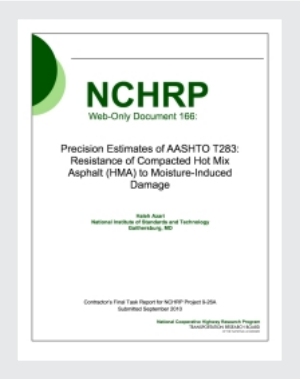

Precision Estimates of AASHTO T283: Resistance of Compacted Hot-Mix Asphalt (HMA) to Moisture-Induced Damage

DETAILS

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ABSTRACT

This work presents an interlaboratory study (ILS) resulting in a precision and bias statement for AASHTO T283, "Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage." To gain insight into the variability of the T283 test results, a micro-scale finite element analysis using X-ray images of the test specimens was conducted. The ILS included preparing and testing 6 replicate specimens according to AASHTO T283 using two different aggregate sources and two compaction methods. The two aggregate sources were selected based on their moisture susceptibility. A sandstone aggregate representing moisture susceptible and a limestone aggregate representing moisture resistance were selected for the study. Marshall and Superpave gyratory compactors were selected as means of compaction to create test specimens with different structures. The statistical analysis of the ILS results indicated that the average tensile strength ratios (TSR) of the Marshall and gyratory specimens and that of limestone and sandstone mixtures were significantly different. Despite the difference in the average TSR values, the variability of TSR of Marshall and gyratory compacted specimens of limestone and sandstone mixtures were not significantly different. In this respect, the TSR statistics of the four specimen types (two mixture types and two compaction methods) were combined to prepare the precision estimates for AASHTO T283. The simulation of moisture infiltration in the X-ray images of gyratory and compacted specimens indicated that moisture penetrates to the center of Marshall specimens much faster than to the center of gyratory specimens. The reason for this was found to be the difference in size and distribution of outside and inside pore spaces in gyratory and Marshall specimens. Additionally, the conditioning procedure, as described in the current T-283 standard was found to not represent the actual moisture infiltration time frame that produced damage in the field. This could explain the often encountered discrepancy between laboratory and field moisture performance.

CHAPTER 1- INTRODUCTION AND RESEARCH APPROACH

1.1 Background

Moisture induced damage in asphalt concrete has been widely acknowledged as a serious cause for diminishing the long-term performance of asphalt friction courses. For this reason, determining moisture susceptibility of asphalt mixtures has attracted serious attention of highway agencies and the pavement industry nationwide. An extensive effort has been made to improve moisture susceptibility laboratory experiments so that they properly characterize and predict the behavior of asphaltic mixes in the field. Currently, the majority of the transportation agencies try to control moisture induced damage failures in the field by specifying such laboratory tests.

The most common moisture susceptibility test is AASHTO T283 (1), in which asphalt/aggregate mixtures are subjected to mechanical loading after they have been exposed to moisture. Because of the frequent use of the test, it is important that the precision estimates that include the information on allowable difference between test results that are measured in one laboratory and the allowable difference between test results measured in different laboratories to be available. In this regard, the AASHTO Materials Reference Laboratory (AMRL) as part of NCHRP 9-26 looked into the variability of the test by conducting an interlaboratory study, in which Tensile Strength Ratio (TSR) data on two mixtures with expected different levels of moisture susceptibility were collected from over 40 different laboratories. Based on the interlaboratory results, repeatability and reproducibility statistics of the TSR results were determined.

Even though this statistical evidence will give a clear indication of the variability of the test, it will not give any insight into the reasons of the possible discrepancies of the test, nor gives any direction towards its improvement. Therefore, to develop a more fundamental understanding of the results of the precision estimates and possible solutions towards an improvement, finite element analyses were made with the Computer Aided Pavement Analyses finite element system, CAPA-3D (2), developed at Delft University of Technology. In the finite element analyses, various micro-scale finite element meshes were made to represent the investigated mixtures. For the finite element meshes, X-Ray tomography scans were made of the representative samples of the mixtures. To simulate the moisture infiltration into the mix components, the finite element meshes were exposed to the same moisture conditioning and temperature cycling as in the laboratory test.

As a first step in the project, a short background is given on the T283 test procedure. The concerns about the test resulted from previous experimental studies and the challenges that have so far been encountered with the test are summarized.

1.2 Background of the test protocol

The AASHTO T283 test method (1) is the result of several alterations to the original Lottman test in an attempt to improve its reliability (3, 4). The basic concept of the test is to compare the indirect tensile strength of dry samples and samples exposed to saturation, freezing, and thawing. The method is used for testing samples prepared as part of the mixture design process, plant control process, and for cores taken from the pavement. The indirect tensile strength test is conducted on the dry and conditioned specimens according to ASTM D 6931 (5). In addition to visual observation for stripping, the ratio of average tensile strength of the conditioned and dry specimens is reported as the tensile strength ratio (TSR):

$$TSR = \frac{S_2}{S_1} \qquad (1)$$

Where S1 is the average dry and S2 is the average conditioned tensile strength of the sample. For the laboratory mixed-laboratory compacted specimens a minimum TSR of 0.80 is recommended for correlation with field performance (6, 7).

Although AASHTO T283 is still the most widely used method for determining HMA moisture susceptibility, highway agencies have reported several shortcomings of the method. One of the major complaints about the test is that the test does not always correctly predict moisture sensitivity of the mixtures as it has been observed in the field. Mixtures that performed well in the field have exhibited unexpectedly low TSR values and poor performing mixtures have indicated unexpectedly high TSR values (8). The research by Epps et al. (9) which included five different mixtures from various states indicated that the sensitivity of the mixtures to moisture damage, as described by the state highway agencies, did not satisfactorily match the observed T283 behavior of a number of mixtures in the study.

Another frequently made complaint with regard to the test is the disagreement of the test results between 100 mm (4”) and 150 mm (6”) in diameter specimens. In a survey of 89 agencies compiled by AMRL, a number of state DOTs reported that 100 mm (4”) Marshall specimens indicate better agreement with the field performance than 150 mm (6”) gyratory specimens. However, Epps et al. (9) have shown that 150 mm (6”) gyratory specimens provide less variable results than 100 mm (4”) Marshall Specimens.

The other complaint about the AASHTO T283 test method is regarding the conditioning of the test. It has been stated that the duration and severity of saturation and moisture conditioning does not always promote the stripping of the mastic. Choubane et al. (10) have suggested saturation levels above 90 % and multiple freeze-thaw cycles in order to promote stripping. They found that degrees of saturation of 55 % versus 80 % would result in significantly different tensile strength of the mixtures. In addition, Kandhal and Rickards (11) showed that in four different case studies of stripping in asphalt pavements, the asphalt pavement was nearly 100 % saturated with water, which is much higher than the saturation level that is recommended in AASHTO T283.

An additional reported complaint about the T283 test is the mode of mechanical testing of the specimens. Kandhal and Rickards (11) have argued that a cyclic load which can simulate the pumping action of traffic load is a better test than loading the samples with a constant rate. Finally, a last complaint about the test that is often reported by state DOT engineers is that the test is very time-consuming. Several state highway agencies follow a shortened version of AASHTO T283 test method, which might provide different findings than if all steps of the test are followed (12).

In this study the variability of the test is being quantified by a means of an interlaboratory study involving two asphalt mixtures with different levels of moisture susceptibility tested by more than 40 laboratories. As a result, precision estimates of AASHTO T283 based on the TSR results from the laboratories will be developed.

In addition, a theoretical and computational analysis of the moisture infiltration in the chosen mixtures and a discussion regarding the structural nature of the test is given, which address both some of the complaints regarding repeatability and comparisons between laboratory results and the field. Toward the end of the report some additional comments are made with regard to the general reported complaints about the test, as summarized in the above.

1.3 Problem Statement

The accurate and precise characterization of moisture resistance of asphalt mixtures is an important aspect of selecting appropriate mixtures for various paving projects. AASHTO T283 has been the most commonly used test method for detecting moisture susceptibility. There are reports on high variability of the test results; however there is no information on the precision estimates for the test method. In addition, the causes of the variability in the test results are not clearly defined.

1.4 Research Objectives

The overall goal of this study is to determine the precision estimates of AASHTO T283 test methods. The following objectives follow from this goal:

1. To evaluate causes of variability of the test results. X-ray tomography images and finite element modeling will be used to examine the effect of specimen structure in moisture conditioning.

2. To recommend modifications for improvement of asphalt mixture moisture damage test.

1.5 Scope of Study

The scope of the project involved the following major activities:

I. Conduct Preliminary laboratory test according to AASHTO T283:

   a. Select materials and mixture design.

b. Prepare the test specimens.
c. Scan the specimens using X-ray computed tomography to obtain insight information of specimens' structure.
d. Condition the specimens according to AASHTO T283.
e. Conduct strength test on the dry and conditioned specimens to evaluate moisture sensitivity of the selected mixtures.
f. Analyze the results of the preliminary study.

II. Design and conduct an interlaboratory study (ILS):
a. Prepare instructions for preparation, conditioning, and testing of the ILS specimens.
b. Identify the laboratories participating in the ILS.
c. Send the materials (aggregate, asphalt) and instructions to the participating laboratories.
d. Analyze results of the ILS to evaluate accuracy and precision of the AASHTO T283 test method in determining moisture susceptibility of the selected mixtures.
e. Prepare a precision statement for AASHTO T283.

III. Examine the causes of variability of the AASHTO T283 test results:
a. Analyze the X-ray images for 3-D computation of size and distribution of air voids in the compacted specimens.
b. Use the CAPA-3D finite element program to simulate the moisture infiltration into the specimens during moisture conditioning.
c. Discuss the possible causes of variability in laboratory moisture damage test.

IV. Make conclusions and recommendations based on the findings of the study.

CHAPTER 2- DESIGN AND CONDUCT OF THE ILS

The availability of precision estimates for AASHTO T283 test method is essential for reliable laboratory determination of moisture susceptibility of asphalt mixtures. In this respect, an interlaboratory study was designed and conducted, in which variability of the test for two different mixtures and two methods of compactions were examined. The following sections will report the details of the design of the ILS based on ASTM E691-07, "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method" (13). The development of a precision statement required participation of a minimum of 6 laboratories with a preferred number of 30 as specified in E691.

2.1 Materials Selection

Since the level of moisture susceptibility of HMA is the main aspect to be determined from the AASHTO T283, mixtures with varying levels of moisture susceptibility were selected in this project. Two aggregates with generally believed low and high moisture sensitivity were obtained for the study. The moisture sensitive aggregate is a sandstone (KST) from Keystone, Maryland. Use of this aggregate without anti-stripping agent was banned by Maryland State Highway for pavement construction. The less moisture susceptible aggregate is a limestone (LST) from Curtain Gap quarry in Pennsylvania. This aggregate has shown good performance both in the field and in laboratory as indicated in NCHRP 9-34 study (8). To keep the number of variables to a minimum, the same unmodified asphalt binder with performance grade of 64-22 was selected for use with both aggregates.

2.2 Design Selection

To better control the variables of the test, a similar aggregate – asphalt system with nominal maximum aggregate size of 12.5 mm was used for the two mixtures. The mastic portion of the sandstone and the limestone mixture consisted of 5.4 % and 4.5% (by aggregate weight) sandstone and limestone dust, passing the #200 sieve and 5.2 % and 5.3% of asphalt binder by total weight of the mixture. The gradations of the two mixtures are provided in Table 2-1.

Given that AASHTO T283 allows both 4" and 6" specimens compacted using various methods, the effect of compaction and specimen size on the test results was also investigated. For this purpose, 100 mm (4") Marshall and 150 mm (6") Superpave gyratory specimens were compacted and tested in the study.

Table 2-1- Percent passing of the limestone and sandstone aggregates

Sieve Opening (mm)	US Sieve Size	% Passing Limestone	% Passing Sandstone
19	3/4"	100	100
12.5	1/2"	95	92
9.5	3/8"	87	76
4.75	# 4	49	52
2.36	#8	34	33
1.18	# 16	21	21
0.60	# 30	15	14
0.30	# 50	10	10
0.15	#100	7	8
0.075	#200	4.5	5.4

2.3 Preliminary Testing

A preliminary experiment was conducted at Turner-Fairbank Highways Research Center (TFHRC) to adjust the mix design for the two material types and compaction methods and to examine the moisture susceptibility of the two selected mixtures. In the preliminary study a total of 28 specimens were mixed, cured, compacted, conditioned, and tested. This included 24 specimens for indirect tensile test and four specimens for Hamburg wheel tracking test. The indirect tensile specimens included six- 4" Marshall sandstone, six- 6" gyratory sandstone, six- 4" Marshall limestone, and six- 6" gyratory limestone. The Hamburg wheel track specimens included two- 6" gyratory limestone and two-6" gyratory sandstone. The specimens for theoretical specific gravity (G_{mm}) measurements were conditioned at the same temperature and for the same duration as the compacted specimens. The specimens prepared for the preliminary study were also scanned using the X-ray tomography machine at TFHRC. The images of the X-ray scans were used for the air void distribution measurement and for the finite element modeling of moisture infiltration. The results of the image analysis and finite element simulation will be presented in Chapter 4.

2.3.1 Results of Preliminary Testing

The results from the preliminary experimental testing included the indirect tensile strength of gyratory and Marshall compacted samples and the deformation measurements from wet Hamburg test on limestone and sandstone mixtures. The following provide explanation of the results.

2.3.1.1 Volumetric measurements

Several volumetric measurements were conducted on the compacted specimens. The maximum and bulk specific gravity measurements were done to sort the specimens into two groups with similar average air voids. The average air void values and percent absorption of the compacted specimens are provided in Table 2-2.

Table 2-2- Measured air void and water absorption. MAR stands for Marshall; GYR stands for gyratory, V_a % stands for percent air voids, and Abs. % stands for percent absorption

specimen	Sandstone				Limestone			
	MAR V_a %	MAR Abs. %	GYR V_a %	GYR Abs. %	MAR V_a %	MAR Abs. %	GYR V_a %	GYR Abs. %
Wet1	6.8	1.1	6.8	1.2	7.2	1.5	6.8	0.8
Wet2	6.6	1.1	6.3	1.0	7.0	1.0	7.1	1.1
Wet3	7.7	1.4	6.6	1.1	7.2	1.7	7.0	1.3
Dry1	6.7	0.9	6.6	1.1	6.8	1.6	6.9	1.4
Dry2	7.6	1.7	6.6	1.3	7.1	1.5	7.1	1.3
Dry3	6.9	1.0	6.5	1.3	7.6	2.0	7.0	1.0
Wet avg	7.0	1.2	6.6	1.1	7.1	1.4	7.0	1.0
Dry avg	7.1	1.2	6.6	1.2	7.2	1.6	7.0	1.2

2.3.1.2 Indirect Tensile Strength Test Results

Following the T283 test method procedure, the three dry specimens, from each mixture, were kept at room temperature for 24 hours and were placed in a 25°C water bath for an additional 2 hours prior to tensile strength testing. The conditioned specimens, prior to tensile strength testing, were subjected to partial vacuum to reach a saturation of 70% to 80%, and then placed for 16 hours at -18°C in a freezer. After this, they were exposed for 24 hours in a water bath at 60°C, and additionally, 2 hours in a water bath at 25°C to reach the testing temperature.

The results of the tests on dry and wet specimens are shown in Table 2-3. Both the Marshall and the gyratory compacted specimens of the sandstone mixture, which was expected to be moisture susceptible, passed the test with very high wet/dry tensile strength ratio (TSR). The average TSR of the Marshall compacted specimens was 0.91 and the average TSR of the gyratory compacted specimen was 0.95. No visual stripping was observed for any of the sandstone specimens.

The results of the TSR test on the mixtures with the limestone aggregate are also shown in Table 2-3. Since the limestone has performed well in both field and laboratory, it was anticipated that this mixture to have high TSR values. Following this expectation, the gyratory specimens' TSR reached the rather high value of 1.06, stating more or less that the conditioning of the specimens had no effect on the tensile strength of the material. The TSR value of the Marshall compacted specimens was, however, unexpectedly low

with a TSR of 0.82. The Marshall compacted samples also showed some visual stripping. These results indicate that the previously expressed concerns regarding the precision of the test and applicability of the T283 procedure to field are valid and cause for a further investigation. In Chapter 4 detailed analyses are given of the possible influences of the moisture conditioning procedure, the variable distribution of the inside and outside porosity of the specimens, and the structural nature of the test.

Table 2-3- Measured tensile strength values (kPa)

Mixtures	Sandstone		Limestone	
Compaction	Marshall	Gyratory	Marshall	Gyratory
Wet1	1024.0	856.0	842.8	811.4
Wet2	960.0	884.0	754.9	849.1
Wet3	940.0	847.0	800.5	843.3
Dry1	1025.0	935.0	1012.9	759.5
Dry2	1077.0	934.0	950.2	769.4
Dry3	1095.0	849.0	966.6	823.6
Wet avg.	974.7	862.3	799.4	834.6
Dry avg.	1065.7	906.0	976.6	784.2
Wet std	43.9	19.3	44.0	20.3
Dry std	36.4	49.4	32.5	34.5
Wet CV %	4.5	2.2	5.5	2.4
Dry CV %	3.4	5.4	3.3	4.4
TSR	0.91	0.95	0.82	1.06

2.3.1.3 Hamburg Wheel Tracking Test Results

The two mixtures of limestone and sandstone were also subjected to wet Hamburg Wheel Tracking test at 50°C. The Hamburg test results indicated more consistency with the field performance of the mixtures. As shown in Figure 2-1, the two sandstone mixtures start to deteriorate before reaching 10,000 cycles, while the two limestone specimens showed resistance to striping even after application of 20,000 load cycles. This leads to speculation that the Hamburg wheel-tracking test might better correlate with field moisture resistance of asphalt mixtures than modified Lottman.

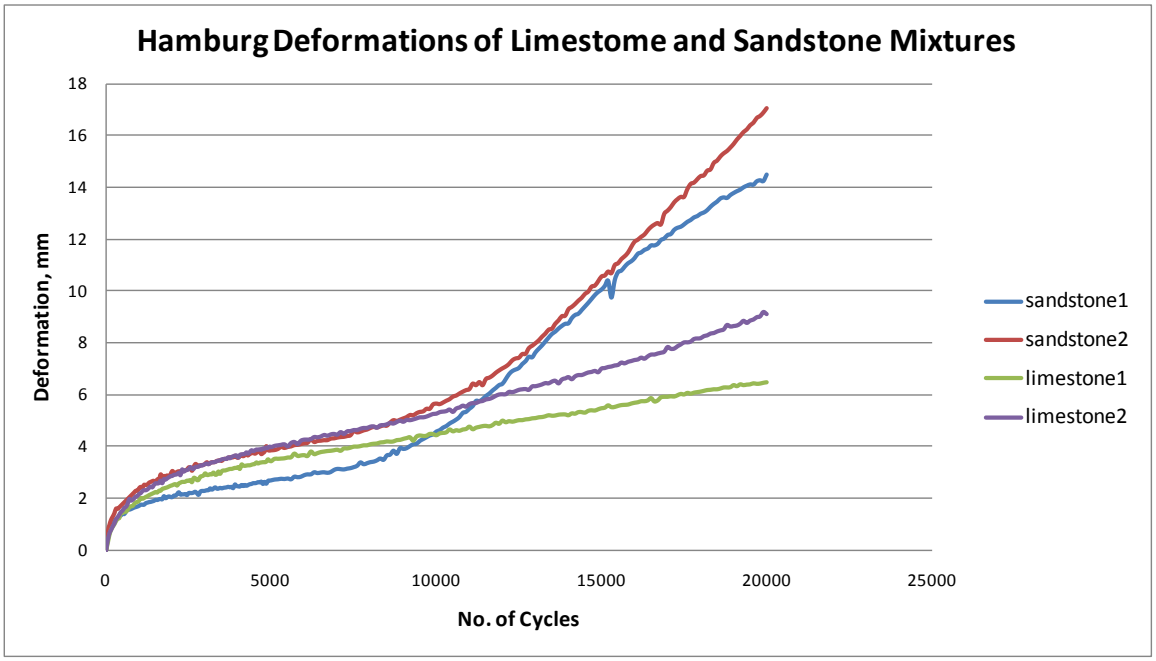

Figure 2-1- Deformation of limestone and sandstone mixture in Hamburg wheel tracking test

2.4 Selection of Participating Laboratories

The state laboratories and private laboratories participating in the AASHTO accreditation program that were in good standing with respect to AASHTO T283 test method were contacted and invited to take part in this study. Sixty laboratories responded to the invitation from which 43 laboratories returned complete sets of results.

2.5 Sample Preparation

Since Hamburg wheel-tracking test clearly indicated the difference between moisture susceptibility of limestone and sandstone mixtures, it was decided to use the same mixtures for the ILS. Adequate amount of each limestone and sandstone aggregate and PG 64-22 asphalt binder for preparing eight compacted and two G_{mm} specimens were processed, packaged, and shipped to each laboratory. This totaled to shipping 120 sets of materials to 60 laboratories from which, 30 laboratories agreed to prepare and test 6" gyratory samples and 30 laboratories agreed to prepare and test 4" Marshall or Hveem Specimens. The shipment of the two aggregates was done in 2-month interval to allow the laboratories complete the testing of the first set of materials before receiving the second set. The reason for sending the raw materials rather than compacted specimens was that AASHTO T283 provides specific steps for curing both uncompacted and compacted specimens within specified time frames. Therefore, to ensure that all steps of the AASHTO T283 test procedure were followed thoroughly, it was necessary that the samples to be mixed and compacted in each participating laboratory. For example, according to T283, the uncompacted samples needed to be at room temperature for 2 hours after mixing, then cured for 16 hours at 60° C, and then at compaction temperature

for 2 hours before compaction. This made it impossible to send laboratories uncompacted mixtures to be compacted. After compaction, AASHTO T283 requires the compacted samples to be conditioned at the room temperature for 24 hours prior to bulk specific gravity measurements. This again made it very difficult to send compacted samples to the laboratories within the required time.

2.6 Instructions for Interlaboratory Study

Laboratory participants were provided with the testing instructions and data sheet for performing the tests and collecting data. Four different sets of instructions were prepared for preparing and testing of the specimens of the two mixture types and compaction methods. The instructions for preparing and testing of limestone gyratory and Marshall specimens and the data sheets for entering measurement results are provided in Appendix A. Similar instructions and data sheets were provided to the laboratories regarding the sandstone gyratory and Marshall specimens.

CHAPTER 3- INTERLABORATORY TEST RESULTS AND ANALYSIS

3.1 Test Data

The data collected from laboratories participating in the interlaboratory study include maximum and bulk specific gravities, percent air voids, the maximum compressive load, level of saturation, and indirect tensile strength values for 6 to 8 replicates of either sandstone, limestone, or both mixtures. The data sets received from the laboratories for each mixture type and compaction method are as follows:

- Twenty laboratories sent complete set of data on the properties of the gyratory compacted limestone mixtures. The results are provided in Appendix B.
- Fifteen laboratories sent complete set of data on the properties of the Marshall compacted limestone mixtures. The results are provided in Appendix C.
- Twenty-one laboratories sent complete set of data on the properties of the gyratory compacted sandstone mixtures. The results are provided in Appendix D.
- Seventeen laboratories sent complete set of data on the properties of the Marshall compacted sandstone mixtures. The results are provided in Appendix E.

