Evaluation of Methods for Measuring Aggregate Specific Gravity

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The current American Association of State Highway and Transportation Officials (AASHTO) procedures for determining the aggregate specific gravities and absorption values are time consuming and the repeatability is less desirable. The standard AASHTO method for fine aggregates has problems with angular and absorptive materials. Due to this problem several agencies have developed alternative methods. Correct measurement of the specific gravity and absorption play a crucial role in the design of hot mix asphalt (HMA) mixtures. Improper measurements can lead to improper acceptance or rejection of HMA.
This research evaluated the specific gravity test methods for fine aggregates. The focus of the research is to find a test method that is suitable for all types of fine aggregates. There were 9 different methods used to determine the fine aggregate specific gravities apart from the standard AASHTO method. All the selected methods are the modifications made by other agencies in order to improve the test accuracy. The comparison between the different methods to the AASHTO method was done using the student t distribution test.
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Chapter 1 Introduction

1.1 BACKGROUND

The specific gravity and absorption of fine and coarse materials need to be measured with high degree of accuracy since they are essential for the development of satisfactory mix designs for the production of the hot mix asphalt (HMA). The American Association of State Highway and Transportation Officials (AASHTO) provide standards for testing of materials. The AASHTO test methods have been in use since their introduction in order to measure the specific gravity and absorption values of aggregate materials. The current tests used for determining the specific gravity and absorption of aggregates are AASHTO T 85 and AASHTO T 84 for coarse and fine aggregates respectively. The corresponding ASTM methods are C 127 and C 128 respectively. The dividing sieve for separating coarse and fine aggregates is the 4.75 mm sieve.

As demonstrated in the literature survey, there have been multiple attempts to refine or replace the AASHTO method, especially for fine aggregates. There are two issues with the AASHTO methods. Both methods require preparing the samples by first drying, then saturating for an extended period of time. This inhibits laboratory productivity. The second problem is with determining the saturated surface dry, SSD, moisture state of the aggregates. For coarse aggregates SSD is determined by visual examination, which is subjective. For fine aggregates common method for determining the SSD state is based on a cone-slump test. In essence this method relies on the surface tension of moisture on the face of the aggregate to maintain the cone shape with the mold is removed. Once the moisture is reduced so the surface of the aggregate is dry, the cone shape should slump when the mold is removed indicating SSD condition. The problem is angular and textured aggregates can retain the shape of the mold even when the moisture is at the SSD condition. Limestone and slag aggregates are susceptible to this problem.

1.2 PROBLEM STATEMENT

Due to the issues with the time required for the aggregate specific gravity test and concerns with determining the SSD state, especially of fine aggregates, multiple alternative test methods have been developed both commercially and by state highway agencies. The West Virginia Division of Highways, WVDOH, relies on the AASHTO methods. However, there is a concern that the AASHTO methods may not yield reliable results for many slag and limestone aggregates. Hence, there is interest in determining if the alternative methods may provide more timely and accurate results than the current methods.

1.3 OBJECTIVE

The objective of this thesis is to evaluate different methods for measuring the aggregate specific gravities for slag and limestone. The results obtained from the alternative methods are statistically compared with results from the standard AASHTO test methods using the Student t distribution test.

1.4 SCOPE AND LIMITATIONS

The specific gravity of coarse aggregates was evaluated using AASHTO T 85 and the CoreLok-AggPlus method. The SSDetect device was not available for this research. No attempts have been made to see if the methods adopted by other states can be helpful to find results similar to those of the standard AASHTO methods.

There were 9 different methods tested other than the standard test method for fine aggregates. The CoreLok-AggPlus device was used in case of the coarse aggregate testing.

1.5 ORGANIZATION OF THESIS

This thesis consists of five chapters. Chapter 1 is the introduction to the thesis. Chapter 2 contains the literature review which shows the previous work on alternative methods to measure specific gravity and absorption of aggregates. Chapter 3 describes the research methodology. Chapter 4 presents the results and statistical analysis. Finally, the conclusions and few recommendations are presented in Chapter 5. Appendix A and B present the CoreLok/AggPlus procedures to determine the specific gravity and absorption values of the fine and coarse aggregates respectively.

Chapter 2 LITERATURE REVIEW

2.1 INTRODUCTION

The literature review starts with a summary of the definitions of the specific gravity of aggregates. Then the equations used for volumetric analysis of asphalt concrete are presented. These equations are used in the analysis of the research data to demonstrate the effect of variance in aggregate specific gravity affect the analysis of asphalt concrete. A summary of the AASHTO and ASTM standards is presented including the alternative methods allowed within the standard test methods. The Arizona, Wisconsin, Texas and California state highway agency methods for fine aggregate specific gravity methods are summarized. Finally research efforts on two commercially available devices are summarized.

2.2 SPECIFIC GRAVITY OF AGGREGATES

Specific gravity of an aggregate has several definitions to account for the treatment of the surface voids of the aggregate. Based on the type of void being considered the specific gravity is defined as bulk, apparent and effective.

Apparent Specific Gravity (G_{sa}) is the ratio of the mass in air of a unit volume of non-permeable portion of aggregate, not considering the permeable voids in the aggregate to the mass in air of an equal volume of gas-free distilled water at a specific temperature. For coarse aggregates, AASHTO T 85, G_{sa} is calculated as:

$$G_{sa} = \frac{A}{A - C} \tag{1}$$

where A = oven dry mass of aggregate

C = mass of aggregate in water

Additionally, fine aggregate G_{sa} can be calculated according to AASHTO T 84 as:

$$G_{sa} = \frac{A}{B + A - C} \tag{2}$$

where A = oven dry weight of aggregate in air

B = weight of pycnometer filled with water

C = weight of pycnometer with aggregate and water to calibration markBulk Specific Gravity (G_{sb}) is the ratio of the mass in air of a unit volume of aggregate to the mass of an equal volume of gas-free distilled water at a specific temperature. The surface voids of the aggregate are included with the volume of the aggregate. For coarse aggregates, AASHTO T 85, G_{sb} is calculated as:

$$G_{sb} = \frac{A}{B - C} \tag{3}$$

where A = oven dry mass of aggregate

B = SSD mass of aggregate

C = mass of aggregate in water

Fine aggregate G_{sb} can be calculated according to AASHTO T 84 as:

$$G_{sb} = \frac{A}{B + S - C} \tag{4}$$

where A = oven dry weight of aggregate in air

B = weight of pycnometer filled with water

C = weight of pycnometer with aggregate and water to calibration mark

S = weight of aggregate in SSD condition

Absorption is the moisture content of the aggregate in the SSD condition, computed as:

$$\%\ \text{Absorption} = \frac{B - A}{A} \times 100 \tag{5}$$

where A = oven dry mass of aggregate

B = SSD mass of aggregate

The volume of the surface voids is determined by measuring the mass of the aggregate when the surface voids are filled with water and the remaining surface if dry, the saturated surface dry (SSD) condition.

The equations for fine aggregates are functionally the same as the coarse aggregate equations with an adjustment for the fact that the mass of the aggregate in water is measured in a calibrated volumetric vessel. This requires an adjustment to the C term in the above equations.

2.3 Application and significance of specific gravity of aggregates

For HMA mix designs the bulk specific gravity is critical information for the design and production of HMA. The bulk specific gravity value is used in the calculation of voids in mineral aggregate (VMA) and effective binder content (P_{be}). The VMA and P_{be} are then used to calculate the voids filled with asphalt (VFA) and the fines to asphalt ratio (F/A) (West et al. 2008). The following are the equations used in calculation of these parameters:

$$\mathrm{VTM} = 100\left(1 - \frac{G_{mb}}{G_{mm}}\right) \qquad (6)$$

$$\mathrm{VMA} = \left(100 - \frac{G_{mb}(1 - P_b)}{G_{sb}} \times 100\right) \qquad (7)$$

$$\mathrm{VFA} = 100\left(\frac{\mathrm{VMA} - \mathrm{VTM}}{\mathrm{VMA}}\right) \qquad (8)$$

$$P_s = 100 - P_b \qquad (9)$$

$$P_{ba} = 100\left(\frac{G_{se} - G_{sb}}{G_{se} \times G_{sb}}\right) \times G_b \qquad (10)$$

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \qquad (11)$$

$$P_{be} = P_b - \frac{P_{ba}}{100} \times P_s \qquad (12)$$

$$\frac{F}{A} = \frac{P_{200}}{P_b} \qquad \{\text{For Marshall Mixes}\} \qquad (13)$$

$$\frac{F}{A} = \frac{P_{200}}{P_{be}} \qquad \{\text{For Superpave Mixes}\} \qquad (14)$$

where:

VTM = Voids in total mix (%)

VMA = Voids in the mineral aggregate (%)

VFA = Voids filled with asphalt (%)

G_{sb} = Bulk specific gravity of aggregate

G_{mb} = Bulk specific gravity of compacted mixture

F/A = Fines to asphalt ratio

P_{200} = Percentage of aggregate passing the #200 (0.075 mm) sieve

P_b = Percent binder

P_{be} = Effective percent binder

P_{ba} = Percent binder absorbed

P_s = Aggregate content, percent by total mass of mixture

G_{se} = Effective specific gravity of aggregate

In HMA mix designs VMA, VFA and F/A are the parameters used as specification criteria to ensure that the mixture has volumetric properties required for the desired performance of the mix. Therefore an error in determining the specific gravity of aggregate will result in an error in the mix design volumetric calculations. During mix design, errors in G_{sb} can result in mixes that are either too lean or too rich in asphalt cement. Lean mixes are prone to rapid weathering, raveling and premature fatigue failure. Rich mixes are prone to rutting, shoving and corrugations. During production of asphalt concrete, errors in G_{sb} can lead to rejecting acceptable mixes or accepting improper mixes.

2.4 CURRENT METHODS AND RELATED PROBLEMS

The current standard methods used to find the specific gravity and absorption values of aggregates are the AASHTO T84 and ASTM C128 for fine aggregate samples and AASHTO T85 and ASTM C127 for coarse aggregate samples.

2.4.1 AASHTO T 84

AASHTO T 84 and ASTM C 128 are used to determine the specific gravity and absorption values of fine aggregates, material passing the No. 4 (4.75 mm) sieve. These test methods are similar; the AASHTO T 84 method is reviewed since it is used by the WVDOH. Before performing the test the pycnometer is calibrated by measuring the mass of the pycnometer filled with water at the specified temperature.

The sample is thoroughly mixed and reduced to sample size in accordance with AASHTO T 248. The sample size for this test should be approximately 1 kg. The test samples are dried to a constant weight in an oven at 230 $\pm$ 9ºF (110 $\pm$ 5ºC) and then cooled to room temperature, approximately 1 to 3 hours. The sample is then soaked in water for the required time based on the test method, 15 to 19 hours for AASHTO T 84. In order to decrease the time to achieve the SSD state AASHTO allows the sand to be soaked in at least 6% moisture content for the prescribed period. The saturated sample is then spread on a flat, nonabsorbent surface and stirred occasionally to assist in homogeneous drying. A current of warm air may be used to assist drying procedures but care should be taken to avoid loss of fine particles.

2.4.1.1Standard Cone Method

The cone method is used to determine the SSD condition of the sand. The cone is placed on a smooth surface with larger diameter facing down. The cone is filled until its overflowing and tamped with 25 light drops of tamper, each drop starting at 0.2 inch above the top of the sample. The mold is carefully lifted vertically. The process is repeated until the aggregate slumps. 500 $\pm$ 10 grams of the SSD aggregate is weighed and used as the sample for determining the G_{sb}.

The SSD sand is introduced into the pycnometer filled with some water. The pycnometer is then filled with water to 90% of pycnometer capacity. Manually roll and agitate the pycnometer to eliminate all entrapped air. The pycnometer is brought to its calibrated capacity by adding water up to the calibrated level. A few drops of isopropyl alcohol may be added to disperse the foam. The total mass of the sample plus water plus pycnometer is recorded to the nearest 0.1 grams. The sample is then dried in an oven regulated at 230 $\pm$ 9ºF (110 $\pm$ 5ºC) and the dry mass is determined. The mass and volume information are used to calculate the specific gravity and absorption.

The cone method is based on the assumption that moist fine aggregate do not slump due to the presence of moisture while performing the test. However, Sholar et al. (2005) has shown the moisture content at slump does not depend just on the moisture content but also on angularity and texture. The percentage of material passing the No. 200 sieve also influences the slump of fine aggregates is (Lee et al. 1990). This shows that the standard method does not work well with aggregates having high angularity, texture and dust content. Hence the use of standard method in these cases leads to an inaccurate determination of the SSD state of aggregates which in turn leads to inaccurate determination of the specific gravity and absorption values.

The test method cannot be completed in a work-day due to the soaking time for the aggregates. Hence, the method is inefficient for quality control purposes.

Due to issues with determining the SSD moisture state of the aggregates, alternative methods have been developed. Three alternative (provisional) methods are included in AASHTO T 84. The methods are described below.

2.4.1.2 Provisional Cone Test

The difference between the provisional cone and the AASHTO T 84 tests is the tamping method. In the provisional cone test the cone mold is filled and only 10 drops of the tamper are made. The mold is again filled with fine aggregate and 10 drops of tamper are again made. Material is added two more times using three and two drops of tamper respectively. Following the tamping process the mold is removed and the slump observed.

2.4.1.3 Provisional Surface Test (AASHTO T 84)

In this method approximately 100 grams of the material being tested is patted down with hand on a flat, dry, clean, dark, or dull, nonabsorbent surface such as a sheet of rubber, a worn oxidized, galvanized, or steel surface, or a black-painted metal surface. The fine aggregate is removed after one to three seconds. If noticeable moisture is visible on the test surface for more than one to two seconds, then the surface moisture is considered to be present. The aggregates are further dried until no considerable amount of moisture is visible.

2.4.1.4 Hard Paper Method

In this method hard-finished paper towels are used to surface dry the fine aggregate samples. The sample is in the SSD state when the paper towel does not pick up moisture from the sample.

2.4.1.5 Informational Note

The appendix of AASHTO T84 contains an informational note that minus No. 200 can affect the results of the specific gravity test. The difference in specific gravity between washed and unwashed samples is less than 0.03 when the amount of minus No. 200 material is less than four percent and may be as great as 0.13 when the amount of minus No. 200 material is greater than eight percent. There is no recommendation in the method about how this information should be implemented. Section 7 P**reparation of Test Specimen** is silent on the issue of washing the sample, implying the sample should not be washed.

