EVALUATION OF NEW TEST PROCEDURES FOR DETERMINING THE BULK SPECIFIC GRAVITY OF FINE AGGREGATE USING AUTOMATED METHODS

Brian D. Prowell
Assistant Director
National Center for Asphalt Technology
277 Technology Parkway
Auburn, AL 36830
Phone: (334) 844-6228
Fax: (334) 844-6248
Email: Bprowell@eng.auburn.edu

Nolan V. Baker
Engineering Associate
Thompson Engineering
3707 Cottage Hill Road
Mobile, AL 36609
Formerly
National Center for Asphalt Technology

Email: NBaker@ThompsonEngineering.com

Corresponding Author: Brian D. Prowell

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ABSTRACT

This study evaluated two automated methods for determining the dry bulk specific gravity (Gsb) of fine aggregates, the Thermolyne SSDetect and InstroTek Corelok. Each proposed method was evaluated against the standard method described in AASHTO T-84. The evaluation was based on a round robin study with twelve labs and six materials, four crushed fine and two uncrushed (natural) fine aggregate sources.

The Corelok and SSDetect methods of determining fine aggregate specific gravity offer significant timesavings over AASHTO T84. Both the Corelok and SSDetect methods generally produce Gsb results that are similar to AASHTO T84. It is believed that AASHTO T84 may not produce accurate results for angular materials with high dust contents. More frequent statistical differences exist between both the Corelok and SSDetect apparent specific gravity (Gsa) and water absorption results than those produced by AASHTO T84. However, Gsa and water absorption are not used in volumetric calculations for hot mix asphalt.

The SSDetect offers improved precision to AASHTO T84. The precision of the Corelok method is slightly worse than AASHTO T84, but expected to improve as technicians become more familiar with the procedure.

INTRODUCTION

Determining the bulk specific gravity of fine aggregate is very important when designing a hot mix asphalt (HMA) pavement and for other uses. The bulk specific gravity is used in calculating the voids in the mineral aggregate (VMA) of an HMA mixture. The current method of determining dry bulk specific gravity (Gsb) of fine aggregates AASHTO T 84 (_1_) or ASTM C 128, uses a cone and tamp to determine the saturated surface-dry (SSD) condition of a fine aggregate. This method does not work well when determining the SSD condition of angular or rough fine aggregates because they do not readily slump. Therefore, a more accurate and more repeatable method of determining Gsb is needed to provide lower variability between operators and to address problems with angular materials. In order to solve this problem, a method that is more automated and less user dependent is needed to determine both Gsb and absorption of fine aggregates.

The GSB of an aggregate is defined as the ratio of the mass of dry aggregate to the mass of water having a volume equal to that of the aggregate including both its permeable and impermeable voids. Permeable voids are those voids that are filled with water when in the SSD condition and impermeable voids are the voids that water cannot penetrate. Gsb is defined by Equation 1.

$$Gsb = Ws / (Vs + Vv)\ \gamma_w \qquad (1)$$

Ws = mass of solid
Vs = Volume of solid (including volume of impermeable voids)
Vv = Volume of water permeable voids
γ_w = Unit weight of water

The apparent specific gravity (Gsa) is defined as the ratio of the weight of dry aggregate to the weight of water having a volume equal to the solid volume of the aggregate excluding its permeable voids. Gsa is defined by Equation 2.

$$Gsa = Ws / (Vs * \gamma_w) \qquad (2)$$

An aggregate is said to be in the SSD condition when the permeable voids in the aggregate are filled with water, but outside (surface) moisture is not present on the particle. To reach this SSD condition, the current method (AASHTO T 84) calls for an aggregate to be immersed in water for 15 – 19 hours and then dried back to this “SSD” state (_1_).

During the 1970’s, The Arizona Department of Transportation (DOT) tried to develop a prototype for determining SSD using a rotating vertical tube. Warm air was blown through the tube while it rotated. Using the plots of the inlet and outlet temperature and the basic principles of thermodynamics, they determined the SSD region of these plots. The prototype gave encouraging results; however, it had a high variability. The researchers recommended testing a wider variety of fine aggregates (_2_).