The measured data and the computed statistics for each specimen type are provided in the tables and displayed in the figures of Appendices B through E. The shaded cells in the tables indicate that the data was considered as an outlier and were eliminated from the analysis. The figures provide graphical display of the data and their associated error bars. For each replicate set, the bottom bar represents the minimum value, the top bar represents the maximum value, and middle point represents the median. The spacing between the median and the top and bottom values indicate the degree of dispersion. This is a useful technique for summarizing and comparing data from three replicates and for determining if differences exist between various laboratories.

3.2 Method of Analysis

The ILS test results were analyzed for precision in accordance to ASTM E 691(13). Prior to the analysis, any partial sets of data were eliminated by following the procedures described in E 691 in determining repeatability (S_r) and reproducibility (S_R) estimates of precision. Data exceeding the critical *h* and *k* statistics, which represent the within and between variability were eliminated as described in Section 3.3. Once identified for elimination, the same data were eliminated from any smaller subsets analyzed. The h and k statistics are provided in the tables and figures of Appendices B through E.

In addition to the analysis of data for precision estimates, the TSR of gyratory and Marshall specimens of both limestone and sandstone mixtures were statistically compared using t- and F-statistics. The rejection probability of the computed t-statistics

for 5 % level of significance would indicate if the difference in TSR values from two compaction processes or two mixture types is significant. The rejection probability of the computed F statistic for 5% level of significance would indicate if the within and between variability of TSR values from the two compactions or two mixture types are significantly different.

3.3 Analysis of Results of Limestone Mixtures

The results from laboratories were first received on limestone mixture. In addition to the tensile strength ratios (TSR), the strength values of the individual replicates were also requested from laboratories. The following sections provide the results of the statistical analysis of the strength and TSR values of gyratory and Marshall compacted specimens.

3.3.1 Superpave Gyratory Compacted Specimens

The dry and wet indirect tensile strength and TSR results of gyratory compacted limestone specimens were received from 20 laboratories. The results are provided in Appendix B. Figure 3-1 shows the average measured dry and wet indirect tensile strength values and their corresponding error bars. As indicated from the figure, in majority of cases, the wet strength values are as high as the dry strength values and in four cases the wet strength is even higher than the dry strength. This is also indicated from Figure 3-2 in which, 4 out of 20 TSR values calculated from wet and dry strength measurements are greater than 1. The low susceptibility of the gyratory compacted limestone mixture agrees well with the field performance of the limestone mixture and with the results of the preliminary study.

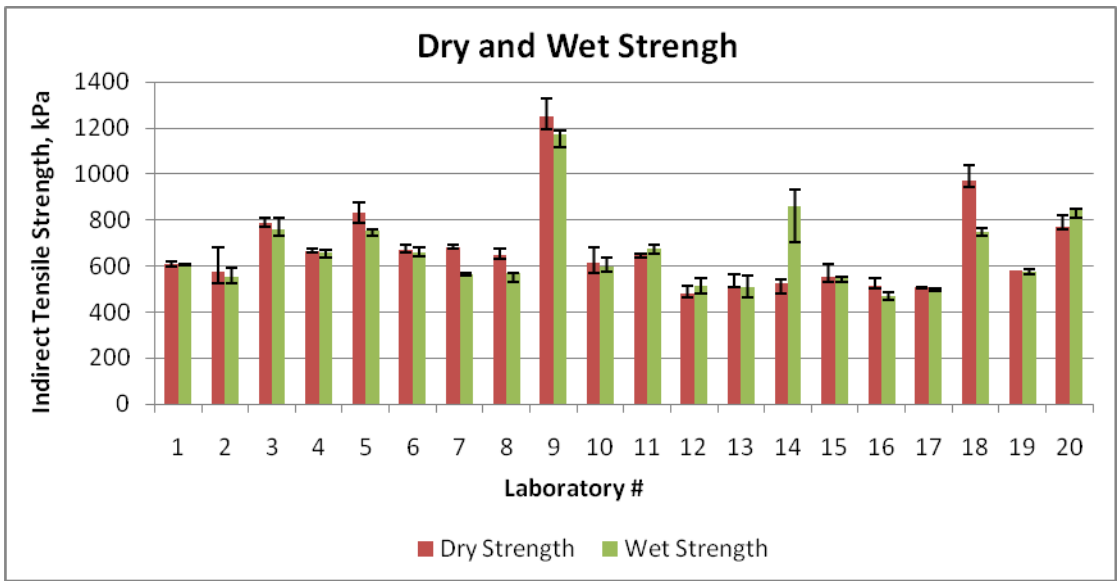

Figure 3-1- Average dry and wet indirect tensile strength values of gyratory compacted limestone mixtures

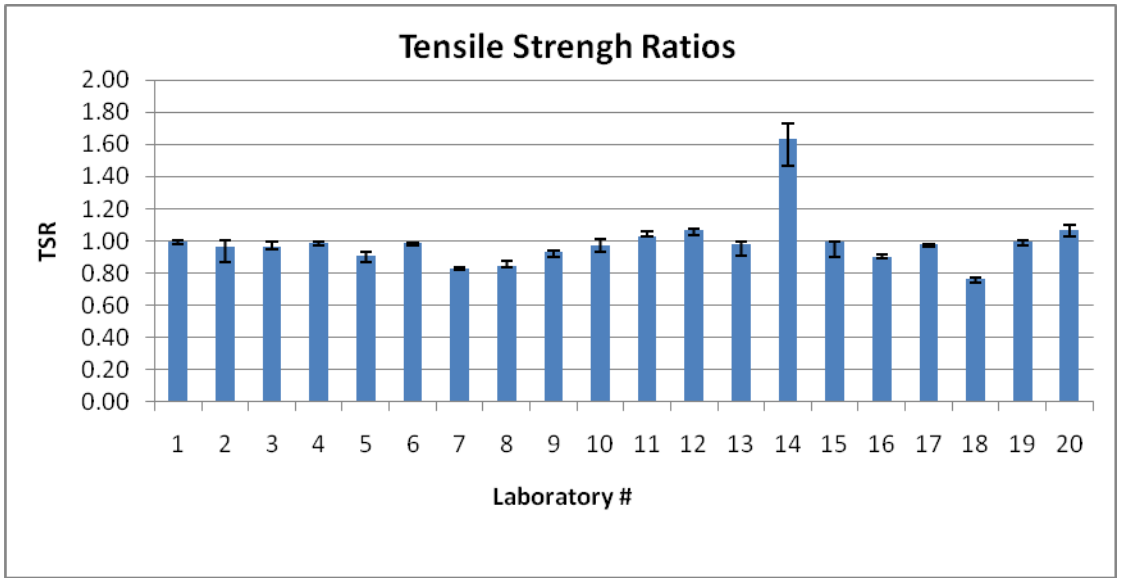

Figure 3-2- Average TSR values of gyratory compacted limestone mixtures

The repeatability and reproducibility variability of the measurements were calculated after eliminating the outlier data. The h- and k- statistics of the data that were used for determining the outlier data are provided in Table B-1 and shown in Figure B-1 of Appendix B with the laboratories identified numerically from 1 to 20. As indicated from Table B-1 and Figure B-1, based on exceedance of h- and k- statistics from the critical h- and k- values, the dry strength values reported by Laboratories 2 and 9, the wet strength values reported by Laboratories 9 and 14, and the TSR values reported by laboratory 14

were eliminated from the analysis. All remaining data were re-analyzed according to the E691 method to determine the repeatability and reproducibility statistics shown in Table 3-1. As indicated from the table, the average wet strength of 616 kPa is only slightly lower than the average dry strength of 647 kPa. The high average value of the wet strength and an average TSR value of 0.95 show the high moisture resistance of the limestone mixture, as was expected.

There has been a discussion among the pavement community regarding the use of indirect tensile strength measurements in place of TSR values for the moisture damage evaluation of asphalt mixtures. A review of the variability values in Table 3-1 indicates important facts about the use of strength values for comparison. As shown in Table 3-1, the within laboratory coefficient of variation of dry and wet strength is comparable with that of TSR (CV of 3.9% and 4.4% versus 3.1% versus); however, the between-laboratory coefficient of variation of dry and wet strength values are significantly larger than that of TSR (21.0 % and 17.6 % versus 9.6 %). This indicates that the strength values can be used for comparison of moisture susceptibility of various mixtures within one laboratory but not between different laboratories. The reason for the large between-laboratories variability might be lack of calibration of the indirect tensile strength loading device. Unless the calibration of the loading device is being periodically checked, use of strength values for comparison of moisture susceptibility of asphalt mixtures between different laboratories is not advisable.

Table 3-1-Statistics of dry and wet indirect tensile strength and tensile strength ratio (TSR) of gyratory compacted limestone mixtures

Property	# of Labs	Average	Repeatability		Reproducibility	
			STD	CV%	STD	CV%
Dry Tensile Strength, kPa	18	647	28.64	4.4	135.97	21.0
Wet Tensile Strength, kPa	18	616	24.08	3.9	108.43	17.6
TSR	19	0.95	0.030	3.1	0.091	9.6

3.3.2 Marshall Compacted Specimens

The dry and wet indirect tensile strength and TSR results of Marshall compacted limestone specimens were received from 15 laboratories. The results are provided in Appendix C. Figure 3-3 shows the average measured dry and wet indirect tensile strength values and their corresponding error bars. As indicated from the figure, other than two cases, the wet strength values are generally smaller than the dry strength values. Figure 3-4 also shows that 2 out of 15 TSR values are greater than 1.00 but 9 out of 15 are less than 0.90. The comparison of Figure 3-4 with Figure 3-2 indicates that Marshall

compacted specimens are more susceptible to moisture than the gyratory compacted specimens where 6 out of 20 TSR values are above 1.0 and only 3 out of 20 TSR were below 0.90.

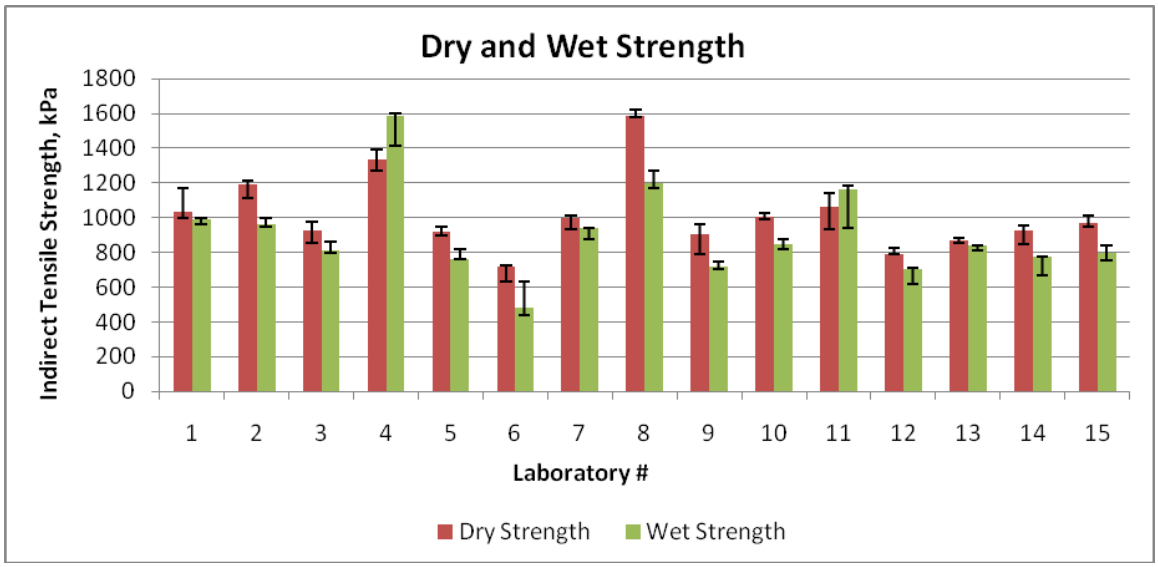

Figure 3-3- Average dry and wet indirect tensile strength values of Marshall compacted limestone specimens

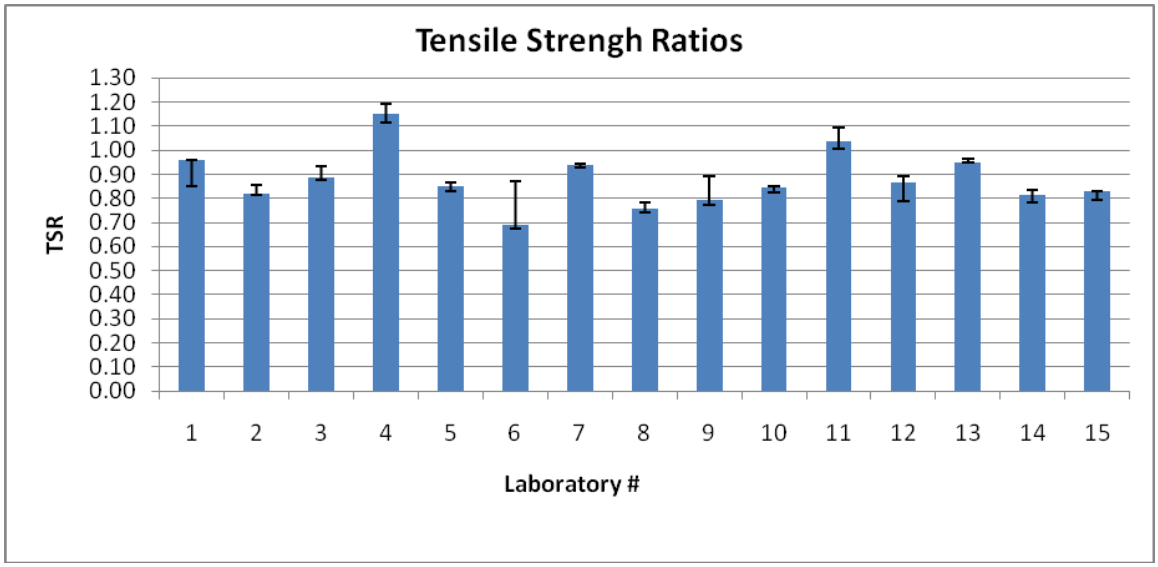

Figure 3-4- Average TSR values of Marshall compacted limestone specimens

The repeatability and reproducibility variability of the strength measurements were calculated after eliminating the outlier data. The h- and k- statistics of the data that were used for determining the outlier data are provided in Table C-1 and shown in Figure C-1 of Appendix C with the laboratories identified numerically from 1 to 15. As indicated

from Table C-1and Figure C-1, based on exceedance of h- and k- statistics from the critical h- and k- values, the dry strength values reported by laboratory 8, the wet strength values reported by laboratory 4, and the TSR values reported by laboratories 4 and 6 were eliminated from the analysis. All remaining data were re-analyzed according to the E691 method to determine the repeatability and reproducibility statistics shown in Table 3-2. As indicated from the table, the average wet strength of 852 kPa is lower than the average dry strength of 970 kPa, resulting in TSR value of 0.87. The TSR of Marshall specimens indicate high moisture resistance of the limestone mixtures but not as strongly as was shown by the gyratory compacted specimens.

The applicability of using strength values for comparing within and between laboratory results was also investigated for the Marshall specimens. A review of the variability values in Table 3-2 reveals that the within laboratory coefficient of variation (CV %) of dry and wet strength are comparable with those of TSR (6.0% and 6.7% versus 4.1%); however, the between laboratory coefficient of variation (CV %) of dry and wet strength values are significantly larger than that of TSR values (16.9 % and 21.4 % versus 9.4 %). This means that while the strength values are significantly different between different laboratories, their TSR values are comparable. As discussed earlier, the highly different strength measurements reported by different laboratories would lead to this conclusion that use of strength values for comparison between laboratory results is not advisable.

Table 3-2-Statistics of dry and wet indirect tensile strength and indirect tensile strength ratios of Marshall compacted limestone specimens

Property	# of Labs	Average	Repeatability		Reproducibility	
			STD	CV%	STD	CV%
Dry Tensile Strength, kPa	14	970	57.74	6.0	163.79	16.9
Wet Tensile Strength, kPa	14	852	56.76	6.7	182.56	21.4
TSR	13	0.87	0.035	4.1	0.082	9.4

3.4 Analysis of Results of Sandstone Mixtures

The results of measurements on the sandstone mixture were received second from the laboratories. The results included the wet and dry strength values of individual gyratory and Marshall replicates and the corresponding tensile strength ratios (TSR). The following sections provide discussion on the statistical analysis of the strength data.

3.4.1 Superpave Gyratory Compacted Specimens

The dry and wet indirect tensile strength and TSR results of gyratory compacted sandstone specimens were received from 21 laboratories. The data are provided in Appendix D. Figure 3-5 shows the average measured dry and wet indirect tensile strength

values and Figure 3-6 shows the average TSR values. As indicated from the figures, all laboratories, except one, reported wet strength values smaller than the dry strength values. This is also indicated in Figure 3-6 as all but one laboratory reported TSR of smaller than 1.0.

The repeatability and reproducibility variability of the strength measurements were calculated after eliminating the outlier data. The h- and k- statistics for determining the outlier data are provided in Table D-1 and shown in Figure D-1 of Appendix D with the laboratories identified numerically from 1 to 21. As indicated from Table D-1 and Figure D-1, based on exceedance of h- and k- statistics from the critical h- and k- values, the dry strength values reported by laboratory 14, the wet strength values reported by laboratories 1 and 14, and the TSR values reported by laboratory 1 were eliminated from the analysis. All remaining data were re-analyzed according to the E691 method to determine the repeatability and reproducibility statistics shown in Table 3-3. As indicated from the table, the average wet strength of 785 kPa is smaller than the average dry strength of 956 kPa resulting in an average TSR of 0.87. Despite the poor field performance of sandstone mixture, the average TSR of 0.87 indicates a moderate moisture resistance of the sandstone mixture. Based on the prior knowledge of the poor field performance of sandstone mixture, average TSR of 0.87 might indicate the shortcoming of the T283 test in predicting the field performance of this mixture.

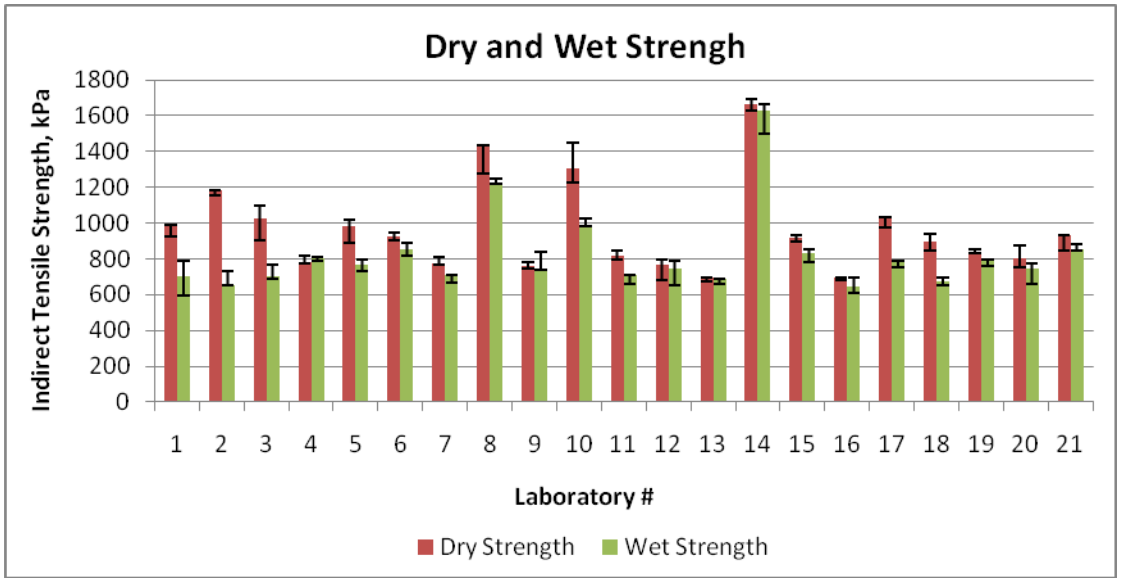

Figure 3-5- Average dry and wet indirect tensile strength values of gyratory compacted sandstone specimens

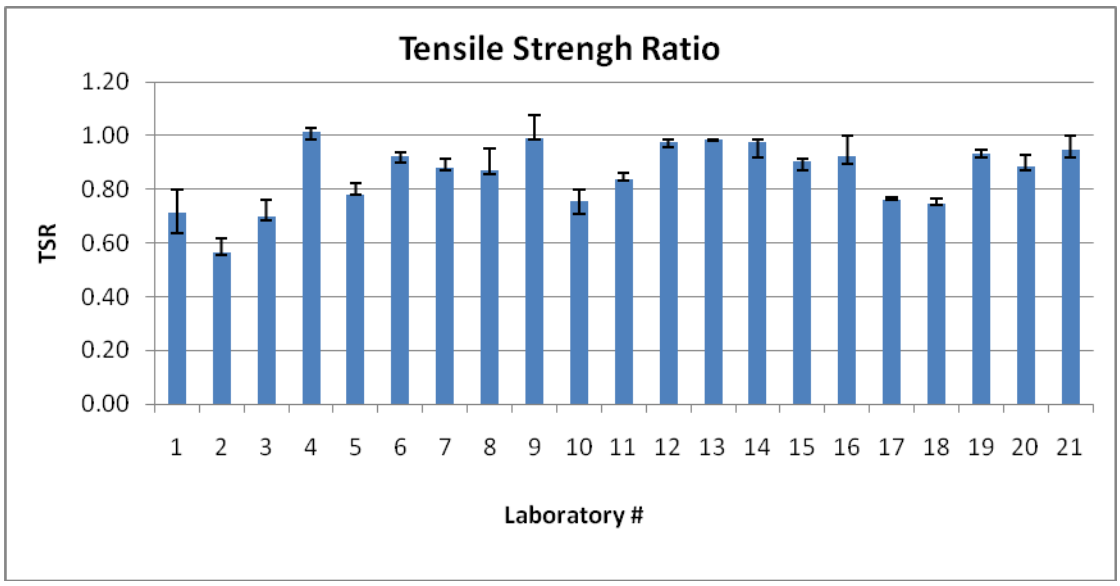

Figure 3-6- Average TSR values of gyratory compacted sandstone specimens

Using also the data from gyratory compacted sandstone mixture, the possibility of using strength values for between-laboratories comparison was investigated. Table 3-3 shows that the within-laboratory variability of dry and wet strength values is comparable to that of TSR (CV of 5.2% and 4.6% versus CV of 3.5%). However, the between-laboratory coefficient of variation of the dry and wet strength values is significantly larger than that of TSR values (30.0 % and 20.2 % versus 9.9 %). This means that while the strength values are significantly different between different laboratories, their TSR values are very similar. Similar to what discussed previously, the highly different strength measurements reported by different laboratories would lead to this conclusion that the comparison of strength values between laboratories is not advisable.

