FINAL REPORT

DEVELOPMENT OF NEW TEST PROCEDURES FOR MEASURING FINE AND COARSE AGGREGATE SPECIFIC GRAVITIES

PI: Zhanping You, Ph.D., P.E.
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
MICHIGAN TECHNOLOGICAL UNIVERSITY
1400 TOWNSEND DRIVE
HOUGHTON, MICHIGAN 49931

SUBMITTED TO

John W Barak, P.E.
MICHIGAN DEPARTMENT OF TRANSPORTATION
CONSTRUCTION PAVING UNIT - C&T
SECONDARY GOVERNMENTAL COMPLEX
8885 RICKS ROAD
LANSING, MI 48909

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16. Abstract

The objective of the research is to develop and evaluate new test methods at determining the specific gravity and absorption of both fine and coarse aggregates. Current methods at determining the specific gravity and absorption of fine and coarse aggregates are the AASHTO T84-00 (ASTM C-128), Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate. In addition to the time consuming 15-19 hours for AASHTO T84-00 (24 for ASTM C-128), experience has shown that the test methods are operator skill dependent, has less repeatability and problematic with angular and rough textured fine aggregates. The new automated SSDetect – equipment utilizes the phenomenon of reflection and scattering of light rays – is evaluated as a potential to replace the existing method.
For the coarse aggregates, the Vacuum Saturation method was explored as a replacement for the conventional AASHTO T85-04 (ASTM C-127). The rationale behind the development of this approach is to reduce the 15-19 hours for AASHTO T85-04 (24 hours for ASTM C-127). The Vacuum Saturation aims at substituting the 15-19 hours (24+4 hours) unagitated soaking time using a 30 mm Hg vacuum saturation process to force water into the permeable voids on the coarse aggregate surface. Statistical analysis on the test results indicated that the specific gravity (Gsb), Gsb (SSD) and Gsa of the SSDetect had no significant difference compared with the AASHTO 84-00. The SSDetect, however, underestimated the water absorption potential than the AASHTO 84-00. The Vacuum Saturation method had no statistical differences for the Gsb (dry), Gsb (SSD), Gsa and Wa % as compared with the AASHTO T85-04 (ASTM C-127).

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EXECUTIVE SUMMARY

In the transportation industry, it has become pertinent to develop new approaches and techniques that can assist in the faster and more accurate determination of the specific gravities and absorption of fine and coarse aggregates.

In terms of fine aggregate specific gravity and absorption determination, the SSDetect is explored as a faster approach to supplement the conventional AASHTO T84. In coarse aggregate side, the Vacuum Saturation Approach or Modified Rice Test is similarly proposed as a faster approach to be used alongside the current AASHTO T 85.
The SSDetect is an automated device that uses the laws of reflection and scattering of light to assess the saturated surface dry state of fine aggregate and ultimately the specific gravity and gravity. This approach can determine the specific gravity and absorption of a fine aggregate in approximately 1 hour 30 minutes. A vacuum saturation technique whereby coarse aggregates are vacuumed at pressures of about 30mm is used to substitute the AASHTO T 85 soaking process. The rationale here is to reduce the test time while forcing sufficient water into the pores of highly absorptive coarse aggregates.
On completion of the AASHTO T 84 and SSDetect investigations, it was shown that contractors, engineers and researchers can use the SSDetect as a replacement for the current AASHTO T-84 in measuring the Gsb (dry) and Gsb (SSD) of single gradation and blended fine aggregates. Comparing how the SSDetect compares with the AASHTO T 84 when the #8, #16, #30, #50, #100 and #200 sieves were tested, it was observed that SSDetect will work better in testing the #8, #16, #30, #50 and #100.

For the coarse aggregate aspect of this research, the vacuum saturation method (10, 20 and 30 minutes of test duration in addition to 30 mm of mercury vacuum pressure) can be used to determine the Gsb (dry), Gsb (SSD), Gsa and Wa% of coarse aggregates. For cost efficiency and further time saving purposes, the 10 minutes of vacuum saturation is proposed herein. Another point of interest from this research is the fact that this approach is convenient to work for both individual and blended coarse aggregates gradations.

A number of recommendations are worth noting as the Michigan Department of Transportation (MDOT) seeks to employ faster methods of specific gravity and

absorption determination alongside the existing methods. These include: 1) Empirical transfer relationship to relate the underestimated Wa% from the SSDetect to the actual Wa% of the AASHTO T 84; 2) The extent of specific gravity and absorption effect on asphalt and concrete mixture volumetric analysis needs to be studied in detail; 3) Relating the economic and cost effective gains of using more accurate values of specific gravity and absorption. This will enable engineers and researchers scale to the bulk level, how accurate specific gravity values determination translates into the economic figures; 4) Further testing of the specific gravity and absorption of highly porous coarse aggregates over 14, 21 and 28 days.

A trial specification criterion on using of the SSDetect and the Vacuum Saturated Methods at testing the specific gravities and absorption of fine and coarse aggregates will be developed in the final stages of this project. Additionally, training tool kits will be prepared to supplement the efforts of the trial specification criterion.

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CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 History of Specific Gravity

The discovery of specific gravity is credited to the famous Greek Mathematician, Archimedes, dating back to 250 B. C. (Rea 1917). The storyline has it that King Heiro II of Syracuse contracted Archimedes to evaluate the gold content in a crown made for him by a metal smith. Archimedes had determined that the quantity of water displaced by his submerged body in a bath pool was equal in measure to the volume his body occupied in the bath. Based on this theory, Archimedes was able to determine that a given mass of silver occupies more volume than an equivalent mass of gold. In his experiment, Archimedes put the crown molded by King Heiro II's metal smith in a container full of water and pure gold in a container of water; he detected that more water spilled from the container when the molded crown was put in it. This made Archimedes confirm that the king's crown was adulterated and not made of pure gold.

1.1.2 Specific Gravity in Civil Engineering Materials

The American Association of State Highway and Transportation Officials (AASHTO) Standard T-85 defines the *specific gravity* of an aggregate as the ratio of the density of a material to the density of distilled water at a stated temperature, the values being dimensionless. Specific gravity is determined at bulk and apparent conditions. In the bulk state, denoted Gsb, both the permeable and impermeable voids on the surface on the aggregate are considered in the volume calculations. Conversely, the apparent specific gravity (Gsa) calculates the specific gravity excluding the permeable voids of the aggregate. The absorption potential of an aggregate is the increase in mass of aggregate due to water penetration into the pores of the particles during a prescribed period of time, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry mass. Gsb (SSD) is used when the fine aggregates are considered to be wet at the time of use.

1.2 Uses & Significance of Specific Gravity and Absorption

Specific gravity and absorption values of fine and coarse aggregates are used in the following applications:

1.2.1 Volumetric Design of Asphalt and Portland Concrete Cement (PCC) Pavements

Voids in the mineral aggregate (VMA), voids filled with asphalt (VFA) and the total voids in mix (VTM) are useful inputs in the volumetric design, mix preparation, and quality control and assurance of asphalt pavement construction. Water-cement ratio determinations for PCC mix are vital in ensuring a mix of high structural integrity and durability. For example, when a highly absorptive aggregate is used in Hot Mix Asphalt (HMA), more asphalt binder is absorbed. In the case of the PCC mix, mixing water requirement for better mechanical strength and durability characteristics is increased when an overly absorptive fine aggregate is used. Less absorptive fine aggregates are satisfactory for the economical design and construction of most construction works.

1.2.2 Freeze Thaw Issues in Civil Engineering Structure

The freeze thaw potential in concrete mixes for civil infrastructure, AC and PCC pavements and structures can be evaluated with the knowledge of the specific gravity and absorption of fine and coarse aggregates. Freeze thaw evaluation is essential for the elimination of damage due to ingression of water, moisture, snow, and other forms of precipitation. The cycle freezing and thawing of fine and coarse aggregates result due to the effect of temperature differential from extreme climatic and environmental changes A high absorption value of fine aggregates tends to result in moisture-related damage.

1.2.3 Stabilization of Earth Structures and Highway Pavements

Specific gravity differentiation techniques are essential in separating good aggregates from deleterious (lighter) materials such as degradable materials like wood, leaves and bones, and non-degradable ones like glass, paper, plastic and rubber. These unwanted materials reduce the overall specific gravity of coarse aggregates. Erosion control techniques, road pavement base and sub-base stabilization measures, and railroad substructure strengthening mechanisms are areas in civil engineering practice where high fine and coarse aggregate specific gravity values are necessary for providing system stability at the optimum layer thickness.

1.3 Problems with AASHTO T 84 Test Method

1.3.1 Time Consuming Nature of AASHTO T84

The AASHTO T84 and its affiliate test, the ASTM C-127, take 15-19 hours and 24±4 hours to complete the test. These test durations are a disincentive for quick AC and PCC mix design, quality control and assurance of construction projects, and research investigations. Averagely, a single test needs a day for the combined process of sample preparation and final testing. The constraints of materials, equipment and man power requirement makes it difficult in terms of time delay for multiple specific gravity and absorption tests on fine aggregates.

1.3.2 Inaccurate Results with Angular & Rough Fine Aggregates

The specification test procedure for the method provides provisional approaches at ascertaining the SSD state of fine aggregates that do not readily slump. These classes of special aggregates include highly angular and rough aggregates. Experience has shown that these aggregates fail to slump considerably when the conventional cone and tamp rod are used in finding the SSD state.

1.3.3 Operator Dependency of Test Method

In using the cone and tamp rod to establish the SSD condition of fine aggregates, operator skill and long term experience is very important. The difficulty in identifying the SSD condition stems from the fact that operator judgment, which is subjective, is the dominating factor. Thus, an experienced materials engineer will obtain different results compared to a student or less experienced engineer.

1.4 Problems with AASHTO T 85 Test Method

1.4.1 Time Consuming Nature of AASHTO T85

Similar to the AASHTO T84, the AASHTO T85 also takes much testing time to conduct. The 24±4 hours creates inconveniences for the facilitation of rapid design, construction quality control and assurance. The construction industry is thus in need of test methods that will reduce drastically the testing time for specific gravity and absorption determination of coarse aggregates.

1.4.2 Underestimation of water absorption of porous coarse aggregates

Work at the Michigan Technological University Materials Laboratory has shown that for some special coarse aggregate types like steel slag and crushed concrete which are highly porous need extended soaking times to satisfy their full absorptive potential.

CHAPTER 2 LITERATURE REVIEW

The development of test methods to determine the specific gravity and absorption of fine and coarse aggregates dates back to the early days of the 20^{th} century. Researchers and engineers tried in earnest to identify single and unique methods to serve all concerned who utilize specific gravity and absorption for practice in civil engineering.

2.1 Fine Aggregate Specific Gravity Test Method Development

Among the early attempts at bulk specific gravity and absorption of fine aggregates was the work undertaken to find the specific gravity of non-homogenous fine aggregates (Rea 1917). Rea's approach found the apparent specific gravity by coating sand materials with kerosene before finding the volume of the sand. The rationale behind coating the fine aggregates is to prevent the penetration of water into the voids. The ASTM Committee C-9 on Concrete and Concrete Aggregates revised this early method, of which the details were carried out in the 1920's ASTM Proceedings report (ASTM 1920)

Further development of a method to find the specific gravity and absorption of sand was shown by Pearson. The method involved finding how dampened grains of sand adhered to the sides of an Erlenmeyer flask (Pearson 1929). Pearson reported that this proposed method underestimated the true absorption value due to incomplete saturation.

Pearson's titration method was modified slightly, and accepted by the ASTM for use as the standard practice for specific gravity and absorption determination (ASTM 1933). The sand was saturated with water and dried back to SSD state based on the operator's visual inspection. 500g of the SSD sample was placed in a 1-qt glass jar, and water added in drops to ascertain whether the material sticks to the sides of the jar. The SSD state condition of this method according to Pearson was highly subjective and thus unreliable.

The use of color change in sand SSD determination has proved to be unreliable and unrepeatable (Chapman 1929) . To further increase the usefulness of the colimetric method of SSD and specific gravity determination, calcium chloride was used to dry the sand for some time (Graf and Johnson 1930). The drying process, it was found unduly removed substantial amounts of water from the SSD sand material.

Additional research worth noting is that of Myers in 1935. Myers found the free moisture in the aggregate using gravimetric, displacement, dilution, colimetric and electrical-resistance principles. All the four methods were not promising due to the fact that visual inspection was used in finding the saturated surface dry state of the fine aggregates during testing (Myers 1935). There have been a number of research advances towards the modification of how the SSD condition of fine aggregate is determined to make the test less prone to error. These advances have also aimed at reducing the test time from about 24 hours to only a few hours.

AASHTO T-84 is currently used to determine the fine aggregate specific gravity and absorption. The method dates back to 1935 when the kerosene method, ASTM tentative method, cone method and visual inspection method were evaluated in order to rank them in terms of which was the most promising. Results from this research showed that the cone method (AASHTO T 84) was the most favorable among the four test methods. The T-84 procedure requires approximately 1kg of the fine aggregate be immersed in water or soaked in at least 6% moisture and allowed to stand undisturbed for about 15 hours. The rationale behind the soaking of the fine aggregate is to enable the full water absorption potential of the aggregate pore surfaces to be satisfied before the specific gravity and absorption are measured in the laboratory. After soaking, the sample is decanted and spread flat on a nonabsorbent surface exposed to a gentle current of warm air, constantly stirred until surface dry, and a cone and tamp rod used to determine its saturated surface-dry state (SSD). The subjectivity of the test in part is when a tester determines when the fine aggregate just slumps after removal of the cone and that in fact the slumped sample is uniformly representative of the approximately 1kg sample.

Attempts at measuring fine aggregate specific gravity based on thermodynamic principles were initiated by the Arizona Department of Transportation (ADOT) (Dana and Peters 1974). Dana and Peters had sought to establish the SSD state of fine aggregates by soaking the sample and placing it in a small rotating drum. As the aggregates were rotated uniformly, hot air was issued through one end to dry it. An attached thermocouple, an electronic device that converted the temperature gradient into an electronic signal, was used to convey data to a digital recorder or sensor. The attainment of the SSD condition caused a sudden drop in the thermal gradient between the incoming and outgoing air. Their work established that the concept of monitoring the temperature gradient of incoming and outgoing air or the relative humidity of the outgoing air had positive results on a wide range of fine aggregates.

Further research on the initiative taken by Dana and Peters added the measurement of the humidity of the outgoing air to the temperature gradient principle (Kandhal et al. 2000). The research demonstrated that the humidity of the outgoing air predicts the SSD condition more accurately than the temperature gradient. A significant recommendation of this work was the improved automation of the thermodynamic device to enable the operation to be stopped immediately after the SSD state is found, and also measuring the final mass of fine aggregate during the process. The device received enhanced modification by the National Center for Asphalt Technology (NCAT) but the repeatability and reproducibility of test results was poor.

In other fine aggregate research developments, the idea of establishing the SSD condition of fine aggregates by examining their flow under gravity off a tilted masonry trowel has been exploited (Krugler et al. 1992). This approach defines the SSD condition to be the state when the aggregates are capable of flowing off freely as discrete individual particles. A second proposed method by Krugler involved placing the fine aggregate samples adjacent to oven-dry ones; and the SSD condition determined as the point where the test materials have the same color as the oven-dry aggregate. Another technique Krugler considered was based upon sliding test samples along the bottom of a tilted pan. When the test sample failed to stick to the bottom and flowed freely, the SSD state was judged to have been reached.

The use of water-soluble glue to detect whether fines aggregates have achieved SSD or not was also developed, and compared to earlier methods at specific gravity measurement (Krugler et al. 1992). Krugler et al. employed a strip of packaging tape (Supreme Super standard gummed paper tape, 5.08 cm medium duty), attached it to a small block of wood and placed the wood with glue on the fine aggregate material. The proposition was that if for two trials not more than one test-sample particle adheres to the tape, the sample was judged to have attained the SSD condition.

Fine aggregates have been known to undergo color transformations with the presence of water on the particle’s surfaces. This colimetric idea of establishing the SSD condition of fine aggregates has been studied and investigated by some researchers

(Lee and Kandhal 1970). The process basically uses a special chemical dye to achieve the same SSD requirements of the AASHTO T-84 procedure. The fine aggregate is first soaked in water containing the dye. When removed from the water, the aggregate which has now taken the color of the dye begins to dry. SSD is said to be reached when the aggregate changes from this color status after receiving dry current from a fan. Lee and Kandhal noted that the dyes never showed well on dark-colored aggregates, exhibited non-uniform mixing when the fine aggregates were being dried and the color change was highly subjective. These notable and problematic observations made this proposition impracticable and difficult.

Some important successes in specific gravity research worth mentioning are Saxer's absorption curve procedure (Saxer 1956), Hughes and Bahramain's saturated air-drying method (Hughes 1967) and Martin's wet and dry bulb temperature method (Martin 1950). These test methods required a high level of expertise to perform and to improve their practicability, extensive modifications were suggested.

Quite recently, automated equipment such as the SSDetect, AggPlus and the Langley system have been developed by material testing engineers to address the aforementioned limitations of AASHTO T84. For example, the SSDetect, which is more scientific in nature, has been known to have statistically similar results with AASHTO T84 according to research conducted on Oklahoma fine aggregates (Cross 2006). Cross et al. also demonstrated that the new SSDetect could have better repeatability than the traditional fine aggregate specific gravity and has great potential in replacing AASHTO T84. Cross et al. reported that this electronic innovation had great potential in specific gravity measurement since the vacuum sealed results were comparable to that of the AASHTO T84.

Another significant scientific input towards improvement in specific gravity determination is the use of the vacuum sealing approach – a single test method (Hall 2002). The method measures specific gravity by using electronic vacuum sealing procedure to expel fine aggregates packed in standard polythene bags. Hall observed also that tests of aggregate blends do not appear to be sensitive to nominal maximum aggregate size, gradation nor mineralogy.

At Michigan Technological (Tech) University, researchers investigated the applicability of the automated helium pycnometer in fine aggregate specific gravity analysis in geotechnical engineering (Vitton et al. 1999). Current specific gravity test methods require soaking for close to 24 hours to satisfy most of the absorption potential. However, it is recognized that for some highly absorptive aggregates, not all of the effective pore space may be saturated after 24 hours. Helium gas, on the other hand, can more easily absorb into a material's effective pore space. The helium pycnometer uses the ideal gas law, $PV=nRT$, to determine the volume of a material based on pressure measurements of helium gas. By knowing the dry mass of a soil, the specific gravity of the aggregate can be determined.

Michigan Tech researchers explored another alternative (Vitton et al. 1999) -- the automated envelope density analyzer. This device determines the bulk volume or envelope volume of a sample by measuring the volume of a fine-grained material in a cylinder, and then again measuring the volume of the fine-grained material plus the sample. By finding the difference in volume between the two measurements, the bulk volume of the sample can be calculated and the bulk specific gravity determined. The findings concluded that the helium pycnometer can be used to automate the testing of aggregate to determine apparent specific gravity. A combination of the helium pycnometer and the envelope density analyzer can be used to calculate the absorption and bulk specific gravity (SSD).

In Michigan Technological University, You et al. (2008) conducted research on the fine aggregate specific gravity by comparing the SSDetect and AASHTO T84. It was found that the SSDetect and AASHTO T84 had very good correlation in specific gravity. This paper is based upon the existing work and expanded tested materials.

There are some other methods such as a gamma-ray method (Core Reader), Paraffin-Coated test, and other methods used in HMA and Portland cement concrete (PCC) materials testing. The CoreLok (vacuum sealing) method has been evaluated further by a number of state transportation agencies and many universities (Prowell and Baker 2004). Table 2 is a summary of some of the research work conducted for fine aggregate specific gravity testing.

2.2 Coarse Aggregate Specific Gravity Test Method Development

The challenges that result from the AASHTO T85 (ASTM C-127) test method for coarse aggregate specific gravity and absorption has prompted many researchers to explore how best this test approach can be improved.

Washburn and Bunting (Washburn and Bunting 1922) employed a gas expansion method based on Boyle's law to determine porosity of coarse aggregates. In this research, isolated voids were counted as solids, and thus the method measured effective porosity if the sample is not powdered. Knowledge of the effective porosity was critical in finding the specific gravity and water absorption percent of the coarse aggregates.

In 1959, Dolch (Dolch 1959) further expanded on the knowledge of effective porosity by conducting tests on limestone aggregates, measuring the parameter with the McLeod gauge porosity developed by Washburn and Bunting (Washburn and Bunting 1922). Dolch's research objective was to evaluate how the physical characteristics of aggregates impact on their specific gravity and absorption determination. The method gives a value for the effective void volume by causing the head to be lowered on a dry sample while it is immersed in mercury. The air in voids expands and leaves the sample and is then measured volumetrically at atmospheric pressure. The porosity was then obtained after the bulk volume of the sample was determined by the use of shaped pieces.

One of the most effective and frequently used methods of determining the specific surface of a solid was the sorption method (Brunauer (1938)). The specific surfaces were obtained from sorption isotherms. The sorption absorption method had also been used indirectly to obtain a curve for pore size distribution. Other methods for determining pore size and specific surface are small angle – ray scattering, heat of immersion, rate of dissolution, ionic adsorption, and radioactive and electrical methods.

During the early 1970's, the most frequently used method of absorption determination was the injection of mercury into the pore system (Ritter and Erich July 1948). The pressed mercury was used in finding the pore size distribution of aggregates. The model was based on the assumption that the pores existed as a system of circular capillaries. Washburn established that the relationship between the applied pressure, p;

radius of the pore, r; surface tension of mercury, σ; contact angle between the mercury and the solid coarse aggregate, θ; is given as:

$$p = - 2 \sigma \cos \theta. \quad [1]$$

Further development was based upon Washburn and Bunting's concept for practical use, and thus an apparatus was developed for measuring the penetration of mercury into aggregate pores (Drake 1945). The apparatus is generally referred to as a mercury porosimeter. Subsequently, Drake (Drake 1945) utilized a high pressure mercury porosimeter. The mercury penetration method has been used over a range of pore sizes in research work and has been applied successfully to PCC aggregates (Hiltrop 1960).

During the first year of a Highway Research Project HR-142 (Lee and Kandhal 1970), a special study was conducted to develop new, simple, and more reproducible method to determine the bulk specific gravity or the saturated surface-dry condition for granular materials. As a result, a new chemical indicator method was developed to determine the saturated surface-dry condition, and a glass mercury pycnometer was designed to determine the bulk specific gravity of large aggregates.

