STANDARD RUGGEDNESS STUDY ON MOISTURE INDUCED SENSITIVITY TESTER (MIST)

By

PREETHAM REDDY KAUKUNTLA

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Osmania University

Hyderabad, India

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STANDARD RUGGEDNESS STUDY ON MOISTURE

INDUCED SENSITIVITY TESTER (MIST)

Thesis Approved:

Dr. Stephen A. Cross

____
Thesis Adviser

Dr. Michael Phil Lewis

____

Dr. Xaioming Yang

____

Name: PREETHAM KAUKUNTLA

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Abstract:

Moisture damage is one of the major issues causing premature failure of Hot Mix Asphalt (HMA) pavements. However, there are no reliable test methods to determine moisture sensitivity in the laboratory. Moisture Induced Sensitivity Tester (MIST) is a new procedure that replicates moisture conditioning in the laboratory. However, the MIST does not have a standard test method and current testing is performed based on the manufacturer recommended settings. A ruggedness study (ASTM E1169) was performed on the MIST to determine if the tolerances of the test parameters have any impact on test results. The study was performed on only one mix. The manufacturer suggested test conditions are pressure, temperature, air void content (VTM) and height of compacted sample. The effect of the tolerances of these test conditions on indirect tensile strength (ITS) and Volume Change of the MIST conditioned samples were analyzed. The results from this study show that the tolerances on VTM and height of the sample had an effect on ITS of the HMA compacted samples while the VTM alone had an impact on Volume Change. A small experiment was performed to determine if the tolerance of the water bath soak after MIST conditioning had an impact on ITS values of the compacted HMA samples. The results suggest that the recommended 2-3 hour water bath soak had an effect on ITS values.

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CHAPTER I

INTRODUCTION

BACKGROUND

Moisture sensitivity of Hot Mix Asphalt (HMA) pavements has been a major issue throughout the country. Federal and state agencies have conducted numerous research studies to determine the major cause of this distress; however, the exact cause has not been completely determine. A number of laboratory tests have been used for determining moisture susceptibility in pavements but none of them have gained wide acceptance. The reason for this is that most of these tests do not relate to field conditions. There is a need for a method to accurately determine moisture susceptibility of HMA in the laboratory that stimulates field conditions.

In order to better simulate the field conditions, it has been suggested that the pumping action of traffic loading load is better replicated by a cyclic load than a constant load (1). InstroTek introduced the Moisture Induced Sensitivity Tester (MIST) which replicates the stripping mechanism in the field caused by cyclic loading and unloading of tire pressure on HMA. The MIST is a new device and does not have a standardized test procedure, only manufacturer recommended procedures

OBJECTIVE

The objective of this study is to perform a ruggedness study according to ASTM E1169 (2) on the test conditions suggested by the manufacturer for moisture conditioning of HMA mixes using the MIST. The Ruggedness Study is performed according to ASTM E1169 to determine if the outputs change as the test conditions fluctuate within the allowable limits.

Task 1 Literature Review

A literature review was performed to gain background information on moisture susceptibility of HMA mixtures. There is a large amount of literature is available on moisture susceptibility of HMA and the different tests used in the laboratory to evaluate moisture damage of HMA mixtures. However, the literature on the MIST is limited as the test is relatively new.

Task 2 Obtain Field Produced Mix

The material used for this study was a plant produced HMA mix obtained from a local contractor.

Task 3 MIST Sample Conditioning

MIST conditioning was performed on laboratory compacted samples of the plant produced mix. The samples were then evaluated for indirect tensile strength (ITS) and Volume Change.

Task 4 Analysis of Data

The ruggedness study was performed on the ITS values and percent Volume Change values obtained through MIST conditioning to determine if the test parameters recommended by the manufacturer have a significant effect on ITS and Volume Change results.

CHAPTER II

LITERATURE REVIEW

MOISTURE SUSCEPTIBILITY

A large number of distresses cause damage to HMA mixes. One of the major issues affecting the performance of HMA mixes is moisture damage. Moisture damage can be defined as a decrease in strength of HMA mixtures due to weakening of the bond between the binder and aggregate or reduction of stiffness of the whole mixture(3).

The two main causes responsible for this mechanism in an asphalt pavement are adhesive and cohesive failures. Adhesion failure occurs when the bond strength between asphalt cement and aggregates reduces due to presence of water and cohesive failure refers to decrease in the strength of the mixture on the whole. Moisture susceptibility is increased by any factor that increases the moisture content in the mix (4).

Extensive research, since early 1930's has been performed, to determine the cause of moisture damage in HMA. Many state agencies have been spending money to conceive a laboratory test method to replicate HMA mix behavior in the field with regard to moisture sensitivity.

FACTORS AFFECTING MOISTURE SUSCEPTIBILITY OF HMA PAVEMENTS

Different factors have an effect on moisture susceptibility. It is difficult to determine which factor has a greater effect on moisture susceptibility. The following factors have been reported to influence moisture susceptibility of HMA mixes. (5)

- **Inadequate Pavement Drainage**

Moisture vapor in the pavement is one of the main ingredients that induces stripping. Excessive water in the pavement can lead to premature stripping of HMA. Study of case histories by Kandhal et al.(6) has suggested that the stripping mechanism is not similar over the entire project. It was observed that stripping occurs in localized areas over-saturated with water mainly due to inadequate subsurface drainage conditions. Research conducted at the University of Idaho (7) revealed that, due to excessive subsurface water, air voids were filled with water and an increase in temperature caused this water to expand resulting in void pressures in the pavement. When the void pressure becomes significant, water could flow out of the voids and relieve the pressure. If the pressure is not relieved, then the tensile stresses developed due to the pressure may break the bonds causing stripping. Stripping that occurs due to traffic and void water pressure appears only inside the specimen and not on the exterior. (5)

- **Inadequate Compaction**

The optimum compacted air void content of HMA is 4-5%. During construction of the pavement, the HMA is compacted to 7-8% air voids with an assumption that 2-3 years of traffic will drive the air void content to its design levels. If compacted to the design air content, the voids are not well connected and the HMA becomes impermeable to water. However, due to poor construction practices, where the HMA is compacted to air voids in excess of 8% during construction, can lead to premature raveling. Stripping is believed to cause this type of premature raveling. Proper mix control and compaction can resolve this issue. (3)

- **Excessive Dust Coating on Aggregate**

The presence of dust and other fine particles on the surface of the aggregates can also lead to stripping. When there is dust on the aggregate, the binder is in contact with the dust layer and not with the aggregate, thus providing a channel for penetration of water. As a result the bond between the aggregate and binder is not very strong leading to adhesive failure.