NCAT continued with Arizona DOT’s ideas. Instead of blowing warm air vertically over the sample, NCAT tried blowing the warm air longitudinally in a steel drum while it was rotating on its side. NCAT discovered that the SSD point could be determined more repeatable by monitoring the outgoing relative humidity. There were several problems with this method though: inconsistent drying, loss of fines, clogging of screens, aggregate sticking to the drum and the prototype was not automated (3).

Haddock and Prowell (4) explored how InstroTek's prototype and Thermolyne's SSDetect determined Gsb. Bulk specific gravities for InstroTek's prototype were determined from the apparent specific gravities measured with the device assuming constant water absorption for each aggregate type (absorption values were determined at the beginning of a project with ASTM C 128). It was concluded that both prototypes improved the precision of Gsb measurements over the standard method.

Hall (5) compared InstroTek prototype's variability to that of the standard method (AASHTO T 84) using six Arkansas aggregates. Hall concluded that from a practical standpoint, the Gsb and absorption values for both methods were comparable in most cases. However, statistically significant differences existed between the absorption and Gsb measured in three of six cases. There were no significant differences between the apparent gravities measured by the two methods.

PURPOSE AND SCOPE

The objective of this study was to evaluate automated methods for determining the Gsb of fine aggregates; each proposed method was evaluated against the standard method described in AASHTO T 84. A round robin was conducted according to ASTM C 802 for each methodology. The round robin data were used to compare the Gsb, Gsa and absorption expected from a cross section of laboratories and materials. The round robin data were also used to develop a precision statement for each method.

MATERIALS

Six different aggregates were selected for the round robin testing (Table 1). A wide variety of aggregates were chosen in an attempt to cover a wide range of material properties. A limestone (material A), medium and high dust diabase (materials B and C), slag (material D), rounded sand (material E) and a crushed gravel (material F) were selected for the study. The percent passing the 0.075 mm (#200) sieve ranged from 14.3 percent for the unwashed diabase (material C) to 0.9 percent for the rounded sand (material E). Material E also had the lowest uncompacted void content as measured by AASHTO T 304 (41.2 percent) whereas; material D had the highest uncompacted void contentwith a value of 50.7 percent.

In order to minimize material variability, all of the material processing was conducted at NCAT. When a material was received at NCAT, it was dried and then broken over a 4.75 mm sieve to remove any plus 4.75 mm material. Next, the material was split into the desired sample sizes. Finally, after all samples had been split out to the appropriate sample sizes, the samples were randomized prior to shipping to the participating labs.

PROPOSED METHODS

Based on the prototype developed in *(3)*, equipment manufacturers were solicited to develop prototypes for evaluation. Three companies emerged with a proposed methodologies for determining the Gsb and absorption of fine aggregate: Gilson, InstroTek and Thermolyne. Each proposed method presented a different approach to obtain Gsb and absorption. Gilson took the “wet to dry” approach. After soaking a sample overnight, they used a warm airflow to obtain Gsb and absorption. InstroTek and Thermolyne both tried the “dry to wet” approach of obtaining Gsb and absorption. InstroTek used a calibrated pycnometer and vacuum pressure whereas; Thermolyne used an infrared (IR) signal to determine SSD combined with a vacuum and agitation system to determine Gsa.

Initially, the three methodologies were evaluated in an internal study conducted at NCAT. The internal study consisted of three operators testing ten replicates of each of seven materials with each of the prototype devices and AASHTO T 84. The internal study is documented in *(6)*. Based on the results of the internal study, modifications were made to each new procedure. Ruggedness studies were performed according to ASTM C 1067 with three participating laboratories for the Instrotek and Thermolyne procedures to refine the test method. A ruggedness study is planned for the Gilson method. The draft AASHTO test protocols are reported in *(6)*.