Vitton et al. (Vitton et al. 1999) investigated the applicability of the automated helium pycnometer in aggregate specific gravity analysis in geotechnical engineering. The research targeted how to best measure the specific gravity of highly absorptive coarse aggregates. This was necessitated by the discovery that the conventional 24±4hours failed to satisfy the full absorption potential of highly absorptive aggregates. Helium gas, on the other hand, can more easily absorb into a material's effective pore space. A helium pycnometer uses the ideal gas law, $PV=nRT$, to determine the volume of a material based on pressure measurements of helium gas. By knowing the dry mass of the aggregate, the specific gravity of the aggregate can be determined. Another alternative Vitton et al. (Vitton et al. 1999) explored was the use of the automated envelope density analyzer. This device determines the bulk volume or envelope volume of a sample by measuring the volume of a fine-grained material in a cylinder, and then again measuring the volume of the fine-grained material plus the sample. By finding the difference in volume between the two measurements, the bulk volume of the sample can be calculated and the bulk specific gravity determined. The findings concluded that the helium pycnometer can be used to automate the testing of coarse aggregates to determine apparent specific gravity while the envelope density analyzer is applicable for specific gravity measurement of coarse aggregates. A combination of the helium pycnometer and the envelope density analyzer can be used to calculate the absorption, and bulk specific gravity (SSD).

Hall (Hall 2002) performed research work on improving the existing AASHTO T 85 method of specific gravity and absorption testing of coarse aggregates. This work concentrated basically on the evaluation of the use of a single test – vacuum sealing approach - to determine specific gravity and absorption of coarse aggregate blends. The process involves using the vacuum sealing device to suck all entrapped air within the dry coarse aggregate which has been placed in a standard plastic bag. The vacuum sealing method eliminates the traditional long soaking periods. Hall compared his results with mathematical combinations of specific gravities from the individual tests. The research revealed statistically similar results. Hall added that the tests of aggregate blends do not appear to be sensitive to nominal maximum aggregate size, gradation or mineralogy.

CHAPTER 3 MATERIALS TESTED

3.1 Fine Aggregate Materials

The aggregates used in the research work were typical of those found in the state of Michigan. Sand and gravel are two of the most important sources of fine aggregates commonly found throughout the northern part of the United States due to glacial deposits and occur in other parts of the United States from old lake or river beds.

The research considered a range of fine aggregate source materials with varying gradations to determine if their specific gravity and absorption values measured by the SSDetect were comparable to AASHTO T 84. Fine materials that have been used in this study are listed in Table 1. The four source materials shown with the various sieve sizes were tested for each sieve fraction as indicated, while the last 10 source materials in the table were tested as "as received" gradation ranging in sieve size from the 4.75 to the 0.075mm sieve. The Ross 2006, FMS 2354-2006, FMS 2370-2006 and FMS 2324-2006 fine aggregates had 44, 58, 51 and 50% carbonate minerals respectively. Siliceous and other minerals contained in the Ross, 2354, 2370 and 2324 were 56, 42, 49 and 50 %, respectively. In addition to the blended 'as received' fine aggregate blend, a number of the aggregates were blended to attain Michigan Department of Transportation (MDOT) specifications, namely gradations. These materials were tested with the SSDetect device. The MDOT blended gradations that were used in this analysis are shown in Table 1.

3.2 Coarse Aggregate Materials

The materials that were considered for this research were typical of natural, recycled and manufactured coarse aggregates currently used in the construction industry in Michigan. Michigan aggregates represent those that are ideal for both the cold (winter) and hot (summer) climates of the United States. These aggregates thus have strength and material properties that are similar to those used in other parts of the United States.

Table 1 Fine aggregate materials tested in the research

MATERIAL	GRADATION RETAINED (mm)
RJH (Crushed Natural Gravel) MHL (Crushed Limestone) RJH (Crushed Steel Slag) Ross 2006 (Natural Sand) FMS 2324-2006 (Fine Manufactured Sand)	2.36
	1.18
	0.600
	0.300
	0.150
FMS 2354-2006 (Fine Sand)	2.36
	1.18
	0.600
FMS 2370-2006 (Manufactured Sand)	2.36
	1.18
	0.600
	0.300
	0.150
	0.075
HMA 5E10 –MKF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 5E10 –MKF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 5E10 -AIF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 5E10 -NLF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 4E10 -ARF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 3E10 -APF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 2E10 -APF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 5E3 -GMF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 2E10 -SLF (Sand/Gravel Blends)	As Received Fine Aggregate
HMA 3E3 -GMF (Sand/Gravel Blends)	As Received Fine Aggregate

For the natural coarse aggregates, the range of materials tested included sand, trap rock, limestone and gravel. Recycled concrete aggregates used were crushed concrete while the manufactured coarse aggregate was steel slag. Selecting these types of coarse materials was important in examining the impact and extent due to aggregate type and properties on the specific gravity and absorption values. The materials tested exhibit diverse physical characteristics such as surface void distribution, angularity and sphericity. The tested materials, with their respective gradations for the research project are given in Table 2.

Table 2 Coarse aggregate materials (including highly absorptive aggregates) tested in the research

Coarse Aggregate Material	Tested Sieve Sizes (Retained)
ROSS (Sand)	# 4
Red Crushed Stone	# 4
Trap Rock	3/8"
Steel Slag (highly absorptive aggregates)	# 4
	3/8"
	1/2"
	3/4"
Crushed (Recycled) Concrete (highly absorptive aggregates)	# 4
	3/8"
	1/2"
	3/4"
Limestone	# 4
	3/8"
	1/2"
	3/4"
	1"
River Gravel	# 4
	3/8"
	1/2"
	3/4"
	1"

In addition to the 24 hours soaking times required for the AASHTO T-85, the specific gravities and water absorption percent of steel slag extended soaking times of 36, 48 and 72 hours were investigated. The tested materials at their various gradations are shown in Table 3. Table 3 shows the different types of absorptive or highly porous coarse aggregates tested in addition to the steel slag. Crushed or recycled concrete, gravel and limestone were evaluated for their absorptive capacity over the extended soaking times.

Table 3 Coarse aggregates tested over extended soaking times

Material	Gradation retained
Slag (highly absorptive aggregates)	#4
Crushed concrete (highly absorptive aggregates)	1/2"
Gravel	3/4"
Limestone	1/2"

CHAPTER 4 RESEARCH METHODOLOGY

4.1 The SSDetect Automated Approach

The research methodology involved the exploration of two methods that could serve as better alternatives for the determination of the specific gravity and absorption of fine and coarse aggregates. For fine aggregates, the Automated SSDetect is selected as a potentially good substitute for the conventional AASHTO T 84. The SSDetect was evaluated to determine its potential to test the fine aggregates in less than 60 minutes while providing more repeatable and accurate results. Additionally, the equipment could eliminate the element of operator dependency which was associated with the AASHTO T 84. The SSDetect basically operates on the laws of reflection and scattering of light rays to determine when fine aggregates have reached their SSD state. The hypothesis is that unlike the AASHTO T 84, the SSDetect could eliminate the subjectivity in finding the SSD condition of the fine aggregates when testing for their specific gravity and absorption. Figure 1 indicates the flow chart diagram for the exploring the difference between the SSDetect and the AASHTO T 84.

4.2 The Vacuum Saturation Approach

The Vacuum Saturation Approach is the proposed method that could serve as a viable alternative for the AASHTO T 85. The approach involves employing the use of the rice vacuum saturation method to replace the existing 24 ±4 hours soaking procedure which is characteristic of AASHTO T 85. The method can be thought of as an incorporation of the standard method for finding the theoretical maximum density, *Gmm*, of asphalt paving mixtures into finding the specific gravity and absorption of the coarse aggregates. Rice in 1952 developed this asphalt mixture testing approach to determine its void content using pressure. The first part of the test procedure is the vacuum saturation process, after which the coarse aggregate SSD state is determined using a dry absorbent cloth which is specified in AASHTO T 85. Vacuum saturating the aggregates were conducted at three selected time periods – 10, 20 and 30 minutes. The choice of these time durations was to evaluate which of the three produces the most statistically similar specific gravity and absorption values with AASHTO T 85. In terms of the vacuum pressure, a 30 ± 2mm (4.0 ± 0.5kPa) was chosen to remove all the entrapped air within the coarse aggregate mass and replace any air voids within the effective pores of the aggregates with water.

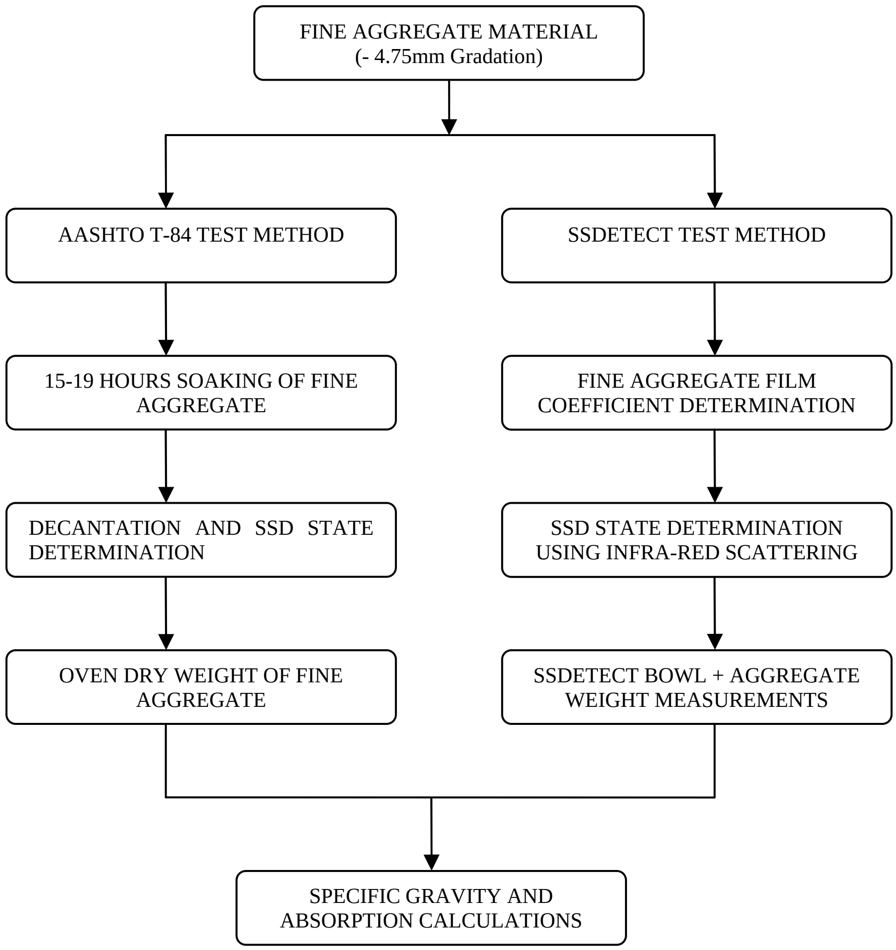

Figure 1. Flow chart indicating the processes carried out for the AASHTO T 84 against the SSDetect

4.3 The Statistical Analysis of Results

Three replicates were tested for each of the fine and coarse aggregate materials. The sources sampled and investigated were natural, manufactured and recycled aggregates.
For both the fine and coarse aggregates, three trial tests were conducted per individual sieve size and blended gradation, and the results averaged to represent the specific gravity and absorption values.

Spearman correlation coefficient, least square difference, Tukey test and paired t-Test for difference in mean values were utilized in analyzing the results of the AASHTO T 84 and SSDetect test methods. In evaluating the difference between the AASHTO T 85 and the Modified Rice Test Method, the paired t-Test for mean difference and the confidence interval for mean values were used.

CHAPTER 5 THE AUTOMATED SSDETECT

5.1 Standard AASHTO T-84 Test Method

The fine aggregates were initially tested according to AASHTO T 84, *Standard Test Method of Test for Specific Gravity and Absorption of Fine Aggregate*. About 1000g of the fine aggregate, sampled using the AASHTO T 248 Test Procedure, *Reducing Field Samples of Aggregates to Testing Sizes*, was dried at a constant temperature of 110 ± 5°C. Upon cooling to handling temperature, the material was immersed in 6-percent moisture and allowed to stand overnight for 15 hours. The water was decanted and spread on a flat non-absorbent surface. With the aid of moving current from a hair drier, the fine aggregates were continuously dried and stirred. Within intervals, portions of the partially dried fine aggregates were put in the frustum cone, and made to heap above the top of the mold. 25 light blows of the tamping rod are applied to the fine aggregate, and into the mold. The slight slump of the tested aggregates gave an indication of the SSD state. The frustum cone and tamping rod used is shown in figure 2. The mathematical calculations of the specific gravities were conducted according to the formulae in the Appendix of the AASHTO T84 test procedure.

Figure 2. The AASHTO T84 set-up

5.2 SSDetect Test Method

The SSDetect device works on the basic principle of the laws of reflection. Objects can be seen by their characteristic nature of reflecting light rays that fall on them. The reflected light rays conform to the scientific law of reflection, which in simpler terms proves that the angle of reflection is equal and opposite to that of the angle of incidence. The law of reflection is represented pictorially in figure 3.

Some objects however exhibit scattering of light rays – a phenomenon which occurs when light rays are reflected at a number of angles after the incident rays fall on uneven or granular surfaces. Fine aggregates, like most materials, obey the law of reflection when viewed on the microscopic level but since the irregularities on its surface are larger than the wavelength of light, the light is reflected in many directions. This phenomenon is indicated in figure 4. The SSDetect operates on this principle to ascertain the SSD state of the fine aggregates when thin films of moisture are coated on the particles. The surface moisture causes diffusive reflection of the rays which are then picked up by the laser system in the SSDetect unit. The new SSDetect basically involves a 2- step procedure: determination of the film coefficient and infra-red detection of the SSD condition of the fine aggregate sample.

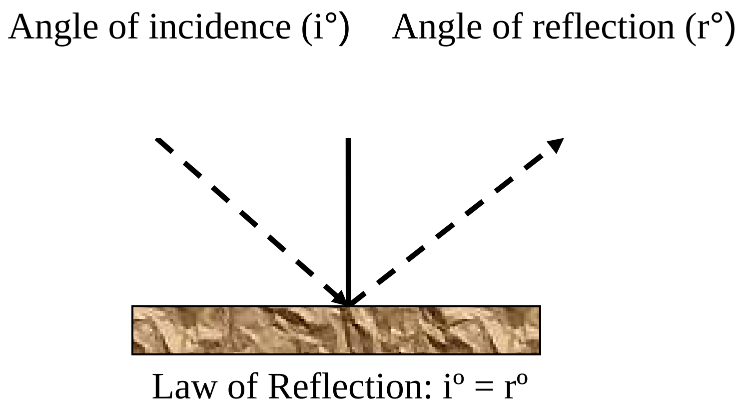

Figure 3. The Law of reflection of light on an even surface

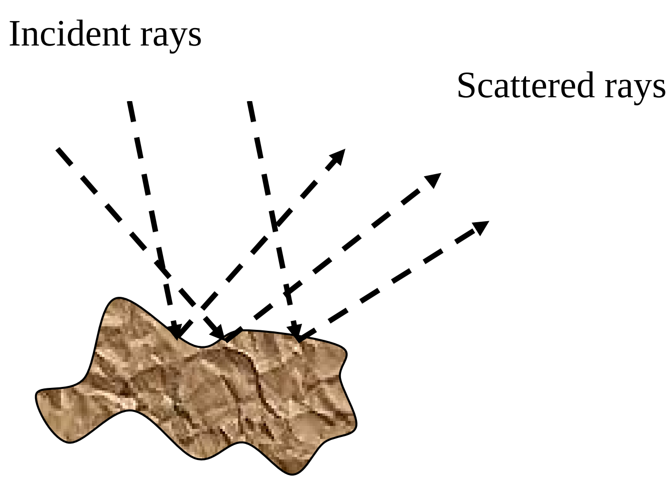

Figure 4. Scattering of light rays on an uneven surface (fine aggregate

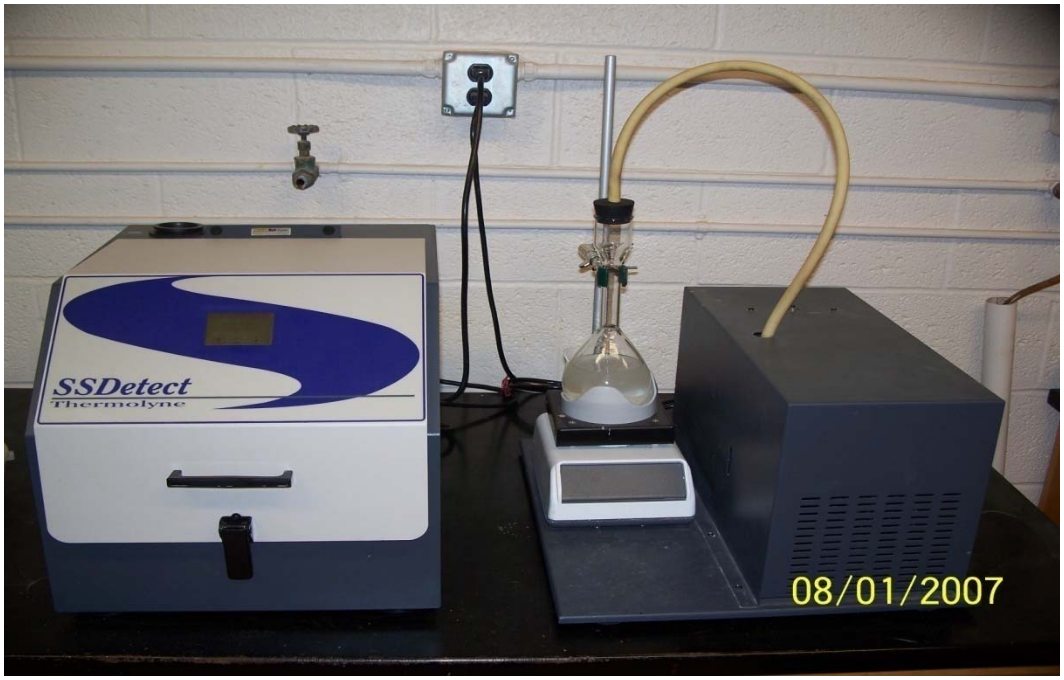

Figure 5. The SSDetect with AVU unit

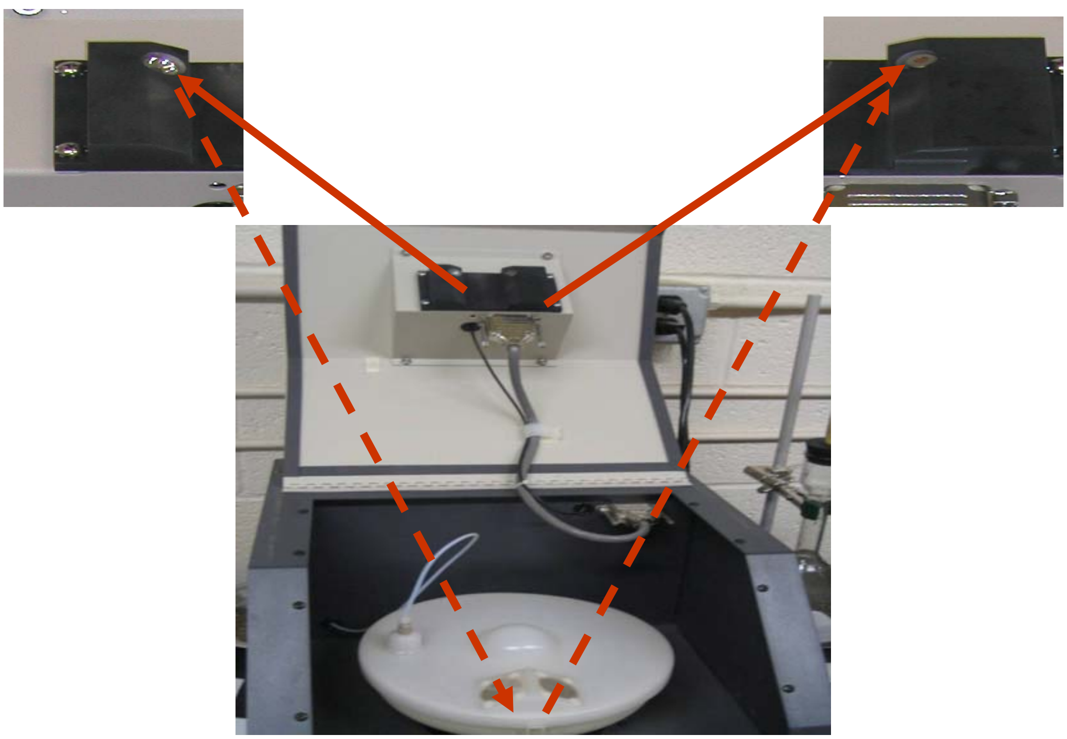

Figure 6 Internal components of the SSDetect

5.2.1 Film Coefficient Determination

The film coefficient or "Baseline" test was conducted to determine the minimum amount of water needed to form an effective film coating on a unit fine aggregate particle. 500g of the fine aggregate and 250ml of water was put into a pycnometer, and water filled to the calibration line before the final total mass was found. After vacuum agitating the pycnometer with contents using the Automated Vacuum Unit (AVU), water was refilled back to the calibration line and total mass of pycnometer plus contents determined. This film coefficient value, which is empirical and increases as aggregate size increases, was calculated by the following formula:

$$F_c = 52 + 4x - (0.11x^2) \qquad [1]$$

Where:

F_c is the film coefficient value and;

x is the difference between the initial and final mass of the pycnometer and its contents.

A plot of the film coefficient of a characteristic film coefficient curve for the fine sand aggregate material used in this research is shown is figure 7.

5.2.2 Infra-Red Detection of SSD Condition of Fine Aggregates

A second 500g of the fine aggregate was put into the special SSDetect bowl and the film coefficient value entered into the system input screen. The special SSDetect bowl has been designed specifically, in terms of dimensions and style, to ensure the complete orbital mixing of the fine aggregate material before it attains the SSD state. Once initiated, the SSDetect unit injected water through a nozzle mounted on the lid of the test bowl into the flow of the material. The SSDetect mixes the fine aggregate inside the bowl by using an orbital motion. Through capillary action and hysteresis, the water is absorbed into the pores of the aggregate. The forces of capillary and hysteresis act very strongly to pull water into the aggregate pores quickly. Upon satisfying the optimum water potential of the fine aggregate pores, the water begins to gather on the surface of the aggregate.

