TECHNICAL REPORT STANDARD PAGE

1. Report No. FHWA/LA. 09/458	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Implementation of Testing Equipment for Asphalt Materials	**5. Report Date** May 2009	
	6. Performing Organization Code LTRC	
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9. Performing Organization Name and Address Louisiana Transportation Research Center 4101 Gourrier Avenue Baton Rouge, LA 70808	**10. Work Unit No.**	
	11. Contract or Grant No.	
12. Sponsoring Agency Name and Address Louisiana Transportation Research Center 4101 Gourrier Avenue Baton Rouge, LA 70808	**13. Type of Report and Period Covered** Final Report 12/01/06 – 05/30/09	
	14. Sponsoring Agency Code LTRC	
15. Supplementary Notes		

16. Abstract

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17. Key Words SSDetect, CoreLok, CoreDry, Lab testing equipment	**18. Distribution Statement** Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
N/A	None	69	N/A

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LTRC Project No. 06-1B
State Project No. 736-99-1366

conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

May 2009

ABSTRACT

Three new automated methods for related asphalt testing were evaluated under this study in an effort to save time and reduce variability in testing. The Therymolyne SSDetect, Instrotek CoreLok and Instrotek CoreDry devices were evaluated throughout the state in nine district laboratories plus the Louisiana Transportation Research Center (LTRC) asphalt laboratory. The test methods for each of these devices were evaluated against the standard methods described in AASHTO T-84 and AASHTO T 166 (DOTD TR 304-03). Each laboratory used the SSDetect device to evaluate the G_{sb} (bulk specific gravity) and absorption properties of fine aggregates. The CoreLok device was used to evaluate the G_{mb} of Superpave gyratory compacted (SGC) asphalt mixtures. The CoreDry device was used to evaluate the dry weights of SGC and roadway core samples of asphalt mixtures. Each of these devices is designed to reduce testing time considerably and to reduce operator error by automating the testing process. Results indicate that the SSDetect device shows better consistency in measuring the G_{sb} (dry) of the #11 limestone when compared to the conventional method, AASHTO T 84. The SSDetect method also shows better repeatability and reproducibility results than conventional methods for testing fine aggregates. Both AASHTO T 166 and CoreLok test methods are capable of measuring G_{mb} values for wearing course mixtures. The CoreLok device is more critical for determining voids in open graded mixtures because the conventional procedure to measure the saturated surface dry (SSD) weight is not applicable to open graded mixtures. The CoreLok procedure for computing the G_{mb} of asphalt mixtures is highly repeatable and reproducible. The CoreLok and CoreDry devices showed no significant difference of G_{mb} values of field cores compared to the conventional method of testing. The CoreDry method is a direct correlation to the conventional method. A cost analysis estimated a total annual savings to LADOTD of approximately $95,000.00. It is recommended that each of these devices be made available to each district for use to provide accurate and timely testing results for satisfying the quality assurance of asphalt materials and mixtures.

ACKNOWLEDGEMENTS

Researchers would like to thank the U.S. Department of Transportation, Federal Highway Administration (FHWA), Louisiana Department of Transportation and Development (LADOTD), and Louisiana Transportation Research Center (LTRC) for financially supporting this research project.

The efforts of each of the nine LADOTD district laboratory engineers and technicians in conducting each of the tests required and presenting the data is greatly appreciated. The efforts of Greg Tullier, Willie Gueho, and Patrick Frazier of LTRC's Asphalt Materials Laboratory for overseeing the distribution of the equipment are also appreciated.

IMPLEMENTATION STATEMENT

Based on the results of the laboratory and field verification data evaluations of test procedures and equipment considered in this study, it is recommended that these devices be made available to each of the nine districts in Louisiana. Subsequently, test procedures for the use of each of these devices are included in the report.

It is anticipated that within the next two years, each of the nine district laboratories and the Materials Laboratory will possess each of the devices evaluated in this report. Also, the new LADOTD specifications for asphalt materials and materials testing will reflect the use of each of these devices as an alternate to the conventional methods now used.

Recent developments regarding the manufacturing of the SSDetect device manufactured by Barnstead International may limit the implementation of the recommendations. Reports from retailers of this equipment indicate that the production of this equipment has been discontinued.

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INTRODUCTION

Three new devices have been developed to improve time and accuracy of asphalt related tests. The first device is the SSDetect. This device is an automated system which facilitates the mechanical measurement of fine aggregate specific gravity in a shorter time removing human bias inherent in current procedures. The approximate test time is 1 hour, starting with dry aggregates. The second device is the CoreLok. The CoreLok is an alternate method of measuring compacted mixture density. This device enables accurate measurements of bulk specific gravities (G_{mb}) of compacted mixtures of open-graded and coarse-graded hot mix asphalt (HMA) mixtures. The CoreLok system automatically vacuum seals HMA samples in puncture resistant bags so sample densities can be measured by the water displacement method. Since HMA samples are sealed in a water proof environment, water infiltration in and out of the sample stops, allowing for an accurate measure of G_{mb}. The third device is called the CoreDry. The CoreDry device decreases the drying time of roadway cores, and therefore, speeds up the process of roadway acceptance based on density allowing same day calculation as opposed to next day. Current test procedures require roadway density cores be oven dried for 16 hours before testing. The CoreDry device dries field cores in approximately 15 minutes.

Current test procedures for determining fine aggregate specific gravity (G_{sb}) and the bulk specific gravity of compacted mixtures (G_{mb}), as specified by AASHTO T 84 and AASHTO T 166 (DOTD TR 304-03) respectively, are very time consuming [*1*], [*2*] . AASHTO T 166 "Bulk Specific Gravity of Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens" and AASHTO T 84 "Specific Gravity and Absorption of Fine Aggregate" normal test time is approximately two days. Also, the calculation of SSD as required in AASHTO T 166 is inaccurate for open-graded and permeable coarse-graded HMA mixtures. Permeability of these types of HMA mixtures allow water to flow in and out of the sample during the determination of G_{mb}, which yields lower sample volumes, higher calculated densities, and lower estimates of air voids [*3*].

This project examines the between laboratory and within laboratory variation of three pieces of testing equipment, SSDetect, CoreLok, and CoreDry. Data has shown that these devices improve testing time and/or accuracy of tests in the aggregate material and HMA mixtures. These three devices were distributed for statewide round robin testing to provide the between laboratory and within laboratory variation for each of these test devices.

OBJECTIVES

The objective of this study was to examine between laboratory and within laboratory variation of the three pieces of test equipment described herein and develop specifications as needed for implementation based on field verification evaluations of test procedures and equipment considered.

SCOPE

Each device (SSDetect, CoreLok, and CoreDry) was purchased under this study. Once purchased, these devices were evaluated in the LTRC Asphalt Laboratory and then sent to each of the nine LADOTD district laboratories for evaluation. Test measurements from each device were compared to values obtained by current specification requirements. Each district was provided test procedures for each device and the required minimum test factorials.

LTRC prepared nine samples of sand and fine aggregate limestone that were evaluated using conventional methods as compared to the SSDetect device by each of LADOTD's nine districts. LTRC also provided three Superpave gyratory compacted specimens and three open graded friction course (OGFC) gyratory compacted specimens that were distributed to each district laboratory and evaluated using the CoreLok device for testing.

Each district laboratory collected a minimum of 15 roadway cores from ongoing projects which were evaluated in accordance with AASHTO T 166 (DOTD 304-03) "Bulk Specific Gravity of Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens" and AASHTO TP 69-04[1] "Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method" [*4*]. In addition, dry weight measurements of the same 15 roadway cores were evaluated using the CoreDry device for comparison with Louisiana's current test methods. This will enable the evaluation of the CoreDry weight vs. oven dry weight and standard SSD measurements vs. CoreLok SSD measurements.

METHODOLOGY

LTRC purchased three new test devices for round robin testing in each of the nine LADOTD districts. The SSDetect, the CoreLok and the CoreDry device were all purchased together for less than $20,000. Each of these new devices were used to test both laboratory and field prepared samples and compared to conventional procedures of testing. Figures 1, 2, and 3 are photographs of each of these devices, which are described below:

- The Thermolyne SSDetect device is manufactured by Barnstead International and used to measure the saturated surface dry condition of fine aggregates. This is accomplished with an infrared light source tuned to water. This infrared signal looks at the surface of the aggregate for traces of water and measures the amount of infrared reflectance, resulting in accurate measurements of the saturated surface dry condition of the aggregate.
- The Instrotek CoreLok is a device used for sealing asphalt samples so sample densities may be measured by the water displacement method. Samples are automatically sealed in specially formulated puncture resistant polymer bags. By removing all the air from the sample, an accurate bulk specific gravity can be measured.
- The Instrotek CoreDry device is an automatic system for the rapid drying of material samples and objects. This system utilizes high vacuum technology and an electronic desiccation system for rapid and safe drying of material samples and objects. The samples stay cool during drying, which preserves the sample composition.

LTRC prepared nine fine aggregate samples, 4,000 grams each of coarse sand and 4,000 grams each of # 11 screenings, for distribution along with the three new test devices to each of the LADOTD nine districts. In addition, three Superpave gyratory compacted samples each of a Wearing Course mixture and of an open graded friction course mixture, were supplied to each district. These same samples were also tested and evaluated in the LTRC Asphalt laboratory.

Development of Test Procedures and Factorial

Table 1 describes the test sample factorial for each test procedure and testing device. The test procedure used for determining the fine aggregate specific gravity (G_{sb}) using the SSDetect device can be found in Appendix A. The test procedures to measure the bulk specific gravity and density characteristics of the pre-made, compacted asphaltic mixtures using the CoreLok and CoreDry devices are described in Appendix B and C, respectively.

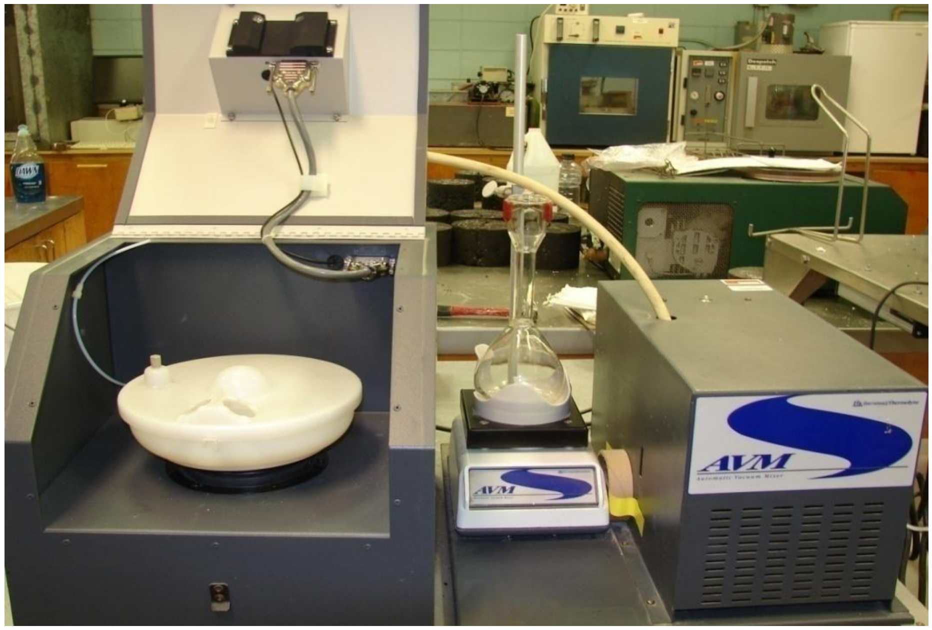

Figure 1
SSDetect device

Figure 2
CoreLok device

Figure 3
CoreDry device

Table 1
Test sample factorial

	Density Measurements					Fine Aggregate Specific Gravity	
District	Roadway Cores AASHTO T 166		CoreLok SSD AASHTO TP 69-04		AASHTO T 166	SSDetect	AASHTO T 84
	CoreDry Weight	Oven Dry Weight	LTRC Prepared Samples	Rdwy Cores	LTRC Prepared Samples	Round Robin	Round Robin
02	0	0	6	0	6	6	6
03	0	0	6	0	6	6	6
04	15	15	6	15	6	6	6
05	15	15	6	0	6	6	6
07	15	15	6	0	6	6	6
08	15	15	6	15	6	6	6
58	15	15	6	0	6	6	6
61	15	15	6	0	6	6	6
62	0	0	6	0	6	6	6

Background

An extensive literature review was conducted, and it was found that numerous research studies have evaluated the use of the CoreLok and SSDetect devices. Traditionally, the water displacement method or SSD method as outlined in AASHTO T 166 is used to measure the G_{mb} of compacted HMA mixtures. Recently, CoreLok, a vacuum sealing apparatus has gained popularity to measure the G_{mb} of HMA mixtures. In Arkansas, a total of 144 lab-compacted samples were prepared from 12.5-mm coarse graded superpave mixtures collected from six filed projects *[5]*. AASHTO T 166, AASHTO T 269 (height and diameter method), and CoreLok methods were used to evaluate and compare the as measured G_{mb} of those samples. Based on the test results and analyses, significant differences between G_{mb} values were determined for each of the methods. On the other hand, the CoreLok method possessed the smallest multi-operator variability. The conclusion of this study included a recommendation for further round-robin and ruggedness testing of the CoreLok method for ultimate adoption as the standard test method for coarse and open-graded mixtures.