InstroTek

InstroTek devised a method using a combination of a calibrated pycnometer and a vacuum-sealing device to determine Gsb and absorption. The pycnometer (volumeter) is used to determine the bulk volume of the sample and the vacuum-sealing device is used in determining the apparent specific gravity. The Gsb is the overall volume of an aggregate particle including the volume of the pores that are filled with water. The InstroTek approach requires that a sample be placed into a calibrated pycnometer. The volume of the pycnometer is calibrated by filling it completely with water (before each set of 10 samples). To test a sample, the container is halfway filled with water and a 500 g dry sample is added. The sample stirred to remove entrapped air. Additional water is added and a lid is then placed on the pycnometer. The remaining air space is then filled with water. This is used to determine the volume of the aggregate by the displacement of water. This whole process is done within two minutes to reduce the amount of water absorbed into the pores of the aggregate, thus giving the bulk volume of the fine aggregate. This process is repeated twice and the results averaged for a single test determination.

The apparent specific gravity is the density of a material calculated using a volume that does not include the pore space within the particles that are accessible to water. To determine the apparent specific gravity a vacuum is pulled on an additional 1000 g sample that is placed in a plastic bag. The bag is sealed. The sample/bag are placed in water and the bag is cut to release the vacuum. In doing so, all of the voids accessible to water within the aggregate are quickly filled with water. The sample is then weighed underwater to determine the volume of the solid mass of the aggregate (excluding the water accessible voids) by water displacement. Knowing the density of the bag, the dry mass of the sample and bag, as well as the weight in water are used to calculate Gsa. Once the samples are prepared, total test time is approximately 30 minutes.

Thermolyne

The equipment for the Thermolyne procedure for determining fine aggregate Gsb and absorption consists of two parts, the AVM unit and SSDetect device. The AVM unit is an automated device for removing entrapped air from a volumetric flask. The unit includes an automated vacuum source and orbital mixer. A 500 ml volumetric flask is partially filled with water. A 500-gram sample of fine aggregate is added to the flask and the flask filled with water to the calibration mark. The flask is loaded in the AVM. The AVM removes the entrapped air through the application of the orbital mixing action and partial vacuum over approximately a 16-minute period. After the flask is refilled to the calibration mark, its weight is determined. The AVM sample is used to determine Gsa and the film coefficient. The film coefficient is a calibration factor for the infrared reflectance measurements made with the SSDetect.

The SSDetect device consists of an orbital mixer, calibrated water injection pump, infrared source, infrared detector and mixing bowl. The SSDetect also includes an integral processor, accessible using a touch screen. The mixing bowl has a lid with two sapphire lenses. The lid prevents evaporation or loss of sample during mixing and the lenses allow transmission of the infrared light. A 500-gram dry fine aggregate sample is placed in SSDetect mixing bowl. The film coefficient determined using the AVM is entered into the SSDetect. Once the unit is started, the calibrated pump begins injecting water into the mixing bowl. The orbital mixer ensures even distribution among the fine aggregate sample. The water is drawn into the sample by capillary action. The infrared light source and detector are used to determine when the sample has reached the SSD state. Infrared light is absorbed by water. The infrared detectors are used to determine when the infrared light is being absorbed, indicating that the sample has reached the SSD state. An audible alarm then indicates that the sample should be weighed. This allows calculation of the samples water absorption. The sample water absorption and Gsa can be used to calculate Gsb. Testing in the SSDetect takes approximately one hour, for a total test time once the sample is prepared of approximately one hour and fifteen minutes.

Round Robin

ASTM C 802 and E 691 (*7*) were used to develop the experimental plan for the round robin. Twelve labs were asked to participate for each device. Data from ten labs has been returned for the Corelok device and nine labs each for the Thermolyne device and AASHTO T 84. Six aggregates were selected for the study as discussed previously. In addition, a series of practice samples were sent to the labs to ensure that they were comfortable with the new test procedures and that the equipment was functioning properly. These samples were tested and reported to NCAT prior to testing the round robin samples. Each laboratory tested three replicates of each material. The distribution of the samples to the participating laboratories was randomized among all of the test methods, as was the testing order.