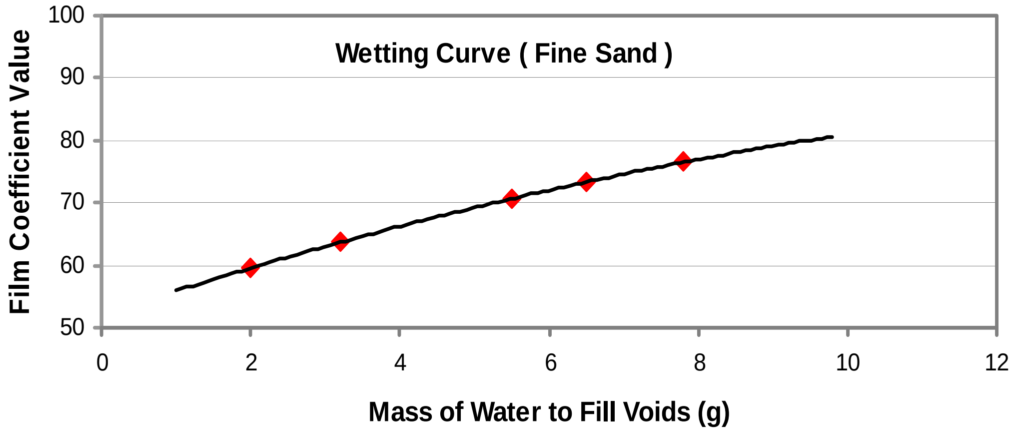

Figure 7 Film Coefficient Curve for the fine sand aggregate

As the process continued, infra-red rays were transmitted through a transparent lens on the top of the bowl unto the fine aggregate surface. The reflected infra-red rays then indicated the SSD state of the fine aggregate. The test duration is approximately 2 hours. After the test, the mass of the SSD sample was determined, and the difference between the 500g fine aggregate and final SSD mass calculated as the water absorbed during the SSDetect test.

5.2.3 SSDetect Mathematical Relationships

Finding the specific gravity and percent absorption with the SSDetect of the fine aggregate involves the following mathematical computations:

$$Gsb\ (Dry) = A/\ (A+B-C+D) \quad [2]$$

$$Gsb\ (SSD) = (A+D)/(A+B-C+D) \quad [3]$$

$$Gsa = E/(E+B-C) \quad [4]$$

$$Wa\% = (D/A) \times 100 \quad [5]$$

Where A is the dry sample mass in SSDetect bowl in grams; B is the mass of volumetric flask filled with water in grams; C is the final mass in grams of flask with contents in film coefficient determination; D is the water absorbed by the 500g fine aggregate in the SSDetect bowl; and E is the mass in grams of dry aggregate in film coefficient determination test.

CHAPTER 6 THE VACUUM SATURATION METHOD

6.1 Standard AASHTO T-85 Test Method

Coarse aggregate samples are immersed in water for an approximate 24±4 hours. This specification was from ASTM C-127 – 04, after which the AASHTO T85 was followed.
The soaked aggregates were then removed from the soaking chamber, and rolled in a dry non-absorbent cloth to trap all the available moisture on the surface of the coarse aggregates. The relevant weights that were taken for the specific gravity and absorption include the SSD weight (submerged and in air condition) and the oven (dry) weights.

6.2 Vacuum Saturation Approach

The proposed research methodology involves employing the use of the rice vacuum saturation method to replace the existing 24 ± 4 h soaking procedure which is characteristic of AASHTO T 180. The method can be thought of as an incorporation of the standard method for finding the theoretical maximum density, Gmm, of asphalt paving mixtures into finding the specific gravity and absorption of the coarse aggregates.
Rice [12] in 1952 developed this asphalt mixture testing approach to determine its void content using pressure. The first part of the test procedure is the vacuum saturation process, after which the coarse aggregate SSD state is determined using a dry absorbent cloth which is specified in AASHTO T 85. Vacuum saturating the aggregates were conducted at three selected time periods – 10, 20 and 30 min. The choice of these time durations was to evaluate which of the three produces the most statistically similar specific gravity and absorption values with AASHTO T 85. In terms of the vacuum pressure, a 30 ± 2 mm (4.0 ± 0.5 kPa) Hg was chosen to remove all the entrapped air within the coarse aggregate mass and replace any air voids within the effective pores of the aggregates with water. Three replicates were tested for each coarse aggregate source. The sources studied were natural, manufactured and recycled aggregates. Averages of the calculated values from the three replicate tests were used as the representative specific gravity and absorption values.

Figure 8. The set-up of the AASHTO T85

Figure 9. The Vacuum saturation apparatus used to expel the air in the coarse aggregate mass and force water into the pores of the aggregates

CHAPTER 7 TESTING BLENDED FINE AND COARSE AGGREGATES

7.1 SSDetect for Blended Fine Aggregates

In the standard AASHTO T-84 specific gravity and absorption testing, blended fine aggregates are tested in two ways: testing the blended fine aggregate together or using the proportionate formula to find a calculated blended specific gravity and absorption value. The calculated specific gravity is obtained using the formula below:

$$Gsbc = 1/ [(Pb1/Gsb1) + (Pb2/Gsb2) + (Pb3/Gsb3) + ...] \quad (6)$$

Where:

Gsbc is the specific gravities at either dry, SSD, or apparent conditions; *Gsb1*, *Gsb2*, and *Gsb3* are the specific gravities of the first, second, and third individual fine aggregates used in the total blend; and *Pb1*, *Pb2*, and *Pb3* are the percentage contributions of the first, second, and third individual fine aggregates used in the total blend.

To determine whether the calculated blend values were comparable to the SSDetect values for the blend, the prepared MDOT blends were tested with the SSDetect and their individual gradation values used to obtain the calculated values. Table 4 gives the fine aggregate MDOT blends tested with the SSDetect.

Table 4 Blended fine aggregates tested (MDOT Designation)

MATERIAL	MDOT RATING	TOTAL PERCENT PASSING					
		# 4	# 8	# 16	# 30	# 50	# 100
Natural Sand, Fine and Manufactured Sand, Limestone, Gravel and Slag Fines	2 NS	100	65	35	20	10	0
	2 SS	100	80	50	25	15	0
	2 MS	100	95	0	0	30	0

7.2 Vacuum Saturation Method for Blended Coarse Aggregates

In parallel with the work done in blending the fine aggregate and testing them as such, the coarse aggregates were blended according to MDOT blend specifications. The coarse aggregate blends, with the respective contributions of the individual sieves, are shown in Table 5.

Table 5 Blended coarse aggregates tested (MDOT Designation)

MATERIAL	MDOT RATING	TOTAL PERCENT PASSING					
		1"	3/4"	1/2"	3/8"	#4	#8
Limestone Steel Slag Crushed Concrete	25A	100	100	96	60	30	0
	26A	100	100	98	60	25	0
	29A	100	100	100	90	10	0
	6AAA	100	85	30	0	0	0
	6AA	95	0	30	0	0	0

CHAPTER 8 RESULTS AND ANALYSIS

8.1 AASHTO T84 versus SSDetect

8.1.1 Individual Gradations and As Received Fine Aggregates

The results of the source aggregates (individual gradations) and the as received fine aggregates are summarized in this section separately. Table 1, 2, 3, and 4 in Appendix A section gives detailed results of the all the Gsb (dry), Gsb (SSD), Gsa and Wa % tests for both AASHTO T-84 and SSDetect, and their standard deviations values.

8.1.2 Bulk Specific Gravity (Dry)

The plot of bulk specific gravity (dry) relationship between the AASHTO T-84 and SSDetect showed a good relationship with an R^2 of 0.925 and is shown in Figure 1 of Appendix B. A large percentage of the fine aggregates tested, 97.7% (42 of 44), satisfied the AASHTO T-84 acceptable standard specification range (single-operator precision) of 0.032 for any similar given fine aggregate material. The paired t-test for mean Gsb (dry) analysis at the 95 % significance level showed that there was no significant difference between the two methods. The confidence interval for difference in mean Gsb (dry) was found to be (-0.0108, 0.0008) about the mean values.

8.1.3 Bulk Specific Gravity (SSD)

The coefficient of correlation for the Gsb (SSD) was good with an R^2 of 0.925 and is shown in Figure 2 of Appendix B. For the Gsb (SSD), 97.7% of the results satisfied the acceptable standard specification range (single-operator precision) of 0.027 representing 42 out of the 44 results. The results also showed no statistical difference at the 95% level of significance with a confidence range of between -0.0039 and 0.0059 about the mean values.

8.1.4 Apparent Specific Gravity (Gsa)

Approximately two thirds, 28 out of the 43 results, satisfied the AASHTO T-84 range (single-operator precision) of 0.027 with an R^2 coefficient of 0.721 and is summarized in Figure 3 of Appendix B. With a mean difference range of between 0.0056 and 0.0264, the paired t-test showed a significant difference between the measurements of the two methods at a 95% level of significance.

8.1.5 Water Absorption (Wa %)

The coefficient of determination was poor with an R^2 of 0.235 and is shown in Figure 4 of Appendix B. 14 of the 44 results (97.7%) satisfied the acceptable standard specification range (single-operator precision) of 0.31. The results also showed statistical difference at the 95% level of significance with a confidence range of between 0.634 and 0.310 about the mean values.

8.2 Spearman Correlation Coefficients

Table 6 summarizes the correlation coefficients between AASHTO T84 and the SSDetect methods for determining the Gsb (dry), Gsb (SSD), Gsa and Wa %. The correlation coefficients are high for Gsb (dry), Gsb (SSD) and Gsa for the two different methods; with all of the values greater than 0.80. However, the correlation coefficient between the two methods is rather low, 0.405, for the Wa %.

Table 6 Spearman correlation coefficients

TEST METHOD / RESULT		AASHTO T84			
		Gsb (dry)	Gsb (SSD)	Gsa	Wa %
SSDETECT	Gsb (dry)	0.894			
	Gsb (SSD)		0.899		
	Gsa			0.801	
	Wa %				0.405

8.3 Least Square Difference & Tukey Test

Statistical means testing was conducted to examine if statistical differences exist between the two methods. The three types of specific gravities and water absorption for the sieve sizes were analyzed using means tests. This consisted of determining the difference between the levels of each factor and calculating a 95% confidence interval. The confidence intervals and the significance of the differences were calculated using two methods: Least Squares Difference (LSD) and Tukey. The LSD method controls the Type I comparisonwise error rate while the Tukey method controls the Type I experimentwise error rate and results in the LSD method being less conservative in the means testing than the Tukey Method. The outcome of these mean tests is summarized in Table 7 and 8.

120 mean comparisons were done for all sieve size combinations using the LSD and Tukey methods. 53 mean differences were identified for the LSD method as identified in Table 7 with “Yes” whereas 36 mean differences were identified for the Tukey method as shown in Table 8. Both methods of determining the three different specific gravities using both types of means comparisons show that the specific gravity values for the sieve sizes (#8, #16, #30, #50, and #100) are different than the #200 sieve size.

The results of the means testing for the other sieve size comparisons for the specific gravities were not consistent as some means were different and in other instances the means were not different. These results lead to the belief that the SSDetect better determines the three specific gravities for the #8, #16, #30, #50, and #100) sieve sizes than for the #200 sieve. This could be due to the fact that the SSDetect laser beam is not effective in finding the SSD state of a closely-packed #200 particles. The closeness of the particles makes it impossible for the infra-red rays to locate other SSD state particles aside the ones at the surface. There is thus, non-uniformity in SSD determination when the #200 is tested.

The outcomes of the means comparisons for the water absorption for both AASHTO T84 and the SSDetect were inconsistent.

Table 7 Summary of LSD Means Testing

Sieve Comparison	AASHTO T-84				SSDetect			
	Gsb, dry	Gsb, ssd	Gsa	Wa	Gsb, dry	Gsb, ssd	Gsa	Wa
#8 vs. #16	**Yes**	**Yes**	No	No	**Yes**	**Yes**	No	**Yes**
#8 vs. #30	No	No	**Yes**	No	**Yes**	No	No	**Yes**
#8 vs. #50	No	**Yes**	**Yes**	No	**Yes**	No	No	**Yes**
#8 vs. #100	No	**Yes**	**Yes**	No	**Yes**	No	No	**Yes**
#8 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#16 vs. #30	No	No	No	**Yes**	No	No	No	No
#16 vs. #50	No	No	**Yes**	**Yes**	No	No	No	No
#16 vs. #100	No	No	**Yes**	**Yes**	No	**Yes**	**Yes**	No
#16 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#30 vs. #50	No	No	No	No	No	No	No	No
#30 vs. #100	No	No	No	No	No	No	No	No
#30 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#50 vs. #100	No	No	No	No	No	No	No	No
#50 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#100 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No

Table 8 Summary of Tukey Means Testing

Sieve Comparison	AASHTO T-84				SSDetect			
	Gsb, dry	Gsb, ssd	Gsa	Wa	Gsb, dry	Gsb, ssd	Gsa	Wa
#8 vs. #16	No	No	No	No	**Yes**	**Yes**	No	No
#8 vs. #30	No	No	No	No	No	No	No	No
#8 vs. #50	No	No	**Yes**	No	**Yes**	No	No	No
#8 vs. #100	No	No	**Yes**	No	No	No	No	No
#8 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#16 vs. #30	No	No	No	No	No	No	No	No
#16 vs. #50	No	No	No	**Yes**	No	No	No	No
#16 vs. #100	No	No	No	No	No	No	No	No
#16 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#30 vs. #50	No	No	No	No	No	No	No	No
#30 vs. #100	No	No	No	No	No	No	No	No
#30 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#50 vs. #100	No	No	No	No	No	No	No	No
#50 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No
#100 vs. #200	**Yes**	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	No

8.4 AASHTO T85 versus Vacuum Saturation Test

The statistical analysis of the AASHTO T85 versus Vacuum Saturation Test is given in Table 9 and 10 below.

8.4.1 Bulk Specific Gravity (Dry)

8.4.1.1 AASHTO T 85 versus 10 Minutes Vacuum Saturation Test

The linear relationship plot for Gsb (dry) between the AASHTO T 85 and the 10 min Vacuum Saturation test has an R^2 of 0.943 and is shown in Fig. 9 of Appendix C. Using the paired T-test for mean difference and a 95% confidence level, the confidence interval for mean difference is (-0.018, 0.014). With 0 not inclusive it is concluded that no statistical difference occurs between the AASHTO T 85 and the 10 minutes Vacuum Saturation test for Gsb (dry).

Table 9 Statistical Analysis of the AASHTO T 85 versus the Vacuum Saturation Test

STATISTICAL MEASURE	Gsb (Dry)			Gsb (SSD)		
	T85 vs. 10''	T85 vs. 20''	T85 vs. 30''	T85 vs. 10''	T85 vs. 20''	T85 vs. 30''
$R^{2\,(\%)}$	94.3	90.3	96.8	93	86.5	96.4
Lower 95% Mean Confidence Interval	-0.018	-0.0183	-0.0234	-0.0234	-0.0214	-0.0266
Upper 95% Mean Confidence Interval	0.014	0.0063	0.0014	0.0094	0.0034	0.001
T - Critical	2.089	2.089	2.089	2.089	2.089	2.089
T – Test (paired T-test for means)	0.264	1.012	1.779	0.947	1.445	2.034
Statistical Difference	No	No	No	No	No	No

Table 10 Statistical Analysis of the AASHTO T 85 versus the Vacuum Saturation Test

STATISTICAL MEASURE	Gsa			Wa%		
	T85 vs. 10''	T85 vs. 20''	T85 vs. 30''	T85 vs. 10''	T85 vs. 20''	T85 vs. 30''
$R^{2\,(\%)}$	76.5	63.2	82.8	77.3	79.0	83.4
Lower 95% Mean Confidence Interval	-0.0522	-0.0435	-0.0478	0.484	0.4694	0.2966
Upper 95% Mean Confidence Interval	0.0142	0.0155	0.0098	-0.755	-0.6707	-0.5346
T - Critical	2.089	2.089	2.089	2.089	2.089	2.089
T – Test (paired T-test for means)	1.186	1.008	1.412	1.046	0.781	0.596
Statistical Difference	No	No	No	No	No	No

8.4.1.2 AASHTO T 85 versus 20 Minutes Vacuum Saturation Test

The linear regression trend has an R^2 of 0.903 and a mean confidence interval of (-0.0183, 0.0063) at the 95% confidence level. The 95% confidence interval of (-0.0183, 0.0063) suggests that no significant different occurs between the two methods. Fig. 10 of Appendix C shows the regression plot.

8.4.1.3 AASHTO T 85 versus 30 Minutes Vacuum Saturation Test

The linear trend has an R^2 of 0.968 and a 95% mean confidence interval of (-0.0234, 0.0014). No statistical difference occurs between the results of the AASHTO T 85 and 30 minutes of the Vacuum Saturation test. The plot of the linear relationship is shown in Fig. 11 of Appendix C.

8.4.2 Bulk specific gravity (SSD)

8.4.2.1 AASHTO T 85 versus 10 Minutes Vacuum Saturation Test

The R^2 for the Gsb (SSD) is 0.930 and is shown in Fig. 12 of Appendix C. The 95% mean–difference confidence interval is between -0.0234 and 0.0094; suggesting statistical similarity between the two methods.

8.4.2.2 AASHTO T 85 versus 20 Minutes Vacuum Saturation Test

Fig. 13 of Appendix C shows the graphical plot between the AASHTO T 85 and 20 min of vacuum saturation for Gsb (SSD), which has an R^2 of 0.865. The results exhibited no statistical difference at the 5% significance level; the mean confidence interval being (-0.0214, 0.0034).

8.4.2.3 AASHTO T 85 versus 30 Minutes Vacuum Saturation Test

No statistical difference occurred at the 5% confidence interval and the relationship was excellent with an R^2 of 96.4% as indicated in Fig. 14 of Appendix C. The confidence mean interval is between -0.0266 and 0.001.

8.4.3 Apparent Specific Gravity (Gsa)

8.4.3.1 AASHTO T 85 versus 10 Minutes Vacuum Saturation Test

The coefficient of relationship for this comparison was 0.765 and is shown in Fig. 15 of Appendix C. The 95% mean confidence interval is between -0.0522 and 0.0142; suggesting statistical similarity between the two methods.

8.4.3.2 AASHTO T 85 versus 20 Minutes Vacuum Saturation Test

The coefficient of linear relationship for this comparison was 0.632 and is shown in Fig. 25 of Appendix C. The 95% mean–difference confidence interval is between -0.0435 and 0.0155; suggesting statistical similarity between the two methods.

8.4.3.3 AASHTO T 85 versus 30 Minutes Vacuum Saturation Test

The R^2 was 0.829 and is shown in Fig. 17 of Appendix C. The 95% mean-difference confidence interval is between -0.0435 and 0.0155; suggesting statistical similarity between the two methods.

8.4.4 Water Absorption (Wa %)

8.4.4.1 AASHTO T 85 versus 10 Minutes Vacuum Saturation Test

As provided in Fig. 18 of Appendix C, the relationship was good with an R^2 of 0.773. Since the confidence interval (-0.7550, 0.4840) contains the null mean i.e. 0, there is no statistical difference between the two methods.

8.4.4.2 AASHTO T 85 versus 20 Minutes Vacuum Saturation Test

The test results showed no statistical difference at 95% significance level, having a confidence interval of between -0.06707 and 0.4694. The graphical plot had an R^2 of 0.79 and is shown in Fig. 19 of Appendix C.

8.4.4.3 AASHTO T 85 versus 30 Minutes Vacuum Saturation Test

The R^2 of the relationship between AASHTO T 85 and 30 min of vacuum saturation was 0.834, and the graph is given in Fig. 20 of Appendix C. There is no statistical difference between the two methods for this comparison. The calculated confidence interval was found to be (-0.5346, 0.2966).

8.5 BLENDED COARSE AGGREGATES

8.5.1 AASHTO T85 versus 10 Vacuum Saturation Test

8.5.2 Bulk Specific Gravity (Dry)

The R^2 between the calculated and combined Gsb (dry) and the single test value for Gsb (dry) using 10 minutes of vacuum saturation was 0.806 as shown in Fig 21 of Appendix C. Additionally, the paired t-Test of means revealed no statistical difference between the calculated Gsb (dry) and the single test laboratory value since the confidence interval of means at the 95% significance level was (- 0.089, 1.164).

8.5.3 Bulk Specific Gravity (SSD)

In terms of the Gsb (SSD), the linear regression coefficient or R^2 between the calculated and combined Gsb (SSD) and the single test value for Gsb (SSD) using 10 minutes of vacuum saturation was 0.652 (shown in Fig. 22 of Appendix C). The 95% confidence interval for mean difference was (-0.256, 1.256) which implied that there is no statistical difference between the two methods.

8.5.4 Apparent Specific Gravity (Gsa)

The linear regression coefficient or R^2 between the calculated and combined Gsa and the single test value for Gsa using 10 minutes of vacuum saturation was 0.445. Fig. 23 of Appendix C shows this linear relationship. The 95% confidence interval for mean difference was (-0.779, 1.716) suggesting no statistical difference between the two methods.

8.5.5 Water Absorption (Wa %)

The R^2 between the two methods was 0.975 as indicated in Fig. 24 of Appendix C, and the 95% statistical confidence interval is (-0.373, 0.373). Since the confidence interval does includes 0, there is no statistical difference between the calculated and combined Wa% and the single test value for Wa% using 10 minutes of vacuum saturation.

Extended Soaking of Coarse Aggregates

Bar charts indicating the relationships between Gsb (dry), Gsb (SSD), Gsa, Wa%, and soaking periods of 24, 36, 48 and 72 hours are shown in Figures 25, 26, 27 and 28 of Appendix C. From the test results of specific gravities and water absorption percentages over extended soaking periods, it is evident that the Gsb (dry) decreases as the soaking period increases from 24 through to 72 hours as shown in the bar charts of Figure 34. In Figure 35, the same trend is evident for the Gsb (SSD) expect for the average Gsb (SSD) at 72 hours, which is an outlier. The Gsa bar chart trend is shown in Figure 36. There is no significant difference between the Gsa results from the 24 hours through to the 72 hours since Gsa values are not affected by the change in degree of water absorption in the coarse aggregate voids. Finally, it can be observed from Figure 37 that the water absorptive capacity of the steel slag generally increases as the time of soaking was extended from 24 hours to 36, 48 and 72 hours. This trend suggests that the 24 hours soaking period might not be sufficient as specified in the specification standard.

On the crushed or recycled concrete, the Wa% capacity showed incremental differences when tested over 24, 36 and 48 hours. The Wa% values were 6.544. 6.75 and 6.93 for the 24, 36 and 48 hours soaking times respectively. At the scale of percent increment, it is showed that from 24 to 36 hours soaking time, the absorptive capacity of the crushed concrete is increased by 3.3%, while from 24 to 36 hours the absorptive capacity experienced an increment of 5.9%. With regard to the absorptive limestone aggregate tested, it was determined that when subjected to 2 hours soaking, the limestone had a water absorptive percent of 0.665 while over 48 hours, the same limestone aggregate had a water absorptive percent of 1.060%. This 56% increase underscores the fact that for some special aggregate types – porous aggregates – the 24 hours or overnight soaking test is inadequate in satisfying the full absorptive capacity of the coarse aggregates.

