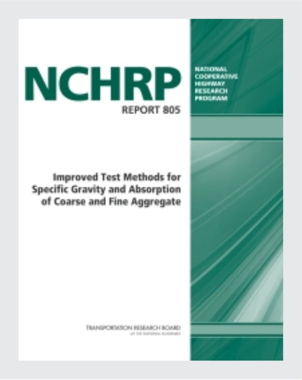
NCHRP
REPORT 805
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Improved Test Methods for Specific Gravity and Absorption of Coarse and Fine Aggregate
TRANSPORTATION RESEARCH BOARD

Improved Test Methods for Specific Gravity and Absorption of Coarse and Fine Aggregate

DETAILS

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Improved Test Methods for Specific Gravity and Absorption of Coarse and Fine Aggregate

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents proposed modifications to AASHTO T 84 and T 85 to improve their accuracy, precision, ease of use, and time required for conditioning and testing. Thus, the report will be of immediate interest to engineers in state highway agencies and the construction industry with responsibility for testing aggregate materials used in asphalt and portland cement concrete mixtures for pavement construction.

Design and production of paving asphalt and portland cement concrete (PCC) mixtures rely on accurate, precise measurement of aggregate specific gravity and absorption. Aggregate specific gravities are needed to calculate the voids in mineral aggregate (VMA) and effective binder content (P_{be}) of asphalt mixtures, which are key volumetric properties used in mix design and acceptance testing. For PCC, aggregate absorption is used to adjust water/cement or water/cementitious material ratios which affect the workability of PCC and are a good indicator of PCC's resistance to freezing and thawing and PCC's durability.

The current AASHTO standard test methods for aggregate specific gravity and absorption, namely, T 84, *Specific Gravity and Absorption of Fine Aggregate,* and T 85, *Specific Gravity and Absorption of Coarse Aggregate,* share several shortcomings in terms of subjectivity of the measurements, time requirements for conditioning and testing, and precision.

The objective of NCHRP Project 4-35 was to develop test methods for determining the specific gravity and absorption of coarse and fine aggregates with improved accuracy, precision, ease of use, and time required for conditioning and testing, compared to the current AASHTO T 84 and T 85 methods. The research was performed by the National Center for Asphalt Technology, Auburn, Alabama, in conjunction with the AASHTO Materials Reference Laboratory, Frederick, Maryland.

The key outcome of the research is the finding that AASHTO T 85 with several proposed changes, AASHTO T 84 (modified to remove and separately test P200 material), and ASTM D7172 (Standard Test Method for Determining the Relative Density (Specific Gravity) and Absorption of Fine Aggregates Using Infrared) provide a good balance of accuracy and precision compared to the other methods evaluated, including the current AASHTO T 85 and T 84. This finding was developed through a critical literature review (see Appendix C available for download from the NCHRP project web page) on the basis of which an initial set of ten test methods was selected for evaluation in a series of five laboratory experiments and a ruggedness study.

This report fully documents the research and includes the following two appendixes:

Appendix A	Revised AASHTO T 85
Appendix B	Revised AASHTO T 84

In addition, seven appendixes are available to download from the NCHRP Project 4-35 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1614:

Appendix C	Literature Review
Appendix D	Testing Results of Experiment 1
Appendix E	Testing Results of Experiment 2
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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction

Background

Accurate measurements of the specific gravity and absorption of coarse and fine aggregates are essential to the development of satisfactory mix designs and production of both portland cement concrete (PCC) and hot mix asphalt (HMA). To determine the specific gravity and absorption of an aggregate blend used in HMA and PCC, the aggregate is separated into two distinct portions—coarse and fine aggregates—based on a particular grain size (i.e., 4.75 mm). The test methods for coarse and fine aggregate portions are different. Current standard test methods for determining the specific gravity and absorption capacity of coarse and fine aggregates are AASHTO T 85 (or ASTM C127) and AASHTO T 84 (or ASTM C128), respectively.

Although these standard test methods can be conducted at a reasonable cost in concrete and asphalt laboratories, they have several shortcomings in terms of subjectivity of measurements, precision, and time requirements for conditioning and testing. Therefore, there is a need to develop new methods or improve the current test methods for determining the specific gravity and absorption of aggregate for use in HMA and PCC mix design/proportioning and production.

Project Objectives

The overall objective of NCHRP Project 04-35 was to develop improved test methods for determining the specific gravity and absorption of coarse and fine aggregates for consideration by the AASHTO Subcommittee on Materials. Detailed objectives of this project were as follows:

- Develop the test methods with balanced improvements in their (1) accuracy, precision, and ruggedness; (2) ease of use; (3) time of conditioning and testing; (4) cost; and (5) ability to uniformly deal with a broad range of natural, crushed, recycled, and manufactured coarse and fine aggregates, compared with current standard methods; and
- Address the ramifications of changes to the test methods on HMA mix design and PCC proportioning, other aggregate characteristics, and technician training and qualification.

Organization of the Project

The project was divided into two phases. The first phase was to identify potential test methods and to plan a laboratory program for screening and evaluating these methods. The second phase included laboratory programs for evaluating those potential test methods, ruggedness studies, and analyses of the impacts of implementation of recommended test methods on current specifications. This report summarizes the findings of the project.

CHAPTER 2

Selection of Test Methods for Evaluation

The first task of this study was to (1) conduct a literature review of new and revised test methods for measuring the specific gravity and absorption of coarse and fine aggregates and (2) to consult with the NCHRP technical panel to select candidate test methods for further evaluation in this study. The results of this task are summarized in this chapter.

Specific Gravity and Water Absorption of Aggregate

Volumetric properties are important for mix design/proportioning and production of PCC and HMA. However, since mass measurements are usually much easier, they are typically taken during testing and converted to volumes by using specific gravities. According to *ASTM C125: Standard Terminology Relating to Concrete and Concrete Aggregates*, specific gravity is defined in Equation 2.1 as the ratio of mass of a volume of material to the mass of an equal volume of distilled water at a stated temperature.

$$G_s = \frac{\frac{M}{V}}{\frac{M_W}{V_W}} = \frac{M}{V\gamma_W} \qquad (2.1)$$

where:

G_s = specific gravity

M = mass of material

V = volume of material

M_w = mass of water

V_w = volume of water = V

γ_w = unit weight of water = 1 g/cm^3

In Equation 2.1, the mass is simply taken in air, and the volume is measured using the water or gas displacement method. Since coarse and fine aggregate particles generally have internal and surface porosity as well as rough surfaces, measurements of a particle's volume must take into account the volume of permeable pores. As a result, depending on the mass and volume measurements used for the calculation in Equation 2.1, the following three specific gravity values are defined for coarse and fine aggregates (*1*, *2*).

$$G_{sa} = \frac{M_s}{V_s\gamma_w} \qquad (2.2)$$

$$G_{sb} = \frac{M_s}{(V_s + V_{pp})\gamma_w} \qquad (2.3)$$

$$G_{ssd} = \frac{M_s + M_{wpp}}{(V_s + V_{pp})\gamma_w} \qquad (2.4)$$

where:

G_{sa} = apparent specific gravity

G_{sb} = bulk specific gravity

G_{ssd} = bulk specific gravity (saturated-surface-dry basis)

M_s = mass of dry solids

M_{wpp} = mass of water filled in permeable pores

V_s = volume of solids

V_{pp} = volume of permeable pores

γ_w = unit weight of water

The mass and volume measurements also are used to determine the water absorption capacity of aggregate. ASTM C125 defines water absorption as the increase in the mass of aggregate due to the water filled in the permeable pores of the aggregate particles that may be dried out in an oven at a temperature between 100° and 110°C. The water absorption capacity is expressed as a percentage of the mass of oven-dried solids, as shown in Equation 2.5.

$$Absorption = \frac{M_{wpp}}{M_s} \times 100 \qquad (2.5)$$

where:

Absorption = water absorption capacity of aggregate, percent

Application of Aggregate Specific Gravity and Water Absorption

The specific gravity and absorption capacity of coarse and fine aggregates are measured for use in mix design/proportioning and quality assurance (QA) of PCC and HMA. The ability to quickly measure these properties of aggregate materials with a high degree of accuracy and repeatability is essential to specifying agencies and contractors.

For PCC, the bulk specific gravity of aggregate is used in calculating the percentage of voids and the solid volume of aggregates in computation of yield. Using an inaccurate specific gravity value may cause an error in the calculated yield or volume of concrete. In addition, since concrete is often sold by volume, this error means that either the purchaser is receiving less concrete than ordered or the producer is supplying more concrete than is being purchased (*3*). The absorption capacity of an aggregate is used for adjusting the batching water quantities and achieving the target water-cement ratio or water-cementitious material ratio. The absorption capacity can also be used as an indicator for the aggregate's resistance to freezing and thawing. Accurate determination of absorption is important to ensure the workability and durability of PCC (*4*, *5*).

The bulk specific gravity of aggregate (Equation 2.3) is critical information for mix design and QA of HMA (*6*). It is used in calculating the voids in mineral aggregate (VMA) and effective binder content (P_{be}), which are then used to calculate the voids filled with asphalt (VFA) and dust proportion (DP). In HMA mix designs, VMA, VFA, and DP are used as specification criteria to help ensure that the mixture has volumetric properties needed to provide desired performance. An error in the aggregate specific gravity, therefore, can cause an error in the mix design volumetric calculations, which can lead to several asphalt pavement performance problems such as raveling, bleeding, and cracking. In addition, since some agencies require the determination of VMA as part of acceptance testing, there is a potential risk of accepting poor mix or rejecting good quality mix due to errors in determining the bulk specific gravity. For HMA evaluation, the absorption capacity of aggregate can be used as an indicator of asphalt absorption (*7*). In addition, some deleterious particles are lighter than the higher quality aggregates. Therefore, tracking specific gravity over time can sometimes indicate a change of material or possible contamination (*8*).

Test Methods for Determining Specific Gravity and Water Absorption

Current standard test methods for determining the specific gravity and water absorption of coarse and fine aggregates are AASHTO T 85 (or ASTM C127) and AASHTO T 84 (or ASTM C128), respectively. In addition, there also are several modified and new test methods, and they range from simple modifications to how the saturated, surface-dry (SSD) state is determined in the standard test methods to new test methods with more complex and costly equipment. Comparisons of these test methods are provided in Tables 2-1 through 2-3. These test methods were compared in terms of precision, ruggedness of equipment, ease of use, soaking and testing time, equipment cost, and potential problems or problematic materials. Detailed information about these test methods is included in Appendix C, which is available on the project web page.

Selection of Test Methods for Evaluation in This Study

After reviewing the findings of the literature review in Task 1, the NCHRP technical panel conducted a ballot. The results of the ballot are presented in Table 2-4. The panel selected 10 test methods that received at least seven "yes" votes for further evaluation in this study.

Table 2-1. Comparison of test methods for determining specific gravity and absorption of coarse aggregate.

ID	Test Method	Vendor	Precision	Ruggedness of Equipment	Ease of Use	Time		Eqmt. Cost	Potential Problems / Problematic Matl.
						Soak	Test		
1	AASHTO T 85 and ASTM C127	Various	Standard	Very good	Manual	15 hrs	30 min	$100 ~ $600	High absorption aggregates
2	AggPlus System using CoreLok Device	InstroTek	Mixed results	Good	Manual	None	30 min	$7,840	High absorption aggregates
3	Rapid AASHTO T 85 with CoreLok	InstroTek	Unknown	Good	Manual	None	30 min	$6,860	High absorption aggregates
4	SG-5 Specific Gravity and Absorption System	Gilson	Unknown	Good	Fully automated	None	20 min	$4,500	Unknown
5	Volumetric Immersion using Phunque Flasks	Humboldt	Unknown	Good	Manual	None	25 hrs	$500	High absorption aggregates

Table 2-2. Comparison of test methods for determining specific gravity and absorption of fine aggregate.

ID	Test Method	Vendor	Precision	Ruggedness of Equipment	Ease of Use	Time		Eqmt. Cost	Potential Problems / Problematic Matl.
						Soak	Test		
1	AASHTO T 84 and ASTM C128	Various	Standard	Very good	Manual	15 hrs	30 min	$100 ~ $300	Angular, high P200, high absorption aggregates
2	Modifications to Determination of SSD Condition in AASHTO T 84 / ASTM C128	Various	Worse	Good	Manual	15 hrs	30 min	Unknown	Highly subjective
3	Modification to Materials Tested in AASHTO T 84/ ASTM C128	Various	Better	Very good	Manual	15 hrs	30 min	$100 ~ $300	Angular and high absorption aggregates
4	SSDrier Device	Gilson	Worse	Good	Partially automated	15 hrs	1 day	$4,500	Problems associated with the device
5	SSDetect System	Thermo Fisher	Better	Good	Automated	None	2 hrs	$7,056	None
6	AggPlus System using CoreLok Device	InstroTek	Mixed results	Good	Manual	None	30 min	$7,840	High P200, high absorption aggregates
7	SG-5 Specific Gravity and Absorption System	Gilson	Unknown	Good	Fully automated	None	20 min	$4,500	Unknown
8	Volumetric Immersion using Phunque Flasks	Humboldt	Unknown	Good	Manual	None	25 hrs	$500	High dust, high absorption aggregates

Table 2-3. Comparison of test methods for determining specific gravity and absorption of combined aggregate.

ID	Test Method	Vendor	Precision	Ruggedness of Equipment	Ease of Use	Time		Eqmt. Cost	Potential Problems / Problematic Matl.
						Soak	Test		
1	AggPlus System using CoreLok Device	InstroTek	Unknown	Good	Manual	None	30 min	$7,840	High P200, high absorption aggregates
2	SG-5 Specific Gravity and Absorption System	Gilson	Unknown	Good	Fully automated	None	20 min	$4,500	Unknown
3	Volumetric Immersion using Phunque Flasks	Humboldt	Unknown	Good	Manual	None	25 hrs	$1,000	Unknown

Table 2-4. Results of Task 1 ballot (courtesy of NCHRP).

ID	Test Method	Select for Evaluation?			Test Selected for Evaluation
		Yes	No	% Yes	
I. Test Methods for Determining Specific Gravity and Absorption of Coarse Aggregate					
1	AASHTO T 85 and ASTM C127	7	2	78	✓
2	AggPlus System using CoreLok Device	2	7	22	
3	Rapid AASHTO T 85 with the CoreLok	7	2	78	✓
4	SG-5 Specific Gravity and Absorption System	7	2	78	✓
5	Volumetric Immersion using Phunque Flasks	5	4	56	
II. Test Methods for Determining Specific Gravity and Absorption of Fine Aggregate					
1	AASHTO T 84 and ASTM C128	7	2	78	✓
2	Modifications to Determination of SSD Condition in AASHTO T 84/ASTM C128	2	7	22	
3	Modification to Materials Tested in AASHTO T 84/ASTM C128	8	1	87	✓
4	SSDrier Device	4	5	44	
5	SSDetect System	9	0	100	✓
6	AggPlus System using CoreLok Device	2	7	22	
7	SG-5 Specific Gravity and Absorption System	7	2	78	✓
8	Volumetric Immersion using Phunque Flasks	8	1	89	✓
III. Test Methods for Determining Specific Gravity and Absorption of Combined Aggregate					
1	AggPlus System using CoreLok Device	3	6	37	
2	SG-5 Specific Gravity and Absorption System	7	2	78	✓
3	Volumetric Immersion using Phunque Flasks	7	2	78	✓

CHAPTER 3

Evaluation of Candidate Test Methods

As shown in Table 2-4, 10 candidate test methods were selected for laboratory evaluation. However, since a production unit of the SG-5 device was not available for evaluation at the time of this study, the list of candidate test methods was revised. Table 3-1 shows the revised list.

The laboratory program was originally planned in two experiments, but was later expanded to five experiments. Experiment 1 was a preliminary evaluation to compare results and variability of the test methods listed in Table 3-1. Experiment 2 was to further evaluate the test methods selected at the conclusion of Experiment 1 with a broader range of aggregate materials.

After reviewing the results of Experiments 1 and 2, Experiments 3, 4, and 5 were added to the laboratory testing program to answer specific questions related to the test procedures previously evaluated. Experiment 3 was added to evaluate modifications relative to the drying and soaking methods in AASHTO T 85 and T 84 to reduce the testing time. Experiment 4 was added to determine the effect of P200 material on AASHTO T 84 test results. Experiment 5 was added to investigate time-zero reading for Phunque methods. Results of Experiments 1 through 4 are presented in this chapter, and results of Experiment 5 are included in Appendix H, which is available on the project web page.

Experiment 1

The objective of Experiment 1 was to compare results and variability of the 10 test methods. Based on the results of this evaluation, promising test methods would be selected for a more detailed evaluation later in the study.

Laboratory Testing

The 10 test methods listed in Table 3-1 were used to determine the specific gravity and water absorption of the coarse, fine, and combined aggregates shown in Table 3-2. The aggregates were selected to include a variety of absorption capacities, shapes, and textures. One operator conducted all testing required in this experiment. The operator was trained to conduct all of the tests, and the equipment was calibrated before testing. Test samples were carefully prepared to ensure they were consistent and homogeneous. Extra samples were prepared for the technician to practice on before running the tests. After samples were prepared, sample numbers were randomized before they were tested. The test methods also were conducted in a randomized order. Triplicate samples were tested using each material and method. To aid in the analysis, the gradation and angularity tests were conducted for all the aggregates, petrographic analyses were conducted on natural sand, granite, gravel, and limestone aggregates, and the test for insoluble residue in carbonate aggregates was performed on natural sand and limestone aggregates. Detailed test results of Experiment 1 are included in Appendix D, which is available on the project web page.

Analysis of Test Results for Coarse Aggregates

Figure 3-1 compares the specific gravity and water absorption results measured by the three test methods for coarse aggregate—AASHTO T 85, Rapid AASHTO T 85 with the CoreLok vacuum saturation, and Phunque Flask. The results measured by the three test methods appeared more comparable for two aggregates with lower water absorption capacities—Columbus granite (AASHTO T 85 water absorption = 0.43 percent) and Elmore gravel (AASHTO T 85 water absorption = 1.13 percent). For Florida limestone (AASHTO T 85 water absorption = 5.53 percent), the Rapid AASHTO T 85 method yielded results that were significantly different from the other two methods, especially the absorption capacity shown in Figure 3-1(d).

Figure 3-2 compares the standard deviations of specific gravity and water absorption results for the three test methods for coarse aggregate. The single-operator precision (i.e., 1S) limits

(text continued on page 8)

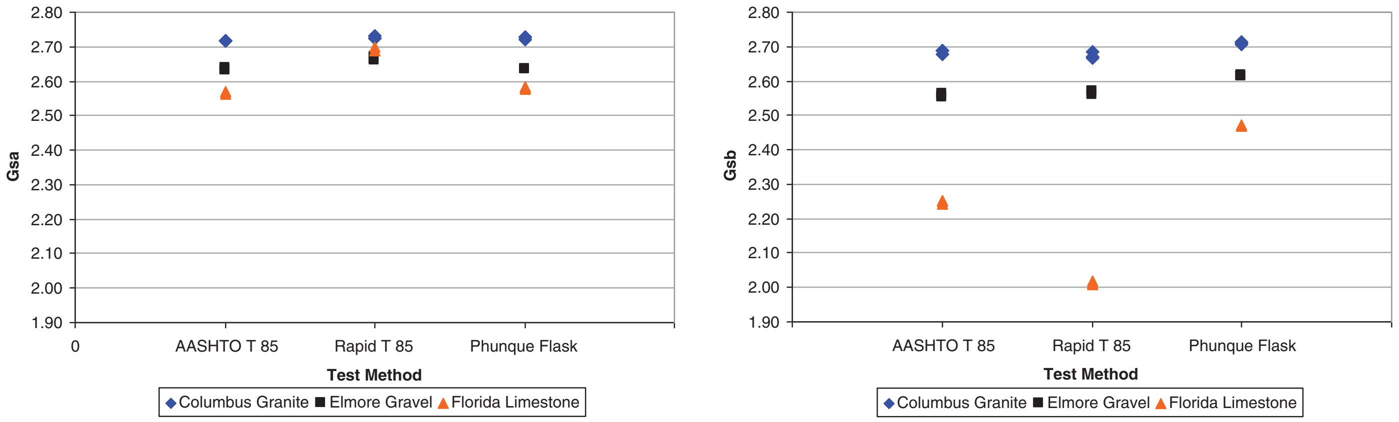
Table 3-1. Revised list of test methods selected for laboratory evaluation.

ID	Selected Test Method	Material Used for Evaluation
I. Test Methods for Determining Specific Gravity and Absorption of Coarse Aggregate		
1	AASHTO T 85 and ASTM C127	Coarse aggregate retained on No. 4 sieve
2	Rapid AASHTO T 85 with the CoreLok	Coarse aggregate retained on No. 4 sieve
3	Volumetric Immersion using Phunque Flasks	Coarse aggregate retained on No. 4 sieve
II. Test Methods for Determining Specific Gravity and Absorption of Fine Aggregate		
1	AASHTO T 84 and ASTM C128	Fine aggregate passing No. 4 sieve
2	Modification to Materials Tested in AASHTO T 84/ASTM C128	Fine aggregate passing No. 4 sieve and retained on No. 200 sieve
3	SSDetect System	Fine aggregate passing No. 4 sieve
4	Modification to Materials Tested in SSDetect System	Fine aggregate passing No. 4 sieve and retained on No. 200 sieve
5	Volumetric Immersion using Phunque Flasks	Fine aggregate passing No. 4 sieve
*	AASHTO T 133 (with Ethyl Alcohol)	Fine material passing No. 200 sieve
III. Test Methods for Determining Specific Gravity and Absorption of Combined Aggregate		
1	Volumetric Immersion using Phunque Flasks	Combined (coarse and fine) aggregate

*This test method is used to determine the apparent specific gravity of fine material passing the No. 200 sieve.

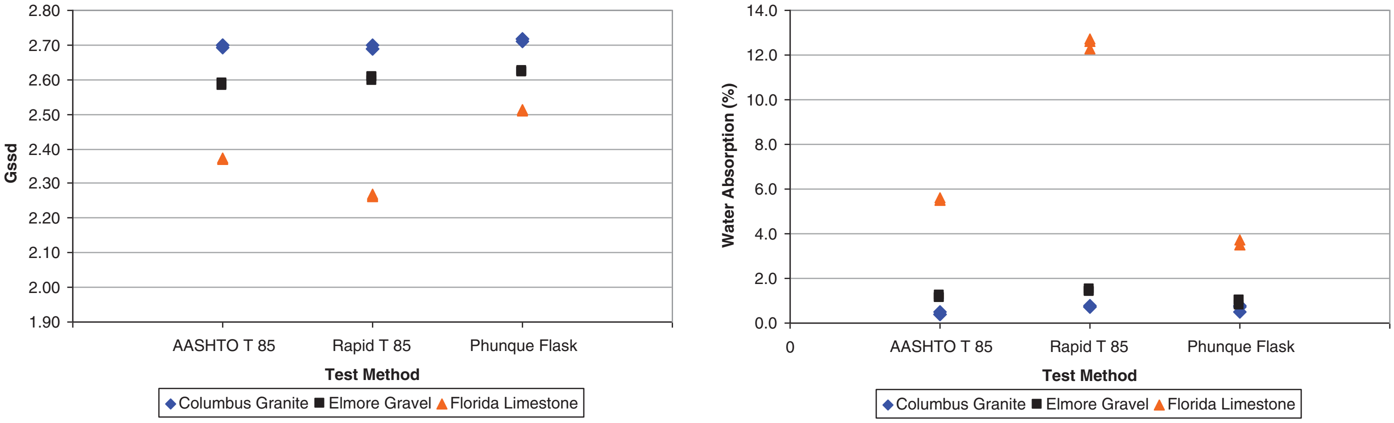
Table 3-2. Aggregate materials used in Experiment 1.

