid documents	
Maryland	To pass test	Liquid	Begin with minimum manufacturer's recommended amount, retest	Maryland DOT MSMT 410	
Massachusetts	To pass HWTT	Liquid or lime	manufacturer's recommended dosage rate	Section M3, 2021 Standard Specifications	
Nevada		Lime	No less than 1% nor more than 2.5% of the mass of dry aggregate	2014 Standard Specifications for Road and Bridge Construction, Section 401.03.08	
New Hampshire			No provisions for antistrip found in State DOT Specifications		No
New Mexico	To pass test	Lime and liquid		2019 Standard Specifications for Highway and Bridge Construction, Section 402.2.3	
New York	To pass test	Liquid		2019 Materials Method MM5.16	
North Carolina	Required in all superpave designs	Lime and liquid		2020 Asphalt Quality Management System	
North Dakota			No provisions for antistrip found in State DOT Specifications	2020 Standard Specifications for Road and Bridge Construction	
Oregon	To pass test	Liquid		Oregon Standard Specifications for Construction, Section 745.11	
Pennsylvania	To pass test	Liquid	AASHTO R 35	Publication 408, Section 413	
Virginia	All mixtures	Hydrated	Hydrated lime added at a rate of not	2020 Road and Bridges Specifications, Section	Yes

Agency	Required?	type	Notes	Reference	Approved list (Yes or No)
		lime or chemical additive	less than 1% by weight of the total dry aggregate. Chemical additive added at a rate not less than 0.30% by weight of the total asphalt content of the mixture	211 (modifications to AASHTO T283)	
Wisconsin	To pass test	Hydrated lime or chemical additive		2022 Section 460.2.4	Yes

10 Appendix D: Laboratory Testing

10.1 Test Plan

The literature search and survey results identified the TSR test (AASHTO T 283 or ASTM D 4867) as the most widely used moisture susceptibility test method by transportation agencies and the HWTT (AASHTO T 324) was identified as the second most used test method. The literature review and survey responses also show a migration from the TSR test to the HWTT by state agencies. The number of agencies which indicated "lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage" was higher for agencies who perform multiple tests or perform the HWTT than for agencies who only perform the TSR test. Given the above, the research team recommended the TSR test, as modified by ODOT Supplement 1051, and the HWTT in accordance with AASHTO T 324 be further evaluated under Task 5. Discussions with the TAC resulted in the proposed test matrix shown in Table 25, for Task 5.3 evaluation of candidate laboratory tests for moisture susceptiblity.

Table 25 Testing Matrix for Task 5.3

	Test Procedure		
Aggregate Type	**Supplement 1051 (gyratory)**	**Supplement 1051 (Marshall)**	**AASHTO T 324**
Granite	1 set (6 samples)	1 set (6 samples)	1 set (4 samples)
Gravel	1 set (6 samples)	1 set (6 samples)	1 set (4 samples)
Limestone	1 set (6 samples)	1 set (6 samples)	1 set (4 samples)

A 19 mm (0.75 in), Superpave mixture, typically used as an intermediate course in Ohio, was chosen for the evaluation since a mixture with larger size aggregate and lower asphalt content should be more prone to stripping than a surface mixture with smaller aggregate and higher binder content. As indicated in Table 25, three aggregate types were chosen; granite, which typically has a history of poor resistance to moisture damage, gravel which has a history of marginal resistance to moisture damage, and limestone, which has a history of good resistance to moisture damage. The granite was obtained from Vulcan Materials' Kennesaw, Georgia quarry. The gravel and limestone aggregates were obtained from quarries supplying aggregate to ODOT projects. The limestone was obtained from Barrett Paving's Miami River Stone Quarry in Dayton, Ohio, and gravel from Shelly Materials' quarry in Massillon, Ohio. To reduce the number of variables in the analysis, RAP was not used in the mixtures. The same binder, a polyphosphoric acid (PPA) modified PG 64-28, typically used in Ohio, was used in all mixes.

The effect of three antistrip additives on the Supplement 1051 and AASHTO T 324 test results for the aggregates with typically poor and marginal moisture resistance, granite and gravel aggregates, were evaluated as part of Task 5.4. Hydrated lime was recommended as one of the additives because it is commonly used nationwide as an antistrip additive. The lime was supplied by Mintek Resources. The other two additives were liquid antistrip. One liquid antistrip additive is a "bio-based adhesion promotor which increases the polarity of the bitumen at the binder/aggregate interface". The other liquid antistrip uses "covalent bond formation to improve adhesion between the aggregate and asphalt". The two antistrips additives will be referred to as “Antistrip A” and “Antistrip B”. The proposed test matrix for this work is shown in Table 26.

Table 26 Testing Matrix for Task 5.4

Aggregate Type	Test Procedure					
	ODOT Supplement 1051 (gyratory)			AASHTO T 324		
	Hydrated Lime	Additive A	Additive B	Hydrated Lime	Additive A	Additive B
Granite	1 set (6 samples)	1 set (6 samples)	1 set (6 samples)	1 set (4 samples)	1 set (4 samples)	1 set (4 samples)
Gravel	1 set (6 samples)	1 set (6 samples)	1 set (6 samples)	1 set (4 samples)	1 set (4 samples)	1 set (4 samples)

10.2 Sample Preparation and Testing

Approximately 500 pounds of aggregate was requested from each quarry. The supplied aggregate was dried and totally fractionated using a sieve stack consisting of the 2”, 1 ½”, 1”, ¾”, ½”, 3/8”, #4, #8, #16, #30, #50, #100, and #200 sieves. The sieved material was stored in individually marked buckets until blended.

To prepare a sample, each aggregate fraction was blended in proportion to the JMF with the exception of samples containing lime, in which the passing 200 material was reduced by the amount of lime added. The final gradation for each of the aggregate types is shown in Table 27

Table 27 Aggregate Gradation

Aggregate Properties			
Aggregate Type	Granite	Gravel	Limestone
Percent Passing: 1” (25.0 mm)	100	100	100
¾” (19.0 mm)	98	95	95
½” (12.5 mm)	80	82	75
3/8” (9.5 mm)	68	72	64
#4 (4.75 mm)	46	53	44
#8 (2.36 mm)	34	41	29
#16 (1.18 mm)	25	30	20
# 30 (600 µm)	18	20	13
#50 (300 µm)	15	10	8
#100 (150 um)	9	6	5
#200 (75 µm)	5.9	2.0	3.1
Quarry Location	Kennesaw, GA	Massillon, OH	Sidney, OH
Binder content (%)	4.5	5.1	5.0

The PPA modified PG 64-28 binder was provided by Shelly Company in 5 gallon buckets. The 5 gallon buckets were heated to 240° F (115° C) and split into 1 gallon buckets. During sample preparation, one gallon of the binder was stored in an oven at 240° F (115° C) until used. When used, liquid additives were incorporated into the mix by first mixing 0.5% by weight of the additive with approximately one gallon of binder. Binder containing additives not used within 2 weeks was discarded.

Aggregate and binder were heated to a temperature of 305° F (152° C) prior to mixing. When lime was incorporated into the mix, the heated aggregate was placed in the mixing bucket, then 1% lime by weight of aggregate was added to the aggregate, and the bucket rotated to mix the lime with the aggregate. A crater was formed in the aggregate/lime mixture and binder was then added and the mixing completed. Loose mix for TSR and Hamburg samples were aged 2 hours at 275° F (135° C), in accordance with the recently revised AASHTO R30 before being compacted.

TSR samples were prepared in accordance with ODOT Supplement 1051 with the following exception. In lieu of the 4 hour requirement in Supplement 1051, loose mix for TSR was aged 2 hours at 275° F (135° C), in accordance with the recently revised AASHTO R30, before being compacted. Supplement 1051 gyratory samples were compacted in the Superpave Gyratory Compactor using a 6 in (150 mm) diameter mold to a target air void of 7.0 ± 0.5%. Supplement 1051 Marshall 4 in (100 mm) diameter specimens were compacted with a Marshall hammer to a target air void of 7.0 ± 0.5%.

After compaction, and before saturation, TSR samples were aged at room temperature for 4 to 24 hours. In accordance with AASHTO T 283, the specimens to be conditioned and the specimens to be used as control should have approximately the same average air void content. Due to equipment and schedule constraints, it was not always possible to mix and compact all samples the same day. Therefore, specimens were tested based on personnel schedule and availability of equipment in order to meet the time requirements in T 283. Gyratory samples tested following Supplement 1051 were saturated to 80 – 90% and Marshall hammer compacted samples were saturated to 70 – 80%. The samples were then placed in an environmental chamber at 0° F (-18° C) for a minimum of 16 hours. The samples were then transferred to a water bath at 140° F (60° C) for 24 hours. The temperature in the water bath was then reduced to 77°F (25° C). After 2 hours, the indirect tensile strength of the specimen was measured using an InstroTek Auto_SCB. After testing, the conditioned samples were visually rated for stripping, with the assistance of personnel from ODOT's Office of Materials Management (OMM), on a scale of 0 to 3 where 0 is no stripping and 3 is extensive stripping.

Prior to each Hamburg test, the wheel loads were calibrated to 158 lbs. using a load cell. The Hamburg specimens were allowed to age at room temperature for at least 24 hours. The samples were then trimmed to fit into the molds, allowing no more than a 0.3 inch (7.5 mm) gap between the two mold halves. The molds were then placed in a Pavement Technology Inc. (PTI) APA Jr test machine, covered with water at 122° F (50° C) for at least 45 minutes but no more than 60 minutes. The test was then initiated. The test was allowed to run for 20,000 passes or until the maximum rut depth was achieved. Initially, during testing of the granite specimens, the maximum rut depth was set to 1.61 inches (40.90 mm), the LVDT displacement specified in T 324-17 at which the "…device will disengage…" if met or exceeded to ensure the test would run the maximum number of passes. During testing of the samples with granite aggregate, the motor on the APA Jr. burned out. The manufacturer and the manufacturer's technician repairing the machine recommended a lower maximum rutting value to limit the stress on the motor. In addition, the 1.61 inches (40.90 mm) criteria were not included in the post 2017 versions of AASHTO T 324. Instead, the current specification, AASHTO T 324-22, states "Select the maximum allowable rut depth based on the applicable specification”. Therefore, testing of the gravel and limestone samples were limited to the manufacturer recommended maximum rut depth of ½” (12.5 mm).

10.3 TSR Test Results

The TSR worksheet for the ODOT Asphalt Mix Design Excel packet was used to record and analyze the TSR saturation and testing process. The worksheets are presented in Appendix I and summarized in Table 28. Results from testing the granite aggregate are shown in Figures 19 through 210; the gravel aggregate in Figures 22 through 24; and the limestone aggregate in Figures 25 through 27.

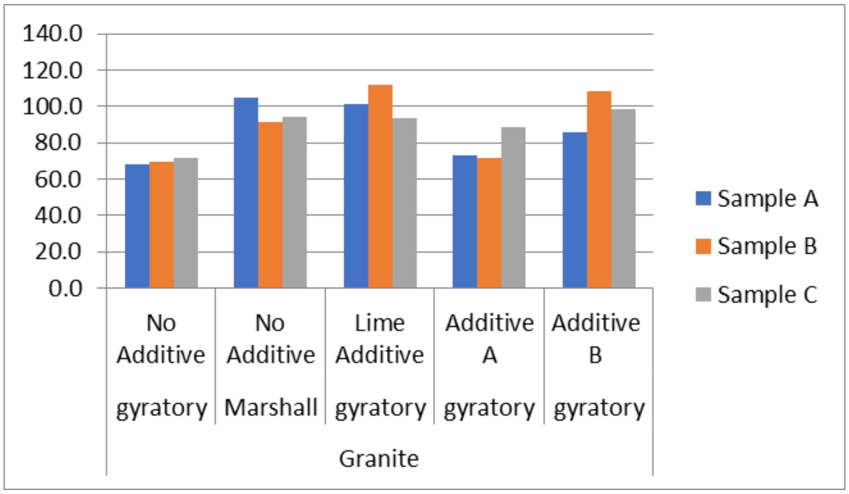


Figure 19 Granite Aggregate Conditioned Sample Strength

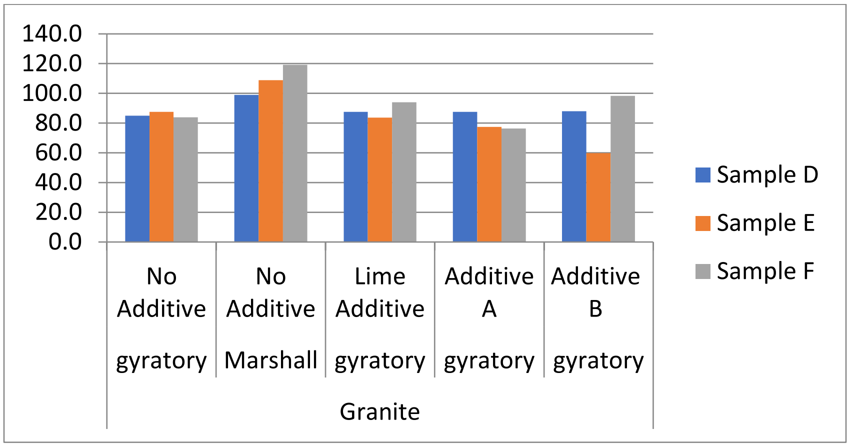


Figure 20 Granite Aggregate Control Sample Strength

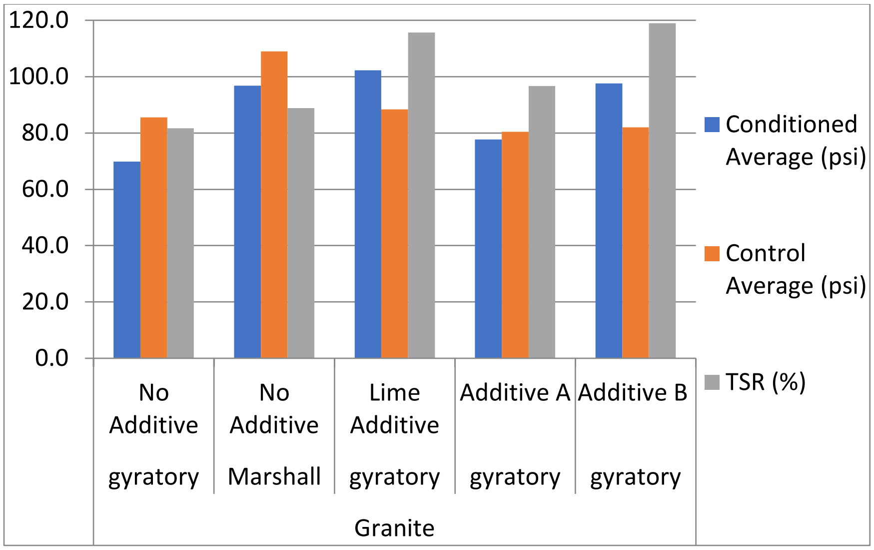


Figure 21 Granite Aggregate TSR Values

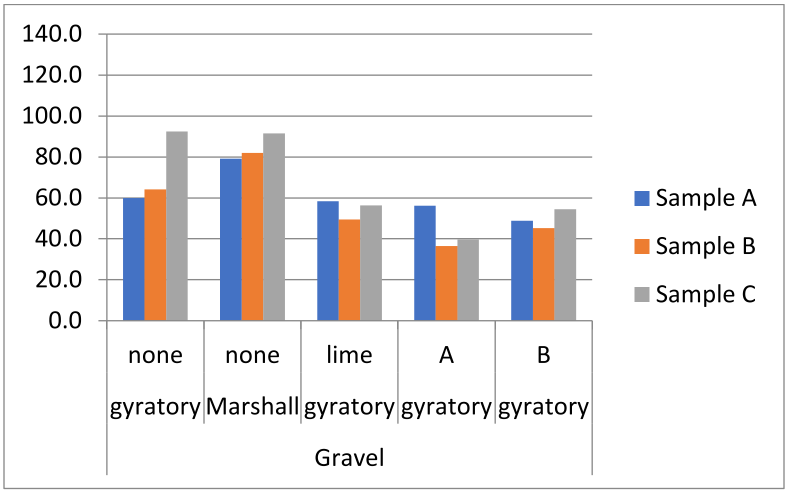


Figure 22 Gravel Aggregate Conditioned Sample Strength

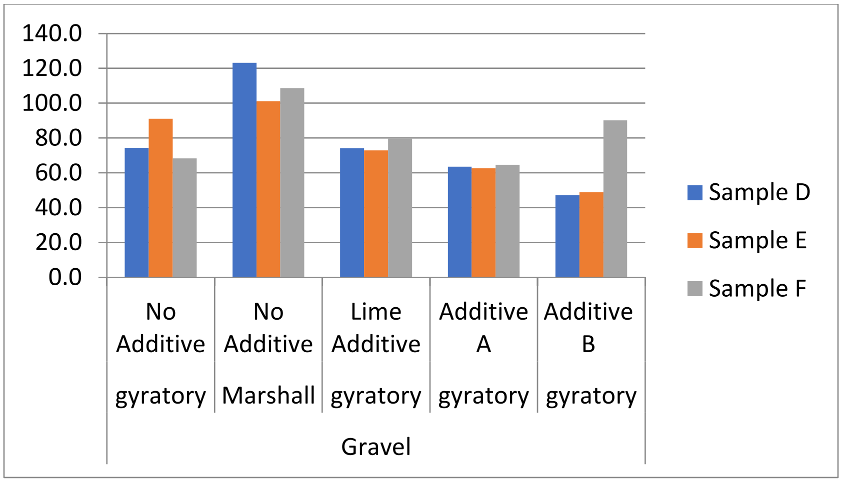


Figure 23 Gravel Aggregate Control Sample Strength

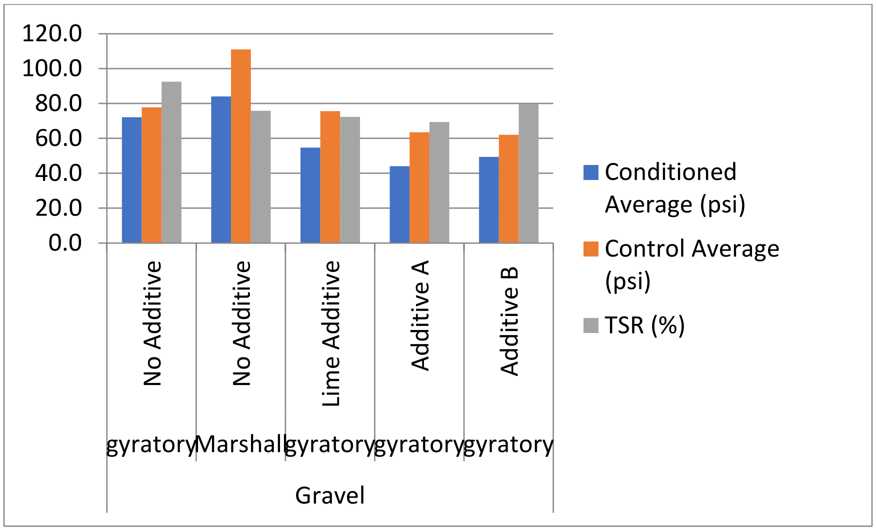


Figure 24 Gravel Aggregate TSR Values

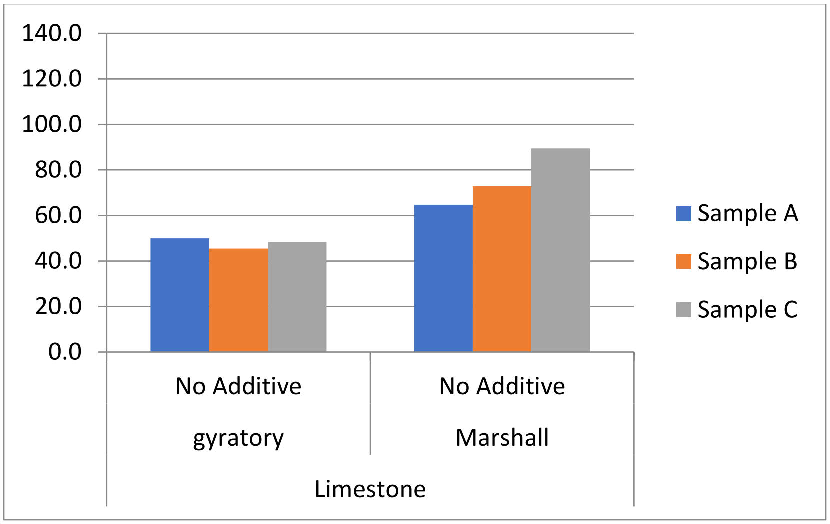


Figure 25 Limestone Aggregate Conditioned Sample Strength

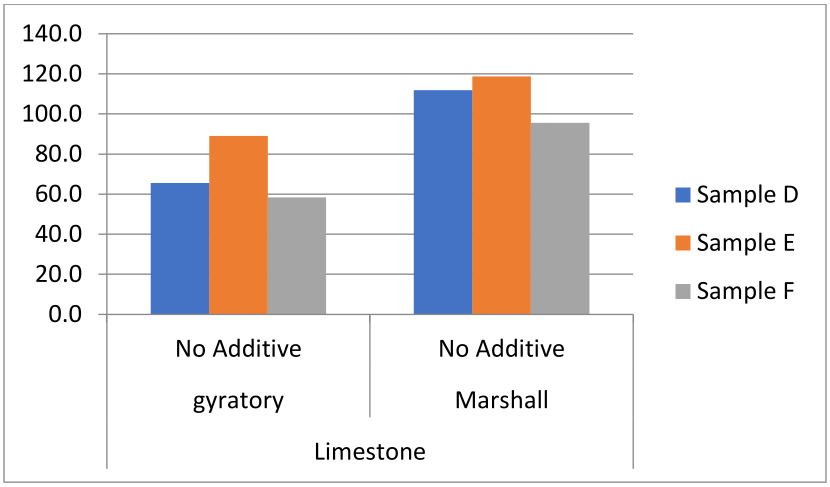


Figure 26 Limestone Aggregate Control Sample Strength

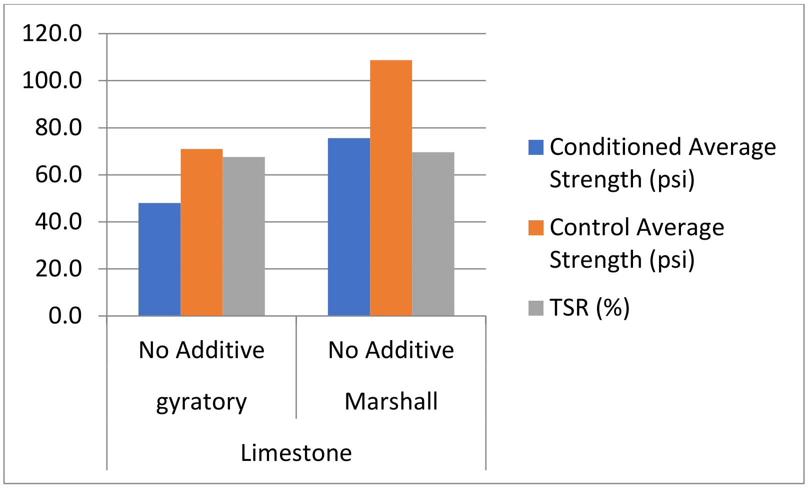


Figure 27 Limestone Aggregate TSR Value

Table 28 TSR Test Results

Aggregate Type	Compaction Method	Additive	Strength (PSI)								TSR (%)
			Conditioned (wet strength, psi)				Control (dry strength, psi)				
			Sample			Average	Sample			Average	
			A	B	C		D	E	F		
Granite	Gyratory	none	68.3	69.7	71.4	69.8	84.9	87.6	84.0	85.5	81.6
	Marshall	none	104.8	91.3	94.3	96.8	98.9	108.8	119.3	109.0	88.8
	Gyratory	lime	101.2	111.8	93.7	102.2	87.5	83.6	94.0	88.4	115.7
	Gyratory	A	72.9	71.9	88.4	77.7	87.5	77.4	76.3	80.4	96.7
	Gyratory	B	85.8	108.5	98.4	97.6	88.0	59.7	98.4	82.0	118.9
Gravel	Gyratory	none	59.9	64.1	92.5	72.2	74.4	91.1	68.3	77.9	92.6
	Marshall	none	79.1	81.9	91.5	84.1	123.2	101.2	108.7	111.0	75.8
	Gyratory	lime	50.0	45.5	48.4	48.0	65.5	72.9	79.8	75.6	72.4
	Gyratory	A	56.2	36.5	39.6	44.1	63.5	62.6	64.7	63.6	69.3
	Gyratory	B	48.8	45.3	54.4	49.5	47.3	48.8	90.2	62.1	79.7
Limestone	Gyratory	none	50.0	45.5	48.4	48.0	65.5	89.1	58.4	71.0	67.6
	Marshall	none	64.7	72.8	89.4	75.6	111.9	118.7	95.6	108.7	69.6

Based on the measured TSR, the moisture resistance of the granite would be expected to be excellent. As shown in Table 28 and Figure 21, all granite samples met ODOT's acceptance criteria for TSR of 80% or higher (70% or higher for Marshall samples). All additives improved the TSR value with additive A providing the least improvement followed by the lime then additive B. Pictures of the conditioned samples after testing are shown in Appendix I, Figures 23 through 32. There were no signs of stripping of the binder from the aggregate in any of the samples.

Based on the measured TSR, the moisture resistance of the gravel would be expected to be marginal, with some samples passing and some failing. As shown in Table 28 and Figure 243, the gravel gyratory and Marshall samples with no additives were the only samples to pass ODOT's acceptance criteria. In order of increasing TSR values were the samples containing additive A, lime, and additive B. The sample with additive B had a TSR, 79.7%, which was slightly below the acceptance level of 80%. Pictures of the conditioned samples after testing are shown in Appendix I, Figures 33 through 38. Some, but not all, of the coarse aggregate in all samples showed a thin coating of binder. All mixtures, with the exception of the mixture containing lime, were given a rating of "1" for visual stripping. The mixture with the lime additive was given a visual rating of "1 to 2" for stripping. It should be noted coarse aggregate with a thin binder coating was also observed in the control samples.

Based on the measured TSR, the moisture resistance of limestone would be poor. As shown in Table 28 and Figure 27, both the gyratory and Marshall samples containing limestone aggregate did not meet the ODOT criteria. Pictures of the conditioned samples after testing are shown in Appendix I, Figures 41 and 42. Other than one sample with a thinly coated aggregate, there were no signs of stripping of the binder from the aggregate.