To clearly emphasize the fact that the extended soaking periods of more than 24 hours is unwarranted for some aggregates, a non-absorptive aggregate (gravel) was tested over 24 and 48 hours. While the 24 hour Wa% was 2.237, that for the 48 hours soaking was 1.915; suggesting that for non-absorptive aggregates, there is no need to test over extended soaking times.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 AASHTO T-84 and SSDetect

9.1.1 Conclusions

The comparison of the SSDetect against the AASHTO T-84 in finding the specific gravities of the tested fine aggregates has led to the following conclusions:

1. For the tested single gradation and as received material, the SSDetect can be confidently used alongsidethe current AASHTO T-84 in Gsb (dry) and Gsb (SSD) measurement with desirable time-saving advantages and better accuracy in testing fine aggregates.
2. In terms of standard deviation comparisons between the AASHTO T-84 and SSDetect test results for the tested single gradation and as received material, the SSDetect proved to have lower deviations for the Gsb (dry), Gsb (SSD) and Gsa, and thus has less variability within the test procedure for these properties. With the SSDetect implementation, there is the beneficial assurance that operator errors will be reduced as compared to AASHTO T-84.
3. When mathematical calculations were used for finding the specific gravities of the blended fine aggregates as against using the SSDetect, no statistical differences occurred between results of the two approaches.
4. The SSDetect is insensitive and unaffected by the presence of different aggregate size mixes and can therefore be used to test for blended fine aggregates similar for testing single gradation fine aggregates.
5. Comparing how the SSDetect compares with the AASHTO T 84 when the #8, #16, #30, #50, #100 and #200 sieves were tested, it was observed that SSDetect will work better in testing the #8, #16, #30, #50 and #100. The SSDetect will however need more validation when used for the #200 sieve-size fine aggregate.
6. The 24 hour soaking period may be inadequate in determining the absorptive capacities of special porous aggregates like steel slag.

9.1.2 Recommendations

It is believed that the SSDetect can be improved for measuring specific gravity of fine aggregates.

- One improvement could be achieved by the inclusion of an extra digital measurement system which automatically finds the bowl mass with contents before and after the SSD operation. This improvement would eliminate the inconvenience of the operator having to wait and monitor closely the SSD attainment stage during the process and immediately remove the sample for mass measurement.
- Extended research should also be carried out to determine whether empirical relationships can be determined between the water film coefficient and the specific gravity of fine aggregate. This development would greatly aid in using the film coefficient to predict the specific gravity of fine aggregates for various gradations. In addition the device could be modified with a better testing fluid, such as an alcohol which has a higher penetration rate into aggregate voids, and is highly applicable to fine aggregates that experience testing issues with water.
- Research work should also be conducted on the automated SSDetect to verify its applicability and feasibility in finding the specific gravity and absorption of a wide range of fine aggregates including recycled, natural, and manufactured aggregates (recycled PCC, recycle asphalt pavement, and slag). Preliminary results of the study have revealed that the SSDetect highly underestimates the absorption potential of highly absorptive fines even though the specific gravity measurements match very well.

9.2 AASHTO T-85 and Vacuum Saturation

9.2.1 Conclusions

The comparison of the specific gravity and absorption of the 10, 20 and 30 minutes of vacuum saturation with AASHTO T85 led to the following conclusions:

1. The vacuum saturation method has potential for use alongside the current AASHTO T85 for Gsb (dry), Gsb (SSD), Gsa and Wa% of coarse aggregates.
2. Even though the three test times: 10, 20 and 30 minutes of vacuum saturation all had statistically a similar result at the 95% confidence interval, 10 minutes is the selected test time due to the least testing time involved.
3. With the statistical similarity between the proposed method e.g. 10 minutes of vacuum saturation and the existing AASHTO T85, the new method will significantly save time in specific gravity and absorption testing in the laboratory.
4. From the blended coarse aggregate testing using the 10 minutes Vacuum Saturation Approach compared with the calculated value of Gsb (dry), Gsb (SSD), Gsa and Wa %, it was observed the proposed Vacuum Saturation approach holds promise for testing blended coarse aggregates, in addition to its applicability for single or individual coarse gradations.
5. In testing highly absorptive coarse aggregates, the Vacuum Saturation approach is best suited since it satisfies the high absorptive requirements by forcing water into the effective pores of the coarse aggregates.

9.2.2 Recommendations

Useful suggestions that have come out of this research include:

- The application of the test method to coarse aggregates of varied nature ranging from manufactured, recycled and natural aggregates.
- The 24 hours soaking time period is not adequate in determining the water absorptive percent of highly porous coarse aggregates.
- It will also be interesting to find the relationship between surface voids of coarse aggregates like steel slag and crushed concrete, and their rate of absorption.
- Further work is also necessary to determine the viability of the new approach in finding the blended specific gravity and absorption of a more varied range of coarse aggregates and possibly fine aggregates too.
- The extent of specific gravity and absorption effect on asphalt and concrete mixture volumetric analysis needs to be studied in detail. For example, how range of specific gravity and absorption values can impact significantly or otherwise on

the Void in Mineral Aggregates (VMA), Volume Filled with Asphalt (VFA) and Voids in Total Mix (VTM). In portland concrete mixes, it will be beneficial to analyze the quantitative and qualitative effect of the specific gravity and absorption on the mechanical properties of fresh and hardened concrete.

- Relating the economic and cost effective gains of using more accurate values of specific gravity and absorption. This will enable engineers and researchers scale to the bulk level, how accurate specific gravity values determination translates into the economic figures.

CHAPTER 10: DEVELOPMENT OF TRIAL SPECIFICATION CRITERION

10.1 MDOT Specification for SSDetect Method

Based on the research findings from the AASHTO T 84 and SSDetect method used in this study, the trial specification criteria or guiding framework on the use of the SSDetect in Michigan for the testing of fine aggregates is developed. The trial specification criteria incorporate: 1) the test procedure for using the SSDetect; 2) the fine aggregate material type in terms of gradations which will provide the best results when using the SSDetect; 3) Within laboratory standard deviation specification boundaries when using the SSDetect.

The SSDetect procedure which this research recommends for implementation by MDOT, alongside the existing AASHTO T 84, is also most recently accepted for use in the United States and is known as ASTM D 7172–06, Standard Test Method for Determining the Relative Density (Specific Gravity) And Absorption of Fine Aggregates Using Infrared. This specification is exactly what was followed in this research investigation.

The draft specification criteria that this research suggests for use by MDOT in determining the specific gravities and absorption of fine aggregates are:

10.1.1 Preparation of Test Specimen

Obtain 1.5 kg of of the fine aggregate from the sample.

Dry it in a suitable pan or vessel to constant mass at a temperature of 110 ± 5°C (230 ± 9°F). Allow it to cool to 23 ± 2.0°C (73 ± 3°F).

10.1.2 Procedure

Make and record all mass determinations to 0.1 g.

Determine the mass of a 500 ml, large neck volumetric flask filled to its calibration capacity with water at 23 ± 2.0°C (73 ± 3°F).

Record the mass and discard the water.

Film Coefficient and Apparent Relative Density (Specific Gravity) Determination:

Put 500g of the fine aggregate and 250ml of water into a pycnometer, and fill with water to the calibration line and determine the final total mass.

With the aid of the Automated Vacuum Unit (AVM) unit, vacuum agitate the pycnometer with its contents.

Refill the pycnometer with its contents back to the calibration line and find the total mass of pycnometer.

The film coefficient value for the fine aggregate being tested is calculated by equation [1]:

$$F_c = 52 + 4x - (0.11x^2) \qquad [1]$$

Where:

F_c is the film coefficient value and;

x is the difference between the initial and final mass of the pycnometer and its contents.

Bulk Relative Density (Specific Gravity) and Percent Absorption Determination:

Turn the infrared unit on and allow it to complete the 30-minute warm up period.

Place the empty, clean and completely dry bowl from the infrared unit on balance and record the mass of the bowl (initial mass).

Place 500 ± 0.1 g of the sample into the bowl and record the mass of the bowl and sample (final mass).

Calculate and record the dry aggregate weight by subtracting the initial mass from the final mass.

Place the bowl with the aggregate into the infrared unit, making certain that the notch in the front of the bowl fully engages in the notch in the front of the metal mounting plate.

Use the ring on the bowl to securely fasten the bowl to the plate by pressing down and turning the ring 1⁄4 of a turn until tight.

Place the top on the bowl and lightly press down to be certain it is engaged.

Close the lid to the infrared unit and latch in the front while ensuring that there is distilled water in the reservoir in the unit.

Set the film coefficient to that determined earlier and press the enter button.

Press the start button.

After the test comes to a stop, press the OK button.

Compare the film coefficient on the display with the measured film coefficient for that material to be certain it was entered properly and then press the OK button.

Open the unit and remove the lid to the bowl and store it.

Remove the bowl and immediately place the bowl on the balance and record the mass (this step should be undertaken immediately after the lid is removed to prevent the drying up of the material).

Finally, determine the amount of water absorbed by fine aggregate during the SSDetect test.

10.1.3 Relevant calculations:

$$Gsb\ (Dry) = A/\ (A+B-C+D) \qquad [2]$$

$$Gsb\ (SSD) = (A+D)/(A+B-C+D) \qquad [3]$$

$$Gsa = E/(E+B-C) \qquad [4]$$

$$Wa\% = (D/A) \times 100 \qquad [5]$$

Where:

A is the dry sample mass in SSDetect bowl in grams,

B is the mass of volumetric flask filled with water in grams,

C is the final mass in grams of flask with contents in film coefficient determination,

D is the water absorbed by the 500g fine aggregate in the SSDetect bowl, and

E is the mass in grams of dry aggregate in film coefficient determination test.

10.2 MDOT Vacuum Saturation (Modified Rice) Method

In terms of the coarse aggregates, the trial specification criteria is developed that involves the test procedure, grades of materials suited for testing, within laboratory standard deviation specification boundaries when using the Vacuum Saturation Approach or Modified Rice Test. Based on this trial specification criterion, engineers, researchers and contractors in Michigan can confidently apply the Vacuum Saturation Approach (Modified Rice Test) in transportation design and construction in Michigan. The procedure is a combination of AASHTO T 209-05 and AASHTO T 85-08

10.2.1 Preparation of Test Specimen

Obtain the minimum amount of the coarse aggregates, according to the AASHTO T 85-08 test method.

Dry the test sample to a constant mass at a temperature of 110 ± 5°C (230 ± 9°F) and allow to cool to a handling temperature (approximately 50°C).

Put sample into pycnometer and remove air trapped in the sample and force water into the permeable pores by applying gradually increased vacuum until the residual pressure manometer reads 3.7 ± 0.3 kPa (27.5 ± 2.5 mm Hg).

Maintain this residual pressure for 10 ± 2 minutes.

Agitate the pycnometer and contents during the vacuum period manually or mechanically.

At the end of the vacuum period, release the vacuum by increasing the pressure at a rate not to exceed 8 kPa per second.

10.2.2 Procedure

Remove the sample from the water and roll it in a large absorbent cloth until all the visible films of water are removed.

Determine the mass of the saturated surface-dry coarse aggregates to the nearest 1.0g or 0.1 percent of the sample mass.

Immediately place the saturated surface-dry coarse aggregates in a wire basket and determine its mass in water at 23.0 ± 1.7 °C (73.4 ± 3°F).

Dry the test sample to a constant mass at a temperature of 110 ± 5°C (230 ± 9°F) and cool in air at room temperature until the aggregates can be comfortably handled (approximately 50°C), and find the sample mass.

10.2.2 Relevant calculations

The relevant calculations were then determined based on the following equations:

$$Gsb\ (Dry) = A / (B - C) \quad [6]$$

$$Gsb\ (SSD) = B / (B - C) \quad [7]$$

$$Gsa = A / (A - C) \quad [8]$$

$$Wa\% = [(B - A) / A]*100\ \% \quad [9]$$

Where A is the mass of oven-dry test sample in air (g),

B is the mass of saturated-surface dry test sample in air (g), and

C is the apparent mass of saturated test sample in water (g).

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APPENDIX A

TABLE OF RESULTS FOR AASHTO T-84 AND SSDETECT

Table 1 Gsb (Dry) and Standard Deviation Results for T-84 and SSDetect

BULK SPECIFIC GRAVITY (DRY)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
Ross 2006 (Natural Sand)	2.36mm (No. 8)	2.595	2.623	0.014	0.002
	1.18 mm (No. 16)	2.547	2.574	0.073	0.004
	0.600mm (No. 30)	2.596	2.618	0.010	0.003
	0.300mm (No. 50)	2.613	2.628	0.055	0.006
	0.150mm (No. 100)	2.637	2.669	0.022	0.011
FMS 2324 - 2006 (Fine Manufactured Sand)	2.36mm (No. 8)	2.583	2.615	0.004	0.015
	1.18 mm (No. 16)	2.562	2.564	0.011	0.019
	0.600mm (No. 30)	2.582	2.584	0.007	0.012
	0.300mm (No. 50)	2.615	2.602	0.006	0.017
	0.150mm (No. 100)	2.658	2.663	0.021	0.005
FMS 2354 - 2006 (Fine Sand)	0.0937 (2.36)	2.586	2.594	0.003	0.004
	0.0467 (1.18)	2.572	2.594	0.005	0.003
	0.0234 (0.600)	2.578	2.588	0.008	0.016
FMS 2370 - 2006 (Manufactured Sand)	2.36mm (No. 8)	2.609	2.637	0.007	0.003
	1.18 mm (No. 16)	2.581	2.592	0.016	0.006
	0.600mm (No. 30)	2.583	2.578	0.007	0.001
	0.300mm (No. 50)	2.590	2.563	0.023	0.004
	0.150mm (No. 100)	2.595	2.624	0.030	0.019
	0.075mm (No. 200)	2.526	2.565	0.007	0.013
RJH1 - 2006 (Crushed Natural Gravel)	2.36mm (No. 8)	2.644	2.659	0.011	0.021
	1.18 mm (No. 16)	2.606	2.615	0.007	0.017
	0.600mm (No. 30)	2.596	2.607	0.004	0.025
	0.300mm (No. 50)	2.565	2.581	0.007	0.028
	0.150mm (No. 100)	2.519	2.541	0.027	0.028
MHL-2006 (Crushed Limestone)	2.36mm (No. 8)	2.703	2.726	0.006	0.016
	1.18 mm (No. 16)	2.695	2.670	0.003	0.017
	0.600mm (No. 30)	2.728	2.740	0.022	0.014
	0.300mm (No. 50)	2.668	2.654	0.011	0.008
	0.150mm (No. 100)	2.620	2.627	0.003	0.015
MHL-2006 (Crushed Steel Slag)	2.36mm (No. 8)	2.788	2.775	0.008	0.006
	1.18 mm (No. 16)	2.784	2.771	0.008	0.019
	0.600mm (No. 30)	2.776	2.763	0.020	0.013
	0.300mm (No. 50)	2.739	2.725	0.012	0.009
	0.150mm (No. 100)	2.734	2.724	0.010	0.002

BULK SPECIFIC GRAVITY (DRY)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
HMA 5E10 - MLK1	Blended	2.657	2.656	0.016	0.009
HMA 5E10 - MKF2	Blended	2.659	2.643	0.015	0.004
HMA 5E10 - AIF	Blended	2.671	2.646	0.008	0.002
HMA 5E10 - NLF	Blended	2.671	2.656	0.031	0.002
HMA 4E10 - ARF	Blended	2.660	2.689	0.018	0.001
HMA 3E10 - APF	Blended	2.662	2.629	0.004	0.012
HMA 2E10 - APF	Blended	2.628	2.635	0.027	0.032
HMA 5E3 - GMF	Blended	2.615	2.630	0.009	0.003
HMA 4E3 - SLF	Blended	2.619	2.599	0.043	0.008
HMA 3E3 - GMF	Blended	2.631	2.622	0.013	0.004

Table 11 Gsb (SSD) and Standard Deviation Results for T-84 and SSDetect

BULK SPECIFIC GRAVITY (SSD)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
Ross 2006 (Natural Sand)	2.36mm (No. 8)	2.660	2.670	0.010	0.001
	1.18 mm (No. 16)	2.613	2.624	0.043	0.002
	0.600mm (No. 30)	2.650	2.656	0.006	0.002
	0.300mm (No. 50)	2.660	2.666	0.028	0.002
	0.150mm (No. 100)	2.676	2.687	0.016	0.006
FMS 2324 - 2006 (Fine Manufactured Sand)	2.36mm (No. 8)	2.642	2.654	0.005	0.009
	1.18 mm (No. 16)	2.626	2.618	0.011	0.010
	0.600mm (No. 30)	2.634	2.627	0.006	0.007
	0.300mm (No. 50)	2.650	2.634	0.007	0.012
	0.150mm (No. 100)	2.701	2.691	0.008	0.005
FMS 2354 - 2006 (Fine Sand)	0.0937 (2.36)	2.650	2.654	0.003	0.004
	0.0467 (1.18)	2.648	2.653	0.002	0.003
	0.0234 (0.600)	2.648	2.651	0.008	0.012
FMS 2370 - 2006 (Manufactured Sand)	2.36mm (No. 8)	2.667	2.677	0.005	0.004
	1.18 mm (No. 16)	2.652	2.643	0.011	0.003
	0.600mm (No. 30)	2.649	2.636	0.004	0.001
	0.300mm (No. 50)	2.642	2.696	0.024	0.002
	0.150mm (No. 100)	2.652	2.662	0.030	0.015
	0.075mm (No. 200)	2.577	2.599	0.007	0.011
RJH1 - 2006 (Crushed Natural Gravel)	2.36mm (No. 8)	2.702	2.691	0.008	0.017
	1.18 mm (No. 16)	2.667	2.660	0.006	0.012
	0.600mm (No. 30)	2.663	2.654	0.002	0.021
	0.300mm (No. 50)	2.633	2.619	0.004	0.025
	0.150mm (No. 100)	2.586	2.592	0.034	0.025
MHL-2006 (Crushed Limestone)	2.36mm (No. 8)	2.769	2.760	0.006	0.016
	1.18 mm (No. 16)	2.761	2.724	0.003	0.017
	0.600mm (No. 30)	2.773	2.776	0.022	0.014
	0.300mm (No. 50)	2.726	2.718	0.011	0.008
	0.150mm (No. 100)	2.682	2.704	0.003	0.015
MHL-2006 (Crushed Steel Slag)	2.36mm (No. 8)	2.813	2.794	0.002	0.005
	1.18 mm (No. 16)	2.810	2.794	0.004	0.018
	0.600mm (No. 30)	2.803	2.813	0.006	0.015
	0.300mm (No. 50)	2.781	2.789	0.009	0.008
	0.150mm (No. 100)	2.781	2.798	0.009	0.001

BULK SPECIFIC GRAVITY (SSD)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
HMA 5E10 - MLK1	Blended	2.691	2.684	0.014	0.009
HMA 5E10 - MKF2	Blended	2.730	2.707	0.012	0.004
HMA 5E10 - AIF	Blended	2.714	2.687	0.008	0.001
HMA 5E10 - NLF	Blended	2.707	2.696	0.030	0.002
HMA 4E10 - ARF	Blended	2.723	2.731	0.013	0.002
HMA 3E10 - APF	Blended	2.702	2.691	0.008	0.011
HMA 2E10 - APF	Blended	2.679	2.680	0.019	0.037
HMA 5E3 - GMF	Blended	2.667	2.668	0.005	0.002
HMA 4E3 - SLF	Blended	2.684	2.657	0.029	0.005
HMA 3E3 - GMF	Blended	2.682	2.688	0.005	0.002

Table 12 Gsa and Standard Deviation Results for T-84 and SSDetect

APPARENT SPECIFIC GRAVITY (Gsa)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
Ross 2006 (Natural Sand)	2.36mm (No. 8)	2.773	2.753	0.006	0.002
	1.18 mm (No. 16)	2.727	2.710	0.049	0.004
	0.600mm (No. 30)	2.745	2.721	0.002	0.002
	0.300mm (No. 50)	2.742	2.731	0.040	0.006
	0.150mm (No. 100)	2.743	2.720	0.006	0.003
FMS 2324 - 2006 (Fine Manufactured Sand)	2.36mm (No. 8)	2.746	2.720	0.007	0.002
	1.18 mm (No. 16)	2.737	2.711	0.012	0.010
	0.600mm (No. 30)	2.724	2.702	0.006	0.002
	0.300mm (No. 50)	2.709	2.688	0.006	0.017
	0.150mm (No. 100)	2.777	2.739	0.031	0.005
FMS 2354 - 2006 (Fine Sand)	0.0937 (2.36)	2.764	2.759	0.003	0.008
	0.0467 (1.18)	2.783	2.756	0.005	0.004
	0.0234 (0.600)	2.774	2.762	0.008	0.009
FMS 2370 - 2006 (Manufactured Sand)	2.36mm (No. 8)	2.768	2.747	0.004	0.006
	1.18 mm (No. 16)	2.779	2.730	0.006	0.002
	0.600mm (No. 30)	2.765	2.737	0.002	0.001
	0.300mm (No. 50)	2.733	2.787	0.028	0.010
	0.150mm (No. 100)	2.754	2.727	0.048	0.009
	0.075mm (No. 200)	2.661	2.654	0.007	0.008
RJH1 - 2006 (Crushed Natural Gravel)	2.36mm (No. 8)	2.807	2.748	0.006	0.012
	1.18 mm (No. 16)	2.776	2.737	0.008	0.006
	0.600mm (No. 30)	2.782	2.733	0.004	0.016
	0.300mm (No. 50)	2.753	2.681	0.015	0.022
	0.150mm (No. 100)	2.698	2.677	0.047	0.022
MHL-2006 (Crushed Limestone)	2.36mm (No. 8)	2.893	2.821	0.008	0.003
	1.18 mm (No. 16)	2.887	2.821	0.004	0.006
	0.600mm (No. 30)	2.855	2.840	0.009	0.023
	0.300mm (No. 50)	2.833	2.837	0.038	0.012
	0.150mm (No. 100)	2.794	2.845	0.020	0.002
MHL-2006 (Crushed Steel Slag)	2.36mm (No. 8)	2.858	2.831	0.018	0.003
	1.18 mm (No. 16)	2.858	2.837	0.019	0.016
	0.600mm (No. 30)	2.852	2.910	0.011	0.008
	0.300mm (No. 50)	2.860	2.910	0.008	0.009
	0.150mm (No. 100)	2.870	2.943	0.010	0.001

APPARENT SPECIFIC GRAVITY (Gsa)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
HMA 5E10 - MLK1	Blended	2.750	2.732	0.014	0.009
HMA 5E10 - MKF2	Blended	2.862	2.822	0.007	0.003
HMA 5E10 - AIF	Blended	2.791	2.759	0.012	0.002
HMA 5E10 - NLF	Blended	2.770	2.768	0.030	0.001
HMA 4E10 - ARF	Blended	2.840	2.809	0.004	0.008
HMA 3E10 - APF	Blended	2.774	2.803	0.006	0.009
HMA 2E10 - APF	Blended	2.769	2.728	0.006	0.005
HMA 5E3 - GMF	Blended	2.758	2.732	0.002	0.001
HMA 4E3 - SLF	Blended	2.801	2.789	0.036	0.052
HMA 3E3 - GMF	Blended	2.772	2.808	0.000	0.001