Table 3-3-Statistics of dry and wet indirect tensile strength and indirect tensile strength ratios of gyratory compacted sandstone mixtures

Property	# of Labs	Average	Repeatability		Reproducibility	
			STD	CV%	STD	CV%
Dry Tensile Strength, kPa	21	956	49.99	5.2	286.87	30.0
Wet Tensile Strength, kPa	19	785	36.08	4.6	158.67	20.2
TSR	19	0.89	0.031	3.5	0.088	9.9

3.4.2 Marshall Compacted Specimens

The dry and wet indirect tensile strength and TSR results of Marshall compacted sandstone specimens were received from 17 laboratories. The results are provided in Appendix E. Figure 3-7 and Figure 3-8 show the average measured dry and wet strength and average TSR values from the 17 laboratories. Despite the reported poor field performance of the sandstone mixture, the wet strength values were not significantly lower than the dry strength values and in one laboratory the wet strength was even higher than the dry strength (Laboratory #10).

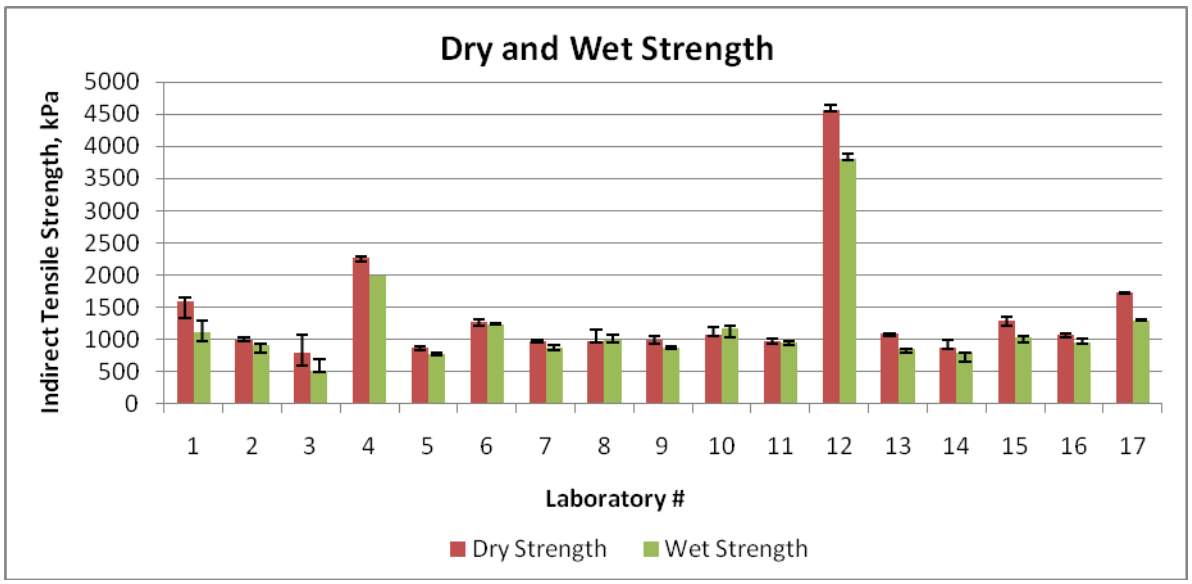

Figure 3-7- Average dry and wet strength values of Marshall compacted sandstone specimens

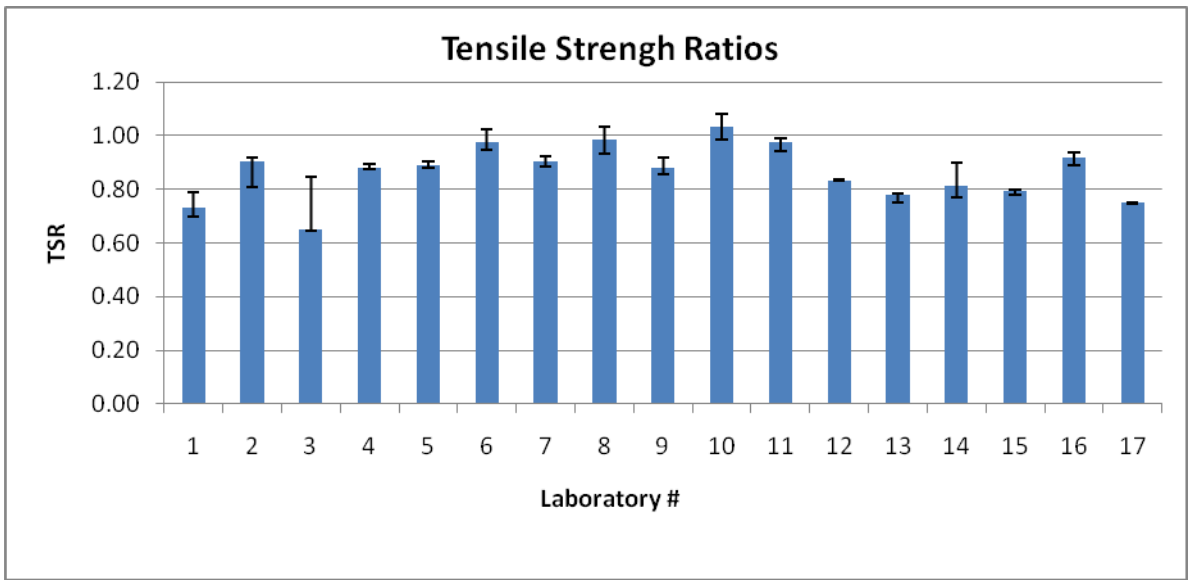

Figure 3-8- Average TSR values of Marshall compacted sandstone mixtures specimens

The statistics of the strength values are provided in Table 3-4. The repeatability and reproducibility variability of the strength measurements were calculated after eliminating the outlier data. The h- and k- statistics of the data that were used for determining the outlier data are provided in Table E-1 and shown in Figure E-1 of Appendix E with the laboratories identified numerically from 1 to 17. As indicated from Table E-1and Figure E-1, based on exceedance of h- and k- statistics from the critical h- and k- values, the dry strength values reported by laboratories 3 and 12, the wet strength value reported by laboratories 1 and 12, and the TSR values reported by laboratory 3 were eliminated from the analysis. All remaining data were re-analyzed according to the E691 method to determine the repeatability and reproducibility statistics shown in Table 3-4. As indicated from the table, the average wet strength of 1013 kPa is lower than the average dry strength of 1205 kPa; however, not as low as it was expected. Despite the poor field performance of sandstone mixture, the average TSR of Marshal compacted sandstone specimens is 0.88 indicating moderate moisture resistance of the sandstone mixture.

Table 3-4-Statistics of dry and wet indirect tensile strength and indirect tensile strength ratio of Marshall compacted sandstone specimens

			Repeatability		Reproducibility	
Property	# of Labs	Average	STD	CV%	STD	CV%
Dry Tensile Strength, kPa	15	1205	67.01	5.6	381.35	32.2
Wet Tensile Strength, kPa	15	1013	55.11	5.4	332.43	35.2
TSR	16	0.88	0.035	4.0	0.087	10.6

The applicability of using strength values of Marshall compacted sandstone specimens for between- laboratories comparison was also investigated using the data from Marshall compacted sandstone mixture. The coefficient of variations in Table 3-4 indicates that while the dry and wet strength values are significantly variable between different laboratories (CV of 32.2 % and 35.2 %), the TSR values are very similar (CV of 10.6 %). This would lead to the conclusion that use of strength values for comparison of laboratory moisture resistance results is not advisable.

3.5 Statistical Comparison of TSR Results of Different Materials and Different Compaction Methods

The average and standard deviations of TSR values of gyratory and Marshall compacted specimens of limestone and sandstone mixtures were graphically and statistically compared. The graphical representations are provided in Figure 3-9 through Figure 3-11 and the results of the statistical comparison are provided in Table 3-5 through Table 3-7. Considering 5 % level of significance, the rejection probabilities that are smaller than 0.05 would indicate that the strength properties of different specimen types are significantly different.

3.5.1 Comparison of Average TSR Values

Figure 3-9 and Table 3-5 show the comparison of average TSR values of gyratory and Marshall specimens and that of the limestone and sandstone mixtures. For the limestone mixture, the average TSR of gyratory specimens is significantly greater than that of Marshall Specimens (0.95 versus 0.87) with the rejection probability of 0.013. However, for the sandstone mixtures, the average TSR of gyratory and Marshall specimens are the same (0.89 versus 0.88) with the rejection probability of 0.916.

Figure 3-9 and Table 3-5 also show the comparison of average TSR values of limestone and sandstone mixtures. For the gyratory specimens, the average TSR of limestone mixture is significantly greater than that of the sandstone mixture (0.95 versus 0.89) with a rejection probability of 0.031. However, for the Marshall specimens the average TSR of limestone and sandstone mixtures are the same (0.87 versus 0.88) with the rejection probability of 0.637.

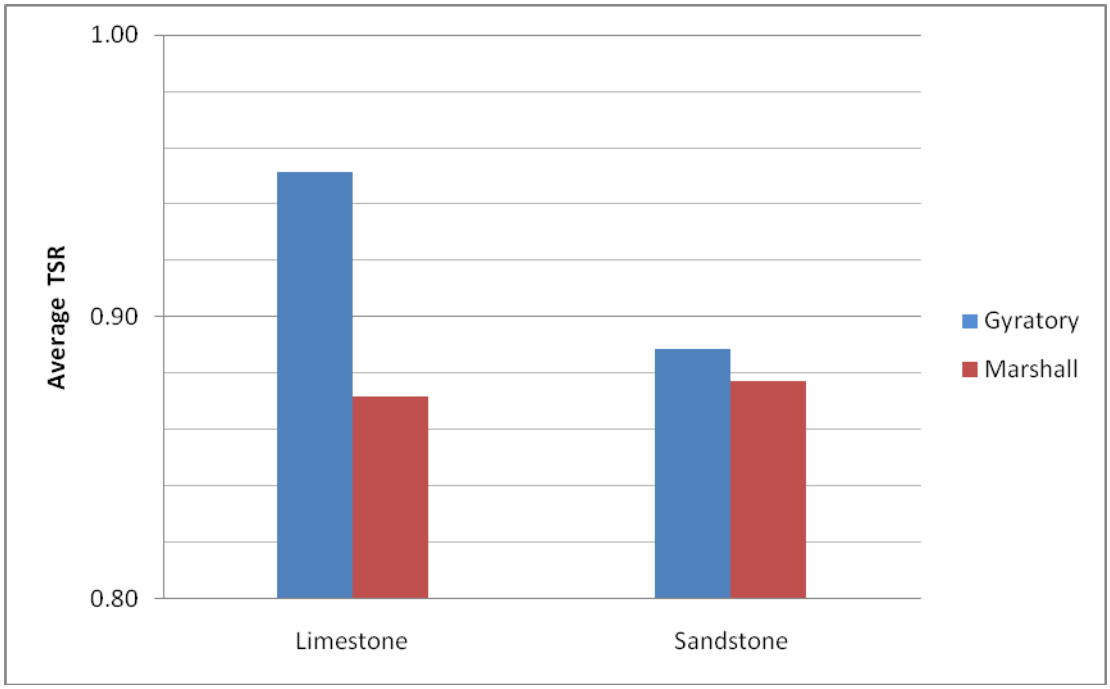

Figure 3-9- Comparison of the average TSR values of gyratory and Marshall compacted limestone and sandstone specimens

Table 3-5- Statistical comparison of the average TSR values of the two material types and two compaction methods

Comparison	Averages	Degrees of Freedom	Critical t	Computed t	Rejection Probability	Decision
Limestone: Gyratory vs. Marshall	0.95 vs. 0.87	30	2.042	2.647	0.0130	Reject
Sandstone: Gyratory vs. Marshall	0.89 vs. 0.88	33	2.036	0.407	0.916	Accept
Gyratory: Limestone vs. Sandstone	0.95 vs. 0.89	36	2.029	2.241	0.031	Reject
Marshall: Limestone vs. Sandstone	0.87 vs. 0.88	27	2.052	0.176	0.637	Accept

3.5.2 Comparison of Within-Laboratory Standard Deviations of TSR

Figure 3-10 and Table 3-6 show the graphical and statistical comparison of the within-laboratory standard deviations of gyratory and Marshall compacted specimens and of the limestone and sandstone mixtures. As shown from Figure 3-10, the repeatability standard deviations of TSR of gyratory specimens are smaller than that of Marshall Specimens (limestone: 0.030 vs. 0.035 and sandstone: 0.031 vs. 0.035). However, the results of F-test on variances in Table 3-6 indicate that the differences between the TSR repeatability values of gyratory and Marshall Specimens are not significant (rejection probabilities 0.239 and 0.340).

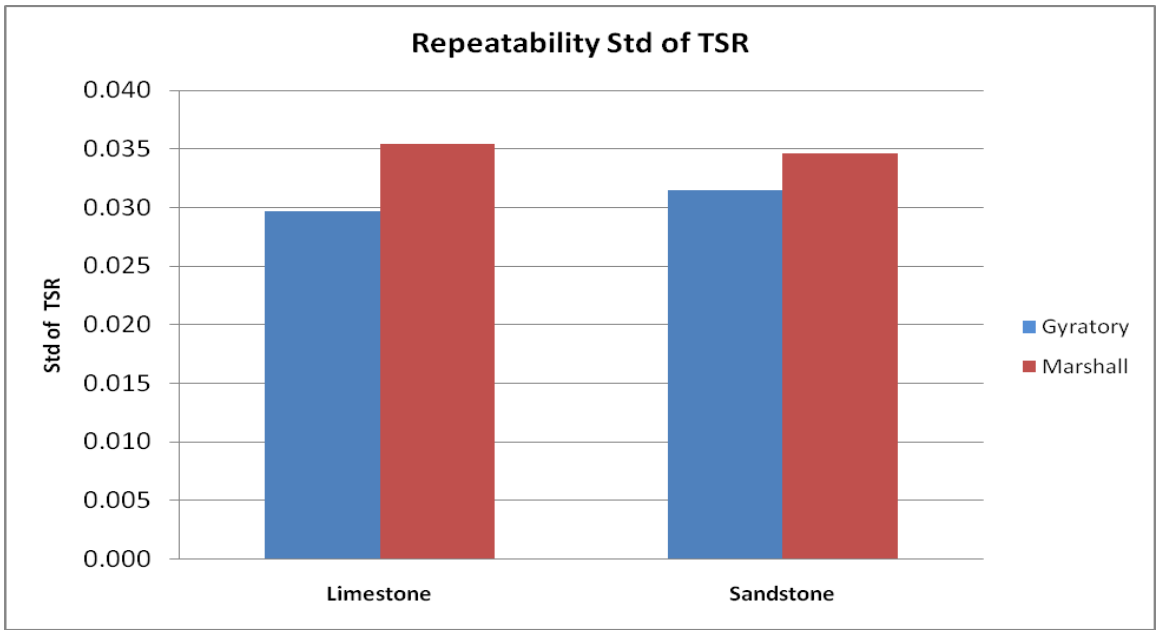

Figure 3-10- Comparison of the within-laboratory standard deviation of TSR values of gyratory and Marshall compacted limestone and sandstone specimens

Table 3-6- Statistical comparison of the repeatability standard deviations of TSR values for the two material types and the two compaction methods

Compare	Within Standard Deviation	Degrees of Freedom	Critical F	Computed F ($S_{r)}$	Rejection Probability	Decision
Limestone: Marshall vs. Gyratory	0.035 vs. 0.030	12 & 18	2.342	1.43	0.239	Accept
Sandstone: Marshall vs. Gyratory	0.035 vs. 0.031	15 & 18	2.269	1.22	0.340	Accept
Gyratory: Sandstone vs. Limestone	0.031 vs. 0.030	18 & 18	2.217	1.12	0.406	Accept
Marshall: Sandstone vs. Limestone	0.035 vs. 0.035	15 & 12	2.617	1.05	0.473	Accept

Figure 3-10 and Table 3-6 also show the comparison of within-laboratory standard deviations of TSR values of limestone and sandstone mixtures. For the gyratory specimens, the within- laboratory standard deviations of TSR of limestone mixture is smaller than that of the sandstone mixture but not significantly (0.030 versus 0.031) with a rejection probability of 0.406. For the Marshall specimens, the within standard deviation of TSR of limestone and sandstone mixtures are the same (0.035 versus 0.035) with the rejection probability of 0.473.

3.5.3 Comparison of Between-laboratory Standard Deviations of TSR

Figure 3-11 and Table 3-7 show the graphical and statistical comparison of the between-laboratory standard deviations of TSR values. The comparison of gyratory and Marshall specimens in Figure 3-11 shows that for the limestone mixture, the between-laboratory standard deviation of gyratory specimens is larger than that of Marshall Specimens (0.091 vs. 0.082). However, the results of F- test on variance indicate that this difference is not statistically significant (rejection probability of 0.353). For the sandstone mixtures the between-laboratory standard deviation of TSR values of gyratory specimens was slightly larger than that of Marshall specimens by not significantly (0.088 vs. 0.087) with the rejection probability of 0.490. In summary, the results of statistical F analysis in Table 3-7 shows that for 5 % level of significance, the between-laboratory standard deviations of TSR values of gyratory and Marshall specimens for both limestone and sandstone mixtures are not significantly different.

Figure 3-11 and Table 3-7 also provide the reproducibility comparison of TSR of limestone and sandstone mixtures. As indicated from Figure 3-11, reproducibility standard deviation of TSR of limestone mixture is larger than those of sandstone mixture using gyratory specimens (0.091 vs. 0.88) and smaller than those of sandstone mixture using Marshall specimens (0.084 vs. 0.093). However, the results of F-test on variances in Table 3-7 indicate that the differences between the reproducibility of TSR values of

limestone and sandstone mixtures are not significant (rejection probabilities 0.452 for gyratory and 0.415 for Marshall compacted specimens).

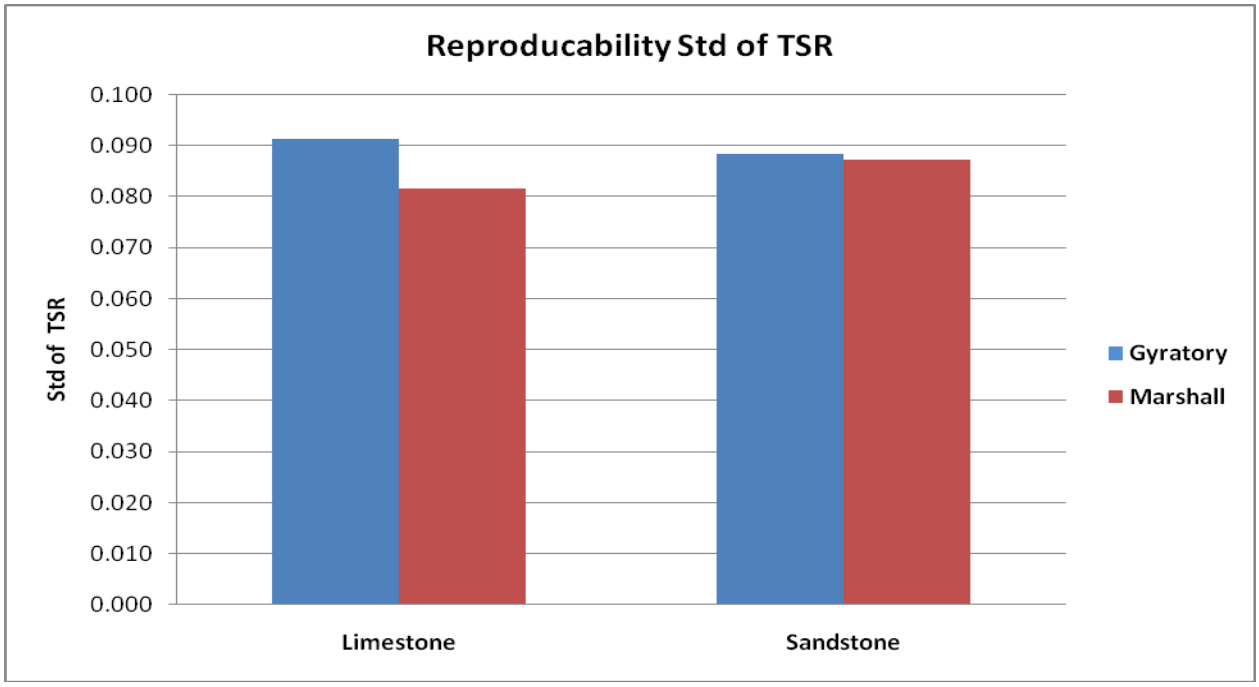

Figure 3-11- Comparison of the between-laboratory standard deviations of TSR values of gyratory and Marshall compacted limestone and sandstone specimens

Table 3-7- Statistical comparison of the reproducibility standard deviations of TSR values of the material types and compaction methods

Compare	Between Standard Deviation	Degrees of Freedom	Critical F	Computed F ($S_{R)}$	Rejection Probability	Decision
Limestone: Gyratory vs. Marshall	0.091 vs. 0.082	18 & 12	2.568	1.25	0.353	Accept
Sandstone: Gyratory vs. Marshall	0.088 vs. 0.087	18 & 15	2.353	1.02	0.490	Accept
Gyratory: Limestone vs. Sandstone	0.091 vs. 0.088	18 & 18	2.217	1.06	0.452	Accept
Marshall: Sandstone vs. Limestone	0.087 vs. 0.082	15 & 12	2.617	1.14	0.415	Accept

3.6 Precision Estimates for AASHTO T283

The precision estimates of AASHTO T283 are presented in Table 3.8. Based on the statistical comparisons discussed in Section 3.4, the repeatability and reproducibility of

TSR values of gyratory and Marshall specimens of limestone and sandstone mixtures were not significantly different. Therefore, the repeatability statistic for AASHTO T283 was determined by pooling the eight within laboratory standard deviations in Table 3-6. Similarly, the reproducibility statistic for AASHTO T283 was determined by pooling the eight between-laboratory standard deviations in Table 3-7. As indicated from the table, the acceptable range of TSR values within one laboratory is about 9% and the acceptable range of TSR values between two laboratories is about 25%. These values very well validate the concerns of the highway agencies about the variability of the modified Lottman procedure. The results of an investigation on causes of the high variability of the test procedure are presented in Chapter 4.

Table 3-8- Precision estimates of TSR

Condition of Test and Test Property	Standard Deviation 1s	Acceptable Range of Two Results d2s
Single-Operator Precision	0.033	0.093
Multi-laboratory Precision	0.087	0.247

CHAPTER 4- IDENTIFICATION OF THE PARAMETERS CAUSING VARIABILITY IN AASHTO T283

In Chapter 3, it was shown that AASHTO T283 is highly variable within one laboratory and between different laboratories. In addition to highly variable measurements, the test method in some occasions provides erroneous results as was observed in this study: the sandstone mixture that was known to be moisture sensitive in the field was evaluated as moisture resistant by the AASHTO T283 ILS and the Marshall compacted specimen of limestone mixture that was known to be moisture resistant indicated moderate resistance to moisture. In this chapter the various variables, which are introduced in the T283 test method due to moisture conditioning procedure are investigated via micro-scale finite element analyses. For the finite element meshes, X-Ray tomography scans are made of gyratory and Marshall compacted mixtures. The mixtures are computationally analyzed for their outside and inside pore-space distribution and moisture infiltration to the center of specimens is simulated. The resulting moisture fronts as a function of air void distribution will be discussed in this chapter. The focus is placed on the importance of knowledge of the actual moisture concentrations inside the material and the relevance of the time-frame over which moisture damage may occur in the field. The results of this investigation intend to give a fundamental explanation of why the AASHTO T283 test may give erroneous conclusions and will define the boundaries under which the test could be used. In addition, the effect of different compactions and geometries on moisture concentrations inside the specimen and their impact on the variability of the test results will be evaluated.