ID	Materials (Abbreviation)	Source	Factors Considered
I. Coarse Aggregates			
1	Columbus granite (CG)	Barin Quarry, Columbus, GA	Very low absorption
2	Elmore gravel (EG)	Elmore Sand and Gravel, AL	Medium absorption
3	Florida limestone (FL)	CEMEX, Brooksville, FL	Very high absorption
II. Fine Aggregates			
1	Ottawa sand (OS)	Ottawa, IL	Low angularity, low P200, low absorption
2	Natural sand (NS)	Foley Materials, Phenix City, AL	High angularity, low P200, low absorption
3	Limestone screenings (LS)	CEMEX, Brooksville, FL	High angularity, high P200, high absorption
4	Granite screenings (GS)	Barin Quarry, Columbus, GA	High angularity, high P200, low absorption
III. Combined Aggregates			
1	CG + OS	50% Columbus granite and 50% Ottawa sand	
2	EG + NS	60% Elmore gravel and 40% natural sand	
3	FL + GS	60% Florida limestone and 40% granite screenings	



(a) Gsa (b) Gsb

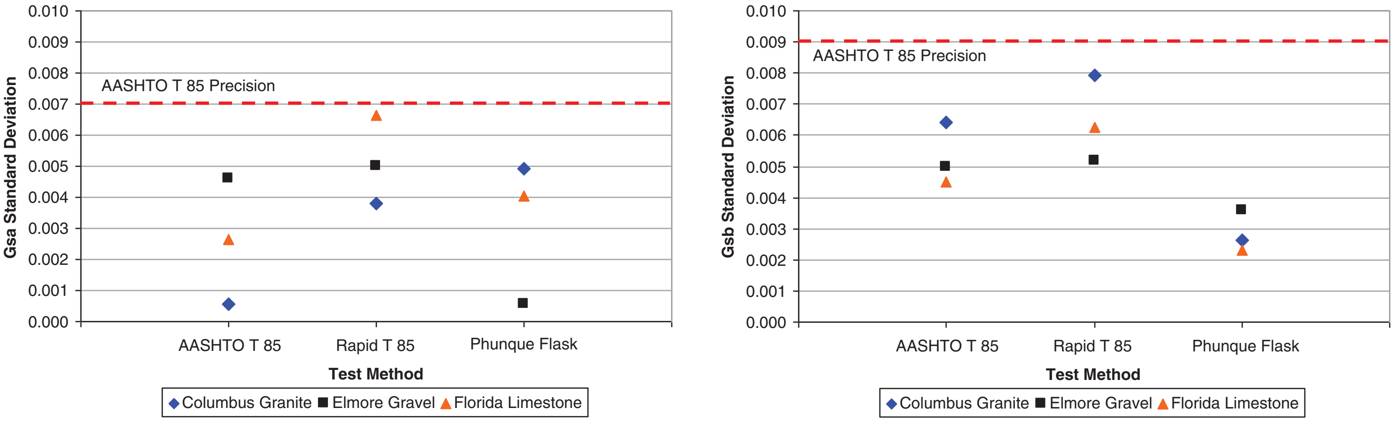
Figure 3-1. Comparison of results determined by three test methods for coarse aggregate.
(continued on next page)



(c) Gssd

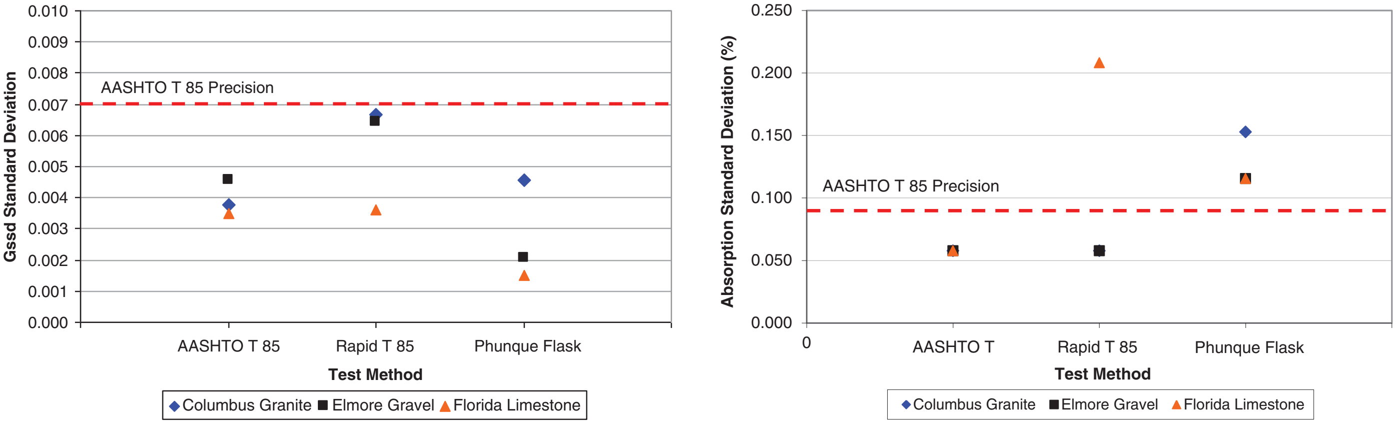
(d) Absorption

Figure 3-1. (Continued).



(a) Variability of Gsa

(b) Variability of Gsb



(c) Variability of Gssd

(d) Variability of Absorption

Figure 3-2. Variability of test results determined by three test methods for coarse aggregate.

in AASHTO T 85 also are shown in Figure 3-2 for comparison. The AASHTO T 85 precision limits were determined based on aggregates with absorptions of less than 2 percent. In Experiment 1, the three test methods met the single-operator precision (1S) limits specified in AASHTO T 85 for specific gravity measurements. However, only the test results determined in accordance with AASHTO T 85 in Experiment 1 met the single-operator precision 1S limit for water absorption for all aggregates tested, as shown in Figure 3-2(d). The repeatability of water absorption results for the Phunque flask is not as good as those of the other two methods. However, the Phunque method yielded the most repeatable results for Gsb.

Further statistical analyses were conducted for the test results to answer two questions:

- Is there a statistically significant difference in the test results (Gsa, Gsb, Gssd, and absorption) determined using the three test methods for each material?
- Is there a statistically significant difference in the variance of the results determined using the three test methods (or difference in the repeatability of the three tests)?

To answer the first question, analyses of variance (ANOVA) (significance level = 0.05) were conducted. Table 3-3 shows a summary of ANOVA results. In Table 3-3, the three test methods produced statistically different mean results, except for Gsa of Columbus granite (CG). The higher the F-statistic, the more significant the difference would be. The three methods yielded the most significantly different results for the Florida limestone material. This observation was previously shown in Figure 3-1.

Bartlett-Box's F-test (significance level = 0.05) was conducted to answer the second question. Table 3-4 summarizes Bartlett-Box's test results for the variances. The variances of the Gsb and water absorption results determined using the three test methods were statistically different, and the difference in the variances of water absorption was more significant.

Table 3-4. Summary of Bartlett's Test for variance of test results.

Response	Bartlett's Test		
	Test Statistic	P-Value	Significant?
Gsa	5.26	0.072	No
Gsb	7.71	0.021	Yes
Gssd	4.40	0.111	No
Abs	14.48	0.001	Yes

In summary, the three test methods for coarse aggregate evaluated in this experiment yielded comparable test results for the low absorption aggregate (i.e., the Columbus granite). However, the differences in the test results were greater for higher absorption aggregate materials, especially the Florida limestone. The reasons are briefly discussed as follows:

- The AASHTO T 85 method uses dry/damp towels to remove water from the surface of aggregate particles to reach the SSD condition after they have been pre-soaked for 15 to 19 hours. For a high absorption aggregate material (e.g., the Florida limestone), this drying process may remove some water in the surface (permeable) voids of each aggregate particle, resulting in a lower volume of permeable voids, which would yield a higher Gsb value and a lower absorption capacity than the true values.
- For the Rapid AASHTO T 85 with the CoreLok vacuum saturation, a dry aggregate sample is vacuum saturated; thus, water may penetrate into deeper voids because the pressure inside the surface voids is much lower than the atmosphere pressure. This produces a much higher volume of permeable voids, resulting in a lower Gsb and a higher absorption capacity.
- For the Phunque method, the volume of aggregate plus volume of impermeable and permeable voids is determined at 30 seconds after the first particle has entered the water and

Table 3-3. Summary of ANOVA for coarse aggregate test results.

Material	Response	P-Value	Significant?	Grouping Using Tukey's Test		
				T 85	Rapid T 85	Phunque
CG	Gsa	0.151	No	A	A	A
CG	Gsb	0.001	Yes	B	B	A
CG	Gssd	0.004	Yes	B	B	A
CG	Abs	0.024	Yes	B	A	A, B
EG	Gsa	0.001	Yes	B	A	B
EG	Gsb	<0.001	Yes	B	B	A
EG	Gssd	<0.001	Yes	C	B	A
EG	Abs	0.001	Yes	B	A	B
FL	Gsa	<0.001	Yes	C	A	B
FL	Gsb	<0.001	Yes	B	C	A
FL	Gssd	<0.001	Yes	B	C	A
FL	Abs	<0.001	Yes	B	A	C

Note: For each measured property and material, methods that do not share a letter are significantly different. A and C represent the highest and lowest values, respectively.

the flask has not been disturbed. There may be two shortcomings for this determination:

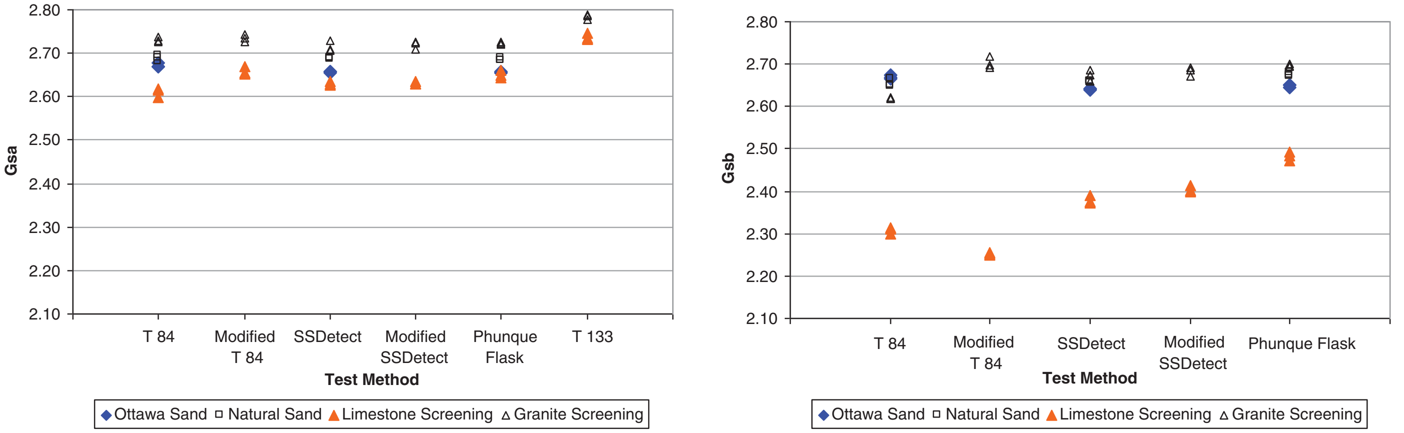
  - Air may be trapped between aggregate particles, resulting in a greater measured volume than the true volume of aggregate and voids. This would result in a lower Gsb and a higher absorption value.
  - For high absorption aggregates (e.g., Florida limestone), water may penetrate into the surface voids within the first 30 seconds, resulting in a lower measured volume of aggregate and voids and yielding a higher Gsb value and a lower absorption capacity.
- Since the aggregate is slowly introduced into the flask, the second shortcoming seems to be more probable; thus, the Phunque method would likely yield a higher Gsb value and a lower absorption capacity than the true values.

Compared to the AASHTO T 85 method, the Phunque method does not appear to provide improved accuracy, repeatability, or time required for testing. Future implementation of the Phunque method would also require an investment in testing equipment and training.

The Rapid T 85 method has the potential to significantly reduce testing time and yield results comparable to AASHTO T 85 for low absorption aggregates (i.e., less than 2 percent). However, the cost of a CoreLok device should be considered for future implementation. For absorptive aggregate, the Rapid T 85 method is believed to yield inaccurate results due to the penetration of water into aggregate voids that would not be permeable under hydrostatic conditions.

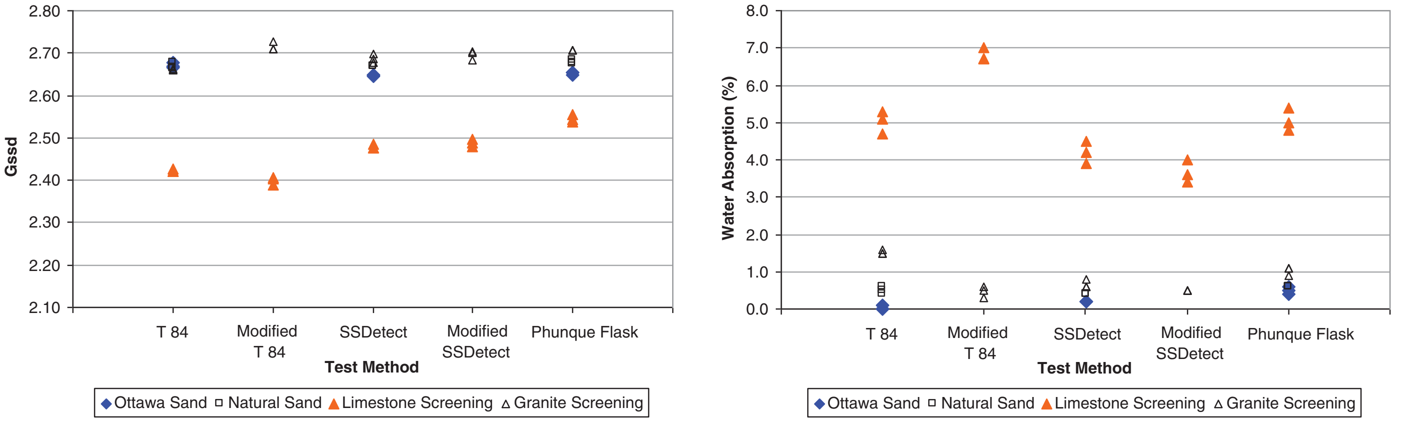
Analysis of Test Results for Fine Aggregates

Figure 3-3 shows comparisons of the specific gravity and water absorption results measured by the five test methods—AASHTO T 84, Modified AASHTO T 84, SSDetect, Modified SSDetect, and Phunque Flask—for fine aggregate and AASHTO T 133 for minus No. 200 materials (P200). Since the Ottawa sand and the natural sand did not contain an appreciable amount of P200 (less than 1.0 percent), they were not tested with the Modified T 84 or Modified SSDetect methods. Also, there was not sufficient P200 material from these sources to test using AASHTO T 133 (with ethyl alcohol).



(a) Gsa

(b) Gsb



(c) Gssd

(d) Absorption

Figure 3-3. Comparison of results determined by test methods for fine aggregate.

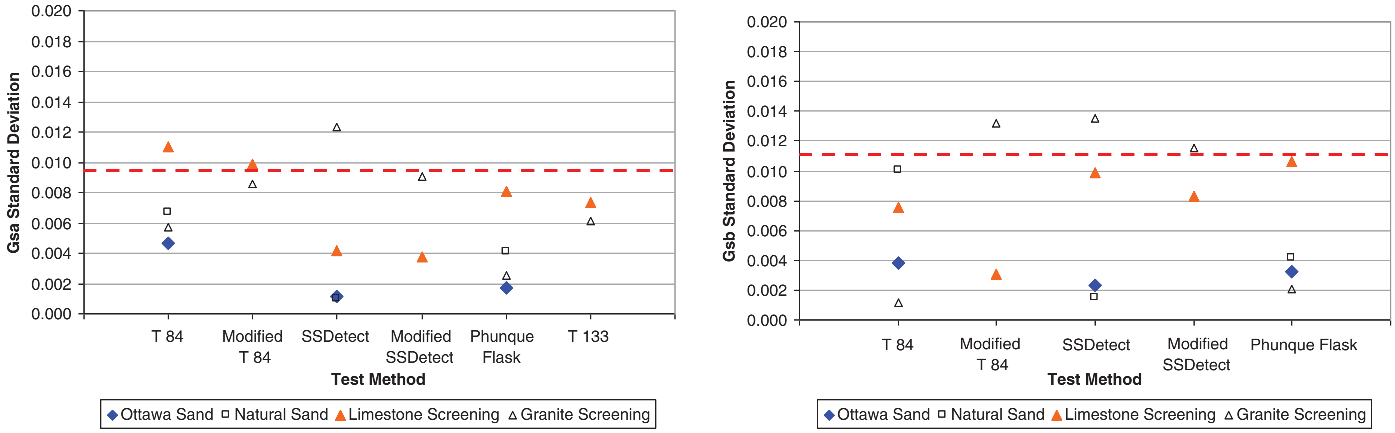
The results determined by these test methods for fine aggregate were more comparable for the three aggregates with lower water absorption capacities—Ottawa sand (AASHTO T 84 water absorption = 0.03 percent), natural sand (AASHTO T 84 water absorption = 0.5 percent), and granite screenings (AASHTO T 84 water absorption = 1.5 percent). However, these methods yielded significantly different results for the limestone screenings (AASHTO T 84 water absorption = 5.0 percent). When comparing the test results conducted on the materials with and without the P200, the differences between the SSDetect and Modified SSDetect results were less than those between the AASHTO T 84 and Modified AASHTO T 84, as shown in Figure 3-3.

Figure 3-4 compares the variability of test results for the selected test methods for fine aggregate. The dash lines in these figures represented the single-operator precision 1S limits in AASHTO T 84. As noted in the standard, these specified precision limits were estimated based on manufactured fine aggregates with absorptions of less than 1 percent. It appears that all the test methods can meet the specified precision in AASHTO T 84 for the Ottawa and natural sands but not for the granite and limestone screenings. This indicates that the precision information for AASHTO T 84 should be updated to include data for fine aggregates having water absorptions greater than 1 percent.

In addition to the graphical comparisons shown in Figures 3-3 and 3-4, further statistical analysis was conducted for the test results of fine aggregates. The analysis was conducted to evaluate

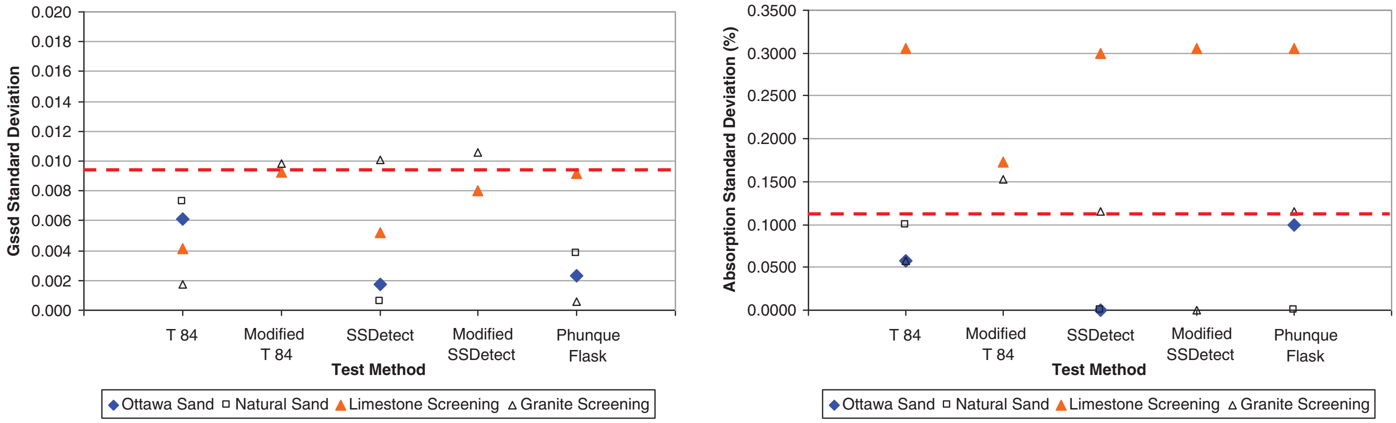
- If there was any statistically significant difference in the test results (Gsa, Gsb, Gssd, and absorption) determined using the five test methods for each material; and
- If there was any statistically significant difference in the variance of the results (Gsa, Gsb, Gssd, and absorption) determined using the five test methods.

Table 3-5 shows a summary of ANOVA (significance level = 0.05) of the test results. This analysis shows that the five methods yield statistically different results. The largest differences were for the Florida limestone.



(a) Variability of Gsa

(b) Variability of Gsb



(c) Variability of Gssd

(d) Variability of Absorption

Figure 3-4. Variability of test results determined by five test methods for fine aggregate.

Table 3-5. Summary of ANOVA for test results of fine aggregate.

Material	Response	P-Value	Significant?	Grouping Using Tukey's Test				
				T 84	Mod. T 84	SSDetect	Mod. SSDetect	Phunque
GS	Gsa	0.079	No	A	A	A	A	A
GS	Gsb	<0.001	Yes	C	A	B	A, B	A, B
GS	Gssd	<0.001	Yes	C	A	B	A, B	A, B
GS	Abs	<0.001	Yes	A	C	C	C	B
LS	Gsa	<0.001	Yes	C	A	B, C	B	A, B
LS	Gsb	<0.001	Yes	D	E	C	B	A
LS	Gssd	<0.001	Yes	C	D	B	B	A
LS	Abs	<0.001	Yes	B	A	C	C	B
NS	Gsa	0.525	No	A		A		A
NS	Gsb	0.015	Yes	B		B		A
NS	Gssd	0.072	No	A		A		A
NS	Abs	0.016	Yes	A, B		B		A
OS	Gsa	0.001	Yes	A		B		B
OS	Gsb	<0.001	Yes	A		C		B
OS	Gssd	0.001	Yes	A		B		B
OS	Abs	<0.001	Yes	B		B		A

Note: Methods that do not share a letter are significantly different. A and E represent the highest and lowest values, respectively. The Modified AASHTO T 84 and Modified SSDetect were not conducted on NS and OS.