Table 13 Wa % and Standard Deviation results for T-84 and SSDetect

WATER ABSORPTION (Wa %)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
Ross 2006 (Natural Sand)	2.36mm (No. 8)	2.470	1.793	0.115	0.058
	1.18 mm (No. 16)	2.586	1.947	0.289	0.046
	0.600mm (No. 30)	2.090	1.447	0.170	0.023
	0.300mm (No. 50)	1.799	1.440	0.210	0.151
	0.150mm (No. 100)	1.455	0.707	0.226	0.196
FMS 2324 - 2006 (Fine Manufactured Sand)	2.36mm (No. 8)	2.302	1.473	0.066	0.250
	1.18 mm (No. 16)	2.496	2.107	0.102	0.284
	0.600mm (No. 30)	2.016	1.693	0.082	0.180
	0.300mm (No. 50)	1.313	1.240	0.033	0.197
	0.150mm (No. 100)	1.602	1.033	0.669	0.031
FMS 2354 - 2006 (Fine Sand)	0.0937 (2.36)	2.494	2.307	0.068	0.115
	0.0467 (1.18)	2.945	2.273	0.103	0.058
	0.0234 (0.600)	2.741	2.440	0.212	0.200
FMS 2370 - 2006 (Manufactured Sand)	2.36mm (No. 8)	2.199	1.520	0.082	0.053
	1.18 mm (No. 16)	2.774	1.953	0.191	0.115
	0.600mm (No. 30)	2.542	2.247	0.099	0.012
	0.300mm (No. 50)	2.024	1.927	0.103	0.185
	0.150mm (No. 100)	2.222	1.440	0.778	0.183
	0.075mm (No. 200)	2.019	1.307	0.038	0.115
RJH1 - 2006 (Crushed Natural Gravel)	2.36mm (No. 8)	2.194	1.220	0.142	0.139
	1.18 mm (No. 16)	2.347	1.707	0.116	0.232
	0.600mm (No. 30)	2.578	1.767	0.106	0.194
	0.300mm (No. 50)	2.663	1.440	0.280	0.122
	0.150mm (No. 100)	2.628	1.993	0.222	0.122
MHL-2006 (Crushed Limestone)	2.36mm (No. 8)	2.438	1.240	0.183	0.200
	1.18 mm (No. 16)	2.473	2.007	0.074	0.170
	0.600mm (No. 30)	1.627	1.287	0.359	0.990
	0.300mm (No. 50)	2.181	2.427	0.436	0.061
	0.150mm (No. 100)	2.376	2.907	0.294	0.221
MHL-2006 (Crushed Steel Slag)	2.36mm (No. 8)	0.875	0.713	0.309	0.042
	1.18 mm (No. 16)	0.929	0.847	0.300	0.050
	0.600mm (No. 30)	0.949	1.840	0.274	0.200
	0.300mm (No. 50)	1.537	2.340	0.158	0.020
	0.150mm (No. 100)	1.729	2.740	0.108	0.040

WATER ABSORPTION (Wa %)					
Material	**Gradation**	**T-84 Average**	**SSDetect Average**	**T-84 St. Dev**	**SSDetect St. Dev.**
HMA 5E10 - MLK1	Blended	1.275	1.040	0.108	0.002
HMA 5E10 - MKF2	Blended	2.668	2.400	0.127	0.020
HMA 5E10 - AIF	Blended	1.612	1.547	0.124	0.042
HMA 5E10 - NLF	Blended	1.345	1.520	0.078	0.020
HMA 4E10 - ARF	Blended	2.382	1.593	0.212	0.115
HMA 3E10 - APF	Blended	1.523	2.367	0.006	0.070
HMA 2E10 - APF	Blended	1.937	1.707	0.306	0.220
HMA 5E3 - GMF	Blended	1.991	1.420	0.147	0.020
HMA 4E3 - SLF	Blended	2.484	2.213	0.779	0.142
HMA 3E3 - GMF	Blended	1.930	2.533	0.189	0.061

APPENDIX B

AASHTO T-84 VERSUS SSDETECT GRAPHICAL PLOTS

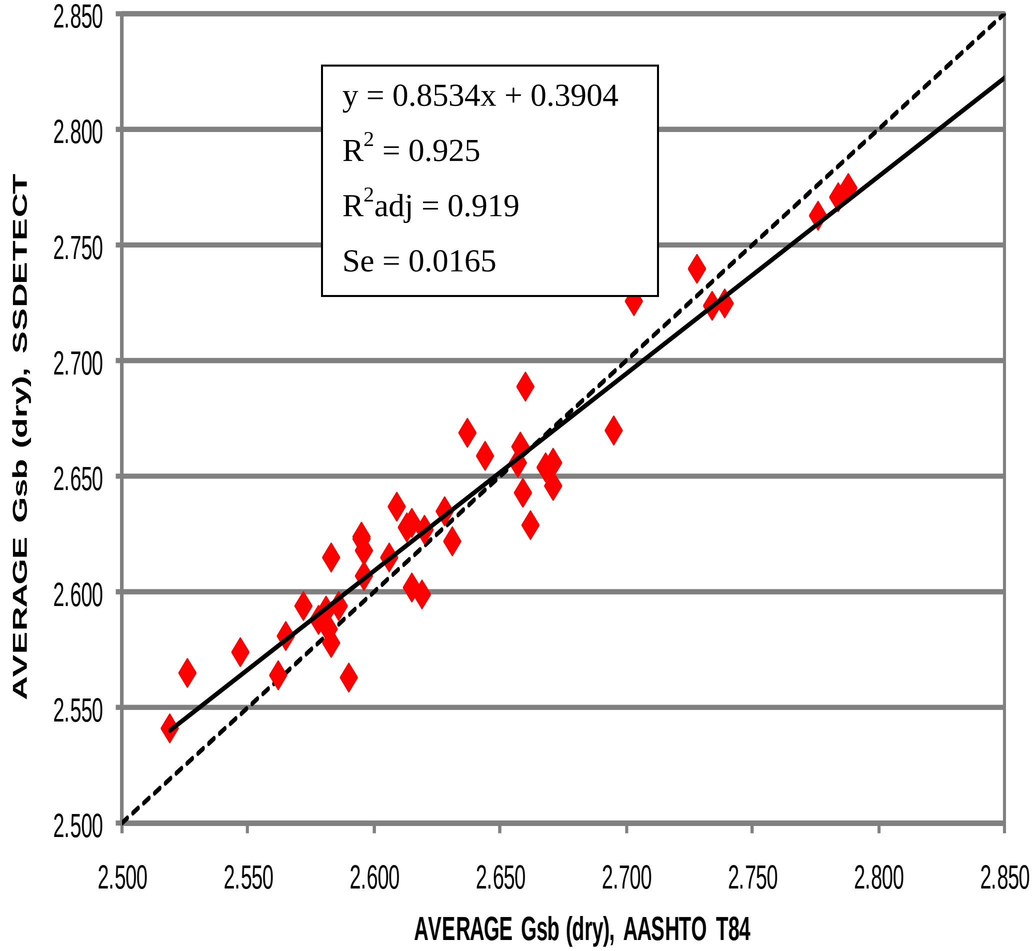

Figure 1 AASHTO T-84 against SSDetect Bulk Specific Gravity (dry)

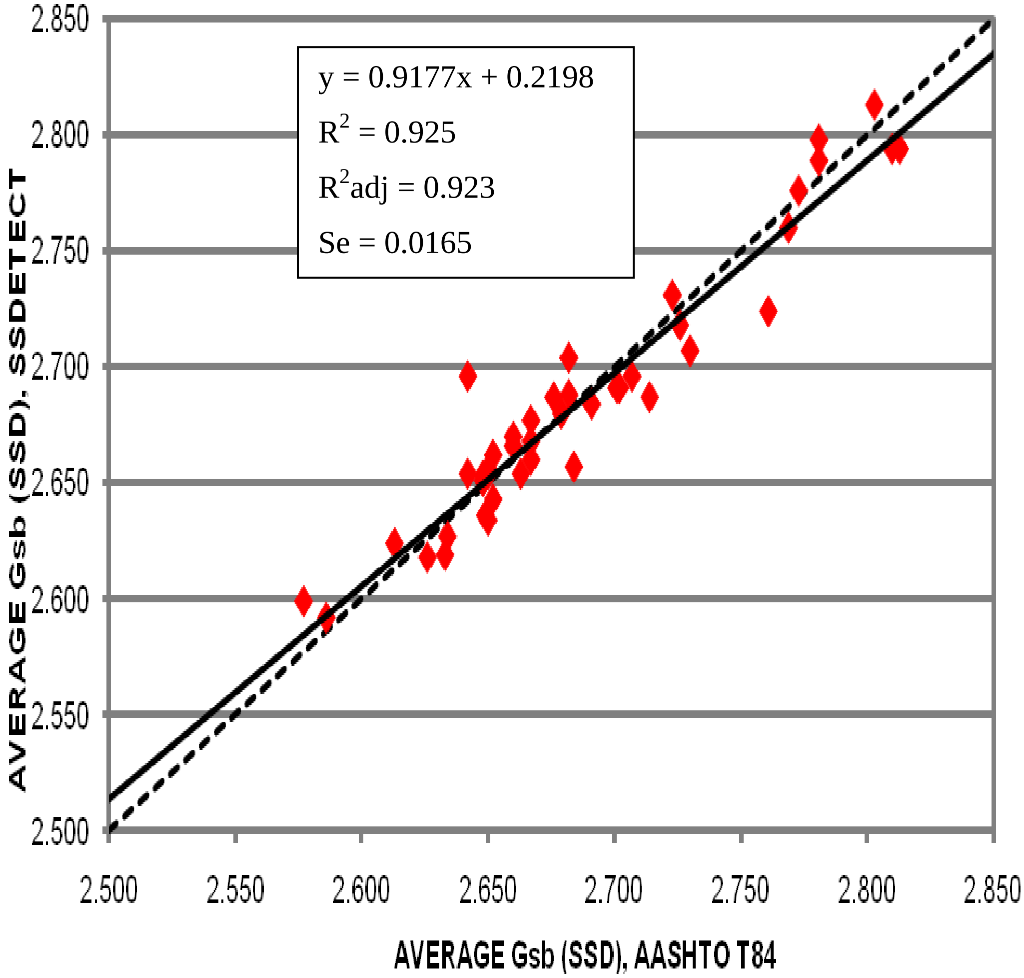

Figure 2 AASHTO T-84 against SSDetect Bulk Specific Gravity (SSD)

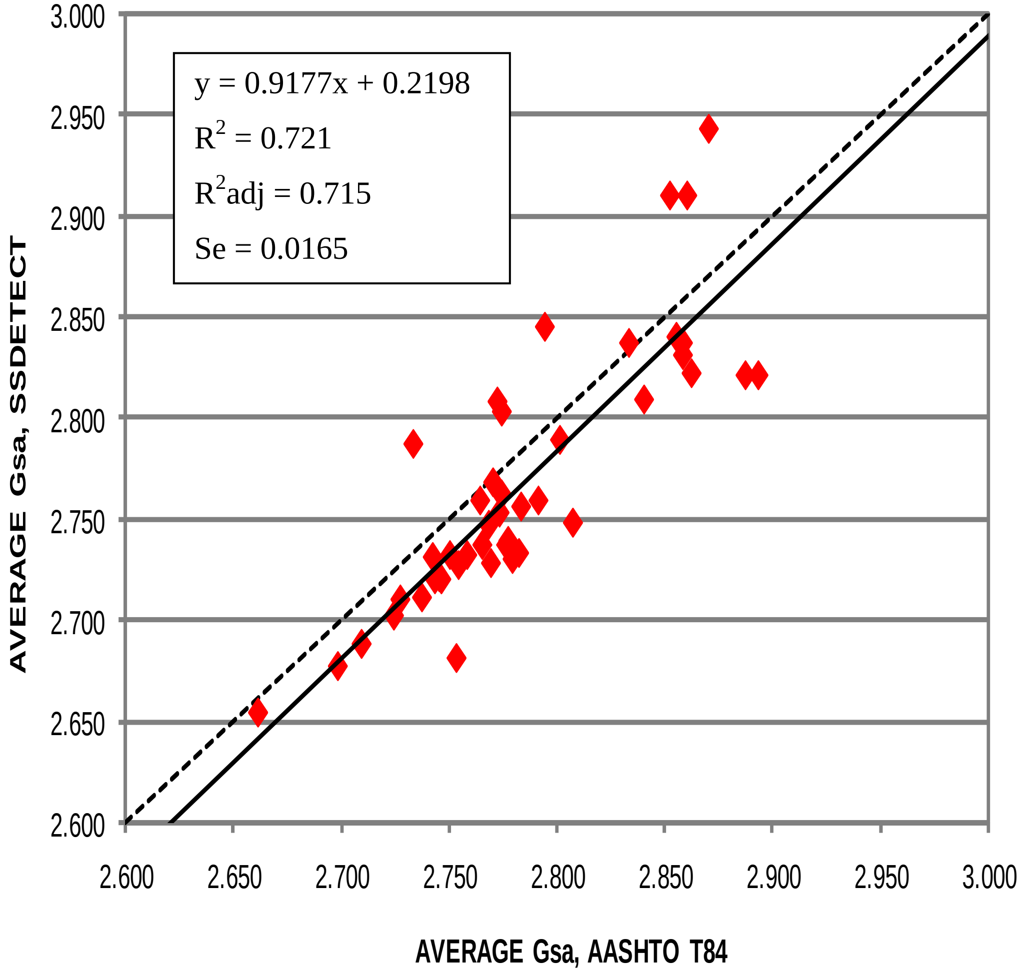

Figure 3 AASHTO T-84 against SSDetect Bulk Specific Gravity (Gsa)

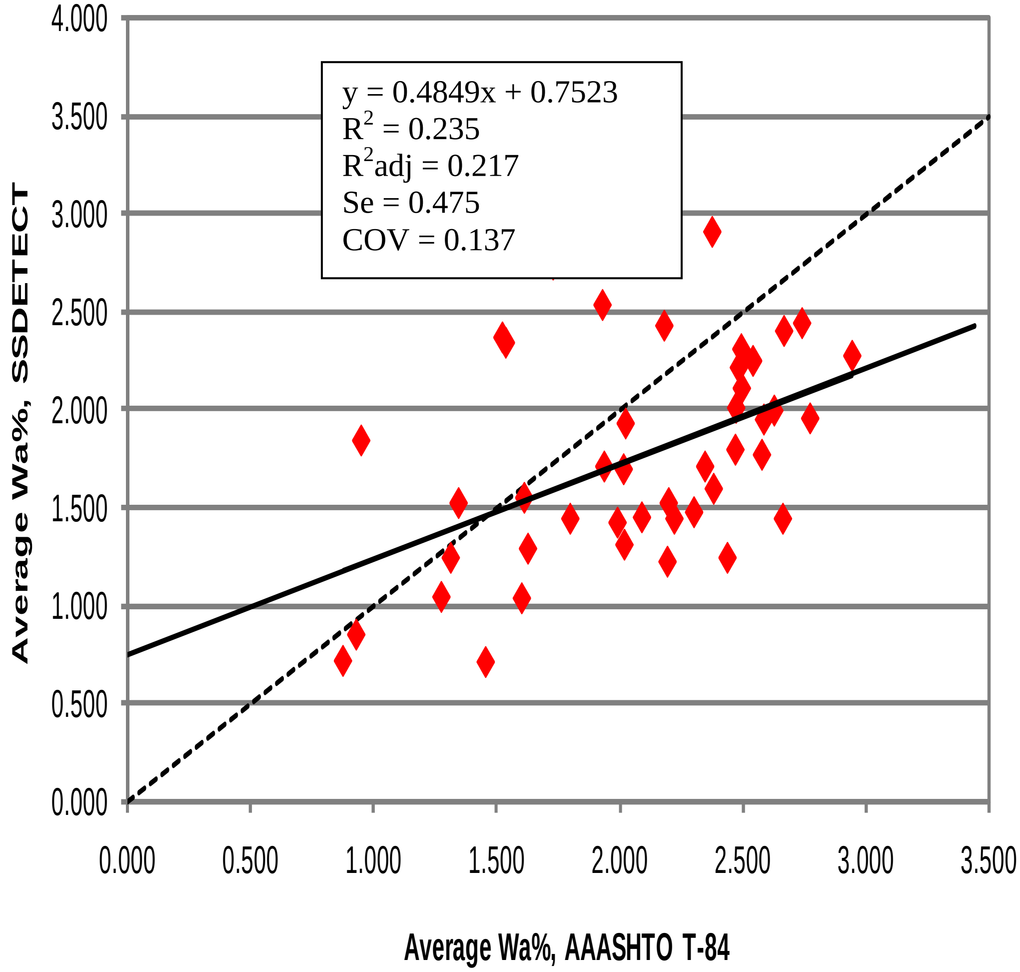

Figure 4 AASHTO T-84 against SSDetect Water Absorption (Wa %)

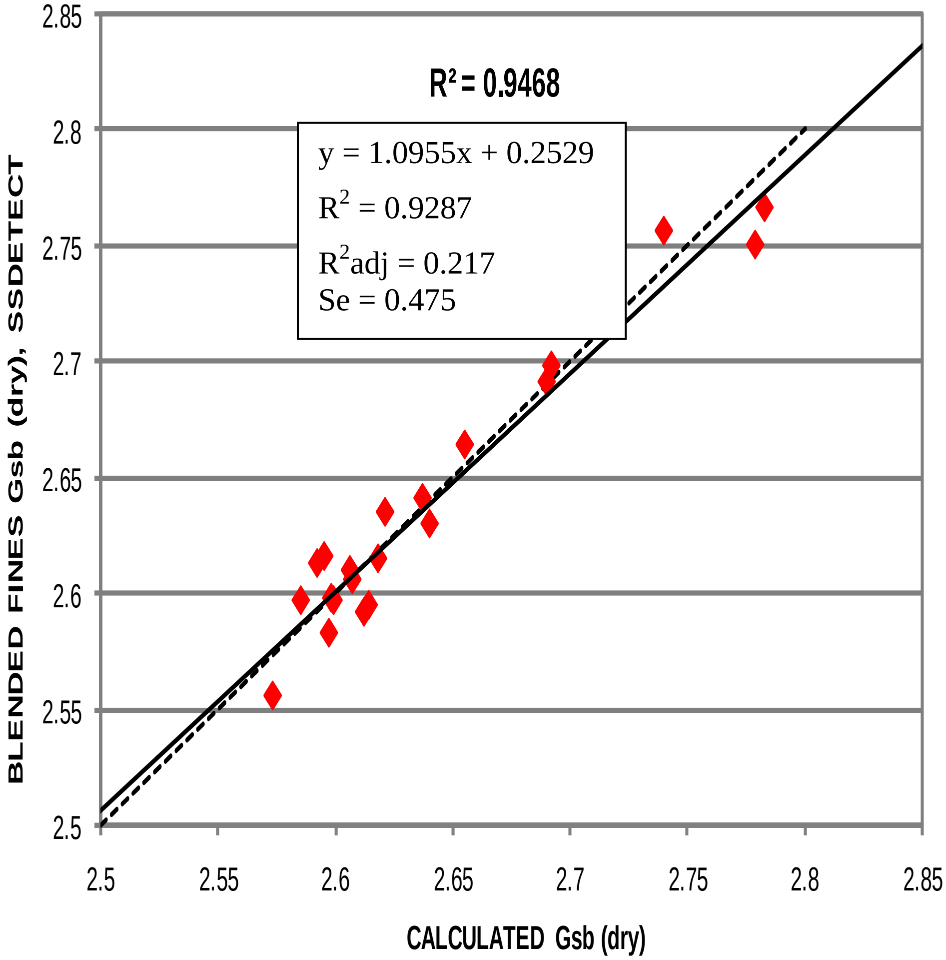

Figure 5 Blended-Calculated against SSDetect Gsb (dry)

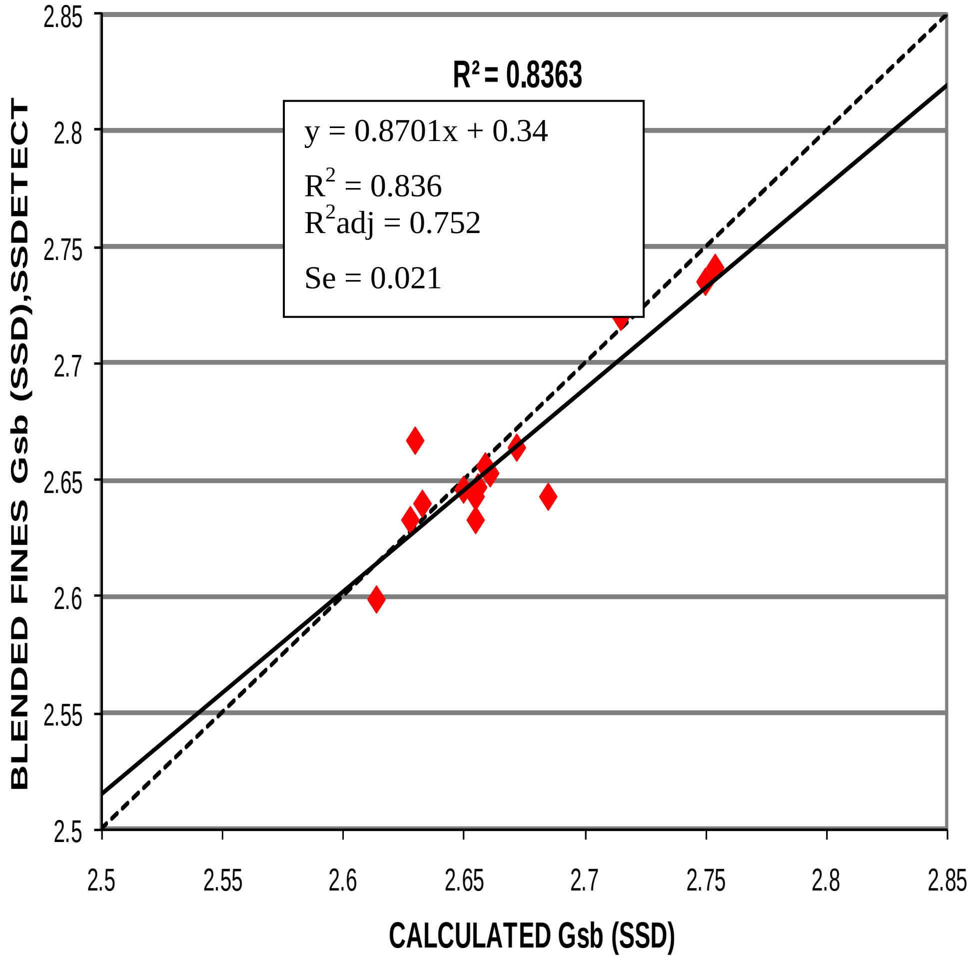

Figure 6 Blended-Calculated against SSDetect Gsb (SSD)