2.4.2 AASHTO T 85

The determination of coarse aggregate G_{sb} starts with mixing the sample thoroughly and reducing it to the required size in accordance with AASHTO T 248. It is then dry sieved through a No. 4 (4.75 mm) sieve and any material passing the sieve is discarded. The retained sample is washed over the No. 4 sieve and dried to constant weight in an oven regulated at 230±9ºF (110±5ºC). The sample is then cooled to room temperature for about 1 to 3 hours and then soaked in water for the 15 to 19 hours. The method requires the samples to be submerged for the soaking period. After the soaking period the entire sample is placed on a large absorbent cloth and rolled until all visible water is removed as indicated by the aggregate having a dull appearance. The larger particles may be wiped individually. A moving stream of air can be used to assist in the drying process. The mass of the sample in the saturated surface-dry condition is measured to the nearest 1.0 gram or 0.1 percent of the sample mass. The sample is immediately placed in a container and its mass in water at 23.0 ± 1.7ºC (73.4 ± 3 ºF) is determined to the nearest 0.1 gram or 0.1 percent of sample mass. The sample is then dried to constant weight in an oven regulated at 230 ± 9ºF (110 ± 5ºC) and then cooled to room temperature for about 1 to 3 hours. After the sample reaches comfortable handling temperature the oven dry weight is recorded to the nearest 1.0 g or 0.1% of total weight, whichever is greater. The three mass measurements are used to determine the specific gravity and absorption values of the sample.

Even though the methods for testing the sample are relatively simple to conduct, they have some key shortcomings in terms of subjectivity of measurements, precision and time requirements for the test procedure as follows (West et al. 2007) :

The technique used to determine the SSD state of coarse aggregates is based on observation and is subjective which can lead to inconsistency between different operators. Some operators may do it based on the water film shine whereas others might judge it based on the color change in the aggregates. Hence the determination of the SSD state is highly operator dependent and the mass of SSD sample and the calculated specific gravity and absorption values are less repeatable and reproducible.

Since the standard AASHTO T 85 test method requires more than an entire working day to be performed it makes this method to be inefficient for quality control purposes where the results are required as rapidly as possible.

2.5 ALTERNATE TEST METHODS

Several new modifications and test methods are available to determine the specific gravity and absorption of fine and coarse aggregates. These include simple changes in determining the SSD state of aggregates or an entirely new method of measuring the specific gravity using other commercially available equipment in the market. Some of the modifications are discussed briefly in the following discussion.

2.5.1 Modifications to Available Test Methods

Kruger et al. (1992) proposed alternate methods for establishing the SSD condition of fine aggregates. The methods that were discussed are (1) comparing the color of test sample with that of the oven dry sample, (2) determining the free flow state of the test sample using a tilted pan, (3) determining of flow of individual aggregate particle using a tilted masonry trowel, and (4) determining the surface dry state of fine aggregate using a water-soluble-glue tape. These methods are currently being used by the Texas Department of Transportation (DOT) test procedure Tex-201-F, Test Procedure for Bulk Specific Gravity and Water Absorption of Aggregate.

A calorimetric procedure was proposed by Kandhal and Lee (1970), which determines the SSD condition of the fine aggregate particles based on the color of aggregate which is dyed with a special chemical. This method of determining the SSD state of aggregates is an optional method in ASTM C 128. The drawback in this method is that the dye does not show well on dark aggregates and hence the determination of color change becomes subjective.

Other research efforts in finding a method for identifying the SSD state of fine aggregates include Howard’s glass jar method, Hughes and Bahramian’s saturated air drying method, Saxer’s absorption time curve procedure, and Martin’s wet and dry bulb temperature method. Even though all these methods were intended to improve the accuracy in determining the SSD state of fine aggregates, these methods were either impractical for implementation or offered little improvement (Kandhal et al. 1999).

The two new test methods available for finding the specific gravity and absorption of aggregate are the SSDetect and the AggPlus system using the CoreLok. The SSDetect system is used only for the fine aggregate testing. It measures the SSD condition of the aggregate using an infrared light tuned to water. This infrared signal looks for traces of water on the surface of the aggregate. The SSD condition can be measured accurately by measuring the amount of infrared reflectance. The AggPlus system using the CoreLok on the other hand uses a controlled vacuum system to seal the samples.

2.5.2 SSDetect System

The SSDetect system consists of two parts: automatic volumetric mixer (AVM) and infrared units as shown in Figure 2.1. The entrapped air in the sample and water mixture is removed by using the AVM unit and the SSD state of the sample is detected by the infrared unit. A detailed test procedure is described in ASTM D 7172, Standard Test Method for Determining the Relative Density (Specific Gravity) and Absorption of Fine Aggregates Using Infrared. The SSDetect system is essentially a two-step process and a brief description of the test method is as follows:

The first step includes pouring a dry sample of 500 ± 0.1 grams into a calibrated 500 ml flask and covering it with approximately 250 ml of water. Immediately after all the sample is poured into the flask and covered with water a timer is started. After five minutes, the flask is filled up to the calibration mark and weighed. It is then agitated and vacuumed for approximately 11 minutes using the AVM unit. After the AVM unit is stopped the flask is re-filled up to the calibration mark and weighed. The film coefficient is determined using the masses of flask before and after the agitation and vacuum process. This film coefficient is used as a calibration factor for the infrared reflectance measurements to determine the SSD condition of the aggregate in the next step. This whole process takes approximately 30 minutes.

In the second step, a dry sample of 500 ± 0.1 grams is placed in the mixing bowl provided with the infrared unit. The film coefficient determined in the first step is keyed in the infrared unit. The infrared unit monitors the moisture content using the infrared light source and detector while water is injected and mixed with the sample. Water begins to gather on the surface of aggregate and absorb the infrared signal, once the permeable pores are filled. The infrared detection device will therefore no longer see the reflection of the infrared signal. The SSD condition is then recognized and the infrared unit is automatically stopped. The mass of sample in SSD state is then determined. Based on the masses of the dry sample, SSD sample, and flask filled with water, the specific gravity and water absorption values can be determined.

Figure 1: Automatic Volumetric Mixer and Infrared Units (Barnstead/Thermolyne)

Several studies have been conducted to evaluate the repeatability and reproducibility of the SSDetect system and the results were compared to those of the standard AASHTO T 84. Prowell and Baker (2005) conducted a round robin study with 12 laboratories using four crushed and two natural fine aggregate sources. The G_{sb} results using the two methods were reported to be statistically different for three aggregates, including washed diabase, rounded natural sand, and angular natural sand. Both the SSDetect system and the AggPlus system yielded lower absorption and higher G_{sb} values for washed diabase and diabase with more than 7.5 percent of dust. SSDetect measured higher absorption and lower G_{sb} values for limestone, slag, rounded natural sand and angular natural sand that had lower dust contents when compared to AASHTO T 84. The precision of the SSDetect method was better than that of AASHTO T 84 and the AggPlus system.

Cross et al. (2006) found significant differences between the G_{sb} and absorption results determined by the SSDetect and AASHTO T 84 methods. The SSDetect method produced the highest G_{sb} results and the lowest absorption values which were followed by the AggPlus system and AASHTO T 84 methods. There was no significant difference in the G_{sa} values found using the three methods. The SSDetect system has better reproducibility than the other two methods.

Bennert et al. (2005) evaluated the SSDetect system using 11 fine aggregates, which include six natural and five manufactured sands. These materials are common sources for HMA and concrete mixtures in New Jersey. The SSDetect system produces slightly higher absorption and lower G_{sb} and G_{sa} results than the AASHTO T 84 method. But the differences are less than those between the AggPlus and AASHTO T 84 methods. As evaluated in the study the SSDetect system has the best repeatability among the tested methods, SSDetect, AggPlus system and SSDrier.

You et al. (2008) evaluated the SSDetect system using 17 fine aggregate gradations made from natural sand, crushed sand, and steel slag. The SSDetect system had better precision than AASHTO T 84. The Gsb results from the SSDetect and AASHTO T 84 methods were not significantly different, but the Gsa values determined using these methods are statistically different (You et al. 2008).

2.5.3 AggPlus System using CoreLok Device

InstroTek, Inc. developed a method using a combination of a calibrated pycnometer and the CoreLok vacuum-sealing device. ASTM D7370 provides the standardized method for using the CoreLok. Figure 2 shows the devices used to find the specific gravity and absorption values. This set up can be used to find the specific gravity and absorption values of fine, coarse and combined aggregate samples.

The test procedure includes two separate methods, one for testing the fine aggregate samples and the other one for the coarse and combined aggregate samples. Both the methods are almost similar except for the sample sizes and pycnometer sizes used. To test the fine aggregates two samples of 500 ± 3 grams for testing in the pycnometer and one sample of 1000 ± 5 grams for vacuum saturation test are required. To test coarse or combined aggregate samples, two samples of 1000 ± 5 grams for testing in the pycnometer and one sample of 2000 ± 10 grams for the vacuum saturation test are required. The process for performing the test is well documented in the Instrotek manual (Instrotek® Inc.-CoreLok), so they are not provided in this thesis.

The CoreLok method determines the percent absorption, apparent density, bulk specific gravity (SSD), and bulk specific gravity (dry weight basis). Software is provided by the manufacture to perform the required calculations.

The CoreLok method for determining aggregate bulk specific gravity is unique in that the sample is never brought to a saturated surface dry state. The bulk specific gravity of the sample in the dry state is determined from the dry weight in air and the weight of the sample submerged in water in an unsaturated state. The test for the bulk specific gravity must be completed within two minutes to minimize water absorption into the voids in the aggregate.

Several researchers have evaluated the AggPlus system using the CoreLok device. Hall (2004) conducted a study to find the G_{sa}, G_{sb}, and absorption of coarse, fine, and combined aggregates using the current standard AASHTO methods (AASHTO T 84 and AASHTO T 85) and the AggPlus system. The materials tested included six coarse aggregate sources whose absorption varied from 0.3 to 2.1 percent, five fine aggregate sources with minus No. 200 material ranging from 0.1 to 25.6 percent, and ten combined aggregates. One operator conducted testing of all five replicates for each aggregate using the three test methods. The AggPlus system tended to produce higher G_{sb} results and lower absorption results for the coarse aggregates tested. Additionally, G_{sb} results for some fine aggregates determined using the AASHTO T 84 and AggPlus procedures were significantly different at 95% confidence level.

Figure 2: CoreLok Device

AASHTO T 84 and T 85 cannot measure the specific gravity of blended coarse and fine aggregates. However the results from the two tests can be mathematically combined if the proportion of the aggregate in the blend is known. Hall (2004) did the mathematical blending to compare to the AggPlus results for the blended aggregates. The AggPlus values and the mathematically combined values were not the same, but the relationships were consistent. Test results using the AggPlus system were not sensitive to nominal maximum aggregate size, gradation, or mineralogy. Hall (2004) concluded there was a need to improve the test consistency and compatibility of the AggPlus results in order to use the AggPlus in place of the existing methods.

Sholar et al. (2005) compared AggPlus to the standard AASHTO methods. The evaluation included 11 coarse aggregate sources with absorption ranging from 0.5 to 3.8 percent and seven fine aggregate sources. One operator tested two replicates for individual aggregates using the three test methods. The AggPlus system produced higher G_{sb}, and the difference was higher with high absorptive aggregates, for the coarse aggregate materials. The absorption values produced from the AggPlus system were lower than those produced by the standard method, and the difference was even higher in case of high absorptive aggregates. The G_{sb} values were not significantly influenced by the aggregate gradation. The AggPlus system had a better repeatability than the standard test method with respect to the bulk specific gravity.

For fine aggregates, both the AggPlus and AASHTO methods had similar G_{sb} values for three low absorptive granite aggregates but different G_{sb} values for four high absorptive limestone aggregates. The AggPlus system produced slightly higher G_{sb} values for granite aggregates and lower G_{sb} values for limestone aggregates. The repeatability of the AggPlus system was better than AASHTO T 84 method for $G_{sb.}$ The difference in G_{sb} would result a change of 5.5 percent for VMA, which would make it impractical to use in the existing HMA specifications. The authors did not recommend the use of AggPlus system as a test procedure for determining the G_{sb} and absorption of aggregates.

Mgonella and Cross (2005) compared the AggPlus system to the standard AASHTO methods. The testing plan included eight crushed coarse aggregates with absorption ranging from 0.6 to 3.5 percent and 14 fine aggregates of various types. The tests were conducted by two operators to determine the interaction between the test methods and the operators. The authors reported coarse aggregates G_{sb} values determined by the AggPlus system were statistically different from the AASHTO T 85 method. The AggPlus system tended to produce higher G_{sb} and lower absorption values. No interactions were found between G_{sb} values and operators. The reproducibility for the two tests was similar. The authors did not recommend the AggPlus procedure as a replacement for the current AASHTO T 85 method. In case of fine aggregates, the study found no significant difference in the G_{sa} values. But the G_{sb} values found using the AggPlus system and the AASHTO T 84 methods were statistically different. The AggPlus system tended to produce higher G_{sb} values. The AggPlus system had a better repeatability than AASHTO T 84.

Prowell and Baker (2005) in which the AggPlus system and the AASHTO T 84 method were evaluated in a round-robin study conducted with 12 laboratories, using six fine aggregate materials, which included four crushed and two natural sources. The G_{sb} values from the two test methods were statistically different for three of the six aggregates, including limestone, washed diabase, and blast furnace slag. The AggPlus system produced higher G_{sb} and lower absorption values for two materials which had dust contents of 7.5 percent and above. The precision indices of the AggPlus system were not as good as those of the AASHTO T 84. The authors suggested that precision would improve as technicians became more familiar with the AggPlus system. Table 1 gives an overview of the G_{sb} and absorption results from the AggPlus system when compared to AASHTO T 84 and T 85 for each researcher.

Table 1: AggPlus results compared to AASHTO T 84 and AASHTO T 85

	G_{sb}*	**Absorption**
Hall (2004)		
Coarse Aggregate	Higher	Lower
Fine Aggregate	Higher	Lower
Combined Aggregate	Higher	Lower
Sholar et al (2005)		
Coarse Aggregate	Higher	Lower
Fine Aggregate		
- Granite	Slightly higher	Lower
- Limestone	Lower	Lower
Mgonella and Cross (2005)		
Coarse Aggregate	Higher	Lower
Fine Aggregate	Higher	Lower
Prowell and Baker (2005)		
Fine Aggregate	Higher	Lower

* Higher indicates AggPlus results higher than AASHTO

2.5.4 Arizona DOT Method (ARIZ 211d)

The procedure followed by Arizona DOT is similar to that of AASHTO T 84 method with just a small difference. Here the weight of representative sample is 1200 grams when compared to 1000 g in AASHTO T 84.

2.5.5 Wisconsin Method (Modified AASHTO T 84)

The Wisconsin method of finding the specific gravity and absorption of fine aggregates is a modification of the AASHTO T 84 method. The only difference between the Wisconsin and the AASHTO T 84 method is that the material tested in the Wisconsin method does not include the material passing the No. 200 sieve.