Table 3-6 summarizes Bartlett's Test for evaluating the variance of test results determined using the five test methods. The variances of the test results were not statistically different.

In Experiment 1, AASHTO T 84 and SSDetect were conducted on the limestone and granite screenings containing the P200 fractions, and Modified T 84 and Modified SSDetect were conducted on these screenings without the P200 fractions. Thus, these test results may not be comparable. A further analysis was conducted by mathematically combining the Gsa, Gsb, and Gssd measured using Modified T 84 and Modified SSDetect with the Gsa of the P200 fractions determined in accordance with AASHTO T 133 (with ethyl alcohol). These values are compared in Figure 3-5. These graphs indicated that both T 84 and SSDetect were influenced by removing the P200 from the samples and testing them separately.

In summary, the following observations can be offered based on the analysis of the test results for fine aggregates:

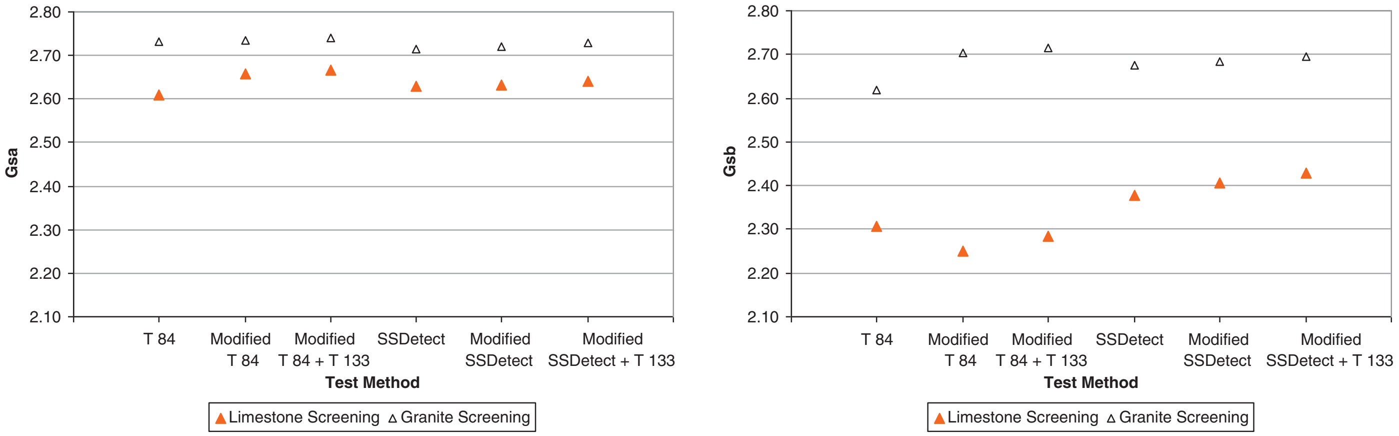
- The logic of the cone and tamping method for determining the SSD condition for fine aggregates is that the cone of aggregate (~71.6°) is greater than the angle of repose for dry material but less than the angle of repose for aggregate with capillary water between particles. However, the angle of repose of fine aggregate is influenced by several material properties, including the absorption, angularity, and amount and nature (e.g., plasticity) of the P200 fraction. A comparison of the difference between AASHTO T 84 and Modified AASHTO T 84 results with that between SSDetect and Modified SSDetect results shows that the presence of P200 in a fine aggregate has more effect on the AASHTO T 84 results, and it has less effect on the SSDetect test results.
- The SSDetect method for determining the SSD condition of a fine aggregate material does not appear to depend on angularity or presence of P200.
- The Phunque flask yields results that are comparable to those of the other test methods.
- All of the test methods have problems determining repeatable absorption results for Florida limestone, which is considered a problematic material in this study. No test method consistently produced more repeatable test results than AASHTO T 84.
- Since the SSDetect and Modified SSDetect methods produce comparable results, the SSDetect method may be used to test fine aggregate materials that include the P200 fraction.
- In consideration of implementation costs, the most expensive option is the SSDetect method, then the Phunque method and the Modified AASHTO T 84. However, implementation of Modified AASHTO T 84 would require another test for the P200 fraction.

Table 3-6. Summary of Bartlett's Test for variance of test results.

Response	Bartlett's Test		
	Test Statistic	P-Value	Significant?
Gsa	2.67	0.614	No
Gsb	8.17	0.086	No
Gssd	8.13	0.087	No
Abs	4.50	0.343	No

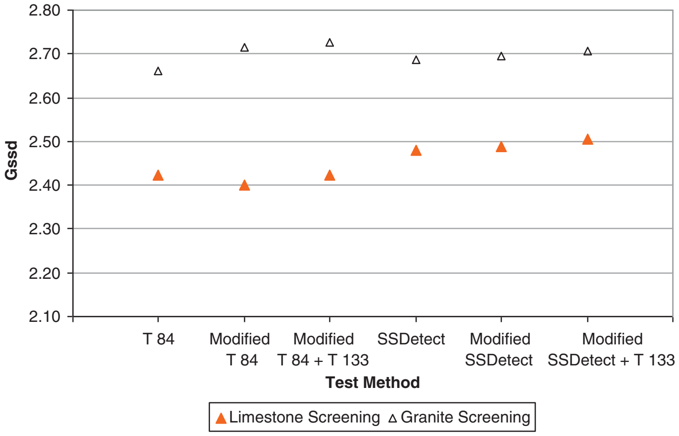
Analysis of Test Results for Combined Aggregate

Testing also was conducted to evaluate if the Phunque flask used for testing coarse aggregate could be used for testing



(a) Gsa

(b) Gsb



(c) Gssd

Figure 3-5. Comparison of test results for fine aggregate with and without P200 fraction.

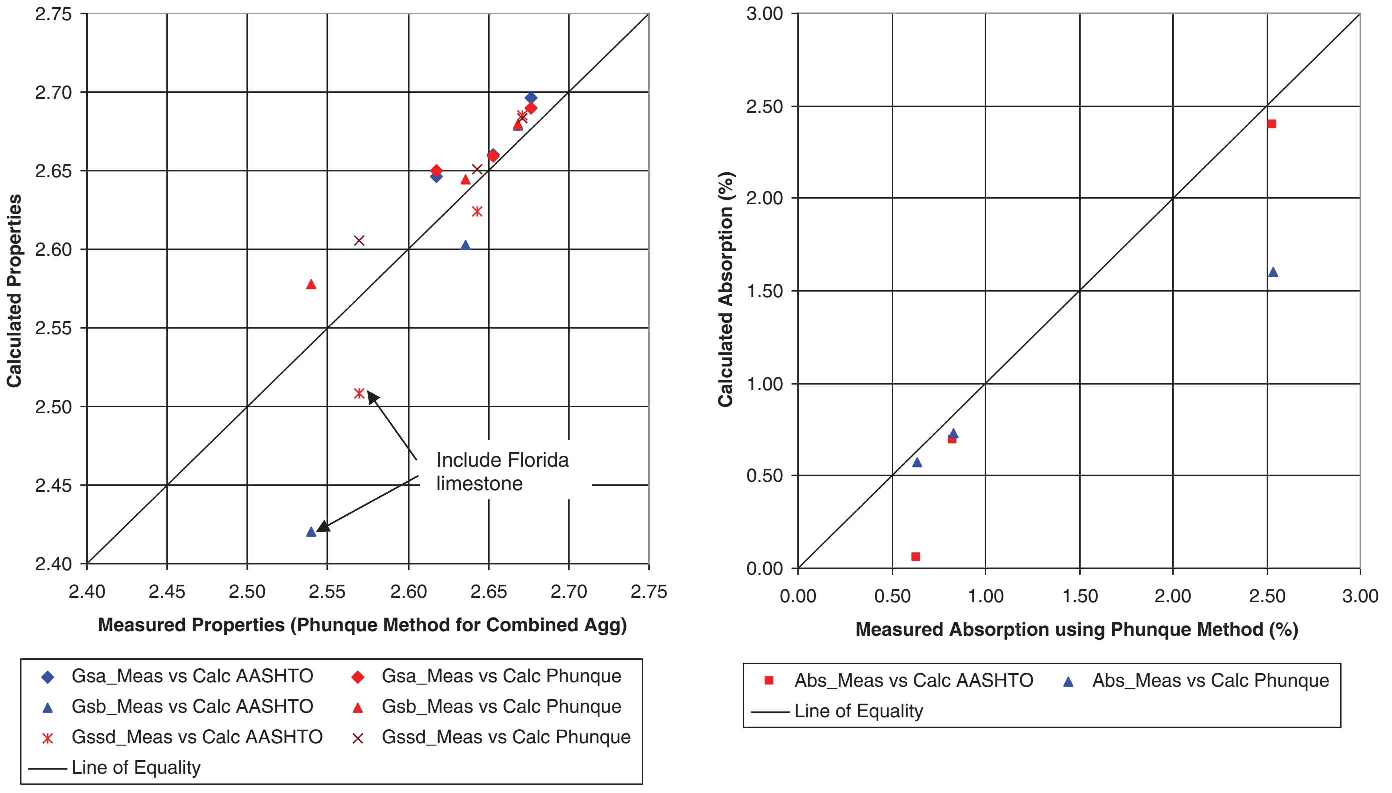
combined aggregate (i.e., a complete gradation). Figure 3-6 shows comparisons of combined specific gravity and water absorption values measured using the Phunque flask and calculated using the AASHTO T 85 and T 84 results and Phunque method results for individual coarse and fine aggregates. In Figure 3-6(a), two data points that were separated from the line of equality were for combined materials that included Florida limestone.

The Phunque method has the potential to determine the specific gravity and absorption for a complete gradation. The drawbacks for implementation of this method include the time required for testing, additional cost for equipment, ruggedness of the current flask, and yielding significantly different results determined by AASHTO T 85 and T 84 for a complete gradation that includes a high absorption aggregate material.

Summary

Based on the key findings of Experiment 1, a comparison of the candidate test methods is shown in Table 3-7. After reviewing the results of Experiment 1, the panel selected six test methods for a detailed evaluation in Experiment 2. The other three test methods were not further evaluated in this study because of additional costs of the CoreLok equipment and bags, the repeatability of SSDetect not being improved by removing the P200 fraction, and the poor precision of the Phunque method for testing a complete gradation. The following six test methods were chosen for Experiment 2:

- Test Methods for Determining Specific Gravity and Absorption of Coarse Aggregate
  1. AASHTO T 85-08, Test for Specific Gravity and Absorption of Coarse Aggregate
  2. AASHTO TP 77-09, Test for Specific Gravity and Absorption of Aggregate by Volumetric Immersion Method (Phunque Flask for Coarse Aggregate)
- Test Methods for Determining Specific Gravity and Absorption of Fine Aggregate
  3. AASHTO T 84-09, Test for Specific Gravity and Absorption of Fine Aggregate



(a) Specific Gravities **(b) Absorption**

Figure 3-6. Comparison of test results for combined aggregates.

Table 3-7. Comparison of test methods for determining aggregate specific gravity and absorption.

ID	Test Method	Comments on Accuracy	G_{sb} Pooled Std. Dev.	Equipment Ruggedness	Ease of Use	Time		Eqmt. Cost	Overall Comments
						Total	Operator		
I. Test Methods for Coarse Aggregate									
1	AASHTO T 85 and ASTM C127	Yields higher Gsb and lower absorption for absorptive aggregate	0.0053	Good	Manual	3 days	30 min.	\$100 ~ \$600	Standard
2	Rapid AASHTO T 85 with the CoreLok	Yields lower Gsb and higher absorption for absorptive aggregate	0.0065	Good	Manual	2 days	30 min.	\$6,860	Costs for equipment and bags; not accurate for absorptive aggregate
3	Volumetric Immersion using Phunque Flask	Yields higher Gsb and lower absorption for absorptive aggregate	0.0029	Fragile in current design	Manual	2 days	2 hrs	\$500	Small equipment cost; questionable accuracy for absorptive aggregate, may be more repeatable than the T 85
II. Test Methods for Fine Aggregate									
1	AASHTO T 84 and ASTM C128	Depends on P200 content, angularity, absorption of aggregate	0.0056	Good	Manual	3 days	1.5 hrs	\$100 ~ \$300	Standard
2	Modification to Materials Tested in AASHTO T 84	Depends on angularity, absorption of aggregate	0.0081	Good	Manual	3 days	1.5 hrs	\$100 ~ \$300	Does not need new equipment, but requires another test for minus #200 material
3	SSDetect System	Depends on absorption of aggregate	0.0050	Good	Auto	1 day	1 hr	\$7,056	Equipment cost, faster results
4	Modification to Materials Tested in SSDetect	Depends on absorption of aggregate	0.0099	Good	Auto	1 day	1 hr	\$7,056	No apparent advantage over regular SSDetect method
5	Volumetric Immersion using Phunque Flask	Depends on absorption; measure SSD volume within 30 sec	0.0077	Fragile in current design	Manual	2 days	2 hrs	\$500	Small equipment cost, somewhat fragile flasks, less repeatable than T 84
III. Test Method for Complete Gradation									
1	Volumetric Immersion using Phunque Flasks	Depends on absorption; measure SSD volume within 30 sec	0.0207	Fragile in current design	Manual	2 days	2 hrs	\$500	Small additional equipment cost; lower precision

4. Modified AASHTO T 84 (Removal of P200), the same as AASHTO T 84, except that the P200 fraction is removed before testing
5. ASTM D7172-06, Test for Determining the Relative Density (Specific Gravity) and Absorption of Fine Aggregates Using Infrared (SSDetect System)
6. AASHTO TP 77-09, Test for Specific Gravity and Absorption of Aggregate by Volumetric Immersion Method (Phunque Flask for Fine Aggregate)

Experiment 2

The objective of Experiment 2 was to further evaluate the test methods selected at the conclusion of Experiment 1 with a broader range of aggregate materials. Based on the results of this experiment, precision information, including repeatability and reproducibility, would be developed for each test method. The most promising test methods would be selected for further evaluation later in the project.

Laboratory Testing

This experiment was designed to allow for a statistical analysis addressing the observed variability in the data and preparation of precision information for two test methods for coarse aggregate and four test methods for fine aggregate. This experiment included three operators reviewing the test methods independently and conducting all testing using three different test devices to simulate multi-laboratory operations for evaluating the precision of the selected test methods.

As shown in Table 3-8, the materials used in Experiment 2 covered a broader range of aggregate materials used for PCC and HMA mixtures, including crushed, natural, recycled, and manufactured coarse and fine aggregates. The coarse aggregate materials covered a wide range of water absorption capacity that was found to have a significant effect on the variability of test results. The fine aggregate materials had a wide range of amount of materials passing the No. 200 sieve (P200) and water absorption.

Three replicates were tested for each factor. For each test method, with three operators and three replicates, nine observations (3 operators and devices × 3 replicates) were determined for each material level. A total of 270 tests were conducted in the laboratory to complete this experimental design, providing data to determine preliminary repeatability and reproducibility of each test method.

Test samples were carefully prepared to ensure they were consistent and homogeneous, especially for materials with high P200 content. Extra samples were prepared for the three technicians to practice on before testing. After the samples had been prepared, they were randomly numbered.

Three operators and three test devices were used to simulate a multi-laboratory study. In this experiment, the three operators were all NCAT employees. The order in which each of the test methods was conducted also was randomized for each operator. Before starting Experiment 2, all testing devices were calibrated, and all technicians involved in this program were carefully trained to operate the test devices. After the laboratory study had started, each operator conducted the tests according to the standardized procedures. No further instructions for performing the tests were given, except that forms and instructions for recording the data were developed and distributed to each operator.

To aid in the analysis of test results determined in Experiment 2, the research team also performed additional tests, as shown in Table 3-9, to characterize gradation, fine aggregate angularity, and other geological and mineralogical properties of the aggregate materials used. Detailed test results of Experiment 2 are included in Appendix E, which is available on the project web page.

Results and Analysis

Factors Affecting Test Results

Analysis of variance (ANOVA) was conducted to determine the effects of material, test method, and operator on the test results, including Gsa, Gsb, Gssd, and water absorption. The

Table 3-8. Sources of aggregate materials used in Experiment 2.

ID	Materials	Source
I	**Coarse Aggregates**	
1	Elmore gravel (EGC)	Elmore Sand and Gravel, Elmore, AL
2	Preston sandstone (PSC)	Arkhola Sand and Gravel, Fort Smith, AR
3	Blast furnace slag (FSC)	Mountain Enterprises, Hager Hill, KY
4	RC limestone (RCC)	SHRP Ref. Material from McAdams LS Products, KS
5	Recycled concrete (REC)	Recycled Materials, Denver, CO
II	**Fine Aggregates**	
1	Rounded natural sand (NSF)	Dredged from Arkansas River at Van Buren, Crawford County, AR
2	Blast furnace slag (FSF)	Mountain Enterprises, Hager Hill, KY
3	Preston sandstone (PSF)	Arkhola Sand and Gravel, Fort Smith, AR
4	Texas limestone sand (TLF)	1604 Operations (Vulcan Materials), San Antonio, TX
5	RC limestone (RCF)	SHRP Ref. Material from McAdams LS Products, KS

Table 3-9. Additional tests for characterizing properties of materials for Experiment 2.

Material		Test Methods						
		Grad.	Angularity	Insoluble Residue	Float Test	Elemental Analysis	Sand Equivalent	Petrograph Exam
I	**Coarse Aggregate**							
1	Elmore gravel (EGC)	x						x
2	Preston sandstone (PSC)	x						x
3	Blast furnace slag (FSC)	x				x		
4	RC limestone (RCC)	x		x				x
5	Recycled concrete (REC)	x						x[1]
II	**Fine Aggregate**							
1	Rounded natural sand (NSF)	x	x		x[3]		x	x[2]
2	Blast furnace slag (FSF)	x	x			x	x	
3	Preston sandstone (PSF)	x	x				x	x
4	Texas limestone sand (TLF)	x	x	x			x	x
5	RC limestone (RCF)	x	x	x			x	x

Notes: [1] Estimate percent cement paste; [2] Determine clay and shale content; [3] Determine light-weight particles.

ANOVA results for coarse and fine aggregate materials are summarized in Tables 3-10 and 3-11, respectively. Detailed ANOVA results are included in Appendix E, which is available on the project web page.

Based on the ANOVA results, the effect of material, test method, and simulated lab was statistically significant on all the test results at a significance level of 0.05, except for the effect of operator on water absorption for coarse aggregate. The F-statistics for the first two sources of effect (material and test method) were much higher than those of the third effect (simulated lab) on all measured responses. Therefore, to simplify analysis and presentation, the test results were later evaluated only at each combined level of material and test method.

Table 3-10. Summary of ANOVA results for coarse aggregate.

Response	Source of Effect	F-Statistic	P-Value
Gsa	Material (BF Slag Coarse, Elmore Gravel, Sandstone Coarse, RC LS Coarse, Recycled Concrete)	904.20	<0.0001
	Test Method (Phunque Coarse, T 85)	188.59	<0.0001
	Simulated Lab (3 Operators, 3 Devices)	7.01	0.002
Gsb	Material	3322.81	<0.0001
	Test Method	3125.38	<0.0001
	Simulated Lab	6.48	0.003
Gssd	Material	1993.85	<0.0001
	Test Method	2108.39	<0.0001
	Simulated Lab	8.11	0.001
Absorption	Material	1820.27	<0.0001
	Test Method	3752.23	<0.0001
	Simulated Lab	0.71	0.497

Table 3-11. Summary of ANOVA results for fine aggregate.

Response	Source of Effect	F-Statistic	P-Value
Gsa	Material (BF Slag Fine, Natural Sand, Sandstone Fine, RC LS Fine, TX LS Sand)	6916.48	<0.0001
	Test Method (Modified T 84, Phunque Fine, SSDetect, T 84)	46.94	<0.0001
	Simulated Lab (3 Operators, 3 Devices)	16.04	<0.0001
Gsb	Material	879.07	<0.0001
	Test Method	163.04	<0.0001
	Simulated Lab	6.36	0.002
Gssd	Material	1869.02	<0.0001
	Test Method	164.95	<0.0001
	Simulated Lab	4.96	0.008
Absorption	Material	465.33	<0.0001
	Test Method	135.21	<0.0001
	Simulated Lab	10.24	<0.0001

Comparing Test Results for Coarse Aggregate

Pairwise comparisons among different levels of material and test method were conducted using Tukey's tests. A summary of Tukey's test results for coarse aggregate materials is presented in Table 3-12. The "difference of means" values shown in Table 3-12 indicate that the Phunque method yielded higher Gsa, Gsb, and Gssd results and lower water absorption values than the AASHTO T 85 method. Based on a significance level of 0.05, the differences in the test results between the Phunque flask and AASHTO T 85 methods were statistically significant for each of the coarse aggregate materials tested in this study, as shown in the "significant" column of Table 3-12. These differences can be seen in Figure 3-7, which presents graphical comparisons of the average Gsa, Gsb, Gssd, and water absorption results for the five coarse aggregate materials tested in Experiment 2.

The differences in Gsb and Gssd values for the two methods were considered significant from a practical point of view. Part of the differences can be attributed to how the two methods account for absorption. In essence, the Phunque method does not take into account the water absorption that takes place from the time when the first aggregate particles enter the water in the flask until the initial reading is made of the water level in the neck of the flask. This may be as much as 30 seconds. Obviously, water is absorbed into the aggregate particles during this time. From Figure 3-7(d), it can be seen that the materials with the greatest differences in water absorption were the recycled concrete and the blast furnace slag. The aggregate particles for these materials have the largest pore sizes and therefore are capable of absorbing water more quickly than the other materials, resulting in lower water absorption values. To correct the problem, timing for the initial water level reading should be varied based on the absorption of each material. However, it is difficult to shorten the 30-second period for the initial reading because it would take that much time to introduce all of the sample into the flask, clean the neck, and take the reading. Further analysis of the test results using a correlation between the water level and time at which the water level reading is taken is conducted in Experiment 5 to estimate the water level prior to 30 seconds.

Comparing Test Results for Fine Aggregate

Tukey's tests were also conducted for test results of fine aggregate materials. A summary of Tukey's test results for Gsa of fine aggregates is presented in Table 3-13. Based on a

Table 3-12. Tukey's pairwise comparisons for coarse aggregate test results.