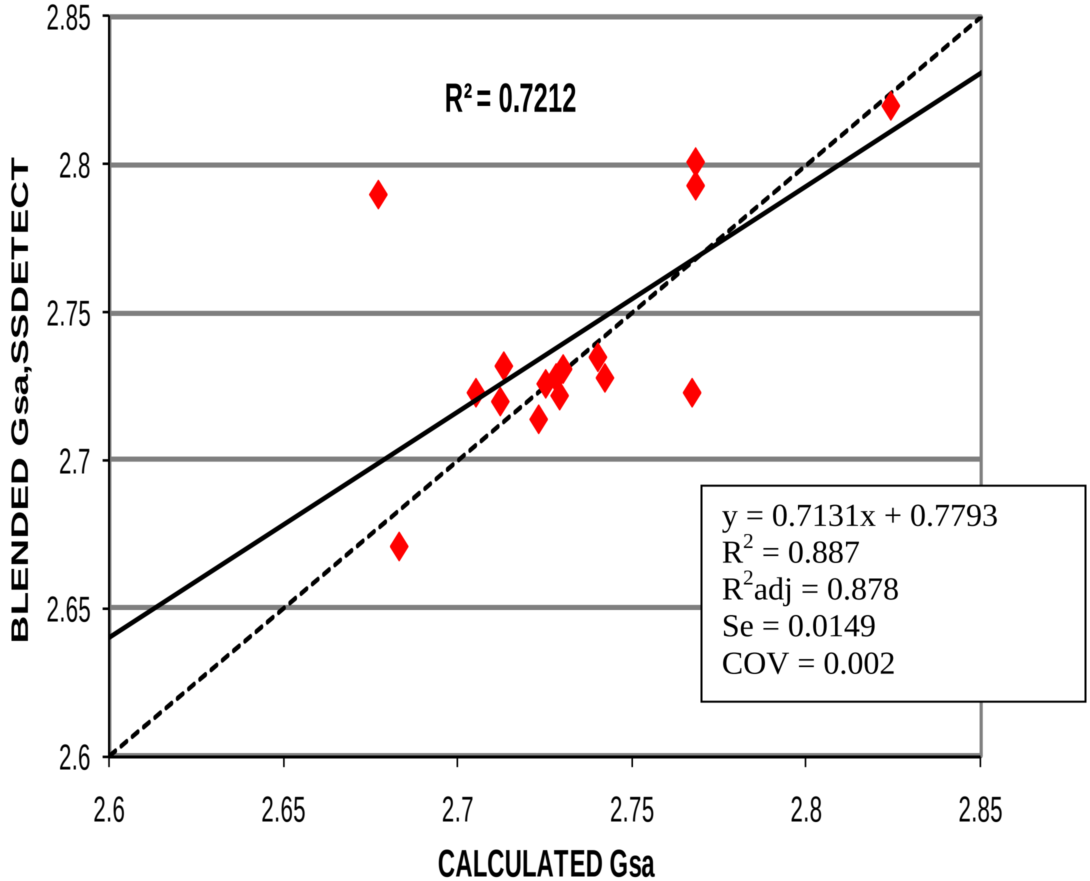

Figure 7 Blended-Calculated against SSDetect Gsa

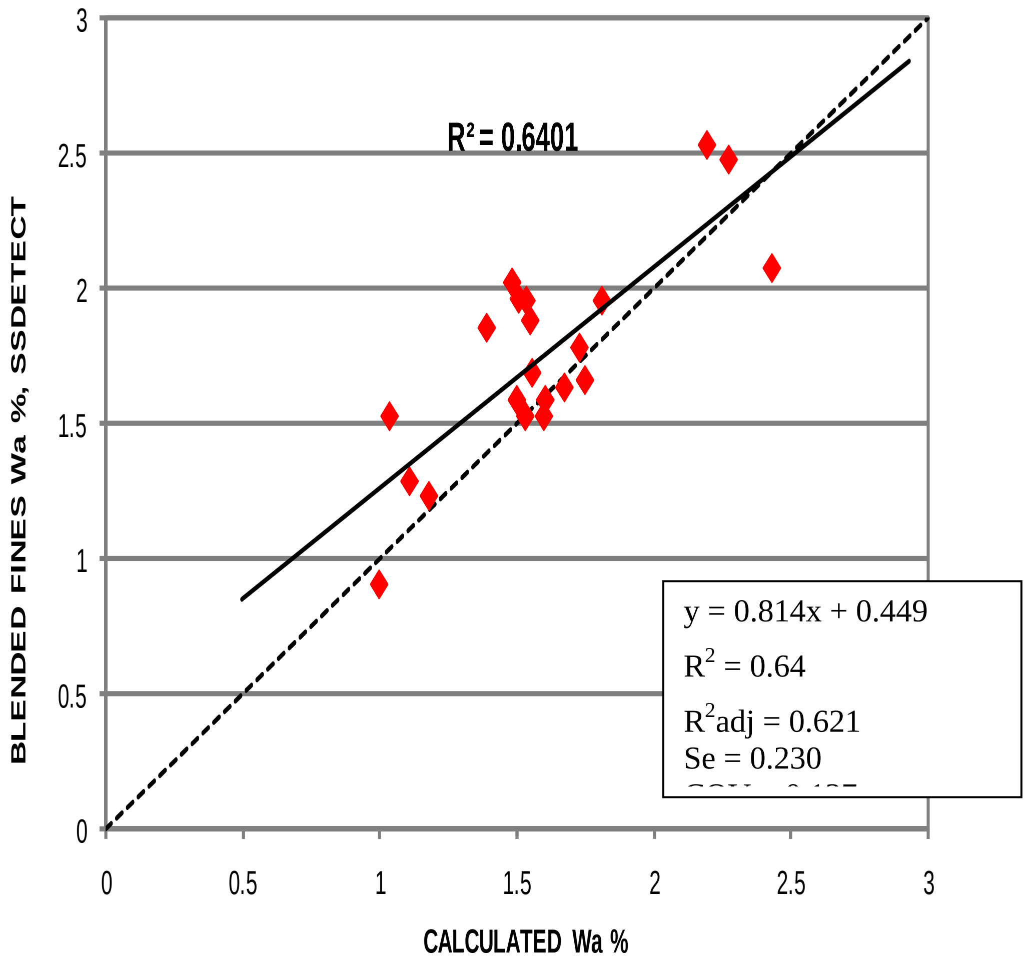

Figure 8 Blended-Calculated against SSDetect Wa%

APPENDIX C

AASHTO T-85 VERSUS VACUUM SATURATION TEST GRAPHICAL PLOTS

EXTENDED SOAKING PERIODS FOR COARSE AGGREGATES

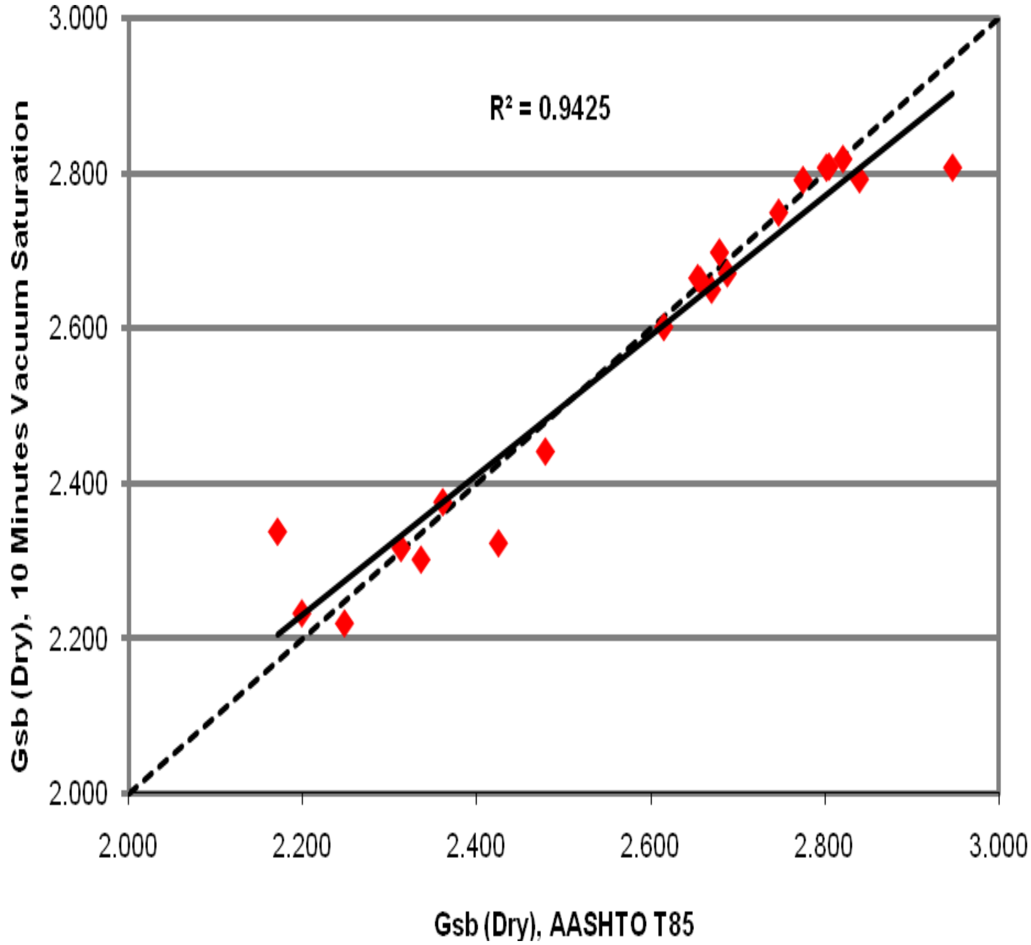

Figure 9 AASHTO T-85 versus 10 Minutes Vacuum Saturation Test for Gsb (Dry)

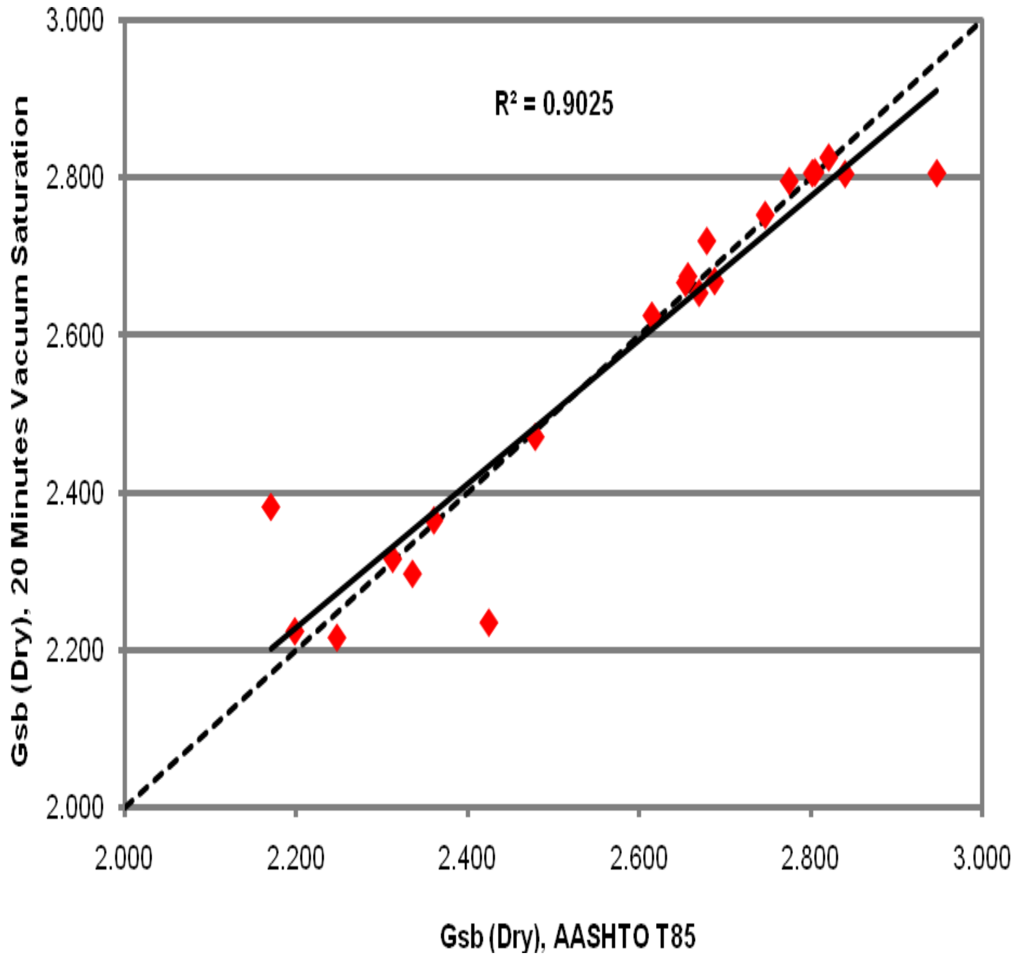

Figure 10 AASHTO T-85 against 20 Minutes Vacuum Saturation Test for Gsb (dry)

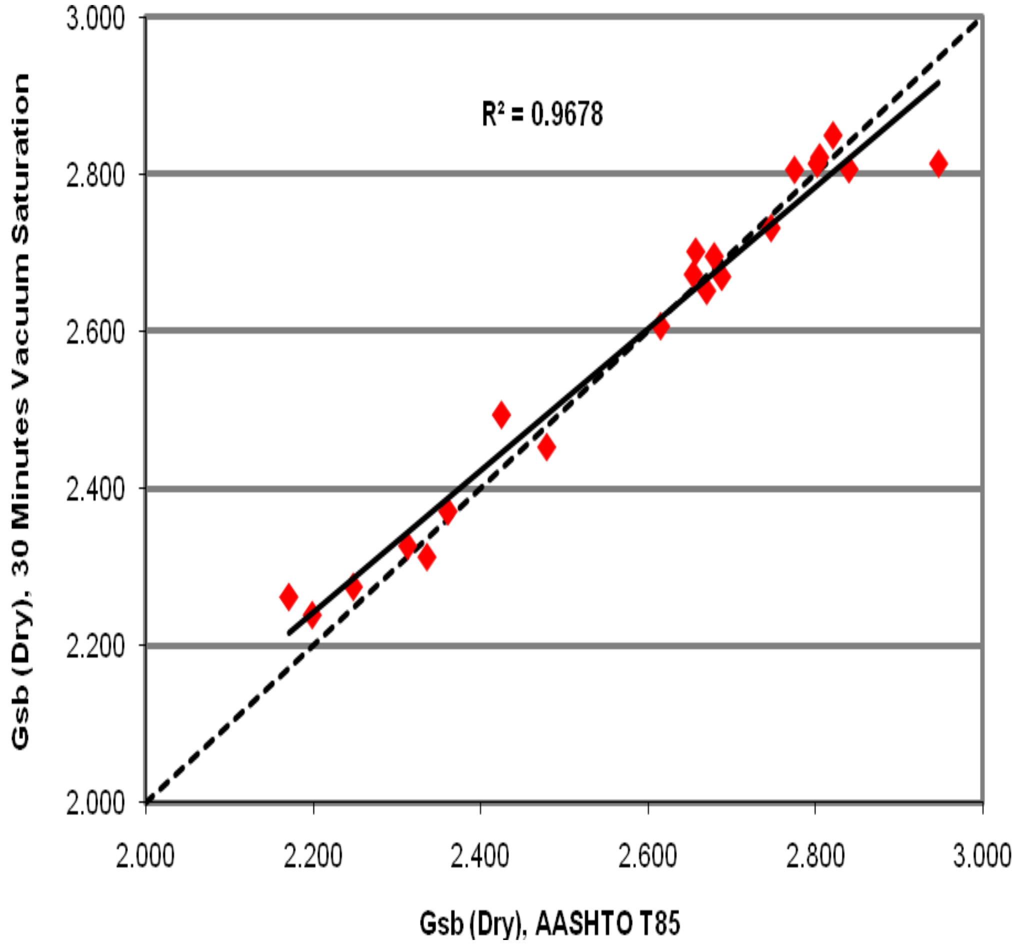

Figure 11 AASHTO T-85 against 30 Minutes Vacuum Saturation Test for Gsb (dry)

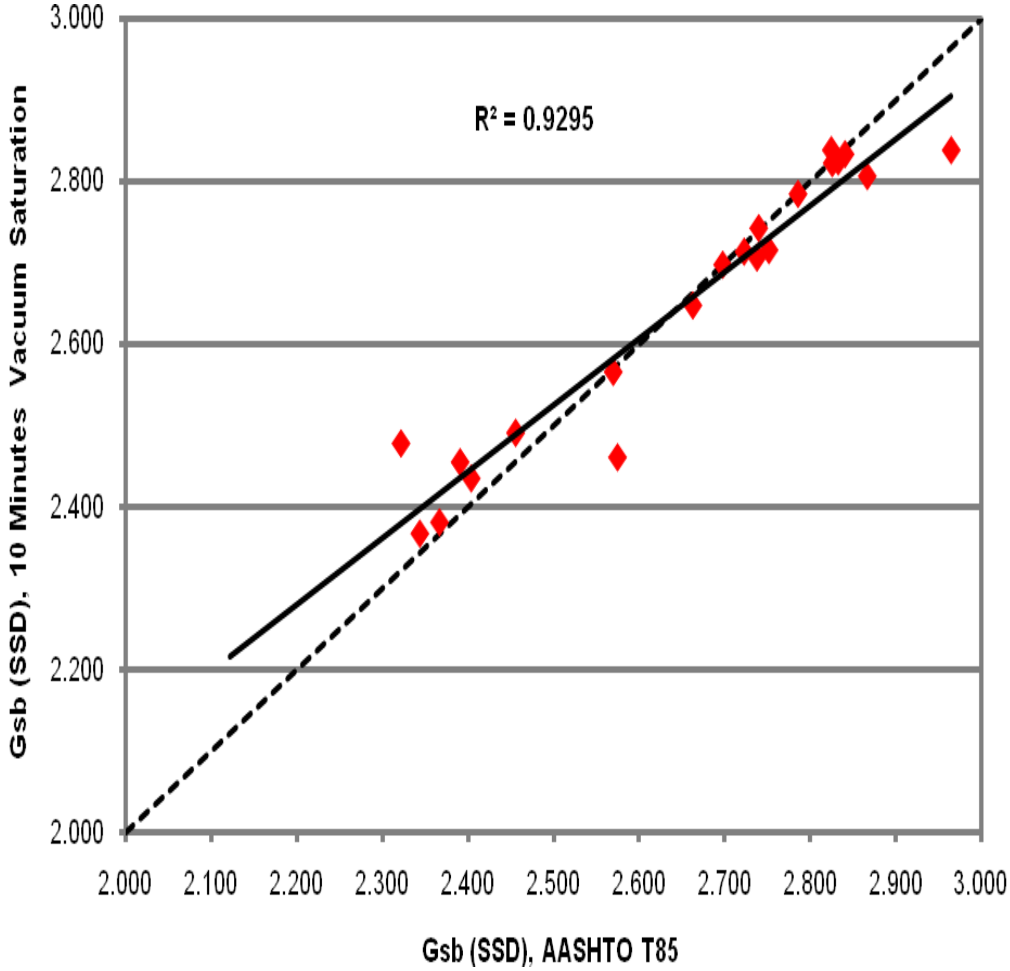

Figure 12 AASHTO T-85 against 10 Minutes Vacuum Saturation Test for Gsb (SSD)

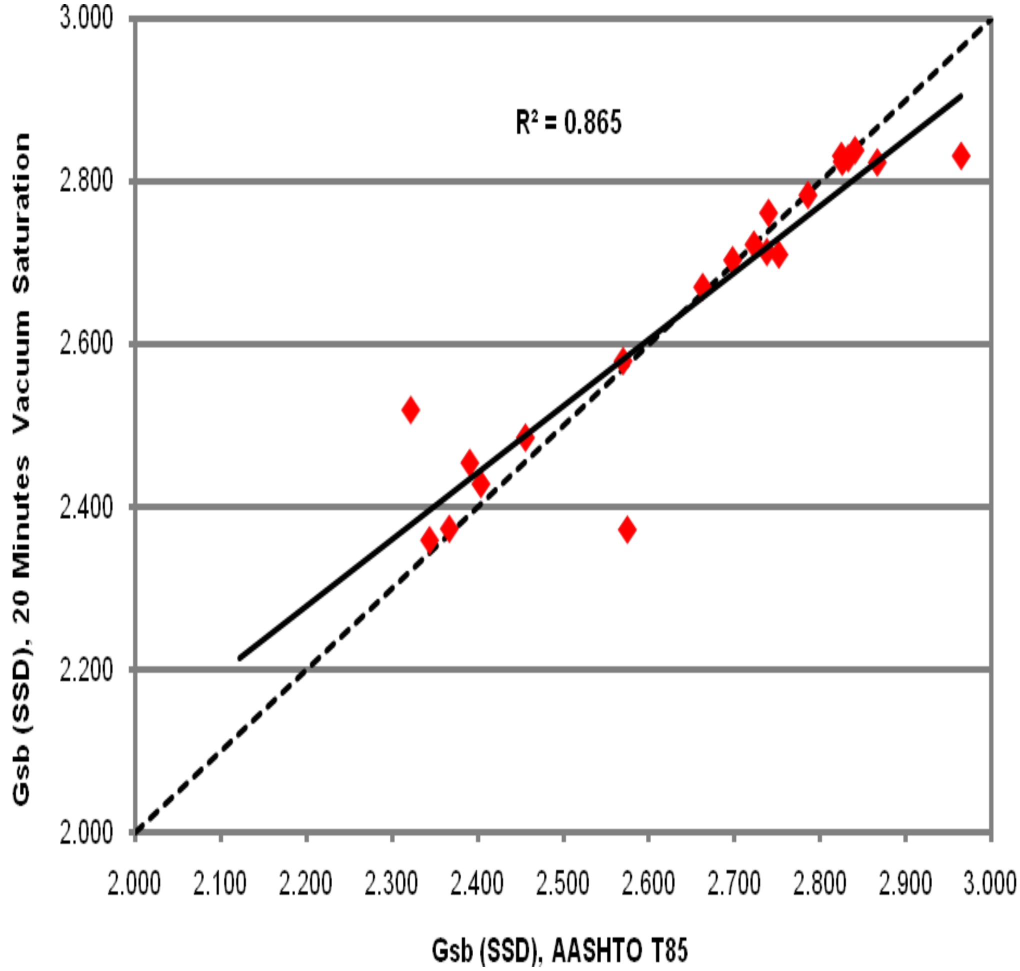

Figure 13 AASHTO T-85 against 20 Minutes Vacuum Saturation Test for Gsb (SSD)