In another research, Buchanan concluded that the CoreLok procedure can determine G_{mb} more accurately than other conventional methods like: water displacement, parafilm, and dimensional analysis *[6]*. Sholar et al. compared the CoreLok method with the long established test procedures of the Florida Department of Transportation to determine the G_{mm} and G_{mb} of asphalt mixtures and G_{sb} of aggregates *[7]*. For G_{mb} measurement, the authors expressed concerns about the accuracy of CoreLok results due to the bridging effect of the plastic bag over the large, mostly unrepresentative surface voids of the specimen. However, for specimens with high air voids, CoreLok was thought to be the better procedure as the SSD water drains off the interconnected surface voids, a portion of which are the true air voids of the mixture.

An extensive round-robin study by Cooley et al. at NCAT confirmed that the repeatability and reproducibility of the CoreLok method are similar to AASHTO T166 *[8]*. Both test procedures measured G_{mb} at the same level and either method can be used for fine aggregates with water absorption less than 2 percent. However, for coarse aggregate the CoreLok method was recommended.

Recently, another testing scheme conducted by Ohio DOT on 109 samples showed that G_{mb} values obtained using the CoreLok method were lower than that of AASHTO G_{mb} *[9]*. Statistical analyses revealed that the difference is significant at 95 percent confidence interval regardless of type of mix, aggregate source, and compaction level. However, the CoreLok equipment was found to be capable of producing precise, consistent, and repeatable test results with significant time savings. Further refinement of the CoreLok test procedures and the use of an appropriate correlation factor to relate CoreLok and AASHTO values were recommended by the authors.

The investigations did not find any studies that have evaluated the CoreDry device. Most of the research conducted only round robin testing within a single laboratory. Of those that performed round robin studies with multiple laboratories, asphalt mixture analysis was not considered. However, all previous research conducted reveals a noticeable time savings and an accuracy of measuring.

The inconsistencies in measuring the specific gravity and absorption of aggregates by current procedures (AASHTO T 84) initiated several studies to evaluate automated testing equipment such as: SSDetect. Cross et al. reported that the SSDetect method produced the highest bulk specific gravity and lowest % of absorption followed by the CoreLok and AASHTO T 84 when tests were performed on selected fine aggregate samples in Oklahoma *[10]*. However, the apparent specific gravity values were found to be statistically insignificant.

Prowell et al. evaluated two automated techniques: SSDetect and CoreLok against the standard AASHTO T 84 method *[11]*. A round robin study with 12 laboratories and six materials indicated that both SSDetect and CoreLok methods produced similar results to AASHTO T 84 with a better precision and significant timesaving.

Laboratory Equipment to Districts

In September 2006, the test equipment was delivered to District 61 to begin this research. Once the district conducted the tests using this equipment, the equipment was distributed to the next district for testing. LTRC personnel continued the process of delivering the equipment to each district until the evaluation was complete. It was estimated that each district would take one month to conduct the testing. Due to the work load and other parameters, it generally took each district approximately two to three months to complete testing.

Testing

The fine aggregate samples were tested and evaluated by each district for bulk specific gravity (G_{sb}) and percent absorption using the conventional test procedure AASHTO T-84, “Specific Gravity and Absorption of Fine Aggregate.” The fine aggregate samples were then tested and evaluated using the new SSDetect testing device. The data were compiled and reported in the Discussion of Results.

The SGC samples were tested and evaluated using AASHTO T 166 (DOTD 304-03) “Bulk Specific Gravity of Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens” and AASHTO TP 69-04 “Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method” test procedures.

Six of the nine districts collected fifteen random roadway cores from actual projects within their district and tested them in accordance with the conventional test procedure, AASHTO T 166, and compared to the results obtained using the CoreDry device for drying samples. A comparison of the dry weights between the conventional method and the CoreDry method are also discussed later in this report. Two of the districts conducted an additional CoreLok test in accordance with AASHTO TP 69-04 procedures on the same 15 random roadway cores.

DISCUSSION OF RESULTS

AASHTO T 84 vs. SSDetect

The bulk specific gravity (G_{sb}) values for sand and #11 limestone (LS) obtained at various district laboratories using both AASHTO T 84 and SSDetect methods are graphically presented in Figures 4 and 5, respectively. In these figures, each vertical bar indicates the average G_{sb} value calculated from three individual specimens. The trend indicates that G_{sb} values for sand determined using the AASHTO T 84 method are higher than the values obtained from SSDetect. However, an opposite trend was observed in the case of #11 LS aggregates as seven out of ten laboratories obtained greater G_{sb} values when using the SSDetect device as shown in Figure 5. The error bars presented in Figures 4 and 5 indicate the ±1 standard deviation of the mean G_{sb} (dry) observed at individual district labs. It is noticeable that SSDetect showed a better consistency in measuring G_{sb} (dry) than that of AASHTO T 84. Figures 6 and 7 represent the coefficient of variances (CV) of G_{sb} (dry) values among the three test specimens tested per district laboratory. Nothing can be concluded from these figures as AASHTO T 84 showed better performances (i.e., lower CVs) for half of the laboratories while the SSDetect performed better for the other half.