Two of the mixes, one granite and one limestone, used in the testing were based on JMFs approved for construction. The approved JMF included TSR testing.

The contractor's JMF was available for the 19 mm mix with granite aggregate and 1% lime approved for use in Georgia. This mix used a PG 67-22 binder rather than the PG 64-28 binder used for the lab testing on this project. The detailed TSR test data were not provided but the average conditioned strength reported on the JMF was 802.3 kPa (116.3 psi), approximately 14% higher than the 704.6 kPa (102.2 psi) measured on the similar mix design for this project, and the average control strength was 876.1 kPa (127.1 psi), 44% higher than the 609.5 kPa (88.4 psi) measured on this project, resulting in a TSR of 91.5%, 21% lower than the 115.7% measured on this project.

The contractor's detailed TSR test data were available for the limestone mix. The JMF TSR test results are shown in Figure 28. The binder grade, PG 64-28, was the same for both mixtures. When compared to the results of the evaluation of the same mix on this project, the dimension, weight and volume data are very similar. The major difference in the tests are the wet strength average, 597.8 kPa (86.7 psi) for the JMF compared to 330.9 kPa (48.0 psi), 45% lower, for the lab test, and the average dry strengths, 683.3 kPa (99.1 psi) compared to 551.6 kPa (80.0 psi), 19% lower, for the lab test, which resulted in a TSR value of 87.5% for the JMF testing, which passes ODOT criteria, and a TSR value of 60.0%, 31% lower, for the lab testing, which does not pass the ODOT criteria.

TENSILE STRENGTH RATIO (TSR) - Supplement 1051

PROJECT:	**104-22**	**MATERIAL TYPE:**	**19.0 mm** **Surface**

	CONDITIONED SAMPLES			***CONTROL SAMPLES***		
SAMPLE ID	**214-1**	**214-2**	**214-3**	**214-4**	**214-5**	**214-6**
DIAMETER (mm.)	150.0	150.0	150.0	150.0	150.0	150.0
THICKNESS (mm.)	96.7	96.6	96.5	96.7	96.6	96.7
DRY WT IN AIR (gm.)	3766.1	3764.6	3770.0	3773.0	3771.9	3769.1
SSD WEIGHT (gm.)	3812.8	3811.9	3799.1	3803.7	3803.8	3809.7
WT IN WATER (gm.)	2182.9	2185.7	2174.7	2180.6	2178.8	2176.4
VOLUME (cc.)	1629.9	1626.2	1624.4	1623.1	1625.0	1633.3
BULK SP GR	2.311	2.315	2.321	2.325	2.321	2.308
MAX SP GR	2.486	2.486	2.486	2.486	2.486	2.486
% AIR VOIDS	7.1	6.9	6.6	6.5	6.6	7.2
VOLUME AIR VOIDS	115.0	111.9	107.9	105.4	107.7	117.2
LOAD (lb.)				3,619	3,483	3,389

SATURATED

SSD WEIGHT (gm.)	3866.8	3860.1	3860.1
WT IN WATER (gm.)	2240.0	2239.2	2233.9
VOLUME (cc.)	1626.8	1620.9	1626.2
VOL ABS WATER (cc.)	100.7	95.5	90.1
% SATURATION	87.6	85.4	83.5
% SWELL	-0.19	-0.33	0.11

CONDITIONED

THICKNESS (mm.)	96.5	96.6	96.8					
SSD WEIGHT (gm.)	3874.1	3874.8	3874.5					
WT IN WATER (gm.)	2241.9	2253.1	2243.7					
VOLUME (cc.)	1632.2	1621.7	1630.8					
VOL ABS WATER (cc.)	108.0	110.2	104.5					
% SATURATION	93.9	98.5	96.8					
% SWELL	0.14	-0.28	0.39					
LOAD (lb.)	3,099	3,058	3,023					**AVG.**
DRY STRENGTH (psi)				**AVG.**	102.5	98.7	96.0	**99.1**
WET STRENGTH (psi)	87.9	86.7	85.5	**86.7**				

TSR (%)	**87.5**
VISUAL STRIPPING:	None

Figure 28 Contractor’s TSR Test Data From Approved JMF for Limestone Aggregate

Figure 29 Contractor's and ODOT's TSR Test Data, Calendar years 2020 and 2021

In summary,

- *Based on TSR values*
    - *The granite mixtures would be resistant to moisture damage*
    - *The gravel mixtures are marginally resistant to moisture damage*
    - *The limestone mixtures are not resistant to moisture damage*
- *Based on the visual observation of the conditioned TSR samples after testing, only the gravel mixtures showed signs of stripping, i.e. thinning of the binder coating on coarse aggregate.*
- *The use of lime or liquid additives*
    - *Improved the TSR values for mixtures using granite aggregates and compacted with the gyratory compactor.*
    - *Did not improve the TSR values for mixtures using gravel aggregate*
- *There were two mixtures for which TSR test data for the same aggregate, different binder, were available from the producer's laboratory.*
    - *The granite with lime treatment JMF passed the TSR criteria during acceptance as did the sample tested for this project.*
    - *The limestone JMF passed the TSR criteria during acceptance whereas the sample tested for this project failed.*

10.4 Hamburg Wheel Testing Results

During Hamburg wheel testing, rut depths at different positions along the specimens are recorded with each load cycle. As shown in Figure 30, the curve can be divided into three main phases including post-compaction phase, creep phase, and stripping phase. The post-compaction phase consists of the consolidation of the specimen that occurs as the wheel load densifies the mixture and the air voids decrease significantly. The creep phase is represented by an approximately constant rate of increase in rut depth with load cycle. The rut depth accumulated in this phase is primarily due to the viscous flow of the asphalt mixture. The stripping phase, if the mix is moisture susceptible, starts once the bond between the asphalt binder and the aggregate starts degrading, causing visible damage such as stripping or raveling with additional load cycles. The stripping inflection point (SIP) represents the number of load cycles on the HWTT curve at which a sudden increase in rut depth occurs, mainly as a result of the stripping of the asphalt binder from the aggregate; it is graphically represented at the intersection of the fitted lines that characterize the creep phase and the stripping phase. SIP is used to evaluate the mixture resistance to moisture damage. Asphalt mixtures with higher SIP values and are considered to have better performance in the HWTT.

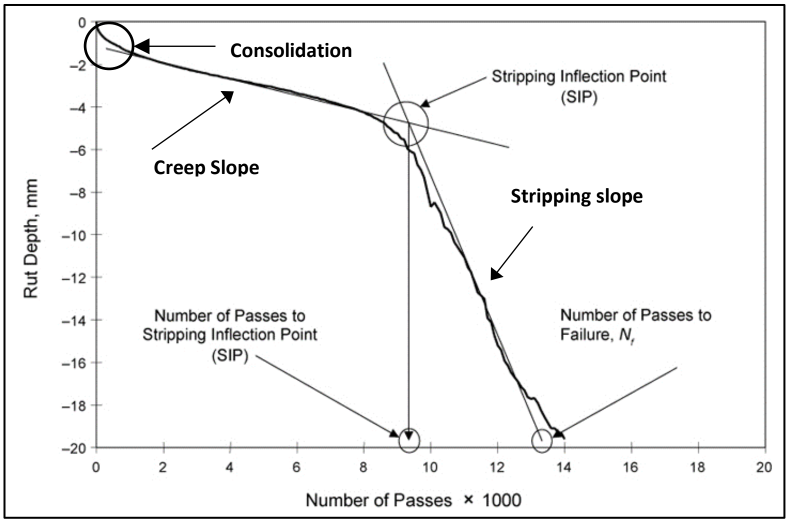


Figure 30 Typical Plot of HWTT Results [AASHTO, 2019]

The Pavement Technology Inc.'s (PTI's) operating software generates an Excel spreadsheet at the end of testing containing raw data, a summary plot, and an estimate of the SIP value. An example of the summary plot with SIP values are shown for all tests in Appendix J. Photos of the test specimens are also included in Appendix J. Initial tests were conducted on granite samples. None of these samples showed a significant break in the slope of the rutting curve which indicates the samples are not stripping. However, the software supplied with the APA Jr. assigned an SIP value. During conversations with PTI, they indicated negative values and extremely high values indicate there is no SIP. During the last test of the granite tests, granite with additive A, the motor on the APA Jr. failed after 9,000 passes. During the motor replacement, routine service and calibration was also performed by PTI, including an upgrade to the operating software. After service, two more sets of tests were performed on mixes with granite aggregate, one with additive A on one side and additive B on the other; the second with no additive on one side and lime additive on the other. These results are shown in Figures 51 and 52. Following a second failure of the APA Jr.'s motor, the maximum allowable rutting was set to 12.5 mm, the maximum recommended by the manufacturer and typically specified by state DOTs, for the testing of the specimens containing gravel and limestone aggregates.

Although the break in slope was not prominent in all plots shown in Appendix J, the shape of some of the curves were sufficient to manually calculate the SIP using the procedure in AASHTO T 324, in which linear regression is used to fit a line to the creep curve and the stripping curve. The value of the number of passes at the intersection of the two lines is the SIP. The SIP values calculated by the PTI software, as well as the SIP values calculated manually, are shown in Table 30.

Control samples for the granite, gravel and limestone aggregates as well as samples with lime additive and additive B were mix and compacted at the ORITE laboratory and shipped to NCAT for testing on a Cox & Son Hamburg Wheel Tester. The results are presented in Appendix K and summarized in Table 31. The granite samples, with and without additives, performed poorly, all samples except one of the samples treated with lime failed an acceptance criteria of no SIP in less than 15,000 load applications. The gravel samples performed moderately, the samples with additive B and one of the samples treated with lime failed an acceptance criteria of no SIP in less than 15,000 load applications while the control samples and the other sample treated with lime passing. Both samples with limestone aggregate failed an acceptance criteria of no SIP in less than 15,000 load applications.

Iowa DOT uses the ratio between the stripping slope and the creep slope to validate the SIP number (Schram et. al., 2012). The SIP number is considered valid if the ratio is 2.0 or greater. Schram reported stripping behavior was not observed in the field in sections with a ratio less than 1.0, even though a SIP number can be calculated. Under the current Iowa DOT specification, if the ratio of slopes is less than 2.0, the SIP is considered invalid and the mix is considered passing. An evaluation of the validity of the calculated SIP based on the Iowa criteria is also shown in Tables 30 and 31 and summarized in Table 29.

Two failure criteria are shown in Table 29. The first is a SIP less than 15,000, the value commonly used by agencies responding to the survey. The second is a SIP less than 15,000 and a stripping slope to creep slope ratio greater than or equal to 2.0, a criteria used by Iowa DOT to validate the SIP criteria. The table shows whether the sample passed based on the SIP calculated with the APA Jr software, a manual calculation of the SIP as detailed above, and the SIP calculated by the NCAT Cox & Sib software. Using the SIP criterion alone, the granite and gravel samples were marginal, with some samples passing and some failing. The limestone samples failed. Using the SIP criteria in combination with the Iowa DOT slope ratio to confirm the SIP is valid, almost all the granite and gravel samples passed, the limestone samples failed the SIP criterion used in this study.

Table 29 Summary of HWTT Results

Aggregate Type	Additive	Fail Criteria				
		SIP < 15,000			stripping line slope/creep line slope ≥ 2.0	
		APA jr	manual	NCAT	manual	NCAT
Granite	none	passed	passed	failed	passed	passed
		passed	passed	failed	passed	passed
		failed	failed		passed	
	A	failed	passed		passed	
		failed	passed		passed	
		failed	passed		failed	
	B	passed	passed	failed	passed	passed
		passed	passed	failed	passed	passed
		passed	failed		failed	
	lime	failed	passed	passed	passed	passed
		failed	passed	failed	passed	passed
		passed	failed		passed	
gravel	none	failed	failed	passed	passed	passed
		failed	passed	passed	passed	passed
	A	failed	failed		passed	
		failed	failed		passed	
	B	failed	passed	failed	passed	passed
		failed	failed	failed	passed	passed
	lime	failed	failed	failed	passed	failed
		failed	failed	passed	passed	passed
Limestone	none	failed	failed	failed	failed	failed
		failed	failed	failed	failed	failed

The following are observations based on the laboratory testing and using a no SIP in less than 15,000 load application criteria to define a moisture susceptible mix:

- *Based on HWTT, the granite mix would be expected to have*
    - *Marginal performance when tested on the APA Jr and analyzed with the APA Jr software. Only the mixture using additive B would pass the criteria.*
    - *Marginal performance when tested on the APA Jr and analyzed manually. Only the mixture using additive A would pass the criteria*
    - *Poor performance when tested with the Cox & Sons and analyzed with the Cox & Sons software. All samples failed the criteria*
- *Based on HWTT, the gravel mix would be expected to have*
    - *Poor performance when tested on the APA Jr and analyzed with the APA Jr software. All samples failed the criteria.*
    - *Poor performance when tested on the APA Jr and analyzed manually. All samples failed the criteria.*
    - *Marginal performance when tested with the Cox & Sons and analyzed with the Cox and Sons software. Only the control passed the criteria.*
- *Based on HWTT, the limestone mix would be expected to have poor performance*
    - *Poor performance when tested on the APA Jr and analyzed with the APA Jr software. All samples failed the criteria.*

    - *Poor performance when tested on the APA Jr and analyzed manually. All samples failed the criteria.*
- *Poor performance when tested with the Cox & Sons and analyzed with the Cox & Sons software. All samples failed the criteria*

10.5 Discussion of the TSR and Hamburg Laboratory Test Results

The results from the laboratory testing do not reflect the typical performance expected for the aggregate types selected based on the historic performance of that aggregate type.

Taylor and Khosla [1983], Santucci [2010], and Sebaaly [2010] identified the following seven processes which contribute to the causes of moisture damage

- *Detachment of the binder film from the aggregate without film rupture,*
- *Displacement of the binder film from the aggregate through film rupture,*
- *Spontaneous emulsification and formation of an inverted emulsion of water in binder,*
- *Pore pressure-induced damage due to repeated traffic loading,*
- *Hydraulic scour at the surface due to tire-pavement interaction*
- *pH instability of the contact water, which affects the binder-aggregate interface, and*
- *Environmental factors such as excessive rainfall, large temperature fluctuations, and freeze-thaw (F/T) conditions.*

When designing the experiment the aggregate sources were selected based on aggregate type since performance data for individual quarries was not available for Ohio sources. It was expected the granite would be the most susceptible to moisture damage, the gravel marginally susceptible to moisture damage, and the limestone the least susceptible to moisture damage as determined by TSR. However, as shown above, the results for this project did not follow the expected trend. The results of the TSR and Hamburg wheel test are typically explained by the first two factors and the last factor, i.e. detachment or displacement of the binder film from the aggregate as a result of being subjected to moisture and freeze/thaw conditions in the case of TSR or high temperature and moisture in the case of the Hamburg wheel test.

The examination of the TSR samples found little evidence of detachment or displacement of the binder from the aggregate, with the exception of some thinning of the asphalt coating on some of the aggregates in the samples containing gravel aggregates. However, this condition was observed on control samples also. In addition, the ineffectiveness of the additives indicates other factors are affecting the outcome of the testing.

As discussed previously, TSR samples tested by contractor's for acceptance of a JMF for the granite with lime and the limestone mix passed the TSR criteria. The only difference between the acceptance samples and the samples compacted in the lab was the binder. The binder used on this project was modified with polyphosphoric acid (PPA) to obtain a PG 64-28 grading. Research has shown PPA can affect the moisture damage resistance of a mix [TRB, 2012]. Buncher and D'Angelo report PPA could improve the moisture resistance of mixes using acidic aggregate, such as granite [TRB, 2012]. Arnold, Youtcheff, and Needham [TRB 2012] have also shown PPA modified binders my increase stripping potential, although the research shows lime should mitigate the potential for moisture damage whereas the ability for liquid additives to mitigate the potential for moisture damage is aggregate/binder specific.

In addition, other factors have been identified which may influence the test results including dust, binder content, porosity, etc. (NCHRP, 2010). HWTT also sensitive to binder grade and test temp. The porosity may explain the performance of the mixture with limestone. During TSR testing, these samples were easily saturated with a low vacuum applied for a short period of time while the granite and gravel samples required a high vacuum applied multiple times for a long period of time.

Finally, test variability as high as 25% has been reported for the TSR test in the literature (Schram, 2012). When contractors in Ohio conduct the TSR test, additional samples are compacted and submitted to ODOT for testing. The data for calendar years 2020 and 2021 were provided to the researcher. Tests with comments indicating issues were removed from the data. The contractor's results, ODOT's results, and whether the sample passed or failed the test are presented in Appendix L. A plot of the data is shown in Figure 29. A linear regression, forced through the origin, has an R^2 of 0.24, indicating very little correlation between contractor's test results and ODOT's results. The contractor's TSR value varied as much as 36% from ODOT's value. NCHRP (2010) reported 70% to 80% saturation level may induce micro-cracks which contribute to test variability. Unlike the TSR test, the literature does not report the HWTT to be a highly variability test procedure.

Table 30 ORITE Hamburg Wheel Test Results

Aggregate Type	Additive	SIP reported by APA Jr. Software	SIP	Creep line slope (mm/1000 passes)[5]	Stripping line slope (mm/1000 passes)[6]	Manually Calculated SIP	Stripping Line slope/ creep line slope Ratio	SIP value valid based on Iowa ratio[3]
Granite	None	140,000	none[1]	note 4	note 4	none		
		-45,604	none[2]	note 4	note 4	none		
		2,015	2,015	0.996	1.328	6,279	1.3	no
	Additive A	8,033	8,033	note 4	note 4	none		
		10,659	10,659	note 4	note 4	none		
		108	108	0.560	1.145	16,875	2.0	yes
	Additive B	-2,083	none[2]	note 4	note 4	none		
		-8,618	none[2]	note 4	note 4	none		
		42,235	none[1]	0.923	1.820	6,471	2.0	yes
	Lime additive	13,654	13,654	note 4	note 4	none		
		11,281	11,281	note 4	note 4	none		
		-49,037	none[2]	0.485	0.531	6,084	1.1	no
Gravel	None	2277	2277	2.284	3.543	3,479	1.6	no
		2896	2896	note 4	note 4	none		
	Additive A	2,004	2,004	4.066	7.227	1,721	1.8	no
		2,147	2,147	5.570	9.314	1,783	1.7	no
	Additive B	2,559	2,559	note 4	note 4	none		
		2,620	2,620	3.774	5.586	1,508	1.5	no
	Lime additive	4,749	4,749	2.424	3.566	2,261	1.5	no
		2,002	2,002	4.413	2.505	4,099	1.8	no
Limestone	None	1905	1905	0.773	2.430	5,123	3.1	yes
		7449	7449	0.938	2.520	4,776	2.7	yes

Notes:

1. *Calculated SIP high, no SIP*
2. *Calculated SIP negative, no SIP*
3. *SIP value is valid if ratio ≥ 2.0*
4. *Break in rutting curve was not observed*

5. *Manual identification of creep line*
6. *Manual identification of stripping line*

Table 31 NCAT Hamburg Wheel Test Results

Aggregate Type	Additive	Side	SIP	Creep line slope (mm/1000 passes)	Stripping line slope (mm/1000 passes)	Stripping Line slope/creep line slope Ratio[1]	SIP value valid based on Iowa ratio[1]
Granite	None	1	6180	0.606	0.980	1.6	No
		2	7440	0.632	1.003	1.6	No
	Additive B	1	6093	1.154	2.095	1.8	No
		2	5817	0.623	1.001	1.6	No
	Lime additive	1	15632	0.136	0.172	1.3	No
		2	9314	0.303	0.458	1.5	No
Gravel	None	1	16035	0.147	0.181	1.2	No
		2	18604	0.163	0.198	1.2	No
	Additive B	1	2993	1.160	2.122	1.8	No
		2	4229	0.866	1.942	3.8	Yes
	Lime additive	1	7948	0.514	1.029	2.0	Yes
		2	15840	0.157	0.258	1.6	No
Limestone	None	1	11080	0.304	0.748	2.5	Yes
		2	9434	0.0274	0.641	2.3	Yes

Notes:

1. *SIP value is valid if ratio ≥ 2.0*

11 Appendix E: Cost Analysis

A life cycle cost analysis (LCCA) was conducted to assess the potential impact of moisture damage, and antistrip usage on the cost of rehabilitation activities needed to keep asphalt pavements pavement in serviceable condition for 35 years in Ohio. This performance period is based on the current analysis period specified in section 703.1 of the Ohio DOT Pavement Design Manual. Per this manual, their recommended rehabilitation schedule for flexible pavements developed from analysis of ODOT pavement performance is as follows:

- *Year 14: 1.5" overlay*
- *Year 24: 3.25" overlay*
- *Year 34: 1.5 " overlay*

The LCCA used in this study utilizes the cost of materials for rehabilitation activities (asphalt overlays) of existing pavements, and does not include any other costs such as user delay cost and agency costs.

The study evaluated three different scenarios:

- Scenario 1-Moisture resistant (control) mixes
- Scenario 2-Moderate stripping potential mixes without antistrip additives
- Scenario 3- Moderate stripping potential mixes with antistrip additives

The analyses conducted rely on the net present value (NPV) for the three scenarios to determine if the higher cost of adding antistrip could be justified by the improved pavement performance. Table 32 summarizes the input data used for the analyses. A 3.5% discount rate was selected based on the ODOT Pavement Design Manual, Section 701.1. Since the analyses only include rehabilitation activities, the analysis period utilized in the NPV analyses is 20 years. The NPV values from these analyzes are presented at the year the first maintenance activity occurs. These analyzes consider that year 0 is the year when the first overlay is placed (year 14 of the analysis period of 35 years specified by ODOT). The cost of HMA is based on Ohio historical average bid data for the years 2021 and 2022 for a typical two-lane resurfacing mix. The cost of antistrip additives is based on an average cost of $2 per pound that corresponds to an approximate cost of $0.50 per cubic yard of HMA assuming a dosage rate of 0.5% by weight of the asphalt binder. The analyses assume a project length of 1 mile, and a lane width of 12 feet.

Table 32 Input Data for Different Scenarios

Variable	**Value**
Discount rate	3.5[1]
Analysis period	20 (year 0 is year 14 of the analysis period of 35years)
HMA cost (per cubic yard)	$155 based on Ohio historical bid data[2]
Cost of antistrip additives (per cubic yard)	$2.40 ($2/lb)
Project length (mile)	1
Lane width (feet)	12

[1] Discount Rate -ODOT Pavement Design Manual Section 701.1 recommends to follow recommendations from Office of Management and Budget (OMB) in Circular A-94 (30-year real interest rate)

[2] Cost reported for a two-lane resurfacing, asphalt concrete surface course average for quantities more or equal than 1000 CY of mix.

Because of the limited data generated in this study, and the lack of conclusive results regarding the use of antistrip additives, one of the assumptions made was that moderate stripping potential mixes with antistrip additives will have the same performance of moisture resistant mixes (control mixes). Although the results of this study did not clearly show the positive effect of antistrip additives based on TSR and HWTT results, this assumption was based on the literature review that indicated that antistrip additives are effective in improving the moisture susceptibility of the mixes based on performance testing.

Since no field performance data were available to assess the life expectancy of asphalt overlays with high stripping potential aggregates, the research team relied on limited data provided by ODOT to quantify it. The information provided by ODOT based on performance models indicates that the statewide life expectancy of asphalt overlays to reach poor condition (PCR<65) is 14 years. It was also indicated that District 3 is the district with history of moisture susceptibility issues. For this district the life expectancy of asphalt overlays to reach poor condition is 8 years. Considering the schedule of rehabilitation activities specified by the ODOT, the first overlay (1.5") occurs at year 14, and subsequent activities occur at intervals of 10 years with the second overlay (3.25") at year 24, and the third overlay (1.5") at year 34. In the analyses it was assumed that moisture resistant mixes, and high stripping potential mixes with antistrip additives will follow the schedule of rehabilitation suggested by ODOT. However, for high stripping potential mixes without antistrip additives overlays will be needed at intervals of 8 years (based on their life expectancy to reach poor condition) indicating 2 years of performance lost for these mixes with respect to control mixes.

Equation 1 was used to determine the NPV of the rehabilitation activities needed during the analysis period.

$$NPV = PV_0 + \Sigma FV_i * \left(\frac{1}{(1+r)^{n_i}}\right) + SV * \left(\frac{1}{(1+r)^{n_s}}\right)$$

Where

NPV = net present value;

PV_0 = present value of the first overlay;

FV_i = future value of the i^th^ overlay;

SV = salvage value at the end of analysis period;

r = discount rate;

n_i = time to apply the i^th^ overlay; and

n_s = analysis period.

Scenario 1- Moisture Resistant (control) Mixes w/o Antistrip Additives

For scenario 1, the rehabilitations activities assumed were as follows:

- *Present value at year 0 was $45,467, this represents the cost of the first overlay (1.5").*
- *At year 10 the second overlay (3.25") was placed, and the present value was $98,511.*
- *At year 20, the third overlay is placed (1.5") and the present value was $45,467.*
- *Based on equation 1 the total NPV for this scenario was $138,153 per lane mile.*

Scenario 2- Moderate stripping potential mixes w/o antistrip additives

For scenario 2, the rehabilitations activities were as follows:

- *Present value at year 0 was $45,467 which represents the cost of the first overlay (1.5”).*
- *The second overlay (3.25”) with a present cost of $98,511 was placed on year 8.*
- *The third overlay was placed at year 16 with a present cost of $45,467.*
- *To reach the analysis period utilized in this analysis, an additional overlay of 1.5” was needed at a cost of $45,467. Since this overlay still had 4 years of performance at year 20, the salvage value of the overlay was $22,733.*
- *Using equation 1, the NPV for this scenario was $157,923 per lane mile.*

Scenario 3- Moderate stripping potential mixes with antistrip additives

Finally, for scenario 3, For scenario 2, the rehabilitations activities were as follows:

- *Activities were identical to the activities for scenario 1 because as it was explained previously, the assumption was that mixes with high stripping potential will achieve a performance equal to the performance of resistant mixes if antistrip agents were used.*
- *The only difference in this analysis was that the cost of HMA per cubic yard was increased by $2.40.*
- *Using equation 1, the NPV for this scenario was $138,857 per lane mile.*

Summary of Cost Analysis Results

The LCCA indicated the use of moisture susceptible aggregates significantly increases the cost of rehabilitation activities required to keep the pavements in good condition. The analysis showed an increase in maintenance cost of $19,066 per lane mile when susceptible aggregates are used instead of moisture resistant aggregates as a result of the reduced service life. The evaluation also showed that the use of antistrip additives had a small impact in the cost of rehabilitation activities ($704 per lane mile), and therefore it is justified to require the use of antistrip additives when the moisture susceptibility potential of the aggregates is unknown or when it is known that the aggregates are susceptible to moisture.