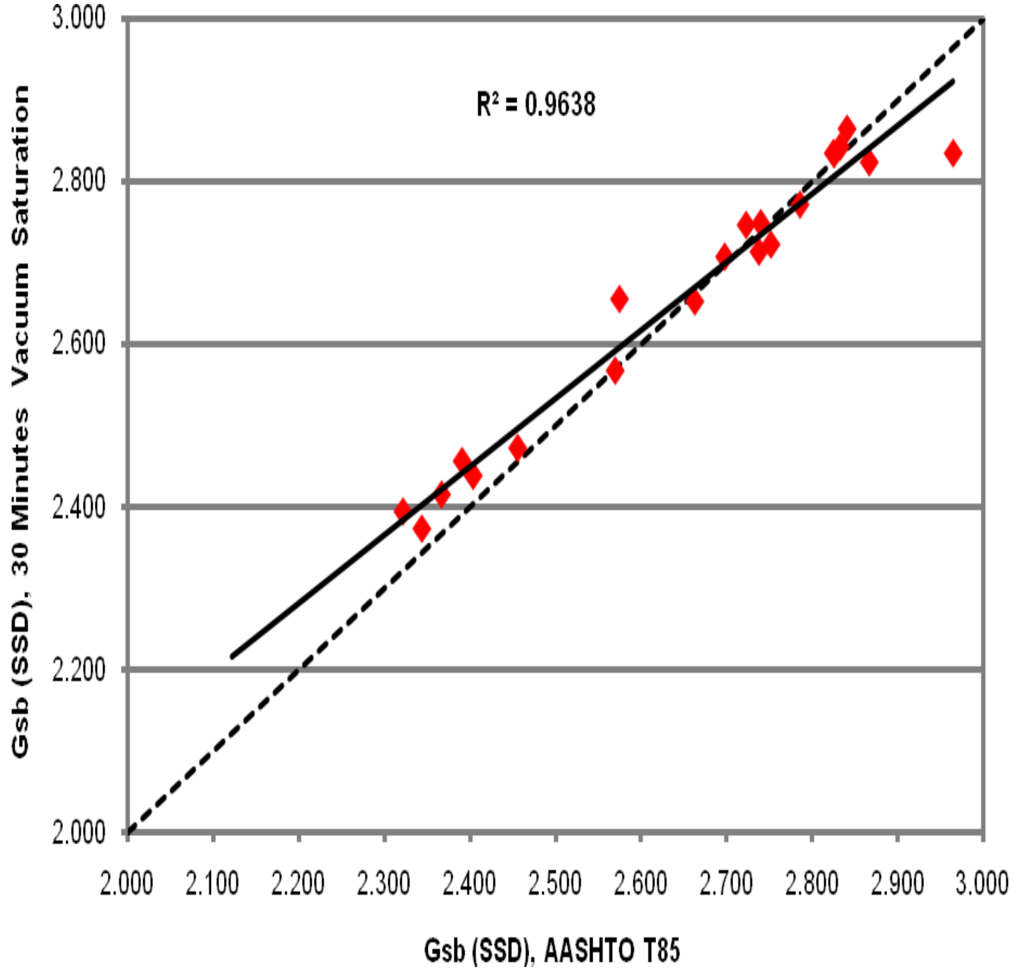

Figure 14 AASHTO T-85 against 30 Minutes Vacuum Saturation Test for Gsb (SSD)

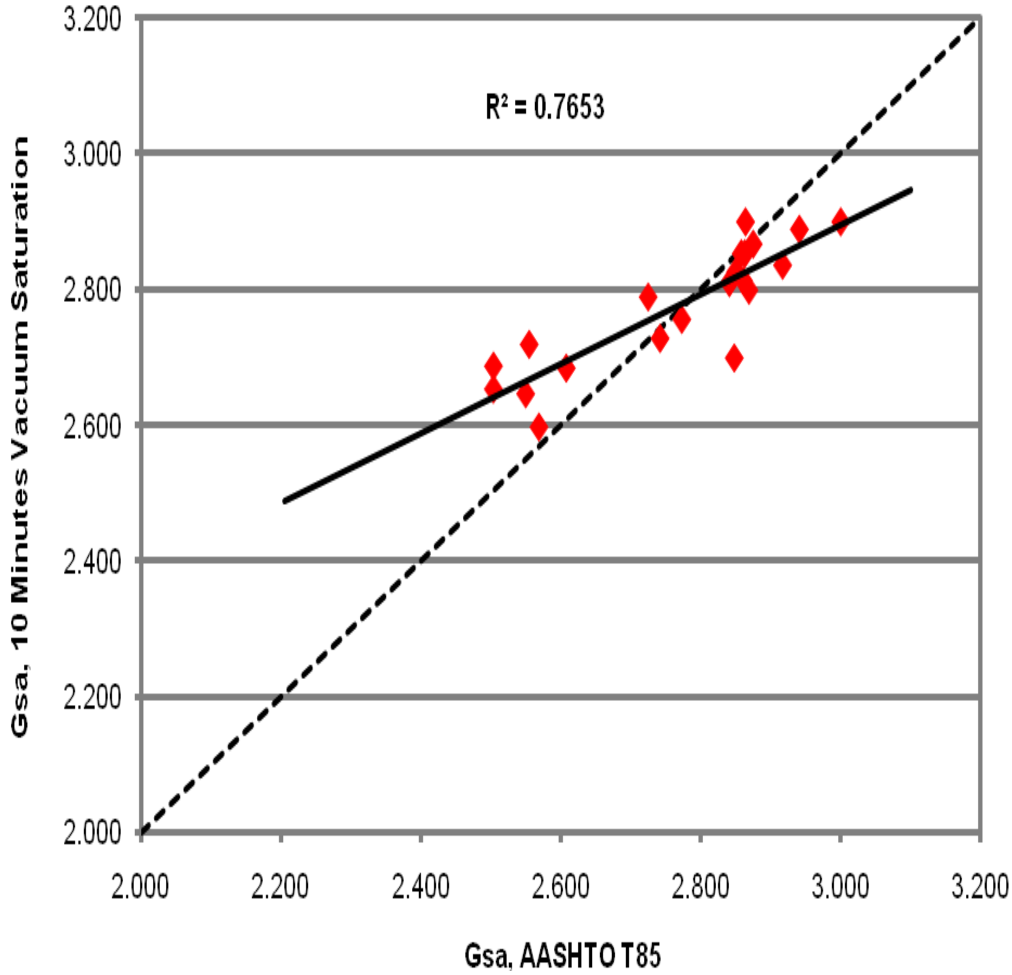

Figure 15 AASHTO T-85 against 10 Minutes Vacuum Saturation Test for Gsa

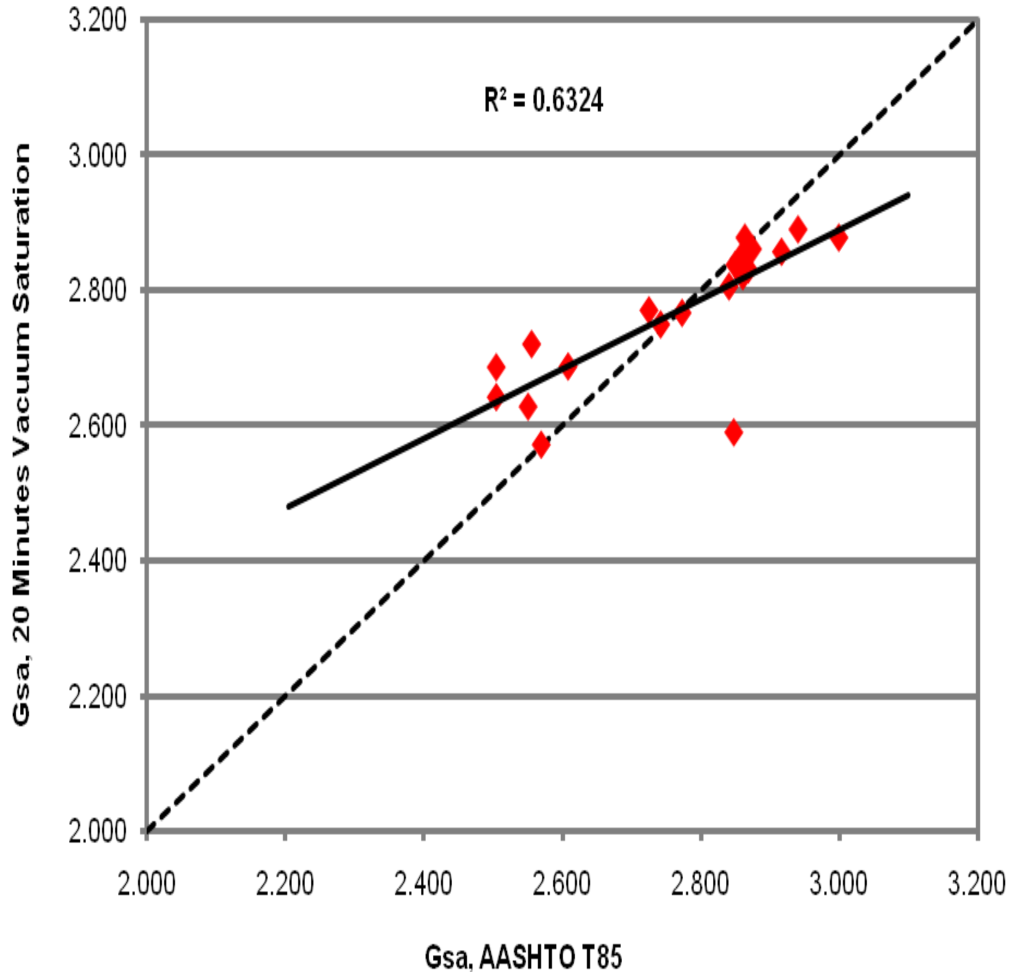

Figure 16 AASHTO T-85 against 20 Minutes Vacuum Saturation Test for Gsa

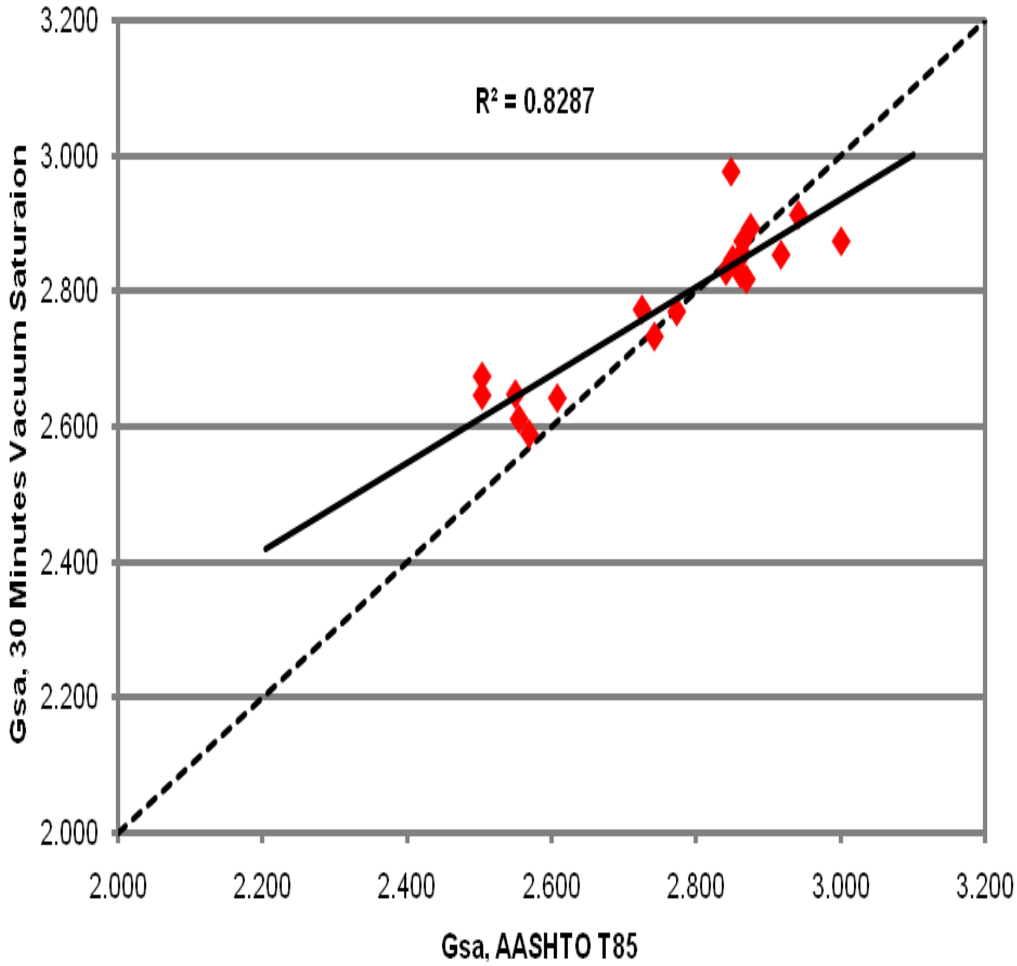

Figure 17 AASHTO T-85 against 30 Minutes Vacuum Saturation Test for Gsa

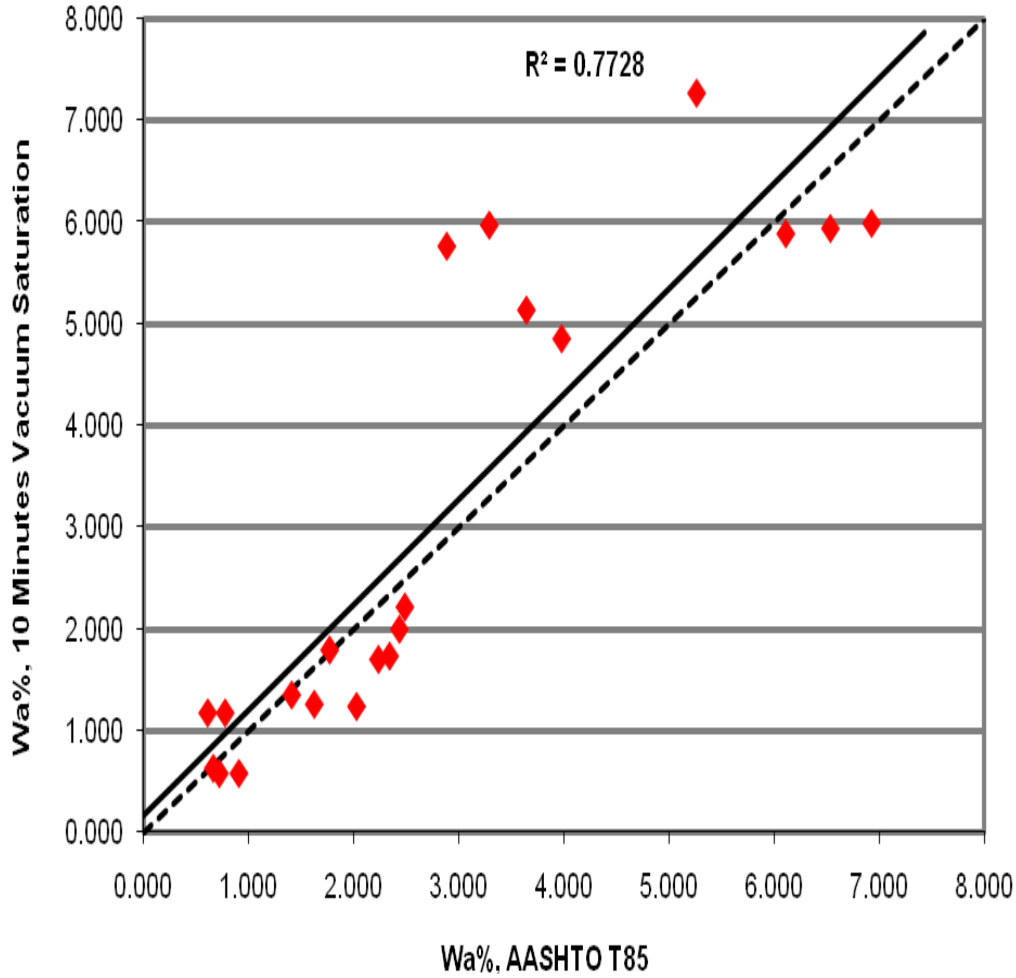

Figure 18 AASHTO T-85 against 10 Minutes Vacuum Saturation Test for Wa%

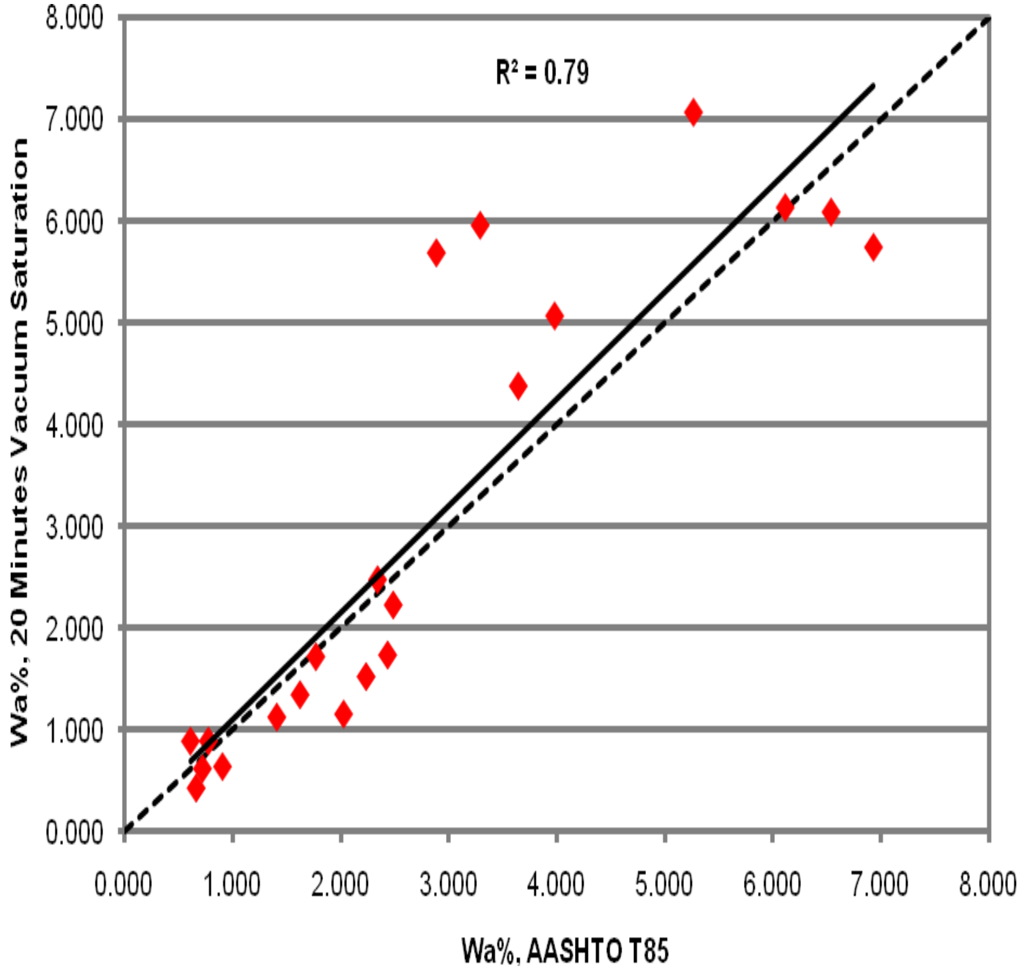

Figure 19 AASHTO T-85 against 20 Minutes Vacuum Saturation Test for Wa%

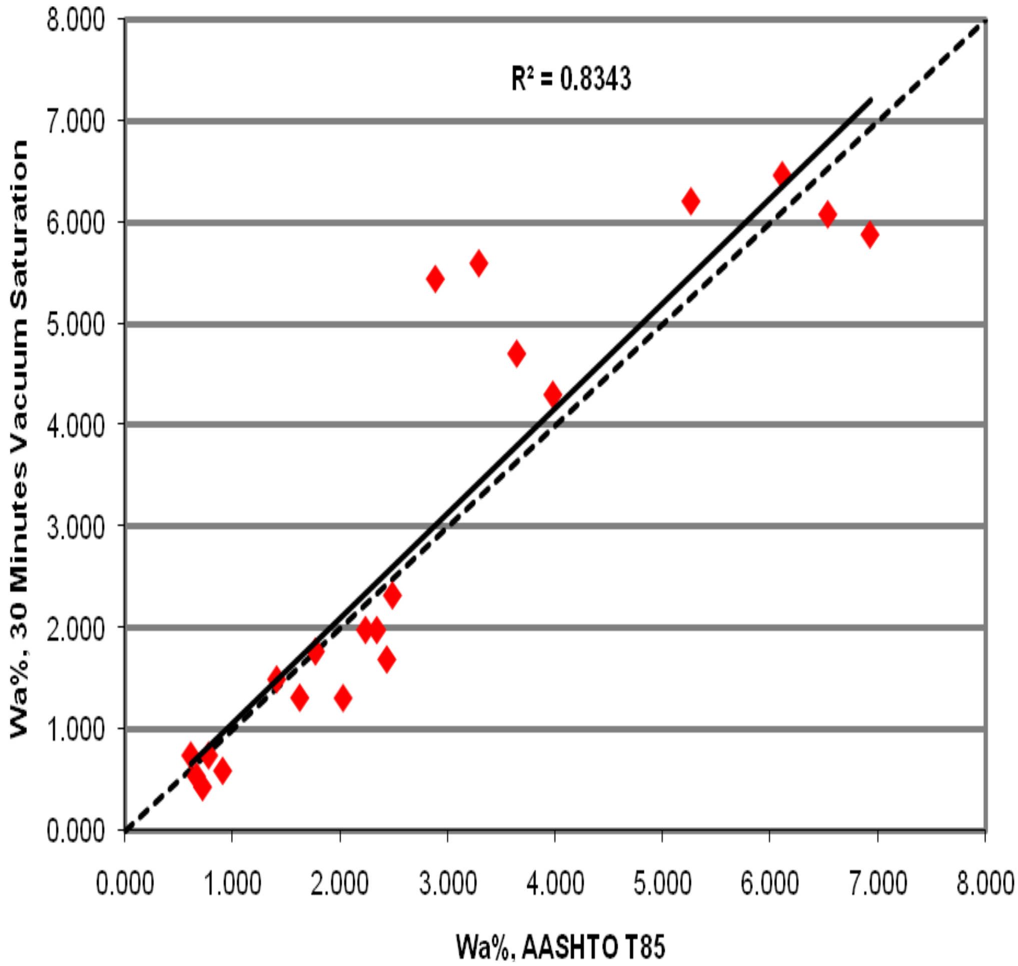

Figure 20 AASHTO T-85 against 30 Minutes Vacuum Saturation Test for Wa%

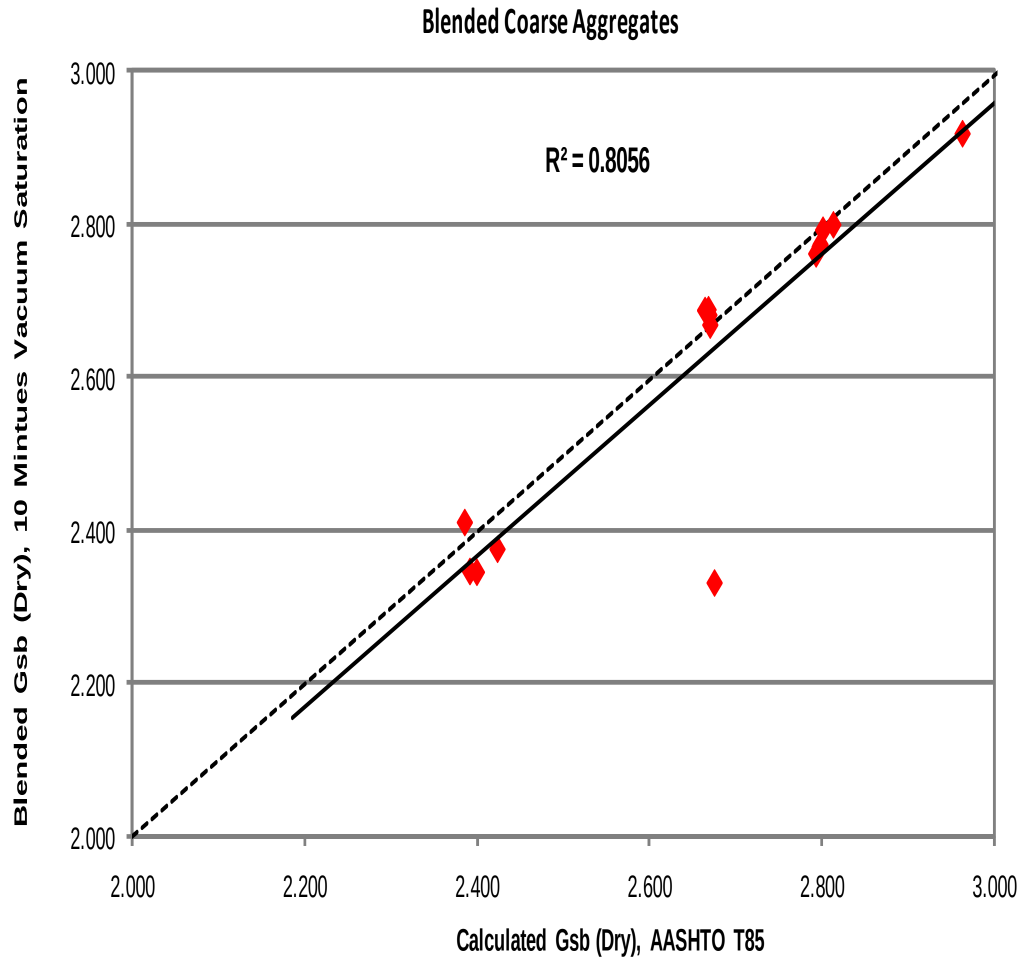

Figure 21 Gsb (Dry): Calculated Value against Single Test Value of 10 Minutes Vacuum Saturation Test

