EVALUATION OF THE HAMBURG RUT TESTER AND MOISTURE INDUCED STRESS TESTER (MIST) FOR FIELD CONTROL OF HOT MIX ASPHALT (HMA) IN OKLAHOMA

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This report covers the evaluation of the Hamburg Loaded Wheel Rut Tester (OHD L-55) and the Moisture Induced Stress Tester (MIST) for field control of Oklahoma HMA mixtures. OHD L-55 was evaluated as a possible replacement for AASHTO T 283 and for suitability for field control of HMA mixtures. The MIST was evaluated for possible replacement of AASHTO T 283.

OHD L-55 was not able to successfully identify mixtures that had failed AASHTO T 283 and is not recommended for replacement of AASHTO T 283 at this time. OHD L-55 does appear suitable for field control of HMA mixtures for rutting. The MIST gave similar but slightly more severe results than AASHTO T 283 and was recommended for further evaluation as a replacement for AASHTO T 283.</td></tr>
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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 yard	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				
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 degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}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	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	35.314	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 degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
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

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1
PROPOSAL

INTRODUCTION

The Hamburg Rut Tester (OHD L-55) and AASHTO T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage*, are currently used in mix design by the Oklahoma Department of Transportation (ODOT) and many other DOTs to evaluate rutting and moisture damage potential of hot mix asphalt (HMA) mixtures (1). AASHTO T 283 is also used for field control of HMA mixtures. Variability of AASHTO T 283 test results has always been an issue and currently ODOT does not check rutting potential of field produced mixtures. In an effort to get away from the variability issues and time requirements of performing AASHTO T 283, many DOTs, most notably TXDOT (2), have begun using the Hamburg Rut Tester to monitor plant produced mixtures for rutting potential and moisture susceptibility. Use of the Hamburg rut tester needs to be evaluated for field control of HMA mixtures in Oklahoma. However, one of the real issues is the need for a better, more realistic test to evaluate moisture susceptibility of HMA mixtures.

BACKGROUND

There is a wealth of information available in the literature on tests for moisture susceptibility and rutting. Numerous test methods have been developed in the past to predict moisture susceptibility of HMA mixes. However, no test thus far has received wide acceptance. This is generally thought to be due to their low reliability and lack of satisfactory relationship between laboratory and field conditions. Test methods used in the past include boiling water tests (ASTM D3625 or variations), static immersion tests (AASHTO T 182), Lottman test (NCHRP 246), modified Lottman test (AASHTO T 283), Tunnicliff-Root (ASTM D4867) and immersion-compression tests (ASTM D1075). As a part of the Strategic Highway Research Program (SHRP) a net adsorption test and the Environmental Conditioning System Test were developed (3). Neither procedure gained acceptance but the net adsorption test has received further study in recent years including work performed at Texas A & M (4), OU (5) and OSU (6). Surface energy methods show promise (7) but the equipment is too costly and the time required too long for routine acceptance methods without further modification.

At about the same time as SHRP interest grew in proof testing HMA mixtures and the Hamburg rut tester and the Asphalt Pavement Analyzer (APA) were introduced (1). The Hamburg originally tested pavement slabs under water at an elevated temperature and was considered a torture test. It has been modified to accept laboratory compacted pills. The APA tests beams or pills at elevated temperatures and can operate either wet or dry. Many agencies, including ODOT, originally adopted the APA which was more readily available but the Hamburg has been steadily gaining acceptance since it became commercially available.

The APA has been used to evaluate both rutting and stripping; however, the use of the APA to detect moisture susceptible mixtures has never gained wide acceptance (8,9). Aschenbrener (10) evaluated several test procedures to predict moisture susceptible mixtures and found none completely acceptable. Aschenbrener recommended modifications to the Hamburg procedure and since that time several agencies have made changes/modifications to the procedure and some have adopted the Hamburg for control of rutting and moisture damage of HMA mixtures (2,10). The Hamburg is now routinely used for evaluation of HMA mixtures (11,12). However, as shown by Aschenbrener (10), slight modifications to test procedures are often necessary before an empirical test procedure can be adopted for use with local materials and environmental conditions.

There is still interest in the mechanisms that cause rutting and a national seminar (13) was held on this topic in 2003. Even though AASHTO T 283 and its modifications are still used, and the Hamburg Rut Tester is gaining acceptance, there was a need voiced at the seminar for a procedure that more closely simulates the stripping mechanisms caused by the cyclic loading and unloading of tire pressure on an asphalt pavement to evaluate the susceptibility of HMA mix designs to moisture damage (13).

Through an Oklahoma Transportation Center project, OSU purchased a Moisture Induced Stress Tester (MIST). The MIST is a new sample conditioning device designed to simulate the stripping mechanisms caused by the cyclic loading and unloading of tire pressure on an asphalt pavement. The MIST replaces the moisture conditioning sequences of AASHTO T 283 with a more realistic sample conditioning and reduces the testing time required to evaluate moisture susceptibility of HMA mixes.

The MIST conditions AASHTO T 283 sized samples (150 mm dia., 95 mm tall, 7±1.0% voids) that can be further tested for conditioned tensile strength and compared to unconditioned samples for tensile strength ratio as in AASHTO T 283. There is a need for independent verification of the ability of the MIST to replace AASHTO T 283 as an indicator test for moisture damage potential.

OBJECTIVES

The first objective of this study is to gather sufficient AASHTO T 283 and Hamburg Rut Test data from laboratory prepared (mix design) samples and plant produced mix from across Oklahoma to determine if the Hamburg Rut Tester can be implemented to monitor plant produced mixtures for rutting and/or moisture susceptibility and to develop draft implementation plans (draft test methods and/or specifications) if test results warrant implementation. The second objective of this study is to test the same plant and laboratory test samples in the MIST to determine the ability of the MIST to identify moisture susceptible mixtures.

Tasks

The objectives of the proposed study would be accomplished by completing the following tasks.

Task 1 Literature Review

There is a wealth of literature on rut testing and moisture damage. The amount of literature is an indication that solutions to these problems have not been completely solved. Moisture damage or stripping is generally thought to be an aggregate and binder compatibility problem and is, therefore, local in nature. The literature review for this study would concentrate on literature from surrounding states to determine how they have implemented the Hamburg Rut Tester, if at all, and whether and how it is used to replace or supplement moisture damage testing (AASHTO T 283 or equivalent).

The MIST is a new device and little other than manufacturer’s literature is available, indicating the need for this study.

Task 2 Obtain ODOT Data for Evaluation

Each ODOT approved mix design requires AASHTO T 283 testing and contractors, on a limited basis, are sending Hamburg Rut Test (OHD L-55) samples to the ODOT Central Lab for testing. AASHTO T 283 test results and corresponding OHD L-55 data will be obtained from ODOT by the Principal Investigator (PI) for statistical analysis to determine if there is any relationship between AASHTO T 283 results and OHD L-55 results.

Task 3 Obtain Plant Produced and Laboratory Prepared Samples

Two types of mixes will be sampled for the study, mixes that require anti-strip to pass AASHTO T 283 and mixes that do not. The intent is to sample mixes that require an anti-strip agent to pass AASHTO T 283, mixes that pass AASHTO T 283 without anti-strip but with a low TSR, and mixes that easily pass AASHTO T 283 without anti-strip.

These mixes will be identified and belt feed samples of the blended aggregates will be obtained along with samples of the asphalt cement and anti-strip agent for producing laboratory compacted samples. Plant produced mix will also be sampled at the same time. For mixtures that are using anti-strip, samples of asphalt cement without the anti-strip will be obtained from either the plant or the supplier. Contractor personnel and a commercial testing laboratory will assist OSU with obtaining samples for testing.

Task 4 Evaluation of Laboratory Produced Samples

Mix designs information will be collected and belt feed aggregate samples will be used to make laboratory compacted samples for OHD L-55, AASHTO T 283 and MIST testing. Mixes that require an anti-strip will be tested with and without the anti-strip. A select number of mixes that do not require anti-strip will be tested using OHD L-55 with 0.5% more asphalt than produced. Samples for MIST testing will be conditioned using the MIST in accordance with the manufacturer’s recommendations. MIST sample conditioning involves cyclic loading to 40 psi of a sample submerged in 50^{o}C water. The samples are then tested for conditioned tensile strength and tensile strength ratio determined by using the control or unconditioned samples from AASHTO T 283. Contractor personnel and a commercial testing laboratory will assist OSU with fabricating and testing laboratory mixed samples.

Task 5 Evaluation of Plant Produced Samples

The same mixes sampled for laboratory testing will be sampled and tested for evaluation of plant produced mixes. Plant produced mix will be tested for MIST, AASHTO T 283 and OHD L-55 testing as described in Task 4. However, it will not be possible to test plant produced samples without anti-strip or with extra asphalt cement.

Task 6 Analysis of Data

Data obtained from tasks 4 and 5 will be analyzed using statistical techniques to determine the relationships between laboratory fabricated AASHTO T 283 test results, OHD L-55 test results and MIST results. Results from plant produced samples will be compared using the same techniques and the differences between field test results and laboratory fabricated test results will be evaluated. The objectives are to compare Hamburg results with AASHTO T 283 results to determine if the Hamburg can replace AASHTO T 283, to determine if the Hamburg is better suited to monitor plant produced mixtures for rutting and moisture susceptibility and to determine if the MIST can replace AASHTO T 283. Draft implementation plans (draft test methods /specifications) will be developed if test results warrant implementation.

Task 7 Progress Reports and Final Report

Progress reports will be submitted quarterly. A final report containing the findings and conclusions from the above tasks will be prepared. The report will contain the results from the analysis as well as a draft test method in AASHTO format, if applicable.

Benefits

At the conclusion of the study the PI will provide an assessment of the test results of the study. The assessment will include a summary of the expected benefits and actions needed for successful implementation of the Hamburg (OHD L-55) and or MIST for field control of rutting and moisture damage of HMA mixes, if indicated by the findings. A draft specification, if applicable, with final recommended implementation activities, methods or schedules to meet ODOT goals, will be included.

The results of this research could lead to the implementation of the Hamburg Rut Tester and or the MIST as a viable test method for evaluating the field performance of HMA mixtures against rutting and moisture induced damage. Based on the number of tons of HMA placed annually, even slight increases in mixture performance can result in significant cost savings to the DOT and traveling public.

CHAPTER 2
LITERATURE REVIEW

MOISTURE DAMAGE

Moisture damage is defined as a reduction in strength of an HMA mixture due to weakening of the bond between the aggregate and the asphalt binder or a reduction in stiffness of the whole mixture (14).

Moisture sensitivity of HMA mixtures is a nationwide problem. According to a 2002 study (15) involving state highway agencies, FHWA Federal Lands Highways and Canadian provinces, it was shown that out of 55 agencies that participated in the study 45 of them reported a moisture damage problem in their HMA pavements. As a result these agencies use some kind of treatment to alleviate this problem. While most agencies use liquid anti-strip agents some use lime as an anti-stripping agent. Agencies are continuously funding research to understand the cause of the problem, improve test methods used and to look for new and more advanced test methods.

Moisture damage is a major cause of distress in HMA pavements and it tends to accelerate existing distresses. According to Hicks et al. (14), moisture susceptibility problems are caused by two types of failures, adhesive and cohesive failures. Adhesive failure is a failure of the bond strength between the aggregate and the asphalt binder whereas cohesive failure is an overall failure of the mixture due to a loss in strength or stiffness. These failures are caused by mechanisms associated with the aggregate, asphalt binder and the interaction between the two. Failure could also be associated with mix design, construction method or climate. The failure could be a localized failure, which is caused by either adhesive or cohesive failure, or it could be a structural strength reduction failure, which is caused by cohesive failure.

According to a theory proposed by Schapery (4), when a load is applied to a material the energy created is balanced by the energy on the faces of the newly created surfaces. This theory of surface energy can be applied to predict adhesion between asphalt and aggregate and cohesion within the asphalt itself as long as the surface energy components are known. When fracture occurs in a material that is considered to be brittle and made up of two different component materials, the materials separate and form their own surface energy. The expended energy during this fracture is equal to the sum of the individual surface energies of the two materials minus the interfacial energy between the two materials. The adhesive energy between asphalt and aggregate in the presence of water can be predicted using the Dupré equation.

$$\Delta G_{ikj} = \gamma_{ij} - \gamma_{ik} - \gamma_{jk} \qquad [1]$$

Where ΔG_{ikj} is Gibbs free energy of adhesion and γ is surface energy. The subscripts designated as i, j, and k represent asphalt, aggregate and water, respectively. When water is present the interaction between asphalt, aggregate and water is known as hydrophobic interaction. During this hydrophilic interaction the adhesive bond strength between asphalt and aggregate becomes repulsive giving a chance for water to strip the asphalt off of the aggregate surface (4).

FACTORS AFFECTING MOISTURE SUSCEPTIBILITY OF HMA

Different factors influence moisture susceptibility; however, it is difficult to know which factor has more influence. In general the factor that increases the moisture content and decreases the adhesion between the asphalt binder and the aggregate has more influence, but it is not easy to distinguish. The following factors listed below affect moisture susceptibility of HMA mixtures (16).

- Asphalt binder characteristics: The viscosity of the asphalt binder affects the susceptibility of the mixture to stripping. The more viscous the asphalt binder the higher the concentration of large polar molecules (asphaltenes); as a result, there will be greater adhesion tension and molecular orientation adhesion, which lowers the mixtures susceptibility to stripping.
- Aggregate characteristics: Aggregates could be hydrophilic (attract water) or hydrophobic (repel water). As a result hydrophilic aggregates are more prone to stripping than hydrophobic ones. The properties that determine the hydrophilic or hydrophobic characteristic of the aggregate are surface chemistry, porosity and pore size.

- Surface chemistry: The more an aggregate bonds with the asphalt binder the less susceptible it will be to stripping. Acidic surfaces do not bond well with asphalt binders making the mixture more prone to stripping.
- Porosity and pore size: Aggregates with high porosity require more asphalt binder. If the amount of binder added is less than the required amount more will be absorbed and there will not be enough binder left to coat the aggregate surface, which leads to stripping and early mixture aging.