- **Aggregates**

Aggregates that have a greater affinity to hold water are more likely to strip than aggregates that are drier. Therefore, it is recommended to completely dry aggregates prior to mixing to avoid stripping (4). Weak aggregates crumble under traffic loading and result in appearance of new uncoated aggregate in the mix and are susceptible to absorbing water resulting in stripping in the mix. Use of durable aggregate is recommended for use in HMA. If aggregates are highly porous then they tend to trap more water due to high absorption and this could lead to stripping in the pavements. (4)

- **Water Proofing Membrane and Seal Coats**

Mckesson (8) has made an interesting observation. “Ground water and water entering the roadbed from shoulders and other surface sources is carried upward by capillarity under a pavement.” This phenomenon is called Drainage by Evaporation. If the top surface of the pavement is covered by seal coat or a waterproof membrane then it becomes difficult for the water to escape by evaporation. Drainage by evaporation is equally as important as drainage by gravitation (5). Water that gets trapped in the mix as a result of this can lead to stripping.

MOISTURE SUSCEPTIBITY TESTS ON HMA

Various tests are available to determine moisture susceptibility of HMA. These tests can be distinguished into two categories, namely tests on loose mixes and tests on compacted mixes. The tests on loose mixes are conducted in the presence of water. These tests usually take shorter duration and require less sophisticated equipment. If a mix fails these tests then it is safe to conclude that the material has a good chance to strip.

Traffic loading mechanism can be replicated by tests conducted on compacted mixes or cores. Stiffness and strength of the compacted HMA mixes are usually measured using these tests. These tests require very complicated test procedures which consume a lot of time and require sophisticated and expensive equipment.

The following test methods are being used for determination of moisture susceptibility of HMA.

- **Boiling Test (ASTM D3625**)

This test is primarily used to determine the presence of an anti-strip agent in the HMA. For this test, about 250g of loose HMA is immersed in hot water and the temperature of water is raised to the boiling point. The mix is allowed to remain in boiling water for 10 minutes. The mix is then allowed to cool and a visual observation is made of the retained bitumen coating on the aggregate.

- **Static Immersion Test (AASHTO T 182)**

In this test, a loose HMA mix is immersed in a water bath at 77^0F. The mix is left in the water bath for 16 to 18 hours and the percentage of total visible gravel that remained coated with binder is estimated. This is reported as above or below 95 percent. This test method was discontinued in 2002 as an AASHTO test procedure.

- **Lottman Test**

This test was introduced by Lottman (1982) at the University of Idaho as part of the National Cooperative Highway Research Program, NCHRP 246 (7). This test predicts moisture susceptibility of HMA mixes. Nine specimens (4" diameter and 2.5" height) compacted to field air void contents are used in this procedure. Compacted samples are divided into three subsets. The first subset is unconditioned (dry), also called the control group. The second subset is vacuum saturated with water at a pressure of 26 inches of Hg for 30 minutes. The third subset is also vacuum saturated same as the second subset, but is followed by a freeze-thaw cycle with a freezing temperature of 0^0F for 15 hours followed by a water soak at 140^0F for 24 hours (7). All 9 specimens are tested for resilient modulus (M_R) and indirect tensile strength (ITS) at 55^0F or 73^0F. Subset 2 relates to field performance of up to 4 years and subset 3 reflects the performance of 4 to 12 years. The tensile strength ratio (TSR) is calculated for subsets 2 and 3. TSR is the ratio of ITS of conditioned specimens to controlled specimens. Lottman recommended a minimum TSR value of 0.70 for specimens to avoid stripping.

- **Tunnicliff and Root (ASTM D4867)**

This is a strength test that utilizes ITS. Six specimens with air voids between 6-8% are compacted and divided into two equal groups of three by air void content. The first group is left unconditioned and is known as the control group while the other group is vacuum saturated to 55-80% saturation under water at 20 inches of Hg for five minutes. Then the second group samples are conditioned in a 60^0C water bath for 24 hours. The control group specimens are conditioned for 20 minutes in a water bath at 77^0F. The ITS test is then performed on specimens of both the groups at a loading rate of 2 in/min at 77^0F. The minimum recommended values for this test is 0.70 to 0.80(9).

- **Modified Lottman Test (AASHTO T 283)**

The modified Lottman test of AASHTO T 283 was first developed by Kandhal (5) and is a combination of Lottman test and Tunnicliff and Root Conditioning test. Six samples are compacted to 7±0.5% air voids and divided into conditioned and unconditioned sets. The dry subset is stored in a plastic wrap at 77±1^{0}F and is submerged in a water bath for 2 hours before determining the ITS. The conditioned set is vacuum saturated to 70-80% with a vacuum of 10-26 in. Hg for 5-10 minutes, then put in a freezer at 0±5^{0}F for 16 hours, followed by a hot soak in a water bath at 140±2^{0}F for 24±1 hours. The samples are then immersed in a water bath at 77±1^{0}F for 2 hours±10 minutes followed by ITS testing. The ratio of the average ITS of the dry specimens and wet specimens give the Tensile Strength Ratio (TSR). The recommended value of TSR for a mix is 0.80 or higher.

TSR testing has been found to be unreliable. Azari (10) conducted a study which revealed that the acceptable range of TSR values inside one laboratory is 9% whereas the range for inter-laboratory testing is 25%. Therefore it is not acceptable to compare moisture susceptibility between laboratories.

- **Immersion-Compression Test (AASHTO T 165)**

In this test, six cores are compacted to four inches height and four inches in diameter. These cores are split into two groups of two each. The first group is unconditioned whereas the second group is conditioned in a water bath at 120^{0}F for four days or at 140^{0}F for one day. The six specimens are then tested for unconfined compressive strength at 77^{0}F at a loading rate of 0.2 in/min. The retained compressive strength is calculated. A minimum retained strength of 70 percent is specified for this test. The drawback of this test is the fact that retained strengths of up to 100% have been obtained (11). This test is not sensitive enough to measure the damage caused by moisture due to the internal pore water pressure that develops (12). This test was withdrawn as an AASHTO test procedure in 2006.

- **Hamburg Wheel Tracking Device (AASHTO T 324)**

The Hamburg wheel tracking device was developed in Hamburg, Germany in the 1970s. This device measures the effects of rutting and moisture on HMA. The device consists of a steel wheel moving constantly over an HMA sample. The device can hold up to 2 specimens at a time. Rutting on the sample, due to the number of wheel passes, is obtained from this test. A graph of rut depth vs number of passes is obtained and it has been suggested that moisture susceptibility can be measured by a stripping inflection point and stripping slope as shown in figure 1. Colorado specifies a rut depth not more than 10mm for 20,000 passes as the criteria for this test. Hamburg could not identify any moisture sensitive mixes in Oklahoma (13).