Response Variable Gsa

Materials	Method	Difference of Means	Adjusted T-Value	Adjusted P-Value	Significant?
BF Slag Coarse	T 85 - Phunque	-0.04912	-15.83	<0.0001	Yes
Elmore Gravel	T 85 - Phunque	-0.01189	-3.83	0.0107	Yes
PS Coarse	T 85 - Phunque	-0.01021	-3.29	0.0492	Yes
RC LMS Coarse	T 85 - Phunque	-0.01218	-3.92	0.0080	Yes
Recycled Concrete	T 85 - Phunque	-0.01188	-3.830	0.0107	Yes

Response Variable Gsb

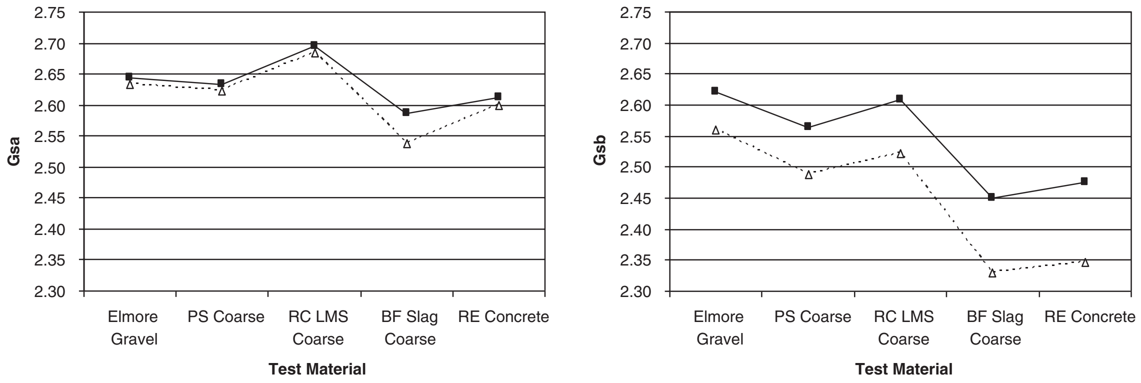
Materials	Method	Difference of Means	Adjusted T-Value	Adjusted P-Value	Significant?
BF Slag Coarse	T 85 - Phunque	-0.1189	-31.45	<0.0001	Yes
Elmore Gravel	T 85 - Phunque	-0.0609	-16.12	<0.0001	Yes
Sandstone Coarse	T 85 - Phunque	-0.0765	-20.24	<0.0001	Yes
RC LS Coarse	T 85 - Phunque	-0.0866	-22.92	<0.0001	Yes
Recycled Concrete	T 85 - Phunque	-0.1296	-34.28	<0.0001	Yes

Response Variable Gssd

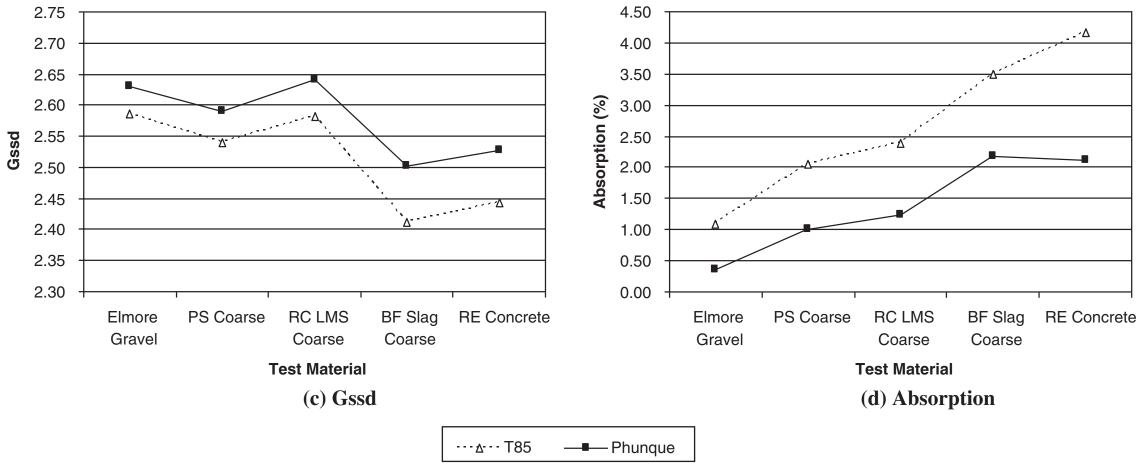
Materials	Method	Difference of Means	Adjusted T-Value	Adjusted P-Value	Significant?
BF Slag Coarse	T 85 - Phunque	-0.09014	-28.33	<0.0001	Yes
Elmore Gravel	T 85 - Phunque	-0.0423	-13.30	<0.0001	Yes
Sandstone Coarse	T 85 - Phunque	-0.0513	-16.13	<0.0001	Yes
RC LS Coarse	T 85 - Phunque	-0.0589	-18.51	<0.0001	Yes
Recycled Concrete	T 85 - Phunque	-0.08400	-26.40	<0.0001	Yes

Response Variable Abs (%)

Materials	Method	Difference of Means	Adjusted T-Value	Adjusted P-Value	Significant?
BF Slag Coarse	T 85 - Phunque	1.335	28.87	<0.0001	Yes
Elmore Gravel	T 85 - Phunque	0.7399	16.00	<0.0001	Yes
Sandstone Coarse	T 85 - Phunque	1.0540	22.798	<0.0001	Yes
RC LS Coarse	T 85 - Phunque	1.1482	24.84	<0.0001	Yes
Recycled Concrete	T 85 - Phunque	2.055	44.46	<0.0001	Yes



(a) Gsa **(b) Gsb**



(c) Gssd **(d) Absorption**

Figure 3-7. Comparison of results determined by two test methods for coarse aggregate.

Table 3-13. Tukey's pairwise comparisons for Gsa of fine aggregate.

Response Variable Gsa

Materials	Method	Difference of Means	Adjusted T-Value	P-Value	Significant?
BF Slag Fine	Phunque - MT 84	0.0169	5.24	0.0002	Yes
BF Slag Fine	SSDetect - MT 84	0.0301	9.32	0.0001	Yes
BF Slag Fine	T 84 - MT 84	-0.0110	-3.41	0.0914	No
BF Slag Fine	SSDetect-Phunque	0.0131	4.08	0.0117	Yes
BF Slag Fine	T 84 - Phunque	-0.0279	-8.65	0.0001	Yes
BF Slag Fine	T 84 - SSDetect	-0.0411	-12.73	0.0001	Yes
Natural Sand	Phunque - MT 84	-0.001103	-0.342	1.0000	No
Natural Sand	SSDetect - MT 84	-0.006213	-1.926	0.9234	No
Natural Sand	T 84 - MT 84	-0.006201	-1.923	0.9246	No
Natural Sand	SSDetect-Phunque	-0.005110	-1.584	0.9886	No
Natural Sand	T 84 - Phunque	-0.005098	-1.581	0.9889	No
Natural Sand	T 84 - SSDetect	0.000012	0.0036	1.0000	No
Sandstone Fine	Phunque - MT 84	0.00493	1.530	0.9923	No
Sandstone Fine	SSDetect - MT 84	-0.01150	-3.565	0.0596	No
Sandstone Fine	T 84 - MT 84	-0.00064	-0.198	1.0000	No
Sandstone Fine	SSDetect-Phunque	-0.01643	-5.095	0.0003	Yes
Sandstone Fine	T 84 - Phunque	-0.00557	-1.728	0.9717	No
Sandstone Fine	T 84 - SSDetect	0.01086	3.367	0.1034	No
RC LS Fine	Phunque - MT 84	0.00928	2.88	0.3204	No
RC LS Fine	SSDetect - MT 84	-0.01909	-5.92	0.0001	Yes
RC LS Fine	T 84 - MT 84	-0.01235	-3.83	0.0266	Yes
RC LS Fine	SSDetect-Phunque	-0.02837	-8.80	0.0001	Yes
RC LS Fine	T 84 - Phunque	-0.02163	-6.71	0.0001	Yes
RC LS Fine	T 84 - SSDetect	0.00674	2.09	0.8550	No
TX LS Sand	Phunque - MT 84	0.022998	7.1310	0.0001	Yes
TX LS Sand	SSDetect - MT 84	0.019817	6.1446	0.0001	Yes
TX LS Sand	T 84 - MT 84	-0.001152	-0.3572	1.0000	No
TX LS Sand	SSDetect-Phunque	-0.00318	-0.986	1.0000	No
TX LS Sand	T 84 - Phunque	-0.02415	-7.488	0.0001	Yes
TX LS Sand	T 84 - SSDetect	-0.02097	-6.502	0.0001	Yes

significance level of 0.05, the differences in Gsa of the natural sand measured by the four test methods (Modified T 84, Phunque fine, SSDetect, AASHTO T 84) were not statistically significant. Since the natural sand was rounded and had a low P200 content with no clay fines, it was not expected to cause discrepancies among the four test methods. The differences in Gsa of the Preston sandstone fine aggregate, except for Phunque vs. SSDetect, also were not statistically significant. For other materials, the four test methods generally produced statistically different Gsa results.

Table 3-14 shows a statistical analysis of Gsb results measured using the four test methods for fine aggregate. Based on a significance level of 0.05, the differences in Gsb results measured using the AASHTO T 84 and Modified AASHTO T 84 procedures were not statistically significant, except for the RC limestone fine aggregate, which has a high percentage (26.5 percent) of P200 material. For the natural sand, the differences in Gsb measured by the four test methods, except for Phunque vs. SSDetect, were not statistically significant. However, for the RC limestone fine aggregate, the four test methods produced statistically different Gsb results.

Table 3-15 shows a statistical analysis for Gssd results measured by the four test methods for fine aggregate. The comparison results of Gssd values were very similar to those for the Gsb results discussed previously. This observation was expected because Gsb and Gssd are both dependent on how the SSD condition and water absorption capacity are determined.

Tukey's pairwise comparisons of water absorption values measured by the four methods for fine aggregate are presented in Table 3-16. The SSDetect and Phunque flask methods had the tendency to yield lower and higher absorption values than AASHTO T 84, respectively. In addition, the Modified AASHTO T 84 procedure produced higher water absorption results than the AASHTO T 84 method; however, the difference was only statistically significant for the RC limestone fine aggregate.

Figure 3-8 shows graphical comparisons of the means of Gsa, Gsb, Gssd, and water absorption measured by the four test methods for fine aggregate. As shown in Figure 3-8(a), the AASHTO T 84 procedure yielded Gsa results that were closest to those of the Modified AASHTO T 84 procedure, then the Phunque method, and finally the SSDetect. Of the four test methods, the SSDetect is the only one that vacuum-saturates fine aggregate samples for measuring the Gsa, which may contribute to the difference of Gsa.

Table 3-14. Tukey's pairwise comparisons for Gsb of fine aggregate.

Response Variable Gsb

		Difference	Adjusted		
Materials	Method	of Means	T-Value	P-Value	Significant?
BF Slag Fine	Phunque - MT 84	0.0524	6.72	0.0001	Yes
BF Slag Fine	SSDetect - MT 84	0.0439	5.63	0.0001	Yes
BF Slag Fine	T 84 - MT 84	0.0048	0.61	1.0000	No
BF Slag Fine	SSDetect-Phunque	-0.0085	-1.09	0.9999	No
BF Slag Fine	T 84 - Phunque	-0.0477	-6.11	0.0001	Yes
BF Slag Fine	T 84 - SSDetect	-0.0392	-5.02	0.0004	Yes
Natural Sand	Phunque - MT 84	0.0125	1.61	0.9868	No
Natural Sand	SSDetect - MT 84	-0.0277	-3.54	0.0634	No
Natural Sand	T 84 - MT 84	0.0000	0.00	1.0000	No
Natural Sand	SSDetect-Phunque	-0.0402	-5.15	0.0002	Yes
Natural Sand	T 84 - Phunque	-0.0125	-1.61	0.9869	No
Natural Sand	T 84 - SSDetect	0.0277	3.54	0.0633	No
Sandstone Fine	Phunque - MT 84	0.0278	3.56	0.0598	No
Sandstone Fine	SSDetect - MT 84	-0.0522	-6.69	0.0001	Yes
Sandstone Fine	T 84 - MT 84	0.0085	1.08	0.9999	No
Sandstone Fine	SSDetect-Phunque	-0.0800	-10.25	0.0001	Yes
Sandstone Fine	T 84 - Phunque	-0.0194	-2.48	0.6013	No
Sandstone Fine	T 84 - SSDetect	0.06065	7.770	0.0001	Yes
RC LS Fine	Phunque - MT 84	0.14003	17.938	0.0001	Yes
RC LS Fine	SSDetect - MT 84	-0.03610	-4.625	0.0016	Yes
RC LS Fine	T 84 - MT 84	0.09214	11.804	0.0001	Yes
RC LS Fine	SSDetect-Phunque	-0.1761	-22.56	0.0001	Yes
RC LS Fine	T 84 - Phunque	-0.0479	-6.13	0.0001	Yes
RC LS Fine	T 84 - SSDetect	0.1282	16.43	0.0001	Yes
TX LS Sand	Phunque - MT 84	0.04457	5.710	0.0001	Yes
TX LS Sand	SSDetect - MT 84	-0.01525	-1.953	0.9142	No
TX LS Sand	T 84 - MT 84	0.00961	1.231	0.9995	No
TX LS Sand	SSDetect-Phunque	-0.05982	-7.663	0.0001	Yes
TX LS Sand	T 84 - Phunque	-0.03496	-4.479	0.0028	Yes
TX LS Sand	T 84 - SSDetect	0.02486	3.184	0.1643	No

Table 3-15. Tukey's pairwise comparisons for Gssd of fine aggregate.

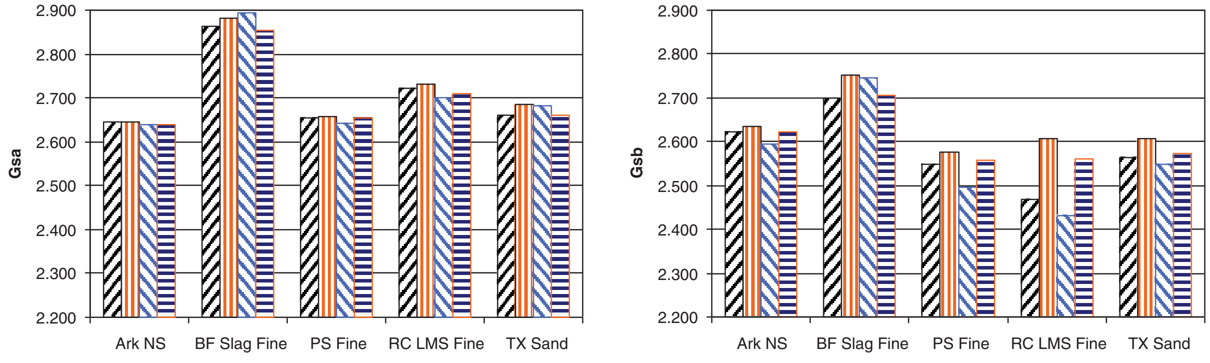
Response Variable Gssd

Materials	Method	Difference of Means	T-Value	Adjusted P-Value	Significant?
BF Slag Fine	Phunque - MT 84	0.0405	7.76	0.0001	Yes
BF Slag Fine	SSDetect - MT 84	0.0385	7.40	0.0001	Yes
BF Slag Fine	T 84 - MT 84	-0.0006	-0.11	1.0000	No
BF Slag Fine	SSDetect-Phunque	-0.0019	-0.37	1.0000	No
BF Slag Fine	T 84 - Phunque	-0.0410	-7.87	0.0001	Yes
BF Slag Fine	T 84 - SSDetect	-0.0391	-7.51	0.0001	Yes
Natural Sand	Phunque - MT 84	0.00740	1.42	0.9969	No
Natural Sand	SSDetect - MT 84	-0.01952	-3.75	0.0346	Yes
Natural Sand	T 84 - MT 84	-0.00233	-0.45	1.0000	No
Natural Sand	SSDetect-Phunque	-0.0269	-5.17	0.0002	Yes
Natural Sand	T 84 - Phunque	-0.0097	-1.87	0.9418	No
Natural Sand	T 84 - SSDetect	0.01720	3.30	0.1232	No
Sandstone Fine	Phunque - MT 84	0.01927	3.70	0.0401	Yes
Sandstone Fine	SSDetect - MT 84	-0.03661	-7.02	0.0001	Yes
Sandstone Fine	T 84 - MT 84	0.00506	0.97	1.0000	No
Sandstone Fine	SSDetect-Phunque	-0.05588	-10.72	0.0001	Yes
Sandstone Fine	T 84 - Phunque	-0.01422	-2.73	0.4186	No
Sandstone Fine	T 84 - SSDetect	0.04166	7.995	0.0001	Yes
RC LS Fine	Phunque - MT 84	0.09180	17.617	0.0001	Yes
RC LS Fine	SSDetect - MT 84	-0.02920	-5.603	0.0001	Yes
RC LS Fine	T 84 - MT 84	0.05397	10.356	0.0001	Yes
RC LS Fine	SSDetect-Phunque	-0.1210	-23.22	0.0001	Yes
RC LS Fine	T 84 - Phunque	-0.0378	-7.26	0.0001	Yes
RC LS Fine	T 84 - SSDetect	0.08316	15.96	0.0001	Yes
TX LS Sand	Phunque - MT 84	0.036435	6.9920	0.0001	Yes
TX LS Sand	SSDetect - MT 84	-0.002430	-0.4663	1.0000	No
TX LS Sand	T 84 - MT 84	0.005578	1.0705	0.9999	No
TX LS Sand	SSDetect-Phunque	-0.03887	-7.458	0.0001	Yes
TX LS Sand	T 84 - Phunque	-0.03086	-5.922	0.0001	Yes
TX LS Sand	T 84 - SSDetect	0.008008	1.537	0.9919	No

Table 3-16. Tukey's pairwise comparisons for water absorption of fine aggregate.

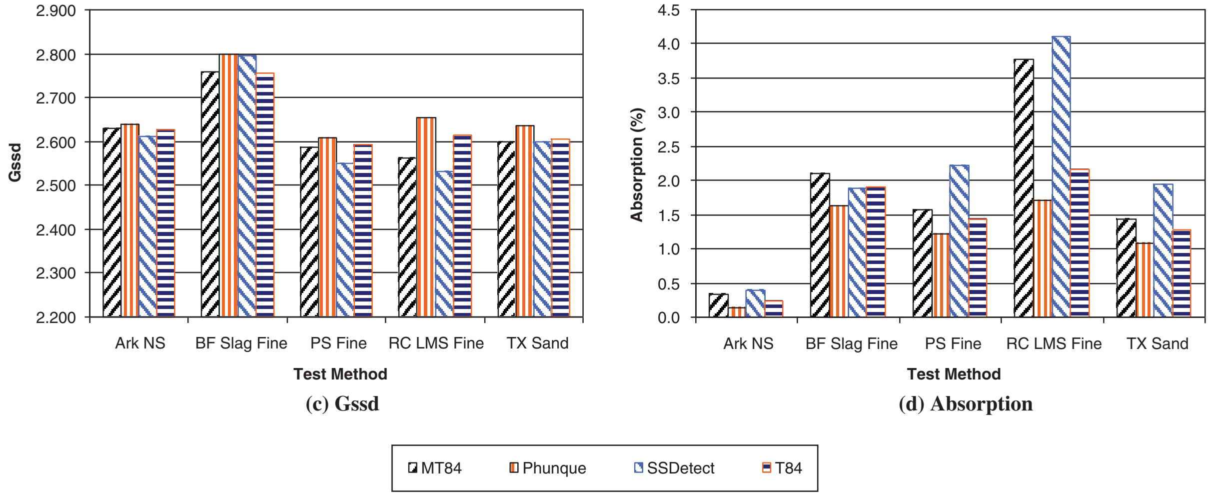
Response Variable Abs (%)

Materials	Method	Difference of Means	T-Value	Adjusted P-Value	Significant?
BF Slag Fine	Phunque - MT 84	-0.473	-3.87	0.0235	Yes
BF Slag Fine	SSDetect - MT 84	-0.227	-1.86	0.9434	No
BF Slag Fine	T 84 - MT 84	-0.201	-1.64	0.9831	No
BF Slag Fine	SSDetect-Phunque	0.245	2.01	0.8931	No
BF Slag Fine	T 84 - Phunque	0.272	2.22	0.7800	No
BF Slag Fine	T 84 - SSDetect	0.026	0.22	1.0000	No
Natural Sand	Phunque - MT 84	-0.1981	-1.622	0.9854	No
Natural Sand	SSDetect - MT 84	0.3174	2.598	0.5129	No
Natural Sand	T 84 - MT 84	-0.0889	-0.727	1.0000	No
Natural Sand	SSDetect-Phunque	0.5156	4.2198	0.0071	Yes
Natural Sand	T 84 - Phunque	0.1093	0.8944	1.0000	No
Natural Sand	T 84 - SSDetect	-0.4063	-3.325	0.1154	No
Sandstone Fine	Phunque - MT 84	-0.3574	-2.925	0.2911	No
Sandstone Fine	SSDetect - MT 84	0.6541	5.354	0.0001	Yes
Sandstone Fine	T 84 - MT 84	-0.1346	-1.102	0.9999	No
Sandstone Fine	SSDetect-Phunque	1.0115	8.279	0.0001	Yes
Sandstone Fine	T 84 - Phunque	0.2227	1.823	0.9529	No
Sandstone Fine	T 84 - SSDetect	-0.789	-6.456	0.0001	Yes
RC LS Fine	Phunque - MT 84	-2.063	-16.89	0.0001	Yes
RC LS Fine	SSDetect - MT 84	0.336	2.75	0.4024	No
RC LS Fine	T 84 - MT 84	-1.613	-13.20	0.0001	Yes
RC LS Fine	SSDetect-Phunque	2.3994	19.639	0.0001	Yes
RC LS Fine	T 84 - Phunque	0.4505	3.687	0.0414	Yes
RC LS Fine	T 84 - SSDetect	-1.949	-15.95	0.0001	Yes
TX LS Sand	Phunque - MT 84	-0.3505	-2.869	0.3249	No
TX LS Sand	SSDetect - MT 84	0.5157	4.221	0.0071	Yes
TX LS Sand	T 84 - MT 84	-0.1607	-1.315	0.9988	No
TX LS Sand	SSDetect-Phunque	0.8662	7.090	0.0001	Yes
TX LS Sand	T 84 - Phunque	0.1898	1.554	0.9909	No
TX LS Sand	T 84 - SSDetect	-0.6764	-5.536	0.0001	Yes



(a) Gsa

(b) Gsb



(c) Gssd

(d) Absorption

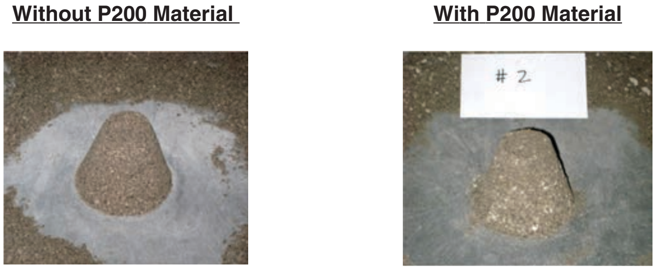
Figure 3-8. Comparison of results determined by four test methods for fine aggregate.