RESULTS AND ANALYSIS

Comparison of Automated Methods and T84 Test Results

Typically, new test procedures are evaluated for both bias and precision. Bias is the difference between the measured result and the true value of the measured property. Precision is a measure of the variability of the test procedure and how repeatable the test will be for a single operator or between different laboratories. Unfortunately, there is no "standard" sample for which the fine aggregate specific gravity is precisely known. Therefore, since AASHTO T 84 is the currently accepted method, comparisons were made between the measured test values of the proposed SSDetect and Corelok test methods and the test values from AASHTO T84. This was accomplished through a round-robin to allow a robust comparison. Thus, though different labs are expected to measure slightly different values for a given aggregate, by examining the results from several laboratories, which have each tested split samples of a range of materials, one can evaluate how well the test methods compare. Still, this comparison has potential error since it is already believed that there is error in the AASHTO T 84 measurements for some types of materials.

Figure 1 through Figure 3 show the average Gsb, water absorption, and Gsa results, respectively for each of the methods. The average is based on 30 test results (10 labs x 3 replicates for the Corelok method, 36 (12 labs x 3 replicates) test results for the SSDetect and 27 test results for AASHTO T 84 (9 labs x 3 replicates). The error bars shown on the bar charts represent plus or minus one standard deviation of the mean. The Gsb, Gsa, and water absorption data are also summarized in Table 2.

Analysis of Variance (ANOVA) was performed using Minitab statistical software *(8)*. Gsb was used as the response and material and method were used as factors. The ANOVA indicated that material, method and the interaction between method and material were all significant. Separate one-way ANOVA analyses were performed for each material. Tukey's family error rate comparisons were performed at the 5 percent significance level to compare the confidence intervals for mean Gsb values for each method. The results are illustrated as A, B, C or AB in Figure 1. A, B and C are statistically different. AB is neither different from A or B. The Corelok Gsb values were statistically different from T84 in three of six cases for limestone, washed diabase and slag. The higher standard deviation for the non-washed diabase prevented a statistical difference. Crushed materials are difficult to test and produce accurate readings with AASHTO T 84. Over drying the sample to produce a slight slump leads to a higher Gsb with AASHTO T 84. The AASHTO T 84 results are higher for two of the three statistical differences. Statistical differences between the Corelok method and AASHTO T 84 in Gsb ranged between 0.035 and 0.108.

The SSDetect values were statistically different from the T84 values in three of six cases for the washed diabase, rounded natural sand and angular natural sand. Statistical differences between the SSDetect Method and AASHTO T 84 ranged from 0.016 to 0.030. Where statistical differences occurred, the differences were larger for the Corelok Method.

Similar to Gsb, ANOVA was performed using the Gsa results as the response and material and method as factors. The ANOVA indicated that material, method and the interaction between method and material were all significant. However, the Tukey's test indicated that the Gsa determined by the SSDetect and AASHTO T 84 were not different. Separate one-way ANOVA analyses and Tukey's comparisons were performed for each material. The results are illustrated as A, B, C or AB in Figure 2. When tested by material, the Corelok water absorptions were statistically different from AASHTO T 84 in all six cases. The SSDetect water absorptions were statistically different in three of six cases. Only one of the cases of significant difference for the SSDetect was for the same material as indicated by Gsb.

ANOVA was performed using the water absorption results as the response and material and method as factors. The ANOVA indicated that material, method and the interaction between method and material were all significant. Separate one-way ANOVA analyses and Tukey's comparisons were performed for each material. The results are illustrated as A, B or AB in Figure 3. When tested by material, the Corelok water absorptions were statistically different from AASHTO T 84 in all six cases. The SSDetect water absorptions were statistically different in three of six cases. Two of the three cases are the same as those indicated for Gsb.

Precision of Test Methods

ASTM E 691 software *(9)* was used to determine the precision of the test methods from the round robin results. Precision of the test method has two components, repeatability and reproducibility. Repeatability (Sr) is the within-laboratory standard deviation of the test results. Reproducibility (SR) is the between laboratory standard deviation of the test results. The Gsb, Gsa and absorption results are shown for each method and material in Table 3.

ASTM E 691 *(9)* uses two statistics to analyze the data for consistency: *h* and *k*. The *h* statistic is an indicator of how one laboratory's average for a material compares with the average of the other laboratories. The *h* statistic is based on Student's *t* test. The *k* statistic is an indicator of how one laboratory's variability for a given set of replicate samples compares with that of all the other laboratories. The *k* statistic is based on the *F* ratio. For Gsb, the *k* statistic analysis indicated three outliers for AASHTO T 84, one outlier for the SSDetect method and six outliers for the Corelok method. One Gsb outlier was indicated for the Corelok method based on the *h* statistic. For the *k* statistic, the outliers could be traced to one erroneous measurement in all cases. These measurements were removed from the data set and the analysis re-run. The precision results for Gsb without outliers are shown in Table 4. Removal of the outliers did not indicate that the Corelok method was more repeatable or reproducible than AASHTO T 84.