Construction weather, climate and traffic are also factors that contribute to stripping. Cool and wet weather could make an HMA pavement more susceptible to stripping. When the weather is cool it could lead to inadequate compaction, which will create excess voids in the pavement making it more vulnerable to stripping. When the weather is wet it increases the moisture content of the mixture. Freeze and thaw cycles and temperature fluctuations also increase the amount of moisture entering an HMA pavement. Increased traffic loading in the presence of water can also increase moisture damage of pavements in two ways. One is pressure build up, which occurs when pores that are filled with water are compressed due to traffic loading and as a result water pressure develops within the pores driving the asphalt away from the aggregate. The other is movement of water in the HMA pavement due to wheel passes, which could remove the asphalt binder from the aggregate with a scouring action (16).

TYPES OF MOISTURE RELATED DISTRESS

Types of distresses related to moisture include bleeding, rutting, raveling and cracking. Raveling is a distress caused by an accelerating loss of surface material from the HMA pavement due to poor compaction, low-grade aggregates, low asphalt content, amount of fine aggregate in the mix, or due to moisture associated damage. Whereas, rutting bleeding and cracking are caused by a complete loss of adhesion between the aggregate and the asphalt binder. This loss of adhesion is caused by the presence of water in the mixture due to poor compaction, wet aggregates, poor drainage and poor aggregate binder interaction. Raveling is provoked by traffic and weathering. Rutting, bleeding and cracking are aggravated by traffic and freeze and thaw cycles (14). Figures 1- 4 below show some examples of moisture related distresses.

Figure 1 Raveling (17).

Figure 2 Cracking (16).

Figure 3 Bleeding (18).

Figure 4 Rutting (18).

TESTS FOR MOISTURE SUCEPTIBILITY

Different causes of moisture damage have been discussed above. The problem that engineers usually face is identifying if these distresses are caused by actual moisture damage or poor construction practices. Distresses caused by poor construction practices are generally due to poor compaction, which leads to high voids and increased permeability, poor mix gradation, and too much or too little asphalt added at the mix design stage. It is ideal to identify distresses caused by moisture damage at the mix design stage by performing testes on both loose mixes and compacted mixes. Tests performed on loose mixes help identify distresses associated with the bond between the aggregate and the asphalt binder. It determines the amount of coating of the aggregate by the asphalt binder when immersed under water. Compacted mixes are used to determine the overall strength or stiffness of the mix and also to determine the amount of rutting caused by moisture damage (14).

There seems to be some problems with the test methods being used today. According to a study by Colorado DOT and the Asphalt Institute (10), moisture related distress was observed in an asphalt pavement located in Colorado. What was surprising about this failure was that tests performed on the pavement before and during construction didn't show any signs of moisture sensitivity. Aschenbrener, et al. (10) showed that none of the moisture sensitivity tests that were performed in the study were able to relate very well to field conditions. After some adjustments were made to the test methods, some were able to correlate better to field conditions than others.

As can be seen from the above studies, tests that are being used today have limitations. A summary of these limitations are listed below (14).

- The results found from the tests are not very repeatable.
- The lab results don't represent what is actually happening in the field (not performance related).
- The effect of traffic and climate is not properly indicated.

These limitations are reasons that researchers are trying to come up with better tests to determine moisture damage of HMA mixtures. A brief description of the test methods that are being used today is given below.

Boiling Test (ASTM D3625)

The boiling test is performed by adding loose HMA mixture to boiling water for ten minutes. The results are obtained by determining the percentage of aggregate that still maintains its original coating after boiling. Less than 95% coating has been used by some agencies to indicate a stripping problem. This test can be used for initial screening as it only requires a minimum amount of equipment. It can also be used to test additive effectiveness and possibly for quality control. This method can be performed on laboratory mixes and plant produced mixes, but it can only be performed on uncompacted mix. The purity of the boiling water affects coating retention. This test is highly dependent on viscosity of the asphalt cement and prefers liquid anti-stripping agents over lime. This test is subjective and has not correlated well with field experience. It also does not include any strength analysis (19).

Lottman Test (NCHRP 246)

The Lottman test is a quantitative strength test. It was developed under the National Corporative Highway Research Program (NCHRP 246) by Lottman. This test requires nine specimens divided into three groups each containing three specimens. Each 4 inch diameter x 2.5 inch height specimen is compacted to an air void content of 3 to 5%.

- Sample conditioning: The samples are divided into three groups containing three samples. The first group is not subjected to any conditioning; it is the control group. The second group is vacuum saturated with water at a pressure of 26 inches of Hg for 30 minutes. The third group is also vacuum saturated like the second group, but after that it is subjected to a freeze and thaw cycle with temperatures of 0^{o}F for 15 hours and 140^{o}F for 24 hours, respectively (19).
- TSR measurement: The conditioned groups are tested to reflect a certain time of field performance. For group two it is up to 4 years and for group three it is from 4 to 12 years. All the specimens including both the control and the conditioned samples are tested for resilient modulus (Mr) and/or indirect tensile strength at temperatures of 55^{o}F or 73^{o}F. For the indirect tensile strength test the loading rate is 0.065 inches/min. TSR is the ratio of the indirect tensile strength of the conditioned specimen to the control specimen. Lottman recommends a minimum

TSR of 0.70 and anything below that could indicate stripping of HMA mixtures (19).

The Lottman test is applied on different mixes including lab, field and core samples. It is a severe test and correlates reasonably well with field performance. This test can differentiate between levels of additives and unlike the boiling test, it gives reasonable results for both lime and liquid anti-strip additives. The disadvantage of this test is that it is time consuming (19).

Modified Lottman Test (AASHTO T 283)

AASHTO T 283 is being used widely in many agencies today. It was first developed by Kandhal and was adapted by AASHTO in 1985. It is a combination of the best features of Lottman test and the Tunnicliff and Root test (19). Even if some improvements have been made, this test is still time consuming and the results are not completely reliable.

AASHTO T 283 requires six specimens divided into two equal groups. Samples are compacted to a height of 95 mm in a 150 mm diameter mold to an air void content of 7 ± 1%. The samples are divided into two groups of three samples with equal voids for conditioning. The first group is not subjected to any conditioning; it is the control group. The second group is vacuum saturated with water at a pressure of 10 - 26 inches of Hg for 5-10 minutes to 70-80 percent saturation. After vacuum saturation, the samples are subjected to a minimum 16 hour freeze cycle at a temperature of 0^{o}F. The conditioned samples are then placed in a water bath at 140^{o}F for 24 hours. After the 24 hour soak the control samples are placed in water proof bags and placed with the conditioned samples in a 77^{o}F water bath for 2 hours and tested for indirect tensile strength. The indirect tensile strength test loading rate is 2.00 inches/min. TSR is the ratio of the indirect tensile strength of the conditioned specimen to the control specimen. A minimum TSR of 0.80 is usually recommended (20).

In this test samples are vacuum saturated to reach a saturation of 70-80%; however, it has been shown that distribution of pore spaces between samples with different geometries such as the gyratory and Marshall compacted samples may be different, which means even if the expected saturation is 70-80%, the actual percent of saturation for each specimen might be different (21). According to Aschenbrener et al. (10), AASHTO T 283 seems to show more reliable results on pavements that perform well and on ones that are highly susceptible to moisture damage. However, when it comes to pavements that are slightly susceptible to moisture damage it doesn't give reliable results.

The major problem with this test is poor repeatability and occasionally invalid results. Azari (22) reported the TSR single operator standard deviation to be 0.033 with an acceptable range of two results of 0.093. The multilaboratory standard deviation was reported as 0.087 with an acceptable range of two results of 0.247.

A finite element analysis on the specimen was done by Azari (21) that showed during moisture saturation of the samples water infiltration is asymmetric. This means the moisture damage throughout the sample is asymmetric and it suggests this might be one of the causes for the non-repeatability of this test. The other problem most agencies mention is the way the load is applied to the specimen. In AASHTO T 283 the load is applied as a constant load; however, what researchers such as Kandhal and Rickards (23) are suggesting is that pumping action of a traffic load is much better replicated by a cyclic load than a constant load.

Tunnicliff-Root Test (ASTM D4867)

ASTM D4867 is similar to AASHTO T 283 and many agencies actually use versions of ASTM D4867 or AASHTO T 283. ASTM D4867 requires six specimens divided into two equal groups. Samples are compacted to a height of 2.5 inches in a 4-inch diameter mold to an air void content of 7 ± 1% but other size samples are allowed. The samples are divided into two groups of three samples with equal voids for conditioning. The first group is not subjected to any conditioning; it is the control group. The second group is vacuum saturated with water at a pressure of 20 inches of Hg for a short time (5 minutes) to 55-80 percent saturation. After vacuum saturation, the samples can be subjected to an optional freeze cycle at a temperature of 0^oF for a minimum 15 hours. The conditioned samples are then placed in a water bath at 140^oF for 24 hours. After the 24 hour soak the conditioned samples in a 77^oF water bath for 1 hour and tested for indirect tensile strength. The control samples are placed in water proof bags and placed a 77^oF water bath for 20 minutes and tested for indirect tensile strength. The indirect tensile strength test loading rate is 2.00 inches/min. TSR is the ratio of the indirect tensile strength of the conditioned specimen to the control specimen. A minimum TSR of 0.80 is usually recommended (24).

Immersion-Compression Test (ASTM D1075)

The Immersion-Compression test has been used to measure moisture susceptibility of HMA mixes, but it is not very popular among agencies. The AASHTO equivalent method has been recently discontinued. This could be attributed to its lack of satisfactory precision. One of the advantages of this test is that it uses actual mix; however, it is very time consuming and equipment is not readily available (19).

For this test six specimens are required. All specimens are compacted to a 6% air void content using double plunger compaction with a pressure of 3,000 psi for 2 minutes. Each specimen has a diameter of 4 inches and a height of 4 inches. The specimens are divided in to two groups each containing three specimens. The first group is the control group and samples are held at 77^oF for 4 hours prior to testing. There are two procedures for conditioning samples. One method consists of conditioning samples under water at 120^oF for 4 days. The other method consists of soaking in a 140^oF water bath for 24 hours and then transferring them to a 77^oF water bath for 2 hours prior to testing. All six specimens are tested for unconfined compressive strength at 77^oF at a loading rate of 0.20 inches/minute (25).

From this test the retained compressive strength of the specimen is measured. A retained strength of 70% is commonly specified, but retained strengths up to 100% have been produced by this test (19).

Loaded Wheel Testers

Loaded wheel testers are mainly used to measure the rutting susceptibility of HMA mixes. Rutting is defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads. The moisture sensitivity of HMA can also be determined through load wheel testers if they measure rutting in the presence of water.

There are different types of loaded wheel testers in the United State, among them are the Georgia Loaded Wheel Tester, Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), LCP (French) Wheel Tracker, Purdue University Laboratory Wheel Tracking Device (PURWheel), and one-third scale Model Mobile Load Simulator. Some of these loaded wheel testers claim to be able to measure moisture sensitivity was well as rutting susceptibility.

The HWTD and the APA are the two most popular devices used to assess rutting potential and occasionally moisture susceptibility of HMA mixtures. The HWTD test is performed in the presence of water at a specified temperature while the APA can be tested at a specified temperature either dry or submerged in water.

Asphalt Pavement Analyzer (APA)

The APA is a modification of the Georgia Loaded Wheel Tester, which was developed in cooperation with the Georgia Department of Transportation by the Georgia Institute of Technology. The APA was developed by Pavement Technology Inc. in the mid 1990's. Most of the load wheel testers are used to measure rutting only. The APA can be used to measure both rutting and the moisture sensitivity of HMA. The test method has been standardized by AASHTO as AASHTO T 340.

HMA specimens are tested in the APA at the high temperature grade of the PG binder. The APA has the capability of testing samples at a maximum contact pressure of 200 psi with a temperature range between 4 and 72^{o}C. However, most agencies specify loading using a 100 pound loaded wheel travelling over a 100 psi hose for 8,000 passes. The APA can test three beam specimens or six pills at one time. Rut depth with passes is recorded with an automated data acquisition system. The procedure takes approximately 2.25 hours to complete a test. Moisture sensitivity of HMA mixtures is determined by performing the test with specimens submerged in a heated water bath inside the APA (26).

Hamburg Wheel Tester (OHD L-55)

The Hamburg wheel-tracking device is used to perform the Hamburg loaded wheel test or Hamburg test. The HWTD was developed in 1970's by Esso A.G. of Hamburg, Germany. The Hamburg test is a pass fail test and is considered by many to be a very severe test. The HWTD measures the rutting resistance of HMA and because samples are tested submerged in water, many claim it can measure the moisture susceptibility of

HMA as well. The test has been standardized by many agencies, including ODOT, (OHD L-55), and by AASHTO as AASHTO T 324. For OHD L-55, samples are compacted to 60 ± 2 mm to 7.0 ± 1% VTM. Specimens are cut to fit the test molds, which hold two specimens. Four specimens can be tested at the same time. Specimens are tested by submerging the samples in a 50^{o}C water bath and loaded with a 158 ± 5 pound steel wheel. Samples are tested for up to 20,000 passes. Rut depths are measured automatically and continuously with linear variable displacement transducers (LVDT) for both the left and right samples. The test takes approximately seven hours to complete.

AASHTO T 324 (27) indicates that the HWTD can give an indication of a specimen's vulnerability to moisture induced damage through determination of a stripping inflection point. The stripping inflection point is defined as a large increase in the rate of deformation in the plot of rut depth versus wheel passes. However, a mixture undergoing tertiary flow rutting would exhibit the same change in slope. Also, a change in water color during the test has been reported as an indication of a moisture susceptible mixture.

Most specifications using the HWTD use a simple pass/ fail criteria to evaluate a mixtures resistance to rutting. A maximum rut depth of 12.5 mm is almost always used with the number of passes usually based on the high temperature PG grade of the binder. Table 1 shows ODOT and TXDOTs Hamburg rut depth requirements.

Table 1 Typical Hamburg Specification Requirements

PG Grade	64-XX	70-XX	76-XX
Passes	10,000	15,000	20,000

Many agencies have accept the HWTD test procedure for determine of rutting and a few, including TXDOT and Colorado DOT, use the HWTD for evaluation of stripping. TXDOT has replaced their previous moisture damage test with the Hamburg.

TXDOT has implemented the HWTD on all the HMA pavement projects. The Hamburg test was first considered in Texas in 2000. In 2002, TxDOT developed a specification limit of a maximum of 12.5 mm rutting for different binder grades with their respective number of passes. The specification was shown in table 1. In 2006 TXDOT considered easing the specification by lowering the number of passes from 10,000 to 5,000 due to the severity of the test (28). It does not appear that this was implemented but is an indication of the severity of typical specifications using the HWTD and the opinion of many that this is a true torture test.