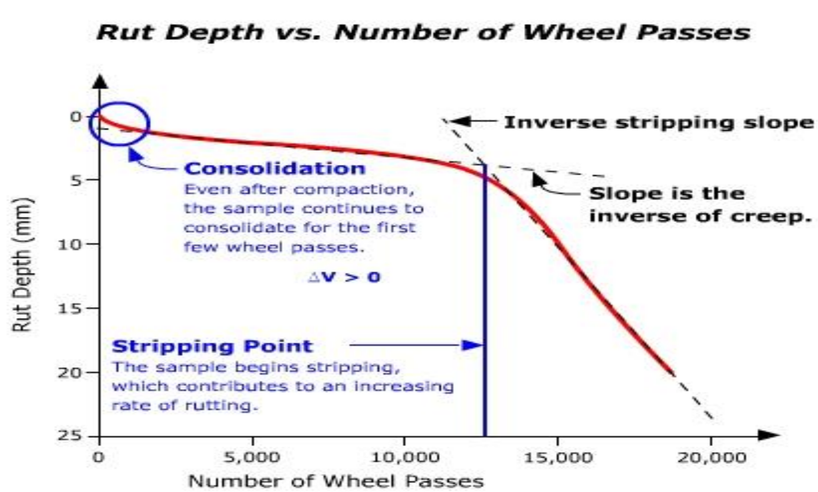

Figure 1, Stripping Inflection Point (14)

- **Moisture Induced Sensitivity Tester (MIST)**

The Moisture Induced Sensitivity Tester (MIST) is a relatively new test for conditioning HMA samples for evaluating moisture susceptibility of HMA mixes. The MIST is a self-contained conditioning unit manufactured by InstroTek (15). The machine can determine the moisture damage caused by water by replicating field cyclic traffic loading at hot in-place pavement temperatures. Each cycle of loading involves pushing water into the sample and pulling the water out, just as in the field when a tire moves over a wet pavement. A moving tire pushes the water into the pavement and pulls the water out when the tire is no longer in contact with the pavement. The literature available on the MIST is limited. The main goal of this test is to replicate field conditions that cause moisture susceptibility in the laboratory in a short period of time. Other test methods take a longer duration to complete usually over 24 hours whereas the MIST can be completed in 6 hours. The MIST consists of a tank that can hold two samples (compacted to 150mm in diameter and 100mm in height) and is filled with water. The test temperature of the machine can be set between 30^0C-60^0C. Seventy five psi of pressure can be reached in the tank. The number of pressure cycles for the test can be set between 1 and 50,000 cycles. The general test conditions of temperature and pressure are 60^0C and 40psi, respectively, as suggested by the manufacturer. The manufacturer recommends 3500 pressure cycles for the test. After the samples are conditioned in the MIST, the height and diameter of the samples are measured. The bulk specific gravity and ITS of the conditioned samples are obtained and the Volume Change and TSR values are determined. The recommended TSR for MIST is a minimum of 0.80 (16). The manufacturer has suggested that 1% Volume Change would mean that the sample is susceptible to stripping.

CHAPTER III

TEST PLAN

OBJECTIVE

The objective of this study is to perform a ruggedness study in accordance with ASTM E1169 on the testing parameters provided by the manufacturer of the Moisture Induced Sensitivity Tester (MIST) for moisture conditioning of Hot Mix Asphalt (HMA) and to determine if the tolerance limits of these parameter levels have a statistically significant impact on test results.

MATERIALS AND TESTING

The HMA mix used for the ruggedness study was a plant produced mix provided by Haskell-Lemon Construction Co. The mix design was available from the Oklahoma Department of Transportation (ODOT). The mix was an ODOT S4 (1/2" nominal) mix and the asphalt cement used was a PG76-28 OK. Table 1 lists the details of the aggregates used in the mix.

Table 1, Aggregate Suppliers and Percentage Aggregates Used

Aggregate	Producer/Supplier	% USED
5/8" Chips	Hanson Aggregates, WRP Inc (Davis, OK)	40
Manufactured Sand	Martin-Marietta (Davis, OK)	13
Manufactured Sand	Hanson Aggregates, WRP Inc (Davis, OK)	25
Screenings	Martin-Marietta (Davis, OK)	10
Sand	General Materials (MacArthur Pit) (OKC,OK)	12

The results of the tests conducted on the aggregates reported in the mix design are shown in table 2.

Table 2, Tests on Aggregates

Tests on Aggregates	Values	Required	Units
Durability Index	75	40 min.	%
F.A.A %U	-	N/A	%
Flat and Elongated	0	10 max.	%
Fractured Faces	100/100	98/95 min.	%
Insoluble Residue	73.6	40 min.	%
LA Abrasion	27	40 max.	%
Micro-Deval	10.8	25 max	%
Sand Equivalent	74	50 min.	%
Asphalt Absorbed	0.87		%
Effective Specific Gravity (Gse)	2.734		
Bulk Specific Gravity (Gsb)	2.671		

The mix properties at the optimum asphalt content from the mix design data are listed in table 3 and the other results for the tests conducted on the compacted mixes, as mentioned in the mix design, are tabulated in table 4.

Table 3, Mix Design Properties at Optimum Asphalt Content

Property	AC %	VTM (%)	VMA (%)	VFA (%)	DP
Value	5.2	4	14.46	74	0.85

Table 4, Properties of the Compacted Samples at Optimum Asphalt Content

Property	Value	Specification
ITS (psi)	143.6	75 min
TSR	0.80	0.8/ 0.75 min. (Design/Field)
Hamburg Rut Depth (mm)	2.53	12.5 @ 20000 cycles
Permeability (10^{-5}cm/s)	3.8	12.5 max.

The optimum Asphalt Content of the mix was 5.2% according to the mix design from ODOT. To verify the mix properties of the plant produced mix, the following tests were performed at the Asphalt Laboratory at Oklahoma State University. The maximum theoretical specific gravity (Gmm) of the mix was determined using AASHTO T 209. The asphalt content of the mix was then determined using the Ignition Furnace according to AASHTO T 309. A washed sieve analysis was then performed on the recovered aggregate according to AASHTO T 30. The mix is heated to a compaction temperature of 300^0F and moisture conditioned according to AASHTO T 283. Six samples were compacted to 95mm and 7 ± 0.5 percent air voids and Tensile Strength Ratio (TSR) determined according to AASHTO T 283.

MOISTURE INDUCED SENSITIVITY TESTER (MIST)

The moisture damage of a sample is traditionally measured according to AASHTO T 283. The test involves water saturation of the compacted HMA samples to between 70-80 percent. The saturated samples are then conditioned under freeze & thaw cycles for 24 hours. The samples are then tested in indirect tension and the tensile strength of the conditioned sample is measured. The tensile strength of the conditioned sample is compared to the tensile strength of unconditioned sample to determine the Tensile Strength Ratio (TSR) of the sample. A minimum TSR ratio of 0.80 is required by most DOTs.