The pooled Sr and SR as well as the acceptable difference between two test results are shown in Table 5. Table 5 was calculated using the pooled precision results from Table 3 (with outliers). The acceptable difference between two test results is the expected difference not to be exceeded with one chance in twenty for either two properly conducted tests by a single operator or two properly conducted tests by two different laboratories. The data in Tables 3, 4 and 5 indicate that the SSDetect offers improved single operator and multilaboratory precision over AASHTO T 84 for Gsb, Gsa and water absorption. The Corelok procedure is more variable than AASHTO T 84. The Corelok test method requires operator skill. It is possible that the precision of the Corelok method will improve with additional experience.

CONCLUSIONS

Three new methods of determining fine aggregate specific gravity have been developed. Two of the methods, the Instrotek Corelok and Thermolyne SSDetect were evaluated in a round robin study.

1. The Corelok and SSDetect methods of determining fine aggregate specific gravity offer significant timesavings over AASHTO T 84. Neither method requires the 16-hour soak period included in AASHTO T 84. This means that hot mix asphalt belt sweep samples could be taken to verify gravities during construction for volumetric calculations in a timely manner.
2. Both the Corelok and SSDetect methods generally produce Gsb results that are similar to AASHTO T 84. Where statistical differences occurred for Gsb between the new methods and AASHTO T 84, the differences were amaller for the SSDetect method. It is believed that AASHTO T 84 may not produce accurate results for angular materials with high dust contents. More frequent statistical differences exist between AASHTO T 84 and both the Corelok and SSDetect Gsa and water absorption results. However, Gsa and water absorption are not used in volumetric calculations for hot mix asphalt.
3. The SSDetect offers improved precision as compared to AASHTO T 84. The precision of the Corelok method is not as good as AASHTO T 84. It is possible that the precision of the Corelok method will improve as technicians become more familiar with the procedure.

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List of Tables and Figures

Table 1. Fine Aggregate Properties

Sieve Size (mm)	Percent Passing					
	Material A Limerock	Material B Washed Diabase	Material C Diabase	Material D Slag	Material E Rounded Natural (uncrushed) Sand	Material F Angular Natural (uncrushed) Sand
4.75	100.	100	100	100	100	100
2.36	87	71	85	78	85	83
1.18	66	46	53	54	68	61
0.600	47	30	40	35	50	34
0.300	32	19	30	22	18	15
0.150	14	12	21	13	2.6	7
0.075	5.9	7.5	14.3	7.1	0.9	3.4
FAA[1]	47.5	48.8	48.8	50.7	41.2	45.1

[1]Uncompacted void content, percent determined according to AASHTO T304 Method A

Table 2. Summary of Round Robin Averages and Standard Deviations for Gsb, Gsa and Water Absorption

Material	Corelok Average	SSDetect Average	T84 Average	Corelok Standard Deviation	SSDetect Standard Deviation	T84 Standard Deviation
			Gsb			
A	2.291	2.314	2.326	0.0323	0.0361	0.0363
B	2.923	2.909	2.881	0.0222	0.0110	0.0319
C	2.893	2.880	2.881	0.1114	0.0138	0.0531
D	2.723	2.811	2.831	0.0542	0.0245	0.0380
E	2.532	2.495	2.525	0.0473	0.0185	0.0223
F	2.539	2.531	2.547	0.0194	0.0161	0.0210
			Gsa			
A	2.701	2.657	2.616	0.0054	0.0087	0.0455
B	2.977	2.972	2.998	0.0045	0.0051	0.0123
C	2.981	2.973	2.998	0.0060	0.0051	0.0165
D	2.944	2.927	2.916	0.0538	0.0236	0.0223
E	2.670	2.648	2.645	0.0545	0.0055	0.0235
F	2.674	2.654	2.662	0.0176	0.0049	0.0175
			Water Absorption			
A	6.7	5.6	4.8	0.43	0.65	0.79
B	0.6	0.7	1.4	0.28	0.11	0.35
C	0.8	1.1	1.4	0.57	0.13	0.61
D	2.8	1.4	1.0	0.34	0.27	0.32
E	2.0	2.3	1.8	0.42	0.29	0.27
F	2.0	1.8	1.7	0.50	0.28	0.28