The main disadvantages of the Hamburg test are its reported poor repeatability and lack of correlation between HWTD rut depth and field performance. This is mainly attributed to the fact that the test measures two distresses at a time and that the applied load can crush the aggregates (29).

Moisture Induced Stress Tester (MIST)

The Moisture Induced Stress Tester (MIST) is a new method for testing moisture damage of HMA pavements. As such, research results available for this method are limited. The MIST is manufactured by InstroTek and determines the moisture susceptibility of HMA mixtures, caused by water, repeated loading, and hot in place temperatures. Unlike AASHTO T 283, this test applies cyclic loading to simulate traffic loading, which is caused by the highly pressurized water load applied by the tire to the wet pavement and then removed when the tire is no longer in contact with the pavement. The MIST is designed to make moisture sensitivity testing less time consuming and to produce more reliable and repeatable results. This test takes a very short time compared to other existing test methods, which take 24 hours or more to complete. The duration for this test is approximately four hours and is completely automated (30).

The MIST consists of four major components. The first component is a sample tank where the samples are placed for testing. This tank can hold two samples at a time. The samples tested in this unit are 6 inch (150 mm) X 4 inch (100mm) in size. The second component is the control electronics module. This component of the unit controls the settings of the test. For the test setting the pressure cycles ranges from 1 to 50,000 cycles with the default being 3000 cycles, the temperature range is from 30^{o}C to 60^{o}C, and the default is 50^{o}C. The maximum pressure that can be applied is 75 psi, with the default setting being 40 psi. The unit also consists of a hydraulic pump system. This system is capable of producing up to 300 psi of pressure. The final component is the pressure transfer system. It consists of a hydraulic cylinder coupled with a pneumatic cylinder. Then the output of the pneumatic cylinder is joined with a bladder inside the tank which creates the pressure transfer system (30).

Figure 5 Moisture Induced Stress Tester (MIST)

After samples are conditioned in the MIST the test results are obtained by measuring the height and diameter of the samples, the bulk specific gravity after conditioning and the indirect tensile strenght. From these measurements the results are calculated and the TSR and volume change is reported. Figure 6 shows samples after conditioning, the sample on the left has no moisture damage and the sample on the right has moisture damage (stripping).

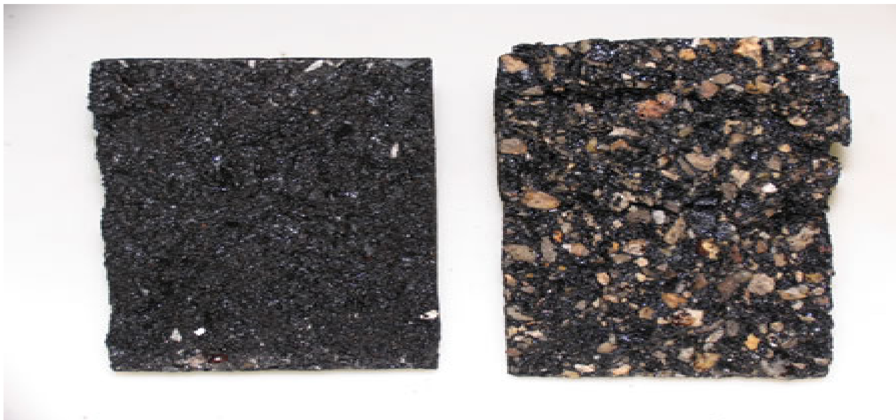

Figure 6 MIST samples with and without moisture damage (stripping) (17).

CHAPTER 3
TEST PLAN AND RESULTS

OBJECTIVE

The objectives of this study is to gather sufficient Hamburg Rut Test, AASHTO T 283 and MIST data from laboratory prepared (mix design) samples and plant produced mix from across Oklahoma to determine if the Hamburg Rut Tester or the MIST can replace AASHTO T 283 as a test for moisture sensitivity and can be implemented to monitor plant produced mixtures.

TEST PLAN

Materials

The mixes used for this study were provided by contractors as cold feed belt samples and as plant produced mixes. The asphalt cement used with each mix was sampled from the respective projects. The anti-strip agent for each project used for the study was obtained from the contractor if readily available or the supplier. The ODOT mix design number, producer, mix designation and asphalt cement grade, design traffic and mix ID code used in this study are listed in Table 2 below. The source and percentage of aggregates used for each mix are listed in Table 3.

Table 2 Mixes Used for the Study

ODOT Design Number	Producer	Mix Type	Design Traffic	Mix ID Code
S4qc0100908201	Cummins Const.	S4 (PG 70-28)	3M+	STW
S4qc0061003500	APAC Central	S4 (PG 76-28)	3M+	Tulsa
S4pv0110900202	Dobson Brothers	S4 (PG 64-22)	3M+	Altus
S4qc0351100100	J&R Sand	S4 (PG 64-22)	0.3M+	J&R
WS4qc0020502200	APAC Central (Arkhola)	S4 (PG 64-22)	0.3M+	Roberts
S4pv0160792200	Silver Star	S4 (PG 64-22)	0.3M+	SS
KDOT SR-12.5A	Venture	SR-12.5A (PG 58-28)	2.3M	KS
S3qc0411100200	Venture	S3 (PG 64-22)	3M+	Alva
WS5qc0131103500	Haskell Lemon	S5 (PG 64-22)	0.3M+	HL-S5

Table 3 Aggregate Sources of the Mixes

MIX ID Code	Aggregates	Supplier	Pit	% Used
STW	1/2" Chips	Hanson	5008	25
	5/8" Chips	Falcon	6707	27
	Blend Sand	TXI Mill Creek	3504	28
	Screenings	Falcon	6707	12
	Sand	Enrem	6304	8
Tulsa	3/4" Chips	APAC	7204	15
	Mine Chat	Mine Chat	Mine Chat	28
	Man. Sand	APAC	7204	25
	Drag Sand	Mine Chat	Mine Chat	5
	Screenings	APAC	7204	10
	Sand	Holiday S & G	7212	15
	B. H. Fines	APAC	7204	2
Altus	5/8" Chips	Martin	3802	33
	Screenings	Dolese	3801	31
	C-33 Screenings	Martin	3802	21
	Sand	Bruce Daniels	Unlisted	15
J&R	3/4" Chips	Dolese	3801	20
	5/8 Chips	Martin	3802	9
	Screenings	Martin	3802	28
	Screenings	Dolese	3801	28
	Sand	J & R Sand	0402	15
Roberts	# 67 Rock	Arkhola	7302	23
	3/8" Chips	Arkhola	1102	36
	Washed Scrns.	Arkhola	1102	24
	Screenings	Arkhola	7302	17
SS	5/8" Chips	Hanson	5008	25
	1/2" Chips	Hanson	5008	18
	Screenings	Hanson	5008	42
	Sand	G.M.I	1402	15
KS	3/4" Rock	ECA	3301	13
	CF	ECA	3301	5
	3/4" 3A	ECA	3301	11
	3A	Klotz	2605	11
	Sand	Klotz	2605	35

Table 3 (Cont.) Aggregate Sources of the Mixes

MIX ID Code	Aggregates	Supplier	Pit	%Used
Alva	3/4" Chips	Dolese	3801	22
	Chat Sand	Mine Chat	Mine Chat	25
	Sand	Hutchison Sand		8
	D' Rock	Martin	3802	10
	Scrns	Dolese	3801	10
	Coarse R.A.P	Contractor		10
	Fine R.A.P	Contractor		15
HL-S5	3/8" Chips	Dolese	5002	25
	Man. Sand	Martin	5005	15
	Man. Sand	Hanson	5008	12
	Scrns	Dolese	5002	23
	Sand	General Materials		10
	Fine R.A.P	Contractor		15

Mix Properties

Mix properties were determined from plant produced mix. If plant produced mix was not available, mix properties at optimum asphalt content from the mix design were used. For plant produced mix, theoretical maximum specific gravity (Gmm) was determined in accordance with AASHTO T 209. After that, the asphalt content was determined using an ignition furnace in accordance with AASHTO T 309. Finally a sieve analysis was performed on the recovered aggregates in accordance with AASHTO T 30. The sieve analysis, Gmm and optimum asphalt content results of the mixes used are shown in Table 4.

TEST RESULTS

Laboratory Samples (Cold Feed Aggregates)

Cold feed aggregate samples were separated by size and recombined to plant produced gradations if the plant produced gradation was available. If the gradation was not available the gradation was determined from the cold feed aggregate sample in accordance with AASHTO T 11 and T 27. Samples were mixed with the plant produced asphalt content if available or the JMF asphalt content if not available.

Table 4 Gradation, Gmm and Asphalt Content of Mixes

MIX ID	**STW***	**Tulsa**	**Altus**	**J&R**	**Roberts ***	**SS**	**KS**	**Alva**	**HL-S5***
Sieve Size	**Percent Passing**								
3/4"	100	100	100	100	100	100	100	100	100
1/2"	99	96	96	88	92	92	92	88	100
3/8"	89	91	90	79	82	81	82	81	99
No.4	60	67	71	68	56	44	50	68	70
No.8	40	39	51	50	34	27	31	52	48
No. 16	27	27	39	35	21	22	21	38	33
No. 30	19	16	31	22	14	18	16	28	25
No. 50	13	7.1	21	14	11	13	12	18	16
No. 100	7	2.6	8.8	9.0	8	7.1	7.5	9.6	8
No. 200	4.5	0.6	5.2	6.4	5.7	4.7	5.2	6.5	5.5
Gmm	2.458	2.447	2.471	2.483	2.442	2.517	2.465	2.462	2.484
% AC	4.8	5.3	4.5	4.7	5.7	5.4	4.3	5.1	5.3

* Gradation from JMF (Job Mix Formula)

Hamburg Test Results

There were two types of mixes obtained; those that required anti-strip to pass AASHTO T 283 and those that did not. For Hamburg samples, mixes that did not require anti-strip were fabricated at the plant produced asphalt content and at plus 0.5%. For mixes that required anti-strip, samples were compacted with and without anti-strip. All Hamburg samples were mixed and compacted in accordance with OHD L-55 to a height of 60 ± 2 mm at an air void content of 7 ± 1%. All Hamburg testing was performed at OSU. Laboratory compacted Hamburg results are shown in Table 5.

AASHTO T 283 and MIST Results

There were two types of mixes obtained; those that required anti-strip to pass AASHTO T 283 and those that did not. MIST and AASHTO T 283 samples that required anti-strip were not tested without anti-strip as it was assumed they failed AASHTO T 283 during the mix design. For mixes that required anti-strip, samples were compacted with and without anti-strip.

Table 5 Hamburg Results, Laboratory Samples

MIX ID	Anti-Strip Required	Test Condition	PG Grade	Specified Cycles	Rut Depth (mm)
Altus	No	Opt. AC	PG 64-22	10,000	1.48
Altus	No	Opt. + 0.5% AC	PG 64-22	10,000	4.87
Tulsa	No	Opt. AC	PG 64-22	10,000	2.48
Tulsa	No	Opt. + 0.5%	PG 64-22	10,000	1.65
STW	No	Opt. AC	PG 70-28	15,000	15.75
HL-S5	No	Opt. AC	PG 64-22	10,000	18.50
SS	No	Opt. AC	PG 64-22	10,000	1.75
SS	No	Opt. + 0.5% AC	PG 64-22	10,000	12.29
Alva	Yes	With AS	PG 64-22	10,000	1.66
Alva	Yes	Without AS	PG 64-22	10,000	1.08
J&R	Yes	With AS	PG 64-22	10,000	5.12
J&R	Yes	Without AS	PG 64-22	10,000	7.94
KS	Yes	With AS	PG 58-28	10,000	1.35
KS	Yes	Without AS	PG 58-28	10,000	5.55
Roberts	Yes	With AS	PG 64-22	10,000	9.95
Roberts	Yes	Without AS	PG 64-22	10,000	13.78

AASHTO T283 and MIST samples were compacted in the SGC in accordance with ODOT's method for preparing samples for AASHTO T283 testing. AASHTO T 283 and MIST samples were compacted to a height of 95 ± 1 mm at an air void content of 7 ± 1%. A total of nine samples were prepared, three for MIST testing and six for AASHTO T 283 testing (3 conditioned and 3 control). AASHTO T 283 control results were used as control data for MIST testing.

After sample preparation, AASHTO T 283 testing takes three days to complete (vacuum saturation, minimum 16 hour freeze cycle, 24 ± 1hour hot soak, 2 hour warm soak). The MIST test was performed according to the manufacturer's recommendations. Since the MIST test is automated, the test procedure is very simple and most of the work is done by the unit itself. Samples were tested for 3,500 cycles at 50˚C with 40 psi water pressure. The test takes approximately six hours to complete, four hours for MIST conditioning and a two hour warm soak before tensile strength testing. A detailed test procedure is included in the appendix.

All MIST tests were performed at OSU. For AASHTO T283, only the Tulsa mix was tested at OSU with the rest of the samples tested at commercial laboratories. AASHTO T283 and MIST average test results are shown in Table 6.

Table 6 MIST and AASHTO T283 Test Results, Laboratory Mixes

MIX ID	Test	Anti-Strip	Control ITS (psi)	Conditioned ITS (psi)	TSR
Altus	MIST	No	137.1	86.8	0.63
Tulsa	MIST	No	148.0	134.4	0.91
HL-S5	MIST	No	124.0	89.0	0.72
SS	MIST	No	181.4	120.9	0.67
Alva	MIST	Yes	221.0	137.1	0.62
J&R	MIST	Yes	160.5	163.2	1.02
KS	MIST	Yes	199.0	154.8	0.78
Roberts	MIST	Yes	120.5	103.1	0.86
Altus	T283	No	137.1	104.7	0.76
Tulsa	T283	No	148.0	126.4	0.85
HL-S5	T283	No	124.0	103.0	0.83
SS	T283	No	181.4	159.7	0.88
STW	T283	No	173.6	74.7	0.43
Alva	T283	Yes	221.0	169.0	0.77
J&R	T283	Yes	160.5	127.9	0.80
KS	T283	Yes	199.0	158.4	0.80
Roberts	T283	Yes	120.5	98.3	0.82

Plant Produced Samples

Plant produced mix samples were compacted by reheating the mix to a compaction temperature of 300°F and immediately compacting to the required height and air void content using a Superpave Gyratory Compactor (SGC). Hamburg samples (OHD L-55) were compacted a height of 60 ± 2 mm at an air void content of 7 ± 1%. AASHTO T 283 and MIST samples were compacted to a height of 95 ± 1 mm at an air void content of 7 ± 1%.

