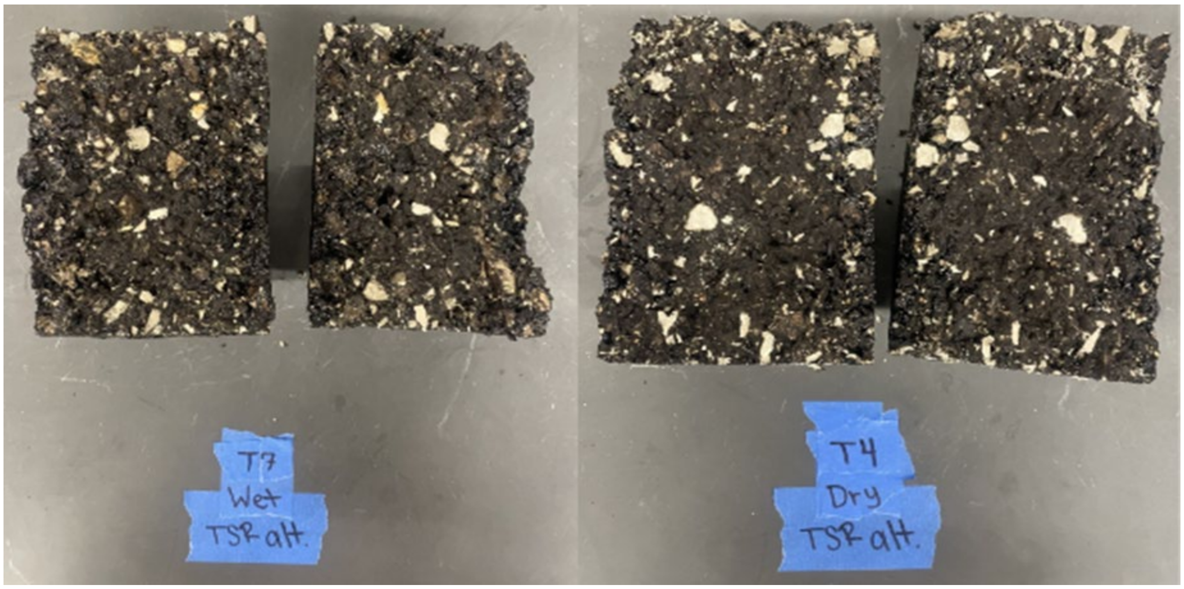
Evaluation of Stripping Tests for Asphalt Mixtures to Replace AASHTO T283 Method in Missouri



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16. Abstract

Currently, many paving agencies in the U.S. including the Missouri Department of Transportation (MoDOT) use the AASHTO T283 method (Tensile Strength Ratio (TSR) test) to determine the moisture damage susceptibility of asphalt mixtures. However, the TSR test has been shown to have a poor correlation with field results based on a review of literature and based on observations reported by MoDOT. In addition, the TSR test is time consuming and may be redundant in light of current requirements to conduct the Hamburg Wheel Tracking Test (HWTT) as part of balanced mix design. As a result, further research on these test methods was conducted. For this research five asphalt mixtures were investigated. The mixtures were subjected to the TSR test and HWTT. The Stripping Inflection Point (SIP) parameter was computed from HWTT using the Iowa method. The SIP parameter was found to be superior to the TSR test in correlating to field performance. Comparison of the RT-Index results with the SIP parameter suggested that the RT index is likely a weak indicator of moisture damage in asphalt mixtures. Based on the results obtained in this limited study, a framework was proposed to replace the TSR method. The framework is as follows; first, the mixtures are screened for rut depths lower than 4.0 mm at 20,000 passes in the Hamburg test. If the mixture exhibits low rut depths in the Hamburg test (less than or equal to 4 mm), it is highly likely that it is resistant to moisture damage and therefore judged as non-stripping. Second, if the rut depth is greater than 4.0 mm then the slope ratio is computed. If the slope ratio is found to be less than 2.0, then the mixture can be categorized as non-stripping. Finally, if the slope ratio is greater than or equal to 2.0, then the SIP is determined. A minimum threshold of 15,000 passes was chosen as the SIP threshold for initial implementation of the framework. Mixtures possessing SIP values less than 15,000 are scored as failing the stripping requirement.

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Executive Summary

Moisture damage in asphalt pavements refers to the degradation process, due to the presence of moisture in any form, that leads to the deterioration of mechanical properties of the materials. It diminishes the strength of adhesion between the asphalt mastic and the aggregate or reduces the cohesion within the mastic itself. This leads to the formation of critical distresses in the pavement such as shoving, potholes, raveling, cracking, and rutting, which in turn result in severe loss of functionality and strength. Currently, most paving agencies in the U.S. use the AASHTO T283 method, also known as the Tensile Strength Ratio (TSR) test, to determine the susceptibility of asphalt mixtures to moisture damage. However, the Missouri Department of Transportation (MoDOT) and other state agencies have reported poor correlation between TSR test results and field performance. Additionally, the TSR test is cumbersome and expensive to run, with its rigorous conditioning procedure. These two factors have led paving agencies to look for an alternative testing procedure or evaluation framework to determine the moisture susceptibility of asphalt mixtures.

MoDOT preliminarily identified five mixtures with known field performance, in terms of moisture damage, for evaluation by alternative test methods. The primary candidate to replace the TSR test was the Hamburg Wheel Tracking Test (HWTT), which is widely used in Missouri to determine the rutting potential of asphalt mixtures. The HWTT is a torturous test conducted at a high temperature in a water bath, which makes it ideal to determine the moisture damage susceptibility of asphalt mixtures. Another rutting test, called the IDEAL-RT, was also conducted to investigate any possible correlation with moisture damage.

Out of the five identified asphalt mixtures, only four were obtained by the research team with the help of MoDOT. In addition, one of the mixtures was tested after removal of the liquid anti-strip (LAS) to determine its effect on performance. The mixtures tested in this study were labeled as follows, (a) Mixture 1 as M1-FC, (b) Mixture 2 as M2-ORG, (c) Mixture 2 with no LAS as M2-ORG No LAS, (d) Mixture 3 as M3-BF, (e) Mixture 4 as M4-B3. It is noteworthy that all the mixtures used a single source of RAP (Recycled Asphalt Pavement), which was different from the original RAP reported in the JMFs due to the lack of availability of obtaining representative, original RAP samples.

The mixtures were subjected to the TSR test as per the AASHTO T283 standard, to the Hamburg Wheel Tracking Test (HWTT) as per the AASHTO T324 standard, and to the IDEAL-RT test as per the ASTM D8360 standard. The Stripping Inflection Point (SIP) parameter was computed from the HWTT rut depth versus wheel passes curve to be used as an indicator of moisture damage in the asphalt specimens. The Iowa method was used to compute the SIP parameter, which is the intersection of the creep and stripping lines drawn on the Hamburg rut depth curve. The creep line in a Hamburg rut depth curve is the initial portion of the curve post-consolidation while the stripping line is the later part of the curve characterized by accelerated rutting. The Iowa method has an additional step prior to the calculation of the SIP, which is computing the slope ratio (SR). The SR parameter is simply the ratio of the stripping slope to the creep slope, and the SIP needs to be calculated only if it is greater than or equal to 2.0. If SR < 2.0, the mixture is deemed to be not stripping (i.e., no moisture damage) and the SIP is unnecessary.

Comparison of the test results showed that the HWTT and TSR agreed on the ranking of only one out of the five mixtures. More importantly, the SIP parameter had a better correlation with the qualitative field performance measure (good versus poor performance) compared to the TSR test. One of the mixtures (M1-FC) which was characterized as a poor performer in the field was shown to have TSR value of above the minimum threshold while the SIP parameter accurately predicted that it was susceptible to moisture damage. Another mixture (M4-B3) was accurately identified as a good performer in terms of stripping potential by the HWTT SIP parameter, whereas the TSR incorrectly classified it as a stripping-prone mixture. The HWTT SIP parameter was able to identify the stripping potential of the asphalt mixtures with a greater degree of agreement with the field results compared to the TSR test, underlining its superiority as a stripping determination test.

The rankings of RT-Index were observed to match SIP and TSR rankings for only one out of the five mixtures. Based on these limited observations, the RT-Index parameter is likely a poor indication of moisture damage in asphalt specimens. This is perhaps not a surprise, as the IDEAL RT test was neither designed to control stripping, nor does it involve a moisture conditioning step.

Based on the results obtained in this limited study, the research team proposed an alternate moisture damage evaluation framework to replace the TSR method. The framework includes three steps. First, it screens for mixtures with rut depths lower than 4.0 mm at 20,000 passes in a HWTT. In general, if a mix exhibits low rut depths in the HWTT, it is highly likely that it is resistant to moisture damage. Second, if the rut depth is greater than 4.0 mm the slope ratio is computed and if the slope ratio is below or equal to 2.0, then the mixture is less likely to be susceptible to moisture damage. Finally, if the slope ratio is greater than or equal to 2.0, then the SIP is determined as a measure of stripping. A minimum threshold of 15,000 passes was chosen as the SIP threshold for initial implementation of the framework.

This study was limited to only a few dense-graded mixtures and was limited to a single RAP source. To gain further confidence in the SIP parameter and to finetune the proposed evaluation framework, a larger number and wider variety of asphalt mixtures with known field performance data should be investigated. While the SIP parameter has been adopted by several agencies and has proven to be an effective indicator of moisture damage, other parameters derived from the HWTT have also been proposed for use by other researcher teams and should be evaluated in the future.

1. Introduction

1.1 Background and Motivation

Moisture damage in asphalt pavements refers to the degradation process, due to the presence of moisture in any form, that leads to the deterioration of mechanical properties of the materials (Caro, 2018). This damage can cause critical distresses in pavements such as shoving, potholes, raveling, cracking, and rutting, which result in severe loss of functionality and strength. Although the specific damage mechanisms may vary, moisture damage can diminish the strength of adhesion between the asphalt mastic and the aggregate or can reduce the cohesion within the mastic itself. Aggregate surfaces are hydrophilic, meaning they have a stronger bond with water compared to asphalt binder. When the interface between asphalt binder and aggregate has prolonged exposure to water, it leads to the weakening of bonds and removal of asphalt binder from the asphalt surface. This is also known as stripping.

There are several factors, working individually and in combination with each other, that contribute to moisture damage in asphalt pavements. These includes aggregate surface texture, aggregate minerology, binder type, excessive traffic loading, extensive exposure to standing water, exposure to abrasive chemicals, and poor construction practices. Efforts to assess moisture damage in asphalt pavements began in the 1960s, but it wasn't until the 1980s that moisture-induced damage, also known as stripping, gained nationwide attention (Field & Phang, 1967; Taylor & Khosla, 1983). In recent times, a survey reported that 17 US states have identified stripping as a major issue in their state (Shah et al., 2022).