Due to the long duration of the moisture conditioning using this test method and also to replicate the pore pressure created by the vehicles in the field, the *Moisture Induced Sensitivity Tester (MIST)* was developed. The pore water pressure created in the field is simulated in the laboratory by the MIST. Figure 2 shows the picture of the MIST equipment.

Figure 2, OSU's MIST

Conditioning

The MIST is a self-contained unit which includes a hydraulic pump and piston mechanism to add and relieve pressure inside the chamber. The test involves placing a pair of 4" or 6" diameter samples of 1" to 6" thickness inside the chamber. The chamber is filled with hot water (Not more than 3^0C less than the test temperature and not more than then test temperature) and the lid is closed and the test is started. The machines heats the water up to the test temperature and will start cycling between zero and the test pressure required. The cycling process takes approximately 3 hours to complete and the samples are then conditioned in a water bath for 2-3 hours at 77^0F. The number of cycles that we used for the MIST conditioning is 3500 cycles. After MIST conditioning, the hot water inside the MIST is drained by opening the drain valve and room temperature water is poured into the MIST to allow the samples to cool before handling. The test is automated and takes approximately 6 hours to complete. There is no standard test procedure for the MIST. The indirect tensile strength (ITS) is not a part of the MIST as the MIST is a sample conditioning device. The manufacturer has recommended looking at Volume Change while other researchers are looking at the ITS. In this study we looked at both the ITS and Volume Change.

Volume Change

The volume of the samples are measured before and after conditioning by water displacement at 77^0F using the following formula.

$$\text{Volume} = \text{SSD} - \text{Submerged} \quad [3.1]$$

SSD = Saturated Surface Dry weight

The difference in volumes of the sample before and after conditioning gives the Volume Change (%) of the sample. This can be measured using the formula in equation 3.2.

$$VC(\%) = ((\text{After} - \text{Before})/\text{Before}) * 100 \quad [4.1]$$

Where

VC= percent Volume Change at 77^0F

After= Volume of sample after MIST conditioning at 77^0F

Before= Volume of the sample before MIST conditioning at 77^0F

Indirect Tensile Strength (ITS)

MIST samples were tested in indirect tension to determine the ITS of the conditioned samples. This value is compared to the dry or conditioned ITS to determine the Tensile Strength Ratio (TSR). ITS values were used rather than TSR values as there was only one dry sample and essentially ITS is divided by a constant to determine the TSR.

WATER BATH CONDITIONING

The manufacturer recommended that samples be immersed in a water bath at 77 ^{0}F for 2-3 hours after the MIST conditioning. Traditionally, the time for which the sample is immersed in water in other moisture sensitivity tests is 2 hours ± 10 minutes. It was noticed during water bath conditioning that the 2-3 hour soak could have had an effect on ITS and Volume Change. Further testing was performed to determine if the tolerance time on soak had any significant effect on ITS values and Volume Change. Eight samples were compacted to a height of 95mm and a VTM of 7±0.5%. Each set of two samples were MIST conditioned at the mid-level testing conditions and were then transferred to the water bath. For each set, one sample was left in the water bath for two hours and the other for three hours, and the tensile strengths were calculated. The procedure was repeated for the other three sets. A t-test was performed on the data obtained and checked to determine if there is a significant effect on the output by conditioning for 2 or 3 hours. This was not included as a part of ruggedness study.

RUGGEDNESS STUDY

The MIST does not have a standardized test procedure. In order for a test procedure to be used as a specification, a Ruggedness Study and Repeatability study are recommended. The Ruggedness Study is performed according to ASTM E1169, to determine if the outputs change as the test conditions fluctuate within the allowable limits. A Ruggedness Study is performed prior to a repeatability study.

The manufacturer suggests the following test conditions for moisture conditioning using the MIST:

- Pressure 36-44 psi
- Temperature 59-61 ^{0}C
- Void Content (VTM) as 6.5-7.5%
- Sample compacted to a height of 90-100mm.

A ruggedness study is an application of a statistically designed experiment. In a ruggedness study, these test conditions are called *factors* and the highs and lows are called *levels*. In this study the two extreme values (two levels) of each test condition (four factors) were tested on samples and the corresponding values of ITS and volumes before and after the conditioning are noted. The ruggedness study tests whether the levels of the factors have any effect on the output (TSR and Volume Change) of the test method.

A ruggedness study can be performed in two ways a) Method of Replicates and b) Method of Fold over. In this study the ruggedness study is performed by the method of replicates. In the method of replicates two sets of samples are tested and analyzed. The first set is called the Original set and the second is called Replicate set. Both sets are identical. Table 5 shows the tolerances (levels) of the test conditions (factors) used during MIST conditioning. The level settings are denoted by L and H (Low and High respectively).

Table 5, Test Conditions for Samples

Tolerance	Pressure (psi)	Temperature ^{0}C	VTM (%)	Height(mm)
LOW (L)	36	59	6.5	90
HIGH (H)	44	61	7.5	100

Table 6 shows the experiment design with four factors having two levels each. The order of testing is identical for both the original and replicate set.

Table 6, Design of Test Conditions for MIST

Sample No.	Pressure	Temperature	VTM	Height
1	L	L	L	L
2	L	L	L	H
3	L	L	H	L
4	L	L	H	H
5	H	L	L	L
6	H	L	L	H
7	H	L	H	L
8	H	L	H	H
9	L	H	L	L
10	L	H	L	H
11	L	H	H	L
12	L	H	H	H
13	H	H	L	L
14	H	H	L	H
15	H	H	H	L
16	H	H	H	H

MIST conditioning is performed on the samples as per the order listed in table 6, on both the original and replicate sets. For each set the ITS values and Volume Change are recorded. The differences and averages of the ITS values for the original set and replicate set are calculated. The procedure is repeated for the differences and averages of Volume Change for the original set of samples and the replicate set. The standard deviation of the differences of each output is then calculated. The estimate of the standard deviation of the test results (s_{reps}) is calculated and from this the estimate of standard error (s_{effect}) is calculated.

The ITS values of each factor on identical level (lows or highs) are obtained and their averages are calculated. The difference of the averages (Lows-Highs) gives the estimated main effects of the factors. These effects of factors are arranged in decreasing order and the student's t value, probability (p) and half normal plot values for each factor are obtained. The effect is then plotted against the half normal values. A line is drawn at a slope of 1/ s_{effect} and through the lowest point on the graph. This line acts as a reference line and any factor whose corresponding point falls to the right of the line is deemed to have a significant effect on the outcome of the test. Thus, the ruggedness study is performed to determine the effect of tolerances on the output of the test result. The procedure was performed for conditioned ITS and Volume Change to determine if any of the factors have an impact on the final result.