A total of 13 samples were prepared for each mix, four for Hamburg testing, six for AASHTO T 283 testing and three for MIST testing. Of the six AASHTO T 283 samples, three were conditioned samples and three were control samples. The results obtained for AASHTO T 283 control samples were used as control data for MIST testing. All Hamburg and MIST plant mix samples were tested at OSU. All AASHTO T 283 plant mix samples were tested at OSU with the exception of the Roberts and Haskell Lemon mixes, which were performed by commercial laboratories.

Plant mix samples were tested as described for laboratory compacted samples. Average test results for Hamburg testing are shown in Table 7. Average test results for both MIST and AASHTO T283 tests performed on field samples are shown in Table 8.

Table 7 Hamburg (OHD L-55) Test Results

MIX ID	Anti-Strip Required	PG Grade	Specified Cycles	Rut Depth (mm)
Altus	No	PG 64-22	10,000	11.63
STW	No	PG 70-28	15,000	1.74
HL-S5	No	PG 64-22	10,000	10.62
SS	No	PG 64-22	10,000	4.17
Alva	Yes	PG 64-22	10,000	1.33
J&R	Yes	PG 64-22	10,000	5.53
KS	Yes	PG 58-28	10,000	2.59
Roberts	Yes	PG 64-22	10,000	13.00

Table 8 Plant Produced MIST and AASHTO T283 Test Results

MIX ID	Test	Anti-Strip Required	Control ITS (psi)	Conditioned ITS(psi)	TSR
Altus	MIST	No	117.7	85.7	0.73
STW	MIST	No	112.4	116.8	1.04
SS	MIST	No	72.5	67.6	0.93
Alva	MIST	Yes	175.8	163.1	0.93
J&R	MIST	Yes	111.1	98.4	0.89
KS	MIST	Yes	140.8	141.1	1.00
Roberts	MIST	Yes	183.3	103.0	0.56
Altus	T-283	No	117.7	94.5	0.80
STW	T-283	No	112.4	111.7	0.99
HL-S5	T-283	No	161.1	129.1	0.80
SS	T-283	No	72.5	70.4	0.97
Alva	T-283	Yes	175.8	131.7	0.75
J&R	T-283	Yes	111.1	95.7	0.86
KS	T-283	Yes	140.8	125.7	0.89
Roberts	T-283	Yes	183.3	132.7	0.72

CHAPTER 4
ANALYSIS OF HAMBURG AND AASHTO T 283 RESULTS

ODOT DATA

Each ODOT approved mix design requires AASHTO T 283 testing and contractors, on a limited basis, are sending OHD L-55 (Hamburg) samples to the ODOT Central Lab for testing. A CD of sorted mix designs from ODOT's mix design web page that contained 183 mixes with AASHTO T 283 results (TSR and ITS) and Hamburg test results (OHD L-55) was supplied by ODOT for statistical analysis.

The statistical analysis consisted of performing correlation analysis of the entire data set and the data sorted by PG Grade and mix type. Correlation analysis returns Pearson's correlation coefficient R. If this coefficient is squared you get the coefficient of determination or R^2 from the more familiar regression analysis. A positive R value means that as one value increases so does the other. A negative R means that as one value increases the other value decreases. The results of the correlation analysis for all of the data and the data sorted by PG Grade and mix type are shown in Tables 9-11, respectively.

There is no correlation of Hamburg rut depths with TSR or ITS. That is not unexpected as ODOT does not allow the production of HMA mixes that fail AASHTO T 283. Therefore, the data base only contains mixtures that passed the Hamburg and TSR tests, resulting in clustered data.

Table 9 Results of Correlation Analysis

		Rut Depth	ITS	TSR
Rut Depth	**R**	1.00	-0.31	-0.18
	N	183	181	183
ITS	**R**	-0.31	1.00	-0.13
	N	181	181	181
TSR	**R**	-0.18	-0.13	1.00
	N	183	181	183

Table 10 Results of Correlation Analysis, by PG Grade

		Rut Depth	ITS	TSR
		PG 76-28		
Rut Depth	**R**	1.00	-0.40	-0.13
	n	46	44	46
ITS	**R**	-0.40	1.00	-0.03
	n	44	44	44
TSR	**R**	-0.13	-0.03	1.00
	n	46	44	46
		PG 70-28 n=26		
Rut Depth	**R**	1.00	-0.42	-0.23
ITS	**R**	-0.42	1.00	-0.26
TSR	**R**	-0.23	-0.26	1.00
		PG 64-22 n=111		
Rut Depth	**R**	1.00	-0.23	-0.21
ITS	**R**	-0.23	1.00	-0.13
TSR	**R**	-0.21	-0.13	1.00

Table 11 Results of Correlation Analysis, by Mix Type

		Rut Depth	ITS	TSR
		S3 n=55		
Rut Depth	**R**	1.00	-0.26	-0.29
ITS	**R**	-0.26	1.00	0.09
TSR	**R**	-0.29	0.09	1.00
		S4 n=106		
Rut Depth	**R**	1.00	-0.35	-0.20
ITS	**R**	-0.35	1.00	-0.22
TSR	**R**	-0.20	-0.22	1.00
		S5 n=16		
Rut Depth	**R**	1.00	-0.27	-0.01
ITS	**R**	-0.21	1.00	-0.25
TSR	**R**	-0.01	-0.25	1.00

In addition to correlation analysis, a frequency distribution plot of the AASHTO T 283 results was developed. The results are shown in the Figure 7. As shown in Figure 7, ODOT does not allow the production of HMA mixes that fail AASHTO T 283. A precision statement for AASHTO T 283 does not appear in the test standard. However, Azari (21) developed precision statements and reported the standard deviation for single operator precision of TSR as 0.033. Using that standard deviation a TSR of greater than 0.85 would be required for there being a risk of less than 5 percent of accepting a failing test result (TSR < 0.80). From the frequency histogram, there were 85 of 183, or 46% of the mixes evaluated where ODOT had a greater than 5% risk of accepting a test result from a mix with a failing TSR (type II error).

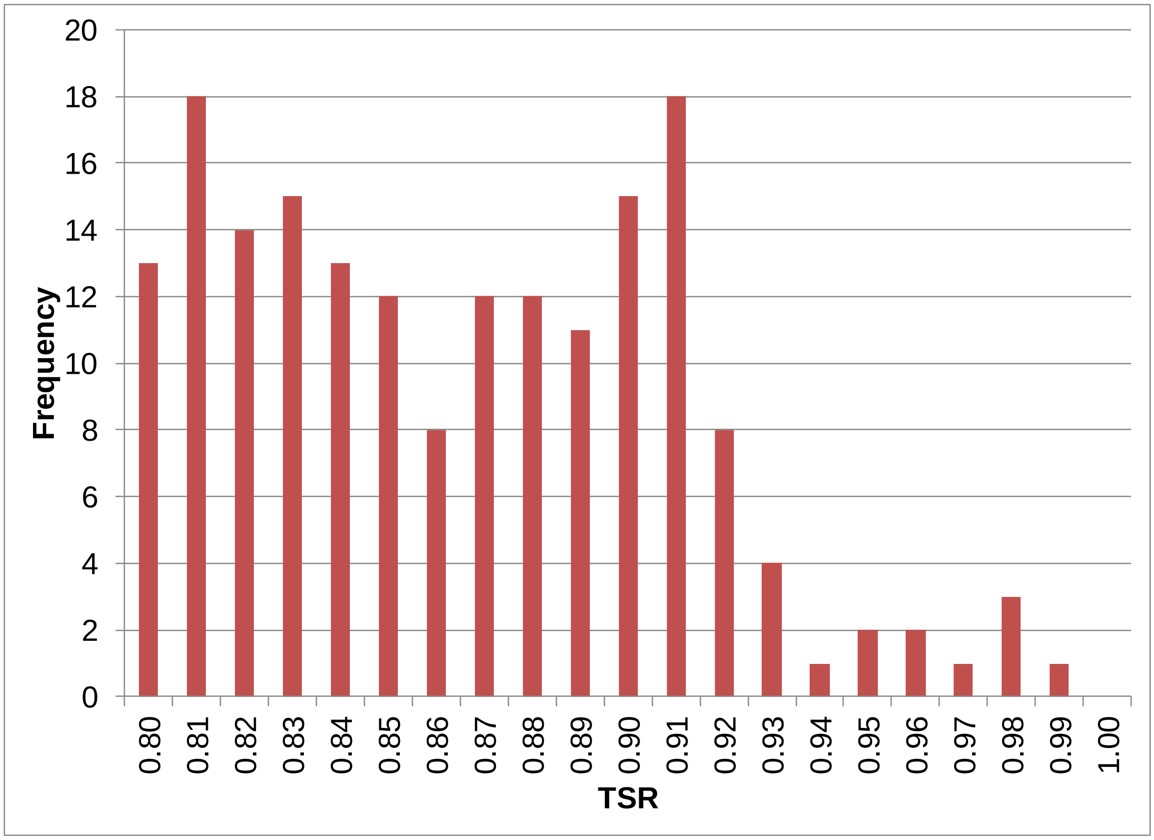

Figure 7 Frequency analysis of AASHTO T 283 results.

HAMBURG TEST RESULTS

There were two types of mixes obtained; those that required anti-strip to pass AASHTO T 283 and those that did not. For Hamburg samples, mixes that did not require anti-strip were fabricated at the plant produced asphalt content and at plus 0.5%. For mixes that required anti-strip, samples were compacted with and without anti-strip. All Hamburg samples were mixed and compacted in accordance with OHD L-55 to a height of 60 ± 2 mm at an air void content of 7 ± 1%. Test results were shown in Chapter 3.

Mixes Without Anti-Strip

Mixes that did not require anti-strip to pass AASHTO T 283 were tested at the plant produced asphalt content and at plus 0.5% to determine if the Hamburg could identify mixes with excess asphalt cement. The results are shown in Figure 8.

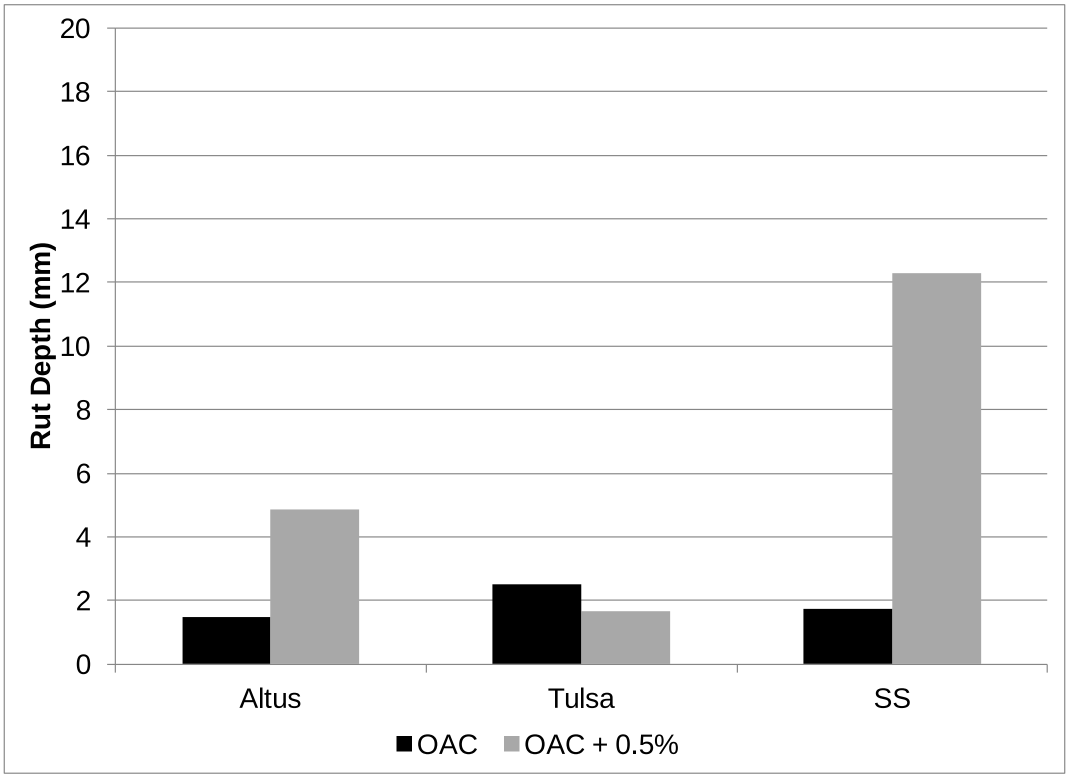

Figure 8 Hamburg rut depth, mixes without anti-strip.

As shown in Figure 8, there were three mixes tested that did not require anti-strip to pass AASHTO T 283 with sufficient cold feed materials to test at the plant produced and at plus 0.5% asphalt cement. Of the three mixes, two showed an increase in Hamburg rut depth with a 0.5% increase in asphalt content. The Tulsa mix did not show an increase in rut depth; however, this mix is very angular and harsh and showed almost no rutting. This is a very limited data set but it does appear that the Hamburg can detect when additional binder will adversely affect test results and possibly performance.

Mixes With Anti-Strip

Mixes that required anti-strip to pass AASHTO T 283 were fabricated and tested at the plant produced asphalt content with and without anti-strip to determine if the Hamburg could identify mixes that failed AASHTO T 283 without anti-strip. The results are shown in Figure 9.