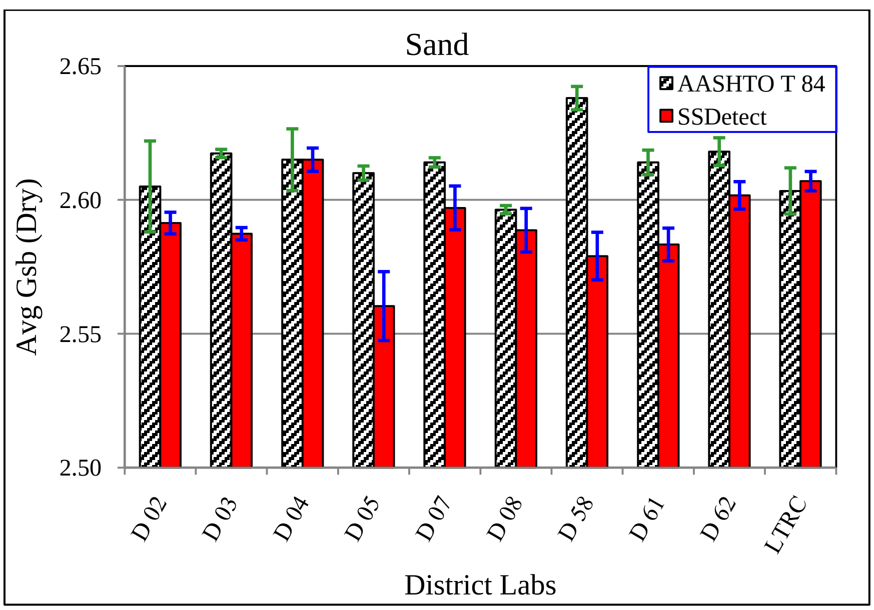

Figure 4
Bulk specific gravity of sand

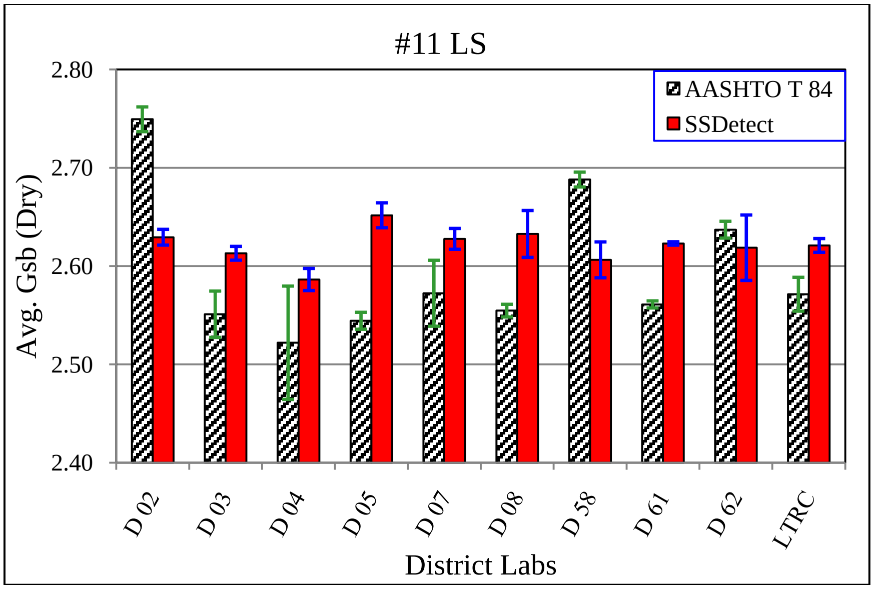

Figure 5
Bulk specific gravity of # 11 LS

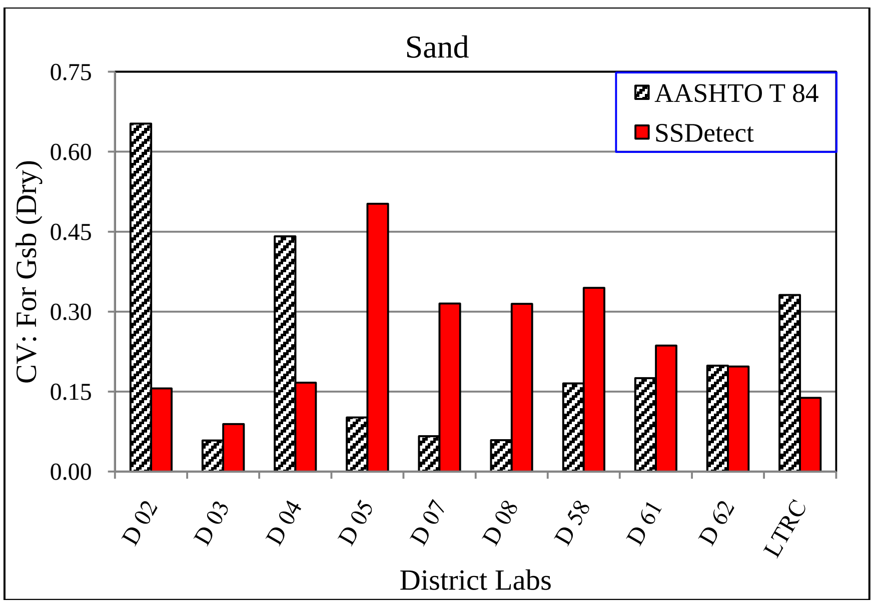

Figure 6
Coefficient of variances for G_{sb} (dry) of sand

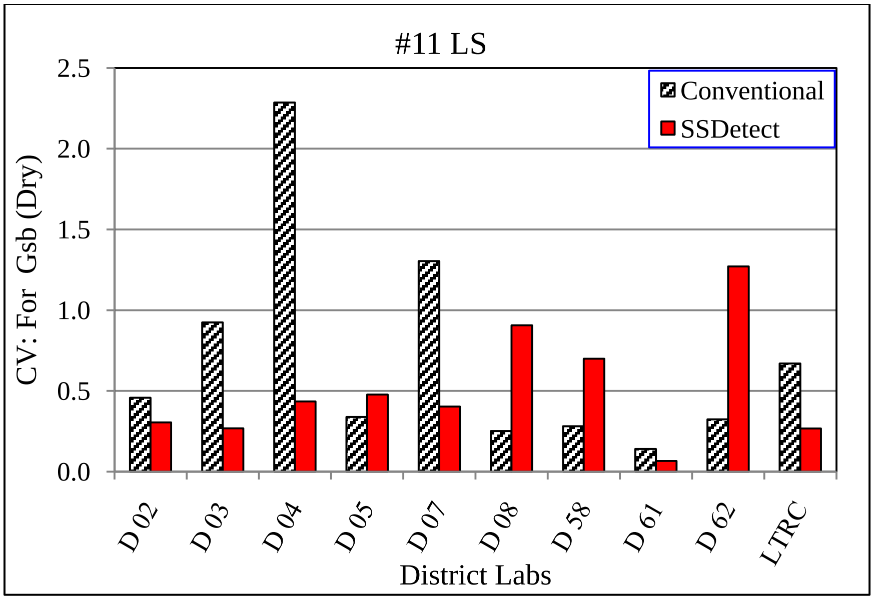

Figure 7
Coefficient of variances for G_{sb} (dry) of # 11 LS

For sand, the highest G_{sb} (dry) value from the AASHTO T 84 method was recorded as 2.64 at District 58; whereas, the lowest one was 2.60 at District 08. Therefore, the numerical difference between these two values is 0.04. Similarly, the difference between the highest and the lowest values of G_{sb} (dry) measured by the SSDetect method for sand was 0.055. On the other hand, for # 11 LS, the differences between the highest and the lowest G_{sb} (dry) values were 0.23 and 0.06 for the AASHTO T 84 and SSDetect methods, respectively. This is another indication that SSDetect was more consistent in measuring the G_{sb} (dry) of # 11 LS across the laboratories included in this study than that of the AASHTO T 84 method. This greater difference in G_{sb} (dry) values may also lead to an even greater variation in the voids in mineral aggregate (VMA) of mixtures when other ingredient-properties of the mixtures are assumed to remain constant. For example, if the G_{mb} and asphalt content of a mixture are assumed to be constant as 2.35 percent and 4 percent, respectively, the differences in the highest and lowest G_{sb} (dry) values measured by the AASHTO T 84 and SSDetect method, respectively, will cause a difference of 7.38 percent and 2.17 percent in VMA of the same mixture.

Comparisons of the percentage of average water absorption results by material and method are shown in Figures 8 and 9. The absorption values measured by the AASHTO T 84 test method were always (except District 04) lower than the SSDetect procedure for sand. However, an opposite trend (higher absorption values when measured by AASHTO T 84) was observed for #11 LS. According to the current methodology of determining G_{sb} (dry) of fine aggregates, AASHTO T 84 uses a cone and tamp to determine the saturated surface dry (SSD) condition of the aggregates. Unfortunately, the method has been found problematic to obtain the SSD of angular or rough fine aggregates as they do not readily slump [*5*].

Possibly this was the contributing factor in getting higher absorption values in the AASHTO T 84 method than that of the SSDetect for #11 LS. Interestingly this observation is similar to the research outcome of Prowell et al., which also reinforces the results of this study [*6*].

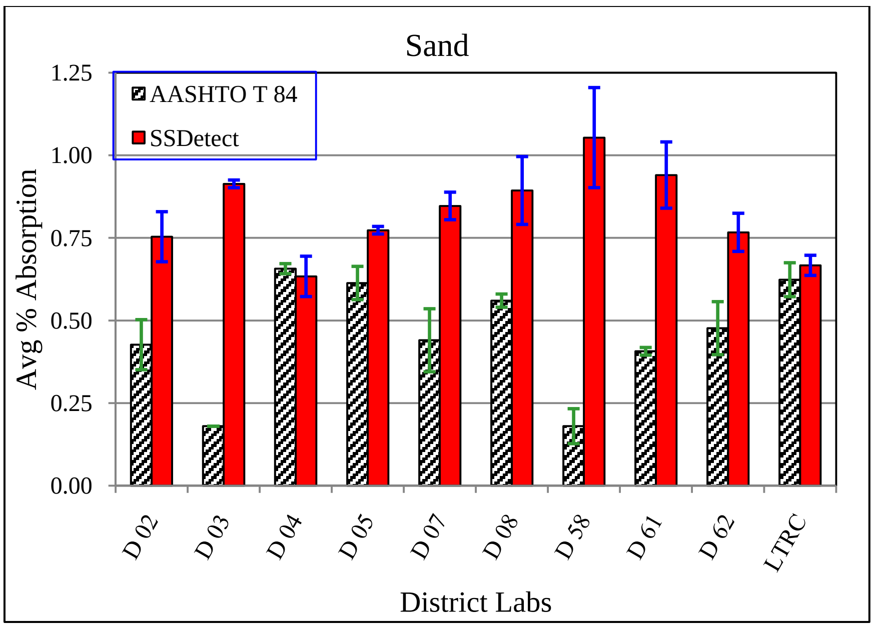

Figure 8
Percentage of water absorption for sand

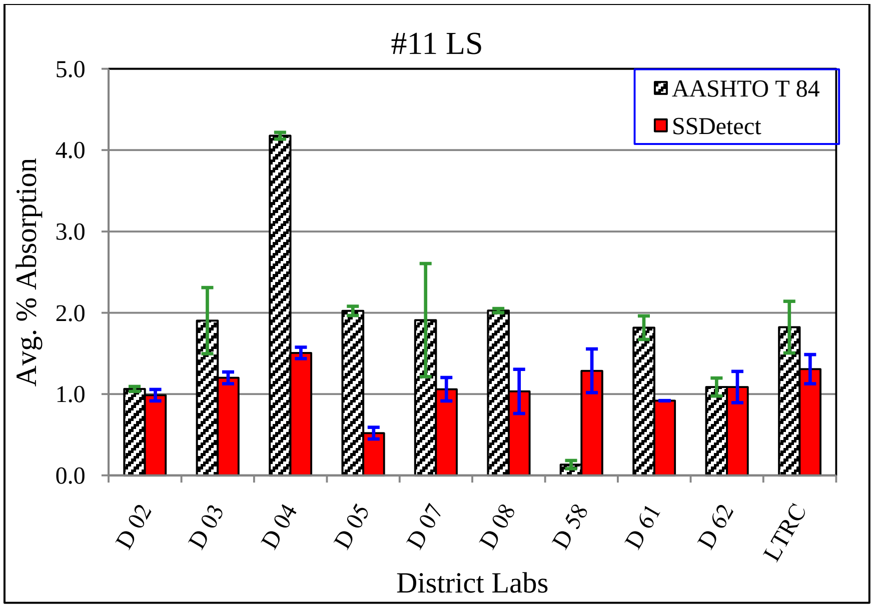

Figure 9
Percentage of water absorption for # 11 LS

The coefficient of variation (CV) values for percent water absorption shows that SSDetect produced a more uniform variation than that of AASHTO T 84 regardless of the aggregate type (Figures 10 and 11). In general, CV below 20 percent is considered to be acceptable results. Figure 10 indicates that for sand the CV's for absorption results computed by AASHTO T 84 are not as consistent as SSDetect. In fact, two of the district labs (District 07 and 58) obtained CV values higher than 20 percent in the AASHTO T 84 method while none of those went higher than 15 percent in the SSDetect method. For #11 LS, three out of the ten district labs obtained CV values higher than 20 percent using the AASHTO T 84; whereas, only District 08 had a CV higher than 20 percent (Figure 11) for the SSDetect method. This is another indication the SSDetect was able to minimize the variation in absorption test results obtained across the various district laboratories.

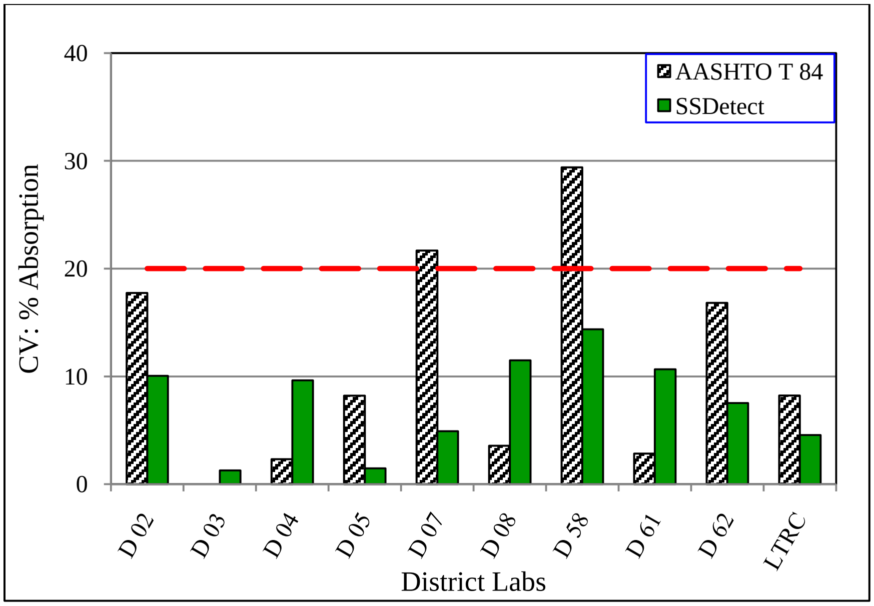

Figure 10
Coefficient of variances for absorption results for sand

Fine aggregate angularity (FAA) is termed as the percentage of air voids in loose or un-compacted aggregates. In general, a higher void assumes more angularity of the material. The G_{sb} (dry) values computed in this study were utilized to compute the FAA of the corresponding aggregates using the following equation:

$$FAA = \frac{V - \frac{M}{G_{sb}}}{V} \times 100 \qquad (1)$$

where,
V = volume of the aggregate, and
M = mass of the aggregate

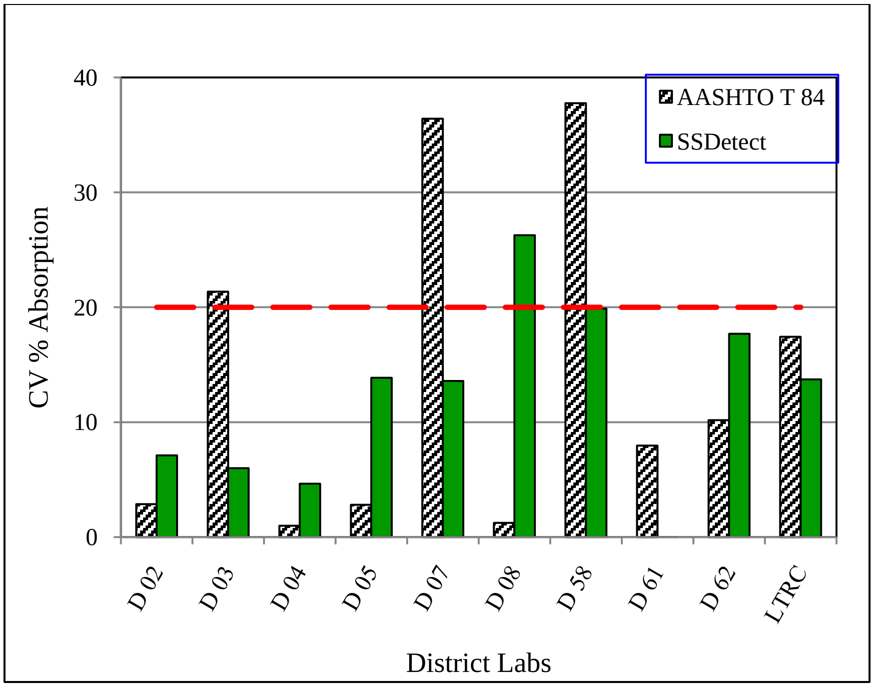

Figure 11
Coefficient of variances for absorption results for # 11 LS

A graphical illustration of the calculated FAA values calculated for sand and #11 LS at various district labs are presented in Figures 12 and 13, respectively. The trend indicates that for sand, the FAA values estimated from AASHTO T 84 are almost always greater than the values determined by the SSDetect. However, both the methods seem consistent to measure FAA. With the exception of 3 labs, the FAA values estimated from AASHTO T 84 are lower than values determined by the SSDetect. Also, a much higher variation (variance = 2.3) was observed for FAA values measured by AASHTO T 84 than that of SSDetect (variance = 0.19).

Precision of Test Methods

Bias and precision are two statistical measures employed to evaluate the goodness of test procedures. Bias is the difference between the population mean of the test results and an accepted or true value of the measured property. On the other hand, precision is the numerical measure of the variability of the population of the measured characteristics.

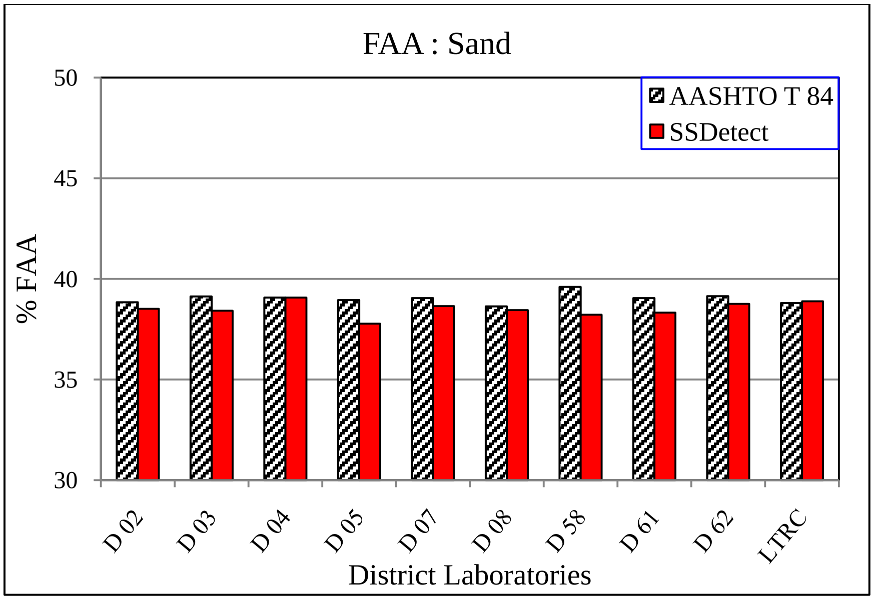

Figure 12
Comparison of FAA for sand

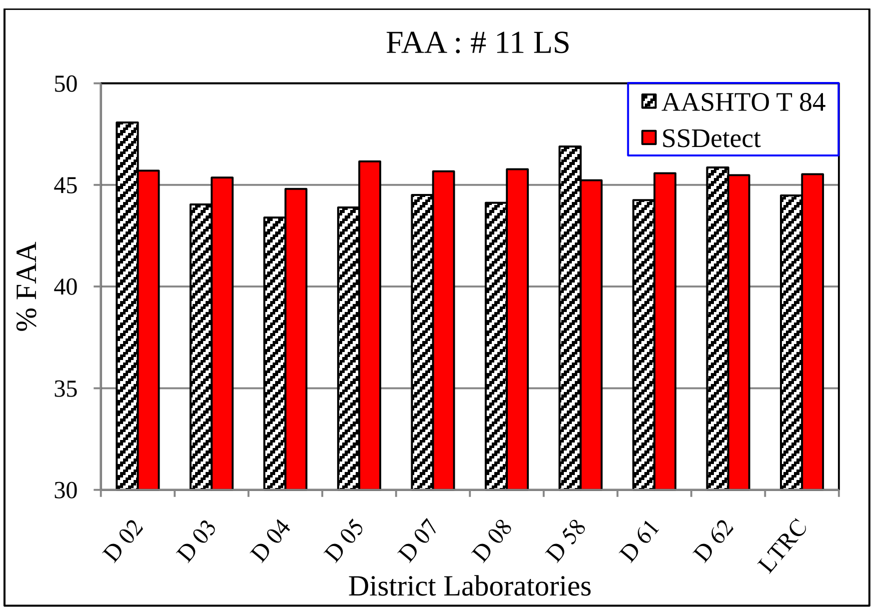

Figure 13
Comparison of FAA for # 11 LS

Greater variability implies smaller precision. In this study, there was no standard specimen whose specific gravity was precisely recognized. Since the conventional AASHTO procedures were also investigated, comparisons were made between test results measured by different test procedures at individual district laboratories.

Repeatability and reproducibility are two components used to characterize the precision criteria of a given test method. Repeatability (within laboratory) is the variability between independent test results obtained within a single laboratory in the shortest practical period of time. Tests are conducted by a single operator with a specific set of test apparatus where specimens are taken at random from a single quantity of homogeneous material obtained or prepared.

Mathematically,

$$S_r = \sqrt{\sum_{1}^{p} \frac{s^2}{p}} \qquad (2)$$

where,

S_r = repeatability of standard deviation,

s = the cell standard deviation (standard deviation of each individual lab), and

p = number of laboratories.

Reproducibility (between laboratory/multi-laboratory) deals with the variability between single test results obtained in different laboratories, each of which has applied the test method to test specimens taken at random from a single quantity of homogeneous material obtained or prepared.

Mathematically,

$$S_R = \sqrt{}\{(S_x)^2 + \left(S_r\right)^2 \frac{(n-1)}{n}\} \qquad (3)$$

where,
S_R = the reproducibility of standard deviation,
S_x = the standard deviation of the cell averages,
S_r = the repeatability of standard deviation, and
n = no. of replicates per lab.

In this study, ASTM E 691 "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method" was used to analyze the precision of the test results [*7*]. Two statistics, *h* and *k*, were used to analyze data for consistency. The *h* statistics is computed from a two-tailed student t-test, and it indicates how one laboratory's average for a material compares with the average of the other laboratories. It should be noted that an *h* statistic value may be either positive or negative. A negative *h* statistic indicates that a given laboratory's average value is less than the combined average of the other laboratories participating in that study; whereas a positive *h* statistic stands for a given laboratory's average value is greater than the combined average of the rest.

The *k* statistic is an indicator if the variability of one laboratory under repeatability conditions is sufficiently different from the pooled variability of the remaining laboratories. It is calculated by the F-ratio from a one-way analysis of variance. Values of *k* greater than 1 indicate a greater within laboratory variability than the average for all laboratories. Data consistency problems from *h* and *k* statistics may be observed when the following patterns occur: (1) *h* values of a single laboratory are opposite all other laboratories and (2) *k* values of a single laboratory are larger for all materials tested as compared to other laboratories [*8*]. The critical values of *h* and *k* at a 0.05 percent significance level were found to be 2.29 and 2.10, respectively, for the 10 laboratories in which three replicates were utilized at each laboratory [*7*].

The *h* and *k* consistency statistics for G_{sb} (dry) and absorption results are presented in Figures 14 and 15, respectively. A total of eight individual test results per laboratory were considered for that analysis. It should be noted that all *h* statics values are within the limit of critical *h*-static value of 2.29. Therefore, the distribution of *h* values between laboratories does not indicate any case for concern. However, plot of *k* values (Figure 15) shows that three districts only had one of the eight tests exceeding the critical *k* value of 2.10. The supporting data for the three samples that exceeded the critical *k* value were re-examined and no specific error was reported. Besides, the other seven material criteria (i.e., G_{sb} and absorption results presented in Figures 14 and 15) reported for the same laboratory were found to be well within the critical limit. Therefore, these samples were kept in the data set when further analysis was performed.