CHAPTER IV

TEST RESULTS

MATERIALS

The mix used for the ruggedness study was obtained from a local HMA contractor. The mix was an ODOT S-4 mix with PG 76-28 asphalt cement. The mix was tested in the laboratory to verify the mix design properties. The maximum theoretical specific gravity (Gmm) of HMA was determined according to AASHTO T 209.The asphalt content of the mix was then determined by the ignition furnace according to AASHTO T 308. The aggregate recovered from the ignition furnace was then subjected to a washed sieve analysis according to AASHTO T 30.

Samples of the plant produced mix was heated up to compaction temperature and compacted to a void content of 7±0.5% air voids in a superpave gyratory compactor to test for moisture sensitivity according to AASHTO T 283.The results obtained from these tests are tabulated in table 7 and the sieve analysis results from the aggregate recovered from the ignition furnace are shown in table 8.

Table 7, Mix Properties

Test Method	Property	Value
AASHTO T209	Theoretical Specific Gravity (Gmm)	2.498
AASHTO T309	Asphalt Content (%)	5.4
AASHTO T283	Tensile Strength Ratio	0.85

Table 8, Sieve Analysis of Recovered Aggregate

Sieve Size	% Retained	% Passing
1/2 inch	8	92
3/8 inch	10	82
No. 4	20	62
No. 8	21	41
No. 16	13	28
No. 30	7	21
No. 50	7	14
No. 100	8	6
No. 200	3	4

INDIRECT TENSILE STRENGTH (ITS)

The test results for the ruggedness study of the moisture conditioning of HMA using the MIST are provided in this chapter. The analysis was made to determine if there is any impact of the extreme high and extreme low testing conditions, suggested by the manufacturer, on the ITS and the Volume Change of MIST conditioned HMA samples. The analysis was performed according to the ASTM E1169, by the method of replicates. The highs and lows of the test conditions used for testing are described in table 5. Sixteen samples were prepared for testing according to the combinations listed in table 6 for each set of samples. These samples were then tested with the MIST and the ITS was recorded for each sample as shown in tables 9 and 10 for the original and replicate sets, respectively.

Table 9, ITS Values for the Original Set of Samples

Sample Number	Pressure	Temperature	VTM	Height	Tensile Strength(psi)
1	L	L	L	L	118.16
2	L	L	L	H	104.29
3	L	L	H	L	100.62
4	L	L	H	H	75.69
5	H	L	L	L	103.41
6	H	L	L	H	122.57
7	H	L	H	L	112.65
8	H	L	H	H	84.94
9	L	H	L	L	107.86
10	L	H	L	H	106.25
11	L	H	H	L	131.40
12	L	H	H	H	103.01
13	H	H	L	L	118.81
14	H	H	L	H	107.58
15	H	H	H	L	111.12
16	H	H	H	H	77.16

Table 10, ITS values of the Replicate Set of Samples

Sample Number	Pressure	Temperature	VTM	Height	Tensile Strength (psi)
1R	L	L	L	L	121.36
2R	L	L	L	H	110.48
3R	L	L	H	L	113.17
4R	L	L	H	H	80.01
5R	H	L	L	L	119.60
6R	H	L	L	H	122.79
7R	H	L	H	L	120.58
8R	H	L	H	H	88.94
9R	L	H	L	L	123.66
10R	L	H	L	H	119.34
11R	L	H	H	L	112.28
12R	L	H	H	H	115.01
13R	H	H	L	L	116.26
14R	H	H	L	H	110.22
15R	H	H	H	L	111.08
16R	H	H	H	H	77.16

VOLUME CHANGE

The volume of each MIST conditioned sample was also calculated before and after the MIST conditioning. Volumes of each sample are calculated by water displacement at 77^0F by subtracting the submerged weight of the sample from the Saturated Surface Dry (SSD) weight. The difference of the volumes of the sample before MIST conditioning and after MIST conditioning (from 4.1) give the Volume Change of the sample expressed in percentage points. Tables 11 and 12 show the Volume Change before and after MIST conditioning of the Original and Replicate sets, respectively.

$$VC = ((After - Before)/Before) * 100 \qquad [4.1]$$

Where

VC= percent Volume Change at 77^0F

After= Volume of sample after MIST conditioning at 77^0F

Before= Volume of the sample before MIST conditioning at 77^0F

Table 11, Volume Change for the Original Set

Sample Number	Pressure	Temperature	VTM	Height	Volume Change (%)
1	L	L	L	L	-0.23
2	L	L	L	H	0.27
3	L	L	H	L	-0.52
4	L	L	H	H	0.19
5	H	L	L	L	-0.16
6	H	L	L	H	0.22
7	H	L	H	L	-0.41
8	H	L	H	H	-0.32
9	L	H	L	L	-0.27
10	L	H	L	H	0.06
11	L	H	H	L	-0.49
12	L	H	H	H	-0.29
13	H	H	L	L	-0.10
14	H	H	L	H	-0.10
15	H	H	H	L	0.27
16	H	H	H	H	0.33

Table 12, Volume Change for Replicate Set

Sample Number	Pressure	Temperature	VTM	Height	Volume Change (%)
1R	L	L	L	L	-0.06
2R	L	L	L	H	0.04
3R	L	L	H	L	-0.04
4R	L	L	H	H	-0.48
5R	H	L	L	L	-0.14
6R	H	L	L	H	0.13
7R	H	L	H	L	-0.68
8R	H	L	H	H	-0.52
9R	L	H	L	L	0.05
10R	L	H	L	H	0.15
11R	L	H	H	L	-0.87
12R	L	H	H	H	-0.58
13R	H	H	L	L	0.12
14R	H	H	L	H	0.13
15R	H	H	H	L	-0.13
16R	H	H	H	H	0.03

WATER BATH CONDITIONING

During the ruggedness study it was observed that the post-MIST conditioning in a 77^{0}F water bath soak of 2-3 hours, as per the manufacturer, could have had an impact on ITS values of the samples as the tolerance was much higher than the conditioning of other methods (2$\pm$10 minutes).

The ruggedness study was performed at 2 hours±10 minutes. A short experiment was performed to see if there was any impact of this duration of post-MIST conditioning on the final results. Eight samples were compacted at 95mm with 7±0.5 % air voids and conditioned in the MIST at 40 psi and 60 ^{0}C for 3500 cycles. These values were considered as they are the mid-points of the recommended ranges. For each set of samples tested, one sample was left in water bath for 2 hours and the other for 3 hours. This was repeated for all four sets. The ITS values obtained are reported in table 13. A t-test was performed to check if the post-MIST water bath conditioning duration had any significant impact on ITS values of the samples. However, this was not a part of the ruggedness study.