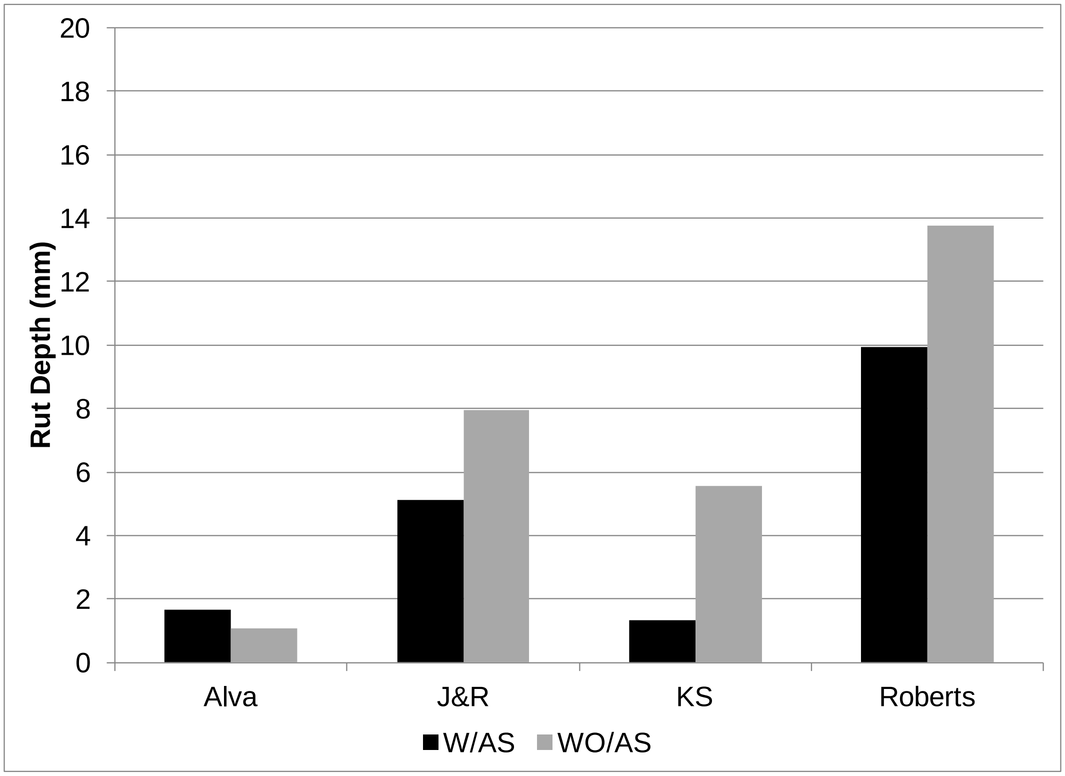

Figure 9 Hamburg rut depth, mixes with anti-strip.

As shown in Figure 9, there were four mixes tested that required anti-strip to pass AASHTO T 283 with sufficient cold feed materials to test at the plant produced asphalt content with and without anti-strip. Of the four mixes, three showed an increase in Hamburg rut depth without anti-strip. The Alva mix did not show an increase in rut depth without anti-strip; however, this mix showed almost no rutting. A t-test on the average rut depth showed no statistical difference in rut depths. The data set is very limited but it does appear that the Hamburg can detect an increase in rut depth when a mix that needs anti-strip to pass AASHTO T 283 is tested without anti-strip.

Hamburg vs. AASHTO T 283

From Figure 9 it can be seen that the lack of anti-strip in mixes that required anti-strip to pass AASHTO T 283 generally resulted in an increase in rut depth. However, the increase appears to be mix specific and there is no apparent simple threshold value to separate moisture sensitive mixes from those that are not. Figure 10 is a plot of Hamburg rut depth at the specified number of passes based on PG grade and AASHTO T 283 TSR. AASHTO T 283 was not performed on laboratory prepared mixes that required an anti-strip as these mixes failed AASHTO T 283 without an anti-strip during the mix design procedure. A TSR of 0.70 was assumed for these mixes in the plot in Figure 10.

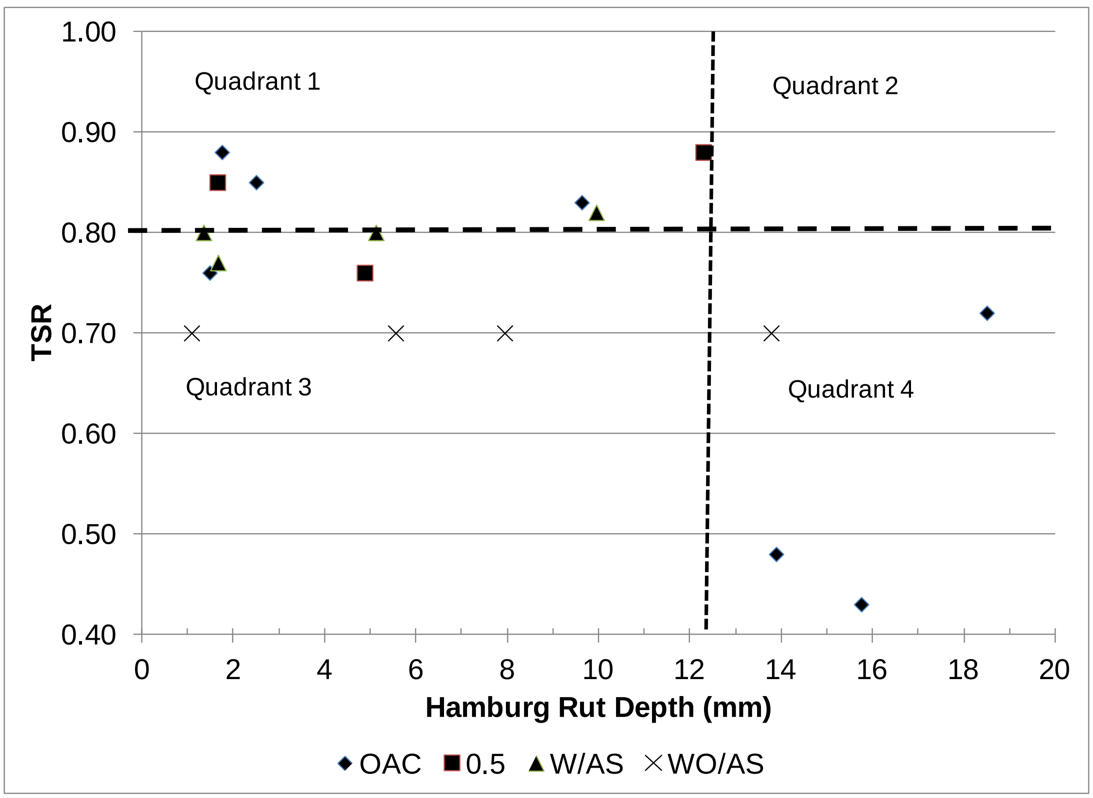

Figure 10 Hamburg rut depths vs. AASHTO T 283 TSR.

Figure 10 is divided into 4 quadrants based on the ODOT specified minimum TSR of 0.80 and maximum Hamburg rut depth of 12.5 mm. Quadrant 1 contains mixes that passed the TSR and Hamburg requirements. There were six mixes that passed both requirements. Four of these mixes were tested in the Hamburg at the plant produced asphalt content and two were tested at plus 0.5% asphalt. Only one of these mixes required and was tested with an anti-strip.

Quadrant 2 contained no mixes even though there were three mixes that passed the TSR requirement but were tested with an additional 0.5% asphalt cement.

Quadrant 3 contains mixes that failed the TSR requirement but passed the Hamburg requirement. There were eight mixes that fell in quadrant 3. Of the eight mixes, three were tested with the required anti-strip but still had failing TSRs. Three of the mixes in quadrant 3 required anti-strip but were tested without anti-strip and still passed the Hamburg requirement. There was one mix that did not require anti-strip but was tested with an additional 0.5% asphalt. This mix did not fail the Hamburg requirement.

Quadrant 4 contains mixes that failed both the TSR and Hamburg requirement. There were four mixes in quadrant 4. Of these four mixes, three were laboratory tested at the plant produced asphalt content and two of these three were laboratory foamed (WMA) mixes. The fourth mix was a mix that required anti-strip but was tested without anti-strip.

If the current specifications are maintained, eight of the 12 mixes that had TSR values below 0.80 passed the Hamburg rut test. As shown in Figure 10, for the mixtures tested, there is no good correlation between Hamburg rut depths and TSR.

AASHTO T 324 mentions a stripping inflection point as being an indication of rutting. Plots of individual rut depths with passes were made to investigate a stripping inflection point. There were plots that showed a marked increase in rut depth or stripping inflection point. However, the existence of stripping inflection points was not consistent between replicates. Some mixes that did not require anti-strip to pass AASHTO T 283 and/or showed low rut depths also had inflection points. A mix that exhibits tertiary flow rutting would have a “stripping inflection point” as well. There was no apparent correlation between TSR and stripping inflection point. In addition, the definition of the stripping inflection point is not well defined making enforcement of a specification using this parameter problematic.

CHAPTER 5
ANALYSIS OF AASHTO T 283 and MIST RESULTS

The analysis of test results for AASHTO T283 and MIST testing was made to determine if there is a statistical difference between AASHTO T283 and MIST results by comparing their conditioned indirect tensile strengths (CITS). Also a series of bar charts were made to compare TSR and CITS between AASHTO T283 and MIST. The analysis was made on results from laboratory and plant produced samples.

LABORATORY TEST RESULTS

Tensile Strength Ratio

Figure 11 is a bar chart showing a comparison between AASHTO T283 and MIST TSR. Of the eight mixes shown, MIST was more severe (lower TSR) for five of eight mixes and AASHTO T 283 more severe in the remaining three mixes. Of the four mixes that did not require anti-strip, MIST was more severe for three of four. Of the four mixes that required anti-strip, MIST was more severe for two of them.

Conditioned Indirect Tensile Strength

Statistical analysis for the study was made on conditioned indirect tensile strength (CITS) rather than TSR. Nine samples were made for testing, three were for MIST conditioning, three for AASHTO T283 conditioning and three for control or dry testing. The same dry ITS results were used to calculate TSR for both MIST and AASHTO T283 tests. Therefore, the only non constant variable is CITS.

Figure 12 is a bar chart showing a comparison between AASHTO T 283 and MIST CITS. Out of the eight mixes shown in the plot, MIST CITS was lower (more severe) for five of the mixes (Altus, HL-S5, SS, Alva, and KS) and AASHTO T 283 was more severe in the remaining three mixes (Tulsa, J&R, and Roberts). For the four mixes that did not require anti-strip, MIST was more severe in three mixes. For mixes that required anti-strip, MIST was more severe for the Alva and KS mix and AASHTO T 283 was more severe for the J&R and Roberts mix; the same as for TSR.

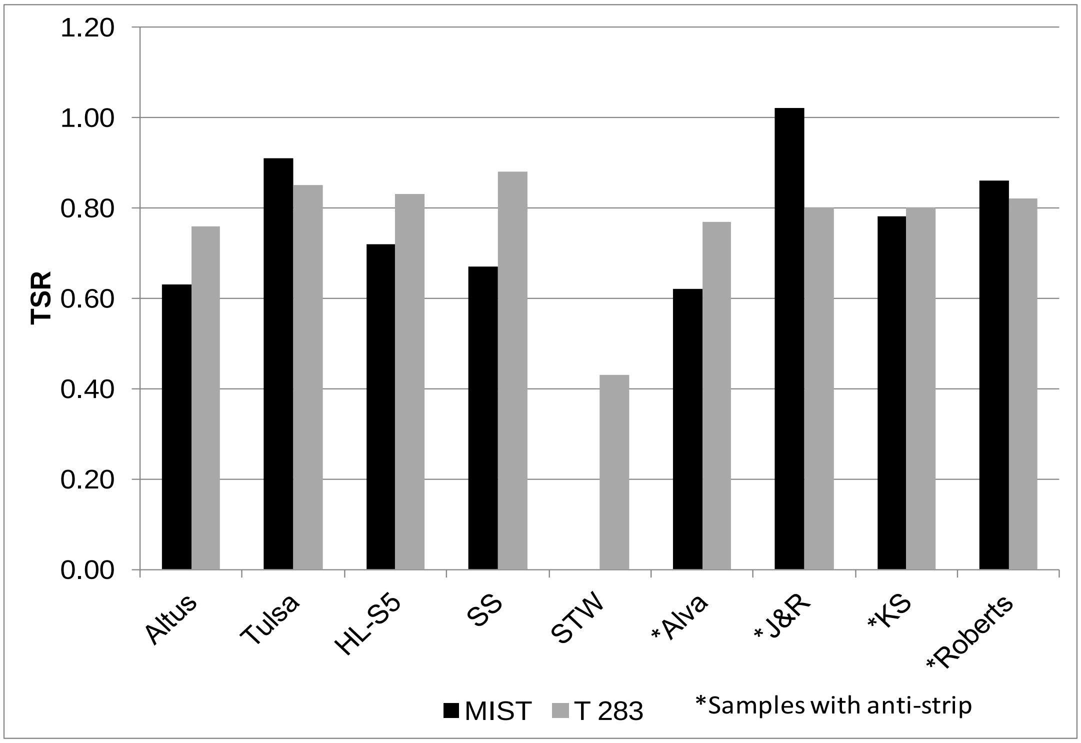

Figure 11 Plot of MIST TSR vs. AASHTO T 283 TSR for laboratory mixes.

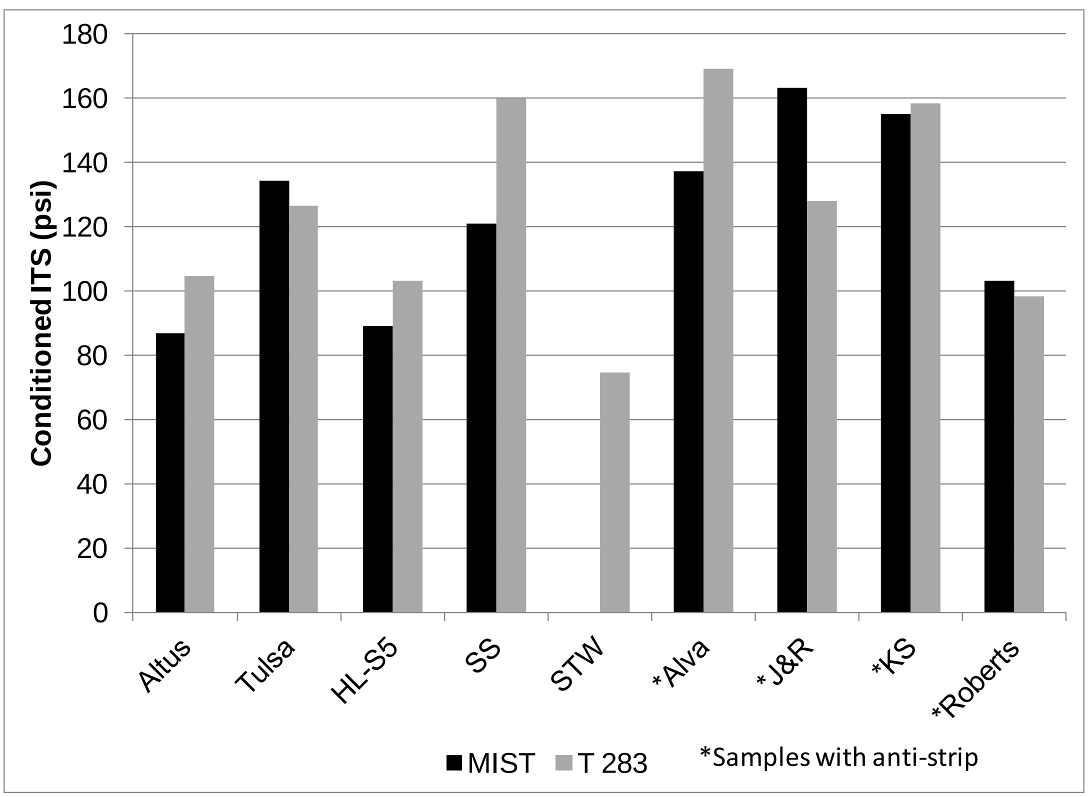

Figure 12 Plot of MIST CITS vs. AASHTO T283 CITS for laboratory mixes.