It is important to point out that this evaluation is very limited, and it was based on the assumption that antistrip additives will provide satisfactory moisture susceptibility performance; however actual field performance data of mixes with susceptible aggregate are needed to verify that the improved performance presented in this analysis can be achieved.

12 Appendix F: References

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13 Appendix G: Literature Review Table

Reference	**Method**	**Standard Procedure**	**Variables Studied**	**Adv. Of test**	**Disadv. Of test**	**Correlation with field**	**Type of Antistrip**	**Dosage Rate**	**Findings**
Maupin 1979	Lottman		Rate of loading				Nostrip ACRA-500	0.5% by weight of asphalt cement	Rate of loading can be increased to 51 mm/minute
Lottman, 1982	Lottman		Lab vs 5 year field performance in 7 states				Kling Beta LV by weight of asphalt cement	1% by weight of asphalt cement	Ranking of the sections in terms of visual rating of stripping and strength ratio of the cores were similar to the ranking based on the testing of samples prior to construction
Kennedy, Roberts, and Lee, 1984	Texas Boiling Test		• *Number of times asphalt and aggregate are mixed* • *Temperature to which aggregate is heated before mixing* • *Type of water used to boil mixture*				• *liquid chemical antistripping additives (11)* • *Hydrated lime*	1-2%	• *Results indicate Texas Boiling Test can detect asphalt mixtures that exhibit stripping tendencies in the field* • *"The mixing temperature produced a significant effect on test results: the higher initial aggregate temperature produced less stripping."*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Tunnicliff & Root, 1984	Lottman		Antistrip agents.			Good correlation with field performance	- *Hydrated Lime* - *Cationic surfactants*	0.125-2%	- *Samples should be compacted to a high void content (6 to 8%) and control the degree of saturation (55 to 80%).* - *High temperatures/ Long test periods are needed to evaluate additive effectiveness*
Hicks, 1991	Lottman		- *Aggregate type and* - *Additive type*				- *Dry Lime* - *Quick Lime*		Several researchers have reported good correlation between laboratory and field results.
	Indirect Tension strength (ITS)/TSR	ASTM D 4867			High variability			1-1.5%	FHWA research found the test "…appears to reflect the field performance results".
	Boiling Test	ASTM D 3625							FHWA research found "…poor results compared with field experience…" whereas other researchers found good correlations with field performance. Several researchers found the test useful for evaluating antistrip additives.
	Immersion Compression Test	ASTM D 1075/ AASHTO T 165							Some research has found this test method can produce retained strength ratios near

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									100 percent even when stripping is present.
	Freeze-Thaw Pedestal Test								While research in Texas has found this test did an excellent job identifying stripping aggregates, research in Alabama found the test had “little potential”.
Tarrer and Wagh, 1991	Literature review	*7.*	• *Effect of aggregate mineralogy* • *Surface properties* • *pH at the water-aggregate interface*						• *Hydrated lime can be used to treat dusty and dirty aggregates* • *Weathered aggregates are more resistant to stripping than freshly crushed aggregates* • *Preheating and weathering aggregates increases asphalt-aggregate bond*
Aschenbrener & McGennis, 1993	TSR	AASHTO 283			Can’t distinguish between poor and bad mixes		Hydrated Lime	1% hydrated lime by weight of aggregate	Reasonably good, but not ideal, correlation in Colorado and recommended a higher minimum TSR, 0.85, to ensure mixtures with marginal performance

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									would be rejected
MacKean (1994)	TSR	AASHTO T283	Test variability		Results vary greatly when performed by different operators				Between laboratory variation of results vary more than 10 times that of within laboratory variation of TSR results
Aschenbrenner (1995)	Hamburg or Loaded Wheel Test (LWT)	AASHTO T 324 - Hamburg				Strong correlation between stripping in laboratory tests and the moisture damage in field			• *Stripping inflection point (SIP) was higher than 10,000 passes* • *Pavements that lasted 1 year, the SIP was less than 3,000 passes* • *Aggregate properties such as dust coating on the aggregates, clay content, and high dust-to-asphalt ratios affect HWTD*
Alam (1997)	Modified ECS					No correlation was found between mixture performance in the ECS and mixture			If circumference of specimen increases more than 2%, mix is susceptible. If Mr(Reselient Modulus) is below 0.8=marginal. If Mr>=0.8, well performing

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
						performance in the field			
Kandhal et al. (1998)	Methylene Blue (MB) Test	Technical Bulletin 145, InternationalSlurry Seal Association	Harmful clays	Screens aggregate types well before mixing	Neglects role of asphalt-aggregate bond				Larger MB values correspond to lower tensile strength ratios from AASHTO T283
Stuart, 1998	TSR	ASTM D 4867/AASHTO T 283	Lab testing of cores vs. field performance for 21 pavements after 9 years						The correlation between test results and performance was poor except when air voids were greater than 6.0%. Recommended a minimum TSR of 0.80 and a maximum visual stripping of 10% criteria.
Bahia and Ahmad, 1999	TSR	AASHTO T 283	Lab vs. field performance						No relationship between lab TSR values and Pavement Distress Index (PSI) for the 14 sections studied.
Epps et al. (2000)	Modified Lottman	AASHTO T283	• *different compaction types* • *diameter of the specimen* • *degree of saturation* • *freeze-thaw cycle*						• *Dry strength of 100-mm Marshall specimens was the same as that of the 150-mm SGC specimens.* • *Dry strength increased as the aging time for the loose mix increased.* • *The tensile strength*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									ratio of 150-mm SGC specimens was similar to the tensile strength ratio of 100-mm Marshall specimens.
Solaimanian and Kennedy 2000	Hamburg or Loaded Wheel Test (LWT)	AASHTO T 324 - Hamburg				Simulates the stripping mechanism during hot periods			Test temperatures should be selected from the hottest time of the year except for locations where water primarily enters the asphalt concrete during the cooler time of the year
Sebaaly et al. (2001)	TSR	AASHTO T283	• *Compaction method (Marshall, 6 in and Superpave, 4 and 6in)* • *Addition of Portland Cemment (PC)*				PC	0.02	• *(Freeze/thaw, No freeze-thaw) conditioning did not show significant difference* • *PC addition in Modified Lottman tests significantly affected strength ratios in 4" and 6" superpave*
	ADOT Immersion Compression Test								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									designs with slightly significant strength ratio difference in 4" Marshall designs • *ADOT Immersion Test did not show efficiency in discriminating poor from good mixes*
Tandon and Nazarian (2001)	Modified ECS		Blind Mixture types			Modified ECS procedure matched field performance in some cases			Deviation from the job mix formula during construction or laboratory testing may favorably or unfavorably affect the moisture susceptibility of the mixture

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Hunter & Ksaibati (2002)	Georgia Loaded Wheel Tester (GLWT)		Freeze-thaw cycling				Lime		• *Tensile strength of the granite aggregate reached failure more rapidly than the limestone aggregate.* • *Asphalt and the aggregate type were shown to have an effect on the moisture susceptibility of the HMA mixtures.* • *Georgia Loaded Wheel Tester (GLWT) was not effective method for moisture damage susceptibility testing*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Zehr (2002)	TSR	AASHTO T283							• *Plant produced TSR are greater than laboratory compacted TSR* • *Differences were evident between lab and plant mixes were evident in 4-inch diameter samples but 6-inch samples* • *Visual stripping of moisture damage provides subjective ratings*
Hicks et al. (2003)	Literature Review								• *Factors that affect moisture damage of asphalt mixtures grouped into mix design, climate, production and construction* • *82% states required antistrip treatment, a*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									significant chunk (56%) by liquid antistrip
Little & Jones, 2003									Mechanisms of stripping - detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour, pH instability and the effects of the environment or climate on asphalt-aggregate material systems
Solaimanian et al. (2003)									Criteria for a succesful moisture susceptibility test procedure - 1.Field simulation 2. Mix differentiation 3. Repeatability 4.Feasibility and Cost

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
West et al. (2004)	APA		• *specimen type* • *load application type* • *conditioning - followed TSR conditioning*		Large variability in testing				• *"Use of the steel wheels for specimen loading is much more severe than using air filled hoses"* • *"Pre-conditioning of specimens using a prescribed vacuum level (28 mm of Hg) and time (6 minutes) followed by a single freeze/thaw cycle appears to help distinguish a stripping prone mixture from a non-stripping prone mixture. "* • *"The research indicates that testing of unconditioned specimens in a submerged (wet) condition does not*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									cause stripping to occur."
Berthelot et al. (2005)							- *Hydrated Lime* - *Liquid ASA*		Lime addition significantly increased the dynamic modulus, phase angle, loading frequency and deviator stress whereas LAS did not.

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Buchanan & Smith (2005)	Rotary wheel tester (RWT)		• *Asphalt binder (PG 67-22 and PG 76-22)* • *Aggregate type* • *Test efficiency*				Lime	1%	• *RWT cheaper ($24,000) than Hamburg wheel tracker (50,000-70,000) and also easier test procedure* • *Gravel mixes showed higher deformations compared to gravel-limestone blended mixes* • *'PG 76-22 asphalt binder improves mix performance to a greater extent than PG 67-22 plus hydrated lime"*
Kanitpong & Bahia(2005)	Indirect Tensile Strength Test	AASHTO T283	• *Polymer and antistripping additive* • *Aggregate type*						• *Antistripping additives did not improve rutting performance* • *Polymer modified mixes performed better than*
	Uni-axial Compression Permanent Deformation Test								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
	Hamburg Wheel Tracking Test	AASHTO T 324							*antistripping additive (ASA) modified mixes* • *ASA affects the adhesive property not cohesive property of mixes*
Mallick et al. (2005)	Accelerated loading equipment		• *Aggregate type* • *Conditioning methods [freeze-thaw, Model Mobile Load Simulator (MMLS3), Moisture Induced Stress Tester (MIST)]* • *Effect of antistripping agent*						• *Accelerated loading equipment shows promise as a moisture susceptibility evaluative test* • *Some aggregates can take up to 10 cycles of freeze thaw to reach 0.8 TSR* • *Hydrated lime improves resistance evidenced in freeze-thaw and MIST*
	TSR	AASHTO T283							
Mc.Cann et al. (2005)	TSR	AASHTO T283					Lime		Significant repeatability of test
	Ultrasonic accelerated moisture conditioni								Strong correlation with IDT test

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
	ng (UAMC)								
Zollinger, 2005	Surface Energy		- *Binder type* - *Aggregate type*	Correlates cohesive and adhesive energy with surface energies of asphalt and aggregates					- *"The ratio of the adhesive bond energy under wet condition to the adhesive bond energy under dry condition (ΔGaW/ΔGaD) can be used to identify possible problematic combinations of aggregates and binder."* - *"The ratio of the shear modulus at failure to the initial shear modulus (G'/G) showed that mixes with poor resistance to moisture damage failed at higher ratios than mixes with good resistance to moisture damage."*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Masad et al. (2006)	X-Ray CT imaging technique		• *Gradation* • *Air void size* • *Aggregate type (Limestone and granite)*						• *“permeability alone cannot be used as an indicator for moisture damage"* • *Granite aggregate showed lesser resistance to moisture damage* • *No direct relation exists between pore pressure distribution and moisture damage*
Putman & Amirkhanian (2006)	TSR	AASHTO T283	ASA				• *Hydrated Lime* • *Liquid ASA*	0.50%	• *Significant difference observed in TSR values between samples treated and non-treated* • *No significant difference amongst differing antistripping agents* • *Boil test was ineffective in differentiating amongst mixes in moisture*
	Boiling Test								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									damage testing
Abo-Qudais & Al-Shweily (2007)	Static creep test						- *Limestone dust* - *Calcium stearate hydroxide*	3,5,7,10,20%	Samples with calcium stearate hydroxide showed lesser stripping than limestone dust samples
	Boiling Test								
Arambula et al. (2007)	Dynamic tension test		Effect of air void (different compaction angles & gradation)						Sample with higher air void content and radius are less susceptible to moisture damage
Bahia et al. (2007)	Energy Ratio Approach		- *Aggregate type* - *Presence and absence of Antistrip agents*		- *High variability* - *Long test period*				Good distinguishing capabilities between good and poor mixes
Chen (2007)	TSR	AASHTO T283	ASA measurement in lab and field				Liquid ASA (LOF 6500 & Morlife 2200)	0.5-2%	- *Change in color intensity corresponding percentage of additive present from litmus and colorimeter testing in the lab and field* - *Significant difference obeserved in TSR values between*
	Litmus and colorimetric tests								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									samples treated and non-treated - *Heating affects the percentage of additive present in a mix*
Hanz et al. (2007)	Stripping test	Develop by Quebec DOT	Potential screening tests				liquid antistripping additives		- *Stripping test cannot be used as a screening test due to its high variability* - *Fracture energy test shows promising results as an evaluative test but high variability may be of concern* - *Aggregate gradation plays a significant role moisture susceptibility*
	TSR	ASTM D4867							
	Fracture Energy Test	Similar to AASHTO T 322, conditioned similar to ASTM D4867							

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Lu et al. (2007)	TSR					Acceptable lab to field performance	- *Lime* - *Liquid antistrip*		- *Rainfall amount and ageing affect moisture damage* - *Different liquid antistripping agents have different effectiveness* - *Correlation between laboratory test results and field performance acceptable but some false positives were recorded*
	Hamburg Wheel Tracking Test								
Sengoz & Agar (2007)	TSR	AASHTO T283	Asphalt film thickness (3-6.5%)						As the asphalt film thickness increases, the TSR values increase as well, this indicates the detrimental effect of water decreases with increase in asphalt film thickness.
Solaimanian et al. 2007	ECS with Dynamic Modulus								- *ECS with Dynamic Modulus performed better than HWTT and TSR* - *Dynamic Modulus (E*)*
	TSR	ASTM D4867							
	HWT	AASHTO T 324							

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									can be used as a material parameter for assessment of extent of damage
Liang (2008)	TSR	AASHTO T283	- *Methods of specimen compaction (Marshall, Superpave gyratory)* - *Aging condition (24 hrs, 72-96 hrs @ room temperature)* - *Degree of saturation (55, 75, and 90%)* - *Freezing thawing condition (16 hrs @ 0F)*						- *Aggregate source, loose mix aging and compaction method have statistical significance on moisture damage where as compaction aging does not* - *Freeze-thaw tensile strength decreases with the increase of saturation level.* - *TSR of 150mm Superpave compacted samples are similar to 100mm Marshall*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Kringos et al. (2009)	TSR	AASHTO T283	• *Aggregate type (limestone and sandstone)* • *Compaction method and size(Marshall, Superpave gyratory)*			Questionable field-lab relationship			TSR of sandstone which is moisture susceptible per field evaluation was higher than limestone evidence of precision and accuracy skeptism on Modified Lotman Test
Nadkarni et al. (2009)	Dynamic Modulus [Asphalt Mixture Performance Tester (AMPT)]			• *Can be used in conjunction with AASHTOW are to predict pavement performance and life cycle costs* • *Same specimens can be teste*					E* stiffness ratio (ESR), was able to successfully able to distinguish between good and poor performing asphalt mixtures

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
				d before and after moisture conditioning					
Solaimanian et al. (2009)	TSR			*8.*			liquid antistripping (LAS) agent lime		- *Lime treated sampled did not offer the best TSR as would have expected* - *Conditioning has no significant effect on air void* - *Significant improvement in resistance upon addition of LAS*
	Model Mobile Load Simulator								
	3rd Scale (MMLS3)								
	Dynamic modulus after repeated freeze-thaw cycles								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
NCHRP (2010)	TSR	AASHTO T283	• *Aggregate type (limestone and sandstone)* • *Compaction method and size(Marshall, Superpave gyratory)* • *Porosity*						• *Water absorption levels increase from 1.5 to 5-6% when vacuum saturated hypothesized arise as a microcrack introduction which may be the source of test variability* • *Contrary to expectation, sandstone compacted samples performed better than limestone compacted samples*
Williams and Breakah (2010)	Dynamic Modulus Test		Variability of tests						• *Dynamic modulus test applied with and without freeze thaw conditions offers better comparison ratios* • *Flow number test offered mixed results* • *The effect of moisture is heightened when tested*
	TSR	AASHTO T283							
	Flow Number Test								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									at higher temperatures and lower frequencies
Tsai et al. (2011)	California Test Method	CT 371-TSR	Additive effect						Lime treated mixes had significant effect on all mix types whiles LAS only showed effect where binder thickness was greater than 8.9micrometer
TRB (2011)	TSR	AASHTO T283	Variability of TSR test						A high variability exists for the TSR test with between laboratories (40 in number) range of 25%
Kim et al. (2012)	TSR	AASHTO T283	Antistripping Agents				• *Hydrated Lime (1%)* • *Fly-ash (1.13%)*	9.	• *Sampled treated with lime and fly ash showed significant improvement in moisture damage resistance only in mixes with unmodified binder and low quality aggregate* • *The use of fly ash as an antistripping agent should be looked into owing to its cheap cost*
	Asphalt Pavement Analyzer (APA)		Aggregate type						
	Boiling water test	ASTM D 3625	Modified binder and Unmodified binder						
	Pull-off tensile strength test								
Schram & Williams	TSR	AASHTO T283						*10.*	• *MiST and HWTD tests*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
(2012)	HWT	AASHTO T 324				Good correlation between results and field observation			*offer better results than the conventional TSR* • *Test parameters considered include swell, wet IDT and TSR parameters* • *For Hamburg Tests the paramters assessed wer strip/creep ratio, SIP, Strip slope and creep slope which all showed favorable results* • *The dynamic Modulus parameter did not show favorable results as a susceptibility test*
	Dynamic Modulus								
	MiST								
	Flow Number								
Moaveni & Abuawad(2012)	IDOT Modified AASHTO T-283								• *At least a single freeze thaw conditioning is necessary to simulate wet-freeze climates*
	TSR	AASHTO T283							

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
	Fracture Energy Test (DCT)	ASTM D 7313 – 07							- *Fracture resistance using the disk shaped compacted specimen (DCT) test has potent in evaluating moisture susceptibility of asphalt mixtures*
Behiry, 2013	Indirect tensile strength (ITS)	AASHTO T283	- *Air voids* - *Saturation levels* - *Antistrip agents*				- *Lime* - *Portland Cement*		- *ITS, Marshall Quotient (MQ) (the ratio of stability to flow), Mr values decreases with increasing air voids* - *Introducing cement and lime to the mixtures reduce moisture susceptibility with the addition of hydrated lime increased the MQ (Marshall Quotient) by about 30% and 100% more than*
	Marshall Test - Resilient modulus (Mr)								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									each cement and untreated specimens
Dave & Baker (2013	TSR	AASHTO T283	taconite tailings (fine-grained crushed siliceous material)						• *Taconite tailings is not moisture damage susceptible* • *Lower fracture energies on taconite mixes might be an indication of possible pavement premature failure*
Watson et al. (2013)	TSR	AASHTO T283					• *Hydrated Lime* • *Liquid ASA (WMX & LAS)*	1%	• *Lime treated samples showed better moisture damage resistance in TSR, HWT and dynamic modulus tests* • *The dynamic modulus and flow number tests are effective in differentiating mixes for moisture damage susceptibility*
	HWT	AASHTO T 324							
	Dynamic Modulus								
	Flow Number tests								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									testing - *Recommends a minimum of 5 freeze cycles for moisture conditioning*
Xiao et al. (2013)	TSR	AASHTO T283	- *WMA moisture damage susceptibility* - *moisture damage susceptibility of moist aggregates* - *Effect of antistripping agent*				- *Lime* - *Liquid ASA*	- *1% and 2%*	- *For moist aggregates better stockpile management should be done, or inclusion of antistripping agents* - *Lime inclusion increases gyratory compaction effort needed to achieve a 7% air void*
Abuawad et al. (2014)	TSR	AASHTO T283	Effect of additive				- *Lime (1%)* - *Liquid ASA (0.75%)*	*11.*	- *Push-pull test shows potent for evaluating moisture damage* - *In all mixes LAS improved moisture damage resistance*
	Complex modulus (E*)	AASHTO TP 62							
	Push-pull (compression-tension) test								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Aman et al. (2014)	TSR	AASHTO T283	Antistripping Agents				• *Ordinary Portland Cement (OPC)* • *Pavement Modifier (PMD)*	• *2%* • *2%*	Samples prepared with PMD filler had higher TSR values and lower air voids compared to OPC treated samples
Liu et al. (2014)	Rolling bottle test (RBT)	BS EN 12697-2012	• *Aggregate type* • *Binder type* • *Antistripping agent type*	Non-destructive					• *Limestone aggregate better resistance than granite* • *Stiffer binder offered better resistance than softer binders*
	Boiling Water Test (BWT)			• *No need for compaction* • *Tests resistance against debonding*					
Ling et al. (2014)	Modified boiling test		CMA moisture susceptibility						• *Boiling test can be used as screening test for moisture damage susceptibility check of Cold mix asphalt (CMA)* • *"limestone mix 16 demonstrates better moisture resistance*
	Binder bond strength test	AASHTO TP-91							
	TSR	AASHTO T283							

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									than granite mix" - *For CMA, a target air void of 12% and emulsion content of 7% is recommended*
Rahman and Hossain (2014)	Hamburg Wheel Tracking Test								Moisture susceptibility increased with increasing RAP amounts
Christensen et al. (2015)	Modified Lottman	AASHTO T 283	- *Saturation level (High/Low) for Modified Lottman* - *Presence and absence of Antistrip agents*	High Saturation level (70-80%) had better mix classification of susceptibility	Low level saturation (30-67%) failed in identifying mixes susceptible to moisture damage	High saturation provided better prediction of field mixes susceptible to mositure damage	Liquid antistrip (Morelife 5000, ArrMaze, Adhere 6601-LS, Suit-Kote)	*12.*	- *False negatives (Type 2 error) rates of test -50% for moderately susceptible mixes in high saturation and 100% for low saturation levels* - *Cost benefit analysis of mandatory antistripping agents beneficial compared to cost implications where optional*

Reference	**Method**	**Standard Procedure**	**Variables Studied**	**Adv. Of test**	**Disadv. Of test**	**Correlation with field**	**Type of Antistrip**	**Dosage Rate**	**Findings**
Hill, R.A. (2015)	TSR	AASHTO T283	Permeable Friction Course (PFC				- *Lime (1%)* - *Liquid ASA (0.50%)*		- *"Cantabro Loss test is the best predictor of the durability of PFC mixtures as determined by field performance"* - *ASTM 7870 MIST conditioning protocol should not be used PFC conditioning*
	HWT	AASHTO T 324							
Figueroa & Reyes (2016)	TSR	AASHTO T283							The MiST procedure is recommended since it factors in the combined effect of water, traffic and tire contact pressure
Han (2016)	APA						Liquid antistrip (Arr-maz LA-2 and AD-Here HP Plus)	0.3 to 0.5%	- *HWLT shows improvement in antistripping agents with higher rut depth recorded* - *"APA results did not indicate any stripping inflection point"*
	HWT								
Martin et al. (2016)	Resilient Modulus		- *Conditioning protocols*		Tests conducted in water				- *Revised WMA moisture*

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
			(MiST, Hot bath, standard modified Lotmman conditioning) - *Specimen drying methods (SSD, Air Dry, CoreDry, OvenDry)*		(saturation) can be misleading				*susceptibility evaluation for mix design or quality assurance* - *CoreDry conditioning is a reliable alternative to saturation*
	IDT strength								
Affrin & Anand (2017)	TSR	AASHTO T283					Lime	1-2.5%	- *Deduced that a dosage of 2% lime produces optimum results based on the mix used* - *Marshall compacted samples performed better than roller compacted samples*
	Retained Stability								
Amoussou-Guenou & Peabody (2017).							Liquid ASA	0.50%	The use of antistripping agents seemed not have any significant effect on moisture damage resistance
Lee et al. (2017)	TSR	AASHTO T283							Dynamic Modulus Ratio (DMR) at a test temperature of 20C

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
	Dynamic Modulus	AASHTO TP 62							should be preferred over the TSR test
Amirkhanian et al. (2018)			Antistripping Agents				• *Lime* • *Liquid ASA*	• *0.70 %*	• *Hydrated lime and Liquid ASA improves moisture damage resistance* • *TSR values from hydrated Lime treated samples all exceeded 85% irrespective of mix type or aggregate source*
Dave et al. (2018)	HWT	AASHTO T 324	Mix types Susceptibility test types				Amine-based antistrip	*13.*	• *HWT offers clearer distinction between poor and good mixes* • *Ultra -sonic pulse velocity can used as a screening test during mix design* • *DCT and SCB were not efficient in distinguishing between good and poor mixes* • *Dynamic modulus test*
	TSR	AASHTO T283							
	Ultra-sonic pulse velocity								
	Dynamic Modulus								
	DCT								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									shows promising results as a test in moisture damage susceptibility testing
Dong et al. (2018)	TSR	AASHTO T283					• *Cement* • *Bentonite*	20%, 40% and 60% of the total weight of the mix of cement	Asphalt cement increases TSR values
Alkofahi & Khedaywi (2019)	ASTM tests						• *Lime (1.5 - 2%)* • *Liquid ASA (Morelife) (0.75 - 1%)*	•	• *Asphalt film thickness of about 55,80 and 100 microns* • *Lime offered better resistance than morelife*
	Texas boiling test								
Do et al. (2019)	TSR	AASHTO T283	Mix types (HMA, SMA, Densed Gap Mixes)				• *Lime (1.5%)* • *Liquid ASA (0.50%)*	•	• *TSR should be combined with wet IDT strength when evaluating moisture damage* • *There exists a high correlation (0.99) between cohesion ratio(CR) and TSR* • *Dynamic*
	Uniaxial compressive strength (UCS) tests								
	Marshall stability								
	Dynamic immersion								

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
									immersion test shows strong correlation with TSR values •
Khedaywi & Kofahi (2019)	modified Texas boiling test		• *Aggregate type (crushed limestone, uncrushed valley gravel and crushed basalt)* • *Antistrip agents*				• *Lime (1.5 - 2%)* • *Liquid ASA (Polyamine) (0.75 - 1%)*		• *Amongst varying factors, aggregate type was the most significant factor affecting moisture damage*
	ASTM (D 3625)								
	Rolling bottle test								
Tayebali et al. (2019)	TSR	AASHTO T283					• *Evotherm - amine based antistrip additive*	• *0.50 %*	• *Boil test in conjunction with MiST conditioning is an effective way of evaluating moisture damage* • *"The Boil test along with colorimeter device can be used to determine optimum antistrip additive content for a given asphalt mixtures"*
	Boil Test with colorimeter	ASTM D3625							

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Haider et al. (2020)	Static Immersion Test	ASTM D1664	• *Modifiers (Polymers, Chemical and Filler based)* • *Aggregates (calcium carbonate, dolomite, dolerite and granite minerals)*						• *Aggregate type lays a mar in antistripping capacity. Calcium carbonate aggregate offered most resistance to stripping while granite offered the least* • *Modifiers generally improve antistripping capacity with filler modifiers offering more stripping resistance than chemical modifiers*
	Boiling Water Test	ASTM D3625							
	Rolling Bottle Test	BS EN 12697							
	TSR	AASHTO T283							
	HWT	AASHTO T 324							
	Marshall Immersion	ASTM D1559							
Karki et al. (2020)			Liquid Antistripping Agents (LSA)				Liquid ASA	0.4-0.5%	Liquid ASA did not show significant difference in chemical composition and dynamic shear modulus G* and δ values
Xu (2020)	Dynamic Modulus Test		Moisture Conditioning						Moisture significantly affects dynamic modulus negatively

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
Akentuna et al. (2021)	Hamburg or Loaded Wheel Test (LWT)	ASTM 7870 - MiST	- *Aggregate type* - *Binder type*				Liquid antistrip additive (Arr-Maz)		- *Prescribed conditioning levels/protocols (freeze-thaw, MiST 3500 and 7000) to identify moisture damage susceptibility* - *Moisture susceptible aggregate showed higher rutting depths, use of SBS polymer-modified asphalt binder is a major contributor to moisture damage resistance* - *Antistripping additives include samples preformed better than non-inclusive samples*
		AASHTO T 324 - Hamburg							
		AASHTO T 283 - Freeze Thaw							
Ali et al. (2021)	TSR	AASHTO T283	Mix type				ASA	0.50%	- *The J-integral parameter from the*
	HWT	AASHTO T 324							

Reference	Method	Standard Procedure	Variables Studied	Adv. Of test	Disadv. Of test	Correlation with field	Type of Antistrip	Dosage Rate	Findings
	SCB								*Semi-circular Bend Test has potent for evaluating moisture damage* • *The toughness index parameter in conjunction with the TSR for better evaluation* • *Mixture containing ASA performed worst in all tests but one*
Jameel et al. (2021)	Rolling bottle test (RBT)	BS EN 12697-2012	Virgin /aged binder	Non-destructive (Performed on Loose samples)					Aging improved moisture damage resistance
Li et al. (2021)	Boiling Water Test	ASTM D3625	Additives				waste polyethylene terephthalate (PET)		Waste PET can be used as an antistripping material in asphalt mixes
	TSR	AASHTO T283							

14 Appendix H: Questionnaire for Practitioners

SURVEY OF STATE HIGHWAY AGENCIES (SHA)

Project Title: Identification of Enhanced Moisture Susceptibility Testing for Asphalt Pavements

Funding Agency: Ohio Department of Transportation.