Table 3. Summary of Round Robin Repeatability and Reproducibility Standard Deviations

Material	Corelok Sr	SSDetect Sr	T84 Sr	Corelok SR	SSDetect SR	T84 SR
			Gsb			
A	0.0332	0.0279	0.0234	0.0360	0.0425	0.0355
B	0.0156	0.0072	0.0122	0.0222	0.0112	0.0231
C	0.1014	0.0106	0.0182	0.1077	0.0145	0.0289
D	0.0495	0.0179	0.0195	0.0627	0.0252	0.0212
E	0.0391	0.0122	0.0108	0.0541	0.0193	0.0132
F	0.0253	0.0067	0.0099	0.0287	0.0205	0.0163
Average	0.0440	0.0138	0.0157	0.0519	0.0222	0.0230
			Gsa			
A	0.0046	0.0044	0.0118	0.0054	0.0082	0.0271
B	0.0039	0.0039	0.0078	0.0056	0.0053	0.0123
C	0.0061	0.0037	0.0125	0.0075	0.0055	0.0152
D	0.0534	0.0191	0.0108	0.0539	0.0211	0.0131
E	0.0523	0.0058	0.0071	0.0523	0.0064	0.0131
F	0.0179	0.0029	0.0059	0.0180	0.0046	0.0101
Average	0.0230	0.0066	0.0093	0.0238	0.0085	0.0151
			Water Absorption			
A	0.4102	0.5160	0.4323	0.5673	0.7702	0.8139
B	0.1890	0.0773	0.1795	0.2831	0.1099	0.3440
C	0.2038	0.1103	0.1613	0.5914	0.1371	0.6056
D	0.3921	0.1859	0.1860	0.7186	0.2792	0.3075
E	0.3754	0.1874	0.1819	0.6563	0.3150	0.2720
F	0.6002	0.1107	0.1608	0.6087	0.3329	0.2850
Average	0.3618	0.1979	0.2170	0.5709	0.3241	0.4380

Table 4. Summary of Round Robin Repeatability and Reproducibility Standard Deviations for Gsb with Outliers Removed

Material	Corelok Sr	SSDetect Sr	T84 Sr	Corelok SR	SSDetect SR	T84 SR
			Gsb			
A	0.0202	0.0203	0.0234	0.0284	0.0373	0.0349
B	0.0083	0.0072	0.0104	0.0136	0.0112	0.0192
C	0.0158	0.0106	0.0176	0.0477	0.0145	0.0311
D	0.0259	0.0179	0.0195	0.0436	0.0252	0.0211
E	0.0212	0.0122	0.0111	0.0402	0.0193	0.0135
F	0.0172	0.0067	0.0125	0.0318	0.0205	0.0166
Average	0.0181	0.0125	0.0158	0.0342	0.0213	0.0227

Table 5. Precision Estimates

Method	Within Laboratory (Single Operator)			Between Laboratory (Multilaboratory)		
	Corelok	SSDetect	T84	Corelok	SSDetect	T84
Pooled Standard Deviation						
Gsb	0.0440	0.0138	0.0157	0.0519	0.0222	0.0230
Gsa	0.0230	0.0066	0.0093	0.0238	0.0085	0.0151
Water Absorption	0.3618	0.1979	0.2170	0.5709	0.3241	0.4380
Acceptable Difference Between Two Results (D2S)						
Gsb	0.1245	0.0389	0.0443	0.1468	0.0628	0.0651
Gsa	0.0651	0.0187	0.0264	0.0672	0.0241	0.0428
Water Absorption	1.0233	0.5598	0.6137	1.6148	0.9166	1.2389