An analysis of variance (ANOVA) was performed on the above results to determine if there is a statistical difference in CITS between mix ID, test methods and the interaction between the two. The results are shown in Table 12.

Table 12 ANOVA on Conditioned ITS, Laboratory Mixes

Source	Degrees Freedom	Sum Squares	Mean Squares	F Value	Prob. > F
ID	7	39243.349	5606.193	29.16	<.0001
Test	1	84.316	84.316	0.44	0.5109
ID*Test	7	5441.041	777.292	4.04	0.0014
Error	50	9613.737	192.275		
Total	65	54382.443			

It can be seen in Table 12 that the CITS between mixes is significantly different at a level of significance greater than 99.9%. No statistical difference was found in CITS between test methods. The mean CITS was 125.1 and 122.8 psi for MIST and AASHTO T 283, respectively. However, there was a significant difference between their respective interactions at a level of significance greater than 99.8%.

To determine which mixes had significantly different CITS means, Duncan's Multiple Range Test was performed. The results are shown in Table 13. Means with the same letter are not significantly different at a significance level of 95% (alpha=0.05). The results indicate that the mixes evaluated had a range of CITS, which was what was desired.

Table 13 Duncan's Multiple Range Test for Mix ID, Laboratory Mixes

Grouping	Mean CITS (psi)	n	Mix ID
A	151.8	9	KS
A&B	144.4	12	Alva
A&B	140.3	6	SS
A&B	136.4	9	J&R
B	130.4	6	Tulsa
C	98.0	8	Altus
C	96.0	6	HL-S5
D&C	87.2	10	Roberts

Due to the significant interaction, an ANOVA on CITS between test methods, by mix, was performed. Table 14 shows the mean AASHTO T 283 and MIST CITS and if the difference in means is statistically significant at a level of significance of 95% (α = 0.05). As shown in Table 14, five of the mixes (Altus, Alva, HL-S5, J&R, and SS) had a statistical difference in CITS. No statistical difference in CITS was found between test methods for the remaining three mixes (KS, Roberts, and Tulsa). Of the five mixes that showed significant difference, MIST was more severe (lower CITS) in four of the mixes (Altus, Alva, HL-S5, and SS) and AASHTO T 283 was more severe in one (J&R).

Table 14 AASHTO T 283 and MIST Mean CITS, by Mix, Laboratory Samples

Mix ID	Mean CITS (psi)	Test	Statistically Significant
Altus	104.7 86.8	T 283 MIST	Yes
Alva	169.0 137.1	T 283 MIST	Yes
HL-S5	103.0 89.0	T 283 MIST	Yes
J&R	163.2 127.9	MIST T 283	Yes
KS	158.4 154.8	T 283 MIST	No
Roberts	103.1 98.3	MIST T 283	No
SS	159.7 120.9	T 283 MIST	Yes
Tulsa	134.4 126.4	MIST T 283	No

PLANT MIX TEST RESULTS

Tensile Strength Ratio

MIST testing was performed on plant produced mix from seven different projects (Altus, STW, SS, Alva, J&R, KS, and Roberts). A comparison between AASHTO T283 and MIST TSR results for plant produced mixes is shown in Figure 13. Of the seven mixes, MIST TSR was more severe for three of the mixes (Altus, SS, and Roberts) and AASHTO T 283 TSR was more severe in the remaining four mixes (STW, Alva, J&R, and KS). Of three mixes that did not require anti-strip MIST was more severe in two and of the four mixes that required anti-strip, MIST was more severe in one. This is different than laboratory samples where MIST was generally more severe.

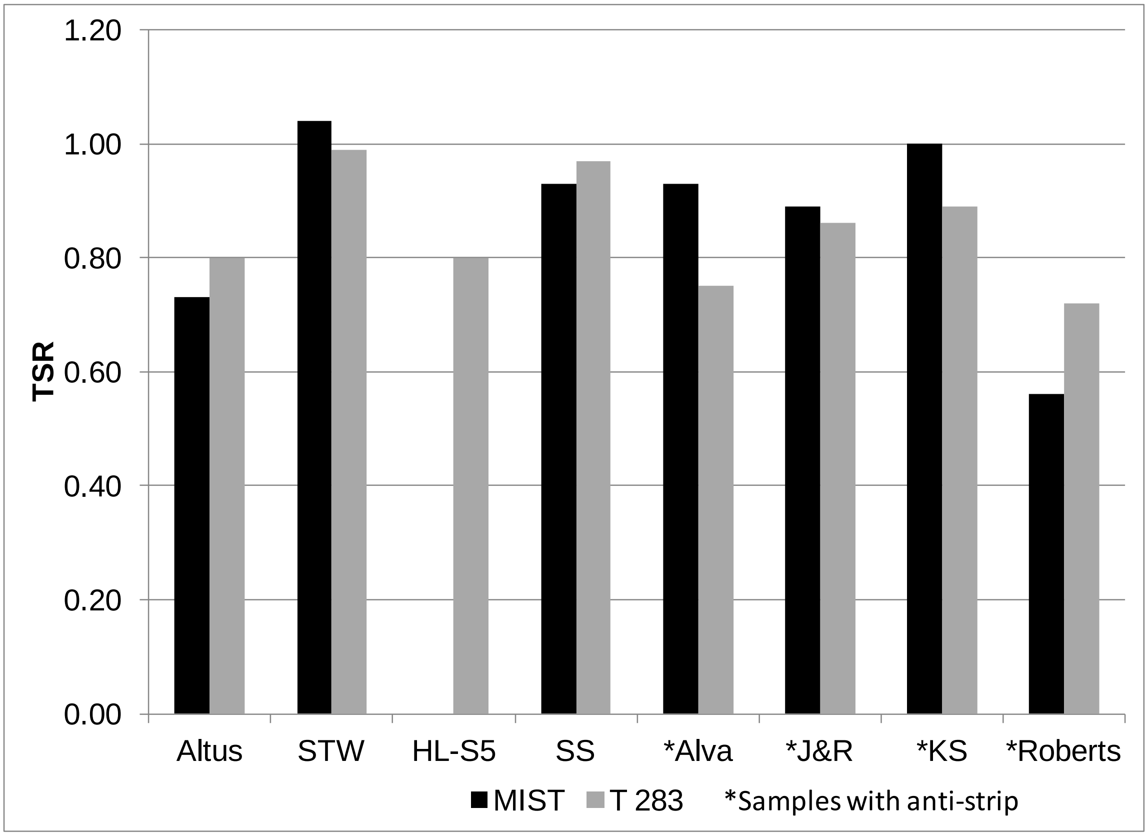

Figure 13 Plot of MIST vs. AASHTO T 283 TSR, plant mixes.

Conditioned Indirect Tensile Strength

An analysis was made on CITS rather than TSR for the same reasons described for laboratory samples. A bar chart for AASHTO T 283 and MIST CITS is shown in Figure 14. The same results will be seen for CITS as for TSR because the dry indirect tensile strengths were the same for both test methods. Of the seven mixes, MIST TSR was more severe for three of the mixes (Altus, SS, and Roberts) and AASHTO T 283 TSR was more severe in the remaining four mixes (STW, Alva, J&R, and KS). Of three mixes that did not require anti-strip MIST was more severe in two and of the four mixes that required anti-strip, MIST was more severe in one.

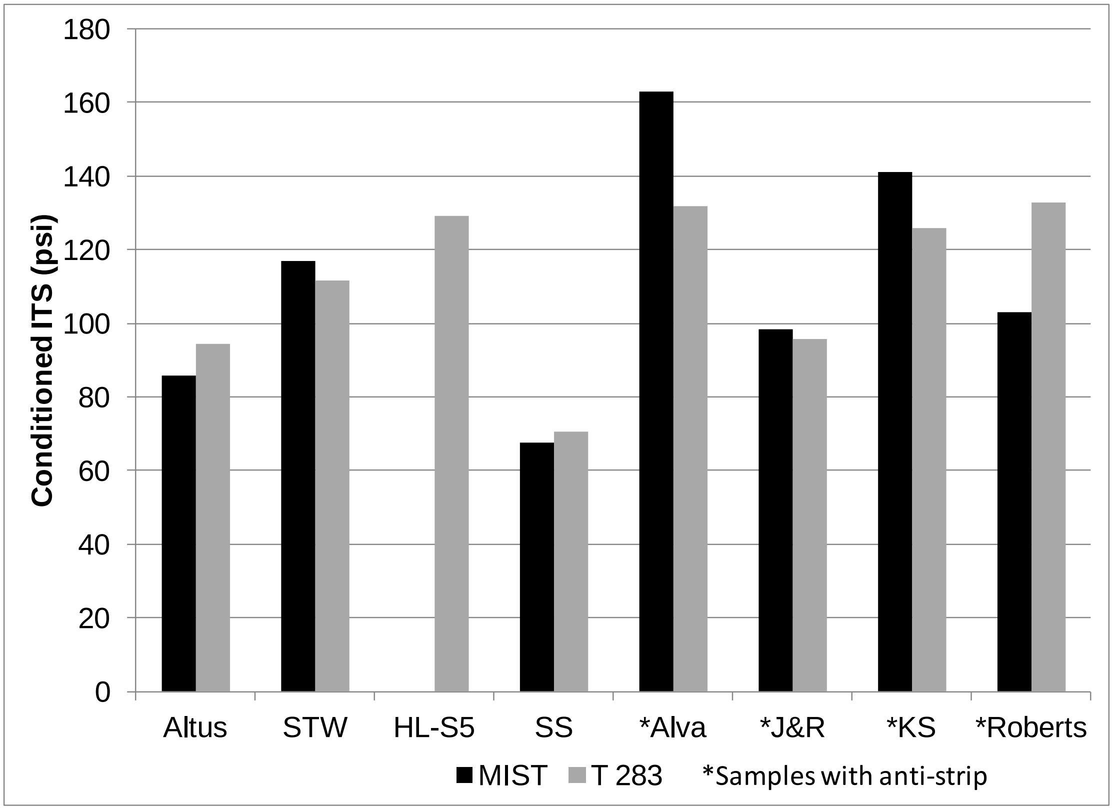

Figure 14 Plot of MIST vs. AASHTO T 283 CITS, plant mixes.

An analysis of variance (ANOVA) was performed on field results to determine if there is a statistical difference in CITS between mixes, test methods and their respective interaction. The results are shown in Table 15.

Table 15 ANOVA on CITS for MIST and AASHTO T-283, Plant Mixes

Source	Degrees Freedom	Sum Squares	Mean Squares	F Value	Prob. > F
Mix	6	25604.370	4267.395	100.17	<.0001
Test	1	37.905	37.905	0.89	0.3536
Mix*Test	6	3297.233	549.539	12.9	<.0001
Error	28	1192.813	42.600		
Total	44	30132.321			

As seen in Table 15, the CITS between mixes is significantly different at a level of significance exceeding 99.9%. Similarly, the interaction between the mixes and test method is significantly different at a level of significance exceeding 99.9%. However, no statistical difference was found in CITS between test methods. The mean CITS was 110.8 and 108.9 psi for MIST and AASHTO T 283, respectively.

To determine which mixes had significantly different plant produced CITS, Duncan's Multiple Range Test was performed. The results are shown in Table 16. Means with the same letter are not significantly different at a significance level of 95% (alpha=0.05). It results indicate that the plant mixes evaluated had a range in mean CITS, as desired.

Table 16 Duncan's Multiple Range Test for Mix ID for Plant Mixes

Grouping	Mean CITS (psi)	n	Mix ID
A	147.4	6	Alva
B	133.4	6	KS
C	117.9	6	Roberts
C	114.2	6	STW
D	97.0	6	J&R
D	90.1	6	Altus
E	69.0	6	SS

Due to the significant interaction, an ANOVA on CITS between test methods, by mix, was performed. Table 17 shows the mean plant AASHTO T 283 and MIST CITS and if the difference in means is statistically significant at a level of significance of 95% ($\alpha = 0.05$). Out of the seven mixes tested, four showed a significant difference between test methods. Out of the four mixes that were significantly different, three required anti-strip (Alva, KS, Roberts) and one did not (Altus). Of the remaining three mixes where there was no statistical difference in mean CITS, Altus and SS did not require anti-strip. Of the four mixes that showed significant difference in CITS, MIST was more severe (lower CITS) for Altus and Roberts and AASHTO T 283 was more severe for Alva and KS.

Table 17 ANOVA of CITS for MIST and AASHTO T-283, by Mix, Plant Mixes

Mix ID	Mean CITS (psi)	Type	Statistically Significant
Altus	94.5 85.7	T 283 MIST	Yes
STW	116.8 111.7	MIST T 283	No
SS	70.4 67.6	T 283 MIST	No
Alva	163.1 131.7	MIST T 283	Yes
J&R	98.4 95.7	MIST T 283	No
KS	141.1 125.7	MIST T 283	Yes
Roberts	132.7 103.0	T 283 MIST	Yes

CHAPTER 6
COMPARISION OF LABORATORY AND PLANT RESULTS

A comparison between laboratory and plant produced results was made to determine if plant production affects results. To show this comparison, a series of bar charts were made and an analysis of variance was performed for AASHTO T283 and MIST testing.

HAMBURG RESULTS

Plant produced mixes were compared to the equivalent laboratory produced mixes to determine if there was a significant difference in test results and to determine if the Hamburg could be used for field control of HMA mixes. The results of the average Hamburg rut depth for plant and laboratory produced mixes are shown in Figure 15.