Summary of Study: Ohio University is conducting this study in collaboration with the National Center of Asphalt Technology (NCAT). The objectives of this study is to identify current test methods in use by agencies to predict moisture damage in asphalt mixtures and to determine if the Ohio DOT's current procedure, modified AASHTO T 283, can be enhanced or replaced to improve the identification of moisture susceptible mixtures. An additional objective is to determine if antistrip agents can be used in certain situations in lieu of testing to provide a low risk, cost effective alternative to testing.

The questions on this survey are categorized into two specific sections – ***moisture susceptibility testing and use of antistrip agents.***

Thank you for your willingness to participate in our survey.

If you have any specific questions or comments pertaining to this study, please feel free to contact either:

- Roger Green by phone: (740) 681-3741 or email: greenr1@ohio.edu ; and/or
- Mary Robbins by phone: (740) 681-3739 or email: robbinm1@ohio.edu.

If you prefer to complete the survey using this pdf form, you may send your completed survey along with any relevant information to Roger Green via email (greenr1@ohio.edu) or via physical mail at the following address:

ORITE
Stocker Center 231
1 Ohio University
Athens, OH 45701-2979

DEMOGRAPHIC INFORMATION

Name:

Position:

Agency:

Phone Number:

Email Address:

SECTION 1: Questions on Moisture Susceptibility Testing.

Questions 1 – 18 pertain to Moisture Damage of Asphalt Mixtures

Q1. Is moisture damage of the asphalt mixture one of your concerns regarding premature failure of pavements?

☐ YES
☐ NO

Q2. What are the distresses that you attribute to moisture damage? (**select all that apply**)

☐ Raveling
☐ Stripping
☐ Rutting
☐ Delamination/Potholes
☐ Load Related Cracking
☐ Block Cracking
☐ Transverse Cracking
☐ Other (please specify below)

____

____

Q3. How early do the moisture damage problems typically occur in your pavements?

☐ Do not have moisture damage problems
☐ 0 to 2 years
☐ 3 to 5 years
☐ 6 to 8 years
☐ 9 to 11 years
☐ 12 to 14 years
☐ 15 years or greater

Q4. What aggregate types are used in your asphalt mixtures?

Aggregate Type (e.g. Dolomite)	% mixes with this aggregate type	Moisture Damage History (Y or N)
______________	________________	_______________
______________	________________	_______________
______________	________________	_______________
______________	________________	_______________

Q5. Which mixtures or aggregates do you test for moisture susceptibility?

☐ Do not test asphalt mixtures for moisture susceptibility (***skip to question*** **Q19**)
☐ Test all asphalt mixtures or aggregates
☐ Test mixtures with specific aggregate(s) type, Specify type(s) tested: ____________
☐ Other: ____

Q6. What test(s) has your agency adopted for the purpose of screening asphalt mixtures for moisture susceptibility? (**select all that apply**)

☐ Tensile Strength Ratio (TSR) (AASHTO T 283)
☐ Hamburg Wheel Tracking Test (AASHTO T 324)
☐ Immersion Compression Test (AASHTO T 167/ASTM D 1075)
☐ Asphalt Film Retention Test (AASHTO T 182)
☐ Retained Stability Test (AASHTO T 245)
☐ Moisture Induced Stress Tester (MIST) (AASHTO TP 140)
☐ Boiling Water Test (ASTM D 3625)
☐ Other (please specify below)
____
____

Q7. For each test that you selected above, please specify your agency's mix acceptance criteria when screening asphalt mixtures for moisture damage.

Tensile Strength Ratio (AASHTO T 283)
____
____

Hamburg Wheel Tracking Test (AASHTO T 324)
____
____

Immersion Compression Test (AASHTO T 167/ASTM D 1075)
____
____

Asphalt Film Retention Test (AASHTO T 182)
____
____

Retained Stability Test (AASHTO T 245)

____

____

Moisture Induced Stress Tester (MIST) (AASHTO TP 140)

____

____

Boiling Water Test (ASTM D 3625)

____

____

Other

____

____

Q8. Please provide your specification(s)/standard(s) for testing aggregate and/or asphalt mixtures for moisture damage. Please provide a URL link to the specifications. Alternatively, you may email or mail specifications to the addresses provided on the first page.

____

____

Q9. How do you accept moisture damage test results for mix design acceptance (select all that apply)?

☐ Contractor test results only (no agency verification)
☐ Contractor test results and agency verified with Contractor prepared specimens
☐ Contractor test results and agency verified with Agency prepared specimens
☐ Agency verification only

Q10. Has lab testing and asphalt mix acceptance criteria reduced the occurrence of moisture damage?

☐ YES
☐ NO
☐ Unsure

Q11. Have you modified or changed the test method used to screen asphalt mixtures for moisture susceptibility in the last 10 years?

☐ YES
☐ NO **(skip to question Q15)**

Q12. What was the previously used procedure?

____
____

Q13. Why did you change (**select all that apply**)?

☐ The new procedure better correlated with field performance
☐ The new procedure provided less variable results
☐ The new procedure is less complicated
☐ The new procedure is less subjective
☐ The new procedure provides faster results
☐ The new procedure cost less
☐ Other (please specify below):

____
____

Q14. If research was used to support the change, please provide a reference and/or a URL link to the research document.

____
____

Q15. What corrective measures do you recommend if the mix design fails the moisture damage test?

☐ Reject mixture
☐ Add antistrip and retest
☐ Add hydrated lime and retest
☐ Add antistrip or hydrated lime and retest
☐ Add antistrip or hydrated lime, no additional testing required
☐ Other (please specify below):

____
____

Q16. Has your agency developed correlations between laboratory measurements and moisture damage measured/observed in the field?

☐ YES (please provide a reference and/or a URL link to available documentation)

____

____

☐ NO

Q17. Does you agency or the contractor perform moisture susceptibility testing during production to verify lab tests?

☐ YES

☐ NO

Q18. As an agency, have you encountered instance(s) where an asphalt mixture has passed laboratory testing criteria but performs poorly in the field with regard to moisture damage?

☐ YES

☐ NO

SECTION 2: Questions on Antistrip Agents.

Questions 19 – 25 pertain to antistrip agents

Q19. What is your current practice with regard to the use of antistrip agents in asphalt mixtures?

☐ Do not use (**skip to question Q25**)
☐ Required
☐ Allowed

Q20. How are antistrips specified?

☐ Antistrip is required for all mixtures
☐ Antistrip are required/allowed when using certain aggregates or mixtures (please list aggregates/mixtures where required/allowed
____
☐ Antistrip is required/allowed to pass specific test requirement
☐ Other (Please specify below)
____
____

Q21. If asphalt antistrips are required or allowed, what type(s) are used? **(select all that apply)**

☐ Hydrated Lime
☐ Liquid antistrip
☐ Other (Please specify below)

____
____

Q22. Please explain how your agency determines the dosage of asphalt antistrip agents used? Alternatively, list the dosages recommended and/or the URL link to specifications requirements.

____
____

Q23. Does your agency have a list of approved antistrip agents (please email a list or provide a link)?

____
____

Q24. If antistrip agents are required, has your agency eliminated moisture susceptibility problems?

☐ YES
☐ NO
☐ Unsure

Q25. If you would like, you may provide any additional information or comments related to your moisture susceptibility tests and/or use of antistrip agents which may be useful to the researchers:

____
____
____

FOLLOW-UP AVAILABILITY

Q26. If the need arises for the researchers to contact you for further information/clarifications, are you willing to speak to them?

☐ YES
☐ NO

We thank you for your time spent taking this survey.

15 Appendix I Laboratory TSR Test Results and Photographs

TENSILE STRENGTH RATIO (TSR)

PROJECT:	**Marshall granite**	**MATERIAL TYPE:**	**19.0 mm** Intermediate

	CONDITIONED SAMPLES				***CONTROL SAMPLES***		
Name	3-1	3-2	3-4		3-3	3-5	3-7
SAMPLE ID	A	B	C		D	E	F
DIAMETER (mm.)	101.7	101.3	101.5		101.7	101.6	101.7
THICKNESS (mm.)	63.1	67.1	65.5		65.0	65.9	64.6
DRY WT IN AIR (gm.)	1196.4	1267.1	1245.3		1236.6	1256.9	1231.1
SSD WEIGHT (gm.)	1206.1	1275.6	1254.8		1243.4	1264.2	1239.2
WT IN WATER (gm.)	712.7	753.1	743.1		732.1	748.6	731.9
VOLUME (cc.)	493.4	522.5	511.7		511.3	515.6	507.3
BULK SP GR	2.425	2.425	2.434		2.419	2.438	2.427
MAX SP GR	2.610	2.610	2.610		2.610	2.610	2.610
% AIR VOIDS	7.1	7.1	6.8		7.3	6.6	7.0
VOLUME AIR VOIDS	35.0	37.0	34.6		37.5	34.0	35.6
LOAD (lb.)					1,593	1,773	1,910

SATURATED

SSD WEIGHT (gm.)	1223.6	1294.4	1271.7
WT IN WATER (gm.)	729.7	770.3	759.7
VOLUME (cc.)	493.9	524.1	512.0
VOL ABS WATER (cc.)	27.2	27.3	26.4
% SATURATION	77.7	73.7	76.4
% SWELL	0.10	0.31	0.06

CONDITIONED

THICKNESS (mm.)	63.3	66.6	65.4					
SSD WEIGHT (gm.)								
WT IN WATER (gm.)								
VOLUME (cc.)	0.0	0.0	0.0					
VOL ABS WATER (cc.)	-1196.4	-1267.1	-1245.3					
% SATURATION	-3417.4	-3422.6	-3601.9					
% SWELL	-100.00	-100.00	-100.00					
LOAD (lb.)	1,642	1,501	1,523					**AVG.**
DRY STRENGTH (psi)				**AVG.**	98.9	108.8	119.3	**109.0**
WET STRENGTH (psi)	104.8	91.3	94.3	**96.8**				

TSR (%)	**88.8**
VISUAL STRIPPING:	None

TENSILE STRENGTH RATIO (TSR)

PROJECT: Granite TSR

MATERIAL TYPE: 19.0 m
Intermed

	CONDITIONED SAMPLES			*CONTROL SAMPLES*		
Name	TSR 3-7	TSR 3-5	TSR 3-1	TSR 3-9	TSR 3-4	TSR 3-2
SAMPLE ID	A	B	C	D	E	F
DIAMETER (mm.)	149.6	150.5	149.7	149.8	149.8	149.8
THICKNESS (mm.)	92.1	92.0	91.7	91.3	92.1	92.0
DRY WT IN AIR (gm.)	3803.7	3814.5	3797.6	3826.2	3830.7	3803.7
SSD WEIGHT (gm.)	3842.5	3853.3	3833.6	3863.3	3868.3	3842.2
WT IN WATER (gm.)	2267.5	2279.3	2273.6	2286.6	2283.0	2276.2
VOLUME (cc.)	1575.0	1574.0	1560.0	1576.7	1585.3	1566.0
BULK SP GR	2.415	2.423	2.434	2.427	2.416	2.429
MAX SP GR	2.610	2.610	2.610	2.610	2.610	2.610
% AIR VOIDS	7.5	7.1	6.7	7.0	7.4	6.9
VOLUME AIR VOIDS	117.6	112.5	105.0	110.7	117.6	108.6
LOAD (lb.)				2,827	2,941	2,819

SATURATED

SSD WEIGHT (gm.)	3909.0	3939.1	3881.9
WT IN WATER (gm.)	2302.0	2302.0	2299.5
VOLUME (cc.)	1607.0	1637.1	1582.4
VOL ABS WATER (cc.)	105.3	124.6	84.3
% SATURATION	89.5	110.7	80.3
% SWELL	2.03	4.01	1.44

CONDITIONED

THICKNESS (mm.)	92.1	92.0	91.7				
SSD WEIGHT (gm.)	3931.9	3951.9	3944.2				
WT IN WATER (gm.)	2301.1	2311.5	2304.6				
VOLUME (cc.)	1630.8	1640.4	1639.6				
VOL ABS WATER (cc.)	128.2	137.4	146.6				
% SATURATION	109.0	122.1	139.6				
% SWELL	3.54	4.22	5.10				
LOAD (lb.)	2,292	2,348	2,388				
DRY STRENGTH (psi)				AVG.	84.9	87.6	84.0
WET STRENGTH (psi)	68.3	69.7	71.4	69.8			

TSR (%)	81.6
VISUAL STRIPPING:	None

TENSILE STRENGTH RATIO (TSR)

PROJECT: **Granite Additive A** **MATERIAL TYPE:** **19.0 mm** Intermediate

	CONDITIONED SAMPLES			CONTROL SAMPLES		
Name	3-2C	3-4C	3-5C	3-3C	3-6C	3-7C
SAMPLE ID	A	B	C	D	E	F
DIAMETER (mm.)	150.0	150.2	149.8	149.6	149.9	149.7
THICKNESS (mm.)	91.9	91.3	91.5	91.8	91.8	91.8
DRY WT IN AIR (gm.)	3820.8	3801.9	3816.1	3828.0	3825.5	3831.3
SSD WEIGHT (gm.)	3859.7	3842.0	3856.8	3864.3	3867.1	3871.7
WT IN WATER (gm.)	2283.7	2270.4	2288.3	2290.8	2286.9	2291.7
VOLUME (cc.)	1576.0	1571.6	1568.5	1573.5	1580.2	1580.0
BULK SP GR	2.424	2.419	2.433	2.433	2.421	2.425
MAX SP GR	2.610	2.610	2.610	2.610	2.610	2.610
% AIR VOIDS	7.1	7.3	6.8	6.8	7.2	7.1
VOLUME AIR VOIDS	112.1	114.9	106.4	106.8	114.5	112.1
LOAD (lb.)				2,923	2,593	2,554

SATURATED

SSD WEIGHT (gm.)	3912.2	3895.5	3904.3
WT IN WATER (gm.)	2327.8	2313.1	2324.0
VOLUME (cc.)	1584.4	1582.4	1580.3
VOL ABS WATER (cc.)	91.4	93.6	88.2
% SATURATION	81.5	81.4	82.9
% SWELL	0.53	0.69	0.75

CONDITIONED

THICKNESS (mm.)	91.8	91.4	91.4					
SSD WEIGHT (gm.)	3909.3	3885.2	3892.0					
WT IN WATER (gm.)	2324.8	2308.4	2317.2					
VOLUME (cc.)	1584.5	1576.8	1574.8					
VOL ABS WATER (cc.)	88.5	83.3	75.9					
% SATURATION	79.0	72.5	71.3					
% SWELL	0.54	0.33	0.40					
LOAD (lb.)	2,443	2,403	2,946					**AVG.**
DRY STRENGTH (psi)				**AVG.**	87.5	77.4	76.3	**80.4**
WET STRENGTH (psi)	72.9	71.9	88.4	**77.7**				

TSR (%)	**96.7**
VISUAL STRIPPING:	None

TENSILE STRENGTH RATIO (TSR)

PROJECT: Granite Additive B

MATERIAL TYPE: 19.0 mm
Intermediate

	CONDITIONED SAMPLES				CONTROL SAMPLES		
Name	3-7 E	3-8 E	3-9 E		3-10 E	3-13 E	3-14 E
SAMPLE ID	A	B	C		D	E	F
DIAMETER (mm.)	150.1	150.0	150.0		150.0	150.3	150.0
THICKNESS (mm.)	91.7	91.8	91.4		91.2	91.3	91.7
DRY WT IN AIR (gm.)	3810.6	3835.5	3803.1		3792.8	3804.8	3843.1
SSD WEIGHT (gm.)	3847.3	3872.6	3845.2		3832.2	3843.6	3875.1
WT IN WATER (gm.)	2274.0	2286.1	2275.5		2265.2	2274.0	2297.1
VOLUME (cc.)	1573.3	1586.5	1569.7		1567.0	1569.6	1578.0
BULK SP GR	2.422	2.418	2.423		2.420	2.424	2.435
MAX SP GR	2.610	2.610	2.610		2.610	2.610	2.610
% AIR VOIDS	7.2	7.4	7.2		7.3	7.1	6.7
VOLUME AIR VOIDS	113.3	117.0	112.6		113.8	111.8	105.5
LOAD (lb.)					2,933	1,995	3,296

SATURATED

	A	B	C
SSD WEIGHT (gm.)	3902.9	3930.5	3895.0
WT IN WATER (gm.)	2311.5	2332.0	2312.9
VOLUME (cc.)	1591.4	1598.5	1582.1
VOL ABS WATER (cc.)	92.3	95.0	91.9
% SATURATION	81.5	81.2	81.6
% SWELL	1.15	0.76	0.79

CONDITIONED

	A	B	C		D	E	F	
THICKNESS (mm.)	91.7	91.8	91.5					
SSD WEIGHT (gm.)	3891.6	3912.5	3884.2					
WT IN WATER (gm.)	2314.3	2328.4	2309.4					
VOLUME (cc.)	1577.3	1584.1	1574.8					
VOL ABS WATER (cc.)	81.0	77.0	81.1					
% SATURATION	71.5	65.8	72.0					
% SWELL	0.25	-0.15	0.32					
LOAD (lb.)	2,871	3,637	3,288					AVG.
DRY STRENGTH (psi)	11.729	14.856	13.429	AVG.	88.0	59.7	98.4	82.1
WET STRENGTH (psi)	85.8	108.5	98.4	97.5				

TSR (%) 118.9

VISUAL STRIPPING: None

TENSILE STRENGTH RATIO (TSR)

PROJECT: **Granite Lime Additive** **MATERIAL TYPE:** **19.0**
Intem

	CONDITIONED SAMPLES				CONTROL SAMPLES		
Name	4-7	4-8	4-9		4-3	4-6	4-10
SAMPLE ID	A	B	C		D	E	F
DIAMETER (mm.)	149.6	149.6	149.9		149.9	149.7	149.9
THICKNESS (mm.)	92.5	92.8	91.4		91.5	92.1	91.9
DRY WT IN AIR (gm.)	3825.5	3841.4	3790.8		3797.0	3818.3	3804.8
SSD WEIGHT (gm.)	3865.8	3878.6	3833.2		3835.7	3860.0	3844.8
WT IN WATER (gm.)	2288.9	2298.7	2264.1		2269.2	2280.9	2266.0
VOLUME (cc.)	1576.9	1579.9	1569.1		1566.5	1579.1	1578.8
BULK SP GR	2.426	2.431	2.416		2.424	2.418	2.410
MAX SP GR	2.599	2.599	2.599		2.599	2.599	2.599
% AIR VOIDS	6.7	6.5	7.0		6.7	7.0	7.3
VOLUME AIR VOIDS	105.0	102.7	110.5		105.6	110.0	114.9
LOAD (lb.)					2,923	2,804	3,152

SATURATED

	A	B	C
SSD WEIGHT (gm.)	3913.7	3924.6	3880.8
WT IN WATER (gm.)	2328.0	2324.1	2304.4
VOLUME (cc.)	1585.7	1600.5	1576.4
VOL ABS WATER (cc.)	88.2	83.2	90.0
% SATURATION	84.0	81.0	81.4
% SWELL	0.56	1.30	0.47

CONDITIONED

	A	B	C		D	E	F
THICKNESS (mm.)	92.7	93.1	91.8				
SSD WEIGHT (gm.)	3897.4	3917.5	3870.9				
WT IN WATER (gm.)	2320.1	2327.6	2299.3				
VOLUME (cc.)	1577.3	1589.9	1571.6				
VOL ABS WATER (cc.)	71.9	76.1	80.1				
% SATURATION	68.5	74.1	72.5				
% SWELL	0.03	0.63	0.16				
LOAD (lb.)	3,418	3,789	3,138				
DRY STRENGTH (psi)				**AVG.**	87.5	83.6	94.0
WET STRENGTH (psi)	101.2	111.8	93.7	**102.2**			

TSR (%)	**115.7**
VISUAL STRIPPING:	None

TENSILE STRENGTH RATIO (TSR)

PROJECT: **Marshall Gravel** **MATERIAL TYPE:**

	CONDITIONED SAMPLES			*CONTROL SAM*	
Name	Marshall 27	Marshall 28	Marshall 29	Marshall 11	Marshall 23
SAMPLE ID	A	B	C	D	E
DIAMETER (mm.)	101.6	101.6	101.7	101.7	101.6
THICKNESS (mm.)	64.1	64.1	64.0	68.8	64.1
DRY WT IN AIR (gm.)	1161.8	1161.5	1161.2	1256.9	1160.3
SSD WEIGHT (gm.)	1166.7	1166.3	1166.6	1261.6	1165.2
WT IN WATER (gm.)	657.0	659.5	657.8	714.1	655.7
VOLUME (cc.)	509.7	506.8	508.8	547.5	509.5
BULK SP GR	2.279	2.292	2.282	2.296	2.277
MAX SP GR	2.461	2.461	2.461	2.461	2.461
% AIR VOIDS	7.4	6.9	7.3	6.7	7.5
VOLUME AIR VOIDS	37.6	34.8	37.0	36.8	38.0
LOAD (lb.)				2,097	1,605

SATURATED

SSD WEIGHT (gm.)	1191.0	1186.2	1187.2
WT IN WATER (gm.)	679.7	678.6	677.9
VOLUME (cc.)	511.3	507.6	509.3
VOL ABS WATER (cc.)	29.2	24.7	26.0
% SATURATION	77.6	70.9	70.3
% SWELL	0.31	0.16	0.10

CONDITIONED

THICKNESS (mm.)	64.1	64.1	63.9			
SSD WEIGHT (gm.)	1192.0	1186.3	1189.9			
WT IN WATER (gm.)	679.4	676.9	678.8			
VOLUME (cc.)	512.6	509.4	511.1			
VOL ABS WATER (cc.)	30.2	24.8	28.7			
% SATURATION	80.3	71.2	77.7			
% SWELL	0.57	0.51	0.45			
LOAD (lb.)	1,253	1,298	1,447			
DRY STRENGTH (psi)				**AVG.**	123.2	101.2
WET STRENGTH (psi)	79.1	81.9	91.5	**84.1**		

TSR (%)	**75.8**
VISUAL STRIPPING:	1

TENSILE STRENGTH RATIO (TSR)

PROJECT: Gravel TSR

MATERIAL TYPE: 19.0 mm
Intermediate

	CONDITIONED SAMPLES				CONTROL SAMPLES		
Name	TSR 6	TSR 7	TSR 8		TSR 4	TSR 9	TSR 11
SAMPLE ID	A	B	C		D	E	F
DIAMETER (mm.)	150.1	150.3	150.2		150.3	150.0	150.5
THICKNESS (mm.)	95.5	94.1	94.3		95.7	95.9	96.1
DRY WT IN AIR (gm.)	3839.2	3765.0	3769.3		3814.1	3831.6	3840.8
SSD WEIGHT (gm.)	3849.5	3776.5	3783.2		3830.0	3843.4	3849.4
WT IN WATER (gm.)	2181.8	2129.0	2137.4		2159.9	2173.7	2173.7
VOLUME (cc.)	1667.7	1647.5	1645.8		1670.1	1669.7	1675.7
BULK SP GR	2.302	2.285	2.290		2.284	2.295	2.292
MAX SP GR	2.461	2.461	2.461		2.461	2.461	2.461
% AIR VOIDS	6.5	7.1	6.9		7.2	6.8	6.9
VOLUME AIR VOIDS	107.7	117.6	114.2		120.3	112.8	115.0
LOAD (lb.)					2,605	3,188	2,406