Since the Phunque flask consistently produced lower water absorption results for all the fine aggregates, as shown in Figure 3-8(d), it was suggested that some water penetrates into the surface voids of the aggregate particles within the first 30 seconds of the test before the initial water level reading is taken. Differences between the results of AASHTO T 84 and Modified AASHTO T 84 suggest that the presence of P200 material only significantly affected the RC limestone, especially the water absorption.

To gain a better understanding of the difference in the results of the RC limestone when tested with the AASHTO T 84 (with P200) and Modified AASHTO T 84 (without P200) methods, a small experiment was performed to quantify the impact of removing the P200 material on the results of the cone test. As previously discussed, the RC limestone material contained 26.5 percent P200 and had a sand equivalent value of 39.6.

For this small experiment, two samples of RC limestone fine aggregate were prepared. One sample was dry-sieved over the No. 200 sieve to remove the P200 material while the other sample was not. The samples were placed in a plastic bag with approximately 12 percent moisture and allowed to soak overnight (as per the AASHTO T 84 procedure). The samples were then air-dried using a hair drier, and the cone test was performed at various times during the drying process. Each time the cone test was performed on the material, a photograph was taken of the aggregate cone. The material from the cone was then removed from the overall sample and weighed. This material was later dried out in order to determine the moisture content of the aggregate sample that corresponded to the composition of that particular cone test. A total of five cone tests were performed on each sample.

Figure 3-9 shows photographs of the cone tests performed on the aggregate samples at various moisture conditions. Figure 3-9 (A1) and (B1) show photographs of cone tests performed prior to the samples reaching an SSD condition, and the color of materials in the two figures was very similar. Figure 3-9 (A2), (A3), (B2), and (B3) show cones that were very close to the typical definition of an SSD condition in AASHTO T 84. Figure 3-9 (A4), (A5), (B4), and (B5) show the aggregate materials after being dried beyond the typical SSD condition (with progressively less of the material retaining the cone shape). The lighter color of aggregate samples with P200 material (on the right) at and after SSD conditions indicated that these samples were drier than those with the P200 material removed.



(A1) Cone #1: Wet Condition **(B1) Cone #2: Wet Condition**

(A2) Cone #3: Early SSD Condition **(B2) Cone #4: SSD Condition**

(A3) Cone #5: SSD Condition **(B3) Cone #6: SSD Condition**

(A4) Cone #7: Past SSD Condition **(B4) Cone #9: Past SSD Condition**

(A5) Cone #8: Past SSD Condition **(B5) Cone #10: Past SSD Condition**

Figure 3-9. Cone tests at various moisture conditions for RC limestone.

Figure 3-10 shows a comparison of the measured moisture contents taken from the cone test material for each of the photographs shown in Figures 3-9. The data clearly showed a significant difference between the moisture contents of the material with and without P200 material after the start of SSD condition. The moisture contents varied by approximately 2 percent for the samples tested after the material had reached SSD by the definition set forth in AASHTO T 84. This provided the evidence that the P200 material of the RC limestone caused a difference in the moisture contents determined by AASHTO T 84 for the two types of material. This was likely due to the cohesive nature of these fines that allowed the material to retain the cone shape even after it had reached the SSD condition.

Variance Estimates for Coarse Aggregate Test Methods

The next analysis step was to determine estimates of within- and between-laboratory variances for each test

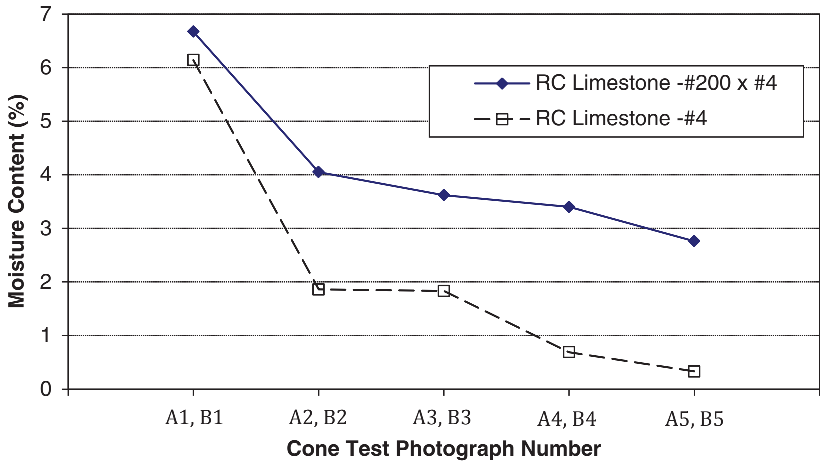
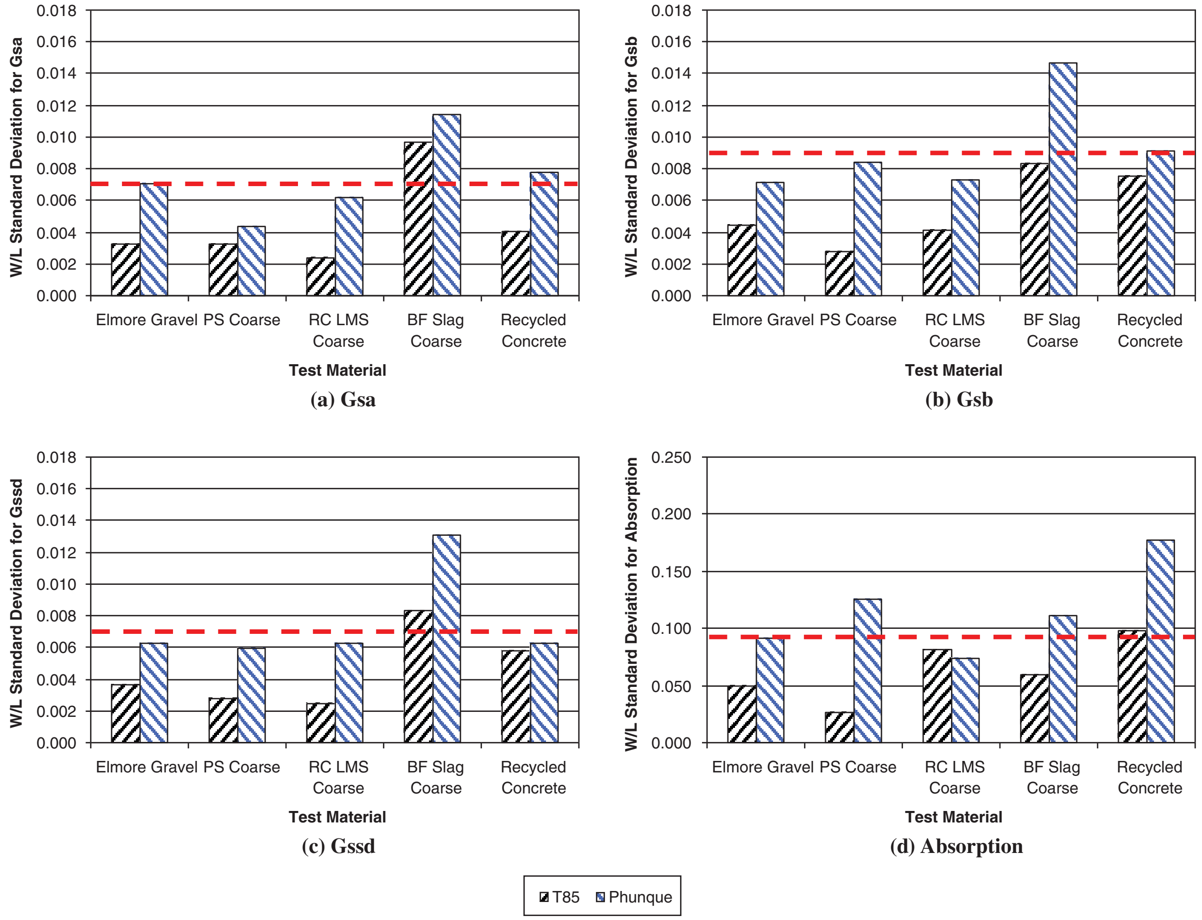


Figure 3-10. Moisture contents corresponding to various cone tests.

method. Detailed results of the within- and between-laboratory variance components for each material evaluated in Experiment 2 are presented in Appendix E, which is available on the project web page.

Figures 3-11 and 3-12 compare the within-lab and between-lab standard deviations, respectively, for the AASHTO T 85 and Phunque methods for Gsa, Gsb, Gssd, and water absorption. The dash lines in these figures represent the single-operator standard deviations from AASHTO T 85 for comparison. It should be noted that the AASHTO T 85 precision information was estimated based on aggregates with absorptions of less than 2 percent.

In these figures, the AASHTO T 85 procedure was more repeatable and reproducible than the Phunque method in



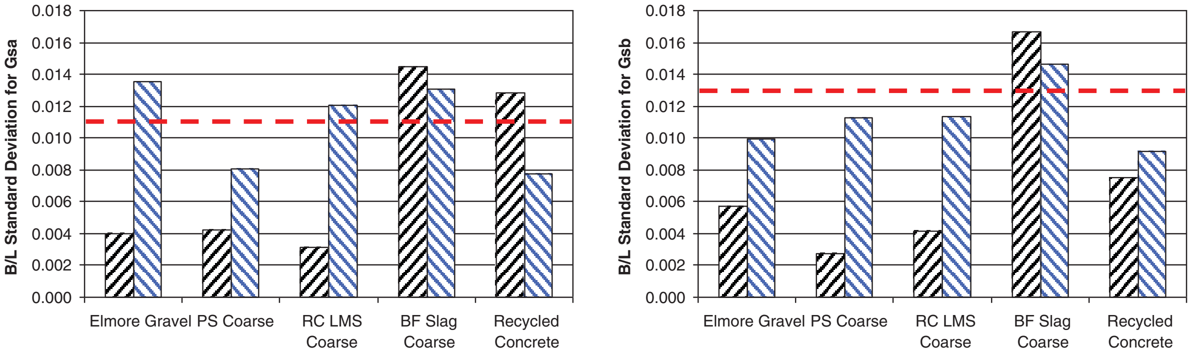
(a) Gsa

(b) Gsb

(c) Gssd

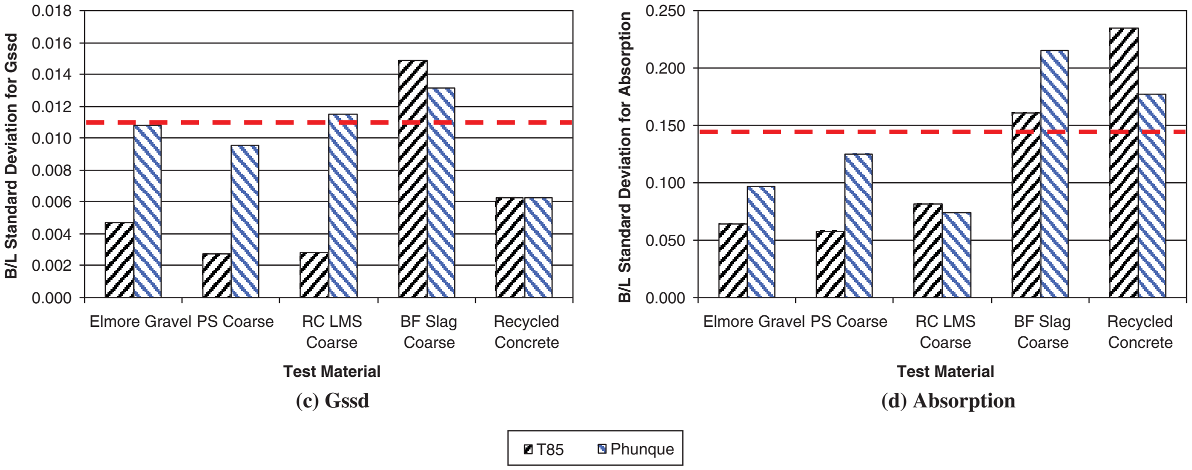
(d) Absorption

Figure 3-11. Within-lab standard deviations for coarse aggregate test methods.



(a) Gsa

(b) Gsb



(c) Gssd

(d) Absorption

Figure 3-12. Between-lab standard deviations for coarse aggregate test methods.

almost all of the comparisons. The comparisons (also confirmed by Bartlett's test) show that there should be two levels of precision: one for materials with absorptions of less than 2.5 percent (Elmore gravel, Preston sandstone, and RC limestone) and another level for more absorptive materials (blast furnace slag and recycled concrete). Thus, the precision information determined in this study for the two methods for coarse aggregate are shown in Table 3-17. The precision information was determined based on limited data generated in this project, so a round robin is needed to verify this precision information prior to future implementation. Table 3-17 also includes the precision information (based on aggregates

Table 3-17. Precision information for two test methods for coarse aggregate.

			Standard Deviation (1s) Determined in NCHRP 4-35		Standard Deviation (1s) Given in AASHTO T 85	
Response	**Method**	**Absorption**	**W/L**	**B/L**	**W/L**	**B/L**
Gsa	T 85	< 2.5%	0.003	0.004	0.007	0.011
		≥ 2.5%	0.007	0.011		
	Phunque	< 2.0%	0.006	0.012		
		≥ 2.0%	0.001	0.011		
Gsb	T 85	< 2.5%	0.004	0.004	0.009	0.013
		≥ 2.5%	0.008	0.013		
	Phunque	< 2.0%	0.008	0.011		
		≥ 2.0%	0.010	0.012		
Gssd	T 85	< 2.5%	0.003	0.004	0.007	0.011
		≥ 2.5%	0.007	0.011		
	Phunque	< 2.0%	0.006	0.011		
		≥ 2.0%	0.010	0.011		
Abs (%)	T 85	< 2.5%	0.06	0.07	0.088	0.145
		≥ 2.5%	0.08	0.20		
	Phunque	< 2.0%	0.01	0.10		
		≥ 2.0%	0.15	0.20		

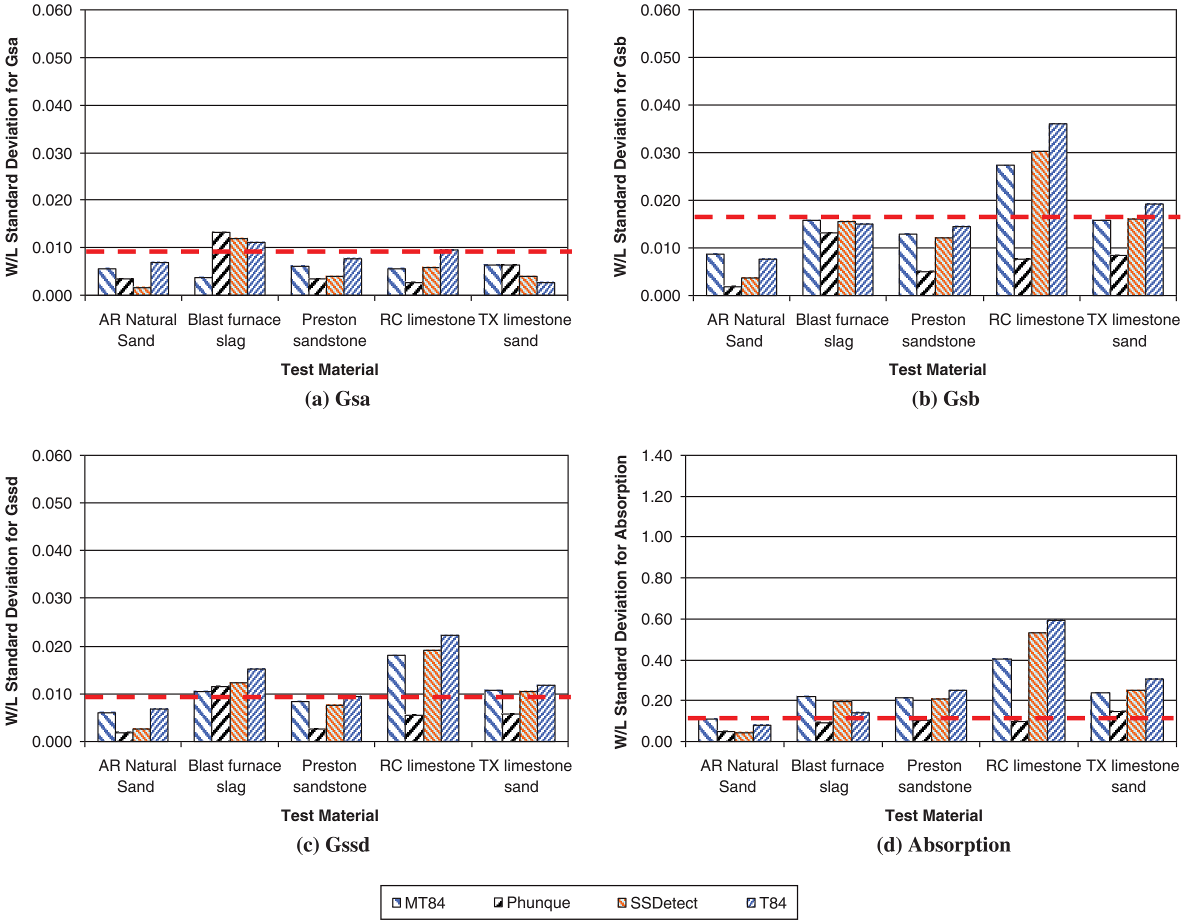
with absorptions of less than 2 percent) given in the current AASHTO T 85 test method for comparison.

Variance Estimates for Fine Aggregate Test Methods

Figure 3-13 compares the within-lab standard deviations, and Figure 3-14 compares the between-lab standard deviations for the four test methods (Modified AASHTO T 84, Phunque, SSDetect, and AASHTO T 84) for Gsa, Gsb, Gssd, and water absorption. The dash lines represent the AASHTO T 84 single-operator standard deviations in Figure 3-13 and multi-laboratory standard deviations in Figure 3-14 for comparison. The AASHTO T 84 precision information was based on aggregates with absorptions of less than 1 percent.

Based on the comparisons shown in Figures 3-13 and 3-14, the following observations are offered:

- Compared to the within-lab standard deviation for Gsa set forth in AASHTO T 84, the Phunque, SSDetect, and AASHTO T 84 methods had higher standard deviations for the blast furnace slag but lower standard deviations for the other materials, Figure 3-13(a), and the Modified AASHTO T 84 method showed lower within-lab standard deviations for Gsa for all the materials. In addition, each of the test methods had lower between-lab standard deviations for Gsa than the standard deviation specified in AASHTO T 84 for all of the materials except the blast furnace slag, Figure 3-14(a).
- Test results were generally most repeatable and reproducible for the natural sand that had low angularity, low P200 content, and low absorption capacity. High contents of P200 and/or clay materials in the fine aggregates (e.g., RC limestone and Preston sandstone) can significantly increase the variability of the test results.
- The Phunque method appeared to yield the most repeatable within-lab results for most materials. The Phunque method also had the most reproducible (between-lab comparison) results for absorption. The within- and between-lab standard deviations for the Phunque method seemed to be more consistent across the range of materials in this experiment. In other words, the repeatability and reproducibility of the Phunque method did not appear to be as sensitive to material properties.



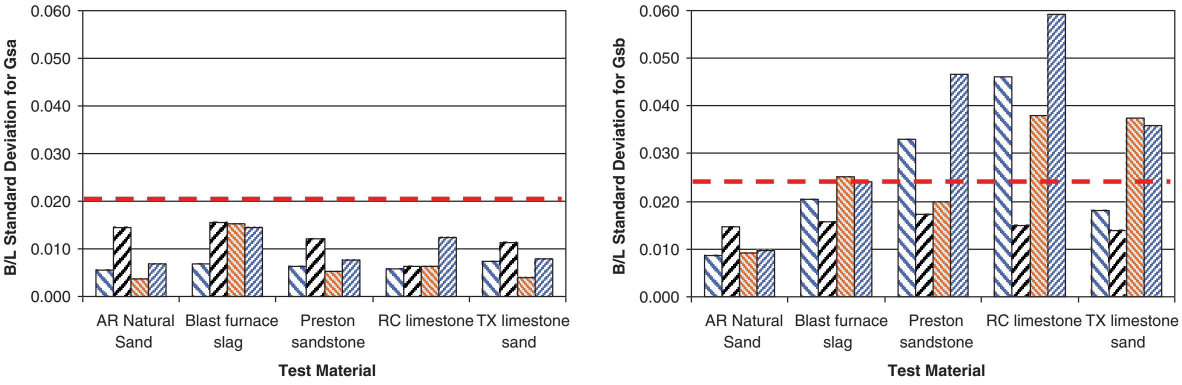
(a) Gsa

(b) Gsb

(c) Gssd

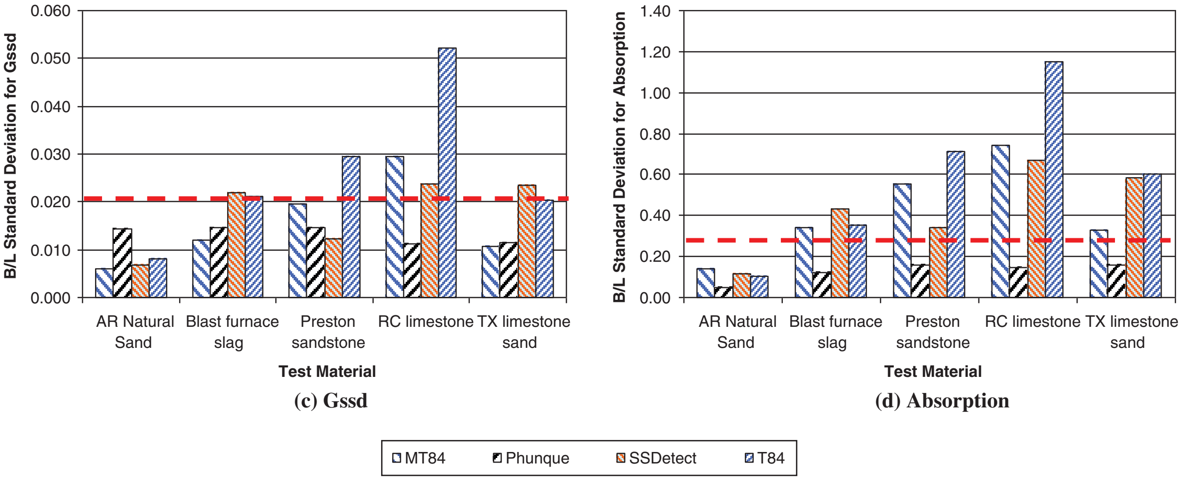
(d) Absorption

Figure 3-13. Within-lab standard deviations for fine aggregate test methods.