Table 13, ITS Values for 2 and 3 Hour Soak in Water Bath

Set ID	ITS Values (psi) Water Bath Conditioning	
	2 Hours	3 Hours
1	93.8	85.12
2	92.54	81.7
3	89.09	83.39
4	93.56	82.34

CHAPTER V

ANALYSIS OF TEST RESULTS

RUGGEDNESS EVALUATION OF INDIRECT TENSILE STRENGTH

After MIST conditioning, the samples were tested in indirect tension and the peak load noted. The Indirect Tensile Strength (ITS) value of each sample is obtained by using the equation [5.1]. The ITS values obtained from the MIST conditioned Original and Replicates sets from tables 9 and 10 were analyzed according to ASTM E1169. Table 14 shows the ITS of the original and replicate sets along with their differences and averages.

$$S_t = 2P/(\pi * t * D) \qquad [5.1]$$

Where:

S_t = ITS, psi

P = Maximum load, lb.

t = specimen height taken before breaking, in.

D = specimen diameter, in.

Table 14, ITS of Original and Replicates Sets of Samples with their Differences and Averages

Original set ITS (psi)	Replicate set ITS (psi)	Average ITS (psi)	ITS Difference) (Replicate-original) (psi
118.16	121.36	119.76	3.20
104.29	110.48	107.38	6.19
100.62	113.17	106.89	12.55
75.69	80.01	77.85	4.32
103.41	119.60	111.50	16.19
122.57	122.79	122.68	0.22
112.65	120.58	116.61	7.93
84.94	88.94	86.94	4.00
107.86	123.66	115.76	15.80
106.25	119.34	112.79	13.09
131.40	112.28	121.84	-19.12
103.01	115.01	109.01	12.00
118.81	116.26	117.53	-2.55
107.58	110.22	108.90	2.64
111.12	111.08	111.10	-0.04
77.16	77.16	77.16	0.00

First, the standard deviation (S_d) of the ITS replicate differences is calculated (S_d) from equation [5.2]. Next, the estimate of the standard deviation of the test results (S_{reps}) is calculated from formula [5.3] and from this the estimate of standard error (S_{effect}) is calculated using equation [5.4]. The calculated values are shown in table 15.

$$S_d = \text{standard deviation} = (\Sigma(X\text{-}Y)^2/N)^{0.5} \qquad [5.2]$$

Where

X = each value in data set of ITS replicates difference

Y = mean of all values in data set

N= number of runs = 16

$$S_{reps} = (S_d/2^{0.5}) \qquad [5.3]$$

$$S_{effect} = (4S^2_{reps}/((N)(Reps)))^{0.5} \qquad [5.4]$$

Where

N= number of runs = 16

Reps = number of replicates of design = 2

Table 15, Standard Deviation and Error for ITS Values

Standard Deviation (S_d) (psi)	8.73
Estimate of standard deviation of results (S_{reps}) (psi)	6.17
Estimate of standard error (S_{effect}) (psi)	2.18

The ITS values of each factor on identical levels (lows or highs) are obtained from the data in tables 9 and 10 and their averages are calculated. The difference of the averages (Lows-Highs) gives the estimated main effects of the factors. Table 16 shows the average ITS values for high and lows for each factor and also their main effect on the test.

Table 16, Average ITS Values (psi) for Each Level of Each Factor and Main Effect of Factors

Condition	Pressure	Temperature	VTM	Height
	ITS (psi)			
Av. Highs H'	106.55	109.26	100.92	100.34
Av. Lows L'	108.91	106.20	114.54	115.12
Main Effect (L'-H')	2.35	-3.05	13.61	14.78

The estimated effects of all factors are arranged in a decreasing order of values and these values are divided by the standard error to obtain the *Student's T value* of the effect. *Probability (p-value)* of each factor is calculated using equation [5.5]. Half normal plotting values for each factor are obtained from table A2.1 of the ASTM E1169 based on the number of effects and ordered effects. The half normal plot values are plotted against the absolute estimated effect. A line is drawn through the lowest point with a slope of 1/ S_{effect}, which equals 0.45 for ITS values. This is a reference line and all the points that fall on the right side of the line have a significant effect on the final result.

$$p\text{-}value = (N-1)(reps-1) = (15)(1) = 15 \quad [5.5]$$

where

N= number of runs = 16

Reps = number of replicates of design = 2

Table 17 shows the effects of factors in order and their corresponding statistical values along with their half normal plot values. The effects are arranged based on the decreasing value of their corresponding estimated effect. A half normal plot is then plotted with the Effect on the horizontal axis and the Half Normal values on the vertical axis as shown in figure 3. A reference line is drawn with a slope of 1/ S_{effect} which is 0.45. According to the ASTM E1169, potentially significant effects are those that are farthest to the right of the line

Table 17, Statistical Significance of Effects for the Ruggedness Test on the MIST for ITS

Effect Order, e	Effect	Est. Effect	Student's t	*p*-value	Half Normal Plotting Values
4	Height	14.79	6.77	<0.001	1.53
3	VTM	13.61	6.23	<0.001	0.89
2	Pressure	2.36	1.08	0.30	0.48
1	Temperature	-3.06	-1.40	0.18	0.16

The p-values from table 17 show that the tolerances on pressure and temperature do not have a significant effect on ITS values but the tolerances on the height of the sample and VTM have a significant impact on ITS values at a level of significance exceeding 95% ($\alpha = 0.05$).