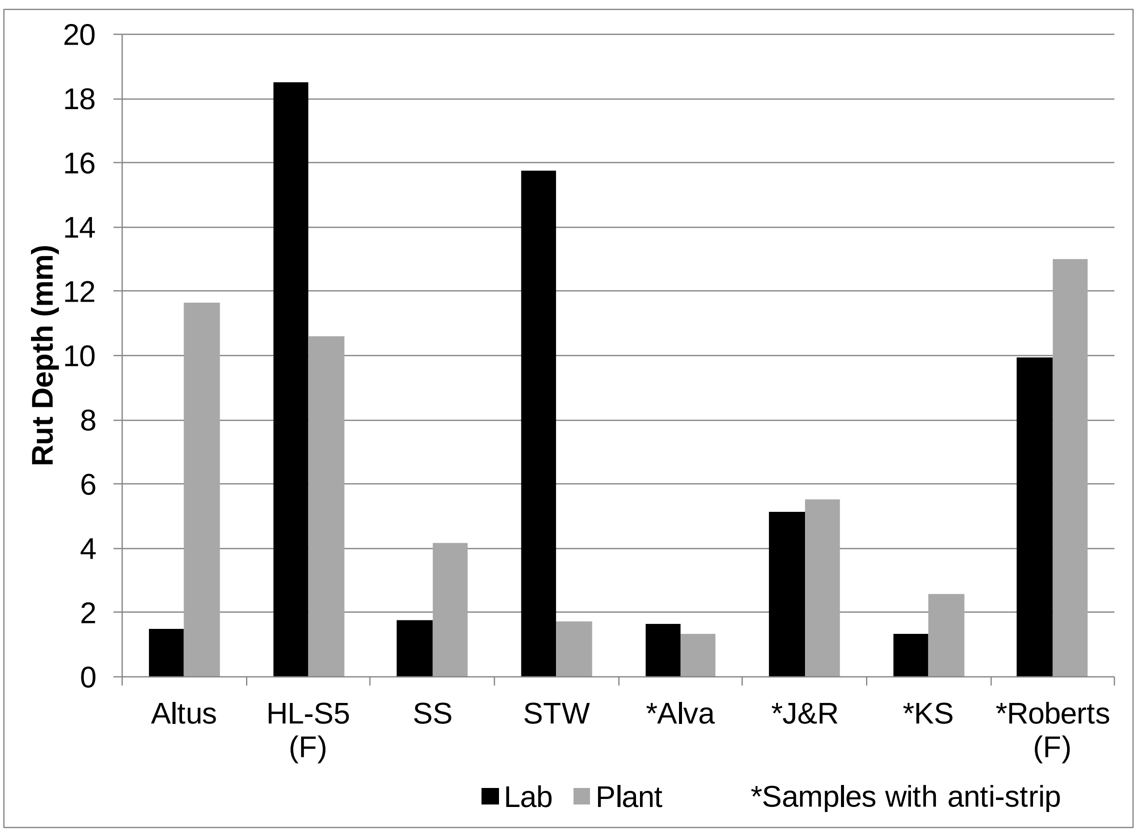

Figure 15 Plant and laboratory Hamburg rut depths.

As shown in Figure 15, there were five of eight mixes where the plant produced mix rutted more than the lab mix. Of the four mixes that required anti-strip, three of four plant mixes rutted more than the lab mix. Of the four mixes that did not require anti-strip, the plant mix rutted more than the lab mix in two mixes. Two of the plant produced mixes were WMA mixes using foam (Roberts and HL-S5). These plant mixes were compared to laboratory foamed mixes foamed using the Foamer™. The two WMA mixes tended to have higher Hamburg rut depths than conventional HMA and there was no trend between plant produced and laboratory produced samples. A t-test on average rut depth showed no statistical difference in rut depths between lab and plant produced mixes. There was considerable scatter in the Hamburg data. There is no precision statement available for the Hamburg (OHD L-55) and the effect of sample age on Hamburg rut depths is unknown.

MIST RESULTS

Tensile Strength Ratio

Figure 16 is a bar chart showing a comparison between plant produced and laboratory TSR results for MIST testing. As shown in Figure 16, the plant produced TSR was greater than the laboratory TSR for four of six mixes. Of the four mixes that required anti-strip, the plant produced TSR was greater for two mixes. A t-test indicated that there was not a statistically significant difference between plant and laboratory TSR.

Conditioned Indirect Tensile Strength

There were no replicates for TSR and MIST conditioning is only different for conditioned samples. Therefore, further analysis was performed on conditioned indirect tensile strength (CITS). Figure 17 is a bar chart showing a comparison between plant produced and laboratory CITS results for MIST testing. As shown in Figure 17, the laboratory CITS was greater than the plant CITS for four of six mixes. Of the four mixes that required an anti-strip, the laboratory TSR was greater for two mixes.

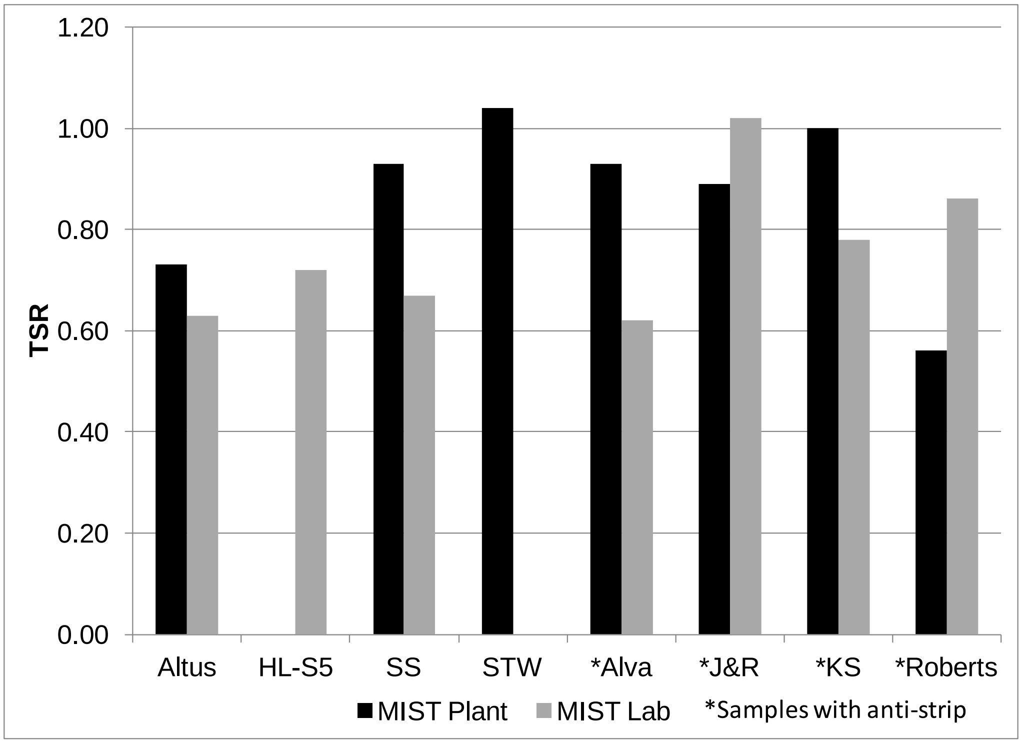

Figure 16 Plot of MIST laboratory vs. MIST plant TSR.

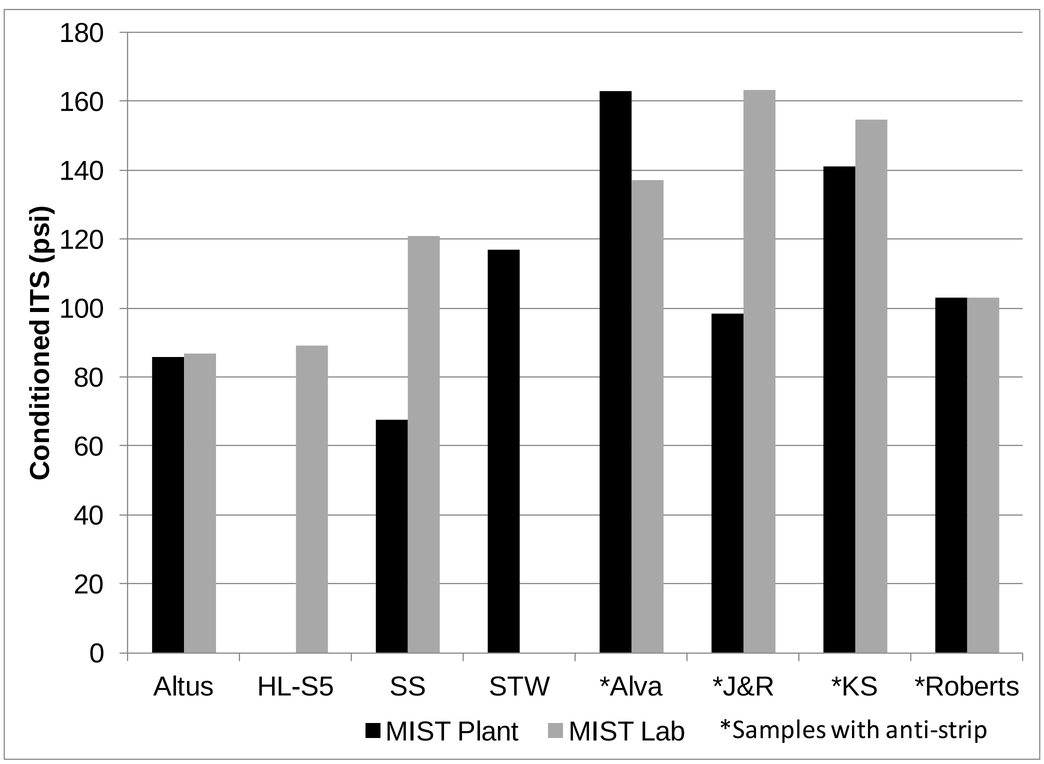

Figure 17 Plot of MIST laboratory vs. MIST plant CITS results.

As seen in Figure 17, the MIST laboratory and plant results seem to have similar values for Altus and Roberts mix; however, for the remaining mixes the laboratory and plant results appear to be different. An analysis of variance (ANOVA) was performed on laboratory and plant MIST CITS results to determine if there is a statistical difference between mix types, mix ID and their respective interaction. The results are shown in Table 18.

Table 18 ANOVA of MIST CITS for Laboratory and Plant Mixes

Source	Degrees Freedom	Sum Squares	Mean Squares	F Value	Prob. > F
Type	1	3245.057	3245.057	88.72	<.0001
Mix	5	22740.663	4548.133	124.35	<.0001
Type*Mix	5	8901.673	1780.335	48.68	<.0001
Error	23	841.233	36.575		
Total	34	35728.627			

As can be seen in Table 18, the CITS between laboratory and plant mix (Type), mixes and their respective interaction is significantly different at a level of significance beyond 99.9%. The average MIST CITS for laboratory mixes was 129.1 psi and for plant mixes 109.8 psi. To determine which mixes were significantly different, Duncan’s Multiple Range test was performed on the mean CITS. The results are shown in Table 19. It can be seen from the table that except for Alva and KS mixes, all the remaining mixes had significantly different CITS.

Table 19 Duncan’s Multiple Range Test for CITS, by Mix ID, Laboratory and Plant Mixes

Grouping	Mean CITS (psi)	n	Mix ID
A	150.1	6	Alva
A	147.9	6	KS
B	130.8	6	J&R
C	103.1	5	Roberts
D	94.3	6	SS
E	86.3	6	Altus

Due to the significant interaction, an ANOVA on CITS between MIST laboratory and plant results, by mix, was performed. Table 20 shows the mean laboratory and plant CITS and if the difference in means is statistically significant at a level of significance of 95% (α = 0.05). As shown in Table 20, four of the mixes (Alva, J&R, SS, and Roberts) are significantly different at a significance level of 95% and no significant difference was seen for Altus and KS mixes. Of the four mixes that showed a significant difference (Alva, J&R, SS, and Roberts), laboratory results were more severe (lower CITS) for Alva and Roberts mixes and plant results were more severe for J&R and SS mixes. Of the mixes that were significantly different, Alva, J&R, and Roberts mixes had anti-strip and SS mix did not require anti-strip. For mixes that did not show any significant difference, Altus did not require anti-strip and KS required anti-strip.

Table 20 MIST Laboratory and Field Mean CITS Results

Mix ID	Mean CITS (psi)	Type	Statistically Significant
Altus	86.8 85.7	Lab Plant	No
Alva*	163.1 137.1	Plant Lab	Yes
J&R*	163.2 98.4	Lab Plant	Yes
KS*	154.8 141.1	Lab Plant	No
SS	120.9 67.6	Lab Plant	Yes
Roberts*	132.7 98.3	Plant Lab	Yes

*Mixes that required anti-strip

AASHTO T 283 RESULTS

Tensile Strength Ratio

Figure 18 is a bar chart showing a comparison between plant produced and laboratory TSR results for AASHTO T 283 testing. As shown in Figure 18, the plant produced TSR was greater than the laboratory TSR for five of eight mixes. Of the four mixes that required an anti-strip, the plant produced TSR was greater for two mixes. A t-test indicated that there was not a statistically significant difference between plant and laboratory AASHTO T 283 TSR.

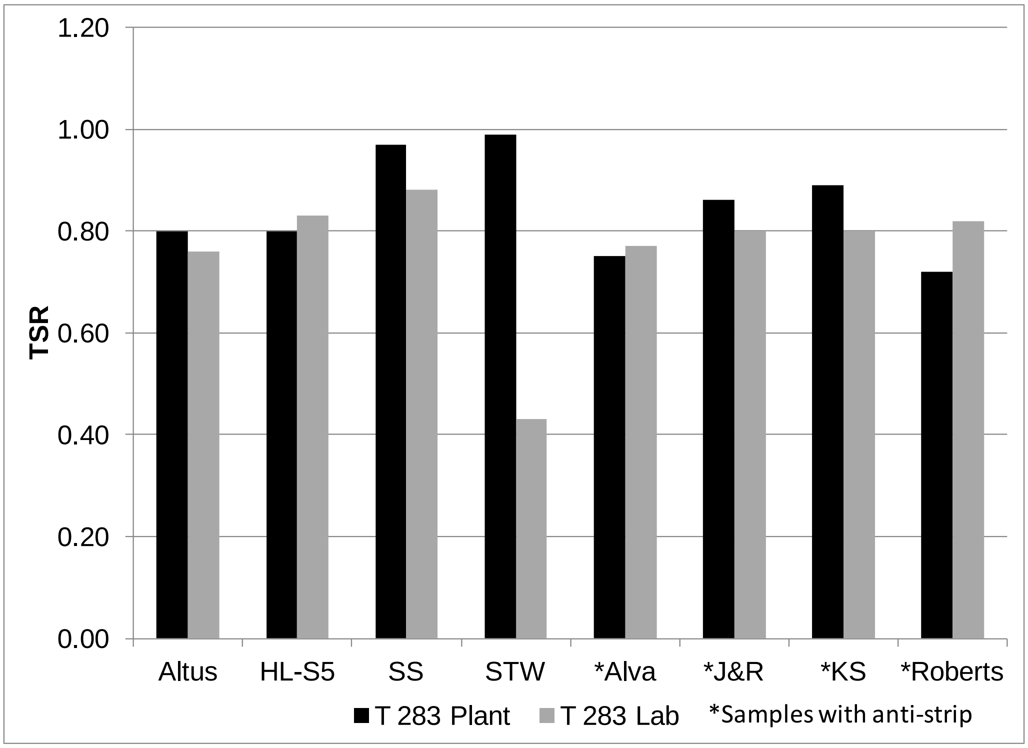

Figure 18 Plot of AASHTO T 283 laboratory and plant TSR.