SATURATED

	A	B	C
SSD WEIGHT (gm.)	3925.6	3860.5	3861.9
WT IN WATER (gm.)	2248.9	2209.2	2210.4
VOLUME (cc.)	1676.7	1651.3	1651.5
VOL ABS WATER (cc.)	86.4	95.5	92.6
% SATURATION	80.2	81.2	81.1
% SWELL	0.54	0.23	0.35

CONDITIONED

	A	B	C		D	E	F	
THICKNESS (mm.)	95.8	94.4	94.5					
SSD WEIGHT (gm.)	2553.8	2215.0	3867.3					
WT IN WATER (gm.)	3931.5	3867.5	2216.2					
VOLUME (cc.)	-1377.7	-1652.5	1651.1					
VOL ABS WATER (cc.)	-1285.4	-1550.0	98.0					
% SATURATION	-1193.7	-1317.6	85.8					
% SWELL	-182.61	-200.30	0.32					
LOAD (lb.)	2,098	2,214	3,195					AVG.
DRY STRENGTH (psi)				AVG.	74.4	91.1	68.3	77.9
WET STRENGTH (psi)	59.9	64.1	92.4	72.1				

TSR (%)	92.6
VISUAL STRIPPING:	1

TENSILE STRENGTH RATIO (TSR)

PROJECT: Gravel Additive A

MATERIAL TYPE: 19 mm
Intermediate

	CONDITIONED SAMPLES			CONTROL SAMPLES		
Name	1C	3C	4C	6C	7C	8C
SAMPLE ID	A	B	C	D	E	F
DIAMETER (mm.)	150.1	150.4	149.9	150.5	150.4	150.6
THICKNESS (mm.)	94.3	95.4	94.8	94.9	95.1	94.4
DRY WT IN AIR (gm.)	3779.3	3778.2	3776.8	3772.6	3777.2	3779.1
SSD WEIGHT (gm.)	3787.8	3794.4	3789.3	3788.2	3793.4	3788.7
WT IN WATER (gm.)	2144.6	2136.0	2142.2	2134.9	2135.8	2141.9
VOLUME (cc.)	1643.2	1658.4	1647.1	1653.3	1657.6	1646.8
BULK SP GR	2.300	2.278	2.293	2.282	2.279	2.295
MAX SP GR	2.461	2.461	2.461	2.461	2.461	2.461
% AIR VOIDS	6.5	7.4	6.8	7.3	7.4	6.8
VOLUME AIR VOIDS	107.5	123.2	112.4	120.3	122.8	111.2
LOAD (lb.)				2,208	2,181	2,240

SATURATED

SSD WEIGHT (gm.)	3865.8	3878.0	3867.5
WT IN WATER (gm.)	2213.9	2209.7	2209.0
VOLUME (cc.)	1651.9	1668.3	1658.5
VOL ABS WATER (cc.)	86.5	99.8	90.7
% SATURATION	80.4	81.0	80.7
% SWELL	0.53	0.60	0.69

CONDITIONED

THICKNESS (mm.)	94.4	95.3	94.9					
SSD WEIGHT (gm.)	3864.6	3877.0	3865.6					
WT IN WATER (gm.)	2213.3	2206.8	2205.4					
VOLUME (cc.)	1651.3	1670.2	1660.2					
VOL ABS WATER (cc.)	85.3	98.8	88.8					
% SATURATION	79.3	80.2	79.0					
% SWELL	0.49	0.71	0.80					
LOAD (lb.)	1,940	1,272	1,370					**AVG.**
DRY STRENGTH (psi)				**AVG.**	63.5	62.6	64.7	**63.6**
WET STRENGTH (psi)	56.2	36.5	39.6	**44.1**				

TSR (%)	**69.3**
VISUAL STRIPPING:	1

TENSILE STRENGTH RATIO (TSR)

PROJECT:	**Gravel Additive B**	**MATERIAL TYPE:**	**19.0 mm** Intermediate

	CONDITIONED SAMPLES				*CONTROL SAMPLES*		
Name	6E	7E	9E		1E	3E	8E
SAMPLE ID	A	B	C		D	E	F
DIAMETER (mm.)	149.8	149.9	149.8		150.4	150.1	150.0
THICKNESS (mm.)	95.5	94.4	95.4		95.2	94.6	94.6
DRY WT IN AIR (gm.)	3781.8	3780.9	3781.6		3779.4	3779.4	3780.4
SSD WEIGHT (gm.)	3797.0	3790.0	3792.9		3795.9	3791.2	3790.4
WT IN WATER (gm.)	2151.2	2146.0	2137.0		2138.7	2144.7	2143.9
VOLUME (cc.)	1645.8	1644.0	1655.9		1657.2	1646.5	1646.5
BULK SP GR	2.298	2.300	2.284		2.281	2.295	2.296
MAX SP GR	2.461	2.461	2.461		2.461	2.461	2.461
% AIR VOIDS	6.6	6.5	7.2		7.3	6.7	6.7
VOLUME AIR VOIDS	109.1	107.7	119.3		121.5	110.8	110.4
LOAD (lb.)					1,649	1,688	3,117

SATURATED

SSD WEIGHT (gm.)	3871.8	3868.5	3879.6
WT IN WATER (gm.)	2209.7	2212.0	2216.2
VOLUME (cc.)	1662.1	1656.5	1663.4
VOL ABS WATER (cc.)	90.0	87.6	98.0
% SATURATION	82.5	81.4	82.2
% SWELL	0.99	0.76	0.45

CONDITIONED

THICKNESS (mm.)	95.5	94.3	95.4					
SSD WEIGHT (gm.)	3863.9	3865.1	3879.8					
WT IN WATER (gm.)	2208.3	2212.2	2216.1					
VOLUME (cc.)	1655.6	1652.9	1663.7					
VOL ABS WATER (cc.)	82.1	84.2	98.2					
% SATURATION	75.2	78.2	82.3					
% SWELL	0.60	0.54	0.47					
LOAD (lb.)	1,700	1,560	1,893					AVG.
DRY STRENGTH (psi)				AVG.	47.3	48.8	90.2	62.1
WET STRENGTH (psi)	48.8	45.3	54.4	49.5				

TSR (%)	**79.7**
VISUAL STRIPPING:	1

TENSILE STRENGTH RATIO (TSR)

PROJECT: Gravel Lime Additive **MATERIAL TYPE:** 19.0 Intem

	CONDITIONED SAMPLES				CONTROL SAMPLES		
Name	GL11	GL13	GL14		GL7	GL9	GL17
SAMPLE ID	A	B	C		D	E	F
DIAMETER (mm.)	149.8	149.9	149.9		150.1	149.9	150.2
THICKNESS (mm.)	95.2	95.7	95.5		96.3	95.4	95.5
DRY WT IN AIR (gm.)	3780.2	3787.6	3780.5		3779.4	3780.2	3780.0
SSD WEIGHT (gm.)	3792.3	3800.1	3795.3		3793.3	3794.5	3792.5
WT IN WATER (gm.)	2142.0	2144.7	2139.0		2138.2	2143.5	2131.9
VOLUME (cc.)	1650.3	1655.4	1656.3		1655.1	1651.0	1660.6
BULK SP GR	2.291	2.288	2.282		2.283	2.290	2.276
MAX SP GR	2.461	2.461	2.461		2.461	2.461	2.461
% AIR VOIDS	6.9	7.0	7.3		7.2	7.0	7.5
VOLUME AIR VOIDS	114.3	116.4	120.1		119.4	115.0	124.6
LOAD (lb.)					2,611	2,537	2,787

SATURATED

SSD WEIGHT (gm.)	3872.3	3881.8	3876.9
WT IN WATER (gm.)	2206.0	2212.7	2206.2
VOLUME (cc.)	1666.3	1669.1	1670.7
VOL ABS WATER (cc.)	92.1	94.2	96.4
% SATURATION	80.6	81.0	80.2
% SWELL	0.97	0.83	0.87

CONDITIONED

THICKNESS (mm.)	95.3	95.7	95.6				
SSD WEIGHT (gm.)	3876.3	3883.9	3879.8				
WT IN WATER (gm.)	2215.3	2219.3	2215.8				
VOLUME (cc.)	1661.0	1664.6	1664.0				
VOL ABS WATER (cc.)	96.1	96.3	99.3				
% SATURATION	84.1	82.8	82.7				
% SWELL	0.65	0.56	0.46				
LOAD (lb.)	2,026	1,730	1,968				
DRY STRENGTH (psi)				**AVG.**	74.2	72.9	79.8
WET STRENGTH (psi)	58.3	49.5	56.4	**54.8**			

TSR (%)	**72.4**
VISUAL STRIPPING:	1 to 2

TENSILE STRENGTH RATIO (TSR)

PROJECT: Limestone Marshall **MATERIAL TYPE:**

	CONDITIONED SAMPLES				*CONTROL SAMI*	
Name	L17	L20	L21		L3	L12
SAMPLE ID	A	B	C		D	E
DIAMETER (mm.)	101.7	101.5	101.6		101.7	101.5
THICKNESS (mm.)	64.0	64.0	64.2		66.8	64.8
DRY WT IN AIR (gm.)	1160.4	1160.2	1160.4		1194.9	1160.2
SSD WEIGHT (gm.)	1173.1	1173.7	1176.9		1210.1	1176.6
WT IN WATER (gm.)	673.3	672.1	674.3		693.8	675.0
VOLUME (cc.)	499.8	501.6	502.6		516.3	501.6
BULK SP GR	2.322	2.313	2.309		2.314	2.313
MAX SP GR	2.486	2.486	2.486		2.486	2.486
% AIR VOIDS	6.6	7.0	7.1		6.9	7.0
VOLUME AIR VOIDS	33.0	34.9	35.8		35.6	34.9
LOAD (lb.)					1,851	1,900

SATURATED

SSD WEIGHT (gm.)	1186.0	1185.1	1186.3
WT IN WATER (gm.)	688.3	681.4	682.7
VOLUME (cc.)	497.7	503.7	503.6
VOL ABS WATER (cc.)	25.6	24.9	25.9
% SATURATION	77.5	71.3	72.3
% SWELL	-0.42	0.42	0.20

CONDITIONED

THICKNESS (mm.)	64.1	64.0	64.1			
SSD WEIGHT (gm.)	1197.7	1190.9	1192.9			
WT IN WATER (gm.)	692.0	685.0	687.4			
VOLUME (cc.)	505.7	505.9	505.5			
VOL ABS WATER (cc.)	37.3	30.7	32.5			
% SATURATION	112.9	87.9	90.7			
% SWELL	1.18	0.86	0.58			
LOAD (lb.)	1,025	1,151	1,419			
DRY STRENGTH (psi)				**AVG.**	111.9	118.7
WET STRENGTH (psi)	64.7	72.8	89.4	**75.6**		

TSR (%)	**69.6**
VISUAL STRIPPING:	None

TENSILE STRENGTH RATIO (TSR)

PROJECT: **Limestone** **MATERIAL TYPE:**

	CONDITIONED SAMPLES				*CONTROL SAM*	
Name	L4	L6	L7		L9	L10
SAMPLE ID	A	B	C		D	E
DIAMETER (mm.)	150.2	150.0	149.9		150.1	149.9
THICKNESS (mm.)	95.2	95.7	95.6		95.7	95.6
DRY WT IN AIR (gm.)	3794.9	3797.1	3797.5		3786.1	3797.4
SSD WEIGHT (gm.)	3833.9	3836.8	3837.7		3823.4	3841.0
WT IN WATER (gm.)	2200.4	2191.1	2197.5		2192.7	2206.3
VOLUME (cc.)	1633.5	1645.7	1640.2		1630.7	1634.7
BULK SP GR	2.323	2.307	2.315		2.322	2.323
MAX SP GR	2.486	2.486	2.486		2.486	2.486
% AIR VOIDS	6.5	7.2	6.9		6.6	6.6
VOLUME AIR VOIDS	107.0	118.3	112.6		107.7	107.2
LOAD (lb.)					2,290	3,108

SATURATED

SSD WEIGHT (gm.)	3880.5	3896.3	3889.4
WT IN WATER (gm.)	2240.9	2245.9	2242.8
VOLUME (cc.)	1639.6	1650.4	1646.6
VOL ABS WATER (cc.)	85.6	99.2	91.9
% SATURATION	80.0	83.8	81.6
% SWELL	0.37	0.29	0.39

CONDITIONED

THICKNESS (mm.)	95.1	95.7	95.5			
SSD WEIGHT (gm.)	3891.3	3902.8	3898.2			
WT IN WATER (gm.)	2240.3	2244.0	2246.1			
VOLUME (cc.)	1651.0	1658.8	1652.1			
VOL ABS WATER (cc.)	96.4	105.7	100.7			
% SATURATION	90.1	89.3	89.4			
% SWELL	1.07	0.80	0.73			
LOAD (lb.)	1,738	1,589	1,689			
DRY STRENGTH (psi)				**AVG.**	65.5	89.1
WET STRENGTH (psi)	50.0	45.5	48.4	**48.0**		

TSR (%)	**60.0**
VISUAL STRIPPING:	None

Photographs of Conditioned samples after indirect tension testing:

Figure 31 Granite, Gyratory Compaction, No Additive

Figure 32 Granite, Marshall Compaction, No Additive

Figure 33 Granite, Gyratory Compaction, Additive A

Figure 34 Granite, Gyratory Compaction, Additive B

Figure 35 Granite, Gyratory Compaction, Lime Additive

Figure 36 Gravel, Gyratory Compaction, No additive

Figure 37 Gravel, Marshall Compaction, No Additive

Figure 38 Gravel, Gyratory Compaction, Additive A, Conditioned

Figure 39 Gravel, Gyratory Compaction, Additive A, Control

Figure 40 Gravel, Gyratory Compaction, Additive B

Figure 41 Gravel, Gyratory Compaction, Lime Additive

Figure 42 Limestone, Marshall Compaction, No Additive

Figure 43 Limestone, Gyratory Compaction, No Additive

16 Appendix J: ORITE Hamburg Test Results and Photographs

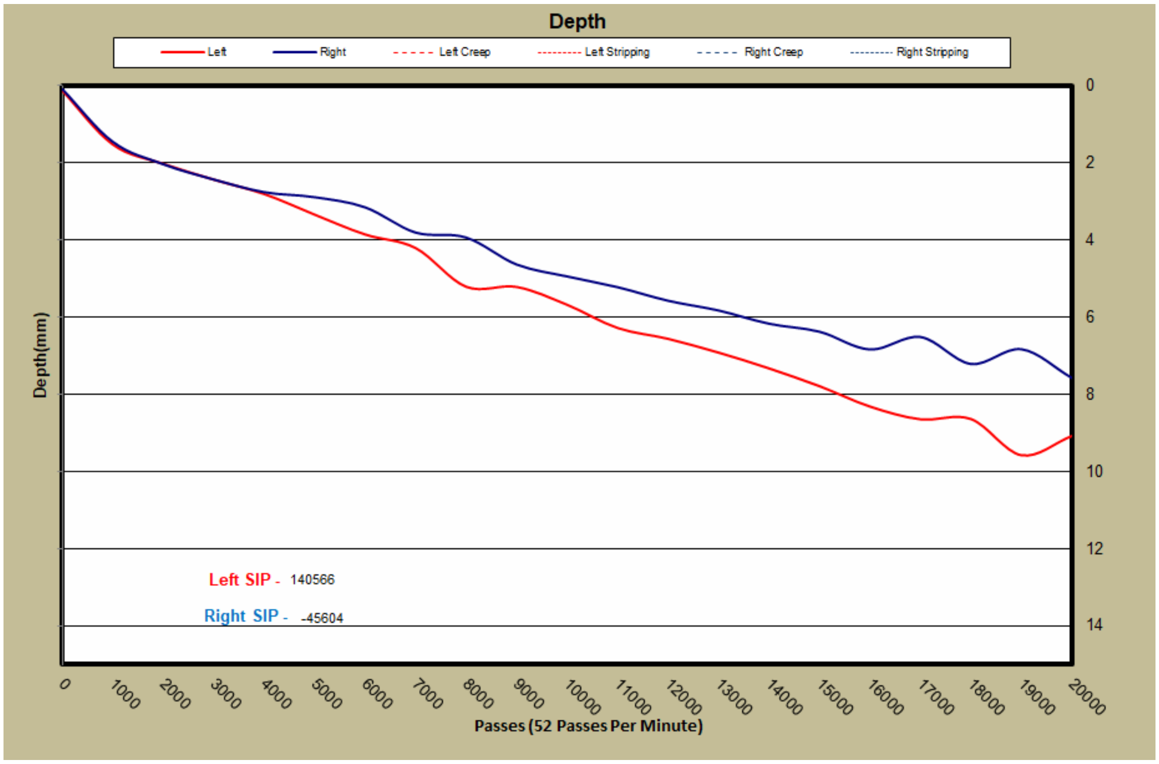


Figure 44 Granite, no additive

Figure 45 Granite, No Additive

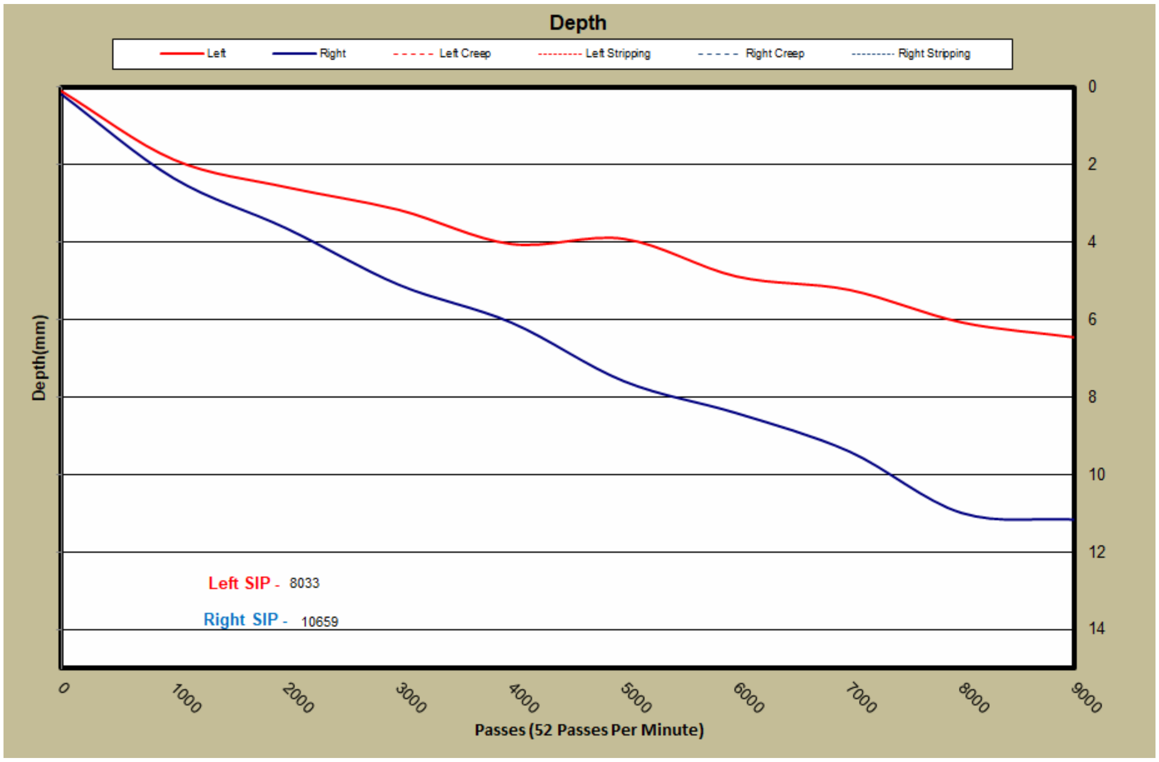


Figure 46 Granite, Additive A

Figure 47 Granite, Additive A

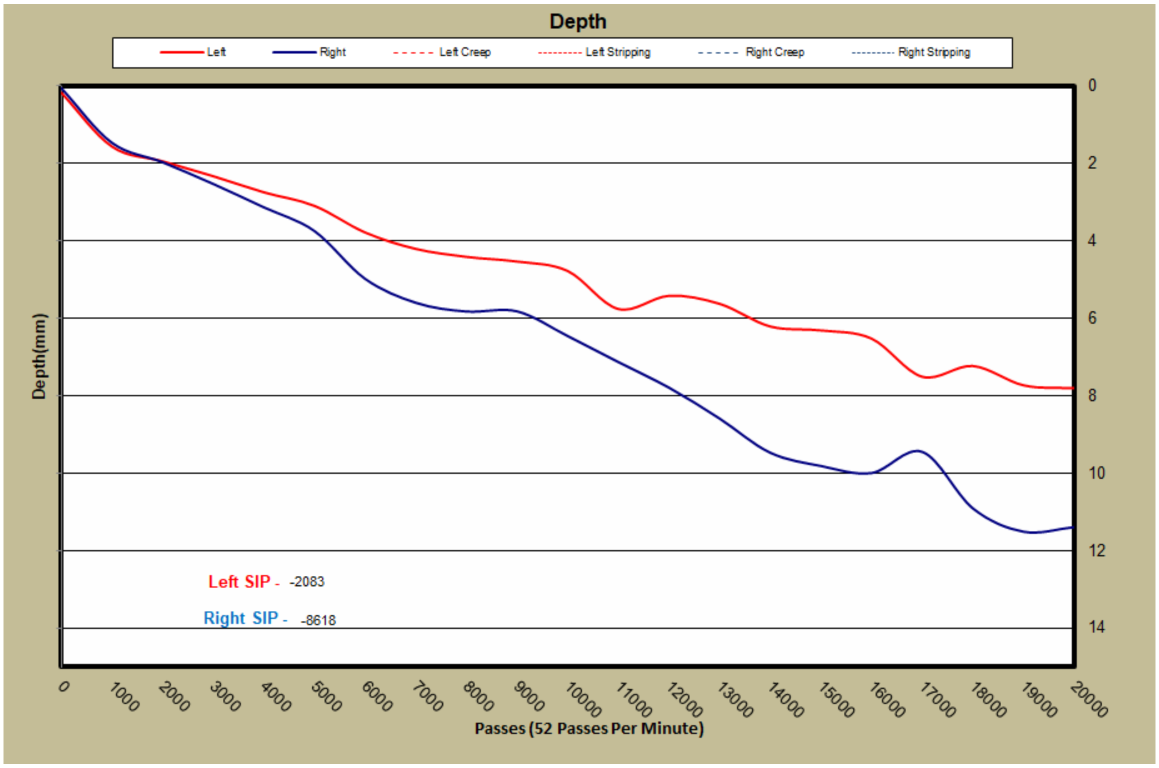


Figure 48 Granite, Additive B

Figure 49 Granite, Additive B

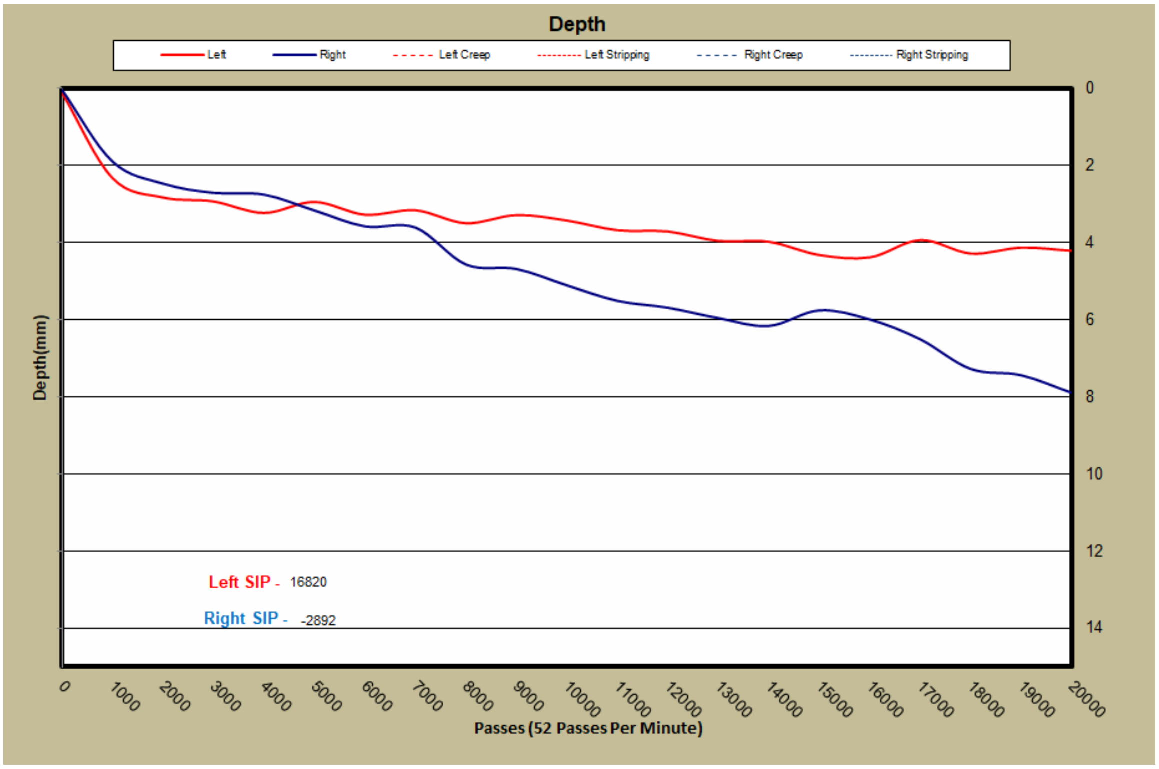


Figure 50 Granite, Lime additive

Figure 51 Granite, Lime Additive

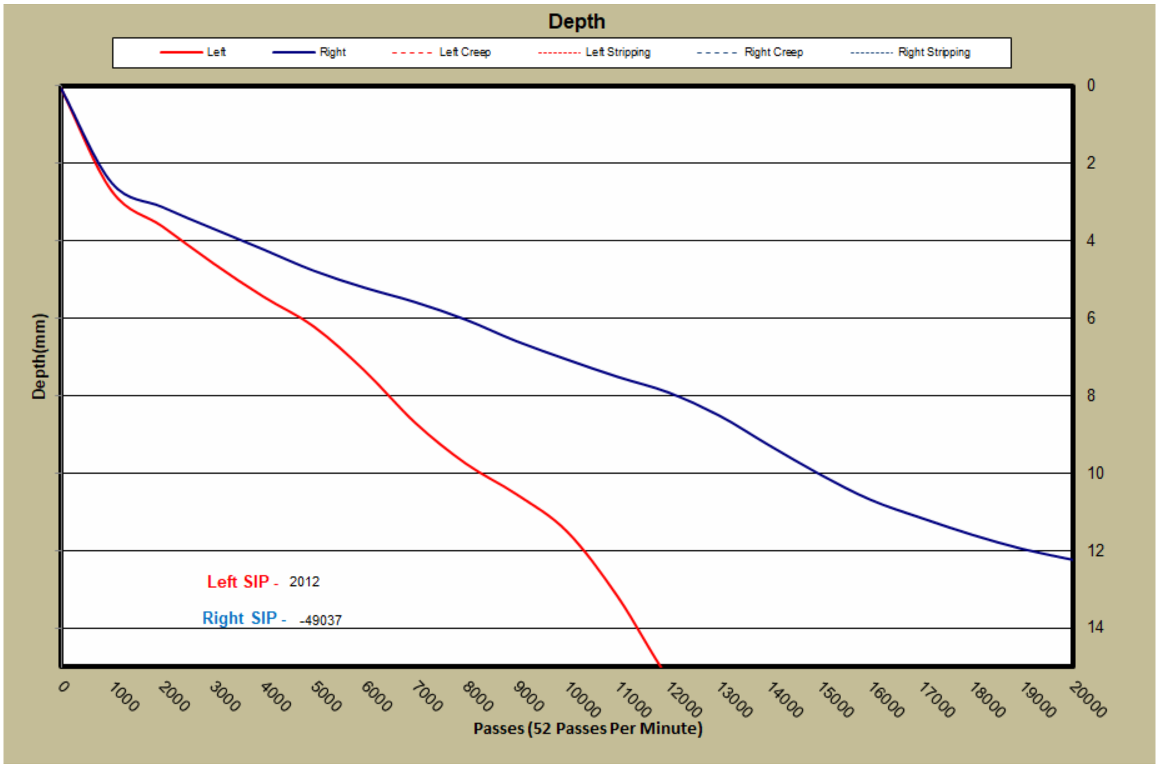


Figure 52 Granite, left no additive, right lime additive

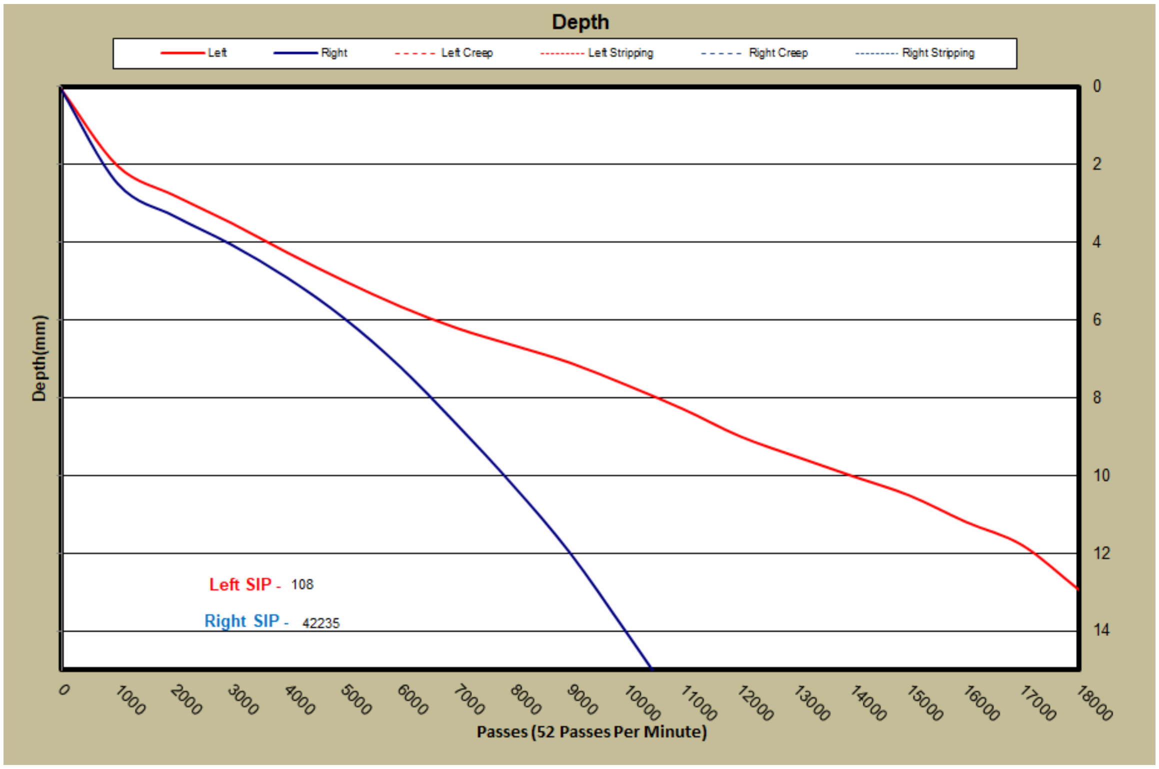


Figure 53 Granite, left additive A, right additive B

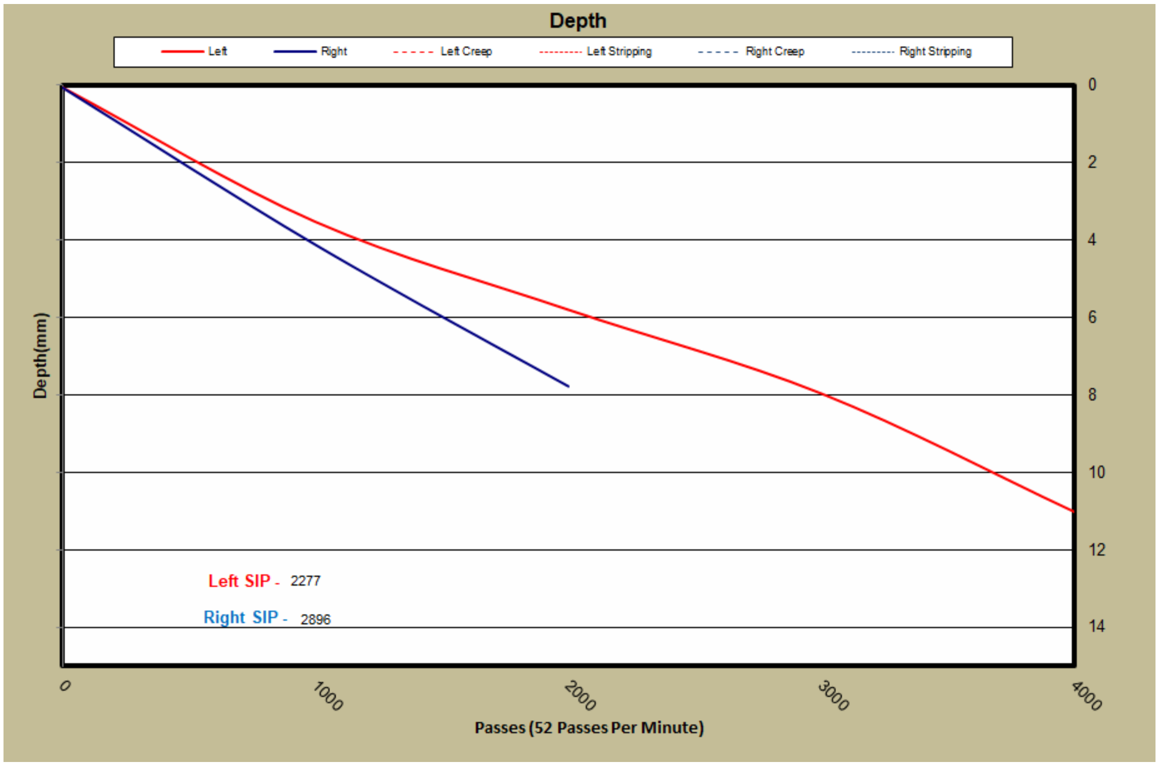


Figure 54 Gravel, No Additive

Figure 55 Gravel, No Additive

Figure 56 Gravel, Additive A

Figure 57 Gravel, Additive A

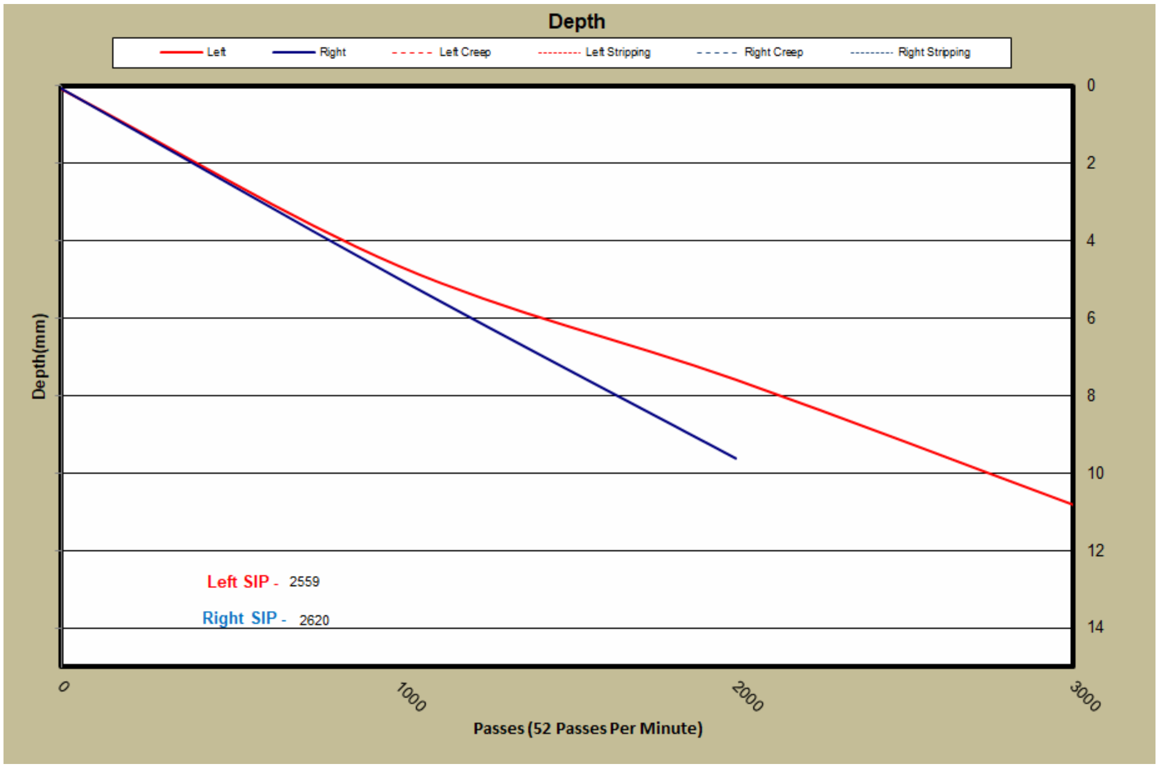


Figure 58 Gravel, Additive B

Figure 59 Gravel, Additive B

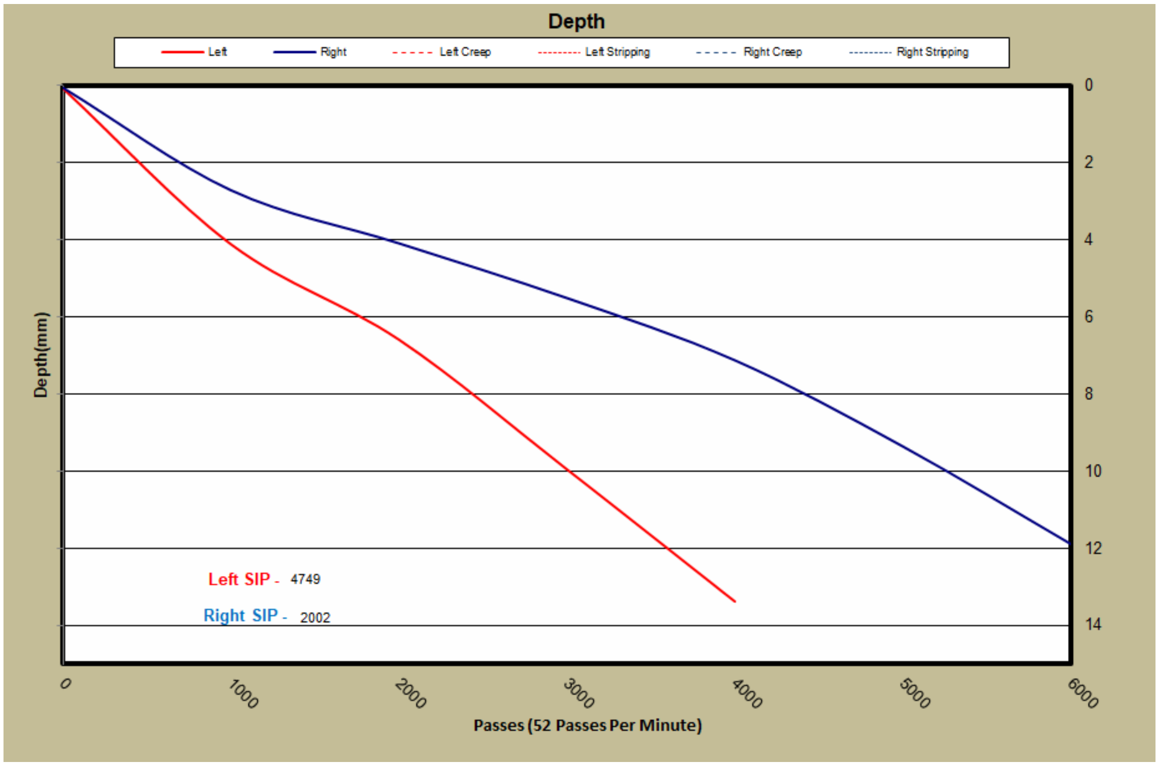


Figure 60 Gravel, Lime Additive

Figure 61 Gravel, Lime Additive

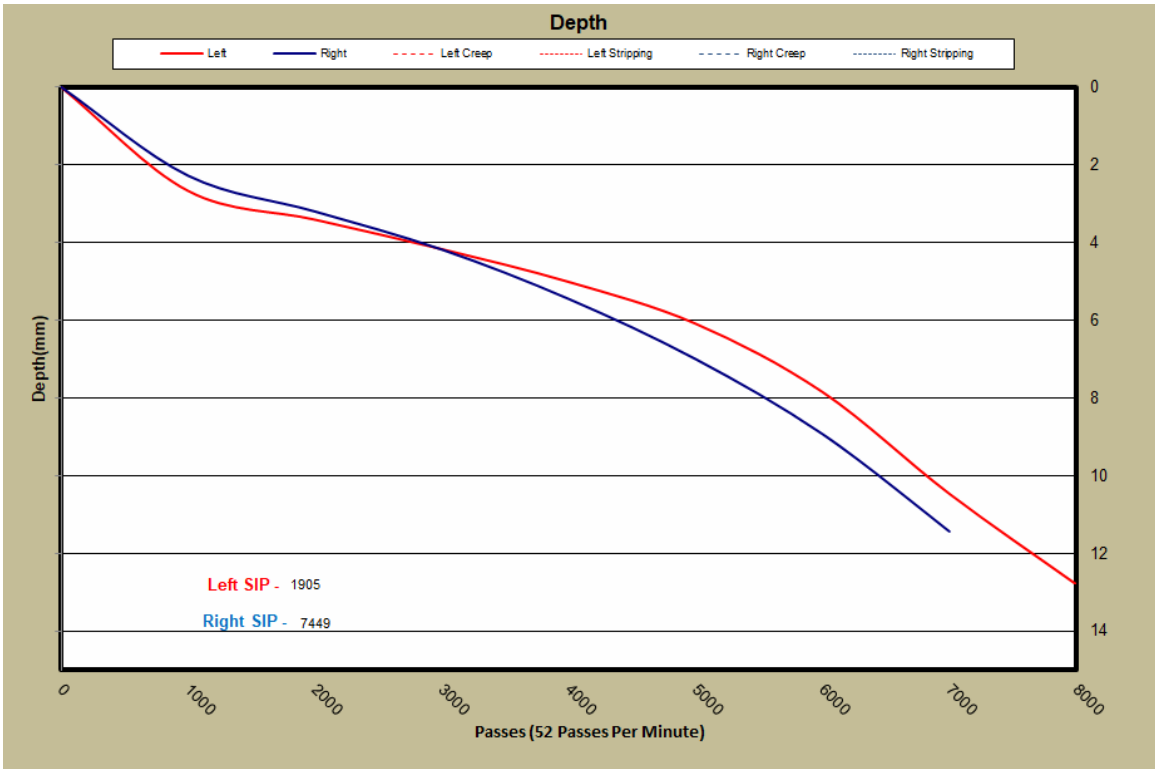
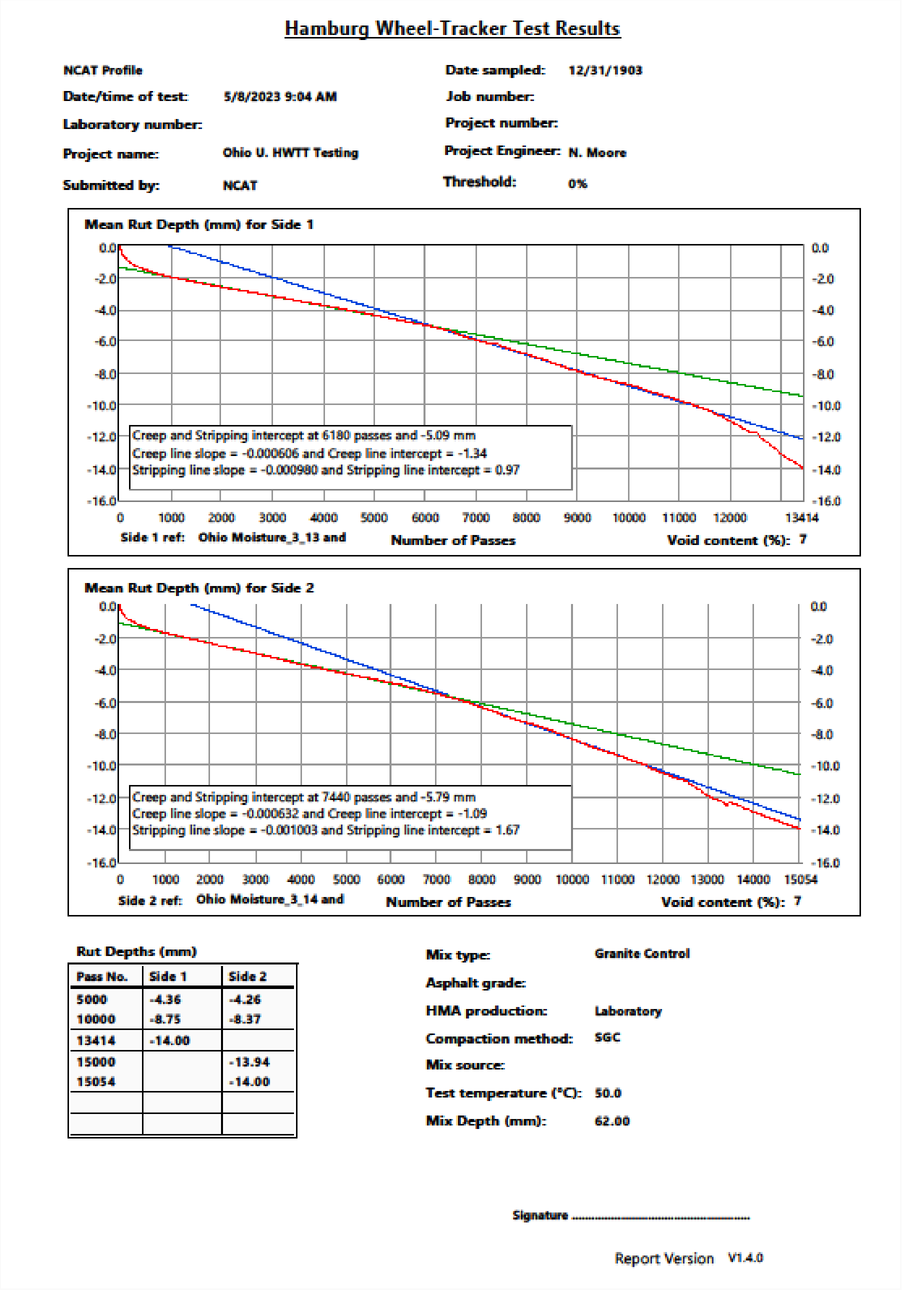


Figure 62 Limestone

Figure 63 Limestone

17 Appendix K: NCAT Hamburg Test Results and Photographs



Hamburg Wheel-Tracker Test Results

NCAT Profile

Date/time of test: 5/8/2023 9:04 AM

Laboratory number:

Project name: Ohio U. HWTT Testing

Submitted by: NCAT

Date sampled: 12/31/1903

Job number:

Project number:

Project Engineer: N. Moore

Threshold: 0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 6180 passes and -5.09 mm
Creep line slope = -0.000606 and Creep line intercept = -1.34
Stripping line slope = -0.000980 and Stripping line intercept = 0.97

Side 1 ref: Ohio Moisture_3_13 and

Void content (%): 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 7440 passes and -5.79 mm
Creep line slope = -0.000632 and Creep line intercept = -1.09
Stripping line slope = -0.001003 and Stripping line intercept = 1.67

Side 2 ref: Ohio Moisture_3_14 and

Void content (%): 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-4.36	-4.26
10000	-8.75	-8.37
13414	-14.00	
15000		-13.94
15054		-14.00

Mix type: Granite Control

Asphalt grade:

HMA production: Laboratory

Compaction method: SGC

Mix source:

Test temperature (°C): 50.0

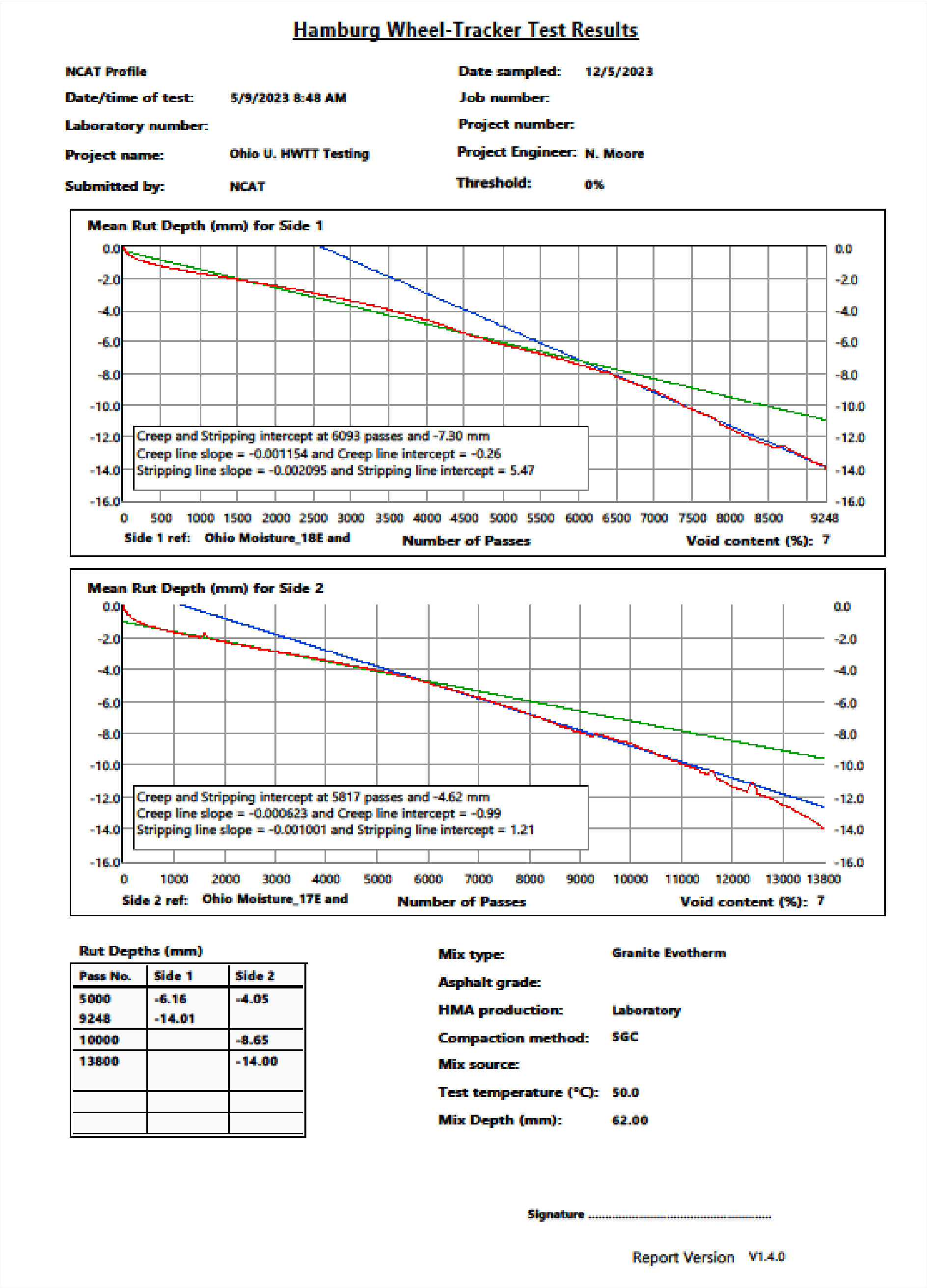
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 64 Granite, Control

Figure 65, Granite Control



Hamburg Wheel-Tracker Test Results

NCAT Profile

Date/time of test: 5/9/2023 8:48 AM

Laboratory number:

Project name: Ohio U. HWTT Testing

Submitted by: NCAT

Date sampled: 12/5/2023

Job number:

Project number:

Project Engineer: N. Moore

Threshold: 0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 6093 passes and -7.30 mm
Creep line slope = -0.001154 and Creep line intercept = -0.26
Stripping line slope = -0.002095 and Stripping line intercept = 5.47

Side 1 ref: Ohio Moisture_18E and **Number of Passes** **Void content (%):** 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 5817 passes and -4.62 mm
Creep line slope = -0.000623 and Creep line intercept = -0.99
Stripping line slope = -0.001001 and Stripping line intercept = 1.21

Side 2 ref: Ohio Moisture_17E and **Number of Passes** **Void content (%):** 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-6.16	-4.05
9248	-14.01	
10000		-8.65
13800		-14.00

Mix type: Granite Evotherm

Asphalt grade:

HMA production: Laboratory

Compaction method: SGC

Mix source:

Test temperature (°C): 50.0

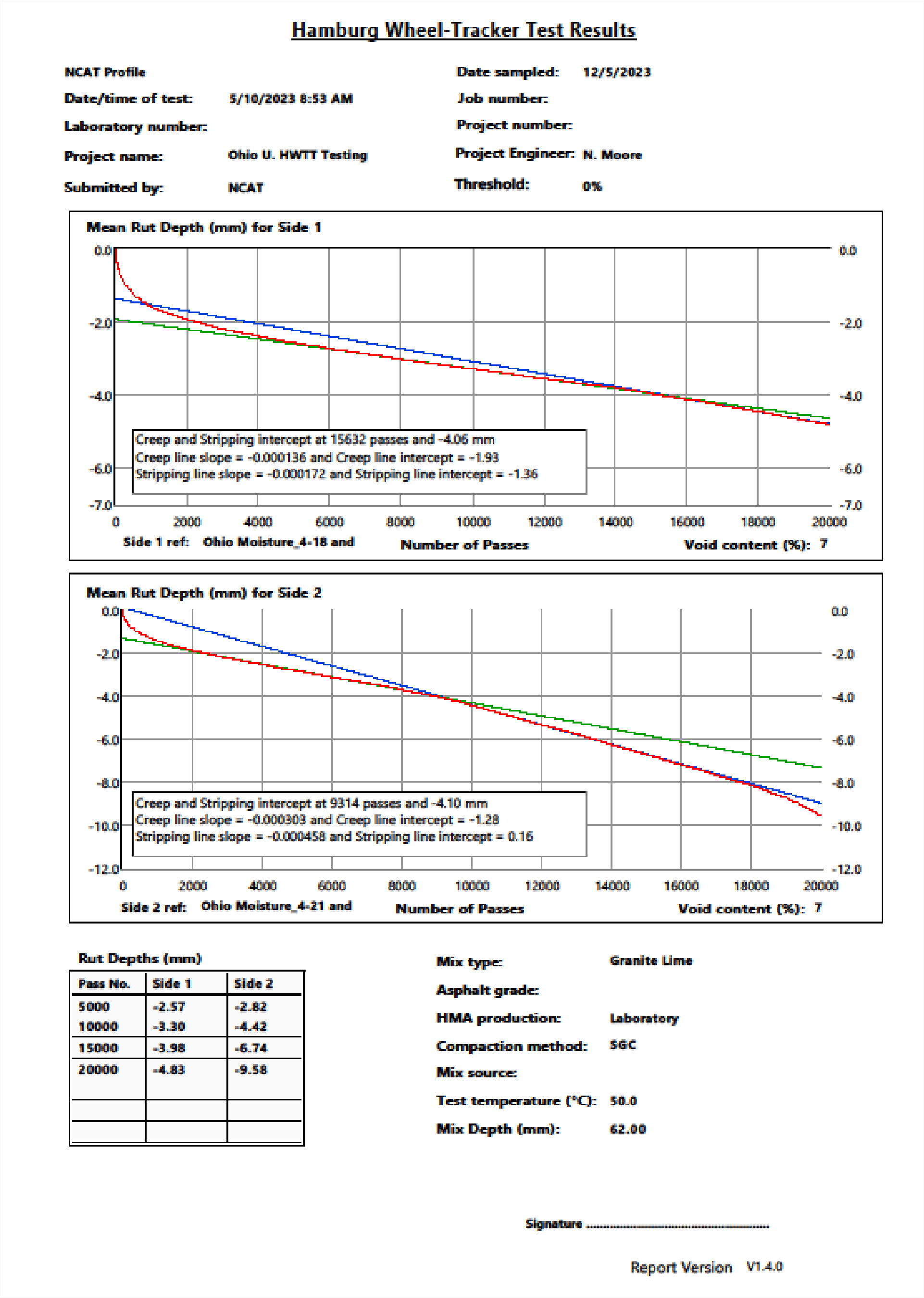
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 66 Granite, Additive B

Figure 67 Granite, Additive B



Hamburg Wheel-Tracker Test Results

NCAT Profile

Date/time of test: 5/10/2023 8:53 AM

Laboratory number:

Project name: Ohio U. HWTT Testing

Submitted by: NCAT

Date sampled: 12/5/2023

Job number:

Project number:

Project Engineer: N. Moore

Threshold: 0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 15632 passes and -4.06 mm
Creep line slope = -0.000136 and Creep line intercept = -1.93
Stripping line slope = -0.000172 and Stripping line intercept = -1.36

Side 1 ref: Ohio Moisture_4-18 and

Number of Passes

Void content (%): 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 9314 passes and -4.10 mm
Creep line slope = -0.000303 and Creep line intercept = -1.28
Stripping line slope = -0.000458 and Stripping line intercept = 0.16

Side 2 ref: Ohio Moisture_4-21 and

Number of Passes

Void content (%): 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-2.57	-2.82
10000	-3.30	-4.42
15000	-3.98	-6.74
20000	-4.83	-9.58

Mix type: Granite Lime

Asphalt grade:

HMA production: Laboratory

Compaction method: SGC

Mix source:

Test temperature (°C): 50.0

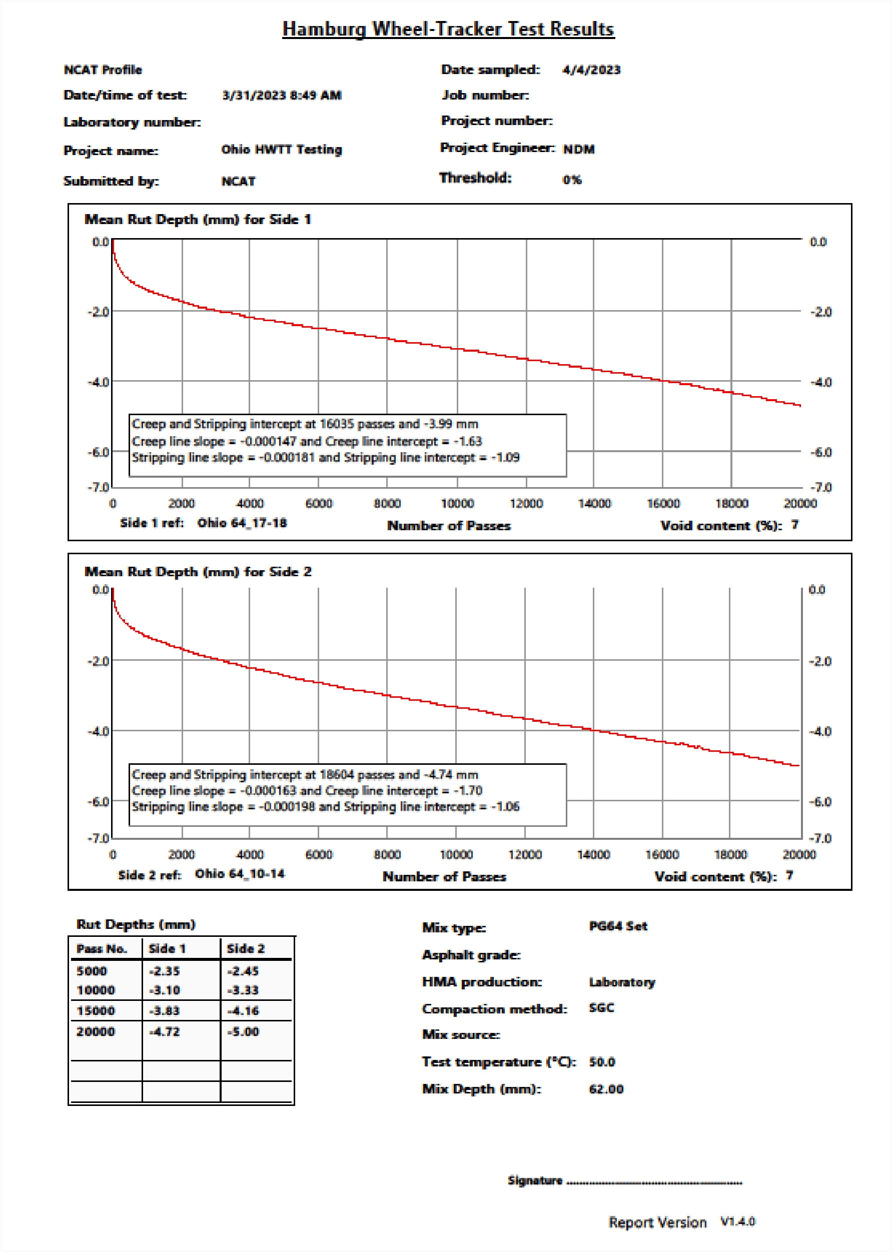
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 68 Granite, Lime Additive

Figure 69 Granite, Lime Additive



Hamburg Wheel-Tracker Test Results

NCAT Profile

Date/time of test: 3/31/2023 8:49 AM

Laboratory number:

Project name: Ohio HWTT Testing

Submitted by: NCAT

Date sampled: 4/4/2023

Job number:

Project number:

Project Engineer: NDM

Threshold: 0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 16035 passes and -3.99 mm
Creep line slope = -0.000147 and Creep line intercept = -1.63
Stripping line slope = -0.000181 and Stripping line intercept = -1.09

Side 1 ref: Ohio 64_17-18

Void content (%): 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 18604 passes and -4.74 mm
Creep line slope = -0.000163 and Creep line intercept = -1.70
Stripping line slope = -0.000198 and Stripping line intercept = -1.06

Side 2 ref: Ohio 64_10-14

Void content (%): 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-2.35	-2.45
10000	-3.10	-3.33
15000	-3.83	-4.16
20000	-4.72	-5.00

Mix type: PG64 Set

Asphalt grade:

HMA production: Laboratory

Compaction method: SGC

Mix source:

Test temperature (°C): 50.0

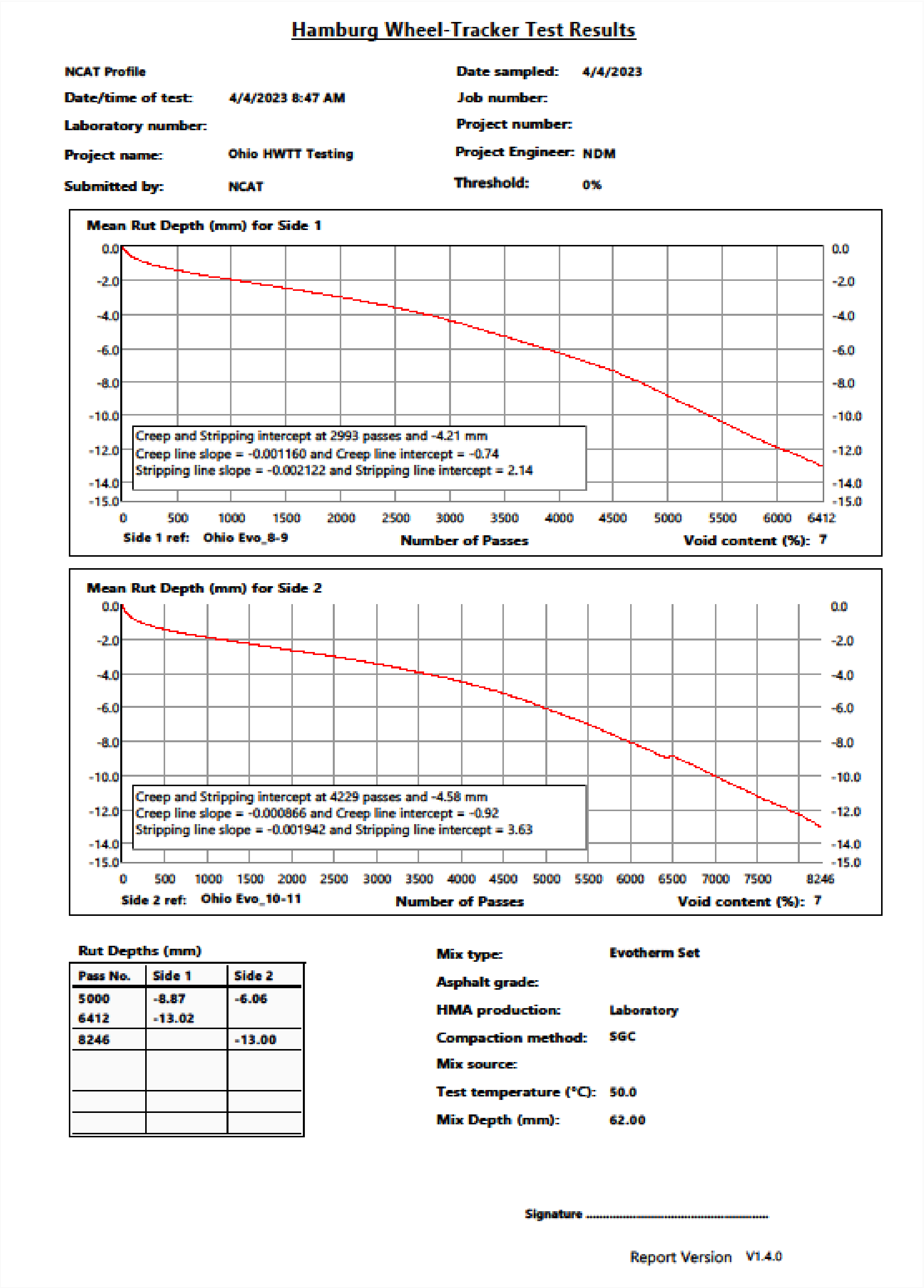
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 70 Gravel, Control

Figure 71 Gravel, Control



Hamburg Wheel-Tracker Test Results

NCAT Profile

Date/time of test: 4/4/2023 8:47 AM

Laboratory number:

Project name: Ohio HWTT Testing

Submitted by: NCAT

Date sampled: 4/4/2023

Job number:

Project number:

Project Engineer: NDM

Threshold: 0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 2993 passes and -4.21 mm
Creep line slope = -0.001160 and Creep line intercept = -0.74
Stripping line slope = -0.002122 and Stripping line intercept = 2.14

Side 1 ref: Ohio Evo_8-9

Void content (%): 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 4229 passes and -4.58 mm
Creep line slope = -0.000866 and Creep line intercept = -0.92
Stripping line slope = -0.001942 and Stripping line intercept = 3.63

Side 2 ref: Ohio Evo_10-11

Void content (%): 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-8.87	-6.06
6412	-13.02	
8246		-13.00

Mix type: Evotherm Set

Asphalt grade:

HMA production: Laboratory

Compaction method: SGC

Mix source:

Test temperature (°C): 50.0

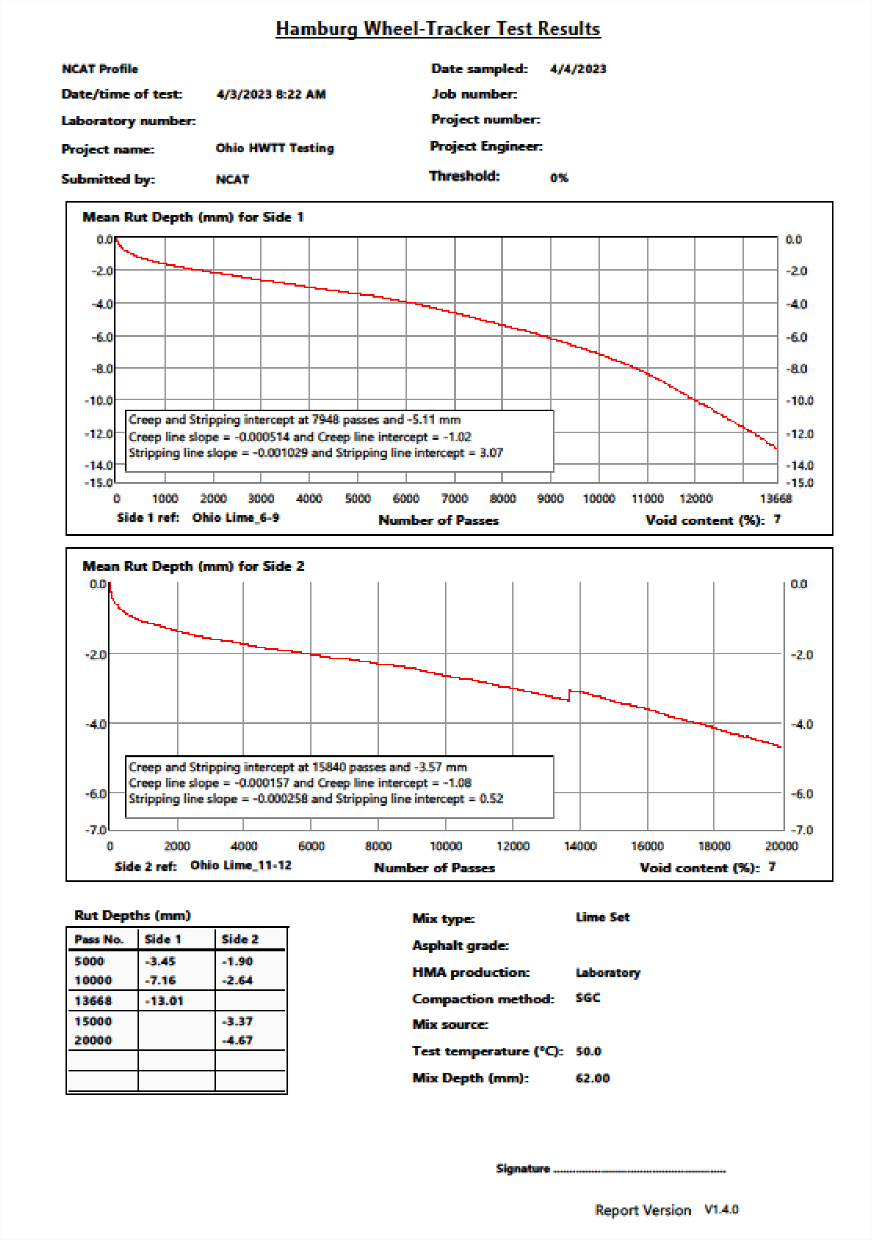
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 72 Gravel, Additive B

Figure 73 Gravel, Additive B



Hamburg Wheel-Tracker Test Results

NCAT Profile
Date/time of test: 4/3/2023 8:22 AM
Laboratory number:
Project name: Ohio HWTT Testing
Submitted by: NCAT
Date sampled: 4/4/2023
Job number:
Project number:
Project Engineer:
Threshold: 0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 7948 passes and -5.11 mm
Creep line slope = -0.000514 and Creep line intercept = -1.02
Stripping line slope = -0.001029 and Stripping line intercept = 3.07

Side 1 ref: Ohio Lime_6-9 **Number of Passes** **Void content (%):** 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 15840 passes and -3.57 mm
Creep line slope = -0.000157 and Creep line intercept = -1.08
Stripping line slope = -0.000258 and Stripping line intercept = 0.52

Side 2 ref: Ohio Lime_11-12 **Number of Passes** **Void content (%):** 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-3.45	-1.90
10000	-7.16	-2.64
13668	-13.01	
15000		-3.37
20000		-4.67

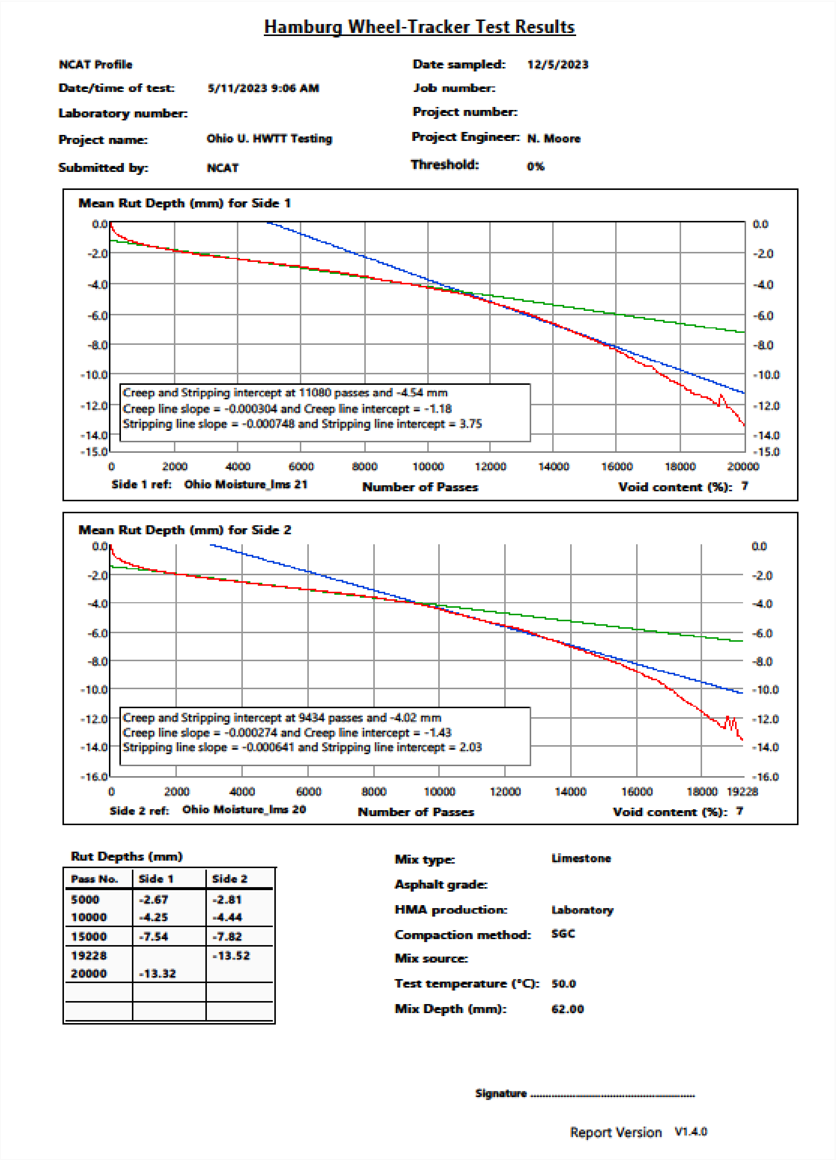
Mix type: Lime Set
Asphalt grade:
HMA production: Laboratory
Compaction method: SGC
Mix source:
Test temperature (°C): 50.0
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 74 Gravel, Lime Additive

Figure 75 Gravel, Lime Additive



Hamburg Wheel-Tracker Test Results

NCAT Profile		**Date sampled:**	12/5/2023
Date/time of test:	5/11/2023 9:06 AM	**Job number:**	
Laboratory number:		**Project number:**	
Project name:	Ohio U. HWTT Testing	**Project Engineer:**	N. Moore
Submitted by:	NCAT	**Threshold:**	0%

Mean Rut Depth (mm) for Side 1

Creep and Stripping intercept at 11080 passes and -4.54 mm
Creep line slope = -0.000304 and Creep line intercept = -1.18
Stripping line slope = -0.000748 and Stripping line intercept = 3.75

Side 1 ref: Ohio Moisture_lms 21 **Number of Passes** **Void content (%):** 7

Mean Rut Depth (mm) for Side 2

Creep and Stripping intercept at 9434 passes and -4.02 mm
Creep line slope = -0.000274 and Creep line intercept = -1.43
Stripping line slope = -0.000641 and Stripping line intercept = 2.03

Side 2 ref: Ohio Moisture_lms 20 **Number of Passes** **Void content (%):** 7

Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-2.67	-2.81
10000	-4.25	-4.44
15000	-7.54	-7.82
19228		-13.52
20000	-13.32	

Mix type: Limestone
Asphalt grade:
HMA production: Laboratory
Compaction method: SGC
Mix source:
Test temperature (°C): 50.0
Mix Depth (mm): 62.00

Signature ....