4.1 X-Ray Tomography Scanning

Specimens that were prepared for the preliminary experiment were used for X-ray tomography scanning. Following the fabrication, specimens were scanned using X-Ray computed tomography system of Federal Highway Administration at Turner-Fairbank Highway Research Center (TFHRC). The X-Ray system at TFHRC has a 420 keV X-Ray source and a 512 pixel x 1 mm linear array detector. The X-Ray computed tomography scanning of the specimens was done continuously in 0.8 mm intervals for the entire depth of the specimens. The resolution of the images of 4” specimens is 0.20 mm (each millimeter is represented by 5 pixels) and the resolution of 6” specimens is 0.33 mm (each millimeter is represented by 3 pixels). The pixel size is chosen based on several factors, including the distances of the X-ray source and camera to the sample.

In X-ray CT, X-rays penetrate a 3-D sample at many different angles and the absorption is measured (14). A computer-based reconstruction technique then makes gray level images, where each image is a slice of the sample and the contrast in gray levels is caused by the different X-ray absorption properties of the materials in the sample, which usually are caused by density differences (14).

The resulting 3-D image is made by stacking the many 2-D images of the sample in gray-scale. In this study, the 3-D images are dispersion of the three phases of asphalt concrete:

aggregates, mastic, and air voids in a cylindrical specimen, which are clearly shown in the image. Since intensity of each pixel is proportional to object density, air voids with the lowest density are shown black while the solids vary from dark to light gray depending on their relative densities. The intensity differences in the image are sufficient to clearly distinguish the aggregates from the mastic (see Figure 4-1).

The X-Ray images were used for quantifying the air void distribution of the compacted samples. The X-ray images were also used for creating finite element meshes for the modeling of moisture infiltration in 4" Marshall and 6" gyratory specimens using the CAPA 3-D finite element program.

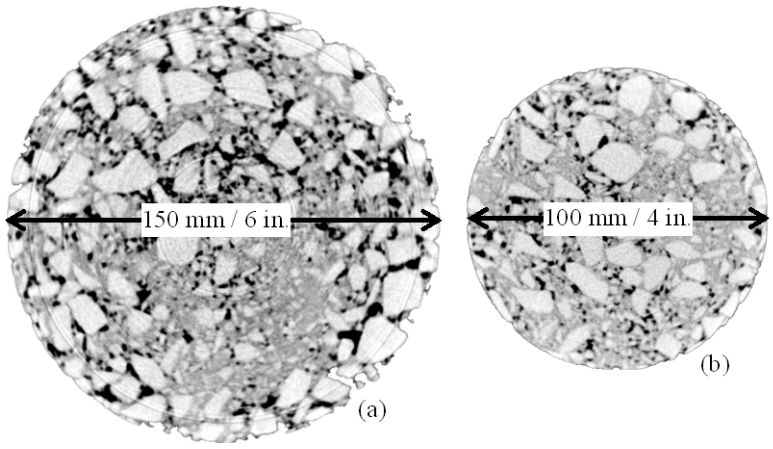

Figure 4-1- Typical X-ray tomography images of 6" gyratory and 4" Marshall compacted specimens

4.2 X-Ray Measurement Test Results

4.2.1 Inside and outside porosity

To quantify the inside and outside porosity, the X-Ray scans of all the specimens are assembled into the three dimensional representations, whereby the size of the smallest element (voxel) is 0.2 mm x 0.2 mm x 0.8 mm for 4" Marshall specimens and 0.33 mm x 0.33 mm x 0.8 mm for 6" gyratory specimens. From the X-Ray scan assembly, both the inside and outside porosity of the tested specimens is calculated, in which a perfect cylindrical shape of the specimen is assumed. In Table 4-1 a summary of the inside, outside and total calculated porosities are given for the sandstone and the limestone samples, respectively. The X-Ray scans of sample 4 and 5 of the limestone gyratory compacted specimens and sample 6 of the limestone Marshall compacted specimens were thereby disregarded due to problems with the tomography system.

From the calculated inside and outside porosities, Table 4-1, it can be seen that the target (inside) porosity of 7 % $\pm$ 0.5 was reasonably well met. The measured values of the inside porosity in the laboratory, Table 2-1 are, on average, 1.8% lower than the values computed from the X-Ray scans, which can probably be contributed to inaccuracies in the laboratory measurements and/or the resolution and processing of the X-Ray scans.

Adding the outside porosity to the total porosity measure, it is found that the gyratory specimens have an additional 23% and the Marshall have an additional 45% of pore space. This indicated that the Marshall specimens may have relatively more access to moisture during conditioning times and could therefore reach higher moisture concentrations. Even though the targeted saturated (inside) pore space should be a constant between the specimens, from the above, it can be seen that the total porosity may vary between the samples.

Table 4-1- Inside, outside, and overall air voids (porosity) of specimens from X-Ray scans

	Porosity [%]		
	outside	inside	total
ks_gyr_01	1.5	6.7	8.2
ks_gyr_02	2.0	5.5	7.5
ks_gyr_03	2.2	6.6	8.8
ks_gyr_04	1.7	6.9	8.6
ks_gyr_05	1.6	7.2	8.8
ks_gyr_06	1.3	7.1	8.4
mean	*1.7*	*6.7*	*8.4*
ks_mar_01	2.6	6.1	8.7
ks_mar_02	4.0	6.8	10.8
ks_mar_03	2.9	8.2	11.1
ks_mar_04	3.1	7.0	10.1
ks_mar_05	3.1	7.7	10.8
ks_mar_06	3.4	7.5	10.9
mean	*3.2*	*7.2*	*10.4*

(a)

	Porosity [%]		
	outside	inside	total
ls_gyr_01	1.5	6.5	8.0
ls_gyr_02	1.5	6.7	8.2
ls_gyr_03	1.9	6.8	8.7
ls_gyr_06	0.6	8.2	8.8
mean	*1.4*	*7.1*	*8.4*
ls_mar_01	2.5	7.5	10.0
ls_mar_02	3.1	6.5	9.6
ls_mar_03	4.0	8.4	12.4
ls_mar_04	3.7	6.6	10.3
ls_mar_05	3.4	7.3	10.7
mean	*3.3*	*7.3*	*10.6*

(b)

In AASHTO T283-03, it is recommended to use T 166, Method A, for determining the bulk specific gravity of the specimens. The shortcoming of this procedure for the calculation of the air voids in the specimen is that the inside porosity is measured and that most air voids which are in direct contact with the ‘outside’ are not taken into account. This means that, even though it is aimed in the T283 procedure to group specimens with the same air void percentage, the specimens may very well end up with different moisture conditioning because of a varying ‘outside’ porosity, Figure 4-1. A larger outside porosity, or instantaneous contact surface of water with the specimen, may therefore results into a more severe moisture conditioning in the water bath, even when the inside porosity is the same.

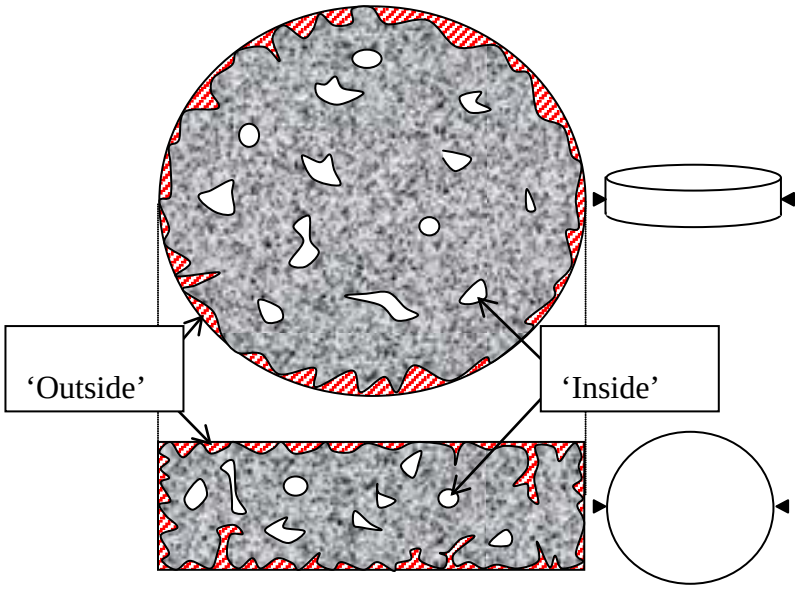

Figure 4-2- Schematic of inside and outside pore-space

4.2.2 Vacuum Induced Micro-Cracking

In this section the measured initially absorbed water percentages are compared with the outside connected pore space as shown in Table 4-2. The third column in the table is showing the difference between the initially absorbed water (i.e. before the vacuum) and the pore space which is directly connected with the water bath. Assuming that all the outside pore space is filled with water, this difference can be seen as the outside 'roughness' of the sample, in comparison with a perfect cylinder, Figure 4-1. It could therefore be concluded that the investigated gyratory compacted samples give, on average, 0.4 % imperfection and the Marshall compacted samples give, on average, 1.9 % imperfection to the cylindrical shape, Table 4-2.

In the case of a perfectly cylindrical specimen, this difference would indicate the pore space which is, in principal, in direct contact with the water bath, but cannot be initially filled with water due to the small pore-size. This would mean that the gyratory compacted specimens have, on average, 1.6 % air voids available for direct saturation. For the Marshall compacted specimens this would be, on average, 3.3%.

The test protocol, however, dictates a saturation level of 70 % - 80 % of mixtures with a targeted air void of 7 % $\pm$ 0.5. This comes down to a water absorption level of 4.6 – 6.0 %. Therefore, the applied vacuum suction must induce some micro cracking inside the sample to enable the necessary additional pore space. This induced micro-cracking can be an important factor which contributes to the variability of the test.

Table 4-2- Comparison of initial absorption and outside connected porosity

Sample ID	Initial absorption %	Outside porosity %	Difference
KS_GYR	1.2	1.7	0.5
KS_MAR	1.2	3.2	2.0
LMS_GYR	1.2	1.4	0.2
LMS_MAR	1.6	3.3	1.7

4.2.3 Distribution of inside porosity

Another important variable which could influence the moisture infiltration within the sample, is the distribution of the inside pore space. Since in the indirect tensile test, the tensile fracture area is located in the center of the specimen, the actual location of the infiltrated water is quite important. It could, for instance, be possible that, due to a clustering of the pore space on the outside of the specimens, most moisture damage is occurring away from the tensile area and is therefore not detected. To quantify the distribution of the pore space, the assembled X-ray scans were divided into 8 parts (15). To quantify the distribution of the possible moisture infiltration through the macro-pores of the mix, for each 1/8 specimen, a calculation was made of the connected outside air voids and the inside air voids.

In Table 4-2 it was shown that the Marshall compacted specimens have a rather high percentage of outside pore-space. The calculated inside and outside pore-space distributions of the limestone (LMS) specimens are plotted in Figure 4-3 and Figure 4-4. From Figure 4-3 it can be seen that the gyratory compacted specimens include higher outside porosity on the ‘top’ (Section 1 to 4) and a lower outside porosity on the ‘bottom’ (Section 5 to 8). This would indicate that one side of the specimen is more moisture conditioned than the other side. From the inside porosity distribution it can be seen that the gyratory compaction creates a rather well distributed pore-space, with a maximum variation of 2.5% from the mean.

It is also seen from Figure 4-4 that the Marshall compacted specimens exhibit an overall higher porosity on the ‘top’ (section 1-4) and a lower porosity on the ‘bottom’ (section 5-8) of the specimens. From the inside porosity distribution it can be seen that Marshall compaction creates a less dispersed inside pore-space and tends to create clusters of air-voids. This could indicate a very asymmetric moisture front inside the Marshall compacted specimens which could lead to unexpected bad or unexpected good behavior of the specimens.

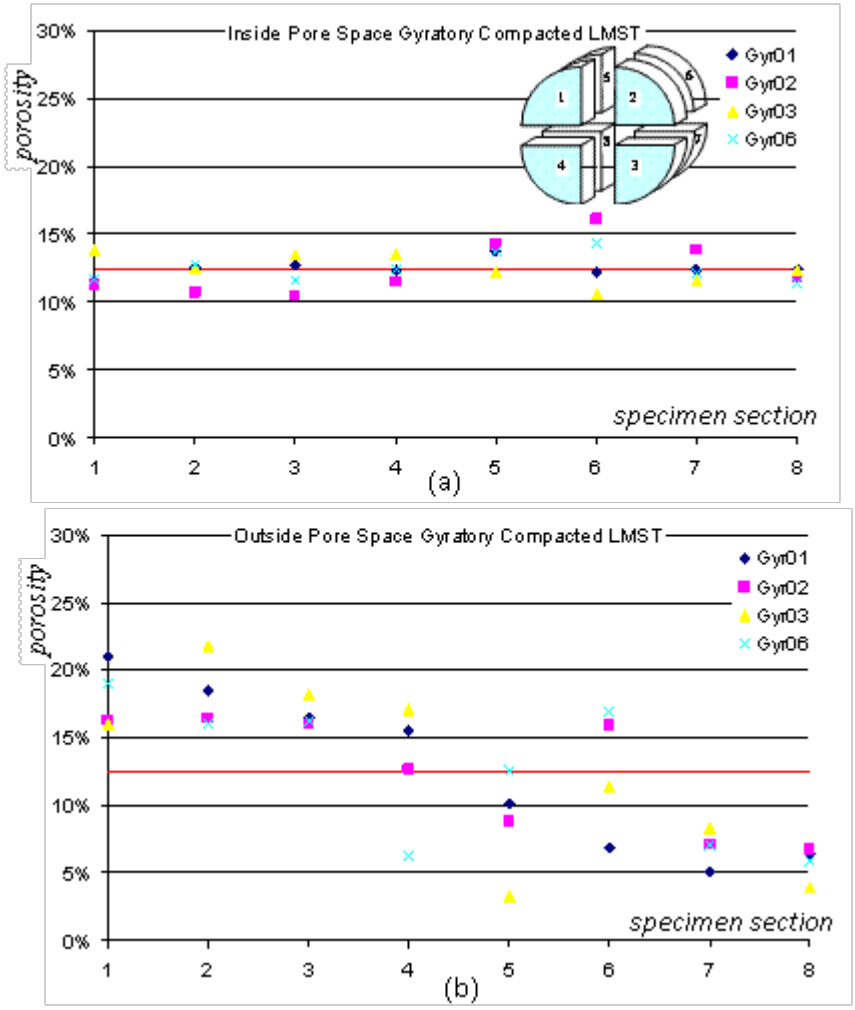

Figure 4-3- Pore space distribution in gyratory compacted limestone (LMST) specimens (a) inside porosity (b) outside porosity

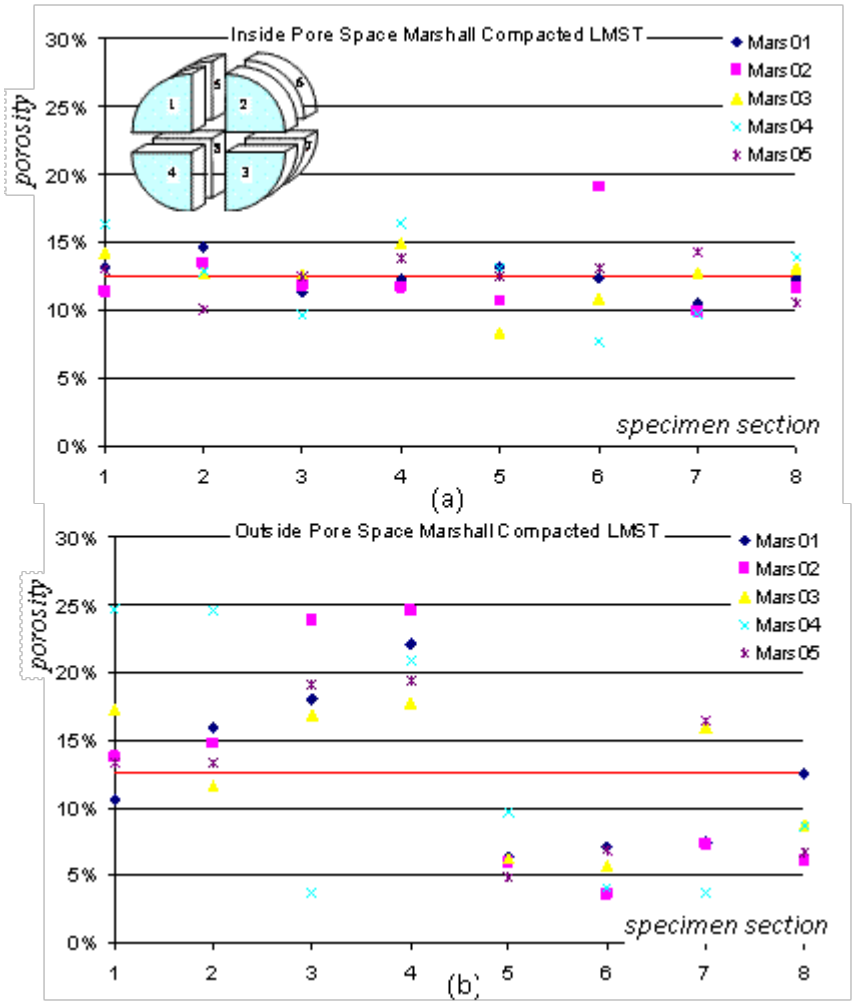

Figure 4-4- Pore space distribution in Marshall compacted limestone (LMST) specimens (a) inside porosity (b) outside porosity

4.3 Moisture Infiltration Simulation

From the above analyses it can be seen that there seems to be quite some variation in the pore space distribution of the gyratory and Marshall compacted specimens. This would indicate that, even if 70-80% saturation is achieved in all specimens, the actual moisture conditioning of the specimens can be very different from case to case.

To visualize the moisture infiltration inside the specimens and to incorporate the effect of the specimen type and size in the moisture conditioning process, a finite element analyses to simulate the moisture infiltration in 6" gyratory and 4" Marshall specimens was conducted. In Figure 4-5, the moisture infiltration front inside the gyratory compacted limestone (LMS) specimen is shown. From the moisture front development, in the mid-plane of the cylinder, Figure 4-5 (c), it can be seen that the moisture distributes itself relatively uniformly over the specimen. This is in agreement with the earlier observations

of the pore space distribution in gyratory specimens. The gyratory compacted sandstone (KST) specimen showed a similar moisture infiltration pattern.

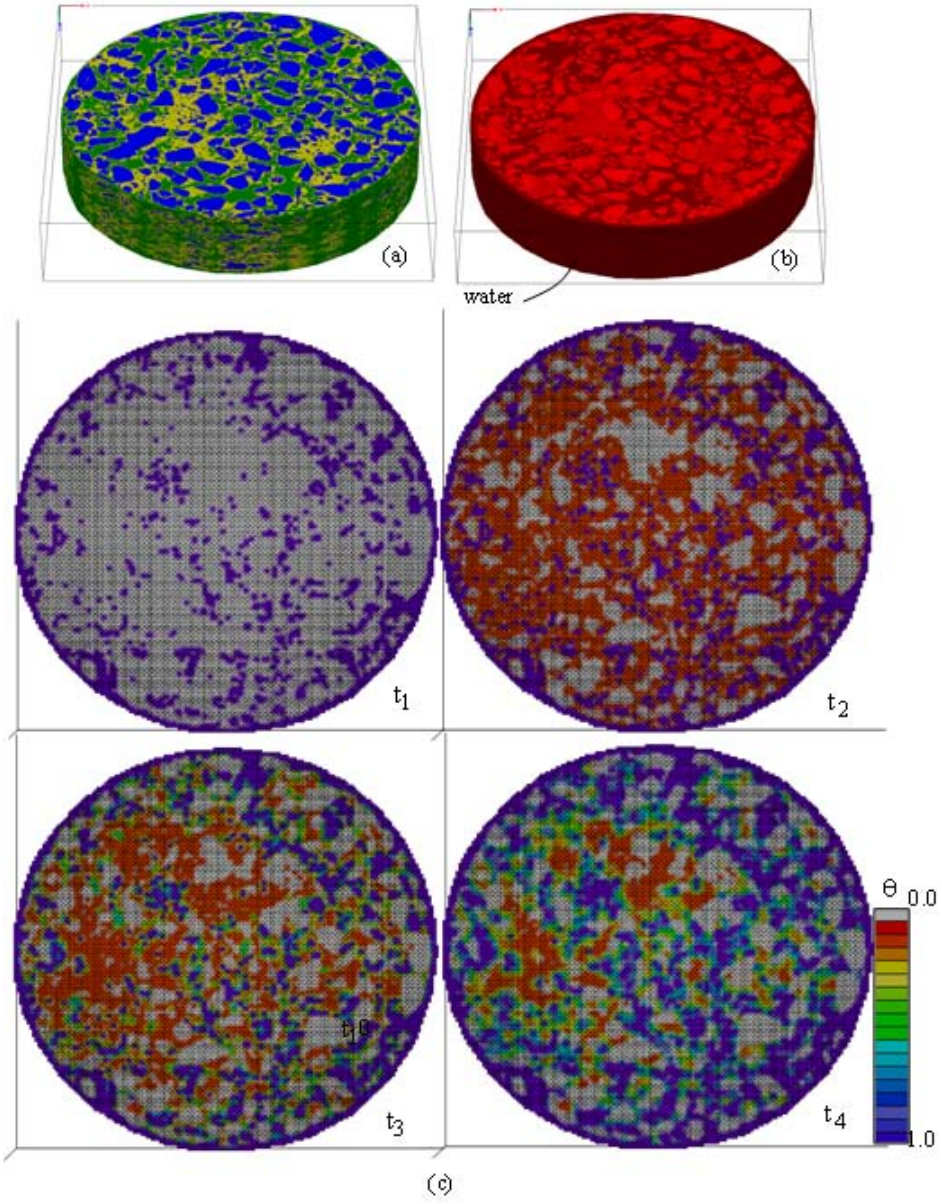

Figure 4-5- Finite element infiltration in Gyratory compacted limestone (LMS) specimen (a) finite element mesh (b) moisture conditioning (c) moisture infiltration in mid-plane for different conditioning times t, in which θ is the moisture content (or normalized moisture concentration)

In Figure 4-6, the finite element simulation of the Marshall compacted KST specimen is shown. From the finite element pictures of the mid-plane of the Marshall compacted KST specimen, it can be seen that a relatively large amount of moisture reaches the center of the core. In this case, the observed clustering seems to concentrate itself in the center of the specimen, which could explain why the Marshall compacted LMS specimens showed an unexpected low moisture resistance. From the analyses of images of the mid-plane of

the specimen it becomes clear that a very asymmetric moisture infiltration is created in the specimen. This would indicate that the material properties of these specimens are degrading asymmetrically and this will certainly contribute to problems with the repeatability of the test and the observed failure.