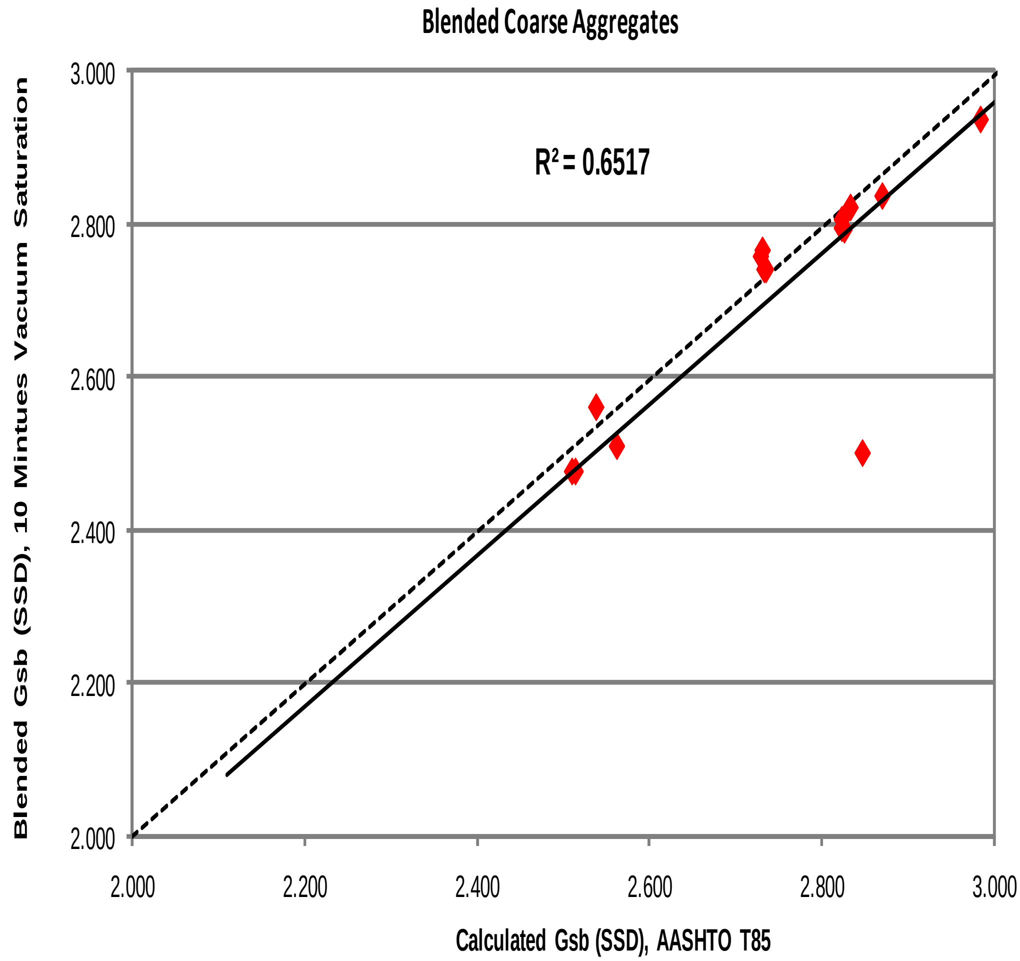

Figure 22 Gsb (Dry): Calculated Value against Single Test Value of 10 Minutes Vacuum Saturation Test

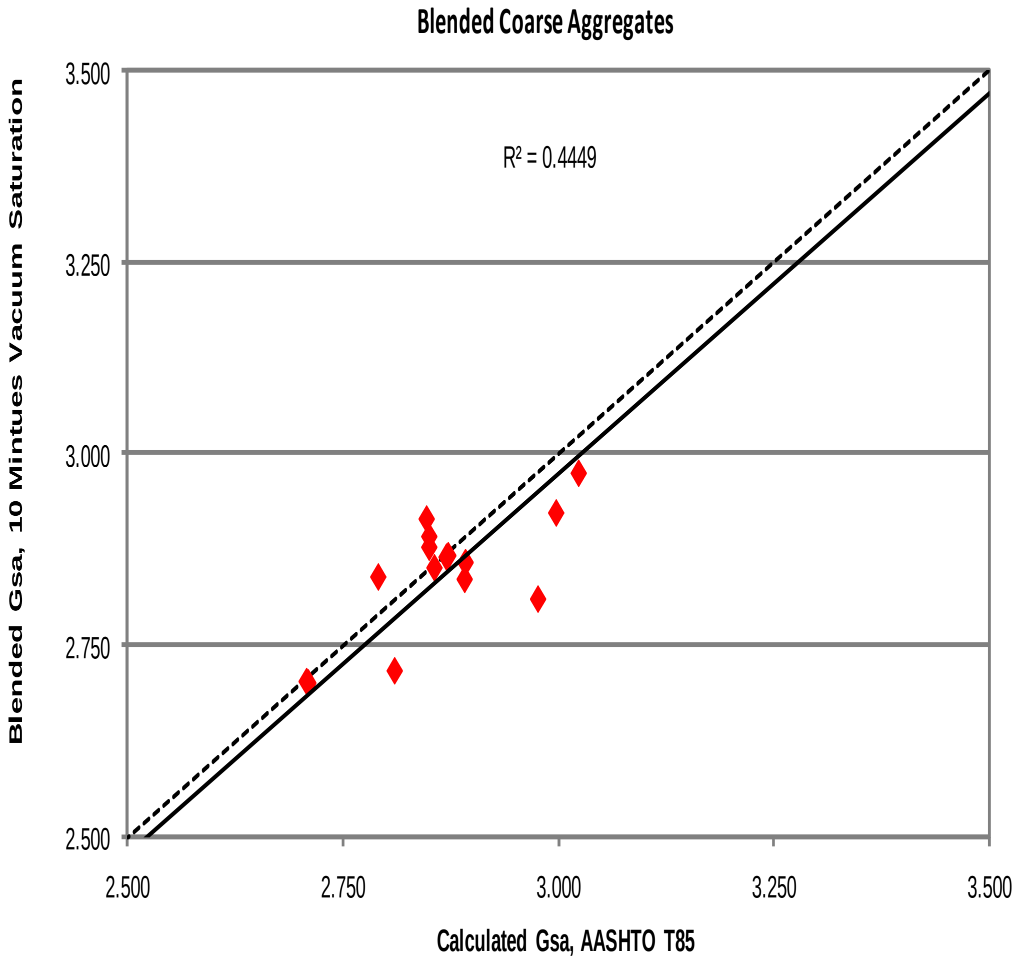

Figure 23 Gsa: Calculated Value against Single Test Value of 10 Minutes Vacuum Saturation Test

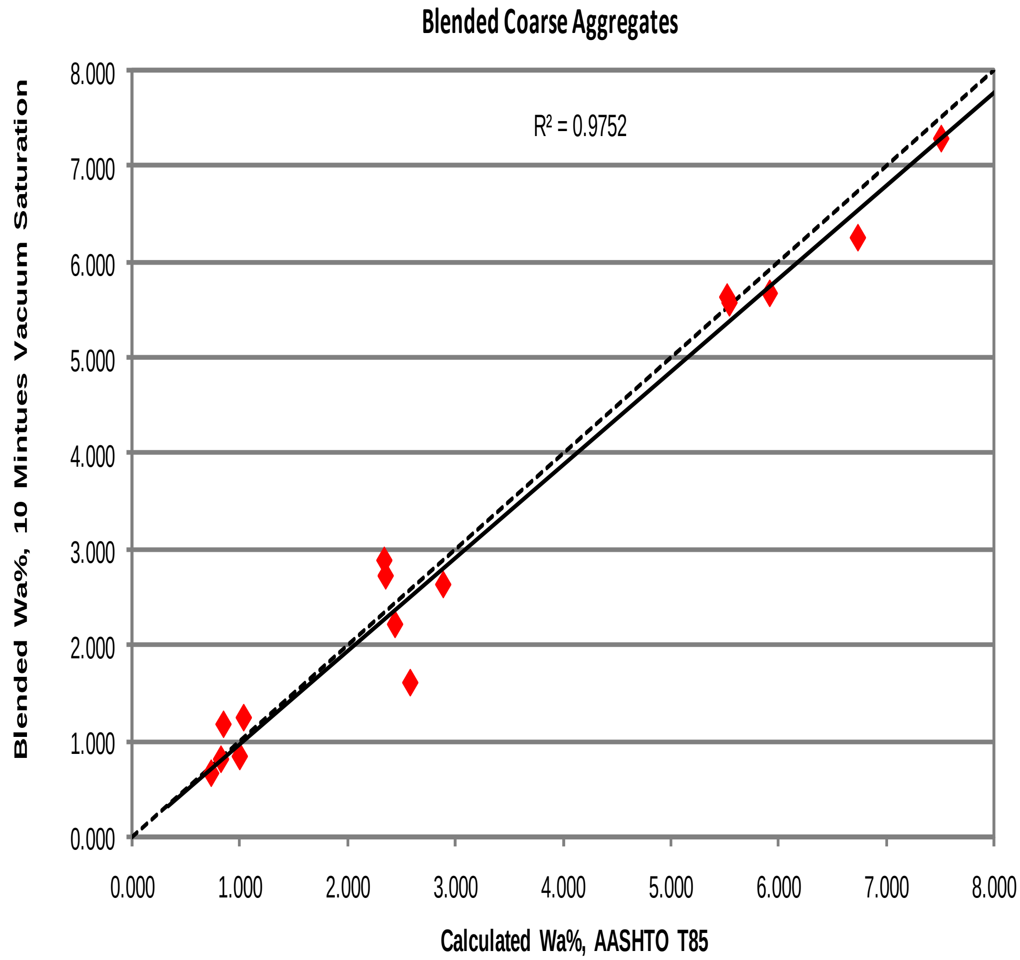

Figure 24 Wa%: Calculated Value against Single Test Value of 10 Minutes Vacuum Saturation Test

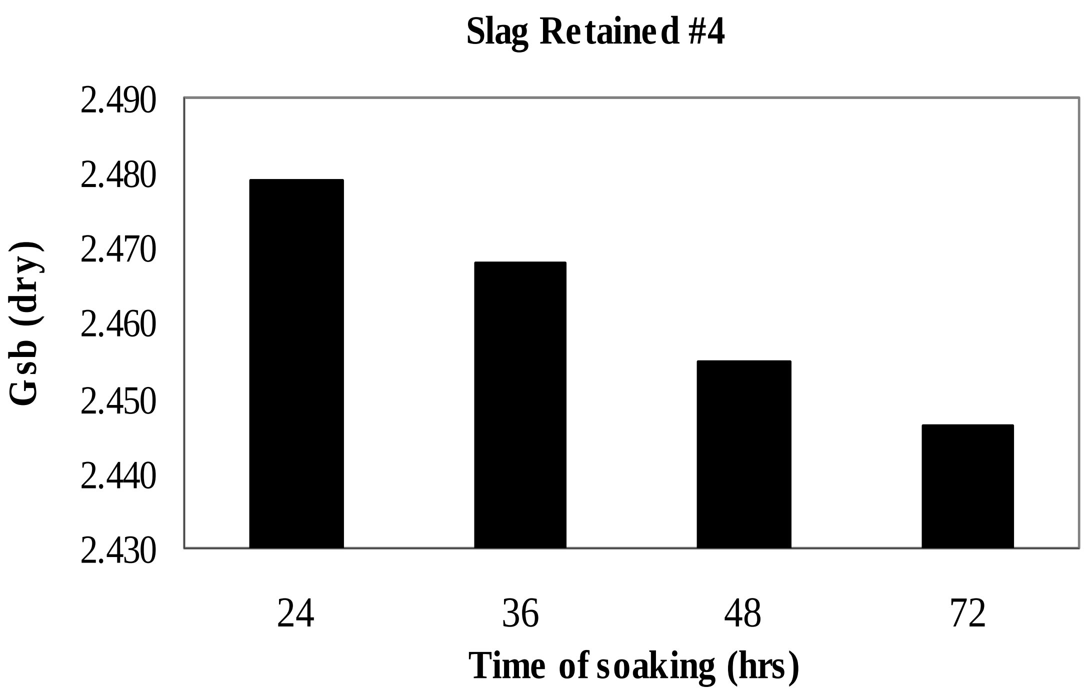

Figure 25 Gsb (dry) test results over 24, 36, 48 and 72 hours of soaking periods

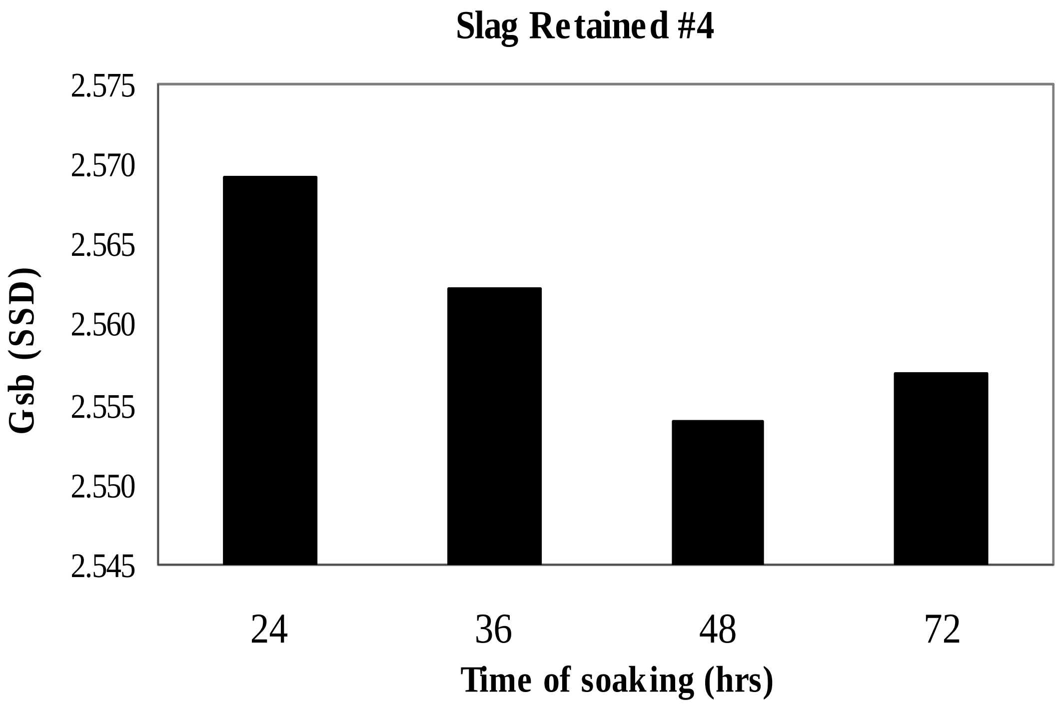

Figure 26 Gsb (SSD) test results over 24, 36, 48 and 72 hours of soaking periods

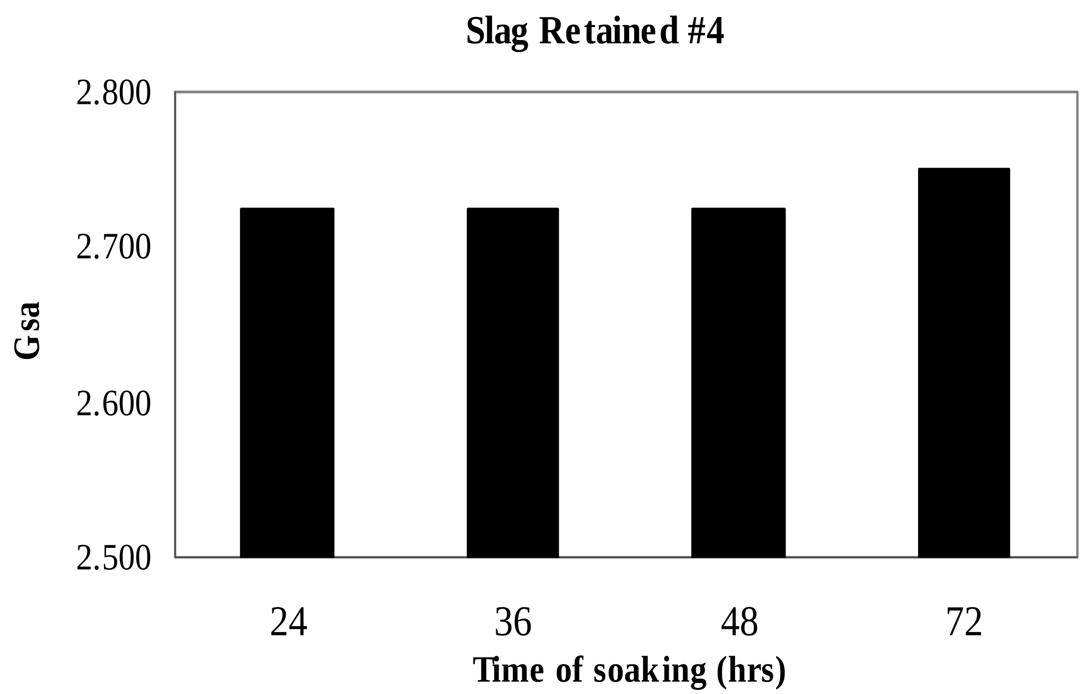

Figure 27 Gsa test results over 24, 36, 48 and 72 hours of soaking periods

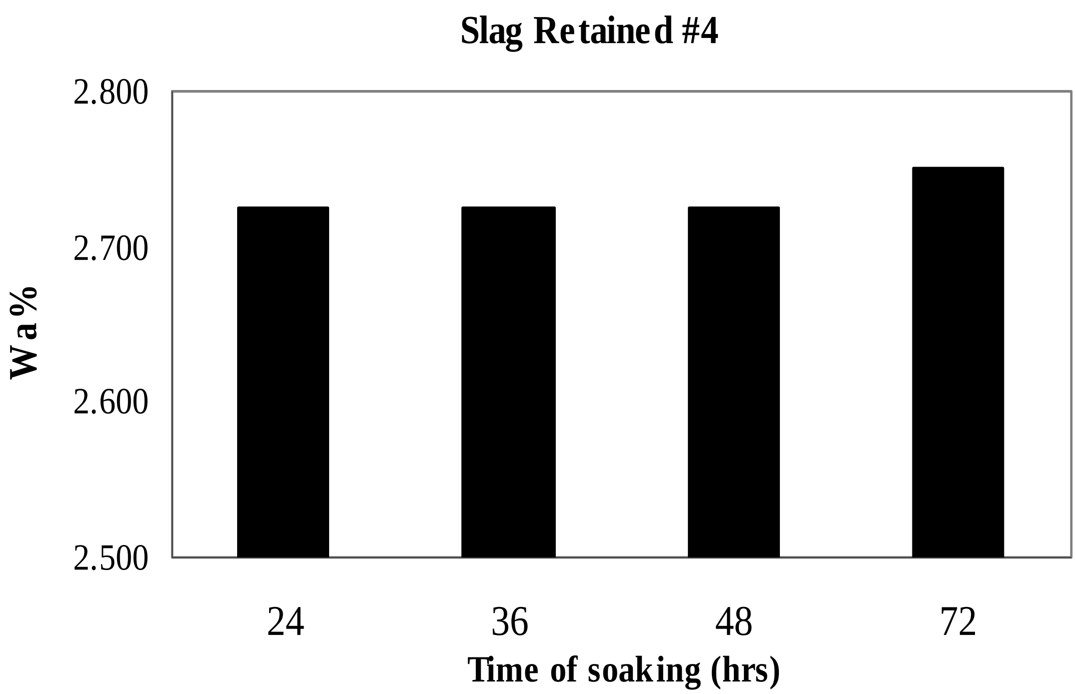

Figure 28 Wa% test results over 24, 36, 48 and 72 hours of soaking periods