2.5.6 Iowa Method (Matls. IM 380)

The Iowa method of finding the fine aggregate specific gravity and absorption values requires the sample to be covered with water and placed under 30 mm mercury vacuum for 30 minutes and then allowed to stand for another 20 minutes. The sample is then rinsed over the No. 200 sieve. The sample is said to have achieved the SSD state when the fine aggregate grains do not adhere to the steel spatula.

2.5.7 Texas DOT Method

According to the Texas DOT a fine aggregate sample is said to achieve SSD condition when two of the following four criteria are met by the sample:

1. Some oven dry sample is placed on a dry pan with a smooth bottom. Then the pan is tilted at a 45 degree angle to the table and the flow pattern of the sample is observed. Finally the test sample is placed on another dry pan and the pattern is observed. The sample is said to be surface dry if it flows in the same manner as that of the oven dry sample.
2. Some amount of oven dry sample is scooped into a trowel or similar equipment and tilted to one side. The flow of aggregate particles is observed. A similar amount of test sample is scooped and tilted in the same manner. If the test sample flows down same as the dry sample then it is surface dry.
3. Approximately 10 cm^2 of paper tape is attached to a small block of wood with the adhesive side outside. Level the sample surface and place the taped face of the wooden block on the sample for 5 seconds. If the adhesive side feels sticky due to humidity rub it rapidly against a dry cloth. The wooden block and tape are gently lifted upward by taking proper care not to slide the taped face on the sample surface. The sample is said to be surface dry when no more than one particle adheres to the tape on two consecutive checks.

4. The oven dry sample is scooped and placed over the test sample. The color change is observed periodically and the point at which the test sample appears to have the same color as of the dry sample it is said to be surface dry.

2.5.8 California Method

The California test 225 method to find the specific gravity and absorption of fine aggregates has a different method of finding the SSD state of the samples being tested. A portion of the test sample is taken and placed in a dry jar. The sample is said to have achieved the SSD condition when it fails to adhere to the dry surface of the glass jar.

Chapter 3 RESEARCH METHODOLOGY

3.1 INTRODUCTION

The objective of this research study was to determine a test method which would produce statistically similar specific gravity results when compared to the standard AASHTO methods. Also, some test methods were selected so as to compare the repeatability of the test results. The research approach was as follows:

- Develop an experimental plan for the research.
- Selecting the aggregates that need to be tested and collection of aggregates.
- Selection of test methods for evaluating the specific gravity of aggregates being tested.
- Randomly divide the aggregates into samples.
- Performing the test methods using a randomized experimental plan
- Performing the required statistical analysis to compare the test results.
- Reporting the results.

3.2 SAMPLE PREPARATION

After the aggregate samples were brought to the laboratory, they were stored in a dry place and were then reduced to testing sizes in accordance with AASHTO T-248. Two fine aggregate types and one coarse aggregate type were tested. The coarse aggregate material contained four different size aggregates.

For the coarse aggregate material, five samples were split from the aggregate stock (AASHTO T-11 and T-27) for each of the test method being performed i.e. AASHTO T 85 and the AggPlus. The samples were screened over the 4.75 mm (No. 4) sieve for the No. 8 material and the 2.36 mm (No. 8) sieve for the No. 9 material per the option allowed in the T 85 method. The samples were then tested as per the procedures in the test method being used.

The fine aggregate material was divided into thirty samples. Three of the samples were prepared with a mass of 2500 grams for testing with the CoreLok; three were prepared with a mass of 1200 grams to test with the Arizona method; the remaining samples were prepared with a mass of 1000 grams. The samples were randomly selected for each of the 10 test methods. For the CoreLok and Arizona methods samples were randomly selected from the specimens prepared for those tests. The Texas DOT method required the samples to be screened over No. 8 sieve and the retained material is discarded. For the Wisconsin method the sample was washed to remove material passing the No. 200 sieve.

The types of materials and tests are summarized in Table 2.

Table 2: Sample Distribution

Type of Aggregate	Number of Samples Tested	Number of Test Methods	Different Aggregate Sizes
Fine Aggregate (Limestone)	3	10	1
Fine Aggregate (Slag)	3	10	1
Coarse Aggregate (Limestone)	5	2	4

The test methods selected for evaluation were:

Fine Aggregates
AASHTO T 84
Provisional Cone Test
Provisional Surface Test
Hard Paper Method
Arizona DOT Method
Wisconsin Method
AggPlus System using CoreLok device
Iowa Method
Texas DOT Method
California Test 225

Coarse Aggregates
AASHTO T 85
AggPlus System using the CoreLok device

3.3 Statistical method

In this report boxplot presentation is used to visually describe the uncertainty in specific gravity measurements within and among different methods. In descriptive statistics, a boxplot as shown in Figure 3 is a convenient way of graphically depicting groups of numerical data through their five-number summaries: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (sample maximum). A boxplot may also indicate which observations, if any, might be considered outliers. The quartiles of a set of values are the three points that divide the data set into four equal groups, each representing a fourth of the population being sampled.

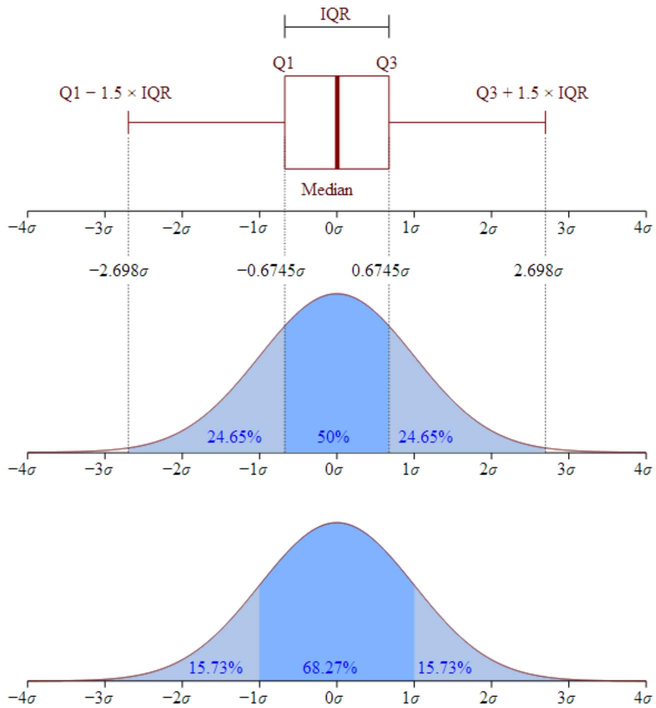

Figure 3: Boxplot presentation

Boxplots display differences between populations without making any assumptions of the underlying statistical distribution. The spacing between the different parts of the box helps to indicate the degree of dispersion (spread) and skewness in the data, and identify outliers.

In this study different types of material have been used to measure the specific gravity using different methods. The equality of means is tested using ANOVA method to see if there are any significant differences among the methods. In case P-value is smaller than 0.05, that means there is at least one method which returns different results and the difference is statistically significant. However, the ANOVA method is not able to identify the difference of any individual method. In case the ANOVA is significant, then it becomes necessary to find about the method(s) which returns different results and how large the difference is. If the ANOVA is not significant than there is no statistical difference between the results from different methods.

Multiple comparison procedures (MCP) can be used to compare and pair of the methods. MCP is indeed multiple t-tests among the group means to find any of the two groups with different means. The only difference is when testing a single hypothesis, a type I error is made if a hypothesis is rejected although the hypothesis is actually true. The probability of making such an error is often controlled to be smaller than a certain level α. If several hypotheses are tested, a type I error can be made for each hypothesis. The probability of making at least one type I error then increases, often sharply, with the number of hypotheses. That is, there is bigger chance to reject a true hypothesis erroneously. Therefore, the P-value needs to be adjusted.

A family of tests is the technical term for a series of tests performed on a single set of data. In this section it is demonstrated how to compute the probability of rejecting the null hypothesis at least once in a family of tests when the null hypothesis is true. For a family of C tests, the probability of not making a Type I error for the whole family is:

$$(1-\alpha)^{c} \tag{15}$$

Looking for is the probability of making one or more Type I errors on the family of tests, this event is the complement of the event not making a Type I error on the family and therefore it is equal to:

$$1-(1-\alpha)^{c} \tag{16}$$

The Bonferroni corrected *p*-value for *C* comparisons, denoted $p_{\text{Bonferroni}}$;*C* becomes

$$P_{\text{Bonferroni}}, C = C \times p \tag{17}$$

Holm's procedure is a sequential approach whose goal is to increase the power of the statistical tests while keeping under control the familywise Type I error. Suppose that the purpose was to evaluate a family comprising *C* tests. The first step in Holm's procedure is to perform the tests in order to obtain their *p*-values, then order the tests from the one with the smallest *p*-value to the one with the largest p-value. The test with the smallest probability will be tested with a Bonferroni correction for a family of *C* tests (Holm used a Bonferroni correction). If the test is not significant, then the procedure stops. If the first test is significant, the test with the second smallest p-value is then corrected with a Bonferroni for a family of *(C-1)* tests. The procedure stops when the first non-significant test is obtained or when all the tests have been performed. Formally, assume that the tests are ordered (according to their *p*-values) from 1 to *C*, and that the procedure stops at the first non-significant test. Using the Bonferroni correction with Holm's approach, the corrected p-value for the i_{th}-test, denoted $p_{\text{Bonferroni}}$, i|C is computed as:

$$P_{\text{Bonferroni}}, i|C = (C-i+1) \times p \tag{18}$$

Chapter 4 RESULTS AND ANALYSIS

4.1 INTRODUCTION

There were three coarse aggregate sizes tested from a single source and two different sources of fine aggregates. The results obtained were used to draw the boxplot diagrams in order to observe the trend followed by the specific gravity and absorption values obtained using the different methods. The values were then used to perform analysis of variance (ANOVA) test to find any difference between the sample means by test methods. In the next step, a statistical multiple comparison procedure using student's *t*-test with an adjusted *p*-value was used to compare pairwise sample means.

The test results for the data of fine aggregate specific gravity and absorptions for the Limestone aggregate type are presented in Appendix 1. These results were analyzed for the ten methods using statistical analysis to compare the difference between values. The results for the fine aggregate specific gravity and absorption for the slag aggregate type and those of the coarse aggregate specific gravities and absorption are presented Appendix 1. Summary tables of the data are presented in Appendix 2.

4.2 LIMESTONE FINE AGGREGATES

Boxplot diagrams for the limestone fine aggregate are shown in Figure 4, Figure 5, and Figure 6 for the bulk specific gravity, apparent specific gravity, and the absorption, respectively. Useful information to prepare the boxplots is presented in Table 3. Figure 4 indicates the California method produced the lowest and CoreLok method produced the highest bulk specific gravity results compared to the other methods. Apparently the other tests can be divided into two groups. The first group including the AASHTO T84, AASHTO Provisional Cone Test, Hard Paper and Arizona methods produced results that appear to be similar. The second group consists of AASHTO Provisional Surface Test, Wisconsin, Iowa and Texas method have their results in a close range but higher than the first group's mean. Differences between the test methods were anticipated as the different methods use alternative techniques for establishing the SSD condition for the aggregates. The apparent specific gravity, presented in Figure 5 shows little variability except for the Wisconsin method. This was expected as the apparent specific gravity is not dependent on the SSD state of the aggregates.

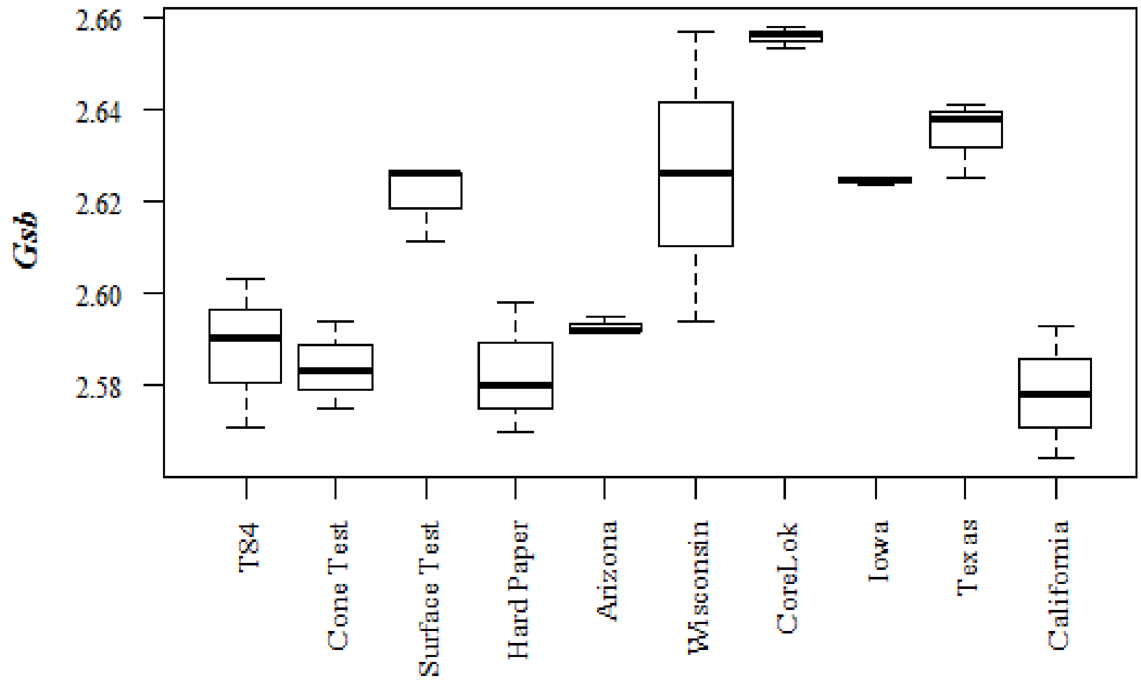

Figure 4: Comparison of Gsb values from different tests for limestone fine aggregates