Report Version V1.4.0

Figure 76 Limestone

Figure 77 Limestone, 1 of 2

Figure 78 Limestone, 2 of 2

18 Appendix L: ODOT’s/Contractor’s TSR Data, 2020 and 2021

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2020	87.0	68.0	1	169.7	Fail	2020	85.5	75.0	1	174.2	Pass
2021	87.3	67.0	2	206.1	Fail	2020	79.4	77.0	1	161.4	Pass
2020	82.8	67.0	1	137.1	Fail	2021	89.1	82.0	1	196.8	Pass
2021	87.5	75.0	2	191.8	Fail	2021	96.8	90.0	1	178.5	Pass
2020	76.0	65.0			Fail	2021	90.3	100.0	1	146.1	Pass
2021	84.3	79.0	2	150.7	Fail	2021	83.5	89.0	1	172.8	Pass
2020	83.9	69.0	1	125.8	Fail	2021	95.0	95.0	1	149.3	Pass
2020	87.6	78.0	1	124.2	Fail	2021	78.2	80.0	1	134.0	Pass
2020	87.0	76.0	1	175.5	Fail	2021	75.1	80.0	1	138.5	Pass
2021	82.4	69.0	2	173.5	Fail	2021	92.2	71.0	2	134.5	Pass
2021	77.1	66.0	2	230.5	Fail	2021	76.6	90.0	1	140.3	Pass
2021	83.5	78.0	3	194.2	Fail	2021	73.2	75.0	1	159.7	Pass
2021	96.8	68.0	1	127.6	Fail	2021	76.2	73.0	1	188.3	Pass
2021	73.6	63.0	2	167.7	Fail	2021	93.6	94.0	1	146.1	Pass
2021	80.1	73.0	1	134.8	Fail	2021	86.6	94.0	1	161.7	Pass
2021	81.2	79.4	1	124.9	Fail	2021	92.0	83.0	1	125.4	Pass
2021	78.2	57.0	3	202.1	Fail	2021	86.3	83.0	1	123.1	Pass
2021	77.1	67.0	3	152.4	Fail	2021	83.5	89.0	2	127.1	Pass
2021	72.5	51.0	3	192.1	Fail	2021	87.9	96.0	2	179.8	Pass
2020	82.4	63.0	2	135.3	Fail	2021	90.4	97.0	2	165.1	Pass
2020	82.0	67.0	2	194.3	Fail	2021	78.2	77.0	2	176.1	Pass
2020	82.1	63.0	1	161.8	Fail	2021	76.1	73.0	2	116.9	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2020	73.0	69.0	2	161.0	Fail	2021	88.5	97.0	1	178.5	Pass
2021	78.1	67.0	2	168.0	Fail	2021	76.7	86.0	1	173.6	Pass
2021	80.1	75.7	1	138.7	Fail	2021	80.9	77.0	1	212.4	Pass
2020	84.6	73.0	1	219.1	Fail	2021	84.7	88.0	1	187.6	Pass
2020	82.3	69.0	1	199.3	Fail	2020	93.9	82.0	1	156.3	Pass
2020	90.4	75.0	1	179.4	Fail	2021	92.8	85.0	2	125.2	Pass
2020	84.0	66.0	1	225.2	Fail	2021	89.0	90.0	1	161.7	Pass
2021	74.0	64.0	1	157.2	Fail	2021	82.5	94.7	1	198.8	Pass
2021	81.7	76.0	1	128.3	Fail	2021	97.6	72.0	2	152.7	Pass
2021	86.3	79.0	1	145.7	Fail	2020	77.6	73.0	1	200.6	Pass
2021	83.5	76.0	1	135.3	Fail	2021	86.3	89.0	2	168.4	pass
2021	84.0	79.0	1	170.5	Fail	2021	81.4	89.0	2	123.5	pass
2021	87.0	73.0	1	191.9	Fail	2021	81.6	89.0	1	157.9	Pass
2021	90.0	79.0	1	145.2	Fail	2021	78.5	93.0	1	150.3	Pass
2021	82.0	77.0	2	184.5	Fail	2021	89.2	82.7	2	113.8	Pass
2021	83.0	76.0		187.4	Fail	2021	86.1	88.0	1	112.7	Pass
2021	81.0	79.0	1	131.5	Fail	2021	84.5	90.0	1	161.8	Pass
2021	92.0	70.0	1	191.0	Fail	2020	86.0	74.0	1	144.4	Pass
2021	85.6	73.0	1	252.6	Fail	2020	79.8	86.0	1	156.8	Pass
2021	86.0	68.0	1	85.8	Fail	2020	88.4	82.0	1	178.7	Pass
2021	88.9	74.0	1	150.7	Fail	2020	72.3	77.0	1	165.8	Pass
2021	77.1	64.0	2	176.6	Fail	2020	85.1	71.0	1	165.8	Pass
2021	81.7	69.0	2	178.9	Fail	2021	88.0	71.0	1	161.8	Pass
2021	85.0	79.0	1	131.3	Fail	2021	94.0	73.0	1	119.7	Pass
2021	93.2	67.0	2	129.9	Fail	2021	98.0	94.0	1	151.5	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	88.0	78.0	1	162.9	Fail	2021	83.2	91.0	2	147.4	pass
2021	90.5	79.0	1	145.0	Fail	2021	81.3	79.0	2	168.7	Pass
2021	90.4	75.0	1	187.6	Fail	2021	75.4	80.0	2	129.2	Pass
2021	96.8	68.0	1	127.6	Fail	2021	81.4	98.0	2	134.3	pass
2021	92.2	69.0		139.8	Fail	2021	80.6	85.0	1	169.8	Pass
2021	87.2	79.0	1	101.7	Fail	2021	81.5	88.0	1	159.1	Pass
2021	83.0	72.0	2	177.7	Fail	2021	81.4	89.0	1	167.3	Pass
2021	98.0	74.0	1	192.8	Fail	2021	81.9	81.4	2	174.4	Pass
2020	76.0	62.0	2	184.0	Fail	2021	85.0	83.0	1	176.4	Pass
2020	85.0	77.0	1	134.8	Fail	2021	90.3	82.0	2	250.5	Pass
2021	90.0	66.0	1	144.0	Fail	2020	98.0	90.0	1	201.9	Pass
2021	72.9	69.0	1	154.3	Fail	2020	73.0	96.0	2	167.5	Pass
2021	79.6	64.0	2	146.4	Fail	2020	78.5	92.0	2	103.9	Pass
2021	86.3	62.0	2	151.1	Fail	2020	87.0	80.0	2	109.4	Pass
2020	91.2	81.0	1	133.0	Pass	2020	76.0	97.0		171.4	Pass
2021	85.5	87.0	2	152.4	Pass	2020	83.8	88.0	1	224.3	Pass
2021	77.7	88.0	2	152.9	Pass	2020	85.7	84.0	1	194.0	Pass
2021	90.4	76.0	1	201.0	Pass	2020	95.5	84.0	1	139.9	Pass
2021	82.4	93.0	1	149.5	Pass	2020	92.7	80.0	1	208.5	Pass
2021	73.9	87.0	2	118.4	pass	2020	92.0	93.0	1	259.3	Pass
2021	84.3	100.3	2	152.7	Pass	2021	90.6	91.0	1	160.6	Pass
2021	97.0	89.0	2	175.0	Pass	2021	94.8	82.0	1	148.5	Pass
2021	83.9	94.2	1	183.0	Pass	2021	75.2	84.0	2	143.5	Pass
2021	85.0	71.0	1	172.2	Pass	2021	76.0	96.0	2	166.0	Pass
2021	93.8	91.0	1	150.2	Pass	2021	93.0	93.0	1	161.7	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	85.5	98.0	1	132.9	Pass	2021	83.5	100.2	1	168.9	Pass
2021	76.0	83.0	2	132.5	Pass	2020	88.6	71.0	1	193.8	Pass
2021	78.2	88.0	1	129.1	Pass	2020	78.5	70.0	1	192.7	Pass
2021	88.4	100.0	1	143.6	Pass	2020	93.1	75.0	1	167.5	Pass
2021	73.1	80.0	1	174.5	Pass	2020	84.5	90.0	1	164.8	Pass
2021	78.4	87.0	1	116.9	Pass	2020	89.0	83.0	1	214.7	Pass
2021	74.1	71.0	1	84.3	Pass	2020	89.6	87.0	1	206.5	Pass
2021	89.2	88.0	1	171.3	Pass	2020	90.4	83.0	1	207.9	Pass
2021	105.2	75.0	1	174.2	Pass	2021	83.1	94.0	2	175.3	Pass
2021	87.8	85.0	1	129.5	Pass	2020	83.4	88.0	1	187.6	Pass
2021	89.1	97.0	1	165.3	Pass	2020	92.2	92.0	1	138.8	Pass
2021	72.0	81.0	1	162.9	Pass	2020	91.3	83.0	1	159.2	Pass
2021	80.3	86.0	1	136.6	Pass	2021	83.2	81.0	1	123.7	Pass
2021	72.0	79.0	1	152.3	Pass	2020	92.7	84.0	1	149.4	Pass
2021	85.0	82.0	1	107.9	Pass	2021	84.3	83.0	1	170.6	Pass
2021	84.3	92.0	2	156.1	Pass	2021	84.4	79.0	1	149.5	Pass
2021	85.4	96.0	2	141.3	pass	2021	90.3	81.0	1	152.7	Pass
2021	74.6	73.0	2	132.2	Pass	2021	82.5	88.0	1	147.9	Pass
2021	89.7	84.0	2	130.4	Pass	2021	75.0	85.0	1	157.6	Pass
2020	82.1	79.0	1	131.8	Pass	2021	92.3	88.0	1	175.3	Pass
2021	74.4	74.0	2	167.3	Pass	2021	93.3	85.0	1	138.1	Pass
2021	84.5	96.0	2	139.3	Pass	2021	84.3	93.0	1	139.5	Pass
2021	83.9	89.0	2	167.0	Pass	2021	81.0	99.0	1	152.2	Pass
2021	81.0	87.0	2	184.1	Pass	2021	90.5	83.0	1	199.8	Pass
2021	70.4	82.0	2	151.2	Pass	2020	78.8	80.0	1	179.9	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	88.6	99.9	1	141.6	Pass	2021	74.1	92.0	1	128.1	Pass
2020	86.7	76.0	1	166.3	Pass	2021	89.0	82.0	1	163.4	Pass
2020	87.1	82.0	1	160.5	Pass	2021	75.1	88.0	1	194.5	Pass
2020	85.7	86.0	1	136.8	Pass	2020	80.9	85.0	1	173.0	Pass
2020	89.8	75.0	1	152.1	Pass	2020	81.1	83.0	1	164.3	Pass
2021	89.9	80.0	2	141.6	Pass	2020	85.5	80.0	1	100.5	Pass
2021	83.8	81.0	2	137.9	Pass	2020	92.3	87.0	1	135.7	Pass
2021	81.0	83.0	2	147.6	pass	2020	75.3	84.0	1	153.2	Pass
2021	83.8	77.0	1	154.2	Pass	2020	91.6	88.0	1	137.6	Pass
2021	85.0	78.0	1	168.5	Pass	2021	94.6	76.0	1	142.4	Pass
2021	89.2	96.0	2	147.4	Pass	2021	89.5	85.0	1	170.5	Pass
2021	70.5	94.0	1	139.0	Pass	2021	85.7	92.0	1	121.0	Pass
2021	85.9	96.9	1	125.8	Pass	2021	81.7	85.0	1	131.2	Pass
2021	85.0	98.0	2	139.8	Pass	2020	75.8	88.0	1	126.1	Pass
2021	85.3	96.0	1	145.3	Pass	2020	87.9	83.0	1	175.8	Pass
2021	78.3	101.6	1	160.2	Pass	2021	96.6	75.0	1	234.9	Pass
2021	97.9	97.0	2	178.7	Pass	2021	80.0	73.0		226.5	Pass
2021	82.7	74.0	1	158.9	Pass	2021	97.5	107.0	1	160.3	Pass
2021	86.4	113.3	2	142.0	Pass	2021	81.8	100.0	1	188.4	Pass
2021	80.5	87.0	1	157.3	Pass	2021	79.2	89.0	1	179.2	Pass
2021	84.9	88.0	1	296.0	Pass	2021	87.9	102.6	1	218.4	Pass
2021	89.7	84.0	1	169.8	Pass	2021	92.8	95.0	1	185.6	Pass
2021	78.4	98.0	2	114.1	Pass	2021	94.7	93.0	1	208.5	Pass
2020	91.3	90.0	1	218.3	Pass	2021	94.9	85.0	1	249.0	Pass
2020	94.4	90.0	1	212.7	Pass	2020	85.4	90.0	1	141.6	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	83.3	116.0	2	116.2	Pass	2020	90.2	74.0	1	178.0	Pass
2021	90.0	73.0	2	140.5	Pass	2020	93.1	73.0	1	173.8	Pass
2021	80.4	116.2	2	128.2	Pass	2021	82.1	99.0	1	162.2	Pass
2021	71.0	82.0	2	136.9	Pass	2020	75.5	74.0	1	153.6	Pass
2021	80.5	109.9	2	145.9	Pass	2021	82.2	92.0	1	140.1	Pass
2021	90.4	108.1	2	171.2	Pass	2021	89.4	98.0	1	154.4	Pass
2021	86.3	91.0	2	170.1	Pass	2021	86.1	98.0	1	220.4	Pass
2021	84.2	94.0			Pass	2021	86.2	83.0	1	215.7	Pass
2021	94.9	83.0	2	185.1	Pass	2021	87.2	97.0	1	215.4	Pass
2021	82.1	83.0	1	240.8	Pass	2020	84.8	77.0	1	119.4	Pass
2021	85.8	92.8	2	228.1	Pass	2021	95.1	94.0	1	146.0	Pass
2021	84.9	96.0	1	230.9	Pass	2021	96.8	100.0	1	147.8	Pass
2021	94.8	85.0	1	185.8	Pass	2021	89.3	102.2	1	131.6	Pass
2020	70.6	78.0	1	219.2	Pass	2021	80.8	96.0	1	133.0	Pass
2020	83.7	84.0	1	175.7	Pass	2021	87.7	95.0	1	159.4	Pass
2021	87.4	80.0	1	241.3	Pass	2021	85.5	85.0	1	120.5	Pass
2021	76.3	71.0	1	258.4	Pass	2021	91.0	99.0	1	148.2	Pass
2021	86.7	100.0	2	184.5	Pass	2021	84.0	94.0	1	146.1	Pass
2021	87.8	88.0	2	187.0	Pass	2021	71.7	74.0	1	176.9	Pass
2021	82.4	90.0	1	123.0	Pass	2020	76.3	83.0	1	147.2	Pass
2021	90.0	91.0	1	149.6	Pass	2020	81.2	84.0	1	143.1	Pass
2021	82.0	86.0	1	161.1	Pass	2021	79.7	80.0	2	109.4	Pass
2021	81.3	90.0	2	168.3	Pass	2021	93.5	98.0	1	134.2	Pass
2021	94.3	98.0	1	158.0	Pass	2021	75.4	75.0	1	135.0	Pass
2021	84.6	82.0	2	186.3	Pass	2021	82.2	91.0	1	170.9	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	92.2	86.0	2	179.6	Pass	2021	88.5	90.0	1	136.5	Pass
2021	89.9	96.0	1	139.9	Pass	2020	87.2	92.0	1	140.0	Pass
2021	90.8	93.0	1	175.9	Pass	2020	79.0	94.0	1	104.4	Pass
2021	87.8	87.0	1	181.1	Pass	2020	77.6	86.0	1	90.5	Pass
2021	89.1	92.9	2	168.8	Pass	2020	75.9	89.0	1	116.3	Pass
2021	81.0	95.0	1	121.3	Pass	2020	83.9	82.0	1	100.7	Pass
2020	86.0	77.0	1	167.3	Pass	2020	81.4	84.0	1	129.0	Pass
2021	90.6	104.9	2	128.8	Pass	2020	85.4	86.0	1	137.1	Pass
2020	88.6	74.0			Pass	2020	81.4	84.0	1	148.5	Pass
2020	83.2	108.4			Pass	2020	87.7	79.0	1	129.6	Pass
2021	74.8	89.0	2	128.4	Pass	2020	87.0	87.0	1	123.8	Pass
2021	84.0	87.0	2	169.4	Pass	2020	90.7	85.0	1	138.8	Pass
2021	88.4	99.0	1	122.9	Pass	2021	92.3	104.4	1	133.0	Pass
2021	84.7	99.0	1	136.5	Pass	2021	88.0	81.0	1	129.2	Pass
2021	89.8	85.0	2	164.7	Pass	2021	94.0	83.0	1	138.4	Pass
2021	78.4	100.0	1	126.7	Pass	2021	94.0	83.0	1	138.4	Pass
2021	80.3	92.0	1	110.3	Pass	2021	74.0	79.0	1	176.6	Pass
2021	76.6	96.0	2	165.2	Pass	2021	79.0	76.0	1	145.7	Pass
2021	87.7	90.0	2	179.4	Pass	2021	77.5	75.0		142.4	Pass
2021	74.2	83.0	2	167.2	Pass	2021	80.0	77.0		138.2	Pass
2020	77.2	85.0	1	121.7	Pass	2021	85.3	88.0	1	139.0	Pass
2020	77.1	90.0	1	122.3	Pass	2021	85.3	103.0	1	159.6	Pass
2020	86.4	88.0	1	109.9	Pass	2021	85.0	99.0	1	131.3	Pass
2020	78.0	85.0	1	109.9	Pass	2021	89.0	86.0	1	121.7	Pass
2020	89.0	81.0	1	121.8	Pass	2021	74.7	87.0	1	104.5	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2020	89.8	88.0	1	131.4	Pass	2021	87.0	95.0	1	149.1	Pass
2020	84.5	73.0	1	139.9	Pass	2021	85.9	85.0	1	125.5	Pass
2020	84.8	85.0	1	147.6	Pass	2021	90.8	81.0	1	181.0	Pass
2020	88.1	88.0	1	123.2	Pass	2021	88.3	88.0	1	135.1	Pass
2021	81.5	84.0	1	136.4	Pass	2021	70.7	93.0	1	116.1	Pass
2021	92.2	84.0	1	148.4	Pass	2021	95.8	96.0	1	113.0	Pass
2021	93.9	99.0	1	144.2	Pass	2021	86.6	89.5	1	142.6	Pass
2021	84.4	71.0	1	107.7	Pass	2021	97.5	98.0	1	144.3	Pass
2021	75.4	91.4	2	118.9	Pass	2021	86.4	96.0	1	144.9	Pass
2021	84.9	90.4	2	143.8	Pass	2021	89.6	101.5	1	111.2	Pass
2021	94.1	100.6	1	114.1	Pass	2021	82.3	97.0	1	132.3	Pass
2021	87.0	84.0	1	132.9	Pass	2021	92.4	92.0	1	197.1	Pass
2021	93.0	89.0	1	142.7	Pass	2021	82.1	91.0	1	120.5	Pass
2020	79.8	73.0	1	131.3	Pass	2021	94.8	97.0	1	140.1	Pass
2020	74.3	71.0	1	131.9	Pass	2021	91.3	100.7	1	168.0	Pass
2020	76.2	75.0	1	116.4	Pass	2021	77.0	95.0	1	133.7	Pass
2020	77.7	77.0	1	154.6	Pass	2021	84.8	98.0	1	121.7	Pass
2021	75.0	80.0	1	132.2	Pass	2021	86.9	98.0	1	129.1	Pass
2021	77.0	73.0	1	136.9	Pass	2021	89.5	100.0	1	125.4	Pass
2021	82.0	72.0	1	126.5	Pass	2021	90.3	82.0	1	127.6	Pass
2021	87.1	87.0	2	113.8	Pass	2021	86.6	73.0	1	120.5	Pass
2021	88.5	85.0	2	154.4	Pass	2021	96.5	97.0	1	124.9	Pass
2021	95.6	95.0	1	120.7	Pass	2021	86.9	100.0	1	119.1	Pass
2021	76.0	84.0	2	106.1	Pass	2021	89.4	100.0	1	112.9	Pass
2021	86.0	96.0	1	164.3	Pass	2021	93.2	95.0	1	140.5	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	89.9	85.0	2	125.2	Pass	2021	94.2	100.0	1	86.5	Pass
2021	86.4	79.0	1	144.3	Pass	2021	90.2	97.0	1	136.5	Pass
2021	87.8	87.0	2	144.7	Pass	2021	75.7	94.0	1	122.9	Pass
2021	84.0	86.0	1	151.8	Pass	2021	76.2	88.0	1	111.2	Pass
2021	85.1	78.0	1	171.8	Pass	2021	80.2	97.0	1	124.6	Pass
2021	77.5	85.0	1	134.0	Pass	2020	98.8	75.0	1	173.9	Pass
2021	93.8	100.0	1	168.6	Pass	2021	92.5	94.0	1	187.6	Pass
2021	96.3	89.0	1	159.4	Pass	2020	89.2	83.0	1	180.2	Pass
2021	89.1	95.0	1	162.4	Pass	2020	89.0	83.0	1	175.4	Pass
2021	80.1	100.0	1	122.9	Pass	2020	83.3	89.0	1	161.9	Pass
2021	90.8	93.0	1	156.6	Pass	2020	84.7	86.0	1	157.8	Pass
2021	94.2	90.0	1	116.1	Pass	2020	83.3	93.0	2	161.7	Pass
2021	90.0	97.0	1	153.7	Pass	2020	79.8	85.0	1	202.3	Pass
2021	79.5	97.0	1	88.6	Pass	2020	74.9	73.0	1	183.8	Pass
2021	90.8	100.0	1	134.1	Pass	2020	79.1	75.0	1	149.3	Pass
2021	80.0	105.0	1	149.0	Pass	2020	77.7	74.0	1	171.4	Pass
2021	80.0	86.0	1	124.8	Pass	2020	86.3	74.0	1	170.9	Pass
2021	86.8	88.0	1	129.1	Pass	2020	83.9	90.0	1	166.7	Pass
2021	92.2	92.0	1	111.5	Pass	2020	84.1	86.0	1	153.9	Pass
2021	86.9	97.0	1	130.2	Pass	2020	84.1	81.0	1	193.1	Pass
2021	92.4	100.7	1	112.0	Pass	2021	80.5	91.0	1	161.1	Pass
2021	89.1	100.0	1	106.4	Pass	2021	91.2	80.0	1	132.1	Pass
2021	83.6	90.0	2	147.8	Pass	2021	98.0	97.0	1	99.9	Pass
2021	77.1	88.0	2	120.4	Pass	2021	85.1	98.0	1	196.7	Pass
2021	95.8	94.0	2	106.9	Pass	2020	86.7	88.0	1	158.9	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	75.2	98.0	1	122.2	Pass	2021	85.7	93.0	1	188.8	Pass
2021	74.8	104.3	1	112.8	Pass	2021	93.2	81.0	1	181.0	Pass
2021	87.0	101.1	1	128.8	Pass	2021	94.9	91.0	1	118.5	Pass
2021	74.8	94.0	2	131.8	Pass	2021	75.8	86.0	1	170.5	Pass
2021	84.2	84.0	1	144.1	Pass	2021	82.4	85.0	1	144.5	Pass
2021	88.5	92.0	1	163.1	Pass	2021	87.3	82.0	1	160.8	Pass
2021	87.8	83.0	2	140.7	Pass	2021	71.5	76.0	1	126.0	Pass
2021	95.6	99.3	1	93.6	Pass	2021	84.6	95.0	1	117.6	Pass
2021	88.3	99.0	1	121.3	Pass	2020	81.7	80.0	1	140.9	Pass
2021	92.3	92.0	1	122.8	Pass	2020	76.6	70.0	1	140.2	Pass
2021	80.5	89.6	2	167.7	Pass	2020	87.9	83.0	1	162.9	Pass
2021	86.8	95.0	2	132.2	Pass	2020	83.2	81.0	1	155.5	Pass
2021	78.6	92.0	2	104.3	Pass	2020	75.9	76.0	1	121.1	Pass
2021	84.4	90.0	2	119.8	Pass	2020	82.1	93.0	1	154.1	Pass
mm	79.7	86.0	2	110.7	Pass	2021	84.4	78.0	1	126.1	Pass
2021	90.0	99.5	2	130.9	Pass	2020	88.9	81.0	1	160.8	Pass
2021	99.4	94.0	2	153.1	Pass	2020	88.8	80.0	1	149.0	Pass
2020	83.2	79.0	1	177.0	Pass	2020	92.5	84.0	1	199.9	Pass
2021	94.3	82.0	1	174.4	Pass	2020	93.5	92.0	1	146.9	Pass
2021	83.0	78.0	1	154.8	Pass	2020	92.0	95.0	1	156.2	Pass
2021	74.9	78.0	1	170.7	Pass	2020	92.1	77.0	1	386.2	Pass
2021	75.4	73.0	2	123.1	Pass	2020	75.9	76.0	1	188.9	Pass
2021	87.9	91.0	1	214.3	Pass	2020	75.4	78.0	1	219.2	Pass
2021	77.2	79.0	2	221.4	Pass	2020	87.2	83.0	1	255.0	Pass
2021	87.2	80.0	2	200.8	Pass	2021	89.7	90.0	1	174.3	Pass

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	84.0	90.0	-	-	Pass	2021	88.9	95.0	1	151.0	Pass
2021	92.7	100.0	1	90.1	Pass	2021	84.6	82.0	1	208.6	Pass
2021	94.6	100.0	2	118.0	Pass	2021	86.8	97.0	1	147.5	Pass
2021	87.5	89.0	2	177.9	Pass	2021	77.1	88.0	1	173.5	Pass
2021	79.5	95.0	2	139.5	Pass	2020	84.6	82.0	1	170.6	Pass
2021	82.3	94.0	2	135.6	Pass	2020	87.9	76.0	1	189.0	Pass
2020	83.3	86.0	1	151.2	Pass	2020	82.9	76.0	1	208.1	Pass
2020	82.9	88.0	1	178.5	Pass	2020	77.3	76.0	1	248.3	Pass
2020	84.0	84.0	1	163.0	Pass	2020	79.7	76.0	1	215.1	Pass
2020	88.1	86.0	1	144.4	Pass	2020	84.7	74.0	1	176.4	Pass
2021	80.3	85.0	2	210.5	Pass	2020	84.7	80.0	1	233.1	Pass
2021	79.6	87.0	2	176.5	Pass	2020	82.3	82.0	1	170.9	Pass
2021	79.6	87.0	2	176.5	Pass	2020	92.2	100.0	1	199.1	Pass
2021	81.5	88.0	1	107.1	Pass	2020	88.6	71.0	1	123.0	
2020	85.5	82.0	1	149.4	Pass	2021	97.8	100.0	1	131.5	
2020	89.2	74.0	1	220.1	Pass	2021	84.0	79.0	1	170.5	
2020	79.7	76.0	1	222.8	Pass	2021	81.4	79.0	1	131.5	
2021	86.7	89.0	2	152.6	pass	2020	84.1	71.0	1	127.6	
2021	82.8	81.0	2	140.8	pass	2020	85.7	78.0	1	164.4	
2021	82.3	78.0	2	189.9	pass	2020	83.7	77.0	1	124.6	
2021	83.1	91.0	1	143.1	Pass	2021	85.2	79.0	1	131.3	
2021	92.5	90.0	1	118.6	Pass	2020	88.8	65.0	1	166.5	
2021	92.1	90.0	1	126.2	Pass	2020	81.2	70.0	1	183.8	
2021	84.9	94.0	1	165.4	Pass	2020	92.5	69.0	1	166.1	
2021	90.7	81.0	1	186.1	Pass	2020	90.9	71.0	1	133.2	

Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result	Year	Contractor's TSR (%)	ODOT's TSR (%)	stripping #	dry strength (PSI)	Test Result
2021	83.7	86.0	1	139.5	Pass	2020	91.5	80.0			
2021	81.6	100.0	1	119.4	Pass	2020	87.1	72.0	1	149.7	
2021	84.3	95.0	1	170.7	Pass	2020	94.5	68.0	1	134.6	
2021	95.7	85.0	2	155.6	Pass	2020	83.6	79.0	1	213.1	
						2020	93.5	68.0	1	219.9	

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