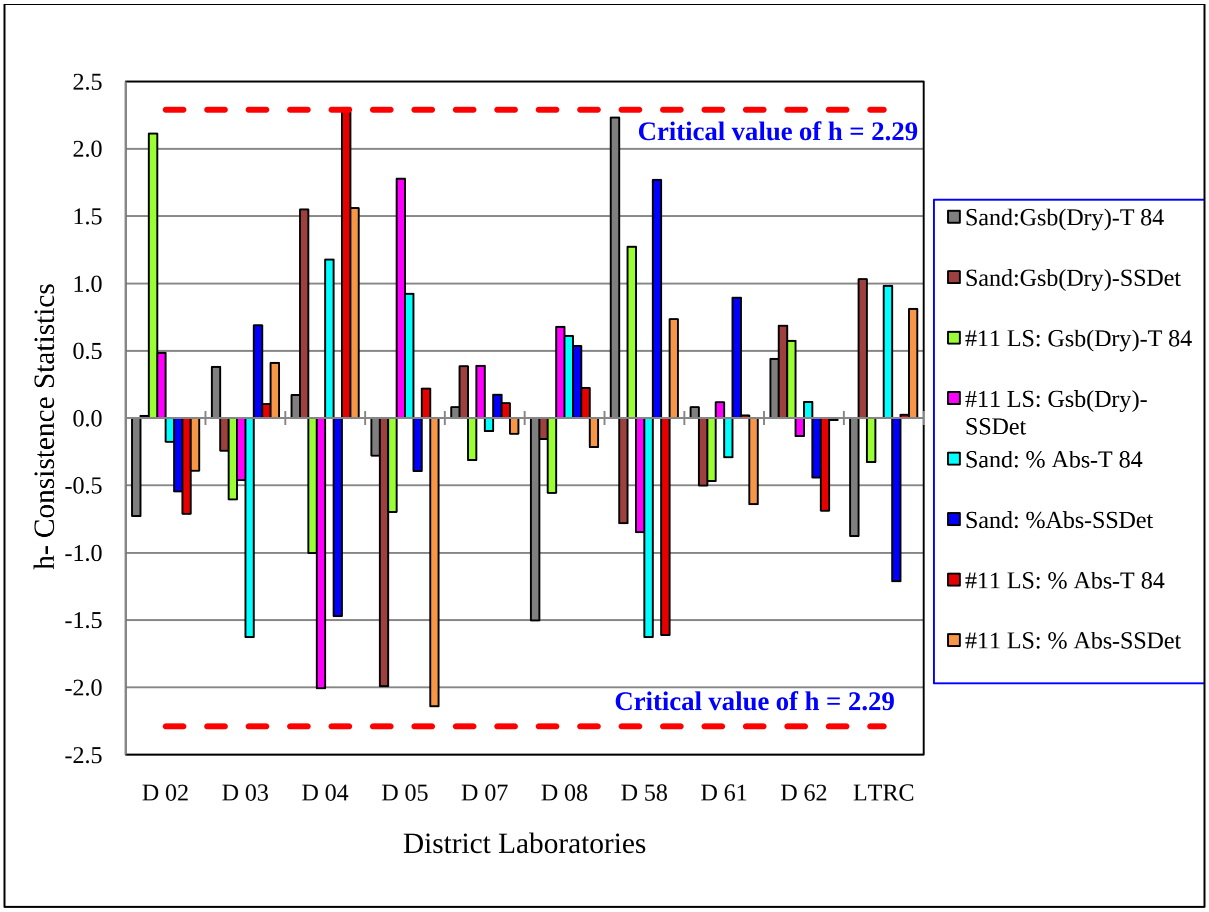

Figure 14
***h* consistency statistics for sand and # 11 LS**

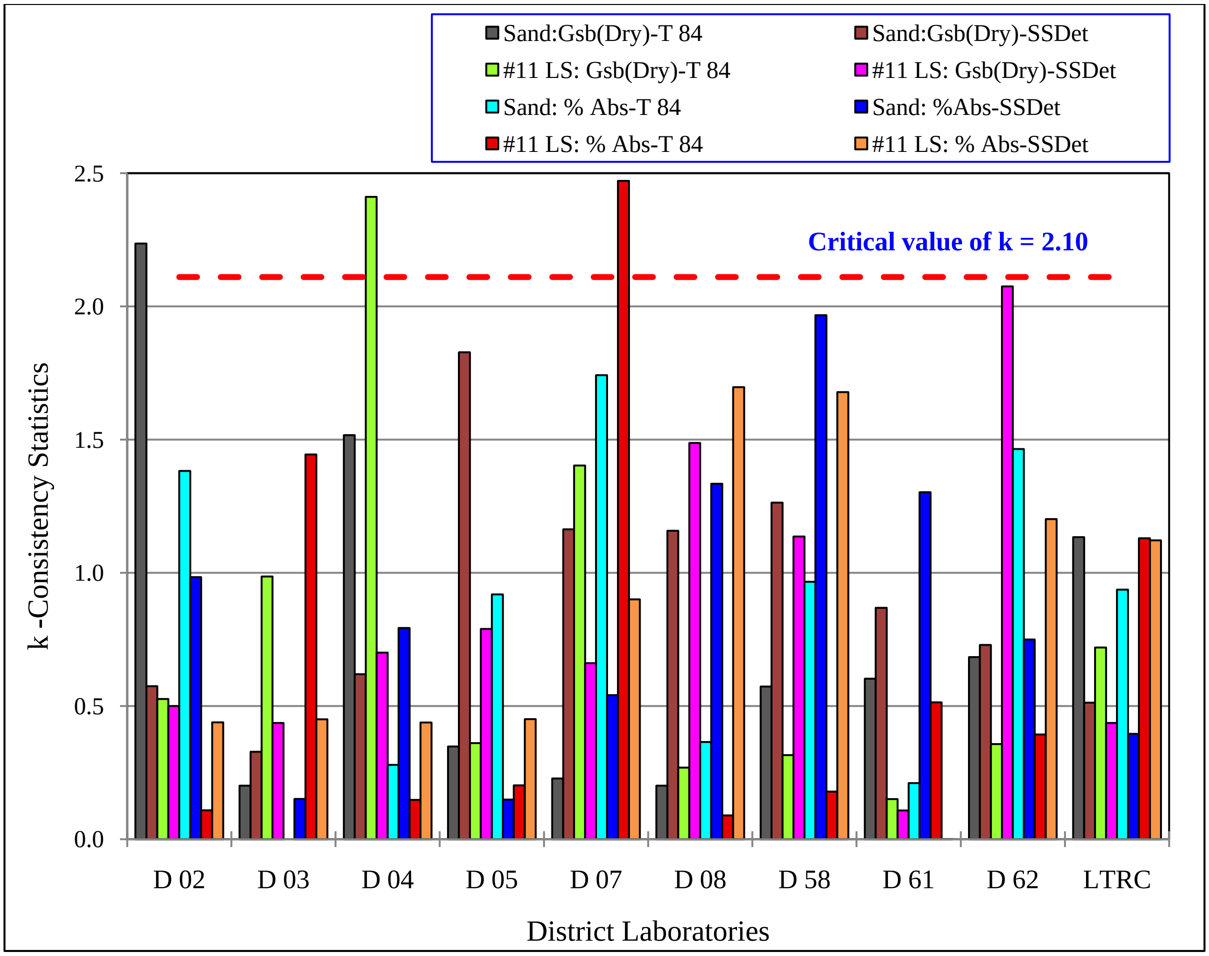

Figure 15
k **consistency statistics for sand and # 11 LS**

The repeatability (within-lab) and reproducibility (between-labs) standard deviations for different aggregate-properties and the difference between two sigma limits (d2s) are reported in Table 2 along with the precision statements mentioned in the AASHTO T 84 test procedure. For sand, the within-lab standard deviations for G_{sb} (dry), G_{sb} (SSD), and absorption are well within the limit specified in the AASHTO T 84 test specification regardless of the test methods (i.e., AASHTO T 84 and SSDetect) employed in this study. However, SSDetect obtained lower repeatability standard deviation values (except % absorption for sand) compared to that of AASHTO T 84. This implies that results from SSDetect are more repeatable when compared to its counterpart. On the other hand, neither AASHTO T 84 nor SSDetect test methods failed to meet the repeatability criteria when #11 LS was tested. The within-lab standard deviations for G_{sb} (dry), G_{sb} (SSD), and absorption were greater than the standard limit mentioned in the AASHTO T 84 specification. However, SSDetect test results still showed better repeatability than that of AASHTO T 84 utilized in this study.

Table 2
Precision estimates for AASHTO T 84 and SSDetect methods

Material Properties		Repeatability (Within-lab)			Reproducibility (Between-labs)		
		AASHTO T 84	SSDetect	Precision Statement in AASHTO T 84	AASHTO T 84	SSDetect	Precision Statement in AASHTO T 84
Pooled Standard Deviation							
Sand	G_{sb} (Dry)	0.0076	0.0070	0.0110	0.0128	0.0165	0.0230
	G_{sb} (SSD)	0.0074	0.0059	0.0095	0.0108	0.0153	0.0200
	% Absorption	0.0548	0.0770	0.1100	0.1758	0.1441	0.2300
#11 LS	G_{sb} (Dry)	0.0239	0.0163	0.0110	0.0755	0.0220	0.0230
	G_{sb} (SSD)	0.0215	0.0128	0.0095	0.0596	0.0157	0.0200
	% Absorption	0.2814	0.1600	0.1100	1.0582	0.2970	0.2300
Acceptable Difference Between Two Results (d2s)							
Sand	G_{sb} (Dry)	0.0215	0.0199	0.032	0.0361	0.0466	0.066
	G_{sb} (SSD)	0.0209	0.0166	0.027	0.0305	0.0433	0.056
	% Absorption	0.1549	0.2177	0.310	0.4973	0.4075	0.660
#11 LS	G_{sb} (Dry)	0.0676	0.0460	0.032	0.2136	0.0623	0.066
	G_{sb} (SSD)	0.0609	0.0362	0.027	0.1687	0.0445	0.056
	% Absorption	0.7960	0.4525	0.310	2.9930	0.8399	0.660

While considering the between-labs (reproducibility) standard deviations for sand, both AASHTO T 84 and SSDetect obtained satisfactory values specified in the AASHTO test specification. For #11 LS, the between-labs (reproducibility) standard deviations for G_{sb} (dry) and G_{sb} (SSD) are well within the limit only when SSDetect was utilized, whereas, none of the results obtained from AASHTO T 84 met the specified precision statement. The difference between two test results (d2s) followed the same trend of within-lab and between-lab standard deviation results. Mathematically, d2s are calculated by multiplying the appropriate standard deviation by the factor $2\sqrt{2}$ (for 95 percent confidence), which explains why it followed a same trend like repeatability and reproducibility values. However, in case of a comparison between more two test results, the range of this difference becomes larger.

AASHTO T 166 vs. CoreDry

A total number of 86 field core specimens were tested at six district laboratories for the bulk specific gravity (G_{mb}) values using both AASHTO T 166 (DOTD TR 304-03) and CoreDry methods. The basic difference between these two methods was the process of drying the field cored specimens. The AASHTO T 166 method uses the conventional oven drying process; whereas, a CoreDry device is used to dry specimens in the CoreDry device. Figure 16 illustrates a graphical comparison between G_{mb} values measured from the Coredry and AASHTO T 166 method. It is clearly evident from this figure that G_{mb} values measured by these two different methods are superimposed on top of each other. The difference between the mean G_{mb} values measured by CoreDry and AASHTO T 166 is 0.00007, while the variances of G_{mb} values computed using these two methods are 0.003579 and 0.003576, respectively. This is another indication that there is almost no difference between G_{mb} values computed using these two methods. The data set were further analyzed, conducting a statistical paired t-test to check the Null Hypothesis H_0. The difference between the average CoreDry G_{mb} value and the average AASHTO T 166 G_{mb} value is 0. A two-tailed p-value of 0.903 at 95 percent confidence interval established the null hypothesis, meaning there is statistically no difference between the average CoreDry G_{mb} value and the average AASHTO T 166 G_{mb} value.

Regression analysis models describe the relationship between two or more variables through a mathematical equation. In this study, a regression analysis was performed to investigate the statistical relationship between G_{mb} values computed from the two test procedures. The goodness of the model was determined by the regression coefficient (R^2), where a higher R^2 value (close to 1.0) was desired. Based upon Figure 17, it is established that there is a direct and strong correlation between the G_{mb} measurements for both the CoreDry and AASHTO T 166 procedure.