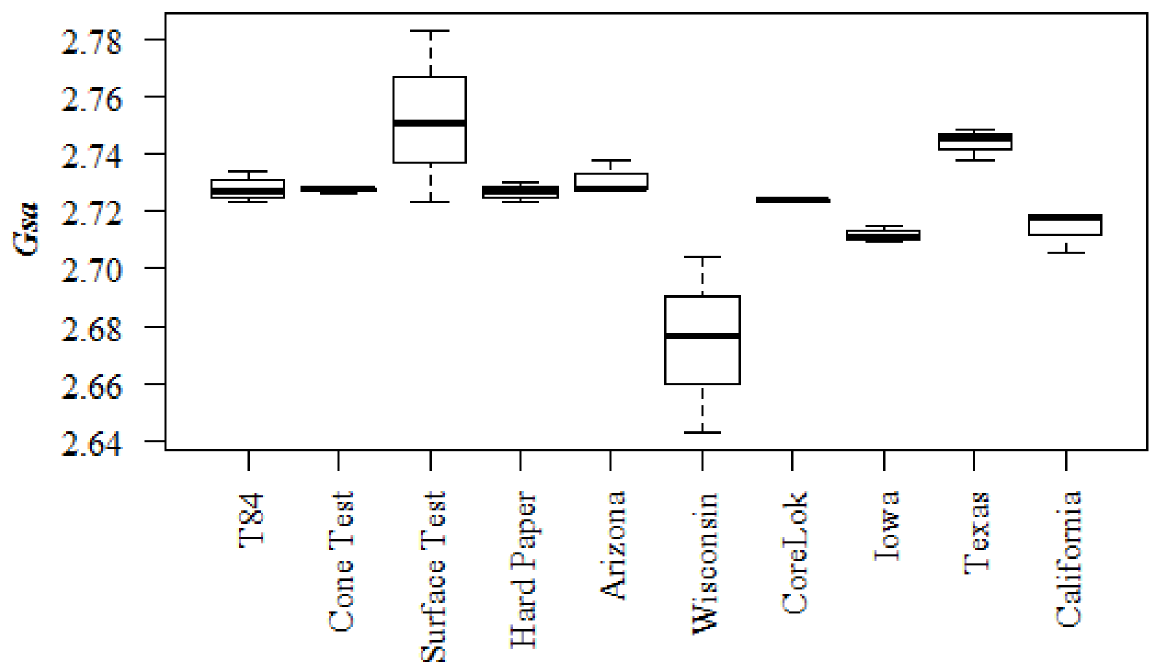

Figure 5: Comparison of Gsa values from different tests for limestone fine aggregates

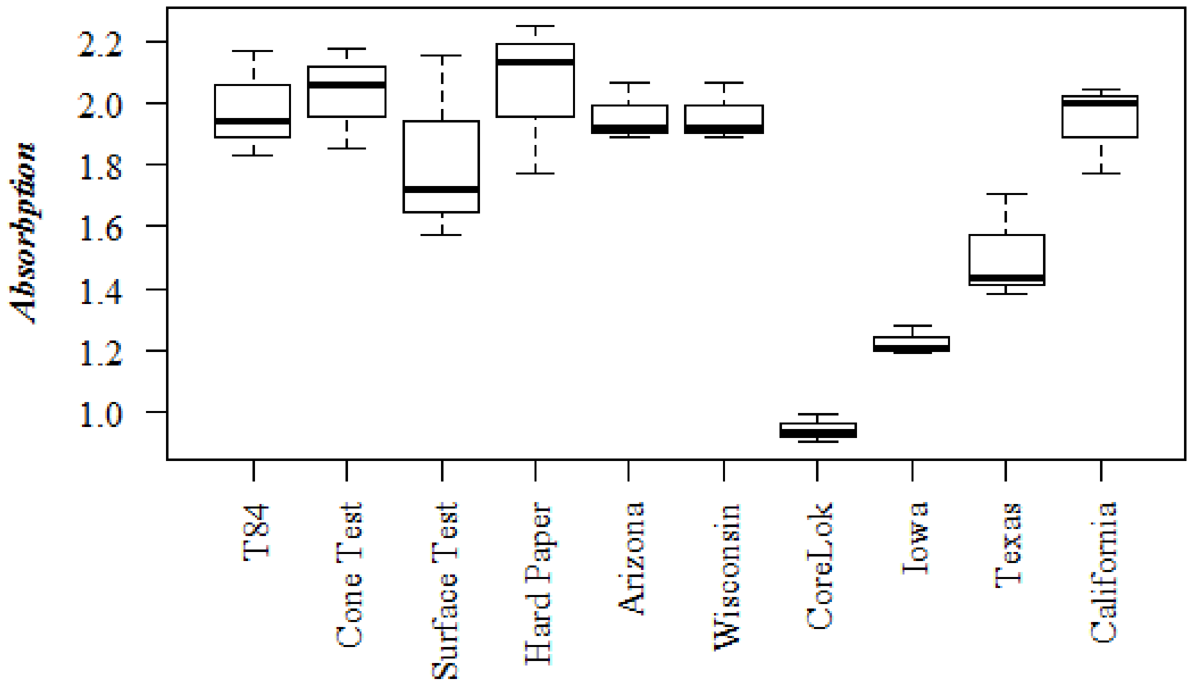

Figure 6: Comparison of percent absorption values from different tests for limestone fine aggregates

The analysis of variance (ANOVA) was performed to investigate any statistically significant difference among the test methods. In the ANOVA table when the *p*-value is less than 0.05 the null hypothesis of equal means is rejected, which means there is at least one method producing different results. When the *p*-value is greater than 0.05, there is insufficient evidences to reject the null hypothesis. Failure to reject the null hypothesis suggests that the methods produce similar results.

If the null hypothesis is rejected across all methods, than multiple student t-tests are needed to identify the differences between methods. As described in Chapter 3, a series of multiple pairwise student’s *t*-tests with adjusted *p*-values can be applied to find the method(s) which produce different results. *P*-values below 0.05 imply insufficient evidences to identify a difference between two test methods.

Table 3: Boxplots' information

		Gsa	Gsb	Absorption			Gsa	Gsb	Absorption
T84	Min. :	2.723	2.571	1.8	**Cone Test**	Min. :	2.726	2.575	1.9
	1st Qu.:	2.725	2.58	1.9		1st Qu.:	2.727	2.579	2.0
	Median :	2.727	2.59	1.9		Median :	2.728	2.583	2.0
	Mean :	2.728	2.588	2.0		Mean :	2.727	2.584	2.0
	3rd Qu.:	2.731	2.596	2.1		3rd Qu.:	2.728	2.588	2.1
	Max. :	2.734	2.603	2.2		Max. :	2.728	2.594	2.2
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
Surface Test	Min. :	2.723	2.611	1.6	**Hard Paper**	Min. :	2.723	2.57	1.8
	1st Qu.:	2.737	2.619	1.6		1st Qu.:	2.725	2.575	2.0
	Median :	2.751	2.626	1.7		Median :	2.727	2.58	2.1
	Mean :	2.752	2.621	1.8		Mean :	2.727	2.583	2.1
	3rd Qu.:	2.767	2.626	1.9		3rd Qu.:	2.728	2.589	2.2
	Max. :	2.783	2.626	2.2		Max. :	2.73	2.598	2.3
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
Arizona	Min. :	2.728	2.592	1.9	**Wisconsin**	Min. :	2.643	2.594	1.9
	1st Qu.:	2.728	2.592	1.9		1st Qu.:	2.66	2.61	2.0
	Median :	2.728	2.592	1.9		Median :	2.677	2.626	1.9
	Mean :	2.731	2.593	2.0		Mean :	2.675	2.626	2.0
	3rd Qu.:	2.733	2.594	2.0		3rd Qu.:	2.691	2.642	2.0
	Max. :	2.738	2.595	2.1		Max. :	2.704	2.657	2.1
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
CoreLok	Min. :	2.723	2.653	0.9	**Iowa**	Min. :	2.709	2.623	1.2
	1st Qu.:	2.724	2.655	0.9		1st Qu.:	2.71	2.624	1.2
	Median :	2.724	2.656	0.9		Median :	2.711	2.624	1.2
	Mean :	2.724	2.656	0.9		Mean :	2.712	2.624	1.2
	3rd Qu.:	2.724	2.657	1.0		3rd Qu.:	2.713	2.625	1.3
	Max. :	2.724	2.658	1.0		Max. :	2.715	2.625	1.3
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
Texas	Min. :	2.738	2.625	1.4	**California**	Min. :	2.706	2.564	1.8
	1st Qu.:	2.741	2.631	1.4		1st Qu.:	2.712	2.571	1.9
	Median :	2.745	2.638	1.4		Median :	2.718	2.578	2.0
	Mean :	2.744	2.635	1.5		Mean :	2.714	2.578	1.9
	3rd Qu.:	2.747	2.639	1.6		3rd Qu.:	2.719	2.586	2.0
	Max. :	2.748	2.641	1.7		Max. :	2.719	2.593	2.0

Bulk specific gravity

The *p*-value, Table 4, for the bulk specific gravity of limestone fine aggregates shows the null hypothesis of equal means across all test methods was rejected. Therefore multiple student *t*-test is performed to identify specific differences between test methods. The results are presented in Table 5. This analysis reveals that:

- AASHTO T84 results are strongly different from CoreLok and Texas method
- AASHTO provisional cone test results differs from CoreLok and Texas method
- Hard paper differs from Wisconsin, CoreLok and Texas method
- Arizona method strongly differs from CoreLok method
- Wisconsin method results are different from Hard paper and California Method
- CoreLok results differ from T84, provisional cone test, Hard paper, Arizona and California methods
- Iowa method produce different results with California methods
- Texas method differs from T84, provisional cone test, Hard paper and California metods
- California method differs from AASHTO provisional surface test, Wisconsin, CoreLok, Iowa and Texas methods

The Student *t*-test results verifies observations from Figure 4. The AASHTO T84 method produced results similar to AASHTO Provisional Cone Test, AASHTO Provisional Surface Test, Hard Paper, Arizona, Iowa, Wisconsin and California method.

Table 4: ANOVA results for fine aggregate G_{sb} (Limestone)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Result	9	0.01934	0.00215	11.24393	0.00000
Residuals	20	0.00382	0.00019		

Table 5: Pairwise student's t-test results for fine aggregate G_{sb} (Limestone)

P value adjustment method: holm

	T84	Cone Test	Surface Test	Hard Paper	Arizona	Wisconsin	CoreLok	Iowa	Texas
Cone Test	1.00								
Surface Test	0.19	0.10							
Hard Paper	1.00	1.00	0.08						
Arizona	1.00	1.00	0.40	1.00					
Wisconsin	0.09	0.05	1.00	0.04	0.20				
CoreLok	0.00	0.00	0.14	0.00	0.00	0.29			
Iowa	0.11	0.06	1.00	0.05	0.24	1.00	0.24		
Texas	0.02	0.01	1.00	0.01	0.05	1.00	1.00	1.00	
California	1.00	1.00	0.04	1.00	1.00	0.02	0.00	0.02	0.00

Apparent specific gravity

The ANOVA analysis in

Table 6 indicates that there are differences among the G_{sa} values. As shown in Table 7, applying the pairwise student's t-test method shows that the difference is produced by Wisconsin method. However, since the calculation of the apparent specific gravity does not include using the SSD weight, there should not be any difference between the values obtained for the apparent specific gravity when found using the different methods. By and large, this expectation was met except for the Wisconsin Method. The only difference between AASHTO T84 and the Wisconsin method is washing the aggregate to remove the material passing the No. 200 sieve. Therefore it appears that the dust is affecting the results.

Table 6: ANOVA results for fine aggregate G_{sa} (Limestone)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Result	9	0.01185	0.00132	6.58660	0.00023
Residuals	20	0.00400	0.00020		

Table 7: Pairwise student's t-test results for fine aggregate G_{sa} (Limestone)

	T84	Cone Test	Surface Test	Hard Paper	Arizona	Wisconsin	CoreLok	Iowa	Texas
Cone Test	1.00								
Surface Test	1.00	1.00							
Hard Paper	1.00	1.00	1.00						
Arizona	1.00	1.00	1.00	1.00					
Wisconsin	0.01	0.01	0.00	0.01	0.00				
CoreLok	1.00	1.00	0.70	1.00	1.00	0.02			
Iowa	1.00	1.00	0.08	1.00	1.00	0.15	1.00		
Texas	1.00	1.00	1.00	1.00	1.00	0.00	1.00	0.41	
California	1.00	1.00	0.13	1.00	1.00	0.10	1.00	1.00	0.64

Absorption

As can be seen in Figure 6, the Texas, Iowa and CoreLok methods all produced percent absorption values lower than the other six methods. In Table 8, the ANOVA indicates that there are differences among percent water absorption by methods. Table 9, presents the pairwise student's t-test results for the percent water absorption. The CoreLok and Iowa method produce results which are different.

Table 8: ANOVA results for fine aggregate water absorption (Limestone)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Result	9	4.13467	0.45941	14.81959	0.00000
Residuals	20	0.62000	0.03100		

Table 9: Pairwise student's t-test results for fine aggregate water absorption (Limestone)

	T84	Cone Test	Surface Test	Hard Paper	Arizona	Wisconsin	CoreLok	Iowa	Texas
Cone Test	1.00								
Surface Test	1.00	1.00							
Hard Paper	1.00	1.00	1.00						
Arizona	1.00	1.00	1.00	1.00					
Wisconsin	1.00	1.00	1.00	1.00	1.00				
CoreLok	0.00	0.00	0.00	0.00	0.00	0.00			
Iowa	0.00	0.00	0.01	0.00	0.00	0.00	1.00		
Texas	0.11	0.02	0.75	0.02	0.11	0.11	0.02	1.00	
California	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.17

4.3 SLAG FINE AGGREGATES

Boxplot diagrams for the slag fine aggregate are shown in Figure 7, 8, and 9 for the bulk specific gravity, apparent specific gravity, and the absorption, respectively. As can be seen in Figure 7 there is no obvious trend in G_{sb}. The AASHTO Provisional Surface Test, CoreLok, Wisconsin, and Texas methods produced values that are consistently higher than the other methods. The Hard Paper and Iowa methods also produced the lowest values. Figure 8 shows the apparent specific gravity results, compared to the G_{sb} values, variation is lower except for the Iowa, California and AASHTO provisional cone test. This was expected as the apparent specific gravity is not dependent on the SSD state of the aggregates. The absorption trend is almost opposite of bulk specific gravity trend; as would be expected.

The analysis of variance for the slag fine aggregate followed the same method as used for the limestone fine aggregate. Tables 10 through 16 present the statistical analysis to detect the differences between the different methods in specifying the fine aggregate specific gravity for slag.