Many state DOTs address stripping, or moisture damage, through testing during the mix design phase by using the Modified Lottman method, commonly referred to as the Tensile Strength Ratio (TSR) test, conducted in accordance with AASHTO T283. The procedure was originally introduced by Lottman in the 1980s and since then it has undergone several modifications (Lottman, 1982; Tunnicliff & Root, 1984). The current test method includes two sets of specimens, one tested dry and other tested after being partially vacuum saturated, subjected to freezing and soaked in warm water. Both the subsets are tested to obtain indirect tensile strength with a minimum ratio of conditioned to unconditioned tensile strength specified (AASHTO, 2014). Many states allow for slight deviations in the test procedure, for instance a modified Connecticut Department of Transportation method specifies a different process for computation of percent saturation and the Illinois modified method does not specify any freeze-thaw cycles (Illinois Department of Transportation, 2022; Mahoney & Stephens, 1999).

Although the TSR test is ubiquitously adopted by state Departments of Transportation (DOTs), there have been several studies that have shown its poor correlation with field performance. This has raised questions on its widespread adoption and led to evaluation of other tests and frameworks to determine moisture susceptibility of asphalt mixtures. Wisconsin DOT reportedly tested twenty-one mixtures from existing pavement sections and found poor correlation of the pavement distresses (including moisture damage) with TSR results. Authors Kanitpong and Bahia noted that the TSR test did not provide good simulation of all the factors that cause moisture damage in the field (Kanitpong & Bahia, 2008). Similar issues were reported by researchers from the New England Transportation Consortium (NETC), which is a research cooperative between the DOTs of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont (Dave et al., 2018). In addition to that, researchers from NETC, Iowa DOT, and Illinois Tollway had pointed to the cumbersome nature of conducting the TSR test as one of the key motivating factors for the paving agencies to evaluate alternate test procedures and frameworks.

One of the alternate tests recommended by these aforementioned paving agencies was the Hamburg Wheel Tracking Test (HWTT). The HWTT is conducted in a water bath at elevated temperatures. The rut depth versus number of passes curve can be used to estimate the onset of moisture damage in an asphalt specimen. As shown in Figure 1.1, the onset of moisture damage is characterized by the Stripping Inflection Point (SIP) in the curve beyond which the damage to the asphalt specimen is significantly accelerated. More details on the SIP computation are discussed in subsequent chapters. The following section outline the key research questions investigated, and the research approaches adopted in this study.

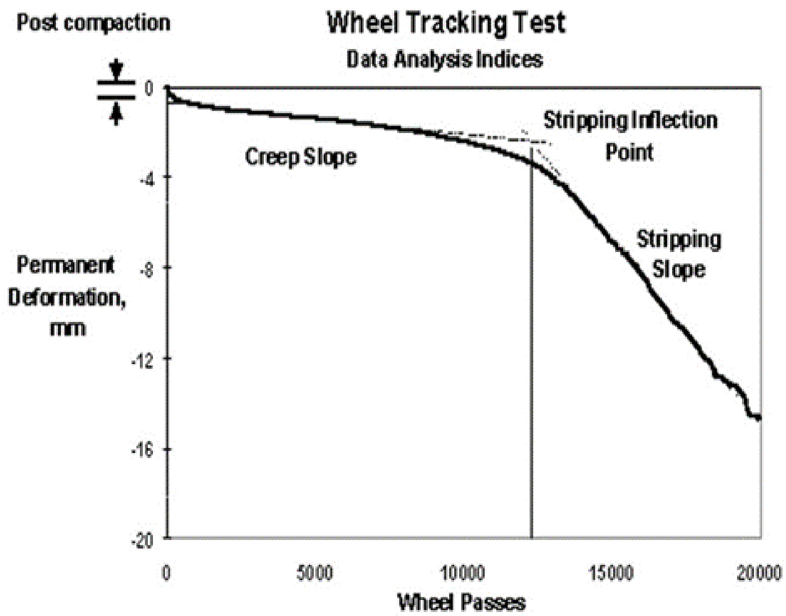


Figure 1.1. Typical rut depth versus wheel passes data obtained from HWTT and computation of stripping parameters after (Cooley Jr et al., 2000)

1.2 Research Questions and Approaches

The key research question posted in the research study includes:

- Are there discrepancies between TSR test results and performance of existing Missouri mixtures?
    - As noted in the RFP, MoDOT has identified several asphalt mixtures with good and bad performance with respect to moisture damage. In this study, the research team procured materials for the mixtures, if available, and re-produced them in the laboratory. The mixtures were then tested using the existing TSR method

    - (Modified Lottman method), per AASHTO T283 and the Hamburg Wheel Tracking Test, per AASHTO T324 to investigate correlation of the test parameters to moisture damage. In addition, the Ideal Rutting Test (also known as IDEAL-RT), per ASTM D8360 was also conducted to investigate if there is any correlation between the RT-Index parameter and moisture damage.
- Can an alternative evaluation framework to the TSR test be proposed?
    - As noted earlier, the Hamburg Wheel Tracking Test (HWTT) has been proposed as an alternative to the TSR method. HWTT is conducted in a water bath at elevated temperatures, which accelerates moisture damage in asphalt specimens. The Stripping Inflection Point (SIP), measured from the Hamburg rut depth versus number of cycles plot has been shown as a good indicator of the onset of moisture damage in asphalt mixtures. The Iowa method was used to calculate the SIP for the mixtures used in this study.

1.3 Organization of the Remainder of the Report

A comprehensive literature review was conducted and is provided in Appendix A. The insight obtained from the literature review along with consultation from MoDOT assisted in the formulation of this project. Figure 1.2 summarizes the overall project organization as a flowchart.

Chapter two provides details regarding the material sampling and processing. Five asphalt mixes were chosen for testing. Samples from the mixes were collected and sieve analyses were done to ensure the gradations matched the Job Mix Formulas (JMFs).

Chapter three provides the testing and analysis methods used by the Missouri Asphalt Pavement and Innovation Lab (MAPIL) during this project. After collecting aggregate samples MAPIL began fabricating asphalt samples and performance tests were conducted.

Chapter four provides laboratory testing results for the selected mixtures. Details on sampling, mix design, etc. are provided in this chapter.

Chapter five summarizes the recommendations based on the results provided in the previous chapter.

Chapter six provides summary and conclusions of this research investigation. Future research recommendations are also provided.

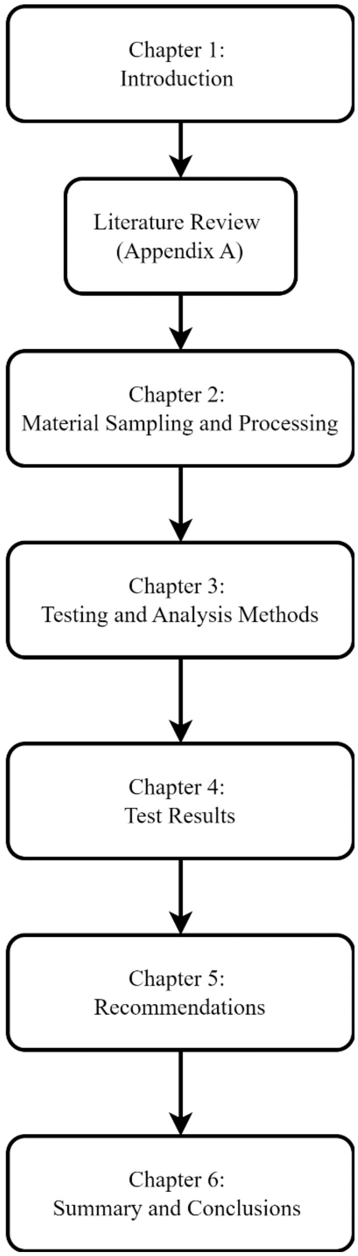


Figure 1.2. Project flowchart

2. Material Sampling and Processing

2.1 Overview

This study was conducted in two phases. In Phase I, the MAPIL research team consulted with MoDOT to procure materials, replicate them in the laboratory, and test them to determine their moisture susceptibility. In Phase II tests such as the Tensile Strength Ratio (AASHTO T283) and Hamburg Wheel Tracking Test (HWTT) (AASHTO T324) were used to establish moisture susceptibility (AASHTO, 2014). In addition, IDEAL RT test (ASTM D8360) was performed to record RT-Index for the mixtures (ASTM D8360-22, 2022). The following sections cover details of the procurement efforts by the research team and the final mix designs investigated2.2 Material Procurement

MAPIL and MoDOT held several meetings to discuss the procurement of the five mixtures identified by MoDOT in the Request for Proposals document. The MAPIL team attempted to procure all the materials by contacting the contractors first to check if there were existing stockpiles of the identified aggregates that could be sampled. If an existing stockpile was unavailable with the contractors, the team contacted the quarry to procure the aggregates. Upon procuring the materials, the aggregate stockpiles were put through a sieve analysis to ensure that they matched the original JMF gradation. MoDOT had listed five mixtures, out of which three were made from aggregate sources that have shown higher moisture damage potential in the past and two had reliably good moisture damage performance. However, only four mixtures were available to be sampled, as shown in Table 2-1. Details of the chosen mixtures are discussed in the following sub-sections. It is worth noting that one of the mixtures (Mixture 2, as shown in Table 2-1) was tested with and without the liquid anti-strip, as discussed further in Section 4.1.

Table 2-1. Mixture Details

Mixture Number	Aggregate Source	Mixture Reference ID	Mixture Type	Asphalt Supplier
Mixture 1	Flint Chat	M1-FC	SP190CLG	PG 64-22, Phillips 66 in KC
Mixture 2*	Osage River Gravel	M2-ORG	SP190C	PG 64-22, Exxon Mobil, St. Louis
Mixture 3	Bethany Falls	M3-BF	SP190CLG	PG 46-34, from Davenport, IA
Mixture 4	Plattin	M4-B3	SP190B	PG 64V-22, Phillips 66 in KC

*Mixture 2 was tested with and without LAS, and is referred to as M2-ORG and M2-ORG No LAS, respectively.

2.2.1. Mixture 1

One of the manufactured sands for this mixture was from the Flint Chat area in northeast Oklahoma. The other aggregates were sourced from the Cedar Valley formation in western Missouri. Thirty percent of the aggregate blend was from the contractor's RAP source. This mixture was designed with a PG64-22 from Phillips 66 in Kansas City, MO. The design was an SP190CLG with design gyrations of 80. This mixture is hereafter referred to as Mixture 1, or M1-FC. It was identified as a poor performer in terms of moisture damage. The aggregate gradation from sieve analysis and the combined gradation from the original JMF is shown in Table 2-2.