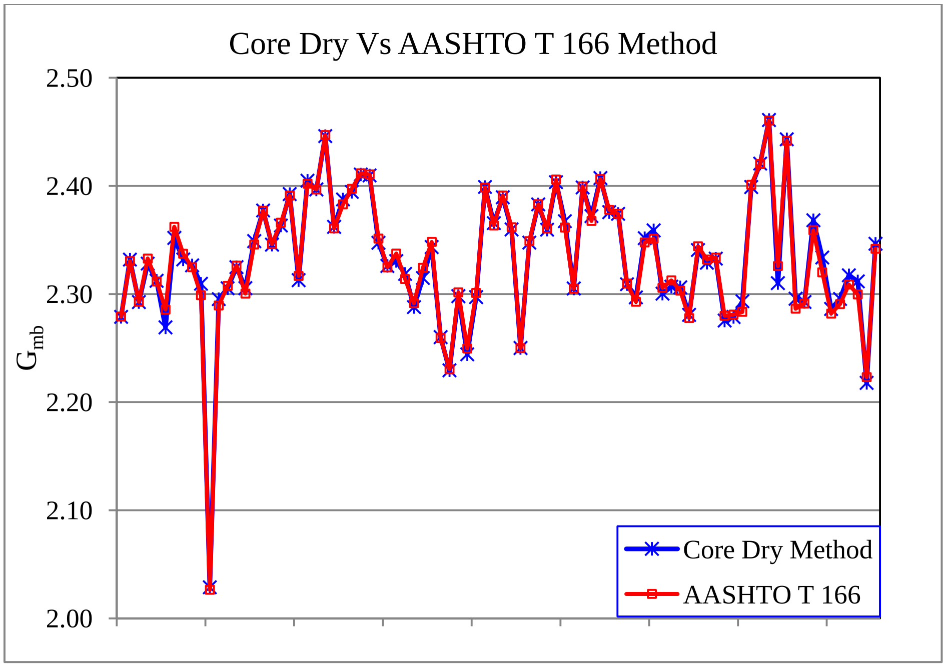

Figure 16

Comparison of G_{mb} values between the CoreDry and AASHTO T 166 method

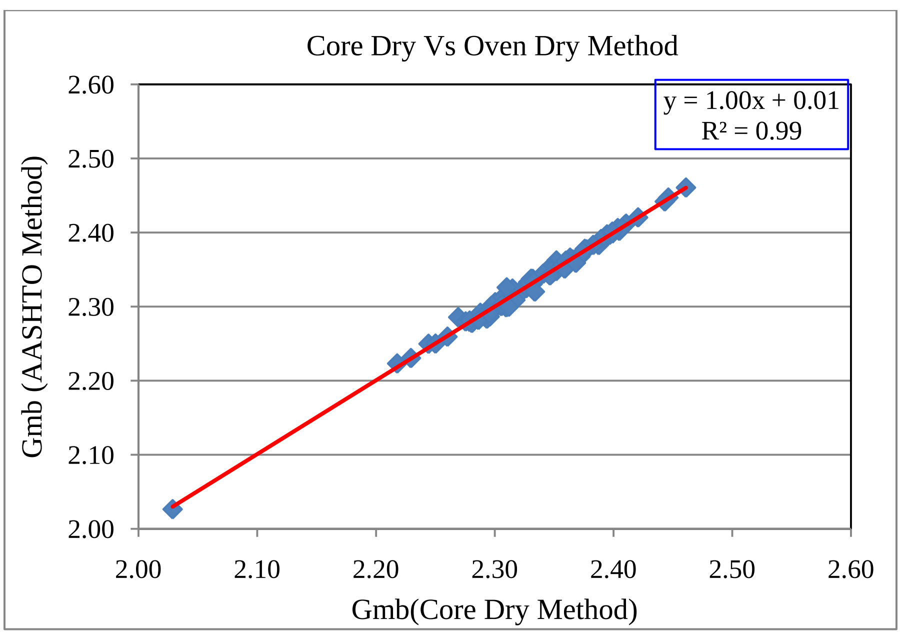

Figure 17

Relationship between G_{mb} measurements for field cores

Comparison of AASHTO T 166 and CoreLok

Two types of mixtures–a Superpave wearing course (WC) and an open graded friction course (OGFC) were employed to compare bulk specific gravity (G_{mb}) values obtained using AASHTO T 166 and CoreLok test procedures. Figures 18 and 19 are the plots of G_{mb} values determined by the aforementioned test methods. It should be noted that triplicate specimens were tested at individual district labs to represent each mixture type. In both cases, the CoreLok was reported to measure lower G_{mb} values (resulting in higher air voids) than that of AASHTO T 166. Moreover, the G_{mb} values representing AASHTO T 166 and CoreLok methods are somewhat close to one another for the wearing course mixtures; whereas, distinct differences are noticeable between the two measurements for the OGFC mixture. This trend clearly follows the research outcome of earlier studies performed by Buchanan et al. and Hall et al. [*9*] [*10*].

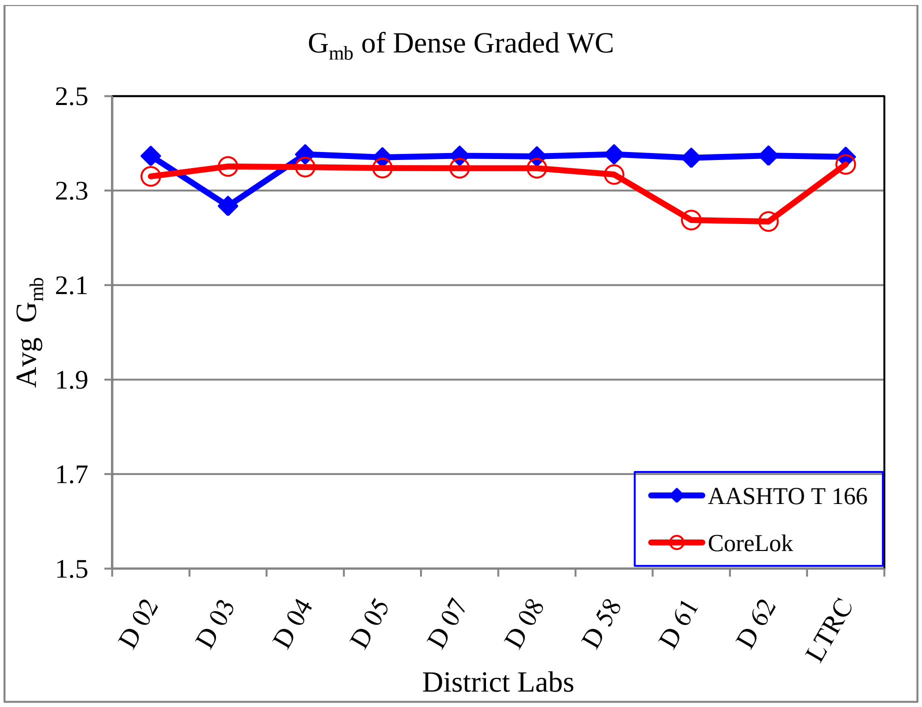

Figure 18
Bulk specific gravity of wearing course mixture

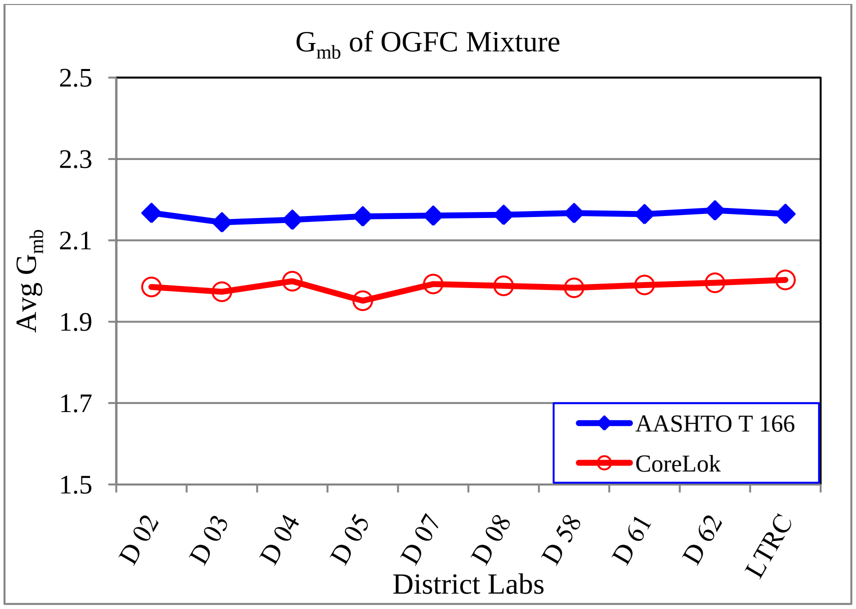

Figure 19
Bulk specific gravity of OGFC mixtures

The coefficient of variance values presented in Figures 20 and 21 indicate that both test methods are able to compute G_{mb} values without substantial variations. Even though AASHTO T 166 is reported to have a comparatively lower variation than its counterpart, CV values for both test methods are well below the limit of 20 percent.

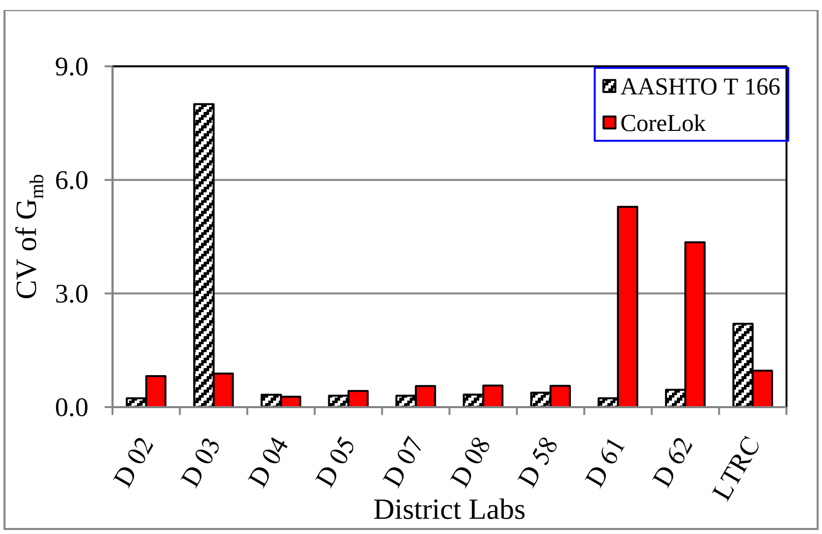

Figure 20
Coefficient of variation for G_{mb} results for WC mixtures

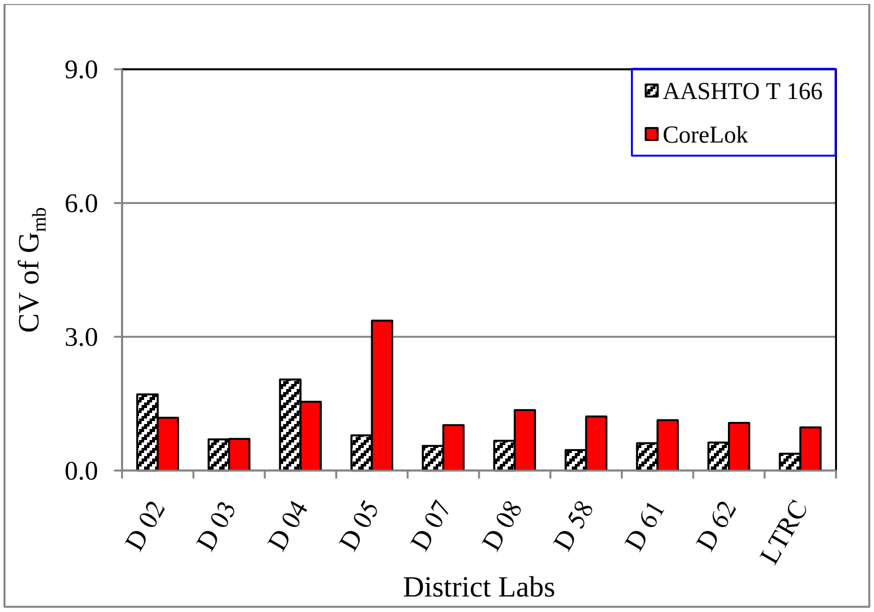

Figure 21
Coefficient of variation for G_{mb} results for OGFC mixtures

Figures 22 and 23 illustrate comparisons of air voids resulting from AASHTO T 166 and CoreLok based G_{mb} values for the WC mixture and OGFC mixture, respectively. Air voids of the mixtures were calculated using a given mixture's maximum specific gravity (G_{mm}) and a percentage of asphalt content. The G_{mm} and percent asphalt content values were considered as 2.426 and 6.68 percent and 2.494 and 4.08 percent for WC and OGFC mixtures, respectively. The computation indicates that by changing the method of measuring G_{mb} there is a difference in air void values ranging from 0.64 percent to 5.59 percent for wearing course mixtures and 6.22 percent to 8.55 percent for OGFC mixtures. That means, even without any physical change in the mixtures, there was a change in the air void results of the same mixture simply because of the test method used to determine the voids. This may play a significant role in real life construction projects and can lead mixtures to fall into two different payment categories, yet those mixtures are physically identical.