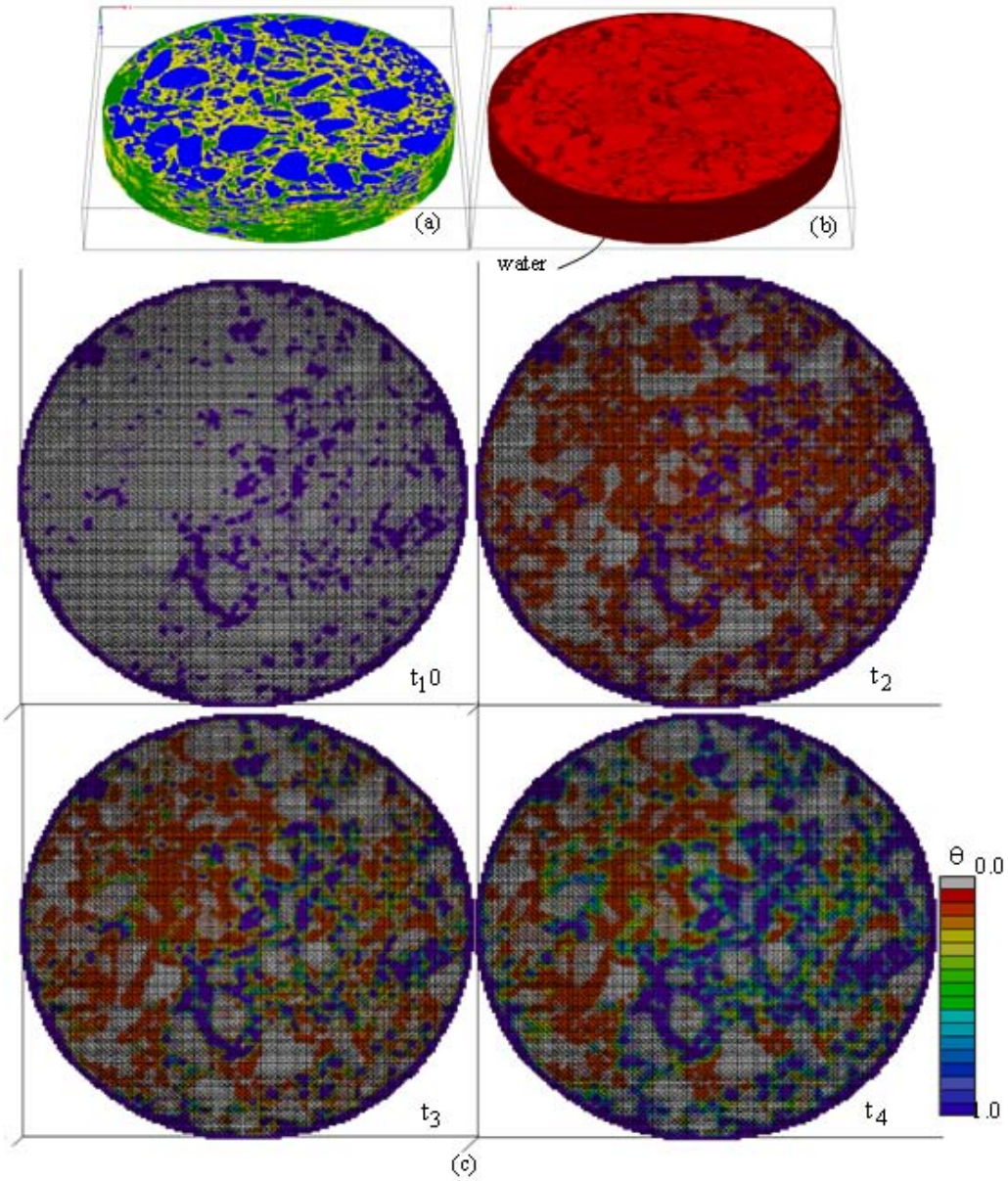

Figure 4-6- Finite element infiltration in Marshall compacted KST specimen (a) finite element mesh (b) moisture conditioning (c) moisture infiltration in mid-plane for different conditioning times t, in which θ is the moisture content (or normalized moisture concentration)

4.4 Mechanical Aspects of the Indirect Tension Test

In the above sections it was shown that the pore space distribution in the T283 test samples can result into varying moisture conditioning between samples. This varying moisture concentrations inside the sample may lead to inhomogeneous moisture induced weakening of the individual mixture components and can largely contribute to the variability of the test results. In order to gain insight into the predominant failure mechanism inside the specimen, the degradation of the mechanical properties of the mix components (mastic, stones and mastic-stone bond) as a function of moisture concentration must therefore be known.

To simulate the mechanical response, on the basis of the developed micro-scale finite element meshes, there are a number of mechanical properties which must be determined. These micro-scale simulations will be important in order to relate the effect of the inhomogeneous moisture infiltration to the resulting overall specimen response, which will contribute to the understanding of the statistical variations of the test and the controlling parameters.

It is, however, also possible to accurately simulate the dry indirect tension test on a continuum finite element basis. In Figure 4-7 an example of a finite element analysis made with CAPA-3D is shown. From the comparison of these finite element simulations with the laboratory test results, Figure 4-8, it can be seen that the analyses was able to capture the overall response of the specimen quite well. From the colors in the plots it can be clearly seen that the specimen is undergoing a complicated stress field during the test:

- At t_1 the specimen is building up tensile stresses in the center of the specimen and is starting to build up a compressive stress field on the top and bottom of the specimen, under the loading platen.
- At t_2 the specimen has not yet failed in tension in the middle, but is already showing considerable bulging on the top and bottom of the specimen due to the shear stresses developing there.
- At t_3 the specimen has failed, since it can no longer transfer tensile stresses in the middle of the sample, which can be seen from the white color in the legend and the large deformations of the finite elements in this area.

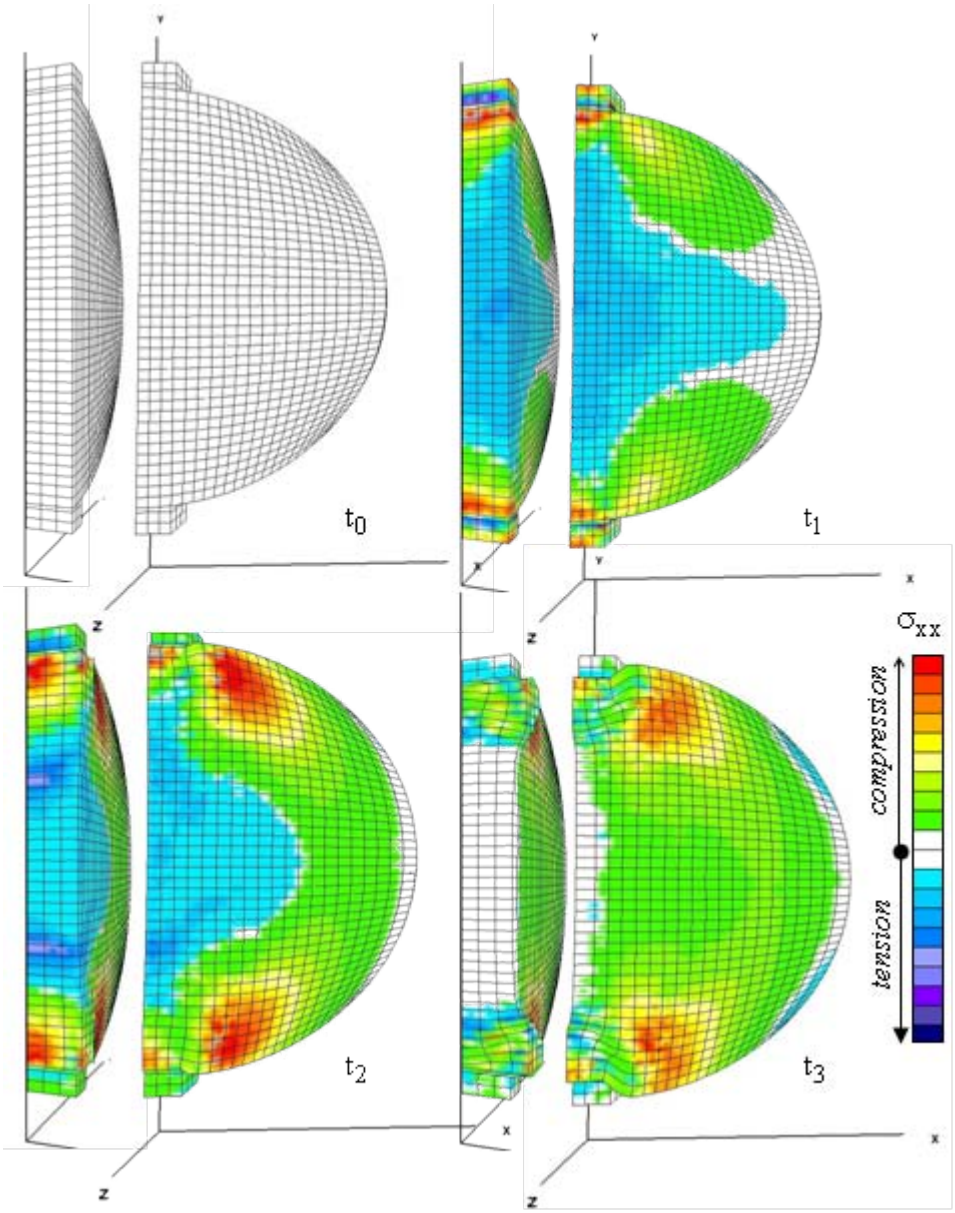

Figure 4-7- Finite element continuum analysis of dry indirect tension test

During the test, each location in the specimen experiences at all times a different stress and strain level and direction (tension in the middle and compression on the top and bottom) and continuously changing rates. By changing the size of the specimen, such as is done for Marshall and gyratory compacted specimens, the material will experience different stresses and strains inside the specimen. It is therefore, from a mechanical point of view, not surprising that a discrepancy is found between the response of the Marshall and gyratory compacted specimens, when tested in the T283. In order to be able to actually simulate this structural test, as shown in Figure 4-7 and Figure 4-8, the asphalt mix must be tested for its tensile and compressive response under various strain rates. For

this continuum analyses, tri-axial direct tension and compression test were performed on the asphalt mixtures.

To accurately simulate the micro-scale response of the samples using continuum mechanics analysis, the mechanical tri-axial response of the material components must be determined. Additionally, the influence of the degradation of these mechanical properties as a function of moisture concentration must be determined for each component. From these analyses it will become clear which failure mechanism and which parameters are dominant for the failure of the specimens and the variability of the test results. These mechanical material tests need to be performed on the mastic and the aggregate-mastic interface (16), so as to enable the micro-scale mechanical finite element simulation, including the freezing cycles.

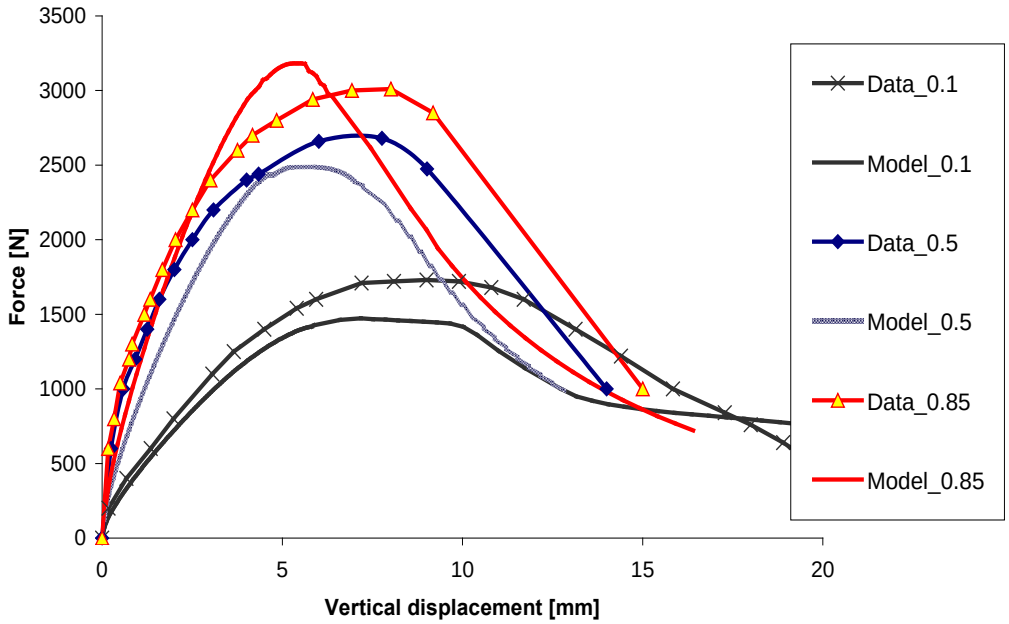

Figure 4-8- Comparison of laboratory indirect tensile test data and CAPA-3D simulation at different loading rates

4.5 Moisture Induced Damage in the Field

One of the documented complaints about the T283 test is that the experienced field moisture sensitivity does not always correlate well with the test results. From the analytical and computational analyses performed in this study it has been discussed that the moisture concentration levels of the various test samples are not necessarily comparable, nor do the samples themselves have a uniform moisture field inside the material.

These variations in the moisture conditioning of the samples can already partly explain some of the variability which is experienced with the test. It also contributes to the

discrepancy between the laboratory moisture conditioning and the moisture conditions in the field. The time-frame over which the moisture can actually infiltrate within the material components, is a crucial factor in this. Even though it is aimed to create similar levels of mix saturation between the laboratory test specimens and the field, it should be kept in mind that the actual weakening of the asphalt mixture comes when the moisture starts infiltrating inside the mix components. This moisture infiltration process will be mainly concentration gradient driven, and will take longer than a pressure driven process. The time frame of moisture conditioning is therefore crucial, and the T283 test protocol is certainly lacking with this respect.

The other moisture induced damage phenomena which can contribute to damage in the pavement are the mechanical and physical manifestations of the 'pumping action' which a (partially) saturated pavement experiences under mechanical loading. In addition to added mechanical stresses inside the material, which may cause added damage, these high water pressures may cause an erosion effect of the mastic, which contributes to the mechanical degradation of the mastic and the progressively increased moisture susceptibility (17, 18). The T283 is not including these pumping action related moisture induced damage phenomena in the test. This means, for instance, that a mixture which is highly susceptible to mastic erosion may perform well in the T283, but would have bad results in the pavement, when exposed to pumping action.

4.6 Variability Due to Other Factors

Two important aspects of the T283 protocol are the vacuum suction and the freezing of the sample. As was shown in the study, the vacuum suction must be inducing micro-cracking within the sample, which is introducing another variable to the test which can contribute to its inconsistency. For the freezing aspect of the test it has been suggested in the past that this would simulate a combination of the aging of the material and the cycling loading and/or pumping action as it would occur in practice. From a materials point of view, aging of the material entails a physical change of its characteristics, which embrittles the material making it thus more susceptible to cracking. From a mechanical point of view, the added stresses inside the mix which are caused by the volumetric expansion when the water turns to ice and the embrittlement of the material at such low temperature will certainly induce damage inside the mixture. This damage is, however, different in nature than the long term effect of cycling loading, in time aging and erosion of the mastic due to pumping action. This could be an additional reason for differences between the laboratory and the field.

Finally, it should be kept in mind that the state of stress which the sample is tested for is highly dependent on the geometry of the sample. So it would make perfect sense that by testing different geometry (such as Marshall versus gyratory), different (structural) result will be found. Likewise, the state of stress which is created in the indirect tension test, Figure 4-7, is of course not similar to the actual stress development in a pavement. Therefore, from a mechanics point of view, the differences between the laboratory and the field make perfect sense.

CHAPTER 5- CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The AASHTO T283 test method, known as modified Lottman, is frequently used for the evaluation of moisture susceptibility of asphalt concrete mixtures. As part of NCHRP 9-26A project, precision estimates of AASHTO T283 test method were investigated using an interlaboratory study (ILS). In addition, the causes of variability of the test were evaluated via analysis of X–ray computed tomography images and micro-scale finite element simulation of the specimens. Two different sources of aggregates, limestone and sandstone, with varying levels of moisture resistivity and two methods of compactions, gyratory and Marshall, for creating different structures were selected for the study. The combination of aggregate types and compaction methods resulted in four sets of specimens to be evaluated in the study. Prior to conducting the ILS, a preliminary study was conducted at Turner-Fairbank Highway Research Center, in which the moisture susceptibly of the four selected specimen types was evaluated using AASHTO T 283 test methods and Hamburg wheel track testing. A total of 40 laboratories participated in the ILS and provided complete sets of data on testing either gyratory, Marshall, or both specimen types.

Detailed volumetric and mechanical data were collected from the laboratories in the ILS. In addition to tensile strength ratios (TSR), laboratories provided the individual indirect tensile strength values of the dry and conditioned specimens. The results of the ILS indicated that while the repeatability standard deviations of dry and wet Strength measurements and their corresponding TSR values were very similar, the reproducibility standard deviations of the reported strength measurements were significantly larger than those of their corresponding TSR values. Therefore, while the wet strength values can be used in place of TSR, as suggested by a number of highway agencies, for comparison of moisture susceptibility of various mixtures within one laboratory, their use for between-laboratory comparison is not advisable.

The variability of TSR data were examined as part of preliminary study and the ILS. It was indicated by both sets of data that the test is in general very variable and sometimes provides erroneous results. The limestone mixture which was known to be highly moisture resistant indicated moderate resistivity to moisture and the sandstone that was known to be moisture sensitive showed relatively good moisture resistant.

The TSR results of the ILS were used to develop precision estimates for the AASHTO T283 test method. Separate within and between standard deviations were prepared for the four types of specimens in the study: gyratory limestone, Marshall limestone, gyratory sandstone, and Marshall sandstone. The statistical t-test on the averages indicated that average TSR of limestone and sandstone mixtures and of the gyratory and Marshall compacted specimens were significantly different. However, the statistical F test on

variances indicated that the within-laboratory and between- laboratory standard deviations of TSR values were not significantly different. Therefore, the within and between standard deviations of TSR of the four specimen types were combined to develop the repeatability and reproducibility precision estimates for AASHTO T283. Based on the precision estimates developed in this study, the allowable difference between two TSR values measured in one laboratory was found as high as 9 % and the allowable difference between two TSR values measured in two different laboratories was found as high as 25%. Although not recommended for addition to AASHTO T 283 test method, a precision statement for AASHTO T283, which provides the combined standard deviations resulted from this study, is presented in Appendix F.

The large repeatability and reproducibility standard deviations obtained here, necessitated looking into the causes of variability of AASHTO T283. To evaluate the causes of variability of the test, the various variables which are introduced in the T283 test method due to moisture conditioning procedure were investigated via micro-scale finite element analyses. For the finite element meshes, X-ray tomography scans were made of the gyratory and Marshall specimens that were compacted as part of the preliminary study. Following discusses the findings of the analysis of X-ray images and micro-scale simulation:

- The X-ray images of the specimens were analyzed for outside pore-space distribution. It was seen that the two different compactions and geometries can result in entirely different outside pore size. It is found that the gyratory specimens have an additional 23% and the Marshall specimens have an additional 45% of outside pore space. This indicated that the Marshall specimens may have relatively more access to moisture during conditioning times and could therefore reach higher moisture concentrations.

- In addition to outside porosity, the inside porosity distribution was evaluated. Although, the target (inside) porosity of 7 % $\pm$ 0.5 was reasonably well met, it was seen that the Marshall compaction creates a less dispersed inside pore-space than gyratory compaction and tends to create clusters of air-voids. This could indicate a very asymmetric moisture front inside the Marshall compacted specimens, which could lead to unexpected bad or unexpected good behavior of the specimens and significant impact on the variability of the test results.

- The finite element analyses of the moisture infiltration to the mid-plane of the specimens indicated that the moisture distributes itself relatively uniform over the gyratory specimens, which was in agreement with the observations on the pore space distribution in gyratory specimens. From the finite element pictures of the mid-plane of the Marshall compacted specimens, it was seen that a relatively large amount of moisture reaches the center of the core where the clustering of void spaces were concentrated. This would indicate that the material properties of these specimens degrade asymmetrically, which will certainly contribute to problems with the variability of the test.

- In addition to the variation in pore-structure of the mixture, the difference in the diffusion properties of the mixture component would affect the rate of moisture infiltration into the tested zone of the specimen. Therefore, the current conditioning procedure, as described in the T-283, does not always represent the moisture infiltration time frame representative of the mixture being tested. In this case moisture may in fact not reach the tested zone in the specimen, thus leading to erroneous conclusions.

- A saturation level of 70 % - 80 % of mixtures with a targeted air void of 7 % $\pm$ 0.5 specified by the test protocol is equivalent to a water absorption level of 4.6 – 6.0 %. Since the original water absorption of the compacted specimens before vacuum is around 1.5%, the applied vacuum suction must induce some micro cracking inside the sample to enable the necessary additional pore space. This induced micro-cracking can be an important factor which contributes to the variability of the test.

From this study it became clear that the TSR test specimens are exposed to large variations of the moisture conditioning of the samples, even when the moisture conditioning protocol is kept the same. Depending on the distribution of the inside pore-space, the added 'moisture accessibility' of the specimen due to increased outside-porosity, the distribution of induced micro cracking due to suction, and the connectivity of the inside pores within the sample, large differences can be expected when comparing the results of the TSR test.

5.2 Recommendations

It was shown that varying moisture concentrations inside the sample could lead to inhomogeneous moisture induced weakening of the individual mix components and can largely contribute to the variability of the test results. Depending on both the pore-structure of the mixture as well as the diffusion properties of the component, moisture may in fact not reach the tested zone in the specimen, thus leading to erroneous conclusions.

Since the conditioning procedure, as described in the current T-283 standard was found to not represent the actual moisture infiltration time frame that produced in field damage, it is recommended to further investigate what can be done to improve the T-283 test procedure to increase its ability for detecting moisture susceptible mixtures. Such a fundamental study should focus on understanding which parameter(s) must be addressed to accurately capture moisture susceptibility and what aspects of the current T-283 must be altered.

In order to gain insight into the predominant failure mechanism inside the specimen and to make a more quantitative basis conclusion, continuum analysis of mechanical test on the specimen can be simulated. For that, the physical and mechanical moisture susceptibility characteristics of the individual mix components (mastic, stones and mastic-stone bond) and the degradation of the mechanical properties as a function of

moisture concentration must be determined. The micro-scale simulations will then relate the effect of the inhomogeneous moisture infiltration to the resulting overall specimen response, which will contribute to the understanding of the statistical variations of the test and the controlling parameters. From these analyses it will become clear which failure mechanism, i.e., adhesion of mastic to aggregate or cohesion of mastic, are dominant for the failure of the specimens and how they affect the variability of the test results. By incorporating the properties of the component materials into continuum mechanics simulation, the effect of different specimen geometries (cut and cored) and different loading modes (tension and compression) on moisture resistance determination of the material can be explored. The results of the simulation can be then validated by laboratory results to recommend improvement to the existing AASHTO T283 moisture damage test protocol.