Table 2-2. Individual aggregate stockpile gradations for M1-FC

Sieve Size (No.)	Sieve Size (mm)	1" Randolph	¾" Randolph	3/8" Randolph	Sand Randolph	RAP	Sand WDM	Final gradation	JMF gradation
Aggregate Blend (%)	-	12.00	14.00	17.00	12.00	30.00	15.00	100.00	100.00
2 inches	50.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 ½ inch	37.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 inch	25.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
¾ inch	19.00	89.80	100.00	100.00	100.00	100.00	100.00	98.78	99.00
½ inch	12.50	45.90	70.90	100.00	100.00	98.00	100.00	88.83	86.70
3/8 inch	9.50	26.00	43.10	100.00	99.78	91.00	100.00	80.43	77.70
No. 4	4.75	1.80	4.20	62.86	74.41	65.00	92.71	53.83	56.40
No. 8	2.36	0.90	1.70	10.24	40.44	46.00	65.15	30.51	32.40
No. 16	1.18	0.70	1.60	5.72	15.75	36.00	47.10	21.04	20.50
No. 30	0.60	0.70	1.50	4.38	8.74	28.00	27.25	14.57	14.70
No. 50	0.30	0.70	1.40	3.87	5.73	22.00	13.07	10.19	9.80
No. 100	0.15	0.60	1.40	3.59	4.41	16.00	3.87	6.79	6.50
No. 200	0.075	0.60	1.30	3.41	4.00	10.60	1.51	4.72	4.70

2.2.2. Mixture 2

The second mixture that was identified by MoDOT used gravel dredged from the Osage River. The other aggregates were from the Gasconade formation in central Missouri. Fifteen percent of the aggregate blend was from the contractor's RAP source. The mixture was designed with a PG64-22 from Exxon Mobil in St. Louis, MO. The binder was dosed with 0.5% of ARR-MAZ's AD-here HP PLUS. The design was an SP190C with design gyrations of 100.

Unfortunately, the quarry used for the Gasconade formation aggregates in this mixture was out of business when this project started. After extensive searching and coordination with MoDOT, contact was made with another nearby quarry operated by a different contractor. The research team was able to verify the aggregates from the new quarry are from the same geologic formation and have similar properties. MAPIL researchers made a trip to two different quarries to get stockpiles of approximately the same Nominal Maximum Size Aggregate Size (NMAS).

These two quarries were sampled on February 1, 2024. The Osage River gravel was sampled on February 15, 2024. During the sieve analysis it was found that the ½" stockpile sampled had far fewer fines than the stockpile used in the mixture design. Further conversation with the new quarry revealed that they did not have any stockpiles with enough fines in them to blend a gradation comparable with the JMF for the original mixture.

This mixture had shown signs of stripping on field and was of particular interest to the MoDOT. Thus, based on the previous discovery and discussion with MoDOT, it was decided to use a fine aggregate stockpile from the Plattin formation. The aggregate chosen was the manufactured sand from the Bussen #3 quarry used in Mixture 4 (discussed later). The gradation created from the newly sourced stockpiles matched the JMF very closely, but after mixing, the volumetric compaction revealed that the mixture was too stiff. At 100 gyrations, the bulk air voids were too high. The stockpile blending was adjusted to keep the same gradation curve but reduce the amount of 1" stockpile. This yielded a mixture that could be compacted to Superpave air void tolerance at 100 gyrations. Only the final gradation is included in the report for brevity, as shown in Table 2-3. The binder was dosed with 0.5% of AD-Here HP Plus, but due to its unavailability during this study LOF-65 was used as a liquid anti-strip (LAS) at the same dosage. This mixture is referred to as Mixture 2 or M2-ORG. This mixture was expected to be poor performing in terms of moisture damage.

Table 2-3. Individual aggregate stockpile gradations for M2-ORG

Sieve Size (No.)	Sieve Size (mm)	1" Bagnell	3/4" Linn Creek	3/8" Wardsville	Sand Eureka	RAP	Final Gradation	JMF
Aggregate Blend (%)	-	13.00	40.00	22.00	19.00	6.00	100.00	100.00
2 inches	50.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 ½ inch	37.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 inch	25.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
¾ inch	90.50	100.00	100.00	100.00	100.00	100.00	98.77	99.00
½ inch	12.50	55.90	87.00	100.00	100.00	98.00	88.69	86.80
3/8 inch	9.50	34.10	66.70	99.60	100.00	91.00	76.32	73.00
No. 4	4.75	7.50	21.60	61.80	99.00	65.0	41.50	43.00
No. 8	2.36	4.70	8.10	34.10	85.00	46.00	25.19	23.10
No. 16	1.18	4.10	5.50	21.00	47.00	36.00	17.01	15.70
No. 30	0.60	3.80	4.50	5.60	27.00	28.00	10.47	12.30
No. 50	0.30	3.40	3.80	2.60	16.00	22.00	7.67	8.80
No. 100	0.15	2.80	2.80	1.00	10.00	16.00	5.38	5.80
No. 200	0.075	2.20	2.20	0.50	7.00	10.60	3.71	3.80

2.2.3. Mixture 3

The third mixture used aggregates from the Bethany Falls formation in northwest Missouri. These were the only virgin aggregates in this mixture. The original quarry listed in the JMF for this mixture was not in use when this project started. The MAPIL team contacted the quarry company which operated multiple quarries in the area, and they were able to help the research team procure representative aggregates. Forty one percent of the aggregate blend was from the contractor's RAP source. The mixture was designed with a PG46-34 obtained from Davenport, IA. The binder was dosed with 0.75% of Ingevity's Pave Bond XD, but due to its unavailability during this study LOF-65 was used as an LAS at the same dosage. The design is an SP190CLG with design gyrations of 80. This mixture is referred to as Mixture 3 or M3-BF. This was expected to be a poor performing mixture in terms of moisture damage. The aggregate gradation from sieve analysis and the combined gradation from the original JMF is shown in Table 2-4.

Table 2-4. Individual aggregate stockpile gradations for M3-BF

Sieve Size (No.)	Sieve Size (mm)	¾" Bethany Falls	3/8" Bethany Falls	3/8" Blue Mound	3/16" Blue Mound	RAP	Final Gradation	JMF
Aggregate Blend (%)	-	30.00	21.00	2.00	6.00	41.00	100.00	100.00
2 inches	50.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 ½ inch	37.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 inch	25.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
¾ inch	19.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
½ inch	12.50	57.00	100.00	100.00	100.00	98.00	86.28	89.8
3/8 inch	9.50	23.00	100.00	100.00	100.00	91.00	73.21	75.2
No. 4	4.75	4.00	50.00	27.00	96.00	65.00	44.65	41.4
No. 8	2.36	4.00	13.00	10.00	70.00	46.00	27.19	25.1
No. 16	1.18	3.00	7.00	5.00	36.00	36.00	19.39	16.8
No. 30	0.60	3.00	7.00	5.00	36.00	28.00	16.11	13.4
No. 50	0.30	2.80	5.40	3.90	18.00	22.00	12.15	10.7
No. 100	0.15	2.80	5.40	3.90	18.00	16.00	9.69	8.1
No. 200	0.075	2.80	5.40	3.90	18.00	10.60	7.48	6.7

2.2.4. Mixture 4

This mixture was from the Plattin formation. It used virgin aggregates from Antire's Bussen #3 quarry in Eureka, MO. This mixture was the least challenging to obtain even though the company which owned the quarry had been sold. Fortunately, the mixture was still being produced regularly, and all the aggregate stockpiles were readily available at the original paving contractor. The MAPIL team confirmed that the stockpiles obtained for this study were from the same ledges as specified in the JMF. The mixture was made with twenty five percent of the aggregate blend coming from the contractor's RAP source. The mixture was designed with a PG64V-22 from Phillips 66 (Apex Oil) in St. Louis, MO. The design was an SP190B with design gyrations of 125. This mixture is hereafter referred to as Mix 4, or M4-B3. This mixture was expected to perform well in terms of moisture susceptibility. The aggregate gradation from sieve analysis and the combined gradation from the original JMF is shown in Table 2-5.

Table 2-5. Individual aggregate stockpile gradations for M4-B3

Sieve Size (No.)	Sieve Size (mm)	1" Eureka	½" Eureka	3/8" Eureka	3/8" Eureka	Sand Eureka	RAP	Min. Filler Ste. Genevieve	JMF
Aggregate Blend (%)	-	12.00	12.00	19.00	19.00	12.50	25.00	0.50	100.0
2 inches	50.00	100.00	100.0	100.0	100.00	100.00	100.0	100.00	100.0
1 ½ inch	37.50	100.00	100.0	100.0	100.00	100.00	100.0	100.00	100.0
1 inch	25.00	100.00	100.0	100.0	100.00	100.00	100.0	100.00	100.0
¾ inch	19.00	75.00	100.0	100.0	100.00	100.00	100.0	100.00	97.0
½ inch	12.50	10.00	80.00	100.0	100.00	100.00	99.00	100.00	86.6
3/8 inch	9.50	2.00	40.00	100.0	100.00	100.00	95.00	100.00	79.8
No. 4	4.75	1.00	4.00	61.00	61.00	99.00	75.00	100.00	55.4
No. 8	2.36	1.00	2.00	10.00	10.00	85.00	55.00	100.00	29.0
No. 16	1.18	1.00	1.00	2.00	2.00	47.00	41.00	100.00	17.6
No. 30	0.60	1.00	1.00	1.00	1.00	27.00	29.00	100.00	11.7
No. 50	0.30	1.00	1.00	1.00	1.00	16.00	19.00	99.00	7.9
No. 100	0.15	1.00	1.00	1.00	1.00	10.00	13.00	95.00	5.6
No. 200	0.075	1.00	1.00	1.00	1.00	7.00	10.00	75.00	4.4

2.2.5. RAP Stockpile

For this study, all mixes were made using a RAP sourced from a contractor located in eastern Missouri, near the St. Louis area, in 2022 by MAPIL. Figure 2.1 shows an image of the RAP stockpile used in this study and Figure 2.2 shows its gradation. Obtaining the original RAP used in the mixtures was not feasible. The researchers are aware that this may have affected the performance of some mixes. The asphalt content (AC) of the RAP stockpile was reported to be 4.7%. Due to the use of different RAP, some of the mixtures had to be adjusted in terms of virgin asphalt content. Details of the final mixture designs are discussed in the next section.