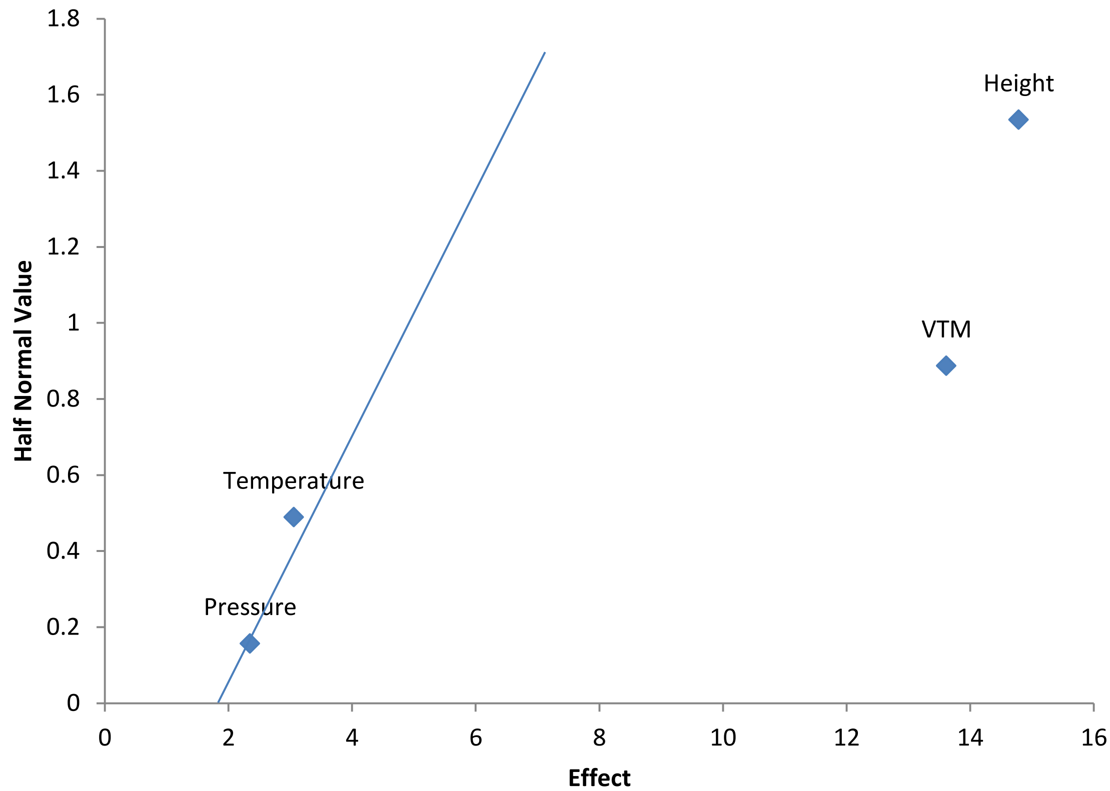

Figure 3, Half Normal plot for MIST conditioning test method for ITS

From the results shown in figure 3, we conclude that Height and Void Content of the samples have a significant effect on ITS when the samples are conditioned by the MIST. The factor having the largest effect is sample height. This means the tolerance levels for height and VTM in a test should be reduced to control the variability between replicates.

RUGGEDNESS EVALUATION OF VOLUME CHANGE

Volume of a sample is calculated by subtracting the difference of saturated surface dry (SSD) and submerged weights of the sample under water at 77^0F [3.1]. Volumes are calculated before MIST conditioning and after MIST conditioning and their difference is obtained [4.1]. This difference is called Volume Change and expressed in percentage points. The analysis was repeated for the Volume Change.

The Volume Change values from the MIST conditioned Original and Replicates sets are analyzed according to the ASTM E1169. Table 18 shows the Volume Changes of the original and replicate sets from tables 11 and 12 along with their differences and averages.

Table 18, Volume Change of Original and Replicate Sets of Samples with their Differences and Averages

Volume Change (original) (%)	Volume Change (Replicates) (%)	Average Volume Change (%)	Volume Change Difference(Original - Replicates) (%)
-0.23	-0.06	-0.14	0.17
0.27	0.04	0.15	-0.23
-0.52	-0.04	-0.28	0.48
0.19	-0.48	-0.14	-0.67
-0.16	-0.14	-0.15	0.02
0.22	0.13	0.179	-0.08
-0.41	-0.68	-0.54	-0.27
-0.32	-0.52	-0.42	-0.20
-0.27	0.05	-0.11	0.32
0.06	0.15	0.10	0.09
-0.49	-0.87	-0.68	-0.38
-0.29	-0.58	-0.43	-0.29
-0.10	0.12	0.01	0.22
-0.1	0.13	0.015	0.23
0.27	-0.03	0.12	-0.30
0.33	0.03	0.18	-0.30

First, the standard deviation (S_d) of the Volume Change replicate differences is calculated (S_d) from equation [5.2]. Next, the estimate of the standard deviation of the test results (S_{reps}) is calculated from formula [5.3] and from this the estimate of standard error (S_{effect}) is calculated using equation [5.4]. The calculated values are shown in table 19

Table 19, Standard Deviation and Standard Error Values for Volume Change.

Standard Deviation (S_d)	0.30
Estimate of standard deviation of results (S_{reps})	0.21
Estimate of standard error (S_{effect})	0.07

The Volume Changes of each factor on identical levels (lows or highs) are obtained from the data in tables 11 and 12 and their averages are calculated. The difference of these averages (Lows-Highs) gives the estimated main effect of the corresponding factor. Table 20 shows the averages of the Volume Change for each level for each factor and also the estimated main effect of each factor.

Table 20, Average Volume Change Values for Each Level of Each Factor and Main Effect of Factors

Condition	Pressure	Temperature	VTM	Height
	ITS (psi)			
Av. Highs H'	-0.075	-0.099	-0.275	-0.045
Av. Lows L'	-0.116	-0.168	-0.007	-0.222
Main Effect (L'-H')	-0.116	-0.069	-0.282	-0.176

The estimated effects of all factors are arranged in a decreasing order of values and these values are divided by the standard error to obtain the *Student's T value* of the effect. *Probability (p-value)* of each factor is calculated using equation [5.5]. Half normal plotting values for each factor are obtained from table A2.1 of the ASTM E1169 based on the number of effects and ordered effects. Table 21 shows effects of factors in decreasing order of magnitudes of estimated effect and their corresponding statistical values along with their half normal plot values. The half normal plot values are plotted against the absolute estimated effect. A line is drawn through the lowest point with a slope of 1/ S_{effect}, which is 12.99 for the Volume Change. This is a reference line and all the points that fall on the right side of the line have a significant effect on the final result.

Table 21, Statistical Significance of Effects for the Ruggedness Test on the MIST for Volume Change

Effect Order, e	Effect	Est. Effect	Student's t	*p*-value	Half Normal Plotting Values
4	VTM	0.282	3.673	<0.001	1.53
3	Temperature	-0.069	-0.896	0.384	0.89
2	Pressure	-0.116	-1.507	0.152	0.48
1	Height	-0.176	-2.286	0.160	0.16

The p-values from table 21 suggest that the tolerances on height of the sample, pressure and temperature do not have a significant effect on Volume Change but the tolerance on VTM has a significant impact on Volume Change at a level of significance not exceeding 95% ($\alpha = 0.05$)..

A half normal plot is then plotted with the Effect on the horizontal axis and the Half Normal values on the vertical axis. A reference line is drawn with a slope of 1/ S_{effect}. According to the

ASTM E1169, potentially significant effects are those that are farthest to the right of the line. Figure 5 shows the half normal plot for the MIST method of conditioning for Volume Change.