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APPENDIX A- INSTRUCTIONS AND DATA SHEET FOR INTERLABORATORY STUDY

Instructions for Preparing Marshall Limestone Mixture

Dear Participants,

You have received two boxes that contain the aggregate and asphalt for preparing 4" Marshall or Hveem specimens. The materials are enough for preparing two trial and eight testing specimens. Use the two trial specimens to determine the compaction effort (i.e. number of blows) that provide specimens with 7%± 0.5 air voids. Please follow the instructions below for preparing and testing the samples. Since it requires five consecutive days to complete the testing, it is suggested to start the work on a Monday to be able to finish the testing by Friday of that week. Otherwise, you have to work through a weekend to not defer any of the steps of the testing.

Prior to Monday:

Prepare the aggregate batches for 2 trial and 8 testing specimens:

1. To avoid the segregation of the fine aggregates, the fine aggregate material needs to be divided into 10 portions before getting dried:
    a. Mix the fine aggregate material thoroughly if it is still wet. If it has lost its free moisture, moisten it to achieve a moist condition and then mix it thoroughly.
    b. Follow Method C (Sections 11 and 12) of AASHTO T 248, "Reducing Samples of Aggregate to Testing Size" to take representative fine aggregate samples for the ten samples.
2. Dry the aggregates of different sizes including the reduced fine aggregate samples in a 110°C - oven.
3. Prepare two aggregate batches for trial specimens according to the proportions in Table 1.
4. Prepare eight aggregate batches for preparing Marshall or Hveem specimens according to the proportions in Table 1.
5. Using the two trial batches and the amount of asphalt in Table 1, mix and compact two specimens to the height of 63.5± 2.5 mm to achieve 7%± 0.5 air voids (try 18 to 20 blows on each side). Measure the height in accordance with ASTM D 3549 and calculate the percent air voids in accordance to T 269. Use maximum gravity of 2.572 to calculate the air voids.

Table A-1- Weight of aggregate and asphalt for preparing 4" diameter specimens

Material	Weight (g)
3/4	0.0
1/2	56.4
3/8	90.2
#4	428.6
#8	169.2
Fine Agg	332.8
Min Filler	50.8
Asphalt	63.1

Monday Activities:

1. At 8:00 AM, set the oven temperature to the mixing temperature of 157ºC and place the aggregate batches in the oven.
2. Place the asphalt quarts in the 157°C oven at 11:30 AM.
3. Start preparing the eight mixtures at 1:00 PM. Weight of the asphalt is given in Table 1.
4. If allowing 10 minutes for mixing of each specimen, it will take about one hour and 40 minutes to complete the mixing process. Place a note with each specimen indicating the exact time of the mixing.
5. Leave the mixtures at room temperature for 2 hours.
6. Set the oven to 60°C.
7. Place the mixtures in the 60°C oven in 10 minute intervals starting at 3:00 PM. The mixtures should go in the oven in the order that they have been mixed. For example, the mixture that has been prepared at 1:10 PM should be placed in the oven at 3:10 PM. Leave the mixtures in the oven for 16 ± 1 hours.

Tuesday Activities:

1. Transfer the mixtures from the 60°C oven at 7:00 ±1 AM to an oven that has been set at the compaction temperature of 145°C. The specimens should be transferred in 10 min interval in the same order that they were placed in the 60°C oven the day before.
2. Leave the specimens at the compaction temperature for 2 hours ± 10 minutes.
3. At 9:00 ±1 AM, remove the specimens from the oven. The specimens should be removed from the oven in the same order that they were placed in the oven.
4. Prepare the specimens to 7%± 0.5 air voids by compacting them to the height of 63.5± 2.5 mm (use the compaction effort that was determined using the trial samples earlier). You will need at least three molds to let the compacted mixtures to cool down while the other mixtures are being compacted.
5. After the specimens have cooled down, remove the compacted specimens from the molds and store them at room temperature for 24 ± 3 hours.

Wednesday Activities:

1. Conduct the following measurements and record the data in the provided data sheet:
    a. Determine height of the specimens in accordance with ASTM D 3549.
    b. Determine each bulk specific gravity by Method A of T 166.
    c. Determine the dry weight of the specimens in the air (A).
    d. Express the volume of specimens (E) as the saturated-surface dry mass minus the mass in water.
    e. Calculate the percent air voids in accordance to T 269.
2. Separate the specimens into two subsets, of at least three specimens each, so that the average air voids of the two subsets are approximately equal. One set will stay dry (referred to as "dry") and the other set will be saturated and freeze- thaw conditioned (referred to as "wet").
3. By entering the volumetric measurements into the provided data sheet, the volume of air voids (V_a) in cm^3 for the set that will be saturated is determined.
4. Leave the "dry" specimens at room temperature for additional 24 ± 3 hours until Thursday morning. This allows the specimens to dry after G_{mb} measurements.
5. After G_{mb} measurement of the "wet" set, place the specimens in the vacuum container supported by a spacer a minimum of 25 mm (1 in.) above the bottom of container.
6. Fill the container with water at room temperature so that there is at least 25 mm of water above the specimen.
7. Apply a vacuum of 13 to 67 kPa absolute pressure (10 to 26 in. Hg partial pressure) for a short time (1 to 3 minutes).
8. Remove the vacuum and leave the specimen submerged in water for a short time (3 to 5 minutes).
9. Determine the mass of saturated, surface-dry specimen after partial vacuum saturation (B'). Record the data in the provided data sheet.
10. The volume of absorbed water (J') in cubic centimeters will be determined using B' and dry mass of the specimen in air (A) in the data sheet.
11. In the provided data sheet, check the degree of saturation (S') that has been determined using the volume of absorbed water (J') and the volume of air voids (V_a). The degree of saturation should be between 70 and 80 percent.
12. If the degree of saturation is between 70 and 80 percent, proceed to Step 15.
13. If the degree of saturation is less than 70%, repeat the procedure beginning with Step 7.
14. If the degree of saturation is more than 80 %, the specimen has been damaged and must be discarded. In this case, repeat the procedure on the next specimen beginning with Step 7 using less vacuum/ or time.
15. Cover each vacuum-saturated specimen tightly with a plastic film. Place each wrapped specimen in a plastic bag containing 10 ±0.5 ml of water, and seal the bag.
16. Place the bags in freezer at a temperature of -18 ± 3°C for a minimum of 16 hours.

Thursday Activities:

"Wet" Specimens:

1. Remove the specimens from freezer on Thursday morning and Place them in a bath containing 60 ± 1°C water for 24 ± 1 hours.
2. As soon as possible after placement in the water bath, remove the plastic bag and film from each specimen.

"Dry" Specimens:

3. Wrap the dry specimens with plastic or place them in a heavy-duty plastic leak proof plastic bag. Place the specimens in 25 ±0.5°C water bath for 2 hours ± 10 minutes with a minimum of 25 mm (1 in.) of water above their surface.
4. Remove the specimens from water bath and conduct indirect- tensile strength test.
5. Enter the measured maximum load into the provided data sheet. The tensile strength and tensile strength ratio will be automatically calculated.
6. Record your visual observations in the table.

Friday Activities:

1. After 24 hours in the 60°C water bath, remove the "wet" specimens from 60°C water bath and place them in a 25°C water bath for 2 hours. The specimens should have a minimum of 25 mm (1 in.) of water above their surface. It may be necessary to add ice to the water bath to prevent the water temperature from rising above 25°C. Not more than 15 minute should be required for the water bath to reach 25± 0.5°C.
2. Remove the specimens from water bath; determine the thickness (t´) by ASTM D 3549 and use that value in the strength calculations.
3. Conduct the indirect- tensile strength test.
4. Enter the measured maximum load into the provided data sheet. The tensile strength and tensile strength ratio will be calculated automatically.
5. Record your visual observations in the table.

Thank you for completing the first set of TSR testing. Please email the data sheet to **hazari@amrl.net**. The materials for the second set of testing will be shipped in December.

Instructions for Preparing Gyratory Limestone Mixture

Dear Participants,

You have received four boxes that contain the following materials:

1- A box of approximately 26 lbs of fine aggregate.
2- A box of approximately 34 lbs of # 4 aggregate.
3- A box containing approximately 14 lbs of #8, 5 lbs of ½", 7 lbs of 3/8", and 4 lbs of mineral filler.
4- A box containing 3 cans of asphalt binder.

The materials are enough for preparing two maximum specific gravity (G_{mm}) and eight gyratory specimens. Please follow the instructions below for preparing and testing the samples. Since it requires five consecutive days to complete the testing, it is suggested to start the work on a Monday to be able to finish the testing by Friday of that week. Otherwise, you have to work through a weekend to not defer any of the steps of the testing.

Prior to Monday:

Prepare the aggregate batches for 2 specific gravity and 8 gyratory samples:

1. To avoid the segregation of the fine aggregates, the fine aggregate material needs to be divided into 10 portions before getting dried:
    a. Mix the fine aggregate material thoroughly if it is still wet. If it has lost its free moisture, moisten it to achieve a moist condition and then mix it thoroughly.
    b. Follow Method C (Sections 11 and 12) of AASHTO T 248, "Reducing Samples of Aggregate to Testing Size" to take representative fine aggregate samples for the ten samples.
2. Dry the aggregates of different sizes including the reduced fine aggregate samples in a 110°C - oven.
3. Prepare two 2000-g aggregate batches for Gmm specimens according to the proportions in Table 1.
4. Prepare eight 3700-g aggregate batches for preparing Superpave gyratory specimens according to the proportions in Table 2.

Table A-2. Weight of aggregate and asphalt for preparing Gmm specimens

Material	Weight (g)
3/4	0
1/2	100
3/8	160
#4	760
#8	300
Fine Agg	590
Min Filler	90
Asphalt	111.9

Table A-3. Weight of aggregate and asphalt for preparing 6" diameter gyratory specimens

Material	Weight (g)
3/4	0
1/2	185
3/8	296
#4	1406
#8	555
Fine Agg	1091.5
Min Filler	166.5
Asphalt	207

Monday Activities:

1. At 8:00 AM, increase the oven temperature to the mixing temperature of 157°C and place the aggregate batches in the oven.
2. Place the asphalt quarts in the 157°C oven at 11:30 AM.
3. Start preparing the 2 Gmm mixtures and eight gyratory mixtures at 1:00 PM. Weight of the asphalt for the two mixtures are given in Tables 1 and 2.
4. If allowing 10 minutes for mixing of each specimen, it will take about one hour and 40 minutes to complete the mixing process. Place a note with each specimen indicating the exact time of the mixing.
5. Leave the mixtures at room temperature for 2 hours.
6. Set the oven to 60°C.
7. Place the mixtures in the 60°C oven in 10 minute intervals starting at 3:00 PM. The mixtures should go in the oven in the order that they have been mixed. For example, the mixture that has been prepared at 1:10 PM should be placed in the oven at 3:10 PM. Leave the mixtures in the oven for 16 ± 1 hours.

Tuesday Activities:

1. Transfer the mixtures from the 60°C oven at 7:00 ±1 AM to an oven that has been set at the compaction temperature of 145°C. The specimens should be

transferred in 10 min interval in the same order that they were placed in the 60°C oven the day before.
2. Leave the specimens at the compaction temperature for 2 hours ± 10 minutes.
3. At 9:00 ±1 AM, remove the specimens from the oven for Gmm measurement and for the compaction. The specimens should be removed from the oven in the same order that they were placed in the oven.
4. Prepare the specimens to 7%± 0.5 air voids by compacting them to the height of 95.7 mm. You will need at least three molds to let the compacted mixtures to cool down while the other mixtures are being compacted.
5. After the Gmm mixtures have reached the room temperature, conduct the maximum specific gravity measurements. Record the Gmm values in the provided worksheet.
6. After the specimens have cooled down, remove the compacted specimens from the molds and store them at room temperature for 24 ± 3 hours.

Wednesday Activities:

1. Conduct the following measurements and record the data in the provided data sheet:
    a. Determine height of the specimens in accordance with ASTM D 3549.
    b. Determine each bulk specific gravity by Method A of T 166.
    c. Determine the dry weight of the specimens in the air (A).
    d. Express the volume of specimens (E) as the saturated-surface dry mass minus the mass in water.
    e. Calculate the percent air voids in accordance to T 269.
2. Separate the specimens into two subsets, of at least three specimens each, so that the average air voids of the two subsets are approximately equal. One set will stay dry (referred to as “dry”) and the other set will be saturated and freeze- thaw conditioned (referred to as “wet”).
3. By entering the volumetric measurements into the provided data sheet, the volume of air voids (Va) in cm3 for the set that will be saturated is determined.
4. Leave the “dry” specimens at room temperature for additional 24 ± 3 hours until Thursday morning. This allows the specimens to dry after Gmb measurements.
5. After Gmb measurement of the “wet” set, place the specimens in the vacuum container supported by a spacer, a minimum of 25 mm (1 in.) above the container bottom.
6. Fill the container with water at room temperature so that the specimen has at least 25 mm of water above it.
7. Apply a vacuum of 13 to 67 kPa absolute pressure (10 to 26 in. Hg partial pressure) for a short time (1 to 3 minutes).
8. Remove the vacuum and leave the specimen submerged in water for a short time (3 to 5 minutes).
9. Determine the mass of saturated, surface-dry specimen after partial vacuum saturation (B’). Record the data in the provided data sheet.

10. The volume of absorbed water (J') in cubic centimeters will be determined using B' and dry mass of the specimen in air (A) in the data sheet.
11. In the provided data sheet, check the degree of saturation (S') that has been determined using the volume of absorbed water (J') and the volume of air voids (Va). The degree of saturation should be between 70 and 80 percent.
12. If the degree of saturation is between 70 % and 80 %, proceed to Step 15.
13. If the degree of saturation is less than 70 %, repeat the procedure beginning with Step 7.
14. If the degree of saturation is more than 80 %, the specimen has been damaged and must be discarded. In this case, repeat the procedure on the next specimen beginning with Step 7 using less vacuum/ or time.
15. Cover each vacuum-saturated specimen tightly with a plastic film. Place each wrapped specimen in a plastic bag containing 10 ±0.5 ml of water, and seal the bag.
16. Place the bags in freezer at a temperature of -18 ± 3°C for a minimum of 16 hours.

Thursday Activities:

"Wet" Specimens:

1. Remove the specimens from freezer on Thursday morning and Place them in a bath containing 60 ± 1°C water for 24 ± 1 hours.
2. As soon as possible after placement in the water bath, remove the plastic bag and film from each specimen.

"Dry" Specimens:

3. Wrap the dry specimens with plastic or place them in a heavy-duty leak proof plastic bag. Place the specimens in 25 ±0.5°C water bath for 2 hours ± 10 minutes with a minimum of 25 mm (1 in.) of water above their surface.
4. Remove the specimens from water bath and conduct indirect tensile strength test.
5. Enter the measured maximum load into the provided data sheet. The tensile strength and tensile strength ratio will be automatically calculated.
6. Record your visual observations in the table.

Friday Activities:

1. After 24 hours in the 60°C water bath, remove the "wet" specimens from 60°C water bath and place them in a 25°C water bath for 2 hours. The specimens should have a minimum of 25 mm (1 in.) of water above their surface. It may be necessary to add ice to the water bath to prevent the water temperature from rising above 25°C. Not more than 15 minute should be required for the water bath to reach 25± 0.5°C.
2. Remove the specimens from water bath and conduct the indirect tensile strength test.

3. Enter the measured maximum load into the provided data sheet. The tensile strength and tensile strength ratio will be automatically calculated.
4. Record your visual observations in the table.

Thank you for completing the first set of TSR testing. Please email the data sheet to **hazari@amrl.net**. The materials for the second set of testing will be shipped in December.

APPENDIX B- RESULTS OF INDIRECT TENSILE STRENGTH TEST OF LIMESTONE GYRATORY SPECIMENS

Table B-1- Statistics of indirect tensile strength properties of limestone gyratory specimens

	Limestone Gyratory			X_bar			S			h			k			X_bar_corr			S_corr		
Lab No	Dry Tensile Strength, kPa	Wet Tensile Strength, kPa	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR
1	619.18	606.01	1.01	607.95	605.01	1.00	10.45	2.65	0.01	-0.32	-0.27	0.06	0.29	0.07	0.32	607.95	605.01	1.00	10.45	2.65	0.01
	606.17	607.01	1.00																		
	598.50	602.01	0.98																		
2	524.41	524.96	1.00	593.20	557.98	0.95	80.21	34.79	0.07	-0.39	-0.53	-0.20	2.24	0.97	1.60	FALSE	557.98	0.95	FALSE	34.79	0.07
	573.88	554.68	0.97																		
	681.30	594.30	0.87																		
3	808.81	729.90	0.95	789.08	766.07	0.97	19.73	39.86	0.03	0.55	0.61	-0.07	0.55	1.11	0.64	789.08	766.07	0.97	19.73	39.86	0.03
	769.36	759.49	0.96																		
	789.08	808.81	1.00																		
4	666.75	638.66	0.97	665.90	655.03	0.98	8.88	15.36	0.01	-0.04	0.01	0.00	0.25	0.43	0.24	665.90	655.03	0.98	8.88	15.36	0.01
	656.63	669.13	0.99																		
	674.32	657.30	0.99																		
5	786.04	733.77	0.93	831.72	749.34	0.90	46.05	14.34	0.03	0.75	0.52	-0.43	1.29	0.40	0.79	831.72	749.34	0.90	46.05	14.34	0.03
	878.14	752.25	0.91																		
	830.98	762.00	0.87																		
6	690.45	660.86	0.97	674.01	660.86	0.98	15.07	19.73	0.01	0.00	0.04	-0.02	0.42	0.55	0.21	674.01	660.86	0.98	15.07	19.73	0.01
	660.86	641.13	0.99																		
	670.72	680.58	0.99																		
7	678.85	569.76	0.82	682.37	564.48	0.83	7.07	6.08	0.01	0.04	-0.49	-0.83	0.20	0.17	0.13	682.37	564.48	0.83	7.07	6.08	0.01
	690.51	557.84	0.83																		
	677.75	565.84	0.83																		
8	649.92	570.04	0.84	652.74	557.67	0.85	20.41	22.94	0.02	-0.11	-0.53	-0.68	0.57	0.64	0.49	652.74	557.67	0.85	20.41	22.94	0.02
	674.40	571.78	0.88																		
	633.88	531.20	0.85																		
9	1193.14	1114.45	0.93	1256.95	1160.22	0.92	66.96	40.53	0.02	2.80	2.77	-0.32	1.87	1.13	0.53	FALSE	FALSE	0.92	FALSE	FALSE	0.02
	1326.66	1191.57	0.94																		
	1251.06	1174.64	0.90																		
10	681.30	635.25	1.01	622.24	603.39	0.97	55.67	29.76	0.04	-0.25	-0.28	-0.06	1.55	0.83	0.93	622.24	603.39	0.97	55.67	29.76	0.04
	614.71	598.62	0.97																		
	570.73	576.30	0.93																		
11	654.07	673.89	1.03	648.12	673.89	1.04	12.06	19.82	0.02	-0.13	0.11	0.29	0.34	0.55	0.37	648.12	673.89	1.04	12.06	19.82	0.02
	634.25	693.71	1.03																		
	656.05	654.07	1.06																		
12	478.96	477.96	1.04	484.70	513.74	1.06	26.80	35.69	0.02	-0.91	-0.77	0.40	0.75	1.00	0.48	484.70	513.74	1.06	26.80	35.69	0.02
	513.90	549.34	1.07																		
	461.22	513.90	1.07																		
13	507.78	506.20	0.91	528.82	509.22	0.96	28.95	48.80	0.05	-0.70	-0.79	-0.12	0.81	1.36	1.09	528.82	509.22	0.96	28.95	48.80	0.05
	561.83	462.01	0.98																		
	516.85	559.46	1.00																		
14	482.51	934.42	1.46	516.38	832.78	1.61	30.22	116.23	0.13	-0.76	0.98	3.28	0.84	3.25	3.22	516.38	FALSE	FALSE	30.22	FALSE	FALSE
	526.08	706.05	1.63																		
	540.56	857.87	1.73																		
15	532.74	532.08	1.00	565.55	544.93	0.97	40.98	11.18	0.05	-0.53	-0.60	-0.10	1.14	0.31	1.30	565.55	544.93	0.97	40.98	11.18	0.05
	611.48	550.29	1.00																		
	552.42	552.42	0.90																		
16	546.86	471.97	0.90	520.93	470.31	0.90	22.98	17.45	0.02	-0.74	-1.00	-0.43	0.64	0.49	0.37	520.93	470.31	0.90	22.98	17.45	0.02
	512.90	486.88	0.92																		
	503.04	452.10	0.89																		
17	502.02	491.67	0.98	506.62	494.58	0.98	3.99	4.89	0.01	-0.81	-0.87	-0.04	0.11	0.14	0.20	506.62	494.58	0.98	3.99	4.89	0.01
	509.07	491.85	0.97																		
	508.76	500.22	0.98																		
18	1037.35	748.61	0.77	985.37	748.73	0.76	47.34	17.89	0.02	1.49	0.52	-1.18	1.32	0.50	0.45	985.37	748.73	0.76	47.34	17.89	0.02
	974.02	730.91	0.77																		
	944.73	766.68	0.74																		
19	581.43	577.29	0.97	581.06	575.80	0.99	0.52	10.75	0.02	-0.45	-0.43	0.03	0.01	0.30	0.42	581.06	575.80	0.99	0.52	10.75	0.02
	580.46	585.72	0.99																		
	581.29	564.37	1.01																		
20	759.50	811.40	1.07	784.17	834.60	1.07	34.51	20.30	0.03	0.53	0.99	0.43	0.96	0.57	0.78	784.17	834.60	1.07	34.51	20.30	0.03
	769.40	849.10	1.10																		
	823.60	843.30	1.03																		
				20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	18.00	18.00	19.00	18.00	18.00	19.00

X_dbl_bar / Sx			Sr / SR			h Critical			k Critical			Corrected X_dbl_bar / Sx			Corrected Sr / SR		
674.89	653.93	0.98	35.83	35.77	0.04	2.56	2.56	2.56	2.21	2.21	2.21	647.10	615.87	0.95	28.64	24.08	0.03
208.01	182.76	0.19	210.05	185.08	0.19							133.95	106.63	0.088	135.97	108.43	0.091