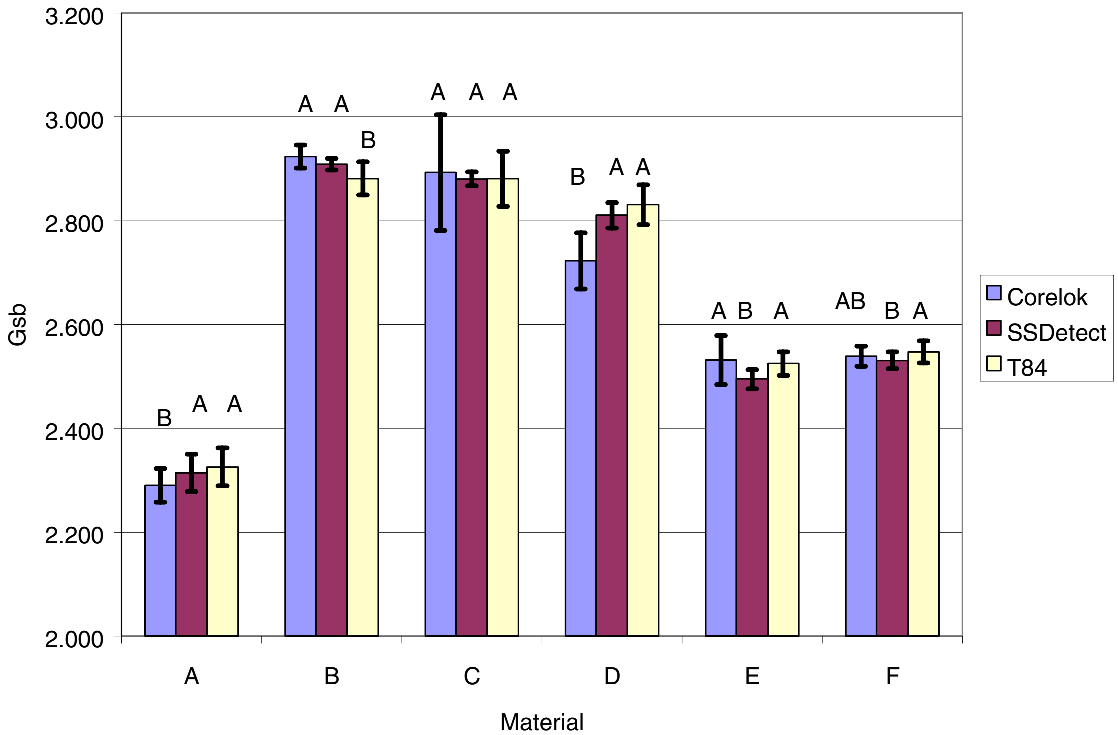

Figure 1. Average Gsb by Material and Method

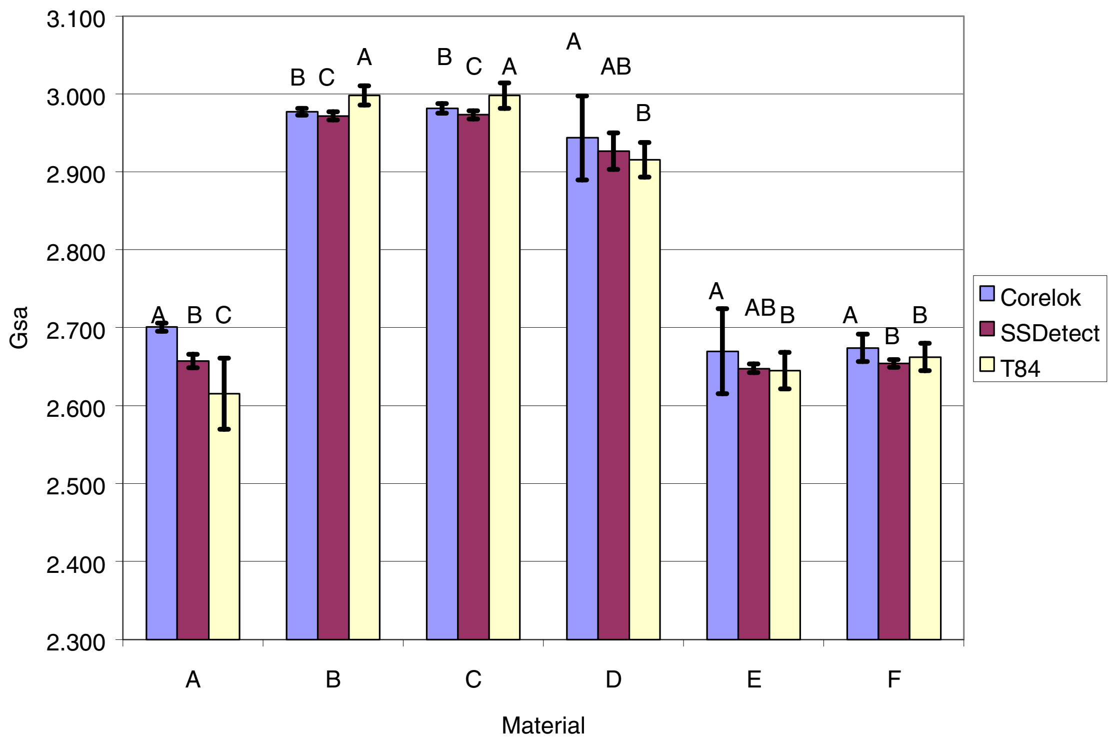