Figure 2.1. RAP Stockpile

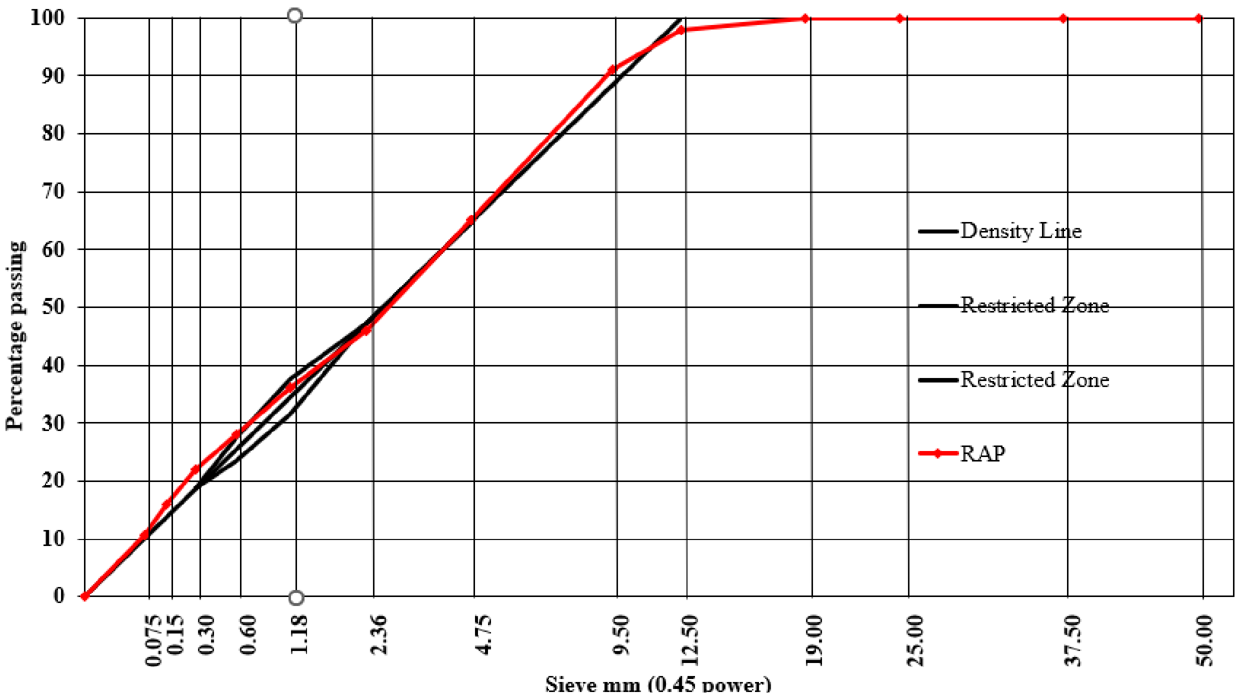


Figure 2.2. Gradation of RAP used in this study

2.3 Mixture Designs

After procuring all the required aggregate stockpiles, the mixtures were re-created. Figure 2.3 shows the gradation for all the mixtures used in this study. The original asphalt binders were not available to the researchers and thus, asphalt binders from MAPIL's material reference library were used for this study. The research team used the same grade of binder for each mix as specified in the original JMF, and wherever possible, from the same region of the state. For instance, in the case of M4-B3, a PG64-22V binder was obtained from a supplier in the St. Louis area for this study. Details of the final mixture designs, including the volumetrics data, are shown in Table 2-6. Additionally, Figure 2.4 shows the comparison of the theoretical maximum specific gravities (Gmm) of the lab-produced mixtures with their corresponding JMF-reported values. Changes in the RAP stockpile and base (virgin) binder are likely the primary reasons for the differences in the Gmm values.

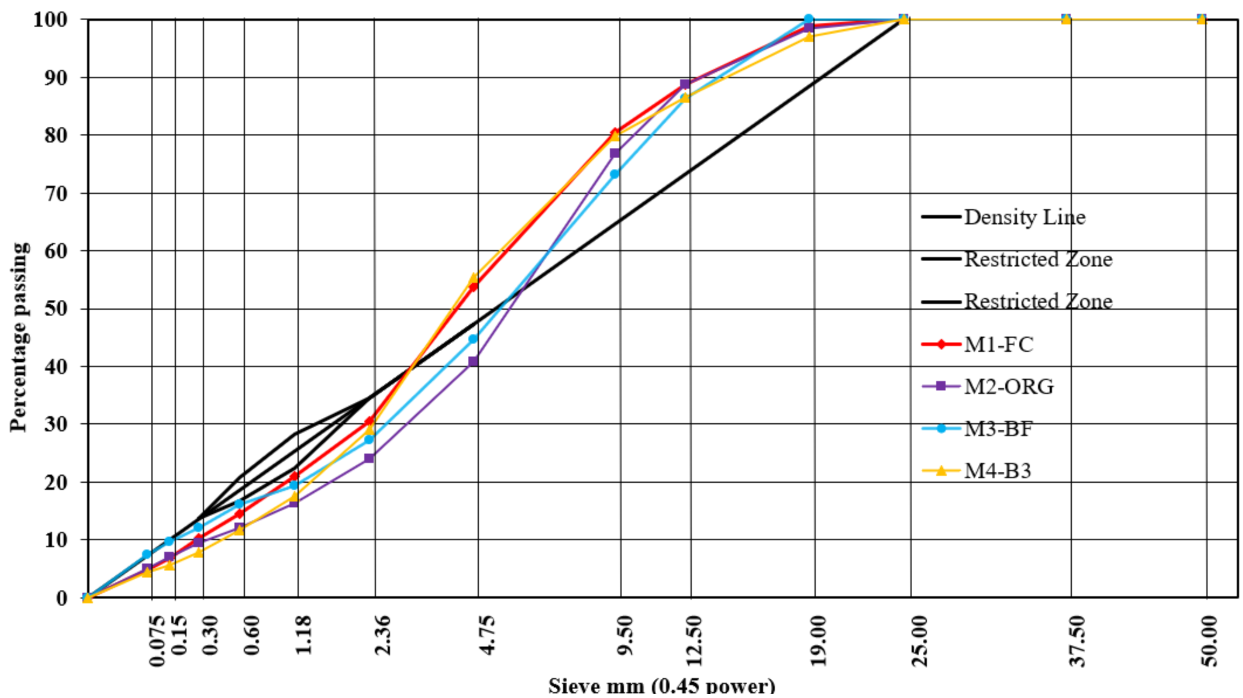


Figure 2.3. Aggregate gradations for all mixtures

Table 2-6. Volumetrics and other information for the mixtures used in this study

Mix	Mix ID	Binder Grade	Virgin Binder Content (%)	RAP Binder Content (%)	Additives	Air Voids	VMA (%)	VFA (%)
M1-FC	SP190CLG 22-41	PG64-22	4.8	1.2	None	3.85	16.3	76.5
M2-ORG	SP190C 09-25	PG64-22	5.0	0.8	0.50% LOF-65	4.51	15.0	70.0
M3-BF	SP190CLG 22-23	PG46-34	2.8	2.1	0.75% LOF-65	3.75	11.9	67.0
M4-B3	SP190B 20-28	PG64V-22	3.9	1.0	None	3.75	12.4	68.9

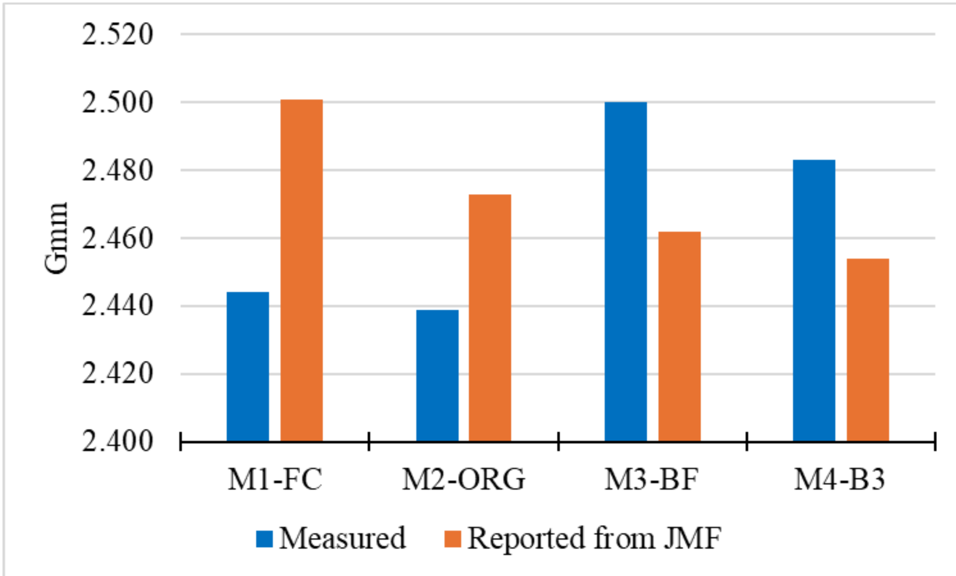


Figure 2.4. Comparing different Gmm values for studied mixtures (Measured = Test performed in MAPIL; JMF = job mix formula)

3. Testing and Analysis Method

3.1 Overview

In this study, the HWTT and IDEAL-RT were used to assess the rutting performance of mixtures. These test results were then compared to the TSR test results. For the HWTT (AASHTO T324), a requirement of 12.5 mm maximum rut depth at 20,000 passes was imposed. A testing temperature of 50° C (122°F) was used. For the TSR test, the AASHTO T283 standard was followed. Six test specimens were produced, out of which three specimens were conditioned and three remained unconditioned. The IDEAL-RT was conducted as per ASTM D8360. The test was run on specimens that were conditioned in air at 50° C for two and a half hours. A loading rate of 50 mm/minute of cross-headed displacement was imposed as per the standard. The performance tests are briefly described below.

3.2 Hamburg Wheel Tracking Test (HWTT)

Rutting (permanent deformation) in asphalt pavement is a result of shear flow and consolidation caused by traffic loading in hot weather. These combined factors result in a gradual accumulation of shear and volumetric strains in the hot mix asphalt (HMA) layers. The lack of shear strength in the asphalt layer lessens the asphalt's ability to resist the repeated heavy static and moving loads. This results in downward movement of the asphalt surface and produces the potential for upheaval and microcracking along the rut edges. In combination with structural failure issues, safety concerns emerge due to the increased potential for hydroplaning, increased stopping distances, and difficulties in vehicle steering due to uneven riding surfaces.

The most popular wheel load tracking (WLT) tests are the Asphalt Pavement Analyzer (APA, formerly known as the Georgia-loaded wheel tester) and the Hamburg Wheel Tracking Test (HWTT). The HWTT is performed following the standards set in AASHTO T324. A loaded steel wheel, with an approximate weight of 71.7 kg, tracks over the asphalt samples, which are placed in a water bath of 50° C (122° F). The number of wheel passes is recorded, along with the vertical deformation of the specimen. The test typically ends when either the number of wheel passes exceeds 20,000 or the specimen deforms by 20mm vertically. A requirement of 12.5 mm maximum rut depth at 20,000 passes was imposed for this project. Figure 3.1 shows the HWTT machine used in this study.