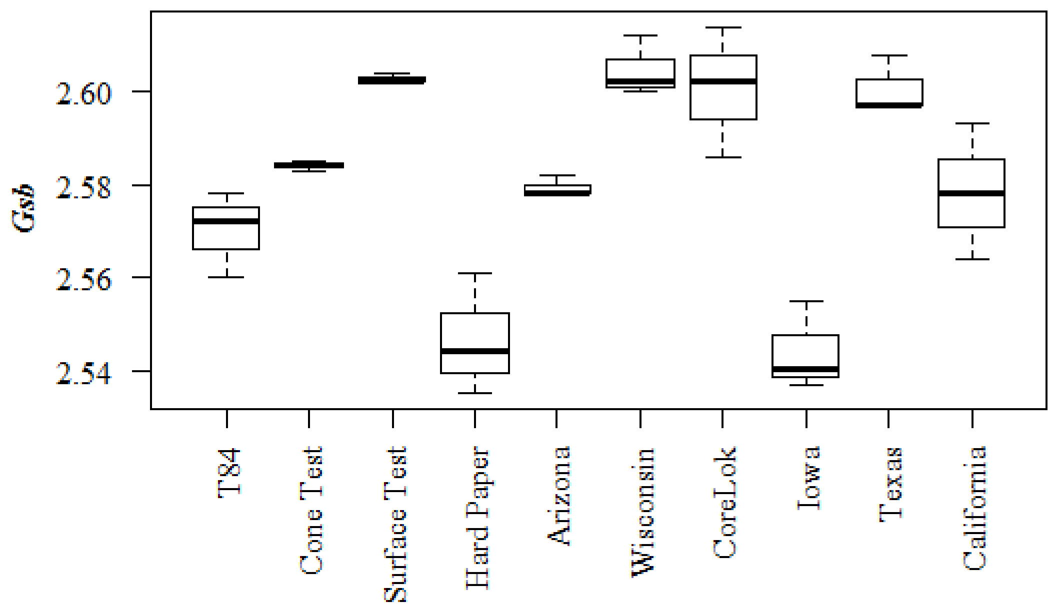

Figure 7: Comparison of Gsb values from different tests for Slag fine aggregates

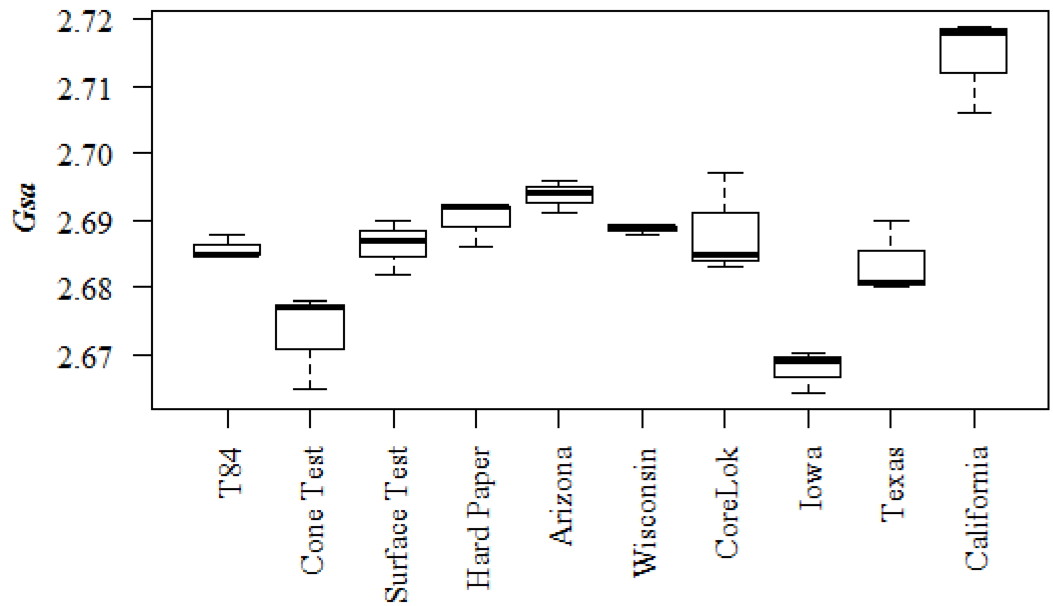

Figure 8: Comparison of Gsa values from different tests for Slag fine aggregates

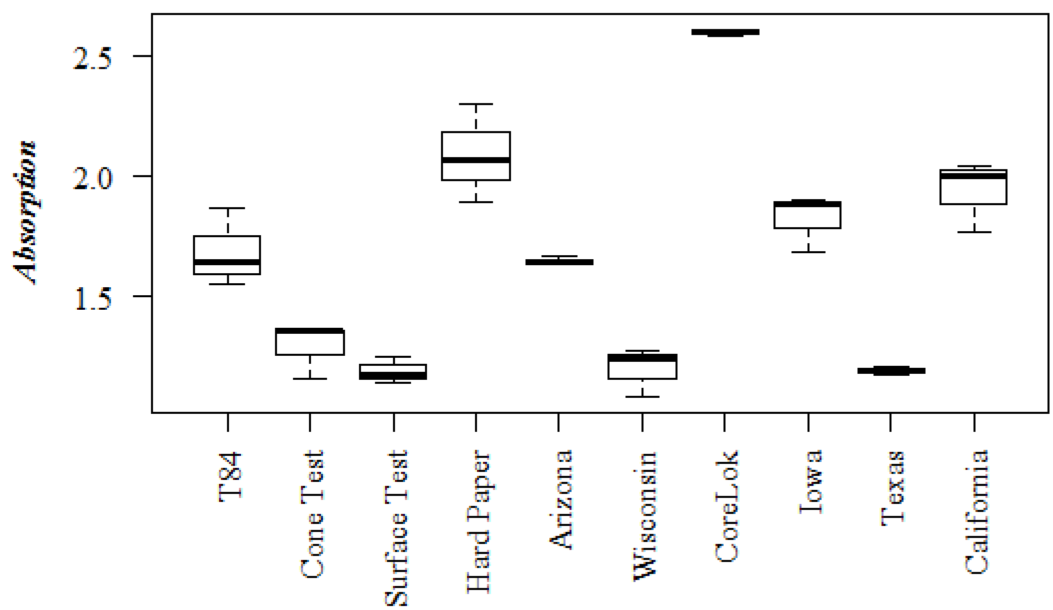

Figure 9: Comparison of absorption values from different tests for Slag fine aggregates

Table 10: Fine aggregate boxplots' information

		Gsa	Gsb	Absorption			Gsa	Gsb	Absorption
T84	Min. :	2.685	2.56	1.6	Cone Test	Min. :	2.665	2.583	1.164
	1st Qu.:	2.685	2.566	1.6		1st Qu.:	2.671	2.583	1.261
	Median :	2.685	2.572	1.6		Median :	2.677	2.584	1.358
	Mean :	2.686	2.57	1.7		Mean :	2.673	2.584	1.296
	3rd Qu.:	2.687	2.575	1.8		3rd Qu.:	2.678	2.584	1.361
	Max. :	2.688	2.578	1.8		Max. :	2.678	2.585	1.365
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
Surface Test	Min. :	2.682	2.602	1.1	Hard Paper	Min. :	2.686	2.535	1.9
	1st Qu.:	2.684	2.602	1.6		1st Qu.:	2.689	2.539	2.0
	Median :	2.687	2.602	1.2		Median :	2.692	2.544	2. 1
	Mean :	2.686	2.603	1.2		Mean :	2.69	2.547	2.1
	3rd Qu.:	2.688	2.603	1.2		3rd Qu.:	2.692	2.553	2.2
	Max. :	2.69	2.604	1.3		Max. :	2.692	2.561	2.3
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
Arizona	Min. :	2.691	2.578	1.6	Wisconsin	Min. :	2.688	2.6	1.1
	1st Qu.:	2.692	2.578	1.6		1st Qu.:	2.688	2.601	1.2
	Median :	2.694	2.578	1.6		Median :	2.689	2.602	1.2
	Mean :	2.694	2.579	1.7		Mean :	2.689	2.605	1.2
	3rd Qu.:	2.695	2.58	1.7		3rd Qu.:	2.689	2.607	1.3
	Max. :	2.696	2.582	1.7		Max. :	2.689	2.612	1.3
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
CoreLok	Min. :	2.683	2.586	2.6	Iowa	Min. :	2.664	2.537	1. 7
	1st Qu.:	2.684	2.594	2.6		1st Qu.:	2.667	2.539	1.8
	Median :	2.685	2.602	2.6		Median :	2.669	2.54	1.9
	Mean :	2.688	2.601	2.6		Mean :	2.668	2.544	1.8
	3rd Qu.:	2.691	2.608	2.6		3rd Qu.:	2.67	2.548	1.9
	Max. :	2.697	2.614	2.6		Max. :	2.67	2.555	1.9
		Gsa	**Gsb**	**Absorption**			**Gsa**	**Gsb**	**Absorption**
Texas	Min. :	2.68	2.597	1.2	California	Min. :	2.706	2.564	1.7
	1st Qu.:	2.68	2.597	1.2		1st Qu.:	2.712	2.571	1.9
	Median :	2.681	2.597	1. 2		Median :	2.718	2.578	2.0
	Mean :	2.684	2.601	1.2		Mean :	2.714	2.578	1.9
	3rd Qu.:	2.685	2.603	1.2		3rd Qu.:	2.719	2.586	2.0
	Max. :	2.69	2.608	1.2		Max. :	2.719	2.593	2.0

Bulk specific gravity

The bulk specific gravity values obtained for the slag fine aggregates were less consistent than those obtained for the limestone fine aggregates. The ANOVA presented in Table 11 rejected the null hypothesis, which means there is at least one method which produces different results. Table 12; presents the pairwise student t-test results. The standard AASHTO T 84 method produced similar results to those obtained from the provisional cone, hard paper, Arizona, Iowa and the California method. Provisional cone method produced similar results when compared to those obtained from T84, provisional surface, Arizona, Wisconsin, CoreLok, Texas and California methods. Provisional surface test produced similar results when compared to hard paper method. Arizona method produced statistically similar results when compared to those obtained from Arizona, Wisconsin, CoreLok, Texas and California method. Hard Paper and Iowa produced results which were different from almost all the other methods.

Apparent specific gravity

The apparent specific gravity values for the slag fine aggregates obtained from the different test methods are statistically different when compared with each other. It can be seen from Table 13 that the null hypothesis is rejected by ANOVA. Table 14 provides the pairwise student *t*-test results. Apparently the AASHTO provisional cone test, Iowa and California method produces different results while the result from all the other test methods are statistically the similar.

Absorption

ANOVA presented in Table 15 explains the differences in percent absorption by different methods. Based on the *p*-values from pairwise student's *t*-test in Table 16 the differences in the results are higher than the limestone and similar results are rare.

Table 11: ANOVA results for fine aggregate G_{sb} (Slag)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Logantests	9	0.01345	0.00149	17.57974	0.00000
Residuals	20	0.00170	0.00008		

Table 12: Pairwise student's t-test results for fine aggregate G_{sb} (Slag)

	T84	Cone Test	Surface Test	Hard Paper	Arizona	Wisconsin	CoreLok	Iowa	Texas
Cone Test	1.00								
Surface Test	0.01	0.35							
Hard Paper	0.13	0.00	0.00						
Arizona	1.00	1.00	0.13	0.01					
Wisconsin	0.01	0.21	1.00	0.00	0.08				
CoreLok	0.02	0.58	1.00	0.00	0.19	1.00			
Iowa	0.07	0.00	0.00	1.00	0.00	0.00	0.00		
Texas	0.02	0.58	1.00	0.00	0.19	1.00	1.00	0.00	
California	1.00	1.00	0.10	0.01	1.00	0.06	0.16	0.01	0.16

Table 13: ANOVA results for fine aggregate G_{sa} (Slag)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Logantests	9	0.00412	0.00046	18.98188	0.00000
Residuals	20	0.00048	0.00002		

Table 14: Pairwise student's t-test results for fine aggregate G_{sa} (Slag)

	T84	Cone Test	Surface Test	Hard Paper	Arizona	Wisconsin	CoreLok	Iowa	Texas
Cone Test	0.12								
Surface Test	1.00	0.10							
Hard Paper	1.00	0.01	1.00						
Arizona	1.00	0.00	1.00	1.00					
Wisconsin	1.00	0.03	1.00	1.00	1.00				
CoreLok	1.00	0.03	1.00	1.00	1.00	1.00			
Iowa	0.01	1.00	0.01	0.00	0.00	0.00	0.00		
Texas	1.00	0.43	1.00	1.00	0.46	1.00	1.00	0.02	
California	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 15: ANOVA results for fine aggregate water absorption (Slag)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Result	9	5.77200	0.64133	48.10000	0.00000
Residuals	20	0.26667	0.01333		

Table 16: Pairwise student's t-test results for fine aggregate water absorption (Slag)

	T84	Cone Test	Surface Test	Hard Paper	Arizona	Wisconsin	CoreLok	Iowa	Texas
Cone Test	0.01								
Surface Test	0.00	1.00							
Hard Paper	0.01	0.00	0.00						
Arizona	1.00	0.07	0.00	0.00					
Wisconsin	0.00	1.00	1.00	0.00	0.00				
CoreLok	0.00	0.00	0.00	0.00	0.00	0.00			
Iowa	1.00	0.00	0.00	0.13	0.51	0.00	0.00		
Texas	0.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	
California	0.27	0.00	0.00	0.92	0.07	0.00	0.00	1.00	0.00

4.4 COARSE AGGREGATES

Boxplot diagrams for the standard AASHTO T 85 method and the CoreLok method for the four different size aggregates are shown in Figure 10, 11, and 12 for the bulk specific gravity, apparent specific gravity, and the percent absorption, respectively. Figure 10 indicates the CoreLok method produced higher values of bulk specific gravity for each of the coarse aggregates tested. From Figure 11 it is clear that the CoreLok method produced lower apparent specific gravity values for all the four different size aggregates when compared to those obtained from the standard AASHTO T 85 method. The percent absorption trend is opposite of bulk specific gravity trend; as would be expected. This can be seen from Figure 12. Details of the box plots are given below

- Top and bottom lines represent the maximum and minimum observations respectively.
- Top of the box represents the 75th percentile of the data.
- Bottom of the box represents the 25th percentile of the data.
- Dark line inside the box represents the 50th percentile, or median, of the data.
- Empty circles represent outliers within the data.

The p-values for the Student's -test analysis of the coarse aggregate specific gravity and absorption are given in Table 18. In all cases the p-values indicate the hypothesis of equal means can be rejected at the 95 percent confidence level.