(a) Gsa

(b) Gsb



(c) Gssd

(d) Absorption

Figure 3-14. Between-lab standard deviations for fine aggregate test methods.

- The AASHTO T 84 method appeared to be the least repeatable and reproducible in the comparisons.
- The variability of the Gsb and Gssd test results appeared to have a trend similar to that of the water absorption capacity.

To develop precision information for the four test methods based on the results of this study, a statistical analysis (Bartlett's test) was conducted to evaluate the effects of water absorption, sand equivalent, and P200 content on the variability of each measured parameter (Gsa, Gsb, Gssd, and water absorption). Table 3-18 summarizes the analysis results, and the shaded cells indicate the material properties that significantly affect the variability of the corresponding test results.

The variability of the Modified AASHTO T 84 test results was significantly influenced by the absorption capacity of the material tested. The variability of the Phunque test was not affected by the three material properties. The variability of the SSDetect method was influenced by the water absorption capacity and the P200 content with the absorption capacity being more significant. The variability of the AASHTO T 84 results was affected by the absorption capacity, clay content (sand equivalent), and P200 content of the material tested with the P200 content showing the most influence.

Based on the comparisons shown in Figures 3-13 and 3-14, as well as the analysis results presented in Table 3-18, the following observations were made:

- There is one level of precision for Gsa for each of the four test methods and one level of precision for Gsb, Gssd, and water absorption for the Phunque method.
- There are three levels of precision for Gsb, Gssd, and water absorption measured by the Modified AASHTO T 84 and SSDetect methods. The three levels are applied for fine aggregate based on the measured water capacity: less than 1 percent, between 1 and 2.5 percent, and greater than 2.5 percent.
- There are also three levels of precision for Gsb, Gssd, and water absorption for AASHTO T 84 corresponding to the amount of P200 material: less than 1 percent, between 1 and 10 percent, and greater than 10 percent.

Based on the above observations, the precision information for the four test methods for fine aggregate are proposed in Tables 3-19 through 3-22. The precision information was

Table 3-18. Correlation between standard deviation of measured parameters and absorption, sand equivalent, and P200.

		Is Effect of Material Property on W/L Variability Significant?			Is Effect of Material Property on B/L Variability Significant?		
Method	**Parameter**	**% Abs**	**Sand Equiv.**	**P200**	**% Abs**	**Sand Equiv.**	**P200**
MT 84	Gsa	No	N/A	N/A	No	N/A	N/A
	Gsb	Yes	N/A	N/A	Yes	N/A	N/A
	Gssd	Yes	N/A	N/A	Yes	N/A	N/A
	% Abs	Yes	N/A	N/A	Yes	N/A	N/A
Phunque	Gsa	No	No	No	No	No	Yes
	Gsb	Yes	No	No	No	No	No
	Gssd	No	No	No	No	No	No
	% Abs	No	No	No	Yes	No	No
SSDetect	Gsa	No	No	No	No	No	No
	Gsb	Yes	No	Yes	Yes	No	Yes
	Gssd	Yes	No	Yes	Yes	No	Yes
	% Abs	Yes	No	Yes	Yes	No	Yes
T 84	Gsa	No	No	No	Yes	No	No
	Gsb	Yes	No	Yes	Yes	Yes	Yes
	Gssd	Yes	No	Yes	Yes	Yes	Yes
	% Abs	Yes	No	Yes	Yes	Yes	Yes

Note: N/A = Not applicable because materials passing the #200 sieve were removed from the fine aggregate tested.

Table 3-19. Precision information for Modified AASHTO T 84 for fine aggregate.

		Standard Deviation Determined in NCHRP 4-35		Standard Deviation Specified in AASHTO T 84	
Parameter	**Absorption**	**W/L**	**B/L**	**W/L**	**B/L**
Gsa		0.005	0.011	0.0095	0.020
Gsb	< 1%	0.009	0.012	0.011	0.023
	1 - 2.5%	0.015	0.024		
	≥ 2.5%	0.027	0.046		
Gssd	< 1%	0.006	0.011	0.0095	0.020
	1 - 2.5%	0.012	0.018		
	≥ 2.5%	0.018	0.029		
Abs (%)	< 1%	0.11	0.19	0.11	0.23
	1 - 2.5%	0.22	0.41		
	≥ 2.5%	0.40	0.74		

Table 3-20. Precision information for Phunque method for fine aggregate.

	Standard Deviation Determined in NCHRP 4-35		Standard Deviation Specified in AASHTO T 84	
Parameter	**W/L**	**B/L**	**W/L**	**B/L**
Gsa	0.006	0.012	0.010	0.020
Gsb	0.007	0.015	0.011	0.023
Gssd	0.006	0.013	0.010	0.020
Abs (%)	0.10	0.12	0.11	0.23

Table 3-21. Precision information for SSDetect method for fine aggregate.

		Standard Deviation Determined in NCHRP 4-35		Standard Deviation Specified in AASHTO T 84	
Parameter	**Absorption**	**W/L**	**B/L**	**W/L**	**B/L**
Gsa		0.006	0.011	0.0095	0.020
Gsb	< 1%	0.004	0.009	0.011	0.023
	1 - 2.5%	0.015	0.028		
	≥ 2.5%	0.030	0.038		
Gssd	< 1%	0.003	0.010	0.0095	0.020
	1 - 2.5%	0.010	0.019		
	≥ 2.5%	0.019	0.024		
Abs (%)	< 1%	0.04	0.11	0.11	0.23
	1 - 2.5%	0.22	0.45		
	≥ 2.5%	0.53	0.67		

Table 3-22. Precision information for AASHTO T 84 method for fine aggregate.

Parameter	Content of Minus #200	Standard Deviation Determined in NCHRP 4-35 W/L	B/L	Standard Deviation Specified in AASHTO T 84 W/L	B/L
Gsa		0.008	0.01	0.0095	0.020
Gsb	< 1%	0.008	0.010	0.011	0.023
	1 - 10%	0.017	0.030		
	≥ 10%	0.025	0.053		
Gssd	< 1%	0.007	0.008	0.0095	0.020
	1 - 10%	0.013	0.021		
	≥ 10%	0.016	0.041		
Abs (%)	< 1%	0.08	0.10	0.11	0.23
	1 - 10%	0.22	0.48		
	≥ 10%	0.42	0.93		

determined based on limited data in this project. A round robin is needed to verify this precision information prior to future implementation. These tables also include the precision information (based on aggregates with absorptions of less than 1 percent and results from more than 10 participating laboratories) set forth in the current AASHTO T 84 test method for comparison.

Summary

Based on the results of Experiment 2, the following conclusions are offered for the six test methods:

- Of the two test methods for coarse aggregate, the AASHTO T 85 method was more repeatable and reproducible than the Phunque method. The disadvantage of AASHTO T 85 is that it takes a day longer than the Phunque method to complete a test.
- The Phunque method can be used to test both coarse and fine aggregate materials; however, different types of flasks are required. Use of the initial water level reading at 30 seconds is likely to yield inaccurate absorption, Gsb, and Gssd results for absorptive aggregate materials. This method requires two or more flasks of the same type if two or more replicates are tested simultaneously. The current design makes the flasks very fragile; if the method continues to be used, the use of a more durable material for the flasks is suggested.
- The AASHTO T 84 method can yield precise results for aggregate materials with less than 1 percent of P200. However, the precision of this method was significantly decreased when used for materials with higher P200 content, especially for fine aggregates with more than 10 percent of P200 material. The accuracy of the test was also questionable when used for materials with more than 10 percent of P200.
- The difference between the AASHTO T 84 and Modified AASHTO T 84 procedures was that the material used for the Modified AASHTO T 84 did not include the P200 material. This modification improved the precision of the AASHTO T 84 procedure. For the materials with high P200/clay content and high water absorption (i.e., Preston sandstone and RC limestone), the Modified AASHTO T 84 procedure yielded results that were as comparable, repeatable, and reproducible as those of the SSDetect method. The disadvantage of this test method is that it does not measure the properties of the P200 material, which would require a separate test.
- The SSDetect utilizes a rational and objective method of determining the SSD condition of fine aggregate. This test method can be used to measure the full gradation of fine aggregate. It produced repeatable and reproducible test results in this study. It offers substantial time savings (1 day), but at a substantially higher equipment cost.

After meeting with the technical panel, the following proposals were made for further research in this project:

- The AASHTO T 85 procedure was proposed for determining specific gravity and water absorption of coarse aggregate. Further experiments should focus on utilizing a vacuum saturation method to reduce the soak time period, which currently requires 15 to 19 hours, so that this test can be done within two working days.
- If the properties of the P200 material are not required for design and construction of PCC and HMA mixtures, the Modified AASHTO T 84 method can be utilized. Further experiments with the Modified AASHTO T 84 method should focus on utilizing a vacuum saturation method to reduce the soak time period.
- If the design and construction of PCC and/or HMA mixtures require the properties of the P200 material, the AASHTO T 84 procedure can be used for testing fine aggregate materials that have less than 10 percent of P200 material. As for the Modified AASHTO T 84 procedure, further experiments should focus on utilizing a vacuum saturation method to reduce the soak time period.

- The SSDetect method is probably a better method for testing fine aggregate that contains 10 percent or more of P200 material. Ruggedness and round robin studies for this test method have been completed under another study published in NCAT Report 05-07 (*25*); thus, no further research is needed.
- If the Phunque method (for coarse and/or fine aggregate) is selected, it is proposed that further research focus on determining optimum time for taking the initial water level reading and a vacuum saturation method to reduce the time required for taking the final water level reading. In addition, more durable flasks are needed.

Additional Experiments

After reviewing the results of Experiment 2, the research team was tasked with conducting additional experiments to answer specific questions related to the test procedures previously evaluated. The objectives of these experiments were as follows:

- Experiment 3 was conducted to evaluate modifications relative to the drying and soaking methods in AASHTO T 85 and T 84 to reduce the testing time.
- Experiment 4 was conducted to determine the effect of P200 on AASHTO T 84 test results.
- Experiment 5 was conducted to investigate the determination of a time-zero reading for Phunque methods.

Results of Experiments 3 and 4 are presented in this section, and results of Experiment 5 are included in Appendix H, which is available on the project web page.

Experiment 3: Evaluation of Drying and Soaking Methods in AASHTO T 85 and T 84

Experiment 3 was planned to investigate the viability of modifications in the drying and soaking methods to reduce the testing time for AASHTO T 85 and T 84. These modifications are underlined in Tables 3-23 and 3-24.

Experiment 3 was divided into three parts, as shown in Figure 3-15. The materials included in the experimental design were previously used in Experiment 2 (see Table 3-8). Sufficient quantities of these materials were available in the NCAT laboratory.

The first part of Experiment 3 was to evaluate two alternatives to the initial oven drying of test samples. One alternative was to use a vacuum drying method (i.e., CoreDry according

Table 3-23. Modifications to AASHTO T 85 drying and soaking methods.

Current AASHTO T 85	Modifications to AASHTO T 85
1. Wash the aggregate to remove P200 and deleterious materials.	1. Wash the aggregate to remove P200 and deleterious materials.
2. Dry the sample using a conventional oven at a temperature range of 105-115°C until there is no mass change in the aggregate. The aggregate is often dried overnight. Let the aggregate cool until it is comfortable to handle.	2. Dry the sample using a vacuum drying method (such as the CoreDry™ device, ASTM D 7227) at room temperature until there is no mass change in the aggregate; or test the aggregate sample without oven-drying.
3. Submerge the aggregate in water at room temperature for 15 to 19 hours.	3. Vacuum saturate the aggregate using a vacuum saturation method (such as the procedure described in AASHTO T 209).*
4. Remove the sample from the water, and roll it in an absorbing cloth. This is to take excess surface moisture off the aggregates. The aggregate should no longer be shiny.	4. Remove the sample from the water, and roll it in an absorbing cloth. This is to remove excess surface moisture from the aggregates. The aggregate should no longer be shiny.
5. Weigh the sample. This is saturated surface dry mass. The measurement should be taken to the nearest 0.5 g.	5. Weigh the sample. This is saturated surface dry mass. The measurement should be taken to the nearest 0.5 g.
6. The aggregate then must be weighed in water. Shake the container to remove entrapped air. Take this weight.	6. The aggregate then must be weighed in water. Shake the container to remove entrapped air. Take this weight.
7. Dry the sample to a constant mass using a conventional oven at a temperature range of 105-115° C. Remove and cool the test sample for 1 to 3 hours in air. Determine the mass.	7. Dry the test sample using a vacuum drier at room temperature until there is no mass change in the aggregate. Determine the mass.

*Note 1: The vacuum procedure described in AASHTO T 209-09 is used to saturate the aggregate sample. "Remove air trapped in the sample 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 a specific time period. Agitate the container and contents using the mechanical device during the vacuum period. At the end of the vacuum period, release the vacuum by increasing the pressure at a rate not to exceed 8 kPa (60 mm Hg) per second." The estimated price for a complete set of equipment for conducting AASHTO T 209-09 is approximately $1,536. The complete set includes a 2-stage vacuum pump ($625), a digital absolute pressure gauge ($450), an in-line dewatering filter ($79), a pycnometer ($357), and a 10-foot vacuum hose ($25).

Table 3-24. Modifications to AASHTO T 84 drying and soaking methods.

Current AASHTO T 84	Modifications to AASHTO T 84
1. This is used to test materials passing the No. 4 sieve.	1. This is used to test materials passing the No. 4 sieve and retained on the No. 200 sieve.
2. Dry the sample using a conventional oven at a temperature range of 105°-115°C until there is no mass change in the aggregate. Let the aggregate cool until it is comfortable to handle.	2. Dry the sample using a vacuum drying method (such as the CoreDry^{TM} device, ASTM D 7227) at room temperature until there is no mass change in the aggregate; or test the aggregate sample without oven-drying.
3. Submerge the aggregate in water at room temperature for 15 to 19 hours.	3. Vacuum saturate the aggregate using a vacuum saturation method (such as the procedure described in AASHTO T 209).*
4. Place the soaked aggregate sample on the flat baking sheet and spread it out. Begin to dry the sample with a hair dryer.	4. Place the soaked aggregate sample on the flat baking sheet and spread it out. Begin to dry the sample with a hair dryer.
5. At regular intervals, determine if the sample reaches an SSD condition using a cone and tamping rod.	5. At regular intervals, determine if the sample reaches an SSD condition using a cone and tamping rod.
6. Partially fill the pycnometer with distilled water and place a funnel in the top part of the neck. Tare this entire apparatus on the scale. Add 500 ± 10 grams of SSD aggregate to the pycnometer. Record this mass as the weight of SSD material.	6. Partially fill the pycnometer with distilled water and place a funnel in the top part of the neck. Tare this entire apparatus on the scale. Add 500 ± 10 grams of SSD aggregate to the pycnometer. Record this mass as the weight of SSD material.
7. Place the exact amount of a separate sample of SSD aggregate used in Step 6 into a separate bowl (labeled properly).	7. Place the exact amount of a separate sample of SSD aggregate used in Step 6 into a separate bowl (labeled properly).
8. Manually or mechanically shake the pycnometer to allow all the air bubbles to escape from the sample.	8. Mechanically shake the pycnometer to allow all the air bubbles to escape from the sample.
9. Fill the pycnometer to the calibrated fill line with distilled water. Use a rolled up towel to remove any deleterious material and air bubbles from the surface of the water. Use the towel to dry the neck of the flask as well. When the flask is filled to the calibration mark with distilled water, record the mass of the pycnometer filled with aggregate.	9. Fill the pycnometer to the calibrated fill line with distilled water. Use a rolled up towel to remove any deleterious material and air bubbles from the surface of the water. Use the towel to dry the neck of the flask as well. When the flask is filled to the calibration mark with distilled water, record the mass of the pycnometer filled with aggregate.
10. Dry the sample (Step 7) in the 110°C conventional oven to a constant mass. Remove the sample, cool in air for 1.0 ± 0.5 hours, and determine the mass.	10. Dry the test sample (Step 7) using a vacuum drier at room temperature to a constant mass. Remove the sample and determine the mass.

*Note 1: The vacuum procedure described in AASHTO T 209-09 is used to saturate the aggregate sample. "Remove air trapped in the sample 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 a specific time period. Agitate the container and contents using the mechanical device during the vacuum period. At the end of the vacuum period, release the vacuum by increasing the pressure at a rate not to exceed 8 kPa (60 mm Hg) per second." The estimated price for a complete set of equipment for conducting AASHTO T 209-09 is approximately $1,536. The complete set includes a 2-stage vacuum pump ($625), a digital absolute pressure gauge ($450), an in-line dewatering filter ($79), a pycnometer ($357), and a 10-foot vacuum hose ($25).

to ASTM D7227), which would eliminate the cooling period for the sample to return to room temperature. The second alternative was to skip the initial drying of the aggregate and test the sample in its in-situ moisture condition as permitted for concrete mix design. Three replicates were prepared and tested for each factor, resulting in a total of 60 tests conducted for this part of Experiment 3.

The second part of Experiment 3 was to evaluate a vacuum saturation method for replacing 15-hour soaking using oven-dried aggregate samples. In Experiment 1, the Rapid AASHTO T 85 procedure using the CoreLok (vacuum sealing) device was used to remove entrapped air within the dry coarse aggregate that had been placed in a plastic bag. The vacuum sealed bag with the aggregate was then opened under water and immersed for 30 min. The aggregate sample was then tested according to AASHTO T 85. This test method allowed water to penetrate into deeper voids because the pressure inside the surface voids was much lower than the atmosphere pressure. This method yielded a much higher volume of permeable voids, resulting in a lower Gsb and a higher absorption capacity. The vacuum method described in AASHTO T 209 was utilized in a previous study by Mills-Beale et al. (*30*). Three vacuum saturation periods, including 10, 20, and 30 minutes, appeared to yield test results that were comparable to those using the 15-hour soak time for coarse aggregate. The authors recommended that a vacuum period of 10 minutes be used. AASHTO T 209 requires asphalt mixtures be vacuum saturated for 15 ± 2 minutes. Hence, for this evaluation, three time periods of 5, 10, and 15 minutes were used for vacuum saturating the aggregate samples. Three replicates were prepared and tested for each factor, resulting in a total of 90 tests conducted for this part.

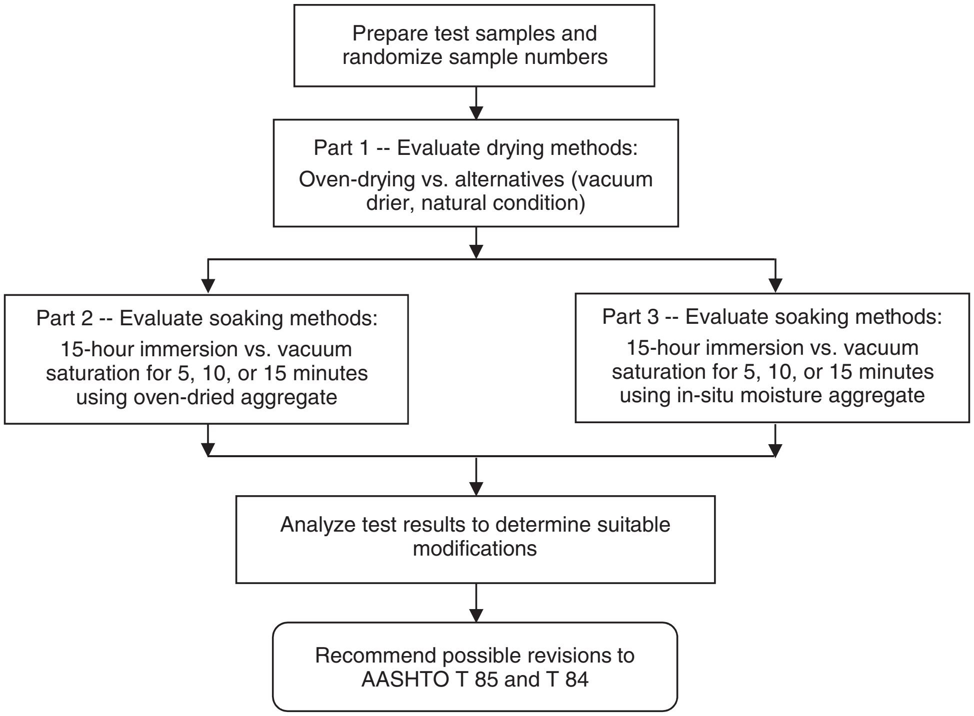


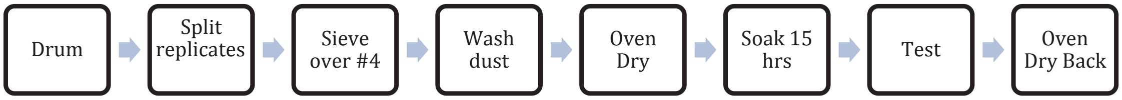
Figure 3-15. Plan for evaluating modifications to AASHTO T 85 and T 84.

The third part of Experiment 3 was to investigate the same vacuum method used in the second part, but the testing was conducted on aggregate samples with in-situ moisture instead of oven-dried samples. For each material, four sets of three replicates were tested, based on four combinations of drying and soaking methods.

A detailed summary of specific gravity and water absorption results of coarse and fine aggregates tested for Experiment 3 is included in Appendix F, which is available on the project web page. The results of the three parts were analyzed to determine if modifications to drying and soaking methods would be suitable, and revisions to the AASHTO T 85 and T 84 would be proposed. Results of this analysis follow.

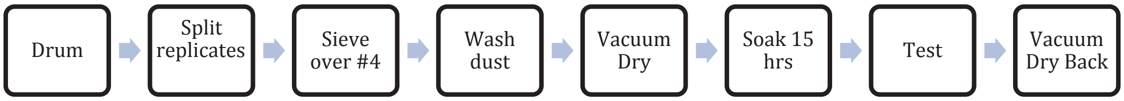
Part 1: Evaluation of Initial Drying Methods for AASHTO T 85 and T 84

Figures 3-16 and 3-17 show how the initial drying methods were incorporated into the laboratory testing procedures for AASHTO T 85 and 84, respectively. Three drying methods



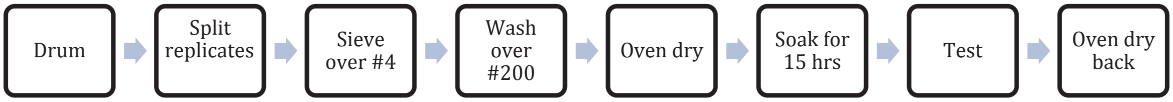
(a) Oven Dry - Tested in Experiment 2

(b) Natural Condition - Tested in Experiment 3



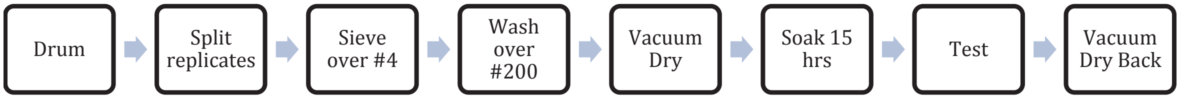
(c) Vacuum Dry - Tested in Experiment 3

Figure 3-16. Laboratory testing plan for evaluating initial drying methods for AASHTO T 85.