The test also provides the opportunity to measure the stripping potential of the asphalt mix since the test is run under water. This value is measured by the Stripping Inflection Point (SIP). The SIP represents the number of passes at which there is an onset of moisture damage in the asphalt specimen. As previously shown in Figure 1.1, the SIP is at the intersection of the creep slope and stripping slope of the rut depth versus number of passes curve. The SIP is characterized by a sharp increase in rut depth (inflection point in the curve). In this study, the Iowa method was used to calculate the SIP mathematically. The Iowa method is described as follows:

- A 6th degree polynomial curve is fitted to the rut depth versus wheel passes data

- The stripping line is determined by using the tangent at the point nearest to the end of the test where the minimum of the first derivative of the fitted curve occurs
- The creep line is determined by using the tangent at the point where the second derivative of the fitted curve equals zero
- The wheel pass at which the creep line and the stripping lines intersect is the SIP

In this study, a MATLAB^{TM} code was used to follow the steps outlined above and to determine the SIP for each of the replicates.

Figure 3.1. Hamburg Wheel Track Test (HWTT) device

3.3 Tensile Strength Ratio (TSR) Test

The TSR tests conducted during this research project followed the AASHTO T283 specification. In this testing two subsets of samples were measured to create an indirect tensile strength ratio. The first subset of samples, which included three replicates of gyratory samples with 95 mm thickness, were considered the dry subset. These samples were compacted and then cooled down at room temperature. The dry samples were then conditioned in a water bath of 25° C for two hours. After the conditioning process, the samples were tested, and the dry indirect tensile strength was recorded.

The next subset of samples, the wet subset, included three replicates with the same air void content and geometry as the dry subset. This subset of samples was subjected to vacuum saturation with a target saturation of 70-80%. The specimens were placed in a vacuum container, on a perforated spacer that sat a minimum of 25 mm (1 in.) above the bottom of the vacuum container. Room temperature potable water was then poured into the container until the specimens had at least 25 mm (1 in.) of water above their surfaces. A vacuum pressure of 13 to 16 kPa (10 to 26 in. Hg partial pressure) was applied to the specimens for approximately 5 to 10 minutes. The vacuum pressure was then removed, and the percentage of saturation of the specimens was measured. This vacuum saturation process was repeated until the samples reached a saturation percent between 70-80%. After vacuum saturation, the samples were wrapped in plastic film and placed in a resealable plastic bag along with 10mL of water. The bagged samples are then placed in a –18° C freezer for >16 hours. After freezing the samples, they are then placed in a warm water bath (60° C) for 24 hours. Following this, the samples were placed in water at 25° C for 2 hours. At the end of the two hours, the samples were then tested, and their wet indirect tensile strengths were recorded.

Finally, after both subsets were tested, the TSR value was calculated as the ratio of wet to dry indirect tensile strength. A higher TSR value indicated a higher resistance to rutting. An example of a test conditioned and unconditioned sample can be seen below in Figure 3.2.

Figure 3.2. Tested conditioned (wet) and unconditioned (dry) specimens

3.4 IDEAL Rutting Test (IDEAL-RT)

The IDEAL-RT test was developed to characterize the rutting potential of asphalt mixtures during design and production. It utilizes a shear strength-based parameter called the Rutting Tolerance Index (RT_{Index}). A specimen, heated to 50° C, is placed in a cradle jig and loaded at three points at a rate of 50.0 mm/min for the duration of the test (see Figure 3.3). This creates two shear planes within the specimen. A higher RT_{Index} value represents higher rutting resistance and lower rut depth in the field. The following calculations were used to calculate the RT_{index}.

$$\tau_f = 0.356 \times \frac{P_{max}}{t \times w}$$

Equation 3-1. Shear Strength

here:

τ_f = shear strength (Pa), $Pmax$ = maximum load (N), t = specimen thickness (m), and w = width of upper loading strip (= 0.0191 m).

$$RT_{Index} = 6.618 \times 10^{-5} \times \frac{\tau_f}{1\ \text{Pa}}$$

Equation 3-2. RT-index

Where:

RT_{index} = rutting tolerance index, and τ_t = shear strength calculated from Eq 1 (Pa).

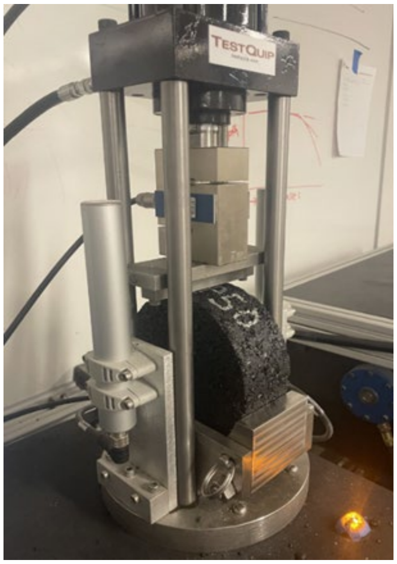


Figure 3.3. IDEAL-RT testing apparatus

4. Test Results

4.1 Hamburg Rut Depth

The Hamburg Wheel Tracking Test was carried out to evaluate the potential permanent deformation (rutting) of the mixtures. The required number of wheel passes to pass the test was 20,000 and the maximum rut depth allowed was 12.5 mm. The measured rut depth for each mixture can be seen below in Figure 4.1.

Only M3-BF failed the rutting criteria based on the imposed threshold of 12.5 mm at 20,000 passes. High rut depths obtained in the HWTT conducted in a water bath could be an indication of moisture damage. Based on field performance information gathered from MoDOT, M1-FC and M3-BF were expected to exhibit stripping potential, which is accompanied by higher rut depths, as recorded in the results. Conversely, M4-B3 was expected to be resistant to stripping, which often results in lower rut depth.

However, M2-ORG mixture, which showed signs of stripping on-field (per discussion with MoDOT) recorded low rut depth and no stripping (discussed in later sections). The use of different aggregates and RAP compared to the original mixture could likely be the reason for this discrepancy. Another reason could be the use of a different LAS than the original JMF. Since the original LAS was not available for use in testing, the team proceeded to test the mixture without any LAS to investigate if its removal affects the rutting and stripping results. The resulting mixture, named as M2-ORG No LAS, recorded marginally lower rut depth.

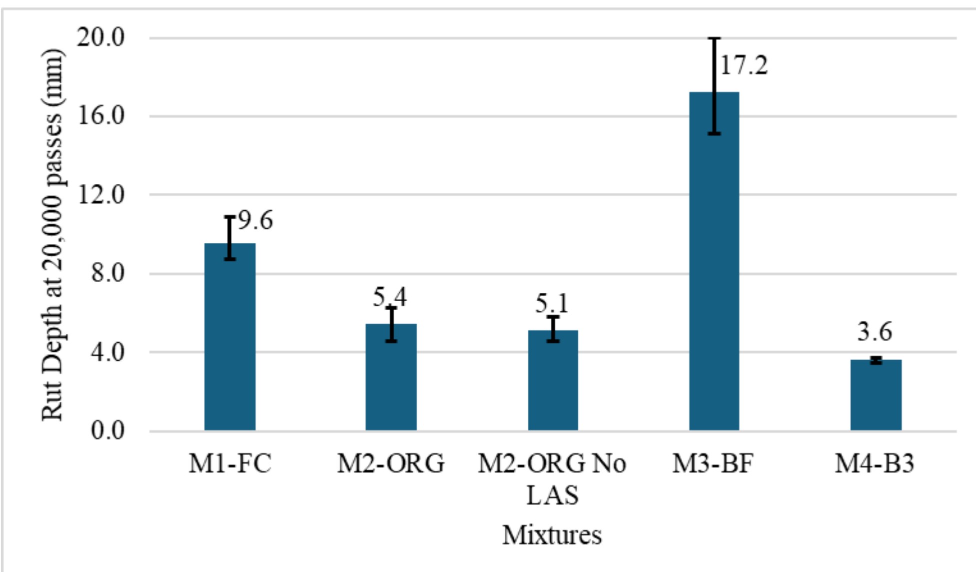


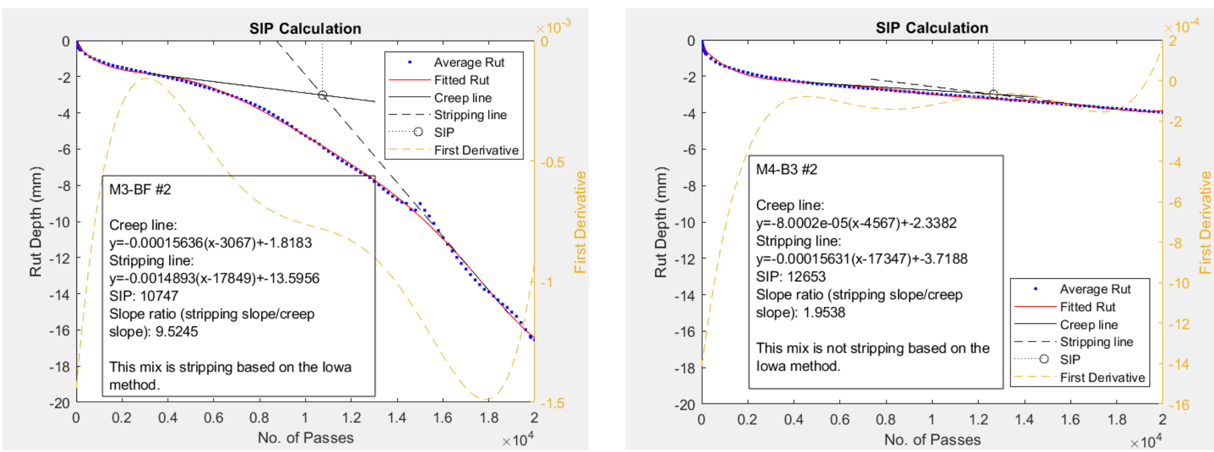
Figure 4.1. Rut depth reported at 20,000 passes for each mixture

4.2 Hamburg Stripping Inflection Point

As mentioned in earlier sections, SIP computed from the HWTT was used to evaluate the moisture damage potential of each mix. A higher SIP value indicates the mixture's increased ability to resist potential moisture damage. Following the Iowa method criteria, a mixture is identified as exhibiting stripping potential when the ratio of the stripping line slope and the creep line slope is greater than or equal to 2.0. Examples of SIP calculations are provided below in Figure 4.2. As can be seen from the examples, in Figure 4.2 (a) the M3-BF #2 mixture has a slope ratio of greater than 2.0 and hence was deemed to be stripping based on the Iowa method. On the other hand, in Figure 4.2 (b), the M4-B3 #2 mixture shows an example of a non-stripping mixture with a recorded slope ratio of less than 2.0.