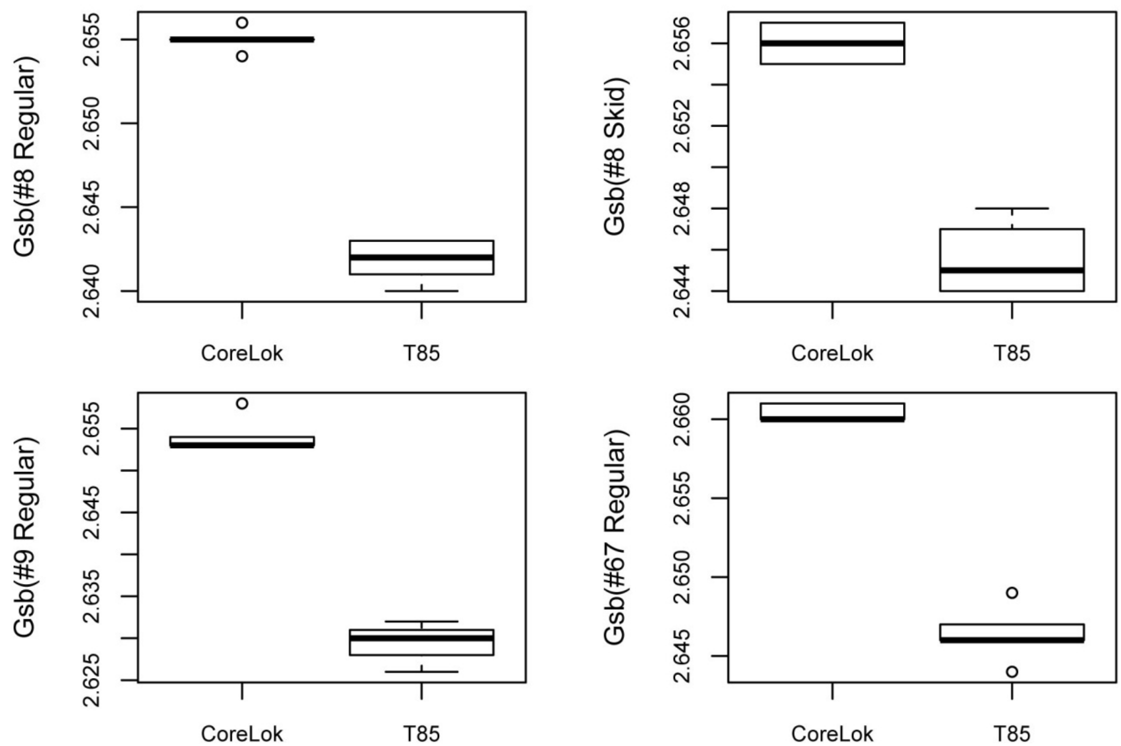

Figure 10: Comparison of Gsb values for coarse aggregates

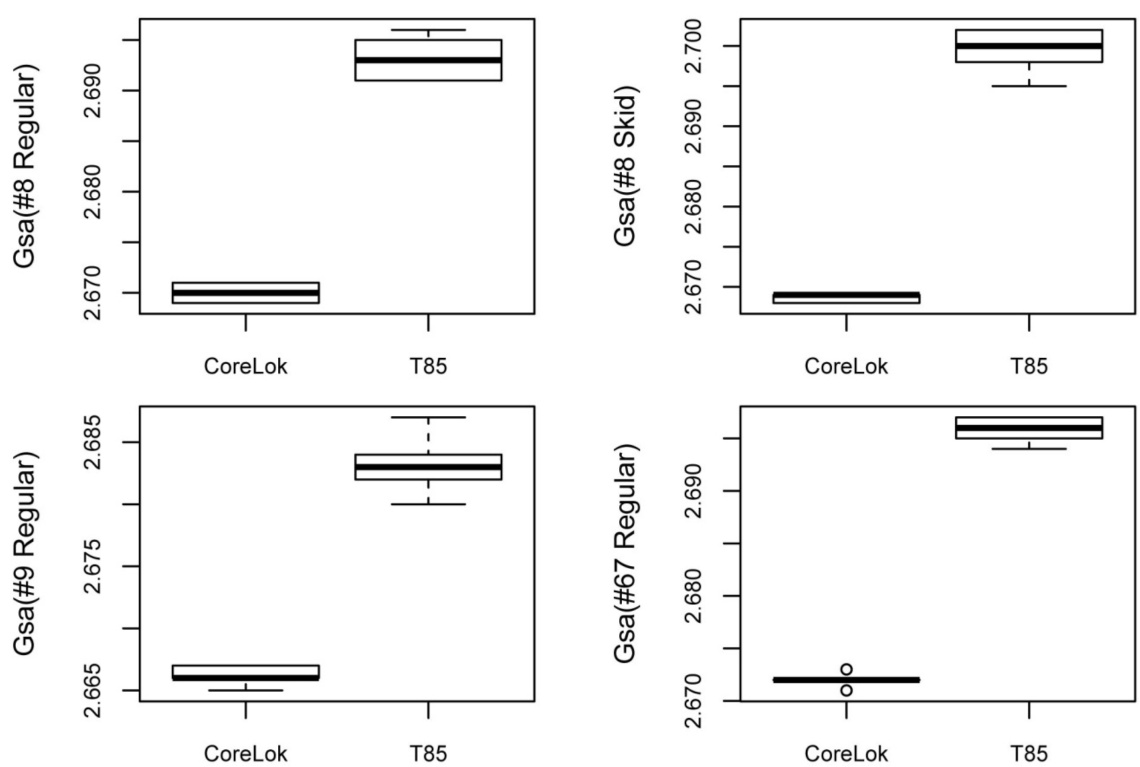

Figure 11: Comparison of Gsa values for coarse aggregates

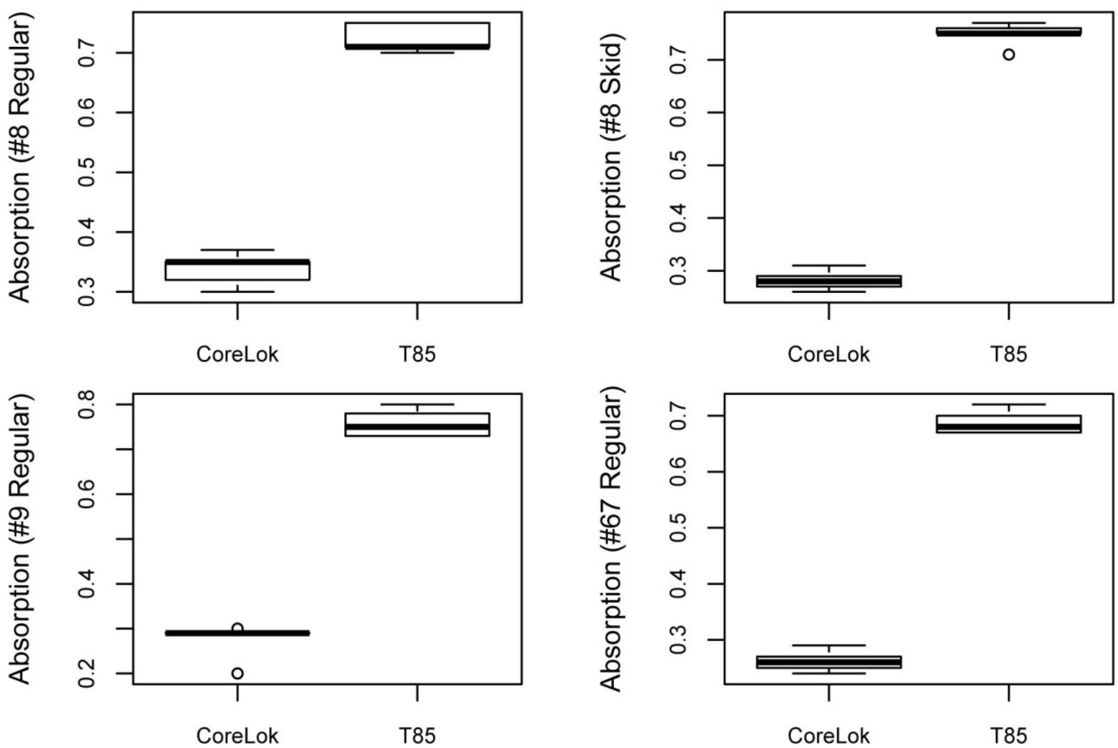

Figure 12: Comparison of percent absorption values for coarse aggregates

Table 17: Coarse aggregate boxplots' information

		CoreLok			T85		
		Gsa	Gsb	Absorption	Gsa	Gsb	Absorption
#8 Regular	Min. :	2.669	2.654	0.3	2.691	2.64	0.7
	1st Qu.:	2.669	2.655	0.3	2.691	2.641	0.7
	Median :	2.67	2.655	0.4	2.693	2.642	0.7
	Mean :	2.67	2.655	0.3	2.693	2.642	0.7
	3rd Qu.:	2.671	2.655	0.4	2.695	2.643	0.8
	Max. :	2.671	2.656	0.4	2.696	2.643	0.8
#8 Skid	Min. :	2.668	2.655	0.3	2.695	2.644	0.7
	1st Qu.:	2.668	2.655	0.3	2.698	2.644	0.8
	Median :	2.669	2.656	0.3	2.7	2.645	0.8
	Mean :	2.669	2.656	0.3	2.699	2.646	0.8
	3rd Qu.:	2.669	2.657	0.3	2.702	2.647	0.8
	Max. :	2.669	2.657	0.3	2.702	2.648	0.8
#9 Regular	Min. :	2.665	2.653	0.2	2.68	2.626	0.7
	1st Qu.:	2.666	2.653	0.3	2.682	2.628	0.7
	Median :	2.666	2.653	0.3	2.683	2.63	0.8
	Mean :	2.666	2.654	0.3	2.683	2.629	0.8
	3rd Qu.:	2.667	2.654	0.3	2.684	2.631	0.8
	Max. :	2.667	2.658	0.3	2.687	2.632	0.8
#67 Regular	Min. :	2.671	2.66	0.2	2.694	2.644	0.7
	1st Qu.:	2.672	2.66	0.3	2.695	2.646	0.7
	Median :	2.672	2.66	0.3	2.696	2.646	0.7
	Mean :	2.672	2.66	0.3	2.696	2.646	0.7
	3rd Qu.:	2.672	2.661	0.3	2.697	2.647	0.7
	Max. :	2.673	2.661	0.3	2.697	2.649	0.7

Table 18: Coarse aggregate p-values from Student t analysis for CoreLok versus T 85

Aggregate	Bulk Specific Gravity	Apparent Specific Gravity	Absorption
# 8 regular	0.0077	*	*
# 8 Skid	0.0191	*	*
# 9	*	*	*
# 67	*	*	*

*P-value less than 0.001

4.5 VOLUMETRIC PROPERTIES

The volumetric properties that are dependent on the bulk specific gravity calculations are the voids in mineral aggregate (VMA) and the voids filled with asphalt (VFA). From Equation 7 it is clear that keeping all the other parameters constant and changing the value of the bulk specific gravity of aggregates, the VMA can either be higher or lower based on the obtained results from different test methods. In case of the fine limestone aggregates the bulk specific gravity values obtained in all the alternative methods are higher than those obtained from the standard AASHTO T 84 test method. This would mean an increase in the VMA values. The VFA is dependent on the VMA and VTM of the mix. The following analysis is based on assuming the VTM is at the target value of mix design of 4 percent. Since the VTM is not varying in this analysis, VMA and VFA will show the exact same trends so only the VMA analysis is presented.

The potential effect of changing the test method to determine the bulk specific gravity of the aggregates was examined by computing the VMA and VFA of a mix assuming all other factors remained the same. The mix properties on the summary sheet were:

- $G_{mm} = 2.476$
- VTM = 4.0
- $P_b = 5.9$
- VMA = 15.7
- Percent aggregate by type – 37% No. 8, 14% No. 9 and 49% Fine aggregate

These values were used to compute $G_{mb} = 2.377$ for the mix and $G_{sb} = 2.653$ for the aggregate blend. The blended bulk specific gravity values for the aggregate blend were computed using each of the fine aggregate test methods and both the T85 and CoreLok method as presented in Table 19. Comparing the blend result using the T 84 method for the fine aggregates and T 85 for the coarse aggregate to the contractor's G_{sb} value shows a difference of 0.032. The precision statements for T 84 and T 85 indicate the difference in test results between two labs should be less than 0.066 and 0.038 respectively. Hence, the test results measured in this work are in reasonable agreement with the contractor's results.

Table 19 Blended bulk specific aggregate values

	Fine aggregate test method									
Coarse aggregate test method	T 84	PC	PS	HP	AZ	WI	CA	IO	TX	CL
T85	2.621	2.641	2.635	2.637	2.631	2.653	2.639	2.638	2.643	2.644
CL	2.623	2.643	2.637	2.639	2.633	2.655	2.641	2.640	2.645	2.646

The values in Table 19 were used to compute the VMA and VFA for the mix for the different values of aggregate bulk specific gravity. Figure 13 shows the VMA values vary from 14.7 to 15.8 depending on the test method. The lowest result is obtained from the AASHTO test methods, the maximum VMA was obtained using the Wisconsin method for the fine aggregates and the CoreLok method for the coarse aggregates. Figure 14 shows the line of equality graph comparing the effect of T 85 versus the CoreLok method. There is good agreement between the methods, however the VMA values are consistently higher when G_{sb} of the coarse aggregates is determined with the CoreLok. Figure 14 also demonstrates that the fine aggregate test method has a larger effect on VMA than the coarse aggregate test method. The maximum difference in VMA that could be attributed to the coarse aggregate test method is 0.1 while the maximum difference that could be attributed to the fine aggregate test method is 1.1.