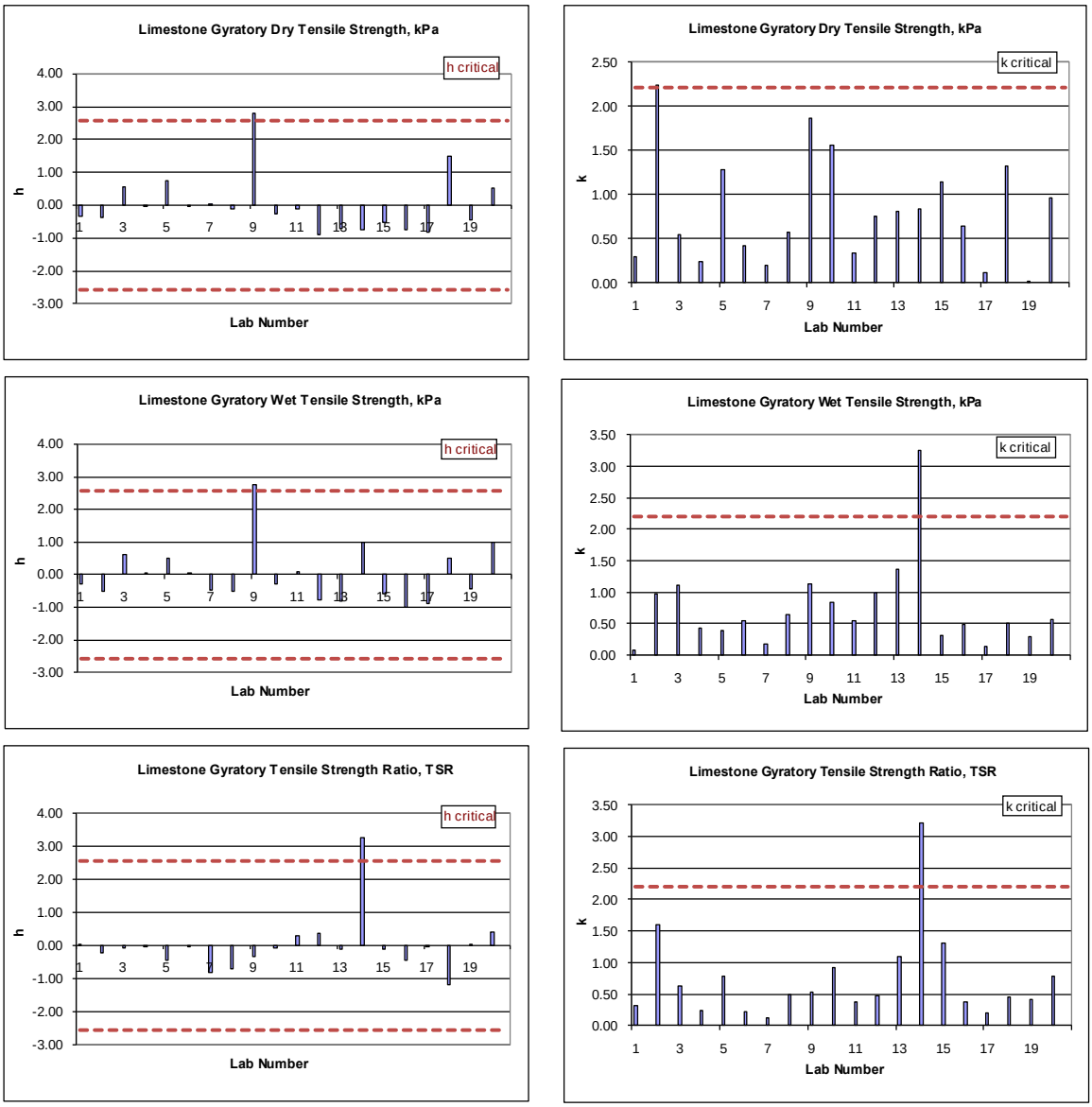
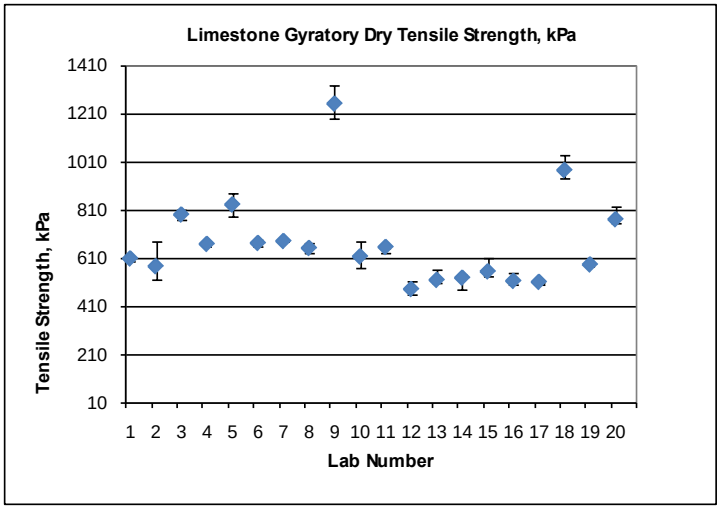
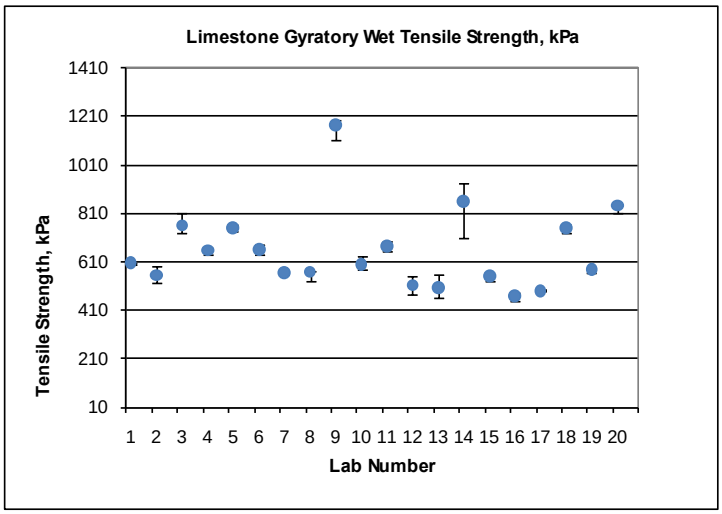


Figure B-1- h and k statistics of indirect tensile strength properties of limestone gyratory specimens





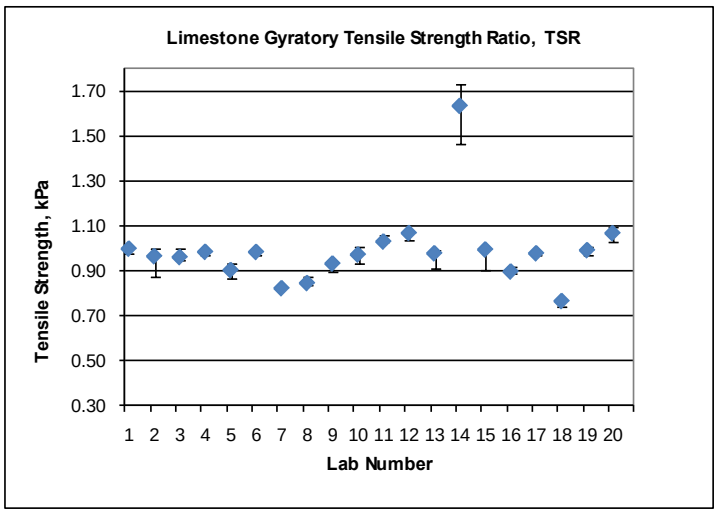


Figure B-2- Error band of indirect tensile strength properties of limestone gyratory specimens

APPENDIX C- RESULTS OF INDIRECT TENSILE STRENGTH TEST OF LIMESTONE MARSHALL SPECIMENS

Table C-1- Statistics of indirect tensile strength properties of limestone Marshall specimens

	Limestone Marshall			X_bar			S			h			k			X_bar_corr			S_corr		
Lab No	Dry Tensile Strength, kPa	Wet Tensile Strength, kPa	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR
1	1000.11	996.73	0.96	1069.01	983.61	0.92	90.23	19.66	0.06	0.26	0.35	0.38	1.61	0.32	1.41	1069.01	983.61	0.92	90.23	19.66	0.06
	1035.79	993.09	0.96																		
	1171.15	961.01	0.85																		
2	1216.65	951.20	0.85	1173.56	971.82	0.83	52.63	24.30	0.02	0.73	0.30	-0.50	0.94	0.40	0.49	1173.56	971.82	0.83	52.63	24.30	0.02
	1114.90	998.61	0.81																		
	1189.13	965.66	0.82																		
3	928.73	813.40	0.94	919.44	825.73	0.90	60.68	34.42	0.03	-0.42	-0.29	0.16	1.08	0.56	0.71	919.44	825.73	0.90	60.68	34.42	0.03
	854.66	864.62	0.88																		
	974.95	799.16	0.89																		
4	1267.66	1601.85	1.11	1330.26	1533.94	1.15	60.82	105.85	0.04	1.44	2.60	2.50	1.08	1.73	0.86	1330.26	FALSE	FALSE	60.82	FALSE	FALSE
	1333.98	1587.99	1.19																		
	1389.13	1411.98	1.15																		
5	918.95	763.95	0.85	921.41	782.77	0.85	27.31	33.77	0.02	-0.41	-0.47	-0.30	0.49	0.55	0.38	921.41	782.77	0.85	27.31	33.77	0.02
	895.43	821.75	0.83																		
	949.87	762.61	0.87																		
6	724.24	437.19	0.69	692.22	517.78	0.75	50.57	101.23	0.11	-1.45	-1.55	-1.27	0.90	1.65	2.46	692.22	517.78	FALSE	50.57	101.23	FALSE
	718.49	484.77	0.67																		
	633.92	631.40	0.87																		
7	1012.61	879.11	0.94	980.55	919.57	0.94	42.31	35.12	0.01	-0.14	0.09	0.52	0.75	0.57	0.15	980.55	919.57	0.94	42.31	35.12	0.01
	932.59	937.47	0.94																		
	996.46	942.15	0.93																		
8	1577.39	1271.91	0.74	1594.81	1213.33	0.76	21.97	53.67	0.02	2.64	1.29	-1.13	0.39	0.88	0.52	FALSE	1213.33	0.76	FALSE	53.67	0.02
	1619.49	1166.50	0.76																		
	1587.55	1201.58	0.79																		
9	907.00	706.00	0.89	887.67	724.00	0.82	87.61	20.30	0.06	-0.56	-0.71	-0.58	1.56	0.33	1.41	887.67	724.00	0.82	87.61	20.30	0.06
	964.00	746.00	0.79																		
	792.00	720.00	0.77																		
10	993.62	846.43	0.82	1007.12	846.63	0.84	16.66	27.84	0.01	-0.02	-0.21	-0.39	0.30	0.45	0.33	1007.12	846.63	0.84	16.66	27.84	0.01
	1002.01	874.57	0.84																		
	1025.74	818.88	0.85																		
11	934.91	1159.43	1.01	1046.13	1094.18	1.04	104.04	132.61	0.04	0.16	0.80	1.50	1.86	2.16	0.96	1046.13	1094.18	1.04	104.04	132.61	0.04
	1141.07	1181.53	1.09																		
	1062.42	941.60	1.04																		
12	787.52	712.55	0.79	800.41	678.80	0.85	20.00	50.70	0.05	-0.96	-0.89	-0.32	0.36	0.83	1.19	800.41	678.80	0.85	20.00	50.70	0.05
	790.26	703.35	0.89																		
	823.44	620.50	0.87																		
13	883.04	837.08	0.95	869.39	829.47	0.95	13.63	13.65	0.01	-0.64	-0.28	0.67	0.24	0.22	0.17	869.39	829.47	0.95	13.63	13.65	0.01
	855.78	837.62	0.96																		
	869.33	813.71	0.95																		
14	849.30	665.02	0.78	908.72	737.87	0.81	53.56	63.11	0.03	-0.47	-0.65	-0.66	0.96	1.03	0.60	908.72	737.87	0.81	53.56	63.11	0.03
	923.58	775.85	0.84																		
	953.27	772.73	0.81																		
15	1012.90	842.80	0.79	976.57	799.40	0.82	32.52	43.96	0.02	-0.16	-0.40	-0.59	0.58	0.72	0.46	976.57	799.40	0.82	32.52	43.96	0.02
	950.20	754.90	0.83																		
	966.60	800.50	0.83																		
				15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	14.00	14.00	13.00	14.00	14.00	13.00

X_dbl_bar / Sx			Sr / SR			h Critical			k Critical			Corrected X_dbl_bar / Sx			Corrected Sr / SR		
1011.82	897.26	0.88	56.07	61.27	0.04	2.47	2.47	2.47	2.17	2.17	2.17	970.18	851.78	0.87	57.74	56.76	0.04
221.04	244.90	0.11	225.73	249.96	0.11							156.86	176.58	0.076	163.79	182.56	0.082

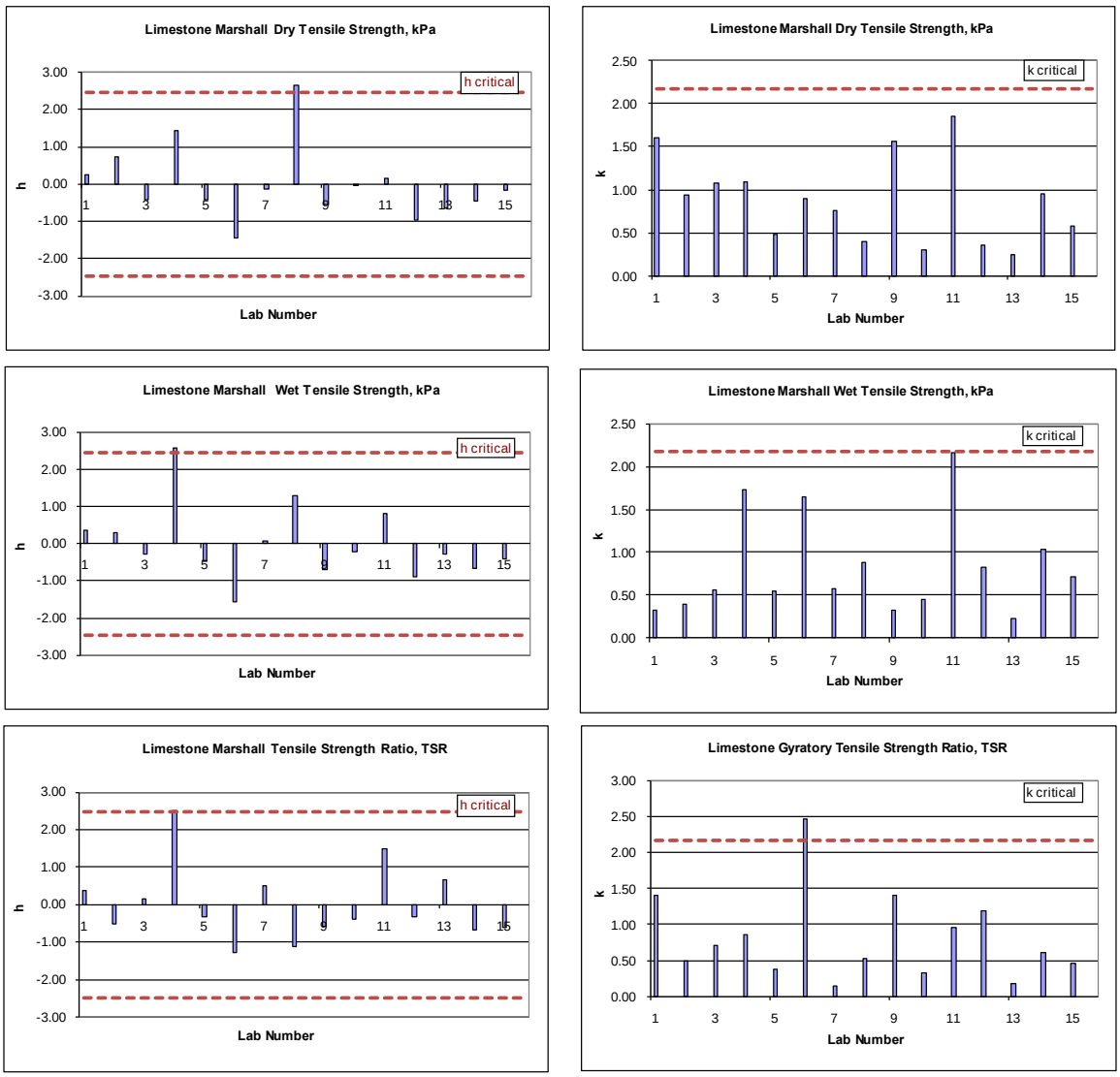
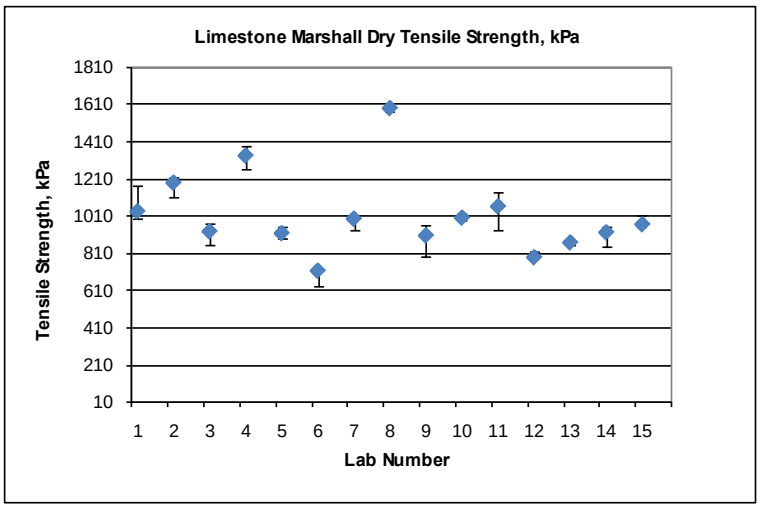
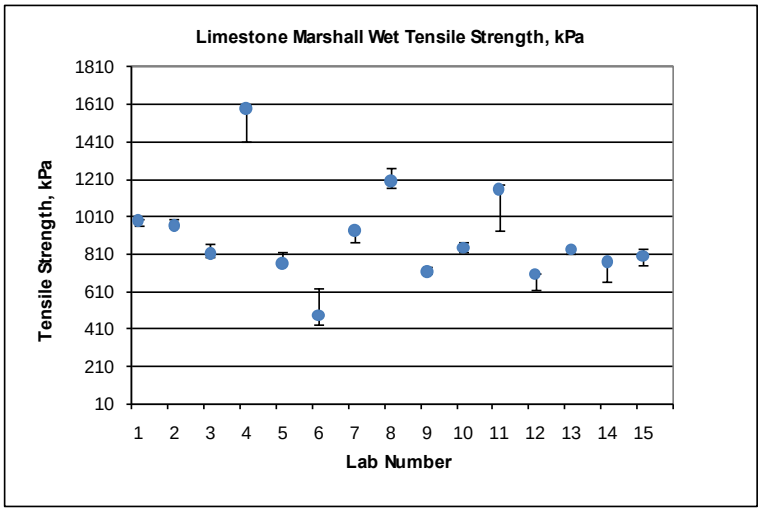


Figure C-1- h and k statistics of indirect tensile strength properties of limestone Marshall specimens





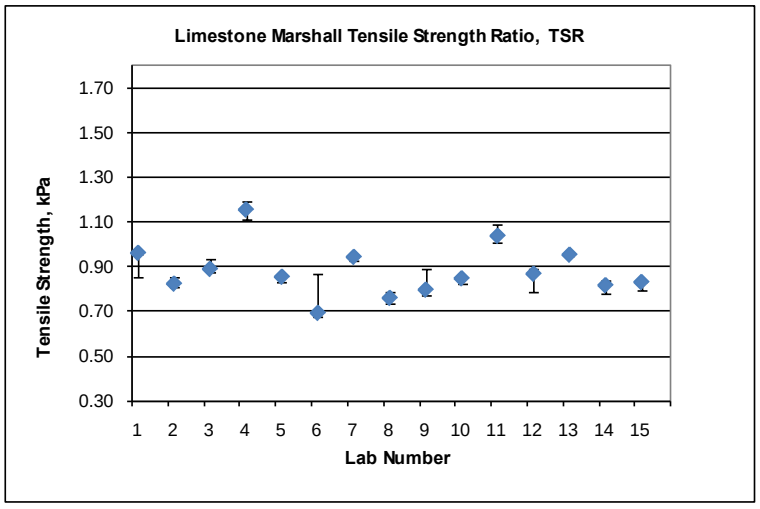


Figure C-2- Error band of indirect tensile strength properties of limestone Marshall specimens

APPENDIX D- RESULTS OF INDIRECT TENSILE STRENGTH TEST OF SANDSTONE GYRATORY SPECIMENS

Table D-1- Statistics of indirect tensile strength properties of limestone Marshall specimens