Table 4-1 shows more details for the mixture stripping potential including the slope ratios of the individual replicates and the average SIP. Except the M4-B3 mixture, at least one replicate of all other mixtures had a slope ratio of greater than 2.0, indicating susceptibility to stripping. However, considering the average slope ratios, only two mixtures, M1-FC and M3-BF, were deemed to be stripping. The other mixtures – M2-ORG, M2-ORG No LAS, and M4-B3 – had an average slope ratio of less than 2.0 and were non-stripping.

In the next section, the TSR results are presented and compared to the SIP results discussed herein.



(a) (b)

Figure 4.2. Examples of SIP determinations, a) M3-BF #2 shows a stripping mixture with a slope ratio > 2.0 and, b) M4-B3 #2 shows a non-stripping mixture with a slope ratio < 2.0

Table 4-1. Identifying the presence of stripping according to SIP

Mix. ID #Replicate	Slope Ratio (S = Stripping, NS = Not Stripping)	Average Slope Ratio	SIP	Average SIP
M1-FC #1 M1-FC #2 M1-FC #3	1.9 (NS) 4.6 (S) 4.1 (S)	3.5	12,053 12,804 11,356	12,071
M2-ORG #1 M2-ORG #2 M2-ORG #3	1.3 (NS) 2.5 (S) 1.6 (NS)	1.8	N/A	N/A
M2-ORG No LAS #1 M2-ORG No LAS #2 M2-ORG No LAS #3	1.3 (NS) 1.7 (NS) 2.0 (S)	1.7	N/A	N/A
M3-BF#1 M3-BF #2 M3-BF #3	3.8 (S) 9.5 (S) 8.2 (S)	7.2	10,163 10,747 11,547	10,819
M4-B3 #1 M4-B3 #2 M4-B3 #3	1.3 (NS) 1.9 (NS) 1.3 (NS)	1.5	N/A	N/A

4.3 TSR Testing Results

The TSR results are shown in Figure 4.3. Using MoDOT's criteria of a minimum of 80% TSR, only two of the original four mixtures, M1-FC and M2-ORG, pass. The other two mixtures, M3-BF and M4-B3 recorded lower than 80% TSR values. In addition, the M2-ORG No LAS mixtures recorded a significantly higher TSR compared to its original counterpart. Interestingly, the wet condition for the mixture exhibited higher strength compared to the dry conditioned specimens. It was also noteworthy that the recorded peak strengths for the mixture in wet and dry conditions were the lowest amongst all tested mixtures.

Figure 4.4 shows the comparison of the lab measured TSR values to the ones reported on the original job mix formulas (JMFs). All the mixtures were reported to have a passing TSR score of above 80%. It is worth recalling that all the mixtures were produced using a different RAP source than their original JMFs, which could affect the results.

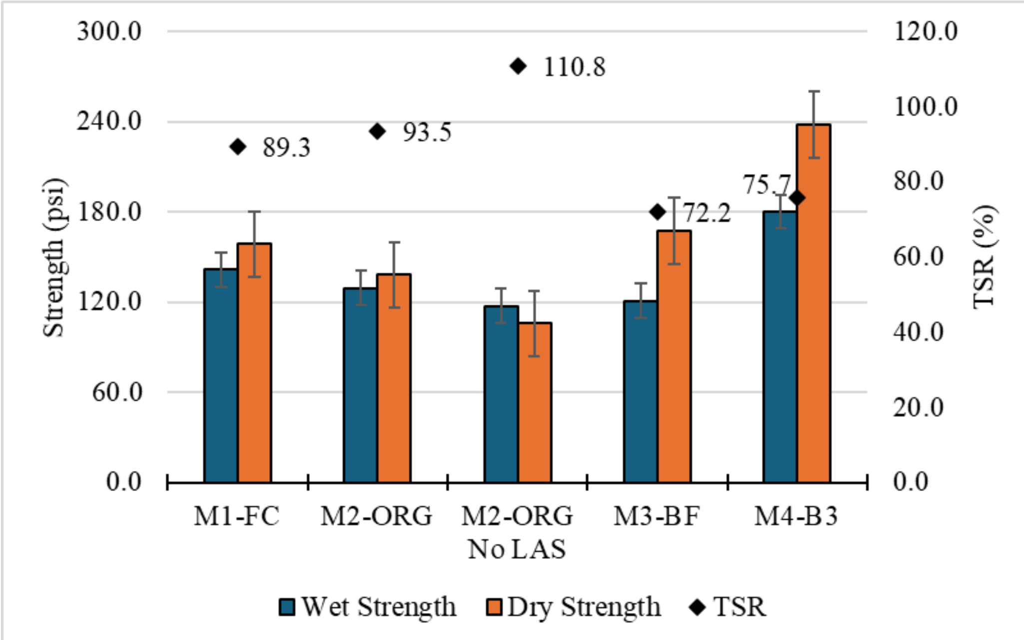


Figure 4.3. Indirect tensile strength in wet and dry conditions, and TSR for all mixtures

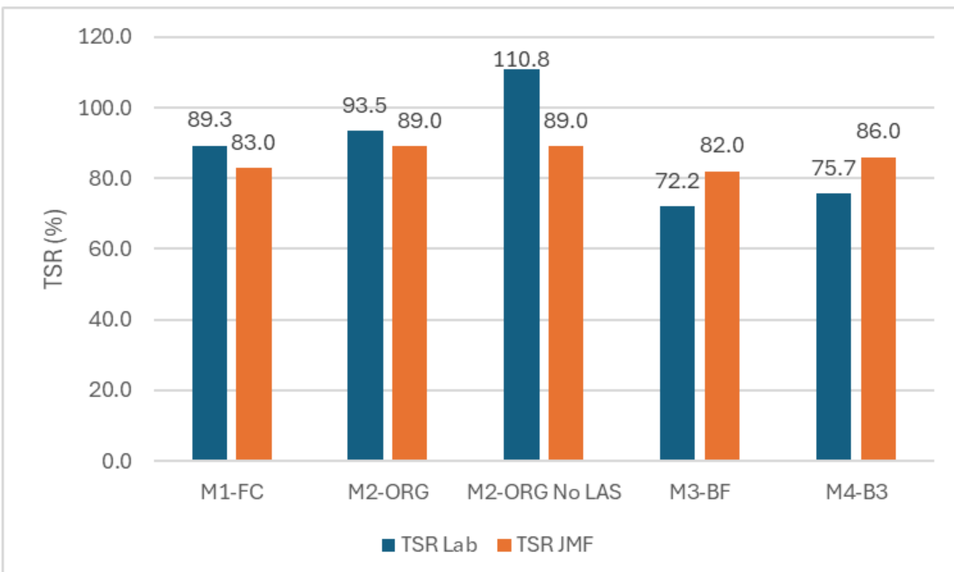


Figure 4.4. Comparison of TSR values obtained in this study with the values reported in the JMFs

4.4 IDEAL-RT Testing Results

In addition to evaluating the HWTT and TSR test, the IDEAL-RT test was also conducted to determine if any correlation exists between the RT-Index and moisture damage susceptibility. Table 4-2 shows the RT-Index results obtained from the test. MoDOT's current RT-Index limits specify a threshold of 50 for PG64-22S and PG58-28H binders (contract grade), 65 for PG64-

22H/70-22 binders, and 80 for PG64-22V/76-22 binders. Based on the specifications, all mixtures pass the RT-Index threshold.

Table 4-2. Mixture results for RT Index

Mix	Contract Grade	Peak Load (kN)	Shear Strength (kPa)	RT Index
M1-FC	PG 64-22	3.09	928.18	61.43
M2-ORG	PG 64-22	2.81	843.25	55.81
M2-ORG No LAS	PG 64-22	2.86	858.81	56.84
M3-BF	PG 64-28	4.94	1486.44	98.38
M4-B3	PG 76-22	5.44	1635.55	108.25

4.5 Comparison of TSR and HWTT SIP Results

One of the key questions investigated in this study was the comparison of the ability of the TSR test and the HWTT to determine the moisture damage susceptibility of asphalt mixtures. The TSR criteria is a simple pass/fail criteria. On the other hand, the SIP parameter, based on the HWTT, involves a 2-step process. The first step determines if the mix is stripping and hence, susceptible to moisture damage. The second step provides further information on when the onset of moisture damage occurs in the asphalt specimen in terms of the Stripping Inflection Point (SIP). The frameworks for both the tests are shown in Figure 4.5 and Table 4-3 shows the comparison of the implementation of these two frameworks for the five mixtures evaluated in this study.

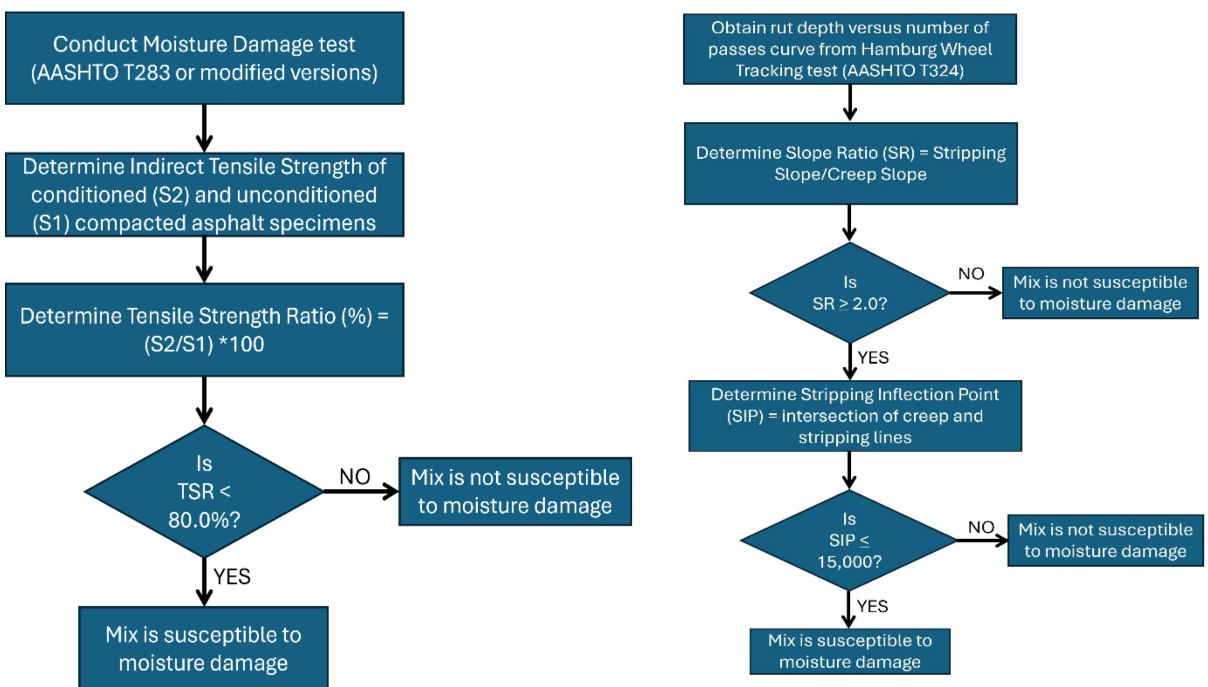


Figure 4.5. Framework for determination of moisture susceptibility for (a) TSR tests, and (b) HWTT