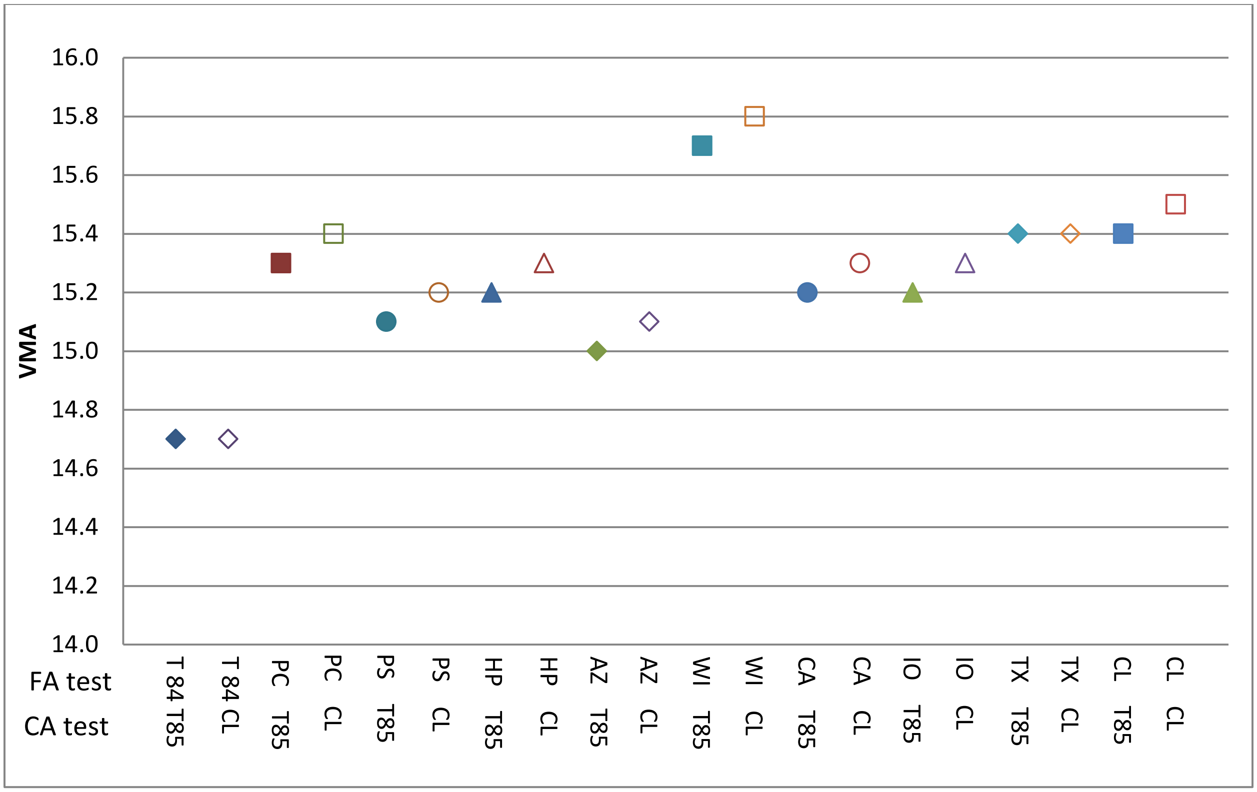

Figure 13: VMA values using specific gravity values from different methods

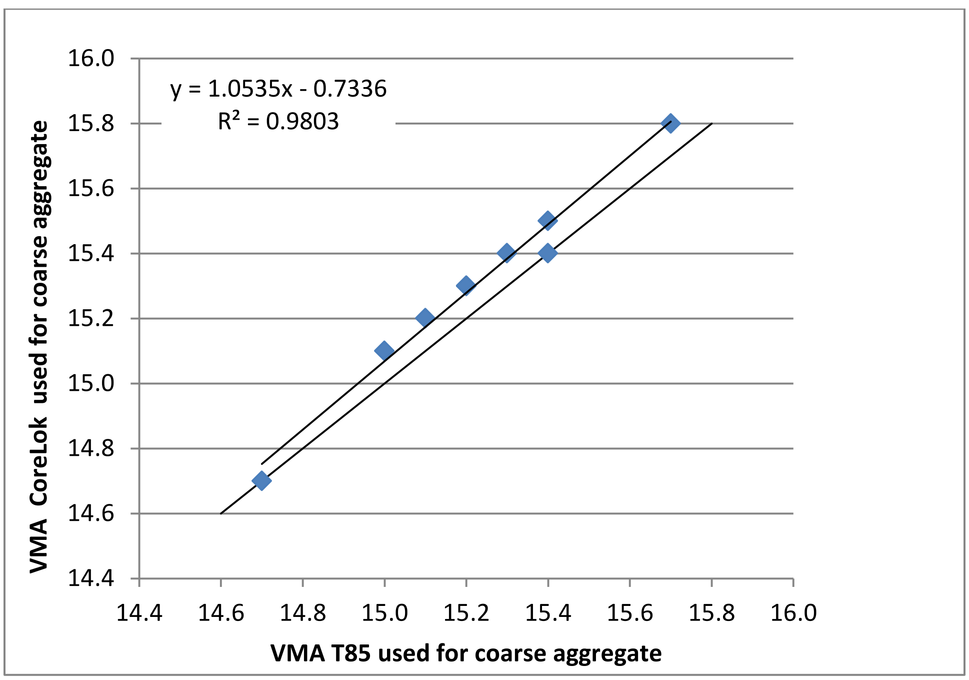

Figure 14: Line of equality comparison of VMA from different test methods

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

The accurate determination of aggregate specific gravity is needed for proper determination of the volumetric properties of asphalt concrete mixes. The literature review demonstrated that there are at least ten different test methods for measuring the specific gravity and absorption of fine aggregates and two methods for coarse aggregates. The abundance of test methods for fine aggregates indicates the paving community is concerned over the accuracy and reliability of the standard methods in ASTM and AASHTO. In particular, there is concern in determining the saturated surface dry state of fine aggregates with high texture and angularity, such as the crushed limestone fine aggregate commonly used in West Virginia.

5.1 CONCLUSIONS

One of the difficulties in evaluating alternative test methods is the "truth" is not known. If it can be demonstrated that the standard method produces the truth then there would not be a need to examine alternative test methods. (Assuming the standard method can be performed in a "reasonable" amount of time, effort, equipment needs, etc.) The fine aggregate specific gravity results for limestone, Table 5, demonstrate the G_{sb} values obtained with the standard AASHTO T84 method produce similar results with AASHTO provisional cone test, Hard Paper, Arizona and California method. Statistically speaking, however the analysis fails to reject the equality of means for AASHTO provisional surface test, Wisconsin and California methods. Moreover, the statistical procedure states that the CoreLok and Texas methods produce results which are different from AASHTO T84.

The CoreLok method consistently returns the highest G_{sb} value among all the methods. Wisconsin is also one of the methods which produced higher G_{sb} values compared to the standard AASHTO T84. The primary difference between the standard and Wisconsin methods is the removal of material by washing the sample over the No. 200 sieve. (This process is actually presented in the AASHTO T 84 appendix as "non-mandatory information") The difference between the T 84 and Wisconsin method G_{sb} methods was in the range identified in T 84 for comparing washed and unwashed samples. Samples for the Iowa method are also washed over the No. 200 sieve, but the method for determining the SSD state is different from T 84.

The apparent specific gravity values for limestone fine aggregates using all the different methods showed that only Wisconsin method produced statistically different results when compared to the standard AASHTO T 84 results. Since the calculation of apparent specific gravity does not include using the SSD weight of aggregates being tested, it is expected that all the test methods will return similar results. The difference in G_{sa} reported by Wisconsin may be from washing the aggregate which lead to a loss of some fine particles.

Other than the CoreLok and Iowa methods, almost all the other methods showed statistical similarity in case of the absorption values calculated for the limestone fine aggregates.

Over all, compared to the limestone results, slag fine aggregate results showed higher inconsistency with regard to specific gravities and absorption by different methods used in this report. Based on the statistical analysis the AASHTO T 84 results for fine slag material is similar AASHTO provisional cone test, Arizona and California methods. However the statistical analysis fails to reject the similarity between the T84 results, hard paper and Iowa methods but compared to the aforementioned methods the recent ones are approved at lower power. In addition to the CoreLok and Texas methods which produced different results for limestone, the provisional surface test and Wisconsin method also produced different results for slag material.

For the calculation of apparent specific gravities values for slag fine aggregates, all the tested methods showed statistically similar results except for the Iowa and California method. It shows that since the SSD weight of aggregates is not included, there is not much difference between the values of apparent specific gravities for the slag fine aggregates. When the absorption values were compared there was much higher inconsistency in the results obtained. The results obtained in finding the absorption values for slag fine aggregates showed almost a similar trend to the bulk specific gravity values obtained but in reverse, except for the CoreLok method. Hence for absorption values the provisional surface test, Wisconsin and Texas method produced the lowest values. Based on the statistical analysis for absorption, only the Arizona, Iowa and California method produced similar results with standard AASHTO T84.

For the coarse aggregates, the bulk specific gravity values obtained from the two test methods produced statistically different results for all the four sizes of aggregates tested. Although the statistical student’s *t*-test rejected the hypothesis of equal means, the difference between the T 85 and CoreLok results was less than the d2s limit in the T85 precision statement.

5.2 RECOMMENDATIONS

This research was limited to testing just two sources of fine aggregates and one source of coarse aggregate. Further research can be done on some other types of aggregate sources in order to see if these methods work well with other aggregates. The aggregate types that are found to cause the problem of inaccurate judgment in SSD state of fine aggregates should be studied and used in further research.

Since this research was completed in a single laboratory, there are chances of inaccuracies in operator judgments and hence the same types of aggregates need to be tested among other laboratories to have a better understanding of the operating errors in the experiments conducted. The use of high resolution cameras can help improve the accurate determination of the dull state of the aggregates reaching the SSD state. This can help in reducing the operator errors which can cause some changes in the results obtained for any test method.

After comparison of the AASHTO T84 method for fine aggregate to the alternative AASHTO T84 provisions and state procedures do not suggest that any of these procedures are superior to the T84. Due to the simplicity and speed of the CoreLok Agg/Plus system there is interest in using the method. However, the results produced in the research indicate the CoreLok Agg/Plus method produced different results than the AASHTO T84, these differences are enough to cause issues with the volumetric analysis of asphalt concrete. Since the asphalt concrete limits were developed around the results of conventional materials and testing methods, it is recommended that T84 be used as the required test method.

Similarly, the comparison of the AASHTO T85 method for coarse aggregate to the CoreLok Agg/Plus system has produced results that indicated a variation between the two methods that is statistically significant. It is recommended that AASHTO T85 continue to be used as the required test method.

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APPENDIX 1 Data

Limestone Fine Aggregate

AASHTO T84

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
# 1	499.6	664.3	509.3	980.7	2.590	2.727	2.640	1.942
# 2	491.5	666.5	500.5	978.2	2.603	2.734	2.651	1.831
# 3	493.4	666.5	504.1	978.7	2.571	2.723	2.627	2.169

Provisional Cone Test

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	GSB @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	495.4	664.4	505.6	978.2	2.583	2.728	2.636	2.059
#2	501.5	666.7	510.8	984.2	2.594	2.726	2.643	1.854
#3	496.7	664.3	507.5	978.9	2.575	2.728	2.631	2.174

Provisional Surface Test

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
# 1	493.5	664.3	502	978.4	2.626	2.751	2.672	1.722
# 2	496.8	666.6	507.5	984.9	2.626	2.783	2.682	2.154
# 3	496.1	666.4	503.9	980.3	2.611	2.723	2.652	1.572

Hard Paper Test

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	496.9	664.3	507.5	979.2	2.580	2.730	2.635	2.133
#2	493.1	666.6	504.2	978.9	2.570	2.727	2.627	2.251
#3	496.2	664.3	505.0	978.3	2.598	2.723	2.644	1.773

Arizona DOT Method

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	495.4	664.4	504.9	978.2	2.592	2.728	2.642	1.918
#2	498.7	666.8	508.1	982.7	2.595	2.728	2.644	1.885
#3	499.2	666.6	509.5	983.5	2.592	2.738	2.645	2.063

Wisconsin Method

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	500.3	664.5	503.6	979.8	2.657	2.704	2.674	0.660
#2	497.4	666.6	501	978.2	2.626	2.677	2.645	0.724
#3	502.4	666.4	506	978.7	2.594	2.643	2.612	0.717

CoreLok Method

Sample ID	Container Size	Container Calibration Weight (Avg) (g)	Dry Sample Weight (N1,N2,N3) (g)	Sample Weight in Container Filled with Water (N1,N2,N3) (g)	Bag Weight (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
Sample 1	Small	4228.633	500.2	4543.5	24.2	1000	630.2	0.936	2.723	2.68	2.656
Sample 2	Small	4228.567	500.35	4543.65	24.4	999.9	630.2	0.904	2.724	2.682	2.658
Sample 3	Small	4228.567	500.2	4543.35	24.9	1000.1	630.3	0.991	2.724	2.679	2.653

Iowa Method

Sample	Weight of Pycnometer in Water (gms)	Weight of Dry Sample gms	Weight of Pycnometer+ Sample in Water gms	Temperature of Water (°C)	Correction Multiplier (R)	SSD Weight without Passing #200 Materical gms	Dry weight without Passing #200 Material	G_{sb}	G_{sa}	% Absorption
1	1321.0	2005.8	2587.9	25	1	1809.6	1786.7	2.623	2.715	1.282
2	1321.0	2000.4	2583.6	25	1	1795.34	1773.9	2.625	2.711	1.209
3	1321.0	2002.2	2584.2	25	1	1804.2	1782.9	2.624	2.709	1.195

Texas Method

Sample	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	499.4	1493.6	506.3	1810.6	2.638	2.738	2.675	1.382
#2	501.2	1494	508.4	1812.6	2.641	2.745	2.679	1.437
#3	498	1494	506.5	1810.8	2.625	2.748	2.670	1.707

California Method

Mass of SSD Sample	Mass of Pail in Water	Mass of Pale and Sample in Water	Mass of Dry Sample	Gsb @ SSD	Gsb	Gsa	Absorption
1016.3	1321	1952.2	998.6	2.639	2.593	2.718	1.772
1018.9	1506.6	2138.1	998.9	2.630	2.578	2.719	2.002
1018.2	1506.6	2135.7	997.8	2.617	2.564	2.706	2.044

Slag Fine Aggregates

AASHTO
T-84

Sample #	Dry Weight	Pycnometer +Water	SSD Weight	Pycnometer +Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	491.5	664.3	502.1	985.8	2.721	2.891	2.780	2.157
#2	496.6	666.6	507	991.4	2.726	2.891	2.783	2.094
#3	493.1	664.3	502.2	985.8	2.729	2.874	2.779	1.845

AASHTO Provisional Cone

Sample #	Dry Weight	Pycnometer+ Water	SSD Weight	Pycnometer +Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	494.5	664.1	506.5	987.6	2.702	2.892	2.768	2.427
#2	482.7	666.6	494	982.1	2.704	2.887	2.768	2.341
#3	480.4	664.2	491.9	978.4	2.703	2.890	2.768	2.394

Provisional
Surface

Sample #	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	480.2	664.4	497.1	978.2	2.620	2.886	2.712	3.519
#2	489.1	666.6	505.4	986.7	2.640	2.894	2.727	3.333
#3	491	664.2	507.8	985.5	2.633	2.893	2.723	3.422

Hard Paper

Sample #	Dry Weight	Pycnometer +Water	SSD Weight	Pycnometer+ Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
# 1	486.2	664.3	494.8	980.5	2.722	2.860	2.770	1.769
# 2	490.1	666.5	499.3	986.1	2.727	2.874	2.779	1.877
# 3	492	664.2	501.4	985	2.724	2.874	2.776	1.911

Arizona Method

Sample #	Dry Weight	Pycnometer +Water	SSD Weight	Pycnometer+ Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
# 1	497.2	664.2	507.5	988.4	2.712	2.874	2.769	2.072
# 2	490.6	666.5	500.6	987.5	2.732	2.893	2.787	2.038
# 3	489.3	664.2	498.5	983.7	2.734	2.882	2.785	1.880

Wisconsin Method

Sample #	Dry Weight	Pycnometer+ Water	SSD Weight	Pycnometer+ Sample	G_{SB}	G_{SA}	G_{SB} @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	491.8	664.2	499.9	985.1	2.747	2.878	2.793	1.647
#2	492.2	666.5	500.2	987.6	2.748	2.877	2.793	1.625
#3	492.1	664.1	498.4	985.5	2.780	2.883	2.816	1.280

CoreLok

Sample ID	Container Size	Container Calibration Weight (Avg) (g)	Dry Sample Weight (g)	Sample Weight in Container Filled with Water (g)	Bag Weight (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
Sample 1	Small	4228.2	500.3	4551.5	24.2	1000.3	661	3.678	2.971	2.777	2.678
Sample 2	Small	4228.2	500.6	4551.05	23.8	1000.6	661.1	3.904	2.970	2.765	2.661
Sample 3	Small	4228.2	500.45	4550.4	24.5	1000.4	660.9	4.124	2.970	2.755	2.646