(a) Oven Dry - Tested in Experiment 2

(b) Natural Condition - Tested in Experiment 3



(c) Vacuum Dry - Tested in Experiment 3

Figure 3-17. Laboratory testing plan for evaluating initial drying methods for AASHTO T 84.

were evaluated for each test method: oven drying, natural condition, and vacuum drying.

The effect of initial drying methods on test results was analyzed in two steps. First, ANOVA and Tukey's pairwise comparisons among levels of material and drying method were conducted to determine the effects of three initial drying methods (oven drying, natural moisture condition, and vacuum drying) on the test results (Gsa, Gsb, Gssd, and water absorption). Tables 3-25 and 3-26 summarize the results of the statistical analyses for AASHTO T 85 and 84, respectively. Based on a significance level of 0.05, the effect of the three initial drying methods was determined, as shown in the "significance" column. Grouping of test results that were not significantly different was conducted according to Tukey's test method. In the last three columns (note that Tukey's comparisons should be made across the rows of the table, not down the columns), initial drying methods that did not share a letter yielded statistically different aggregate properties. For all materials except the gravel coarse aggregate and natural sand fine aggregate, the results using the initial drying methods were significantly different for at least one of the measured aggregate properties. An analysis of the variability of test results showed that the initial drying methods did not significantly affect the precision of AASHTO T 85 and T 84.

Second, the research team used graphical comparisons to illustrate the trends of the differences in the measured properties.

Table 3-25. ANOVA results for AASHTO T 85—initial drying methods.

Results	Materials	P-Value	Significant?	Grouping Using Tukey's Method		
				Oven-Drying	Natural	CoreDry
Gsa	BF Slag Coarse	0.000	Yes	B	A	C
	Elmore Grav	0.093	No	A	A	A
	PS Coarse	0.002	Yes	B	A	B
	RC LMS Coarse	0.000	Yes	B	A	B
	RE Concrete	0.000	Yes	B	A	C
Gsb	BF Slag Coarse	0.022	Yes	B	B	A
	Elmore Grav	0.787	No	A	A	A
	PS Coarse	0.111	No	A	A	A
	RC LMS Coarse	0.003	Yes	B	A	A
	RE Concrete	0.000	Yes	B	B	A
Gssd	BF Slag Coarse	0.015	Yes	B	A	B
	Elmore Grav	0.586	No	A	A	A
	PS Coarse	0.332	No	A	A	A
	RC LMS Coarse	0.001	Yes	B	A	A
	RE Concrete	0.127	No	A	A	A
Abs	BF Slag Coarse	0.000	Yes	B	A	C
	Elmore Grav	0.246	No	A	A	A
	PS Coarse	0.000	Yes	B	A	C
	RC LMS Coarse	0.002	Yes	A	A	B
	RE Concrete	0.000	Yes	B	A	C

Note: For each measured property and material, methods that do not share a letter are significantly different. A and C represent the highest and lowest values, respectively.

Table 3-26. ANOVA results for AASHTO T 84—initial drying methods.

Results	Materials	P-Value	Significant?	Grouping Using Tukey's Method		
				Oven-Drying	Natural	CoreDry
Gsa	Ark NS	0.118	No	A	A	A
	BF Slag Fine	0.000	Yes	B	A	B
	PS Fine	0.030	Yes	B	B	A
	RC LMS Fine	0.015	Yes	B	B	A
	TX Sand	0.491	No	A	A	A
Gsb	Ark NS	0.059	No	A	A	A
	BF Slag Fine	0.012	Yes	A	B	A
	PS Fine	0.002	Yes	B	A	A
	RC LMS Fine	0.228	No	A	A	A
	TX Sand	0.013	Yes	B	A	A
Gssd	Ark NS	0.058	No	A	A	A
	BF Slag Fine	0.047	Yes	A	A	A
	PS Fine	0.001	Yes	B	A	A
	RC LMS Fine	0.286	No	A	A	A
	TX Sand	0.012	Yes	B	A	A
Abs	Ark NS	0.228	No	A	A	A
	BF Slag Fine	0.001	Yes	B	A	B
	PS Fine	0.007	Yes	A	B	B
	RC LMS Fine	0.132	No	A	A	A
	TX Sand	0.031	Yes	A	B	A

Note: For each measured property and material, methods that do not share a letter are significantly different. A and B represent the highest and lowest values, respectively.

Figure 3-18 compares the coarse aggregate test results measured in accordance with AASHTO T 85 using the three initial drying methods. The effects of the initial drying methods were more profound for absorption and Gsa and less significant for Gsb and Gssd. Compared to the oven drying method, the natural condition yielded the same or higher Gsa and absorption results, whereas the vacuum drying (CoreDry) methods yielded the same or lower absorption and Gsa values, which was likely because the CoreDry method was not able to dry back the aggregate completely. Within each measured property (Gsa, Gsb, Gssd, or water absorption), the effects of the initial drying methods were more significant for BF slag and recycled concrete coarse aggregates that had higher water absorption.

Figure 3-19 compares the fine aggregate test results conducted according to AASHTO T 84 using the three initial drying methods. The effects of the initial drying methods on fine aggregate properties were more significant for absorption and less significant for Gsa. This observation suggests that the effect of the initial drying method is less significant than the method of determining the SSD condition, as the measurement of Gsa does not require the determination of SSD condition. Within each measured property, the effects were more significant for BF slag and RC limestone fine aggregates that had higher water absorption.

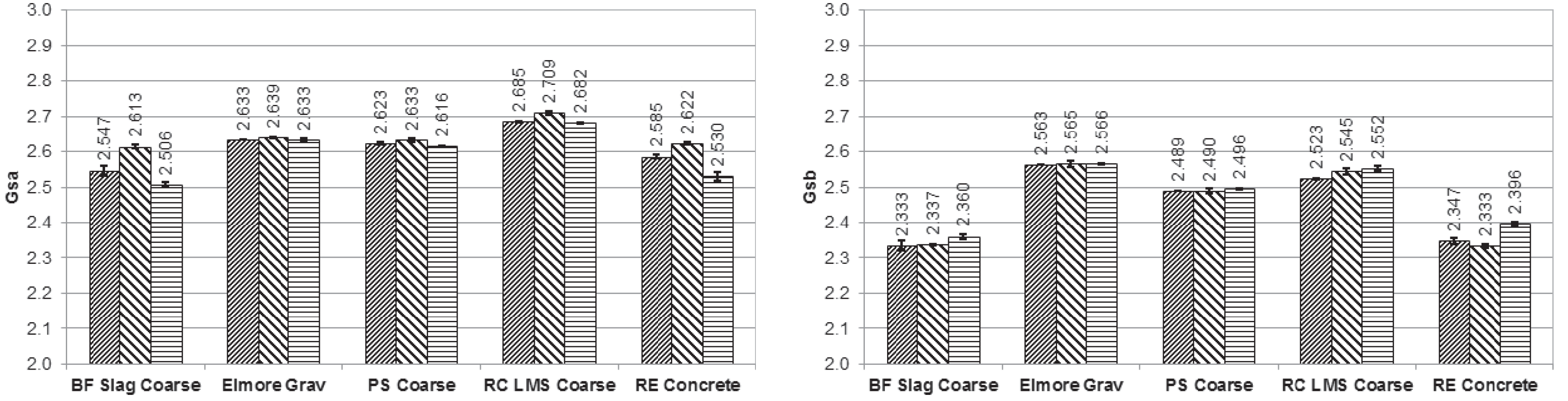
Part 2: Evaluation of Soaking Methods for AASHTO T 85 and T 84 Using Oven-Dried Samples

Figures 3-20 and 3-21 show how the soaking methods were incorporated in the laboratory testing procedures for AASHTO T 85 and 84, respectively. For each test method, the aggregate samples were soaked for 15 hours or vacuum saturated for 5, 10, or 15 minutes before being tested.

The research team conducted the analysis of test results in two steps. First, ANOVA and Tukey's pairwise comparisons among levels of material and soaking method were conducted to determine the effects of four soaking procedures (15-hour hydrostatic soak, 5-minute vacuum soak, 10-minute vacuum soak, and 15-minute vacuum soak) on the test results (Gsa, Gsb, Gssd, and water absorption). Tables 3-27 and 3-28 summarize the results of the statistical analyses for AASHTO T 85 and 84, respectively. Based on a significance level of 0.05, the effect of the four soaking methods was determined, as shown in the "significance" column. Grouping of test results that were not significantly different was conducted according to Tukey's test method. In the last four columns for each row, soaking methods that did not share a letter yielded statistically different results.

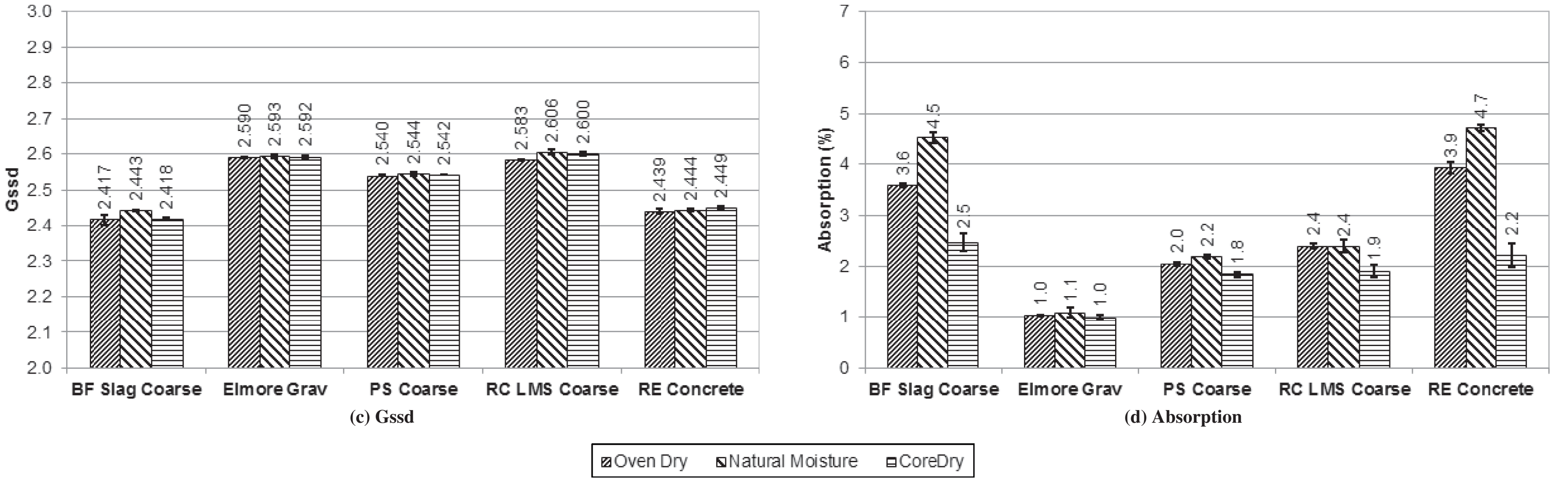
For coarse aggregate, 5- and 10-minute vacuum soaking was not significantly different from the standard 15-hour hydrostatic soak on Gsb and Gssd results. However, each of the coarse aggregate soaking methods yielded statistically different results for Gsa and water absorption.

For fine aggregate, the 5- and 10-minute vacuum soaking methods did not yield statistically different results from the standard 15-hour hydrostatic soak for all of the measured properties, except for the water absorption of PS fine aggregate. An analysis of the variability of test results showed that the soaking methods did not significantly affect the precision of AASHTO T 85 and T 84.



(a) Gsa

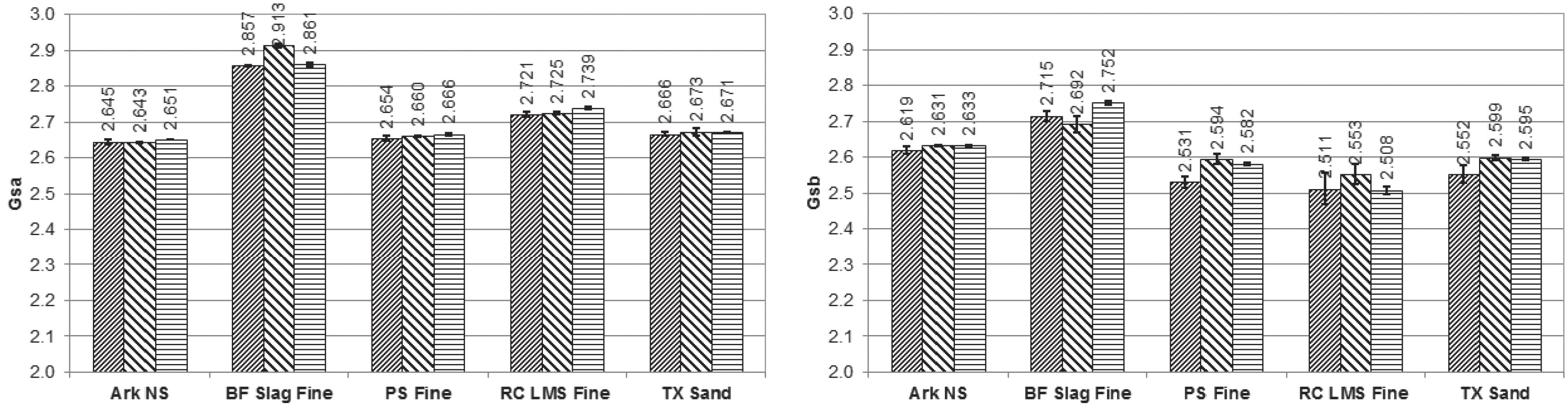
(b) Gsb



(c) Gssd

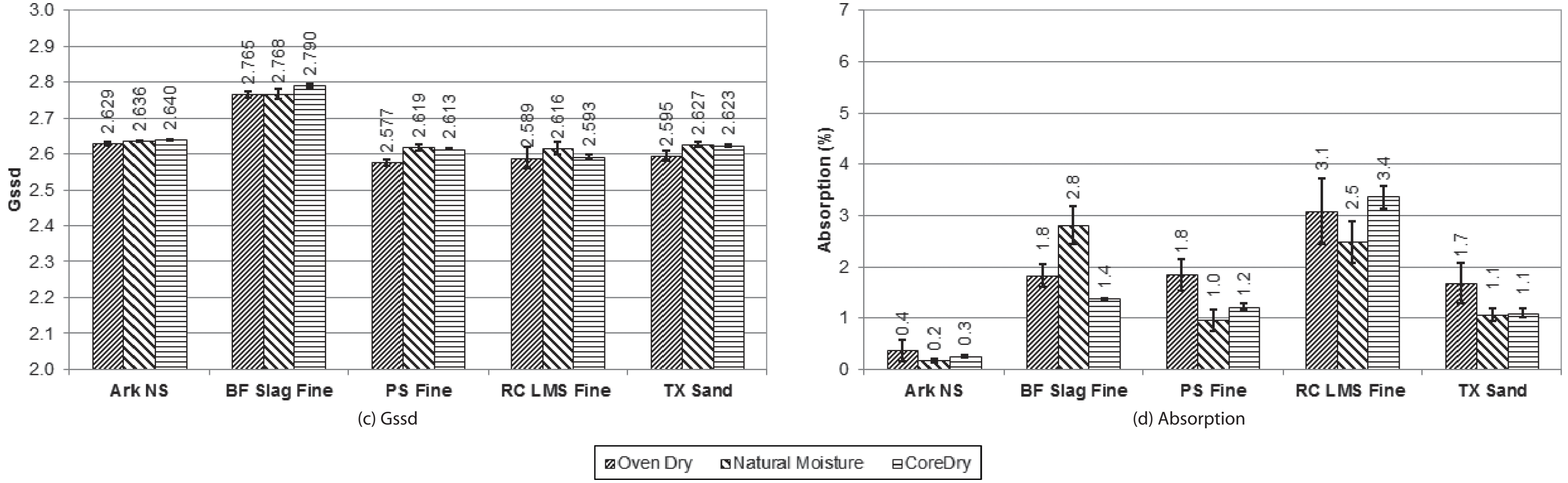
(d) Absorption

Figure 3-18. Effect of initial drying methods on AASHTO T 85 test results.



(a) Gsa

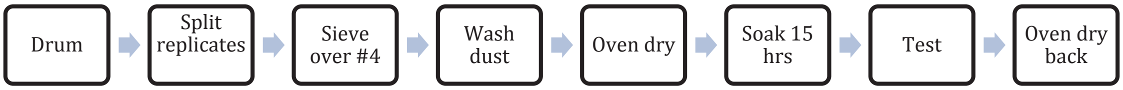
(b) Gsb



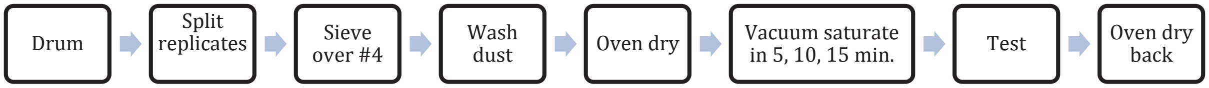
(c) Gssd

(d) Absorption

Figure 3-19. Effect of initial drying methods on AASHTO T 84 test results.

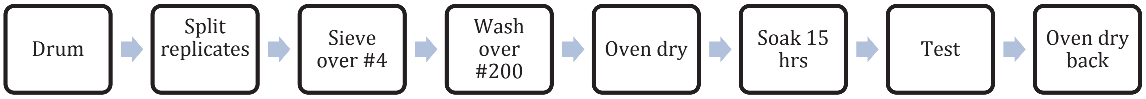


(a) Soak for 15 Hours - Tested in Experiment 2

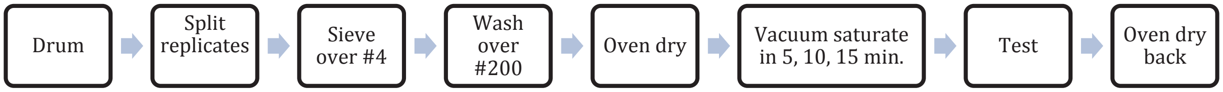


(b) Vacuum Saturate for 5, 10, 15 minutes

Figure 3-20. Laboratory testing plan for evaluating soaking methods for AASHTO T 85.



(a) Soak for 15 Hours - Tested in Experiment 2



(b) Vacuum Saturate for 5, 10, 15 minutes

Figure 3-21. Laboratory testing plan for evaluating soaking methods for AASHTO T 84.

Table 3-27. ANOVA results for AASHTO T 85—oven dried.

Results	Materials	P-Value	Significant?	Grouping Using Tukey's Method			
				15-hr Soak	5-min Vacuum	10-min Vacuum	15-min Vacuum
Gsa	BF Slag Coarse	0.000	Yes	A	A	A	B
	Elmore Grav	0.001	Yes	A	B	B	B
	PS Coarse	0.148	No	A	A	A	A
	RC LMS Coarse	0.002	Yes	A	B	B	B
	RE Concrete	0.000	Yes	A	B	B	B
Gsb	BF Slag Coarse	0.605	No	A	A	A	A
	Elmore Grav	0.517	No	A	A	A	A
	PS Coarse	0.166	No	A	A	A	A
	RC LMS Coarse	0.000	Yes	A	A	A	B
	RE Concrete	0.088	No	A	A	A	A
Gssd	BF Slag Coarse	0.000	Yes	A	A	A	B
	Elmore Grav	0.513	No	A	A	A	A
	PS Coarse	0.663	No	A	A	A	A
	RC LMS Coarse	0.004	Yes	A	A	A	B
	RE Concrete	0.072	No	A	A	A	A
Abs	BF Slag Coarse	0.000	Yes	A	A	A	B
	Elmore Grav	0.209	No	A	A	A	A
	PS Coarse	0.000	Yes	A	A	B	B
	RC LMS Coarse	0.000	Yes	A	B	B	B
	RE Concrete	0.006	Yes	A	B	B	B

Note: For each measured property and material, methods that do not share a letter are significantly different. A and B represent the highest and lowest values, respectively.

Table 3-28. ANOVA results for AASHTO T 84—oven dried.

Results	Materials	P-Value	Significant?	Grouping Using Tukey Method			
				15-hr Soak	5-min Vacuum	10-min Vacuum	15-min Vacuum
Gsa	Ark NS	0.396	No	A	A	A	A
	BF Slag Fine	0.039	Yes	A	A	A	B
	PS Fine	0.033	Yes	A	A	A	B
	RC LMS Fine	0.200	No	A	A	A	A
	TX Sand	0.498	No	A	A	A	A
Gsb	Ark NS	0.269	No	A	A	A	A
	BF Slag Fine	0.745	No	A	A	A	A
	PS Fine	0.002	Yes	A	A	A	B
	RC LMS Fine	0.480	No	A	A	A	A
	TX Sand	0.056	No	A	A	A	A
Gssd	Ark NS	0.361	No	A	A	A	A
	BF Slag Fine	0.792	No	A	A	A	A
	PS Fine	0.001	Yes	A	A	A	B
	RC LMS Fine	0.517	No	A	A	A	A
	TX Sand	0.053	No	A	A	A	A
Abs	Ark NS	0.227	No	A	A	A	A
	BF Slag Fine	0.483	No	A	A	A	A
	PS Fine	0.003	Yes	A	B	B	B
	RC LMS Fine	0.386	No	A	A	A	A
	TX Sand	0.054	No	A	A	A	A

Note: For each measured property and material, methods that do not share a letter are significantly different. A and B represent the highest and lowest values, respectively.

Second, graphical comparisons were conducted to illustrate the statistical analysis results. Figures 3-22 and 3-23 show graphical comparisons of the coarse and fine aggregate properties, respectively, determined using the four soaking methods. The effect of the soaking methods on the measured properties was more profound for Gsa and water absorption results. For each measured property, the effect was more significant for more absorptive and vesicular aggregates, especially the BF slag material. However, the effect of the soaking methods on the test results for fine aggregates was less significant compared to that for the coarse aggregates, likely because the fine aggregates have less connected voids than the coarse aggregates. The effect was more significant for water absorption but less profound for the other measured properties.