Table 4-3. Comparison of TSR and SIP results for the four mixtures evaluated in this study with field performance

Mix	Is the mixture susceptible to moisture damage based on the TSR evaluation?	Is the mixture susceptible to moisture damage based on the HWTT SIP evaluation?	Field Performance*
M1-FC	No (TSR = 89.3)	Yes (SR > 2.0, SIP = 12,071)	Poor
M2-ORG	No (TSR = 93.5)	No (SR < 2.0)	Poor
M2-ORG No LAS	No (TSR = 110.8)	No (SR < 2.0)	N/A
M3-BF	Yes (TSR = 72.2)	Yes (SR > 2.0, SIP = 10,800)	Poor
M4-B3	Yes (TSR = 75.7)	No (SR < 2.0)	Good

*Field Performance was determined based on discussions with MoDOT regarding the mixtures

Comparing the two tests with each other, the ranking of the mixtures based on:

a. TSR results: M2-ORG No LAS > M2-ORG > M1-FC > M4-B3 > M3-BF,
b. SIP and slope Ratio: M4-B3 > M2-ORG No LAS > M2-ORG > M1-FC > M3-BF. Note that only M3-BF and M1-FC have valid SIPs. The other three mixtures could be ranked based on their slope ratios or HWTT rut depths (ranking is the same irrespective of the ranking parameter).

Table 4-3 also includes qualitative field performance results, based on information gathered from MoDOT. On comparing the field performance with the obtained results, the following observations were made:

- M1-FC mixture was accurately identified as a poor performing mixture by the HWTT SIP parameter while the TSR inaccurately characterized it as a good performer in terms of stripping potential.
- M2-ORG and M2-ORG No LAS mixtures were characterized as mixtures with good stripping resistance by both the tests, whereas its field performance was reported to be poor. It is noteworthy that both the mixtures had one replicate which indicated stripping potential based on the slope ratio parameter.

a. M3-BF mixture was accurately identified as a poor performer by both the tests.
b. M4-B3 mixture was accurately identified by the HWTT SIP parameter as a good performer while the TSR inaccurately characterized it as a stripping mixture.

In conclusion, the HWTT SIP parameter was able to identify the stripping potential of the asphalt mixtures with a greater degree of agreement with the field results compared to the TSR test, underlining its superiority as a stripping determination test.

4.6 Comparison of RT-Index with Other Tests

The RT-Index was compared to the other two potential moisture damage tests and the rankings are shown in Table 4-4. The TSR and HWTT SIP rankings were discussed in the prior section. The rankings of RT-Index were observed to match for only one out of fives mixtures tested in this study. Based on these limited observations, the RT-Index parameter is likely a poor indication of moisture damage in asphalt specimens. It is worth noting that the asphalt specimens were not conditioned in a water bath, which is allowed as per ASTM D8360. Conditioning in a water bath at the test temperature of 50° C could perhaps result in a better simulation of moisture damage in asphalt specimens.

Table 4-4. Comparison of RT-Index with TSR and SIP rankings of mixtures

Mix	RT-Index Ranking	TSR Ranking	HWTT SIP Ranking
M1-FC	3	3	4
M2-ORG	5	2	3
M2-ORG No LAS	4	1	2
M3-BF	2	5	5
M4-B3	1	4	1

5. Recommendations

Based on the results of this limited study, the SIP parameter obtained from the HWTT was found to have the best agreement with known field performance as reported by MoDOT. Additionally, while the TSR test involves producing several asphalt specimens and rigorous conditioning, SIP is obtained from the widely used rutting test in Missouri, i.e. the Hamburg Wheel Tracking Test (HWTT), which makes it logistically easier for the DOT and contractors to measure and control moisture susceptibility in the mix design and production stages.

As outlined in Figure 4.5 (b), the Iowa method of SIP determination is a two-step process. Step 1 is a screening process wherein the slope ratio is determined. If the slope ratio is greater than or equal to 2.0, the next step is triggered, which is SIP determination. It has been observed that asphalt mixtures with very low rut depth generally have low slope ratio. Moreover, the HWTT is a torturous test wherein the specimens are subjected to high temperatures, concentrated pressures (wheel passes from rigid steel wheels with edges as opposed to inflated tire wheels), and moisture while enduring the wheel passes. All of these factors significantly increase the chances of moisture damage. Therefore, if the mixture has a noticeably lower rut depth after a HWTT, then the chances of moisture damage occurring are objectively low. Thus, the recommended evaluation framework should have a pre-screening process even before the determination of slope ratio and it should be a maximum limit of rut depth. Another argument in support of inclusion of this pre-screening step would be to avoid cases where the denominator of the slope ratio, i.e. creep slope, is low enough to mathematically inflate the slope ratio to be above 2.0. Though such cases were not explored in this study, the researchers have observed such cases in other projects (Buttlar et al., 2021). Finally, based on this limited study a threshold of 15,000 passes for minimum SIP value seems to be a reasonable and conservative beginning point for dense graded mixtures.

Considering the discussion above, the following evaluation framework for determination of moisture damage is proposed as a replacement of TSR test method, as shown in Figure 4.5 (b):

1. Obtain the Hamburg rut depth versus wheel passes curve, as per AASHTO T324.
2. If Rut Depth ≤ 4.0 mm at 20,000 passes, then the mixture is not susceptible to moisture damage. If Rut Depth > 4.0 mm, proceed to compute Slope Ratio.
3. If Slope Ratio < 2.0, then the mixture is not susceptible to moisture damage.
4. If Slope Ratio ≥ 2.0, then compute and report Stripping Inflection Point.
5. If Stripping Inflection Point ≤ 15,000 passes, then the mixture is susceptible to moisture damage, otherwise, the mixture is not susceptible to moisture damage.

While the use of SIP will be logistically easier and more cost-effective, without validating and adjusting the above-presented evaluation framework with more field data, over-screening of moisture damage resistant mixes may occur. Thus, until more field data is available, the TSR test may be utilized as a secondary stripping determination. If the asphalt mixture does not pass the SIP threshold, then the TSR test can be subsequently performed, and existing thresholds might be utilized for determination of moisture damage susceptibility of asphalt mixtures.

6. Summary and Conclusion

This study was motivated by the need to replace the AASHTO T283 method, also known as the Tensile Strength Ratio (TSR) test, for evaluation of moisture damage susceptibility of asphalt mixtures. The TSR test was not only cumbersome to conduct but it had also exhibited poor correlation with field performance. To that end, the Missouri Department of Transportation (MoDOT) had identified five mixtures with known field performance in terms of moisture damage for evaluation with alternate test methods. The primary candidate for the alternate test method was the Hamburg Wheel Tracking Test (HWTT), which is widely used in Missouri to determine the rutting potential of the asphalt mixtures. The HWTT is a torturous test conducted at high temperature in a water bath, which makes it ideal to determine the moisture damage susceptibility of asphalt mixtures. In addition, the IDEAL-RT test was also conducted to investigate any possible correlation with moisture damage.

The research team worked with MoDOT to obtain the five mixtures but unfortunately only four mixtures could be collected. In addition, the research team testing one of the four mixtures without a liquid anti-strip to investigate the effects of its removal on rutting and stripping results. The mixtures were subjected to HWTT, IDEAL-RT, and TSR tests. Comparison of the test results showed that the HWTT and TSR agreed on the ranking of only one out of the five mixtures. More importantly, the SIP parameter had a better correlation with the qualitative field performance measure (good versus poor performance) compared to the TSR test. One of the mixtures (M1-FC) which was characterized as a poor performer in the field was shown to have TSR value of above the minimum threshold while the SIP parameter accurately predicted that it was susceptible to moisture damage. Another mixture (M4-B3) was accurately identified as a good performer in terms of stripping potential by the HWTT SIP parameter, whereas the TSR incorrectly classified it as a stripping-prone mixture. Comparison of the RT-Index parameter with the SIP and TSR results showed that it is likely a poor predictor of moisture damage.

Based on the results obtained in this limited study, the research team proposed an alternate moisture damage evaluation framework to replace the TSR method. The framework includes three steps – first, it screens for the mixtures with rut depths lower than 4.0 mm at 20,000 passes in a HWTT. If a mix exhibits low rut depths in the HWTT, it is highly likely that it is resistant to moisture damage. Second, if the rut depth was greater than 4.0 mm then the slope ratio was computed and if it was below or equal to 2.0, then the mixture was less likely to be susceptible to moisture damage. Finally, it the slope ratio was greater than or equal to 2.0, then the SIP was determined. A minimum threshold of 15,000 passes was chosen as the SIP threshold for initial implementation of the framework.

This study was limited to only a few dense-graded mixtures. To gain further confidence in the SIP parameter and to finetune the proposed evaluation framework, more types of asphalt mixtures will need to be tested in the lab and a greater number of tests will need to be run. Additionally, comparison of the test results with field data is a crucial step for specification development and should be given prime importance in future studies. While the SIP parameter has been adopted by several agencies and has proven to be an efficient indicator of moisture damage, other parameters derived from the HWTT have also been suggested by other researchers and should be evaluated in the future.

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8. Appendix A: Literature Review

Mechanisms of Moisture Damage

There has been significant research done on moisture damage, also called stripping, and its mechanisms (Caro et al., 2008). Broadly these mechanisms can be grouped into:

a. Detachment/Debonding: This refers to the cases where the bond between asphalt and the surrounding aggregate is broken in the presence of water. As mentioned earlier, aggregates have a higher affinity for water molecules than asphalt, and thus in mixtures where the binder and aggregates are incompatible (charge-wise) to begin with, debonding can readily occur.
b. Displacement: This mechanism is characterized by water molecules penetrating the asphalt coated aggregate and displacing the asphalt binder from the aggregate surface.
c. Spontaneous Emulsification: This occurs when asphalt mixtures are exposed to standing water, which could lead to the inverted emulsion of water droplets (discontinuous phase) in an asphalt binder (continuous phase) and subsequent weakening of bond strength.
d. Hydraulic Scour: This mechanism occurs in a saturated asphalt pavement due to the movement of tires. The asphalt mixture begins to lose fine material from its mastic due to dynamic traffic action.
e. Desorption or Pore Pressure: This mechanism also manifests in saturated asphalt pavements under continuous traffic loading. The asphalt mixture experiences excessive pressure build-up in its macropores leading to internal erosion of the asphalt binder due to the presence of water flow.