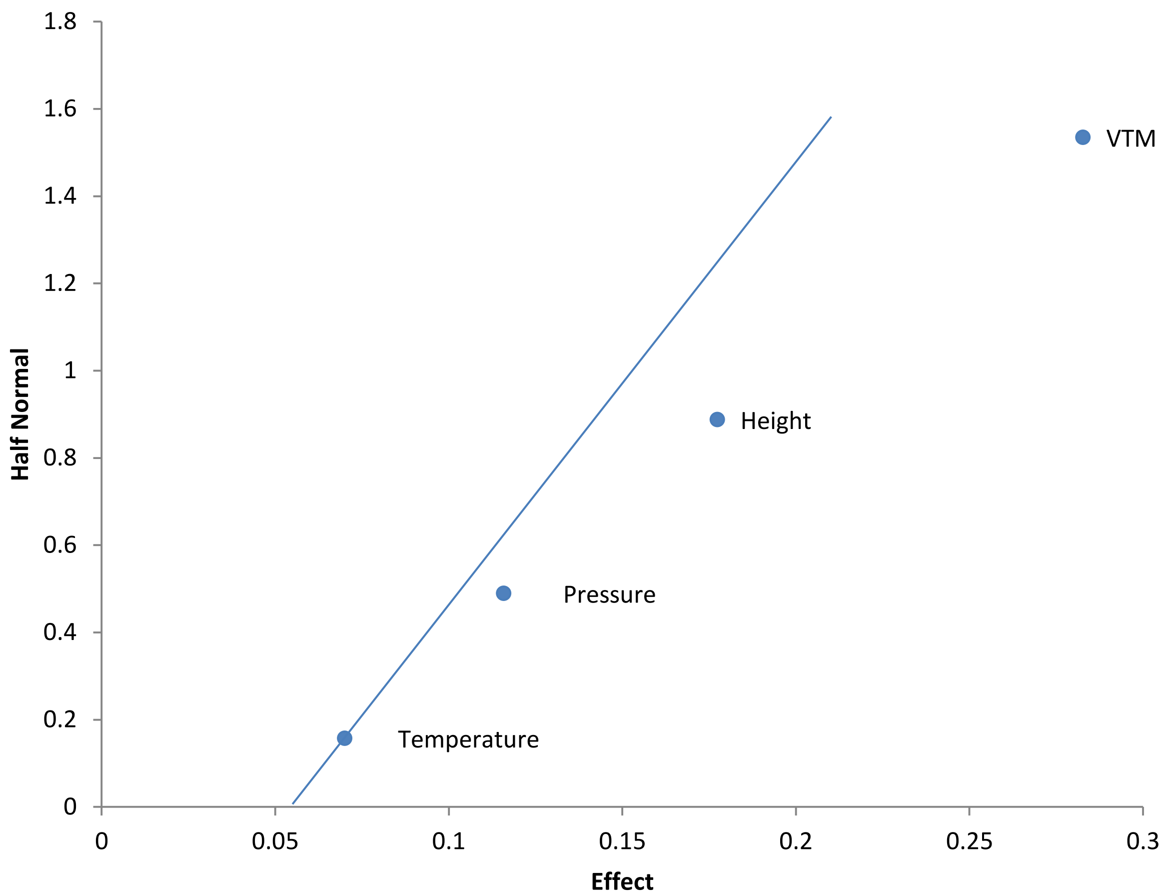

Figure 5, Half Normal plot for MIST conditioning test method for Volume Change.

From the results shown in figure 5, we conclude that Void Content (VTM) of the sample has a significant effect on the Volume Change when the samples are conditioned by the MIST. VTM was also a significant factor for ITS.

WATER BATH CONDITIONING

Indirect Tensile Strength

After MIST conditioning, the samples are conditioned in a water bath for two to three hours according to the manufacturer. Further analysis was performed to determine if the tolerance of this duration has any effect on the outcome ITS of the samples. A two-tailed t test was run on the data from table 13 at a confidence limit of 99% (α=0.01) and determined if there is a statistical difference between the ITS values for two and three hours of water bath conditioning.

Table 22 shows the results of the t-test performed on the ITS values of water bath conditioning post-MIST where samples were held in the water for two hours and three hours.

Table 22, t-Test: Independent Two-Sample t-Test on ITS

	2 hours	3 hours
Sample Size	4	4
Sample Mean	92.24	83.13
Variance	4.72	2.23
Standard Deviation	2.17	1.49
t-statistic	6.902	
Degrees of Freedom	6	
Confidence Level	99%	
t-critical	3.707	

From table 22, t-stat > t critical. We reject the null hypothesis. Hence there is a significant difference between the two sets of data. Therefore the duration of samples in water bath (2-3 hours) has a significant effect on the ITS values

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

A ruggedness study was performed in accordance with ASTM E1169 on laboratory compacted samples of a plant produced mix which was conditioned using the MIST. The factors of the MIST test conditions suggested by the manufacturer were varied to test if the tolerances of these factors had an impact on the outputs of the test. The output parameters that were considered for this test were the Indirect Tensile Strength (ITS) and Volume Change. The mix used was a plant produced ODOT S-4 mix. The following conclusions and recommendations have been made based on the results obtained from this study. The four factors which were tested as part of this study are

1. Pressure (36-44psi)
2. Temperature (59-61^{0}C)
3. VTM (7$\pm$0.5%)
4. Height of the sample (90-100mm)

CONCLUSIONS

Indirect Tensile Strength (ITS)

- Void Content (VTM) and sample height were found to have a significant effect on the ITS of the sample conditioned by the MIST.
- Height of the compacted sample has a bigger impact on the ITS values than VTM.

- The Height of the sample (90mm-100mm) used for MIST conditioning should be reduced slightly as it also had a significant impact on ITS of the sample.

Volume Change

- Void Content (VTM) of the sample before and after MIST conditioning has a significant effect on the Volume Change of the sample. VTM was also a factor affecting ITS values.
- To reduce the variability and improve the accuracy of ITS values after MIST conditioning, a VTM of 7±0.2% is recommended.

Water Bath Conditioning

- The 2-3 hours of water bath soak after MIST conditioning has a significant impact on the ITS values.

RECOMMENDATIONS.

- For samples compacted in the superpave gyratory compactor (SGC), it is easier to control the height of the sample than control the VTM. Using SGC, the samples can be compacted to within one mm of the required height.
- It is recommended to reduce the tolerance for SGC compacted MIST samples to 95±1 mm.
- Reduce the tolerance of post MIST water bath conditioning to 2 hours ± 10 minutes.
- Analysis was performed on a single mix with a TSR of 0.85. Additional analysis is needed on mixes with a wide range of aggregate types, TSR values and mixes with and without anti-strip agents.
- The effect of number of cycles should be evaluated as well

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VITA

Preetham Reddy Kaukuntla

Candidate for the Degree of

Master of Science

Thesis: STANDARD RUGGEDNESS STUDY ON MOISTURE INDUCED SENSITIVITY TESTER (MIST)

Major Field: Civil Engineering

Biographical:

Education:

I completed the requirements for the Master of Science in Civil Engineering/ Pavement and Materials at Oklahoma State University, Stillwater, Oklahoma in May, 2014.

I completed the requirements for the Bachelor of Science in Civil Engineering at Osmania University, Hyderabad, India in 2012.

Experience:

- Graduate Teaching Assistant at Oklahoma State University from January, 2013 to May, 2014.
- Engineering Intern at Ramki Infra from May, 2011 to July, 2011.

Professional Memberships:
Member of American Society of Civil Engineers (ASCE)