Figure 2. Average Gsa by Material and Method

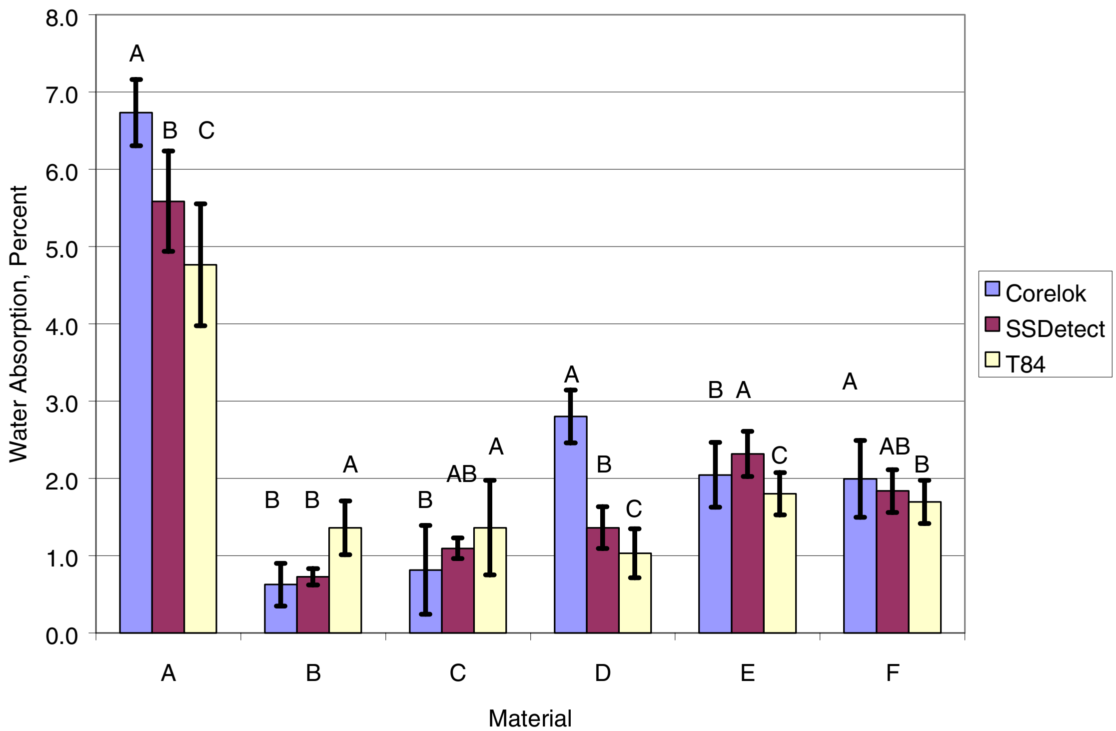

Figure 3. Average Water Absorption by Material and Method