Conditioned Indirect Tensile Strength

As with MIST testing, there were no replicates for TSR and AASHTO T 283 conditioning is only different for conditioned samples. Therefore, further analysis was performed on conditioned indirect tensile strength (CITS). Figure 19 is a bar chart showing a comparison between plant produced and laboratory AASHTO T 283 CITS. As shown in Figure 19, the laboratory CITS was greater (less severe) than the plant CITS for five of eight mixes. Of the four mixes that required an anti-strip, the laboratory CITS was greater (less severe) for three mixes.

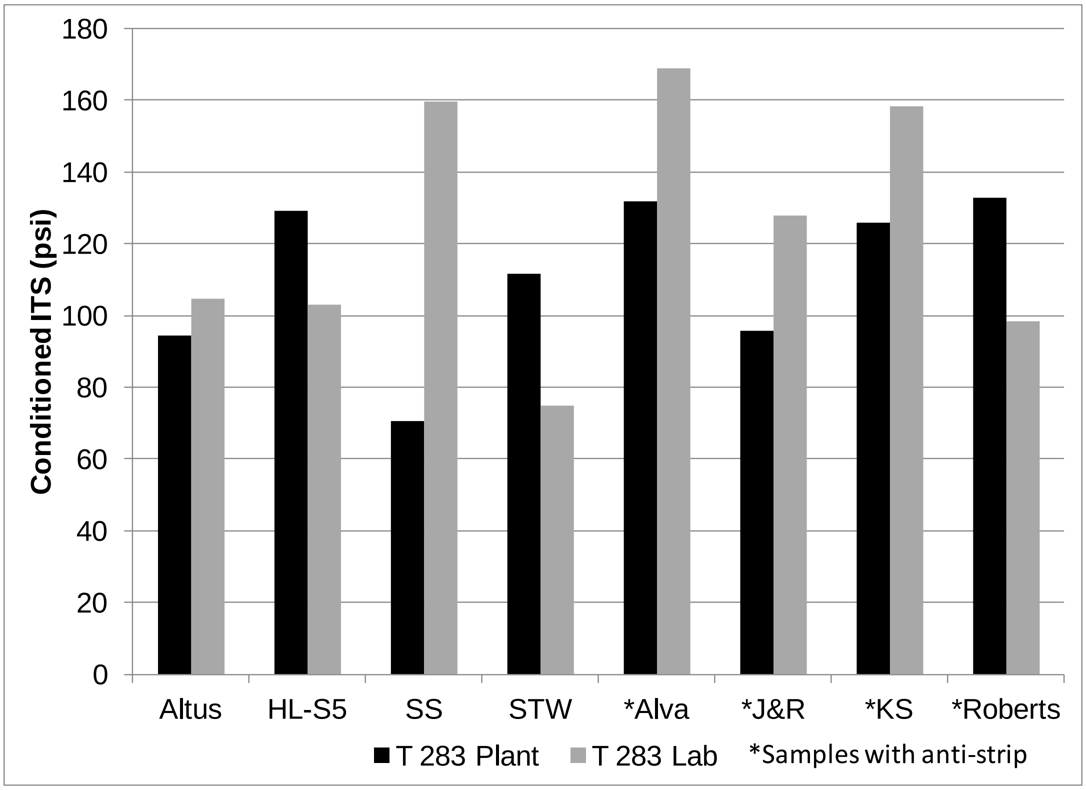

Figure 19 Plot of AASHTO T 283 laboratory and plant CITS.

An ANOVA was performed on AASHTO T 283 laboratory and plant CITS results to determine if there is a statistical difference between mix types. The results are shown in Table 21. It can be seen from the table that CITS between laboratory and field samples is significantly different at a level of significance beyond 99.9%. The average AASHTO T 283 CITS for laboratory mixes was 122.9 psi and for plant produced mix 111.4 psi.

Table 21 ANOVA of AASHTO T283 CITS for Laboratory and Plant Mixes

Source	Degrees Freedom	Sum Squares	Mean Squares	F Value	Prob. > F
Type	1	1651.032	1651.032	35.57	<.0001
Mix	7	16544.365	2363.481	50.92	<.0001
Type*Mix	7	20172.486	2881.784	62.08	<.0001
Error	34	1578.245	46.420		
Total	49	32387.235			

To determine which mixes had significantly different CITS, Duncan's Multiple Range Test was performed. The results are shown in Table 22. It can be seen from the table that no statistical difference is observed between HL-S5, Roberts, SS, and J&R mixes. Similarly no statistical difference was observed between Altus and STW mixes. However, Alva and KS mixes were significantly different from all the other mixes.

Table 22 Duncan's Multiple Range Test, for Mix ID, Laboratory and Plant Mixes

Grouping	Mean CITS (psi)	n	Mix ID
A	150.3	6	Alva
B	142.1	6	KS
C	116.0	6	HL-S5
C	115.5	5	Roberts
C	115.0	6	SS
C	111.8	6	J&R
D	100.9	8	Altus
D	93.2	6	STW

Due to the significant interaction, an ANOVA on CITS between AASHTO T 283 laboratory and plant results, by mix, was performed. Table 23 shows the mean laboratory and plant CITS and if the difference in means is statistically significant at a level of significance of 95% ($\alpha = 0.05$). For seven of the mixes (Altus, Alva, HL-S5, J&R, KS, STW and SS) the CITS is significantly different between laboratory and plant samples; though no significant difference is observed for Roberts mix. Out of the seven mixes that were significantly different (Altus, Alva, HL-S5, J&R, KS, STW and SS), plant CITS results were more severe (lower CITS) in five mixes (Altus, Alva, J&R, KS, and SS) and laboratory results were more severe for HL-S5 and STW mixes. Of the mixes that were significantly different, Alva, J&R, and KS mixes had anti-strip and Altus, STW, HL-S5, and SS mixes did not require anti-strip. The Roberts mix, which didn't show any significant difference, had anti-strip.

From the above analysis between laboratory and field results for MIST and AASHTO T 283, it can be seen that there is a significant difference between laboratory and field results for both AASHTO T 283 and MIST tests.

Table 23 AASHTO T 283 Laboratory and Plant Mean CITS

Mix ID	Mean CITS (psi)	Type	Statistically Significant
Altus	104.7 94.5	Lab Plant	Yes
Alva	169.0 131.7	Lab Plant	Yes
HL-S5	129.0 103.0	Plant Lab	Yes
J&R	127.9 95.7	Lab Plant	Yes
KS	158.4 125.7	Lab Plant	Yes
SS	159.7 70.4	Lab Plant	Yes
STW	111.7 74.7	Plant Lab	Yes
Roberts	103.1 103.0	Lab Plant	No

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the materials tested using the Hamburg loaded wheel tester (OHD L-55), AASHTO T 283 and MIST, the following conclusions are warranted.

ODOT Provided Mix Design Data

- There was no correlation between the ODOT provided OHD L-55 rut depth data and AASHTO T 283 TSR or ITS data.
- Based on the precision statement by Azari (21), of the 183 mixes provided for analysis by ODOT, 46 percent (85 mixes) had at least a 5 percent risk of having a true mean TSR of less than or equal to 0.80.

Hamburg (OHD L-55) Results

- Mixes with 0.5% additional asphalt tended to rut more that mixes tested at the produced asphalt content. However, only one of the three mixes with 0.5% extra asphalt cement failed OHD L-55.
- Three of four mixes that required ant-strip but were also tested without anti-strip had higher rut depths without the required anti-strip. However, only one of the four mixes failed OHD L-55.

Hamburg vs. AASHTO T 283 Results

- A threshold value for OHD L-55 to predict AASHTO T 283 TSR could not be identified. One of the difficulties could be the poor precision of AASHTO T 283 and the unknown precision of OHD L-55.
- There was no correlation observed between stripping inflection point and AASHTO T 283 TSR.

AASHTO T 283 vs. MIST

- Based on the laboratory prepared cold feed aggregate sample results, no statistical difference was found between MIST and AASHTO T283 test methods.

- For laboratory mixes, MIST conditioned indirect tensile strength appeared to be slightly more severe (lower conditioned indirect tensile strength) than AASHTO T283 conditioned indirect tensile strength.
- Based on the plant produced results no statistical difference was found between MIST and AASHTO T283 test methods.
- For plant produced mixes, AASHTO T283 conditioned indirect tensile strength appeared to be slightly more severe (lower conditioned indirect tensile strength) than MIST conditioned indirect tensile strength.
- AASHTO T 283 takes two additional testing days to complete than MIST testing.

Laboratory vs. Plant Produced Mix

- There was no statistical difference between plant produced and laboratory produced OHD L-55 rut depths.
- A significant difference in conditioned indirect tensile strength between MIST laboratory and MIST plant results was observed. The plant produced results were more severe (lower conditioned indirect tensile strength) than laboratory results.
- A significant difference in conditioned indirect tensile strength between AASHTO T283 laboratory and AASHTO T 283 plant results was observed. The plant results were more severe (lower conditioned indirect tensile strength) than the laboratory results.

RECOMMENDATIONS

Based on the materials tested using the Hamburg loaded wheel tester (OHD L-55) AASHTO T 283 and MIST, the following recommendations are made.

- At this time it is not recommended to replace AASHTO T 283 with OHD L-55 for identification of moisture susceptible mixtures. There was no threshold value observed that would allow OHD L-55 to identify mixes with failing AASHTO T 283 TSR values. If additional verification testing is required, samples that fail AASHTO T 283 must be tested without anti-strip to have a valid data set.

- OHD L-55 could be implemented to evaluate plant produced mix for resistance to rutting if desired. However, the repeatability and reproducibility of OHD L-55 should be established to assist with setting specification limits.
- To reduce moisture sensitivity (AASHTO T 283) testing time, the MIST test should be evaluated as an eventual replacement for AASHTO T 283 for identification of moisture sensitivity of HMA mixtures. However, due to the high variability of the results found in this study, additional testing is recommended.
- Comparisons between MIST and AASHTO T283 on additional mixes should be considered. This could be accomplished by having ODOT and industry produce additional MIST samples to test along with their required AASHTO T 283 samples.
- Before implementation of the MIST the repeatability and reproducibility should be established.

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APPENDIX
MIST TEST PROCEDURE

1. Determine pre test bulk specific gravity using AASHTO T 166.
2. Turn the unit on.
3. Open the tank by remove the six hand-bolts and place the lid in the storage sleeve.
4. Fill MIST tank with clean water until water level is 2 inches above sample support plate (bottom plate). Carefully lift and lower the sample support plate to release any trapped air.
5. Place the sample into the tank as quickly as quickly as possible. Center sample on top of sample support plate (bottom plate). Take care to ensure that sample is not touching the heater. Place the sample constraining plate (top plate) on top of the sample. Fill the tank with water until water level is approximately 1 inch above the sample constraining plate. Carefully lift and lower the sample constraining plate to remove any trapped air. Secure the sample constraining plate in place by finger tightening the three retaining nuts.
6. Fill remainder of sample tank with clean water. Replace sample tank lid and secure with six had bolts. Pour water into the overflow cup that is not located in the center of the lid until water can be seen coming through the second overflow cup valve.

Self Test and Pre Conditioning

1. Set the desired settings. The current test settings will be displayed on the LCD. Set the number of cycles to 3500 cycles, water temperature to 50^{o}C, and the water pressure to 40 psi.
2. From the system ready screen, press ‘start’. Current settings will be displayed. If the settings are correct, press ‘start’. The MIST will run a self

test to check the Lower Limit Sensor, Upper Limit Sensor, the Pressure Sensor, and will display the pressure that can be achieved for the sample under test.

3. If the unit is unable to reach max pressure set point, the set point will automatically be reset to the highest pressure obtained (apparent pressure) during the self test. If this occurs, the new set point will be displayed on the LCD. If there are any problems during the self test, contact InstroTek Inc.
4. The MIST will then enter the heat up stage. During this stage, the water in the tank will be heated until its temperature reaches the set point. At this point the MIST will, if enabled, enter the dwell stage. During the dwell stage, the MIST will regulate the temperature at the dwell temperature set point for the duration of the preset dwell time.
5. During the test the display will indicate the number of cycles remaining in the test, the temperature, and the maximum pressure obtained during each cycle.
6. Once the test has finished, place an empty bucket under the drain valve. Open the drain valve and allow the water to drain into the bucket. Take extreme care as the water draining from the tank is hot and can cause injury.
7. Once all the water has drained from the fill cups on top of the lid, remove six had bolts securing the sample lid and carefully place lid in the storage sleeve. Sample tank lid is hot. Use temperature resistant gloves to remove the lid.
8. With sample still in the tank, close the drain valve and then pour room temperature water into the tank. Allow the sample to sit in room temperature water for 5 minutes. This will give the sample integrity during removal. Drain the water out of sample tank.
9. Remove the three retaining nuts securing the constraining plate (top plate) and place the plate into the storage sleeve.

10. Use both hands to lift the sample from the tank. Please use caution when handling the sample as it will be hot. Use temperature resistant gloves to remove the sample from the tank.
11. Immerse sample in the 77^{o}F water bath for a minimum of 2 hours.
12. Measure and record the post test bulk specific gravity of the sample by AASHTO T 166. You may use the same dry mass of the sample from pre test bulk specific gravity.
13. The sample is now ready for tensile strength testing.