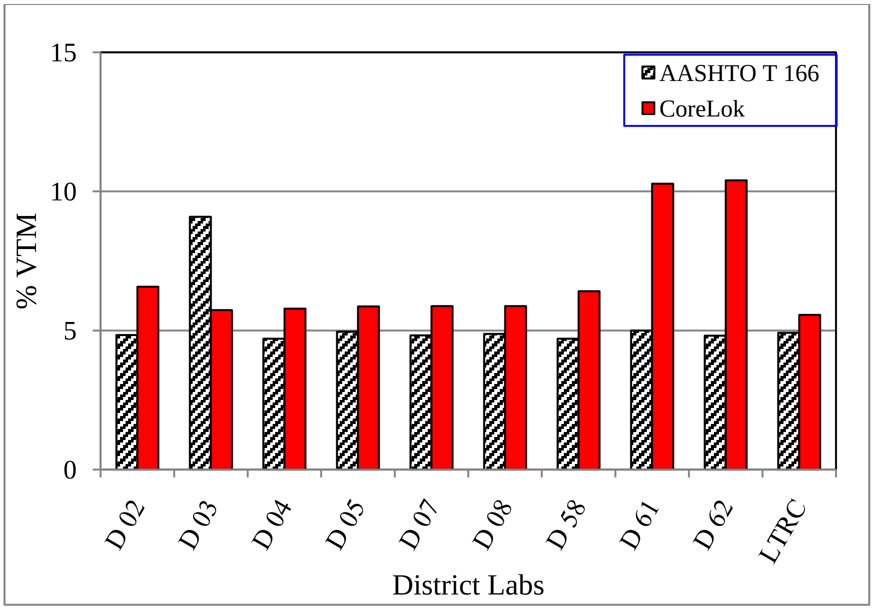

Figure 22
Comparison of air voids for wearing course mixtures

Furthermore, air void results reveal that the AASHTO T 166 method is not suitable to determine the specific gravity of OGFC mixtures. The OGFC mixture used in this study was prepared to obtain an air void of around 18 percent. Unfortunately, none of the district labs were able to achieve that with AASHTO T 166 method. Air void values obtained from AASHTO T 166 ranged from 10.4 to 11.6 percent, entirely too low from the expected target. In contrast, air void results from the CoreLok method were contained between 17.5 percent and 19.6 percent, within the expected range. It appears while taking a saturated surface dry (SSD) weight in the AASHTO T 166 method, the water freely flows out of the specimen for OGFC mixtures. This leads to an erroneous measurement of the volume of the specimen. Previous studies by Watson at el., Buchanan et al., and Williams also recommended that CoreLok procedure is a better method to determine the G_{mb} of mixtures like – OGFC, SMA, or other course graded mixtures that possess relatively higher air voids [*3*], [*9*], [*11*].

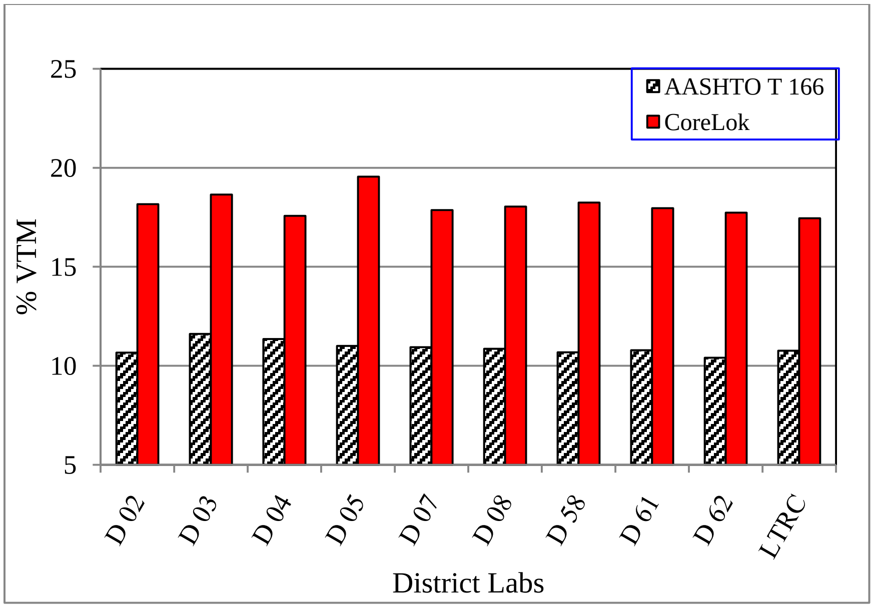

Figure 23
Comparison of air voids for OGFC mixtures

The *h* and *k* consistency statistics for G_{mb} results are presented in Figures 24 and 25, respectively. The *h* and *k* values are calculated in similar methods described in the previous section. The *h* statics values for G_{mb} of WC measured by AASHTO T 166 at District 03 Laboratory and G_{mb} of OGFC measured by CoreLok at District 05 Laboratory exceed the limit of the critical *h* static value of 2.29. Similarly, the *k* statics values for G_{mb} of WC measured by AASHTO T 166 at District 03 Laboratory and G_{mb} of OGFC measured by CoreLok at District 61 Laboratory exceed the limit of the critical *k* static value of 2.10. The whole dataset for those district labs were rechecked and the aforementioned inconsistencies appear to be a scattered incident. Therefore, *h* and *k* distributions for G_{mb} results obtained from this study do not indicate any case for concern, and the G_{mb} results were considered for further analysis.

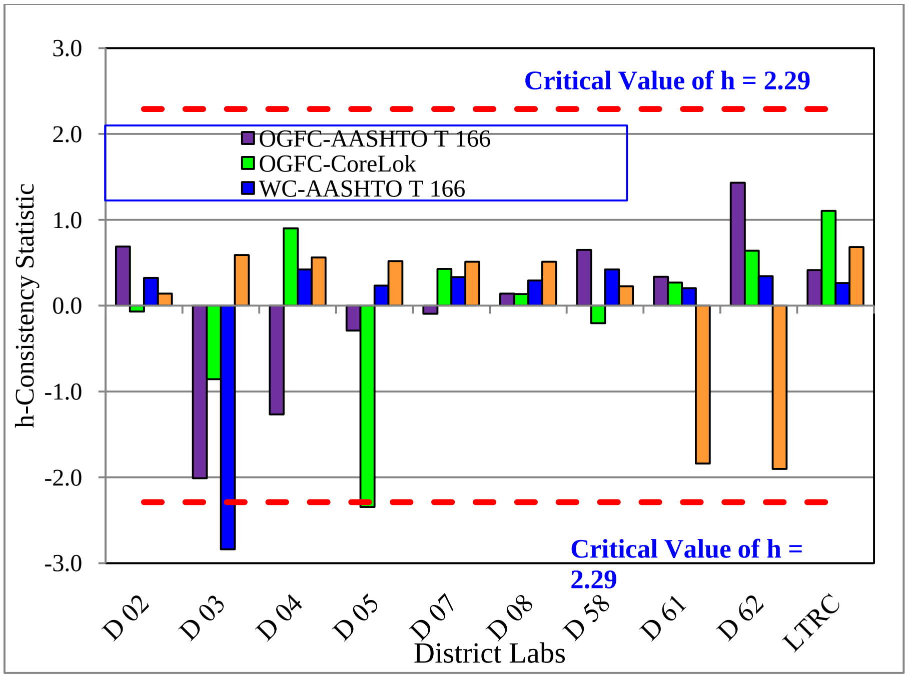

Figure 24
***h* consistency statistics for mixtures**

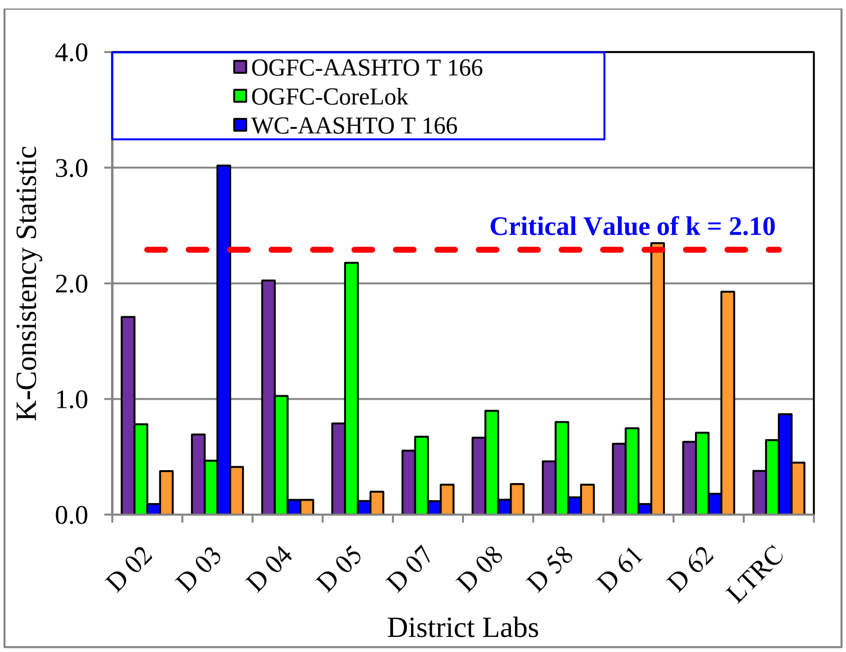

Figure 25
***k* consistency statistics for mixtures**

A paired t-test at a level of significance of 5 percent (alpha = 0.05) was employed to compare the G_{mb} values obtained using these two test methods where significant differences were observed. Because there is no true measure of accuracy for a G_{mb} measurement, it is desirable to choose a procedure that provides precise and accurate results with lesser variability. A summary of the statistical analysis describing the variability (i.e., in terms of repeatability and reproducibility) of test methods is contained in Table 3. It appears that the repeatability and reproducibility values for the CoreLok method are comparable to that of the AASHTO T 166 method of testing.

Table 3
Precision estimates for AASHTO T 166 and CoreLok methods

Material Properties		Repeatability (Within-lab)		Reproducibility (Between-labs)	
		AASHTO T 166	CoreLok	AASHTO T 166	CoreLok
Pooled Standard Deviation					
OGFC	G_{mb}	0.0217	0.0301	0.0197	0.0287
WC	G_{mb}	0.0601	0.0504	0.0594	0.0622
Acceptable Difference Between Two Results (d2s)					
OGFC	G_{mb}	0.0613	0.0852	0.0556	0.0812
WC	G_{mb}	0.1699	0.1426	0.1681	0.1760

Comparison of AASHTO T 166, CoreDry, and CoreLok

Three methods, AASHTO T 166, CoreDry, and CoreLok, were utilized to determine the bulk specific gravity (G_{mb}) of 30 field-cored specimens at two different district laboratories. Due to the unavailability of the equipment, only District 04 and District 08 participated in this portion of the study. G_{mb} values obtained at district laboratories using various test methods are graphically presented in Figure 26, where each vertical bar indicates the average G_{mb} value of 15 individual specimens. Apparently, the equal bars indicate that there is no difference between the G_{mb} values even though they were measured by different test procedures.