	Sandstone Gyratory			X_bar			S			h			k			X_bar_corr			S_corr		
Lab No	Dry Tensile Strength ,kPa	Wet Tensile Strength ,kPa	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR
1	928.14	593.05	0.64	967.98	695.19	0.72	34.51	99.01	0.08	0.04	-0.48	-1.76	0.69	2.21	2.27	967.98	FALSE	FALSE	34.51	FALSE	FALSE
	987.39	701.78	0.71																		
	988.42	790.74	0.80																		
2	1154.37	650.39	0.56	1174.04	680.32	0.58	17.10	47.25	0.04	0.77	-0.54	-3.39	0.34	1.06	1.00	1174.04	680.32	FALSE	17.10	47.25	FALSE
	1182.41	655.79	0.55																		
	1185.34	734.79	0.62																		
3	901.64	686.75	0.76	1009.44	718.94	0.71	99.46	40.51	0.04	0.19	-0.39	-1.79	1.99	0.90	1.16	1009.44	718.94	0.71	99.46	40.51	0.04
	1029.04	705.63	0.69																		
	1097.64	764.43	0.70																		
4	777.04	786.46	1.01	793.04	800.27	1.01	24.08	12.35	0.02	-0.57	-0.07	1.70	0.48	0.28	0.59	793.04	800.27	1.01	24.08	12.35	0.02
	781.36	804.10	1.03																		
	820.73	810.25	0.99																		
5	889.67	732.26	0.82	963.13	764.90	0.80	66.05	31.72	0.02	0.02	-0.21	-0.83	1.32	0.71	0.68	963.13	764.90	0.80	66.05	31.72	0.02
	982.09	766.81	0.78																		
	1017.63	795.62	0.78																		
6	907.06	816.49	0.90	927.00	853.00	0.92	19.94	34.97	0.02	-0.10	0.13	0.64	0.40	0.78	0.51	927.00	853.00	0.92	19.94	34.97	0.02
	927.00	856.32	0.92																		
	946.93	886.19	0.94																		
7	764.43	667.21	0.87	783.44	695.55	0.89	22.67	24.56	0.02	-0.61	-0.48	0.26	0.45	0.55	0.59	783.44	695.55	0.89	22.67	24.56	0.02
	777.37	708.96	0.91																		
	808.53	710.49	0.88																		
8	1278.31	1217.48	0.95	1379.84	1230.14	0.89	87.93	15.71	0.05	1.49	1.60	0.33	1.76	0.35	1.45	1379.84	1230.14	0.89	87.93	15.71	0.05
	1429.48	1225.22	0.86																		
	1431.72	1247.73	0.87																		
9	749.16	739.95	0.99	762.22	776.06	1.02	15.92	54.75	0.05	-0.68	-0.17	1.79	0.32	1.22	1.42	762.22	776.06	1.02	15.92	54.75	0.05
	757.55	749.16	0.99																		
	779.95	839.06	1.08																		
10	1229.50	983.44	0.80	1325.92	998.18	0.76	110.25	23.05	0.05	1.30	0.70	-1.31	2.21	0.51	1.28	1325.92	998.18	0.76	110.25	23.05	0.05
	1302.13	986.36	0.76																		
	1446.12	1024.74	0.71																		
11	794.83	660.97	0.83	820.60	692.80	0.84	25.80	27.58	0.02	-0.48	-0.49	-0.26	0.52	0.62	0.46	820.60	692.80	0.84	25.80	27.58	0.02
	820.53	707.83	0.86																		
	846.43	709.61	0.84																		
12	684.60	655.38	0.96	750.42	731.23	0.97	59.18	68.78	0.02	-0.72	-0.34	1.27	1.18	1.54	0.43	750.42	731.23	0.97	59.18	68.78	0.02
	767.43	748.75	0.98																		
	799.24	789.54	0.99																		
13	676.69	662.38	0.98	690.27	678.93	0.98	11.82	14.39	0.00	-0.94	-0.55	1.39	0.24	0.32	0.11	690.27	678.93	0.98	11.82	14.39	0.00
	695.92	685.96	0.99																		
	698.21	688.46	0.99																		
14	1629.38	1499.22	0.92	1661.72	1596.76	0.96	30.43	86.92	0.04	2.48	3.03	1.12	0.61	1.94	0.99	1661.72	FALSE	0.96	30.43	FALSE	0.04
	1666.01	1625.04	0.98																		
	1689.78	1666.02	0.99																		
15	899.23	784.96	0.87	917.45	822.72	0.90	17.45	34.48	0.02	-0.14	0.01	0.36	0.35	0.77	0.59	917.45	822.72	0.90	17.45	34.48	0.02
	913.10	830.67	0.90																		
	934.01	852.53	0.91																		
16	678.35	607.58	0.90	690.25	649.03	0.94	10.31	44.58	0.05	-0.94	-0.66	0.88	0.21	1.00	1.52	690.25	649.03	0.94	10.31	44.58	0.05
	696.20	643.32	0.92																		
	696.20	696.20	1.00																		
17	975.11	752.27	0.77	1012.72	773.78	0.76	32.86	18.69	0.01	0.20	-0.18	-1.20	0.66	0.42	0.18	1012.72	773.78	0.76	32.86	18.69	0.01
	1027.21	783.05	0.76																		
	1035.85	786.03	0.76																		
18	847.76	648.95	0.77	895.01	671.51	0.75	45.35	22.53	0.01	-0.22	-0.58	-1.36	0.91	0.50	0.37	895.01	671.51	0.75	45.35	22.53	0.01
	899.08	671.58	0.75																		
	938.19	694.01	0.74																		
19	828.88	762.44	0.92	837.29	781.06	0.93	13.23	16.92	0.01	-0.42	-0.15	0.79	0.26	0.38	0.36	837.29	781.06	0.93	13.23	16.92	0.01
	830.45	785.22	0.95																		
	852.54	795.51	0.93																		
20	755.15	657.78	0.87	812.12	726.01	0.89	60.94	60.94	0.03	-0.51	-0.36	0.33	1.22	1.36	0.81	812.12	726.01	0.89	60.94	60.94	0.03
	804.83	745.22	0.93																		
	876.38	775.03	0.88																		
21	849.00	847.00	1.00	906.00	862.33	0.95	49.37	19.30	0.04	-0.18	0.17	1.03	0.99	0.43	1.16	906.00	862.33	0.95	49.37	19.30	0.04
	934.00	856.00	0.92																		
	935.00	884.00	0.95																		

21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	19.00	19.00	21.00	19.00	19.00			

X_dbl_bar / Sx			Sr / SR			h Critical			k Critical			Corrected X_dbl_bar / Sx			Corrected Sr / SR		
956.19	818.99	0.87	49.99	44.77	0.04	2.57	2.57	2.57	2.21	2.21	2.21	956.19	784.57	0.89	49.99	36.08	0.03
283.95	256.39	0.08	286.87	258.99	0.09							283.95	155.91	0.085	286.87	158.67	0.088

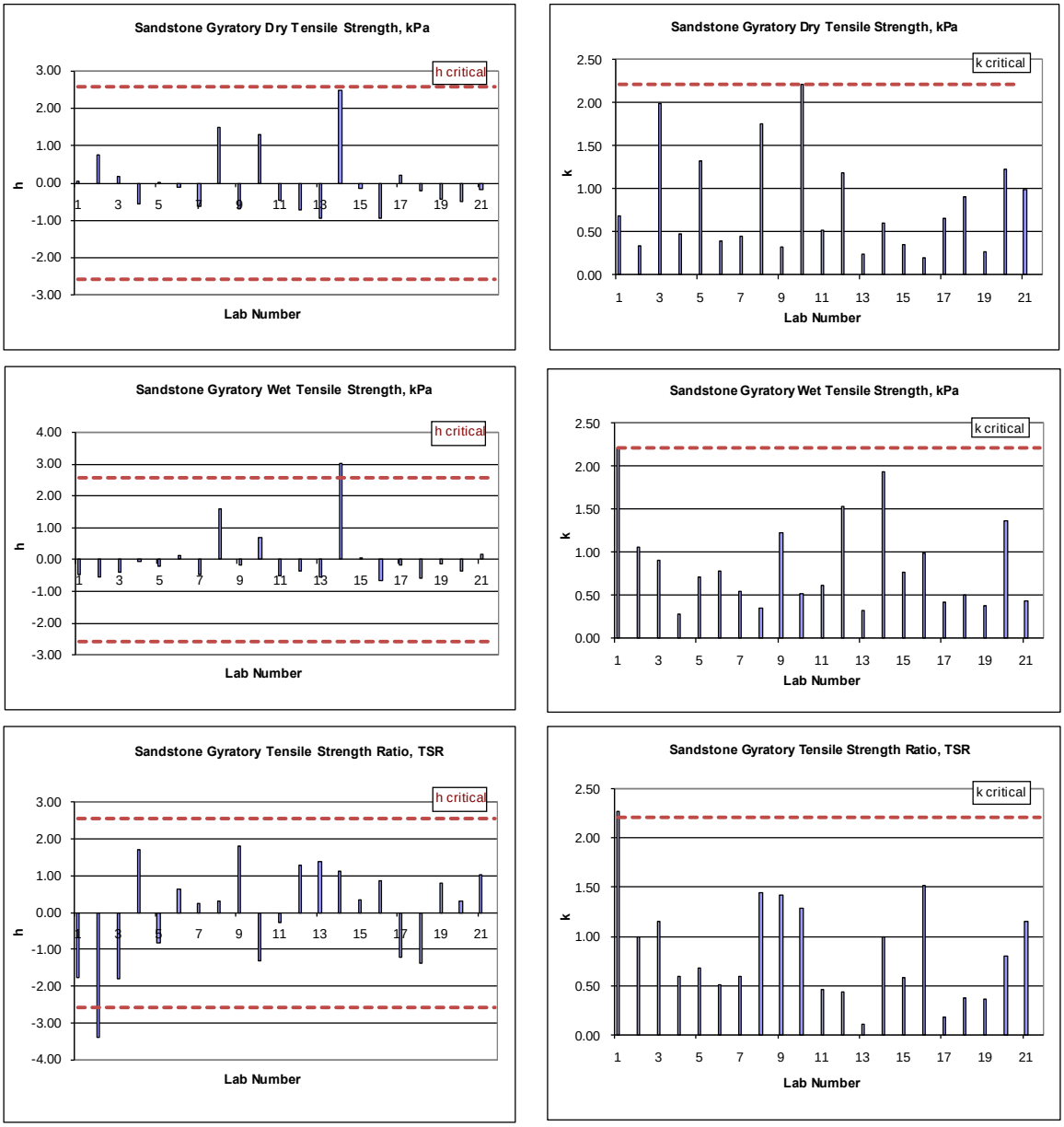


Figure D-1- h and k statistics of indirect tensile strength properties of sandstone gyratory specimens

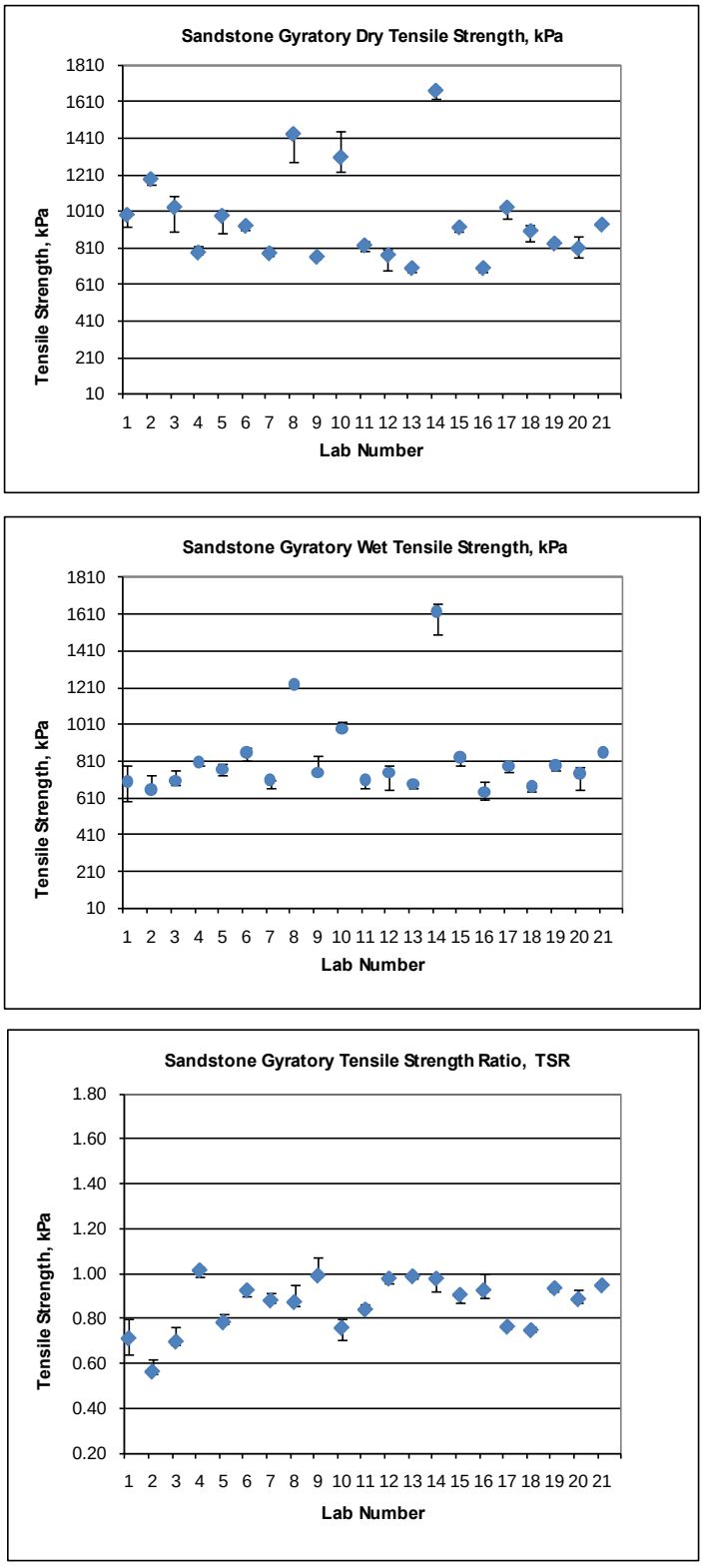


Figure D-2- Error band of indirect tensile strength properties of sandstone gyratory specimens

APPENDIX E- RESULTS OF INDIRECT TENSILE STRENGTH TEST OF SANDSTONE MARSHALL SPECIMENS

Table E-1- Statistics of indirect tensile strength properties of limestone Marshall specimens

	Sandstone Marshall			X_bar			S			h			k			X_bar_corr			S_corr		
Lab No	Dry Tensile Strength, kPa	Wet Tensile Strength, kPa	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR	Dry Tensile Strength	Wet Tensile Strength	TSR
1	1340.57	977.62	0.73	1529.73	1132.26	0.74	165.38	161.22	0.05	0.18	-0.06	-1.56	1.86	2.37	1.02	1529.73	FALSE	0.74	165.38	FALSE	0.05
	1601.60	1119.82	0.70																		
	1647.02	1299.33	0.79																		
2	984.39	797.64	0.81	1005.92	882.91	0.88	32.27	75.31	0.06	-0.37	-0.37	0.02	0.36	1.11	1.31	1005.92	882.91	0.88	32.27	75.31	0.06
	990.34	910.76	0.92																		
	1043.02	940.32	0.90																		
3	598.16	505.64	0.85	822.40	571.82	0.71	238.26	105.48	0.11	-0.56	-0.76	-1.85	2.69	1.55	2.54	FALSE	571.82	FALSE	FALSE	105.48	FALSE
	796.48	516.35	0.65																		
	1072.57	693.45	0.65																		
4	2215.37	1982.08	0.89	2254.83	1991.47	0.88	35.51	9.41	0.01	0.94	1.02	0.10	0.40	0.14	0.22	2254.83	1991.47	0.88	35.51	9.41	0.01
	2264.90	1991.44	0.88																		
	2284.21	2000.90	0.88																		
5	843.13	763.46	0.91	869.11	773.80	0.89	22.76	11.93	0.01	-0.51	-0.51	0.18	0.26	0.18	0.31	869.11	773.80	0.89	22.76	11.93	0.01
	878.73	771.10	0.88																		
	885.49	786.85	0.89																		
6	1209.14	1237.15	1.02	1266.82	1243.31	0.98	56.31	7.90	0.04	-0.10	0.08	1.23	0.63	0.12	0.85	1266.82	1243.31	0.98	56.31	7.90	0.04
	1269.69	1240.55	0.98																		
	1321.64	1252.22	0.95																		
7	952.39	844.10	0.89	971.61	879.10	0.90	19.72	35.85	0.02	-0.40	-0.37	0.34	0.22	0.53	0.41	971.61	879.10	0.90	19.72	35.85	0.02
	970.66	877.46	0.90																		
	991.79	915.74	0.92																		
8	962.75	950.28	0.99	1027.20	1006.84	0.98	107.92	62.26	0.05	-0.35	-0.21	1.24	1.22	0.91	1.10	1027.20	1006.84	0.98	107.92	62.26	0.05
	967.06	996.67	1.03																		
	1151.79	1073.56	0.93																		
9	940.60	861.90	0.92	994.95	877.72	0.88	53.63	16.65	0.03	-0.38	-0.38	0.10	0.60	0.24	0.70	994.95	877.72	0.88	53.63	16.65	0.03
	996.43	876.16	0.88																		
	1047.84	895.09	0.85																		
10	1045.08	1031.13	0.99	1102.65	1139.98	1.03	73.27	98.73	0.05	-0.27	-0.05	1.82	0.83	1.45	1.05	1102.65	1139.98	1.03	73.27	98.73	0.05
	1077.74	1165.06	1.08																		
	1185.12	1223.76	1.03																		
11	938.10	913.30	0.97	977.03	946.43	0.97	43.83	28.81	0.02	-0.40	-0.29	1.08	0.49	0.42	0.55	977.03	946.43	0.97	43.83	28.81	0.02
	968.50	960.40	0.99																		
	1024.50	965.60	0.94																		
12	4548.62	3784.61	0.83	4583.42	3826.73	0.83	45.60	53.24	0.00	3.37	3.32	-0.46	0.51	0.78	0.07	FALSE	FALSE	0.83	FALSE	FALSE	0.00
	4566.61	3809.00	0.83																		
	4635.04	3886.57	0.84																		
13	1062.29	799.04	0.75	1082.88	836.32	0.77	18.84	32.30	0.02	-0.29	-0.43	-1.18	0.21	0.47	0.39	1082.88	836.32	0.77	18.84	32.30	0.02
	1087.10	853.90	0.79																		
	1099.25	856.03	0.78																		
14	848.69	652.71	0.77	904.59	749.12	0.83	73.99	83.90	0.07	-0.47	-0.54	-0.54	0.83	1.23	1.48	904.59	749.12	0.83	73.99	83.90	0.07
	876.59	789.02	0.90																		
	988.50	805.62	0.81																		
15	1215.43	962.15	0.79	1287.67	1017.60	0.79	66.70	48.23	0.01	-0.07	-0.20	-0.97	0.75	0.71	0.23	1287.67	1017.60	0.79	66.70	48.23	0.01
	1300.66	1040.88	0.80																		
	1346.92	1049.78	0.78																		
16	1025.00	940.00	0.92	1065.67	974.67	0.91	36.35	43.88	0.02	-0.31	-0.25	0.45	0.41	0.64	0.49	1065.67	974.67	0.91	36.35	43.88	0.02
	1077.00	960.00	0.89																		
	1095.00	1024.00	0.94																		
				16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	16.00	14.00	14.00	15.00	14.00	14.00	15.00

X_dbl_bar / Sx			Sr / SR			h Critical			k Critical			Corrected X_dbl_bar / Sx			Corrected Sr / SR		
1359.16	1178.13	0.87	88.74	68.13	0.04	2.49	2.49	2.49	2.18	2.18	2.18	1167.19	992.22	0.89	69.25	56.97	0.04
957.56	798.71	0.09	960.29	800.65	0.09							356.65	331.94	0.076	361.10	335.18	0.082

Figure E-1- h and k statistics of indirect tensile strength properties of sandstone Marshall specimens

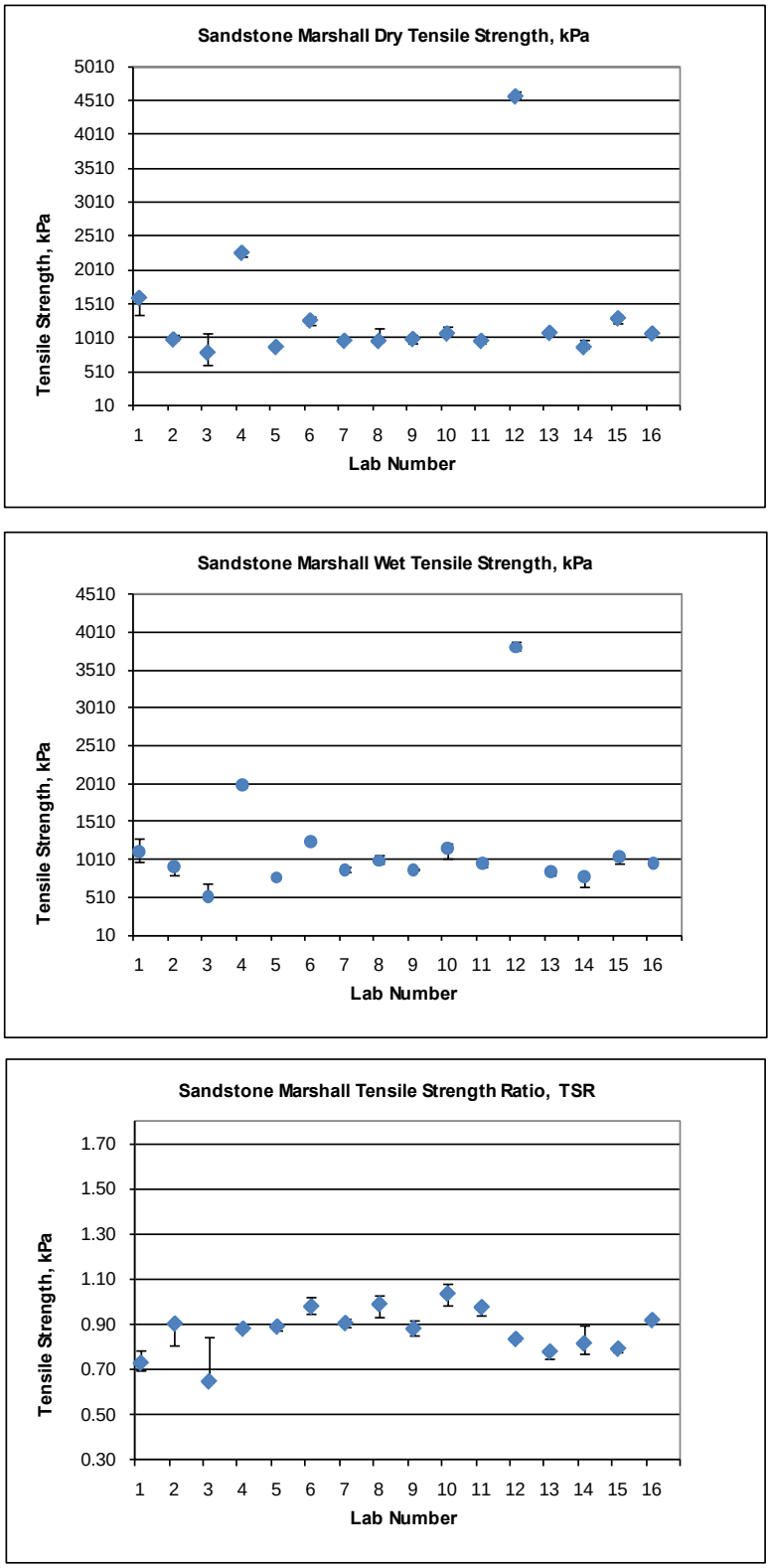


Figure E-2- Error band of indirect tensile strength properties of sandstone gyratory specimens

APPENDIX F- RECOMMENDED PRECISION ESTIMATES FOR AASHTO T283

PRECISION STATEMENT FOR AASHTO T283, STANDARD METHOD OF TEST FOR RESISTANCE OF COMPACTED HOT MIX ASPHALT (HMA) TO MOISTURE-INDUCED DAMAGE

1 Precision and Bias

1.1 Precision - Criteria for judging the acceptability of tensile strength ratios (TSR) obtained by this method are given as follows:

1.1.1 Single-Operator Precision (Repeatability) - The single-operator standard deviation (1s limits) tensile strength ratio (TSR) is shown in Table 1, Column 2. The results of two properly conducted tests obtained in the same laboratory, by the same operator using the same equipment, in the shortest practical period of time, should not be considered suspect, unless the difference in the two results exceeds the single-operator limits given in Table 1, Column 3.

1.1.2 Multi-laboratory Precision (Reproducibility) - The multi-laboratory standard deviation (1s limits) tensile strength ratio (TSR) is shown in Table 1, Column 2. The results of two properly conducted tests obtained in the same laboratory, by the same operator using the same equipment, in the shortest practical period of time, should not be considered suspect, unless the difference in the two results exceeds the Multi-laboratory limits given in Table 1, Column 3.

Table 1 – Precision Estimates for AASHTO T283

Property and Type Index	Standard Deviation [a]	Acceptable Range of Two Results [a]
Single-Operator precision: Tensile strength ratio (TSR)	0.033	0.093
Multi-laboratory Precision: Tensile strength ratio (TSR)	0.087	0.247

[a] These values represent the 1s and d2s limits described in ASTM Practice C670.

Note – The precision estimates are based on the analysis of test results from an AMRL interlaboratory study (ILS). The data consisted of tensile strength ratios of four asphalt mixtures. The mixtures were prepared with two sources of aggregates (limestone and sandstone) and two methods of compactions (Gyratory and Marshall). The details of this analysis are in *NCHRP Web-Only Document 166*.

1.2 Bias– No information can be presented on the bias of the procedure because no comparison with the material having an accepted reference value was conducted.