Testing for Moisture Susceptibility of Asphalt Mixtures

Previously published reports and papers by other researchers have extensively covered the various tests for moisture susceptibility of asphalt mixtures (Airey & Choi, 2002; Shah et al., 2022; Solaimanian et al., 2003). In this section, a brief overview of a few important tests and analysis procedures is provided.

Tensile Strength Ratio (AASHTO T283) Test: This test method is most ubiquitously adopted in the US (Dave & Koktan, 2011). It was originally introduced by Lottman in 1982 and the procedure has undergone several modifications (Tunnicliff & Root, 1984). The current test method includes two sets of specimens, one tested dry and the other tested after being partially vacuum saturated, subjected to freezing, and soaked in warm water. Both the subsets are tested to obtain indirect tensile strength and a minimum ratio of conditioned to unconditioned tensile strength is specified. Many states allow slight deviations to the test procedure, for instance a modified Connecticut DOT method specifies a different method for computation of percent saturation (Mahoney & Stephens, 1999) and the Illinois modified method does not specify any freeze-thaw cycle (Illinois Department of Transportation, 2022).

Hamburg Wheel Tracking Test (AASHTO T324): This is the second most commonly used test to determine moisture damage according to the survey results reported in NCHRP Synthesis 595 (Shah et al., 2022). The loaded wheel tester has the ability to test for rutting and moisture damage simultaneously, as the steel wheels pass over specimens submerged under water at elevated temperature (usually, 50 ºC). Developed in the 1970s, the Hamburg Wheel Tracking Test (HWTT) has gained significant popularity in mixture testing, especially with the advent of

Balanced Mix Design (BMD) methodology. Many states, including Missouri, specify Hamburg rut depth criteria for their BMD mixtures. The test is usually run to 20,000 passes, as specified in AASHTO T324, and the rut depth versus number of passes is reported. It integrates the effects of heavy traffic loads and exposure to moisture, which necessitates computation of stripping-specific parameters such as creep slope, strip slope, Slope Ratio (SR), and Stripping Inflection Point (SIP) to assess the moisture damage of asphalt mixtures (Cooley Jr et al., 2000). However, it has been reported that a few states use maximum rut depth as an indication of moisture damage as well (Shah et al., 2022).

Moisture Induced Stress Tester: The MiST™ device simulates pore pressure buildup and hydraulic scour damage mechanisms generated in a saturated pavement under moving traffic loads (DeCarlo et al., 2020; Mallick et al., 2005). The device houses asphalt specimens in a sealed chamber filled with water and then uses hydraulic systems to apply alternate pressure and vacuum cycles simulating pumping action. According to AASHTO T283 procedure, specimens are required to attain between 70-80% saturation irrespective of specimen void structure, while the MiST conditioning allows for a better simulation of field saturation. At the end of the test, the change in specimen bulk specific gravity (Gmb) is computed and reported as 'specimen swell'. Researchers from North Carolina have reported the use of swell parameter as a possible pre-screening tool for moisture susceptibility of asphalt mixture (Tayebali et al., 2019). Researchers have also used MiST conditioned specimens to compute TSR as an indication of moisture damage, although none of the studies have yet reported a statistical difference in the obtained TSR from the two conditioning protocols (DeCarlo et al., 2020; Shah et al., 2022).

Boiling Water Test: Earlier tests for moisture susceptibility were based on visual rating of conditioned loose mixture, such as the boiling water test (ASTM D3625) or the rolling bottle test (Airey & Choi, 2002). There were obvious drawbacks: a. only individual components were assessed, b. cohesive failure mechanisms were ignored, c. poor repeatability and correlation to field performance. Although, recently, many DOTs have been investigating utilizing visual tests as a screening tool to minimize testing load on contractors.

Dynamic Modulus: Several states are also investigating the changes in dynamic modulus values upon moisture conditioning and its correlation with moisture damage or stripping of asphalt mixtures. A research study presented by Nadkarni et al. reported good correlation of the ratio of dynamic modulus (called E* Stiffness Ratio) and field performance (Nadkarni et al., 2009). Under the NCHRP 9-34 project, Solaimanian et al. combined E* and environmental conditioning system (ECS) to predict moisture susceptibility of asphalt mixtures, which showed good correlation with field performance (Solaimanian et al., 2007). The common criticism of the E* parameter is the extensive specimen preparation and time requirements of the test procedure.

Mixture Conditioning

Modified Lottman Procedure: Per AASHTO T283, the unconditioned (dry) specimens are wrapped in leak-proof plastic and placed in a water bath at 25 ºC, with a minimum of 25 mm of water above the surface of the specimen, before being tested. The conditioned (wet) specimens are subjected to a vacuum of 13-67 kPa absolute pressure (10-26 in. Hg partial pressure) for 5 to 10 minutes. The vacuum pressure is removed and the specimen is left submerged in water for a short time, after which the degree of saturation is computed. If saturation is less than 70 percent, the procedure is repeated with more vacuum pressure, but if the saturation is more than 80 percent then the specimen is discarded. The saturated specimens are then covered with a plastic film and placed in a freezer at a temperature of -18 ºC for 16 hours. Next, the specimens are kept in warm water at 60 ºC for 24 hours before finally testing them at 25 ºC with two hours of test temperature conditioning.

MiST Conditioning: Per AASHTO TP 140, the conditioning comprises of two cycles – first, the adhesion cycle in which the specimen is submerged in water for 20 hours at a specified test temperature (based on binder grade). Second, the cohesion cycle in which the specimen is subjected to a peak hydraulic pressure of 275 kPa (40 psi) at a specified test temperature at a rate of 3.5 seconds per pressure cycle (AASHTO TP 140, 2020).

Multiple Freeze-Thaw Cycles: Several reports and papers have been published on conditioning asphalt mixtures with multiple freeze-thaw cycles to better represent field conditions, especially in northern states (Akentuna et al., 2023; Dave et al., 2018; Jackson & Puccinelli, 2006). However, there is no standardized procedure yet for such conditioning. Moreover, many states such as Illinois, South Dakota, and Alabama currently do not follow the single freeze-thaw cycle specified in the AASHTO T283. Including multiple freeze-thaw cycles would add considerable time to the T283 procedure (Shah et al., 2022).

Other DOT's Experience with AASHTO T283

Other paving agencies have also evaluated alternative tests to replace TSR due to its cumbersome procedure and poor correlation with field performance. Several examples are provided below:

Wisconsin DOT reportedly tested 21 mixtures from existing pavement sections and found poor correlation of the pavement distresses (including moisture damage) with TSR results. Authors Kanitpong and Bahia noted that the TSR test did not provide good simulation of all the factors that cause moisture damage in the field (Kanitpong & Bahia, 2008). The authors noted that using the Pneumatic Adhesion Tensile Testing Instrument (PATTI) might be a better alternative to the TSR test, but the extensive sample preparation made it difficult for widespread adoption (Bahia et al., 2007). The authors also investigated the use of a non-mechanical stripping test called the Quebec Stripping Test in which the weight of loose mixture was compared before and after conditioning in water (similar to the boiling water test) and recommended against its adoption due to its poor repeatability (Bahia et al., 2007). Finally, in 2016, the authors recommended the use of the Stripping Inflection Point (SIP) from the Hamburg Wheel Tracking Test (HWTT) as a measure of moisture damage for the asphalt mixtures (Bahia et al., 2016).

North Carolina DOT (NCDOT) has also evaluated the possibility of modifications to or replacement of the TSR test (Tayebali et al., 2017, 2019). The researchers investigated the use of the boil test with a colorimeter (color measuring device), the impact resonance test, and of MiST conditioning of asphalt specimens (Tayebali et al., 2019). Based on the results from testing on six different mixtures with three different aggregate sources, the researchers concluded that the use of percentage stripping parameter obtained from the Boiling Test with colorimeter and percentage volume change from MiST conditioning could be used in lieu of TSR testing.

Previous research had found change in density post MiST conditioning was a good indicator of cohesive damage to an asphalt mixture (LaCroix et al., 2016).

New-England Transportation Consortium (NETC) researchers set out to propose an alternate test to the TSR test (AASHTO T283) as it was cumbersome to perform and did not give the desired results (Dave et al., 2018). The authors conducted a gamut of testing, which included the Indirect Tension Strength (ITS) test, Disk-shaped Compact Tension (DC(T)) test, Semi-Circular Bend test (SCB), Ultrasonic Pulse Velocity (UPV) test, Dynamic Modulus test, and Hamburg Wheel Tracking Test (HWTT). The authors tested ten asphalt mixtures obtained from different north-eastern states (Maine, Vermont, Connecticut, New Hampshire) and compared the laboratory test results with field performance. In addition, the authors also used various conditioning schemes such as the modified Lottman and the MiST conditioning schemes. The authors concluded that the tensile strength tests, irrespective of the specimen conditioning, were unable to distinguish the poor from the good performers. Similarly, the fracture-based tests (DC(T) and SCB) did not show significant distinction between the mixtures. The UPV test did show small but consistent differences between the good and poor performers. The Dynamic Modulus was able to distinguish between the good and poor mixture but could not significantly distinguish the effects of anti-strip treatments on the mixtures. The authors reported that the HWTT was not only able to properly distinguish the good and poor field performers but was also able to adequately distinguish the effects of anti-strip treatments. The authors had used the traditional HWTT analysis (AASHTO T324) and the modified HWTT analysis adopted from Texas Transportation Institute (TTI) (Yin et al., 2014).

Iowa State researchers evaluated and ranked various moisture susceptibility tests as alternative to the TSR test, which the authors reported as a logistically difficult test to undertake (Schram & Williams, 2012). The authors evaluated and ranked eighteen parameters obtained from various tests such as HWTT, Dynamic Modulus, TSR (AASHTO T283), Flow Number, and MiST. The results were compared with the distress surveys obtained for five pavement sections. The authors concluded that, considering the procedure time and simplicity, the MiST Swell parameter (change in air voids post MiST conditioning) and HWTT parameters (such as SIP, Slope Ratio), should be evaluated as viable alternatives to the TSR test (AASHTO T283).