Iowa Method

Sample	Weight of Pycnometer in Water (gms)	Weight of Dry Sample gms	Weight of Pycnometer+ Sample in Water gms	Temperature of Water (°C)	Correction Multiplier (R)	SSD Weight without Passing #200 Materical gms	Dry weight without Passing #200 Material	G_{sb}	G_{sa}	% Absorption
1	1321.1	2005.7	2637.9	25	1	1851.1	1838.8	2.856	2.911	0.669
2	1321.1	2010.1	2641.2	25	1	1844.3	1830.6	2.851	2.913	0.748
3	1321.1	1996.8	2630.6	25	1	1807.6	1794.5	2.845	2.905	0.730

Texas Method

Sample #	Dry Weight	Pycnometer+Water	SSD Weight	Pycnometer+Sample	GSB	GSA	GSB @ SSD	Absorption %
	(grams)	(grams)	(grams)	(grams)				
#1	493.6	1493.96	504.7	1818.1	2.734	2.913	2.795	2.249
#2	490.4	1493.96	500.7	1815.5	2.737	2.904	2.795	2.100
#3	490.7	1493.96	502.2	1815.8	2.721	2.906	2.784	2.344

California

Mass of SSD Sample	Mass of Pail in Water	Mass of Pale and Sample in Water	Mass of Dry Sample	Gsb @ SSD	Gsb	Gsa	Absorption
2045.7	1321.2	2618.8	1990.4	2.735	2.661	2.873	2.778
2066.1	1506.9	2810.6	2004.3	2.710	2.629	2.861	3.083
2028.3	1321.2	2600.7	1965.1	2.709	2.624	2.866	3.216

Coarse Aggregates

Standard AASHTO T 85

Aggregate Size	Test Method	A (gms)	B (gms)	C (gms)	G_{sb}	G_{sa}	% Absorption
No. 8 Regular	AASHTO T 85	2047.5	2062.8	1288	2.643	2.696	0.75
No. 8 Regular	AASHTO T 85	1994.8	2008.9	1254.2	2.643	2.693	0.71
No. 8 Regular	AASHTO T 85	2032.6	2046.9	1277.4	2.641	2.691	0.7
No. 8 Regular	AASHTO T 85	2015.3	2029.7	1266.3	2.64	2.691	0.71
No. 8 Regular	AASHTO T 85	2022.4	2037.5	1271.9	2.642	2.695	0.75
No. 8 Skid	AASHTO T 85	2050.2	2065.9	1290.9	2.645	2.7	0.77
No. 8 Skid	AASHTO T 85	2011.6	2026.7	1265.9	2.644	2.698	0.75
No. 8 Skid	AASHTO T 85	2028.4	2043.6	1277.6	2.648	2.702	0.75
No. 8 Skid	AASHTO T 85	2035.8	2051.3	1282.3	2.647	2.702	0.76
No. 8 Skid	AASHTO T 85	2004.5	2018.8	1260.8	2.644	2.695	0.71

Aggregate Size	Test Method	A (gms)	B (gms)	C (gms)	G_{sb}	G_{sa}	% Absorption
No. 9	AASHTO T 85	2163.3	2180.7	1357	2.626	2.683	0.8
No. 9	AASHTO T 85	2042.5	2057.9	1281.6	2.631	2.684	0.75
No. 9	AASHTO T 85	2032.8	2047.6	1274.8	2.63	2.682	0.73
No. 9	AASHTO T 85	2007.6	2023.3	1260.5	2.632	2.687	0.78
No. 9	AASHTO T 85	2058.3	2073.4	1290.3	2.628	2.68	0.73
No. 67	AASHTO T 85	2052.8	2066.6	1290.7	2.646	2.694	0.67
No. 67	AASHTO T 85	2025.3	2039.5	1274.3	2.647	2.697	0.7
No. 67	AASHTO T 85	2002.5	2016.9	1259.6	2.644	2.696	0.72
No. 67	AASHTO T 85	2015.2	2029	1267.5	2.646	2.695	0.68
No. 67	AASHTO T 85	2048.4	2062.1	1288.9	2.649	2.697	0.67

CoreLok Method (# 8 Regular)

InstroTek AggSpec 3/7/2012

Sample ID	Container Size	Container Calibration Weight (N1,N2,N3) (g)	Dry Sample Weight (N1,N2,N3) (g)	Sample Weight in Container Filled with Water (Avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
1	Large	5658.2	1000.1	6280.3	72.8	208.2	2000.2	1295.8	0.35	2.67	2.655	2.646
2	Large	5658.2	1000.3	6280.7	72.7	208.2	2000	1295.4	0.3	2.669	2.656	2.648
3	Large	5658.2	999.9	6280	72.9	208.2	2000.4	1296.1	0.37	2.671	2.654	2.645
4	Large	5658.2	1000.4	6280.6	72.8	208.2	2000.3	1295.6	0.32	2.669	2.655	2.647
5	Large	5658.2	1000	6280.2	72.8	208.2	2000.1	1295.8	0.35	2.671	2.655	2.646

CoreLok Method (# 8 Skid)

InstroTek AggSpec 3/7/2012

Sample ID	Container Size	Container Calibration Weight (N1,N2,N3) (g)	Dry Sample Weight (N1,N2,N3) (g)	Sample Weight in Container Filled with Water (Avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
1	Large	5657.9	999.9	6280.1	72.9	208.2	2000	1295.3	0.31	2.669	2.655	2.647
2	Large	5657.9	1000.1	6280.5	72.8	208.2	2000.2	1295.4	0.28	2.669	2.657	2.649
3	Large	5657.9	1000.3	6280.6	72.8	208.2	2000.1	1295.2	0.27	2.668	2.656	2.649
4	Large	5657.9	1000	6280.2	72.7	208.2	1999.9	1295	0.29	2.668	2.655	2.648
5	Large	5657.9	1000.4	6280.8	72.9	208.2	2000.4	1295.5	0.26	2.669	2.657	2.65

CoreLok Method (# 9)

InstroTek AggSpec

Sample ID	Container Size	Container Calibration Weight (Avg) (g)	Dry Sample Weight (Avg) (g)	Sample Weight in Container Filled with Water (Avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
1	Large	5657.7	1000.3	6280.9	72.6	208.2	2000.3	1294.8	0.29	2.666	2.653	2.646
2	Large	5657.7	1000.2	6280.8	72.7	208.2	2000.1	1294.7	0.2	2.667	2.658	2.652
3	Large	5657.7	999.9	6280.6	72.8	208.2	2000.4	1294.7	0.29	2.666	2.653	2.645
4	Large	5657.7	1000.1	6280.8	72.7	208.2	2000.2	1294.8	0.3	2.667	2.654	2.646
5	Large	5657.7	1000.2	6280.8	72.7	208.2	2000.1	1294.4	0.29	2.665	2.653	2.645

CoreLok Method (# 67)

InstroTek AggSpec

Sample ID	Container Size	Container Calibration Weight (Avg) (g)	Dry Sample Weight (Avg) (g)	Sample Weight in Container Filled with Water (Avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
1	Large	5657.9	1000	6281.1	72.8	208.2	2000.1	1296.1	0.25	2.672	2.661	2.654
2	Large	5657.9	999.8	6281	72.8	208.2	2000.2	1296	0.24	2.671	2.66	2.654
3	Large	5657.9	1000.4	6281.1	72.6	208.2	1999.8	1296.2	0.29	2.673	2.66	2.652
4	Large	5657.9	1000.2	6281.2	72.7	208.2	2000.4	1296.4	0.26	2.672	2.661	2.654
5	Large	5657.9	1000.3	6281.2	72.6	208.2	2000.3	1296.4	0.27	2.672	2.66	2.653

APPENDIX 2 Data Summary

Fine aggregate specific gravity and absorption results for limestone

Aggregate	Test Method	Sample	G_{sb}	G_{sa}	% Absorption
Limestone	T 84	1	2.590	2.727	1.942
Limestone	T 84	2	2.603	2.734	1.831
Limestone	T 84	3	2.571	2.723	2.169
Limestone	PCT	1	2.583	2.728	2.059
Limestone	PCT	2	2.594	2.726	1.854
Limestone	PCT	3	2.575	2.728	2.174
Limestone	PST	1	2.626	2.751	1.722
Limestone	PST	2	2.626	2.783	2.154
Limestone	PST	3	2.611	2.723	1.572
Limestone	HPM	1	2.580	2.730	2.133
Limestone	HPM	2	2.570	2.727	2.251
Limestone	HPM	3	2.598	2.723	1.773
Limestone	ADM	1	2.592	2.728	1.918
Limestone	ADM	2	2.595	2.728	1.885
Limestone	ADM	3	2.592	2.738	2.063
Limestone	WM	1	2.657	2.704	0.660
Limestone	WM	2	2.626	2.677	0.724
Limestone	WM	3	2.594	2.643	0.717
Limestone	CL	1	2.656	2.723	0.936
Limestone	CL	2	2.658	2.724	0.904
Limestone	CL	3	2.653	2.724	0.991
Limestone	IM	1	2.623	2.715	1.282
Limestone	IM	2	2.625	2.711	1.209
Limestone	IM	3	2.624	2.709	1.195
Limestone	TM	1	2.638	2.738	1.382
Limestone	TM	2	2.641	2.745	1.437
Limestone	TM	3	2.625	2.748	1.707
Limestone	CT	1	2.593	2.718	1.772
Limestone	CT	2	2.578	2.719	2.002
Limestone	CT	3	2.564	2.706	2.044

T 84 = AASHTO T 84
PCT = Provisional Cone Test
PST = Provisional Surface Test
HPM = Hard Paper Method
ADM = Arizona DOT Method
WM = Wisconsin Method
CL = CoreLok Method
IM = Iowa Method

Fine aggregate specific gravity and absorption results for slag

Aggregate	Test Method	Sample	G_{sb}	G_{sa}	% Absorption
Slag	T 84	1	2.721	2.891	2..157
Slag	T 84	2	2.726	2.891	2.094
Slag	T 84	3	2.729	2.874	1.845
Slag	PCT	1	2.702	2.892	2.427
Slag	PCT	2	1.704	2.887	2.341
Slag	PCT	3	2.703	2.890	2.394
Slag	PST	1	2.620	2.886	3.519
Slag	PST	2	2.640	2.894	3.333
Slag	PST	3	2.633	2.893	3.422
Slag	HPM	1	2.722	2.86	1.769
Slag	HPM	2	2.727	2.874	1.878
Slag	HPM	3	2.724	2.874	1.911
Slag	ADM	1	2.712	2.874	2.072
Slag	ADM	2	2.732	2.893	2.038
Slag	ADM	3	2.734	2.882	1.880
Slag	WM	1	2.747	2.878	1.647
Slag	WM	2	2.748	2.877	1.625
Slag	WM	3	2.780	2.883	1.280
Slag	CL	1	2.678	2.971	3.678
Slag	CL	2	2.661	2.970	3.904
Slag	CL	3	2.646	2.970	4.124
Slag	IM	1	2.856	2.911	0.669
Slag	IM	2	2.851	2.913	0.748
Slag	IM	3	2.845	2.905	0.730
Slag	TM	1	2.734	2.913	2.249
Slag	TM	2	2.737	2.904	2.100
Slag	TM	3	2.721	2.906	2.344
Slag	CT	1	2.661	2.873	2.778
Slag	CT	2	2.629	2.861	3.083
Slag	CT	3	2.624	2.866	3.216

T 84 = AASHTO T 84
PCT = Provisional Cone Test
PST = Provisional Surface Test
HPM = Hard Paper Method
ADM = Arizona DOT Method
WM = Wisconsin Method
CL = CoreLok Method
IM = Iowa Method

Coarse aggregate specific gravity and absorption results

Aggregate	Test Method	Size	Sample	G_{sb}	G_{sa}	% Abs.
Limestone	T 85	No. 8 R	1	2.586	2.667	1.186
Limestone	T 85	No. 8 R	2	2.583	2.671	1.274
Limestone	T 85	No. 8 R	3	2.587	2.668	1.176
Limestone	T 85	No. 8 R	4	2.587	2.671	1.225
Limestone	T 85	No. 8 R	5	2.586	2.667	1.173
Limestone	CL	No. 8 R	1	2.646	2.670	0.347
Limestone	CL	No. 8 R	2	2.648	2.669	0.305
Limestone	CL	No. 8 R	3	2.645	2.671	0.374
Limestone	CL	No. 8 R	4	2.647	2.669	0.323
Limestone	CL	No. 8 R	5	2.646	2.671	0.354
Limestone	T 85	No. 8 S	1	2.580	2.669	1.299
Limestone	T 85	No. 8 S	2	2.577	2.671	1.365
Limestone	T 85	No. 8 S	3	2.580	2.669	1.280
Limestone	T 85	No. 8 S	4	2.583	2.666	1.199
Limestone	T 85	No. 8 S	5	2.579	2.670	1.323
Limestone	CL	No. 8 S	1	2.647	2.669	0.306
Limestone	CL	No. 8 S	2	2.649	2.669	0.277
Limestone	CL	No. 8 S	3	2.649	2.668	0.273
Limestone	CL	No. 8 S	4	2.648	2.668	0.290
Limestone	CL	No. 8 S	5	2.650	2.669	0.265

T 85 = AASHTO T 85
CL = CoreLok Method
No.8 R = Number 8 Regular
No.8 S = Number 8 Skid

Coarse aggregate specific gravity and absorption results

Aggregate	Test Method	Size	Sample	G_{sb}	G_{sa}	% Abs.
Limestone	T 85	No. 9	1	2.591	2.651	0.874
Limestone	T 85	No. 9	2	2.589	2.652	0.913
Limestone	T 85	No. 9	3	2.587	2.655	0.979
Limestone	T 85	No. 9	4	2.592	2.651	0.870
Limestone	T 85	No. 9	5	2.588	2.654	0.966
Limestone	CL	No. 9	1	2.646	2.666	0.295
Limestone	CL	No. 9	2	2.652	2.667	0.201
Limestone	CL	No. 9	3	2.645	2.666	0.293
Limestone	CL	No. 9	4	2.646	2.667	0.297
Limestone	CL	No. 9	5	2.645	2.665	0.286
Limestone	T 85	No. 67	1	2.564	2.686	1.784
Limestone	T 85	No. 67	2	2.570	2.687	1.703
Limestone	T 85	No. 67	3	2.568	2.681	1.641
Limestone	T 85	No. 67	4	2.574	2.685	1.612
Limestone	T 85	No. 67	5	2.567	2.686	1.737
Limestone	CL	No. 67	1	2.654	2.672	0.249
Limestone	CL	No. 67	2	2.654	2.671	0.238
Limestone	CL	No. 67	3	2.652	2.673	0.287
Limestone	CL	No. 67	4	2.654	2.672	0.257
Limestone	CL	No. 67	5	2.653	2.672	0.265

T 85 = AASHTO T 85
CL = CoreLok Method