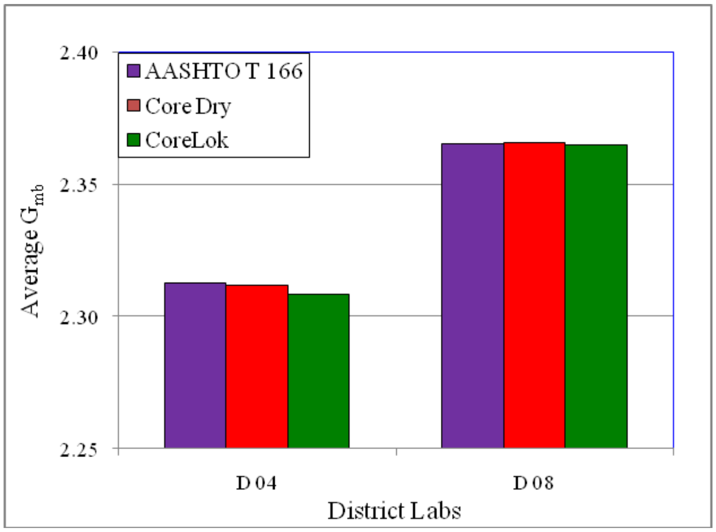

Figure 26
Bulk specific gravity of field cores

For a further statistical analysis, a one-way analysis of variance (ANOVA) was used to determine if there was a significant difference in the mean G_{mb} values determined by the three test methods. A level of significance of 5 percent (i.e., $\alpha = .05$) was used in all cases. Results obtained from the ANOVA are represented in Table 4. For both district laboratories, F test statistics were found to be smaller than $F_{critical}$ values. In addition, the one-tailed p values were always greater than 0.05 (α value). This concludes that there was no significant difference between the mean G_{mb} values obtained from the three test methods considered in this analysis. Therefore, the AASHTO T 166 test procedures should be modified to incorporate these devices.

Table 4
ANOVA results

Districts	F-statics	$F_{critical}$	P-value
District 04	0.101711	3.238096	0.904
District 08	0.001114	3.219942	0.999

Cost Analysis

A cost analysis was examined for each test equipment device for the time saved in performing the test, as compared to the associated conventional test procedures. The SSDetect was the only device that had measurable cost savings when compared to the conventional method. The test procedures using the CoreLok device and compared to the conventional test procedures require the same amount of time to conduct the test, and therefore does not contribute to any time or cost savings. When comparing the CoreDry device to the conventional test procedure, the actual man hours required for a technician to perform each test is essentially the same. In this case however, the test specimens require conditioning overnight before performing the test with the conventional test procedure.

A poll of several districts was conducted that resulted in an estimated 35 G_{sb} tests performed in each district throughout the year. This results in 315 total G_{sb} tests conducted in the districts last year. Our laboratory experience shows an estimated man hour savings of approximately 6 hours when using the SSDetect device as compared to the conventional test procedures. This results in an estimated cost savings of $94,500.00 per year.

District Lab Comments

Each district laboratory was asked to submit comments regarding the use of these automated test devices. These comments are recorded in Appendix D.

The testing devices were not without problems. As indicated from several of the laboratories comments, the CoreLok had problems with the bag developing pin holes after sealing. Special care in handling helped to alleviate the problem. The SSDetect device had some minor problems with the flask.

CONCLUSIONS

An evaluation of the three new automated testing devices has been conducted in each of the nine district laboratories located throughout the state of Louisiana. The following can be concluded from this research:

- The SSDetect method shows better repeatability and reproducibility in measuring the G_{sb} (dry) of the #11 limestone when compared to the conventional method, AASHTO T 84. The current AASHTO T 84 method to determine the saturated surface dry (SSD) condition of angular or rough fine aggregates is quite subjective resulting in a greater variance in repeatability and reproducibility.

- Both AASHTO T 166 (DOTD TR 304-03) and CoreLok test methods are capable of measuring G_{mb} values for wearing course mixtures. The CoreLok device should be required for determining voids in open graded mixtures.

- There is no difference in results between the CoreDry method and the conventional (oven dried) method. Therefore, the CoreDry device should be allowed as an alternate to oven drying the mixture sample.

- A comparison between AASHTO T 166 (DOTD TR 304-03), CoreDry, and CoreLok indicates there is no significant difference between the G_{mb} values of field cores, measured by each of the aforementioned test methods.

- The repeatability and reproducibility measurements indicate that the CoreLok procedure for computing G_{mb} of asphalt mixtures is highly repeatable and reproducible.

- The SSDetect, and CoreDry devices, have proven to offer significant time savings over conventional test procedures. However, only the SSDetect is shown to have a measurable cost advantage of time savings versus the conventional method.

RECOMMENDATIONS

The SSDetect, CoreLok, and CoreDry devices used in this study have proven to improve time and accuracy of asphalt related tests. The following initiatives are recommended in order to facilitate the implementation of this study:

- Require the use of the SSDetect device in each of the district laboratories to determine the bulk specific gravity (G_{sb}) and % absorption of fine aggregates in lieu of the AASHTO T 84 test procedure.

- Allow the use of the CoreLok device for HMA mixtures for computing the bulk specific gravity (G_{mb}) with a correction factor.

- Require the use of the CoreLok device for all open and gap graded hot mix asphalt mixtures for determining the bulk specific gravity, G_{mb}.

- Allow the use of the CoreDry device to obtain the dry weight of mixtures in determining the bulk specific gravity (G_{mb}) of HMA mixtures in lieu of the conventional method.

ANONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of Highway Transportation Officials
ANOVA	Analysis of Variance
CV	Coefficient of Variance
FAA	Fine aggregate angularity
FHWA	Federal Highway Administration
G_{mb}	Bulk specific gravity of asphalt mixture
G_{mm}	Maximum theoretical specific gravity of asphalt mixture
G_{sb}	Bulk specific gravity of aggregates
HMA	Hot mix asphalt
LADOTD	Louisiana Department of Transportation and Development
LS	Limestone
LTRC	Louisiana Transportation Research Center
M	Mass of the aggregate
n	Number of replicates per lab
OGFC	Open graded friction course
p	Number of laboratories
SGC	Superpave gyratory compacted
s	The cell standard deviation
S_R	The reproducibility of standard deviation
S_r	The repeatability of standard deviation
S_x	The standard deviation of the cell averages
SSD	Saturated surface dry
V	Volume of the aggregate
VMA	Voids in mineral aggregate
VFA	Voids filled with asphalt
WC	Wearing course

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APPENDIX A

SSDetect Operation Procedure

Phase One: Compute Film Coefficient

1. Dry 1,050 g ± 5 g of minus No. 4 sieve material to a constant mass.
2. Separate the dry sample into two 500 g ± 0.1 g samples.
3. Calibrate the AVM flask with 25°C water. Record weight.
4. Empty the AVM flask and pour in one 500 g ± 0.1 g into the flask.
5. Add 250 mL of 25°C water to the aggregate sample in the flask. Wait five minutes and fill flask up to the calibration mark. Record weight.
6. Secure the filled flask onto the AVM pedestal. Attach vacuum hose and start the test.
7. After the vacuum process is completed, remove the flask and fill back to the calibration mark. Record weight. Compute film coefficient for use in phase two.

Phase Two: Automated SSD Condition

1. Clean test bowl and lid. Record empty weight.
2. Add the remaining 500 g ± 0.1 g sample to the bowl. Record the combined weight.
3. Attach bowl/sample to the SSDetect table. Secure lid and connect the water supply.
4. Adjust the film coefficient on the main touch screen, and start the test.
5. After test has completed, remove the water supply. Record the weight of the bowl, sample, and lid. You now have all the values needed to calculate the specific gravities of the test specimen.

Note: A spreadsheet has been developed by LTRC to assist in the film coefficient and gravity calculations. The spreadsheet has two tabs. One tab is a blank form and the other is a calculation sheet.

APPENDIX B

CoreLok G_{mb} Procedure

1. Make sure the sample is dried to a constant mass in accordance with standard DOTD practices.
2. Record the weight of the compacted specimen in air.
3. Record the weight of the CoreLok test bag.
4. Inspect the bag for tears or creases that may influence the test.
5. Place the specimen into the CoreLok bag and place both on the pedestal inside the CoreLok vacuum device.
6. Make sure the open end of the bag is properly placed onto the sealing bar of the machine.
7. Set the machine to run Program 1 and start the vacuum process by closing the lid.
8. When the vacuum process is complete, remove the sealed sample from the machine and inspect for punctures (the sample losing vacuum can usually be heard).
9. Submerge the sealed sample under water at 25°C until the scale becomes stable. Record the weight.
10. Remove sample from the water bath, and inspect for leakage (wet spots).
11. Remove the sample from the bag and record the air mass again.
12. Input all of the recorded weights into the CoreLok software to obtain a G_{mb}.
13. Input weights and results in the spreadsheet developed by LTRC.

APPENDIX C

CoreDry vs. Oven Dry Test Procedures

1. Oven dry cores completely.
2. Soak cores for 2 hours.
3. Determine and record dry weight using CoreDry device.
4. Re-soak cores for 2 hours.
5. Dry cores in oven for 16 hours.
6. Determine and record oven dry weight of cores.

APPENDIX D

District Lab Comments

The following districts sent their comments to be published.

District 02
From my experience using the SSDetect device, I would provide the following comments:

- This device was noticeably faster than the previous way, allowing us to perform significantly more tests in a day. This adds greatly to our productivity.
- Virtually all human error was removed by using the SSDetect. This is a good advantage it has over the previous method.

Regarding the CoreLok device:

- The bags used for this device were of poor quality and were prone to tearing, which made the testing difficult.
- I suggest using a much higher quality bag for this device; if that is done, the CoreLok was more efficient.

District 05
I want to thank you for the use of your equipment (sorry we can't keep it). My experience with the equipment was very rewarding.

- The use of the CoreLok (or seal a meal) as I call it, gave me a different look at weighing the G_{mb} specimen in water in a bag.

The automatic vacuum mixer (AVM) and the SSDetect machine is a must have for our district.

- The mixer shakes and vacuums your sample at the same time, which is great when you don't have to roll your sample to get the air out.
- The SSDetect machine I fell in love with. The machine automatically puts the water in, so there is less room for error. The overall use of the gravity machine will expedite the gravity process.

The CoreDry machine really dries the sample quickly. This test proved to me that if you air dry the sample there is still some moisture left in the sample, but as soon as you put it in the CoreDry you can see the moisture leave.

This has been a very useful experiment of the testing equipment. If you ever need more testing done, I will be very glad to volunteer for the task. Again, I say thank you.

District 07

All the equipment was simple to use and I had no problems with any of it. The only advantage to any of it would be with the SSDetect. I think the SSDetect will give more accurate and consistent results, especially for stone.

District 08

First on the SSDetect, it's advised that there needs to be a red line on the flask so that you can see when in the machine. Second, on the CoreDry there was a problem with not being able to know when sample was dry or how long did it take to dry the sample. I was able to know based on having the results from the samples being run the conventional way, but if not having a reference, I'd need some method of knowing when the samples were dry.

District 61

I am currently trying the machine. For plants and validation, it may serve a purpose (results today as opposed to tomorrow). As far as accuracy and reliability, the data from roadway reports (plant), CoreDry, and oven dry are comparable. In some cases, the plant was drier on air weight, some oven dry and some CoreDry. It varies.

For use in district labs, I feel it would be a waste of money. If you want to buy me something, I vote for the SSDetect!

District 62

In December '08 I tested a few samples with the use of the SSDetect and CoreLok devices. Here are my comments:

- Fine Aggregate Specific Gravity: I found that the rubber grips on the arm to hold the flask had a tendency to rub against the flask leaving marks or minor abrasions on the glass (neck of flask), which changed the flask empty weight periodically.
- SSD Condition: The plastic bowl and lid collected a lot of moisture; therefore, while removing the lid to release lock on the machine, you would lose moisture droplets prior to weighing.
- CoreLok Procedure: Spent way too much time trying to buff out roughness on the sample and still the bag would get small holes, releasing vacuum. The bags needed to be folded in water so it wouldn't hit sides of the bath (weight would not stabilize anytime soon because the bag would slowly unfold under water) as well as gather air bubbles that you may or may not be able to clear for an accurate weight. After

releasing air bubbles while under water, you have now handled the bag too much and it has lost its strength and vacuum. Whenever this happened, we lost more time by having to re-dry sample to re-test.