Part 3: Evaluation of Soaking Methods for AASHTO T 85 and T 84 Using In-Situ Moisture Samples

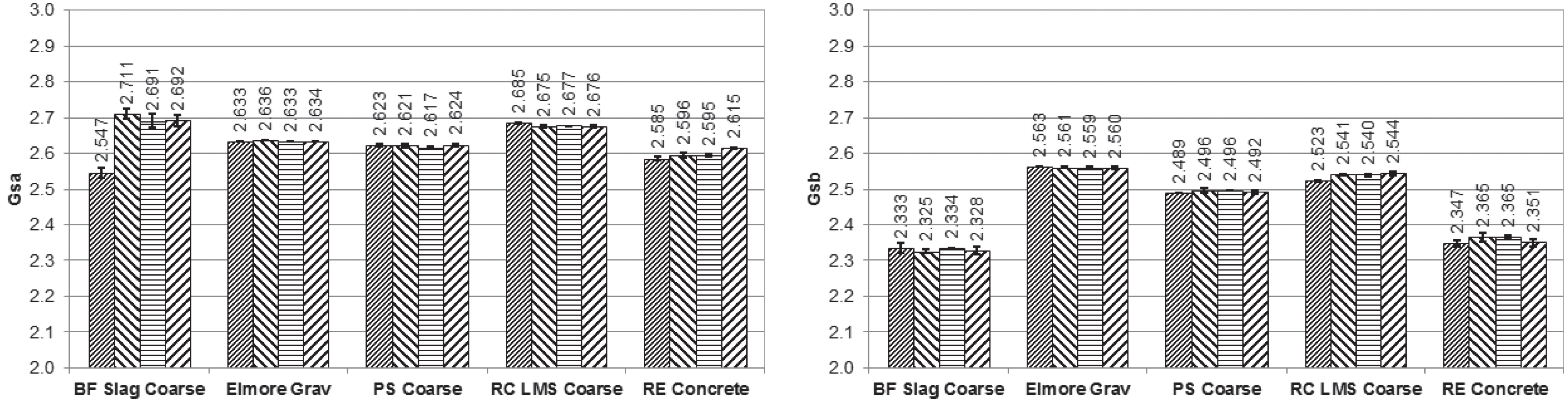
Figure 3-24 shows the procedures for testing coarse aggregates. As shown in Figure 3-24(a), aggregate samples were oven-dried and then soaked for 15 hours before testing. In Figure 3-24(b), samples were tested in their in-situ moisture conditions and vacuum-soaked up to 15 minutes before testing.

Testing of fine aggregates was different depending on the P200 content and composition. Based on results of Experiment 4 presented later in this report, the P200 should be tested separately according to ASTM C110, Section 21 or ASTM D5550 if the sand equivalent (AASHTO T 176) value of the fine aggregate is less than 75. Thus, two test procedures for fine aggregates are shown in Figures 3-25 and 3-26, as follows:

- The Preston sandstone (sand equivalent is 26.1 percent) and RC Limestone (sand equivalent is 39.2 percent) materials were tested according to the procedure shown in Figure 3-25 in which the P200 materials should be tested separately.
- The Arkansas natural sand (sand equivalent is 100 percent), Blast Furnace Slag (sand equivalent is 86.5 percent), and Texas limestone fine aggregate (92.8 percent) were tested without separating the P200 materials.
- Instead of drying and then soaking samples for 15 hours, as shown in Figure 3-25(a) and Figure 3-26(a), the samples can be tested in their natural moisture conditions and vacuum soaked for much less time, as shown in Figure 3-25(b) and Figure 3-26(b).

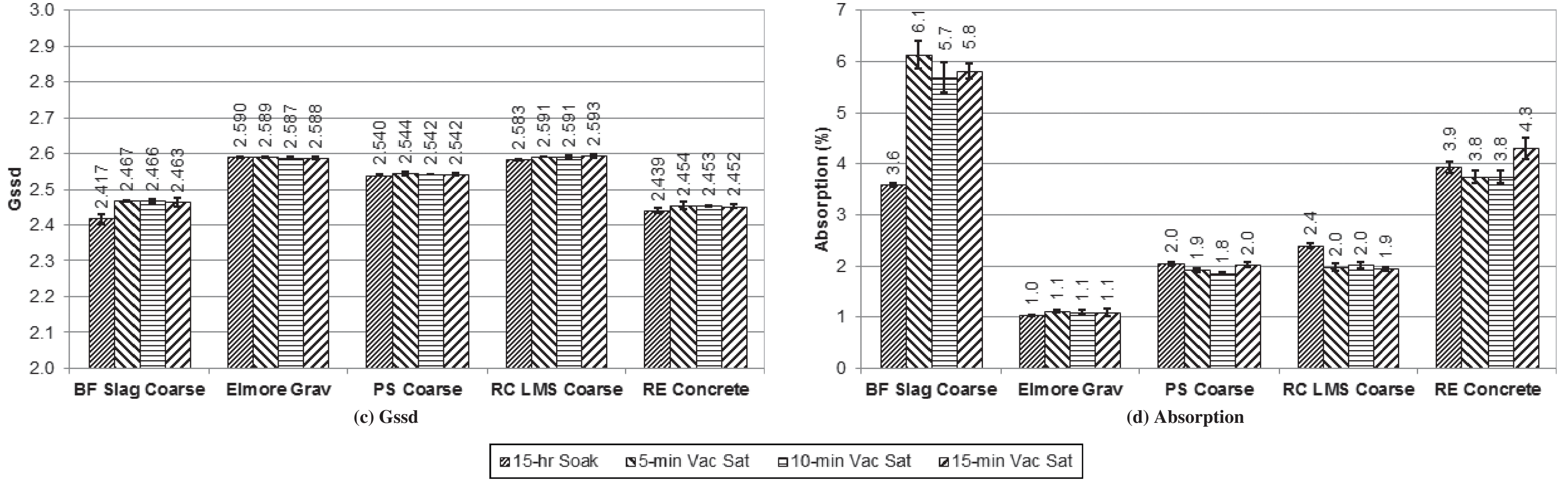
For Part 3, four combinations of drying and soaking methods were tested. In the first combination (control), the aggregate samples were oven-dried and soaked for 15 hours as specified in AASHTO T 84 and T 85. The other three combinations were a combination of one natural moisture condition and three vacuum soaking periods. For each material, 14 replicates were prepared. Four sets of three replicates were randomly selected for testing based on the four combinations of drying and soaking methods. The random selection was carried out to make sure there was no bias toward any sets of replicates or the order in which the samples were prepared. The remaining two samples were kept in reserve.

The in-situ water content and water absorption capacity of the aggregates are presented in Table 3-29. For production of



(a) Gsa

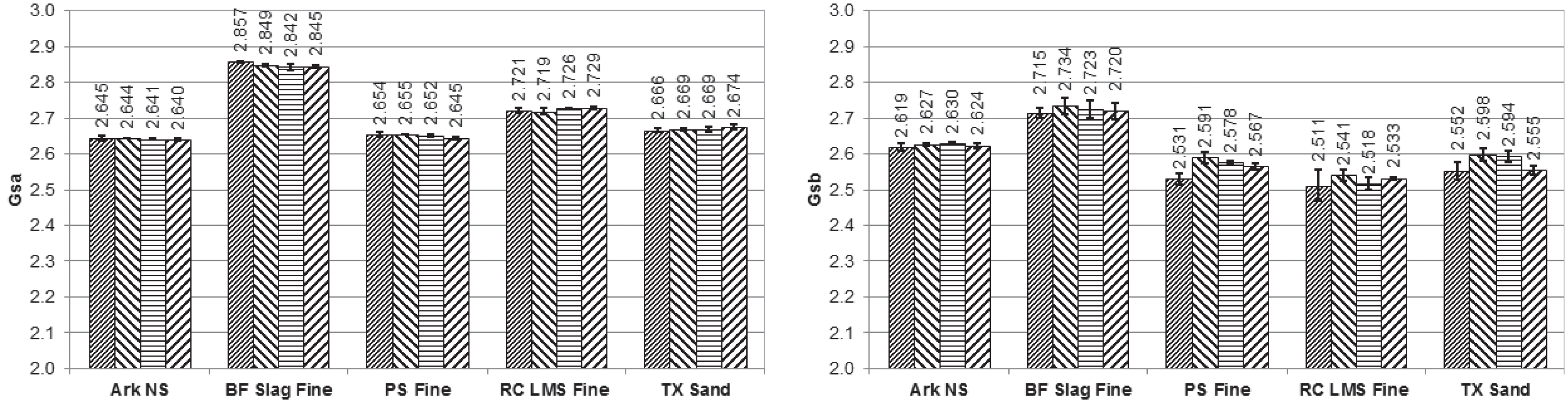
(b) Gsb



(c) Gssd

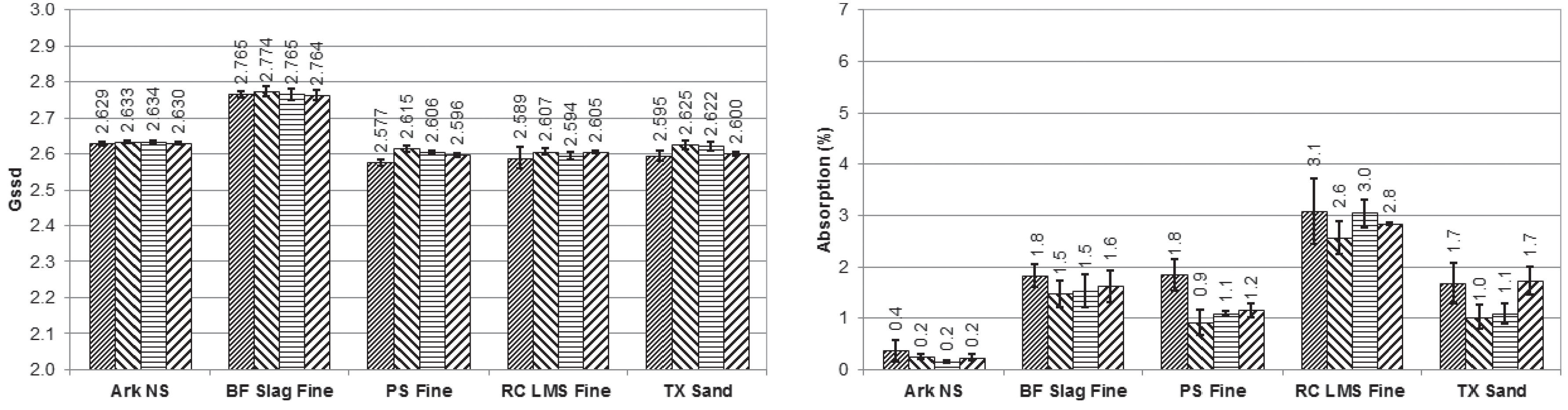
(d) Absorption

Figure 3-22. Effect of soaking methods on AASHTO T 85 test results.



(a) Gsa

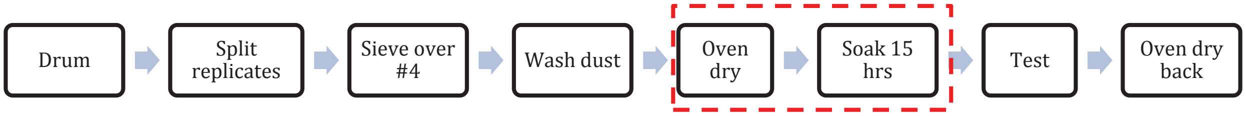
(b) Gsb



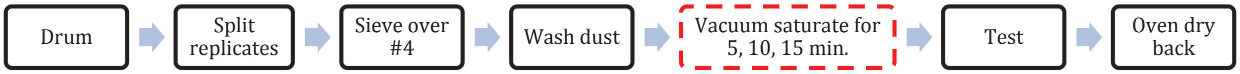
(c) Gssd

(d) Absorption

Figure 3-23. Effect of soaking methods on AASHTO T 84 test results.

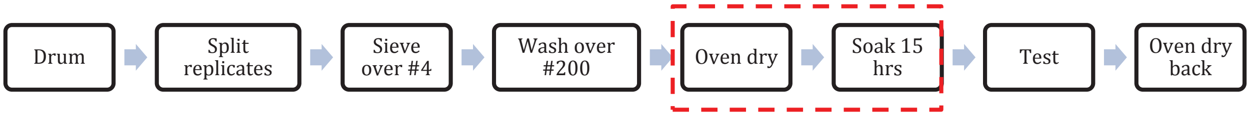


(a) Control--Samples are oven-dried and soaked for 15 hours



(b) Alternatives--Samples are in natural moisture condition and vacuum-soaked for 5, 10, 15 minutes

Figure 3-24. Laboratory testing plan for evaluating soaking methods on in-situ moisture samples for AASHTO T 85 (coarse aggregate).

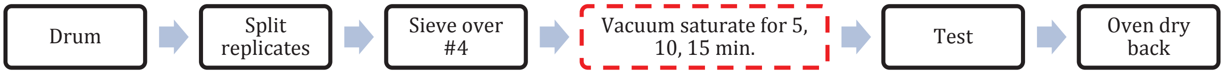


(a) Control--Oven-dried and soaked for 15 hours

(b) Alternatives--Natural moisture condition and vacuum-soaked for 5, 10, 15 minutes

Figure 3-25. Laboratory testing plan for evaluating soaking methods for AASHTO T 84 (fine aggregate) using in-situ moisture, Preston sandstone, and RC limestone (low sand equivalent and P200 removed).

(a) Control--oven-dried and soaked for 15 hours



(b) Alternatives--Natural moisture condition and vacuum-soaked for 5, 10, 15 minutes

Figure 3-26. Laboratory testing plan for evaluating soaking methods for AASHTO T 84 (fine aggregate) using in-situ moisture, natural sand, blast furnace slag, and Texas limestone (high sand equivalent and P200 not removed).

Table 3-29. Water contents of aggregates in barrels.

Material	In-Situ Water Content (%)	Measured Water Absorption (%)*
Coarse Aggregates		
BF Slag Coarse	2.7	3.0
Elmore Gravel	0.6	1.1
PS Coarse	0.9	2.1
RC Limestone Coarse	2.2	2.2
RE Concrete	2.2	4.4
Fine Aggregates		
AR Sand	6.1	0.2
BF Slag Fine	2.0	3.4
PS Fine	7.3	1.0
RC Limestone Fine	0.7	2.3
Texas Limestone Fine	4.6	1.3

*Measured in accordance with AASHTO T 85 and T 84 (oven-dried and soaked for 15 hours).

portland cement concrete, aggregate stockpiles are sprinkled to maintain the moisture content that is often higher than the aggregate absorption capacity, so testing of aggregates in their natural moisture conditions is allowed according to AASHTO T 84 and T 85. However, for production of asphalt concrete, the moisture content of aggregate stockpiles varies, but is often lower than the aggregate absorption capacity, so AASHTO T 84 and T 85 require aggregates be oven-dried before testing.

The effect of using the vacuum method for soaking coarse aggregate samples in their in-situ moisture conditions instead of soaking oven-dried aggregate samples for 15 hours in the AASHTO T 85 procedure was analyzed in two steps. First, graphical comparisons were conducted to determine if there were any trends in the differences in the measured properties and their variances. Second, statistical analyses were performed to check if the differences in the measured results and their variances were statistically significant.

Figures 3-27 and 3-28 compare the average values and standard deviations of coarse aggregate test results based on four combinations of drying and soaking methods. The single-operator standard deviation of AASHTO T 85 also is plotted in these figures for comparison. The effect of the alternative initial drying and soaking methods on the average values was more profound for Gsa and absorption and less so for Gsb and Gssd. Within each measured property (Gsa, Gsb, Gssd, or water absorption), the effect of the alternative methods was most significant for the vesicular BF slag coarse aggregate. The effect of the alternative methods on the variability (standard deviation) was not clear.

Statistical analyses also were conducted to determine if the differences seen in Figure 3-27 were significant. Table 3-30 summarizes the results of ANOVA and Tukey's tests for the measured properties. Based on a significance level of 0.05, the effect of the alternative methods was determined, as shown in the "significance" column. Grouping of test results that were not significantly different was conducted according to Tukey's test method. In the last four columns, groups of initial drying and soaking methods in each row that did not share a letter yielded statistically different aggregate properties, with letter "A" representing the highest value.

The alternative initial drying and soaking methods yielded slightly higher results (letter "A" in Table 3-30). The effect of the alternative initial drying and soaking methods on Gsb was not statistically significant for all of the materials. For the other properties (Gsa, Gssd, and water absorption), the effect of the alternative soaking methods was significant for the BF slag and RC limestone coarse aggregates. For these two materials, the 10-minute vacuum soaking method appeared to yield results that were closer to those of the control (15-hour soaking) method.

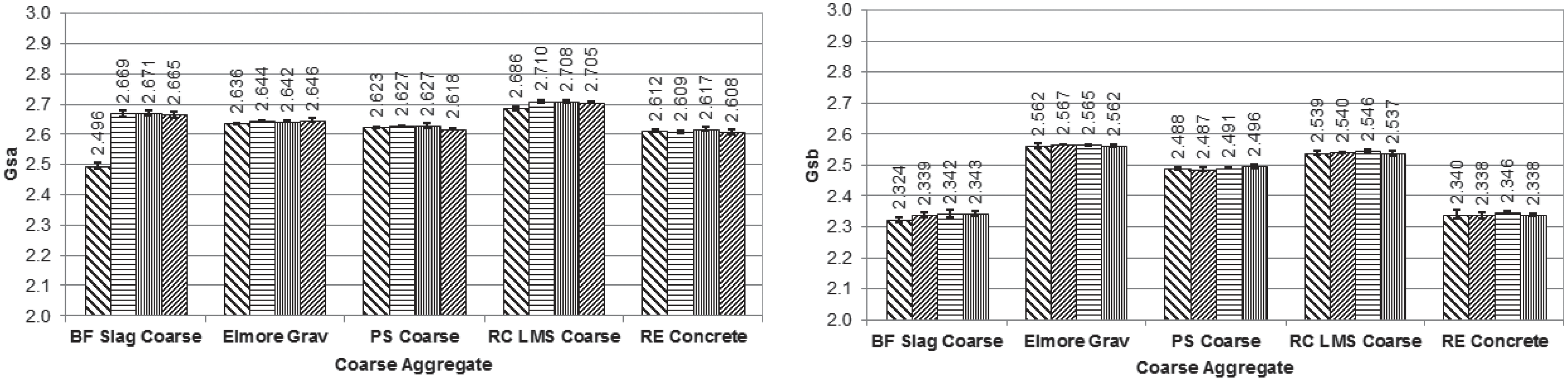
In addition, Bartlett's and Levene's statistical tests also were conducted to determine if the variability of test results shown in Figure 3-28 was statistically different. Table 3-31 summarizes the results of the analysis. Although the two statistical analyses are used to test equal variances, the Levene test is less sensitive to departures of test results from normality. Based on a significance level of 0.05, the difference in the variability of test results was determined, as shown in the "significance" column. Based on Bartlett's analysis, the variability of the test results was statistically different for three groups. Since the Gsb results for Elmore gravel and the Gssd results for Preston sandstone were very consistent, the significant difference in the variance was not a concern. The variability of the absorption results for the control method was higher than that for the alternative methods. Based on the Levene test, the difference in the test variability was not statistically significant.

The effect of using the vacuum method for soaking fine aggregate samples in their in-situ moisture conditions in the AASHTO T 84 procedure also was analyzed in two steps—graphical comparison and statistical analysis.

Figures 3-29 and 3-30 compare the averages and standard deviations of fine aggregate test results measured according to AASHTO T 84 using four combinations of drying and soaking methods as well as the single-operator standard deviation of AASHTO T 84. The Preston sandstone and RC limestone fine aggregates were tested without the P200 materials, and the other three fine aggregate materials—natural sand, blast furnace slag, and Texas limestone—were tested with the P200 in accordance with AASHTO T 84.

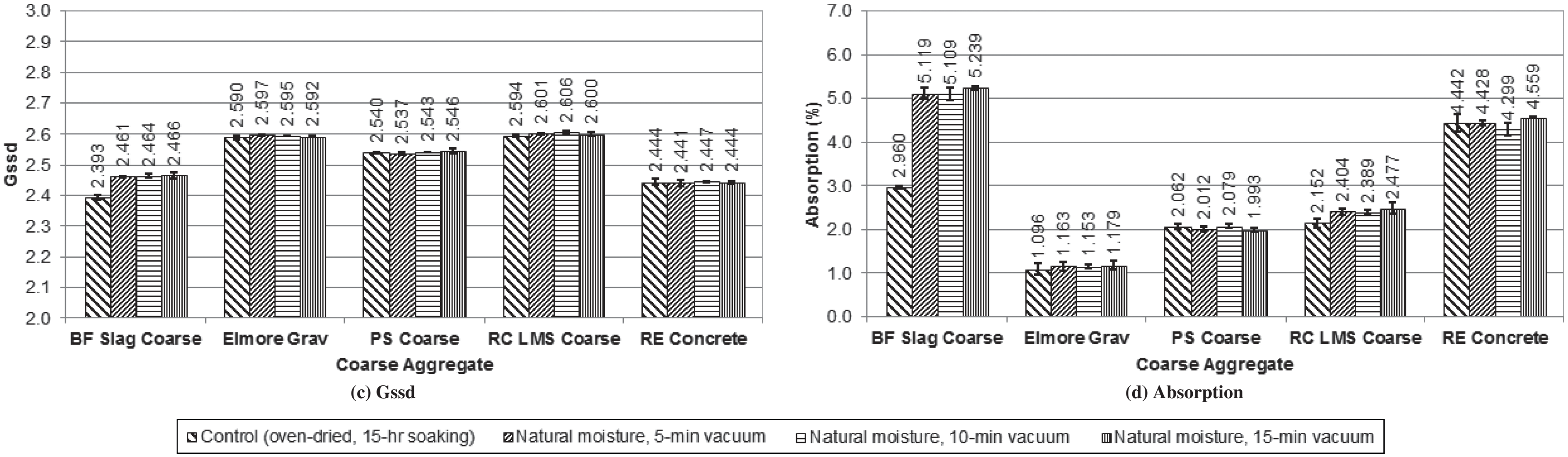
The effect of the alternative initial drying and soaking methods on the mean values was more profound for absorption, Gsb, and Gssd (Gsb and Gssd can be determined based on Gsa and absorption), and less so for Gsa. Within each measured property (Gsa, Gsb, Gssd, or water absorption), the effect of the alternative methods was more significant for the vesicular BF slag and highly absorptive RC limestone. The effect of the alternative methods on the variability (standard deviation) was inconsistent.

Statistical analyses, including ANOVA, Tukey's test, Bartlett's test, and Levene's test, were conducted to determine if the differences seen in Figures 3-29 and 3-30 were significant. Table 3-32 summarizes the results of ANOVA and Tukey's tests for the measured properties. Based on a significance level of 0.05, the effect of the alternative methods was determined, as shown in the "significance" column. Grouping of test results that were not significantly different was conducted according to Tukey's test and is shown in the last four columns. The effect of the alternative initial drying and soaking methods was most significant (very low p-value) on the measured properties of BF slag and RC limestone materials, which are highly absorptive. Where the difference was significant, the 10-minute vacuum soaking method appeared to yield results that were closer to those of the control (15-hour soaking) method.



(a) Gsa

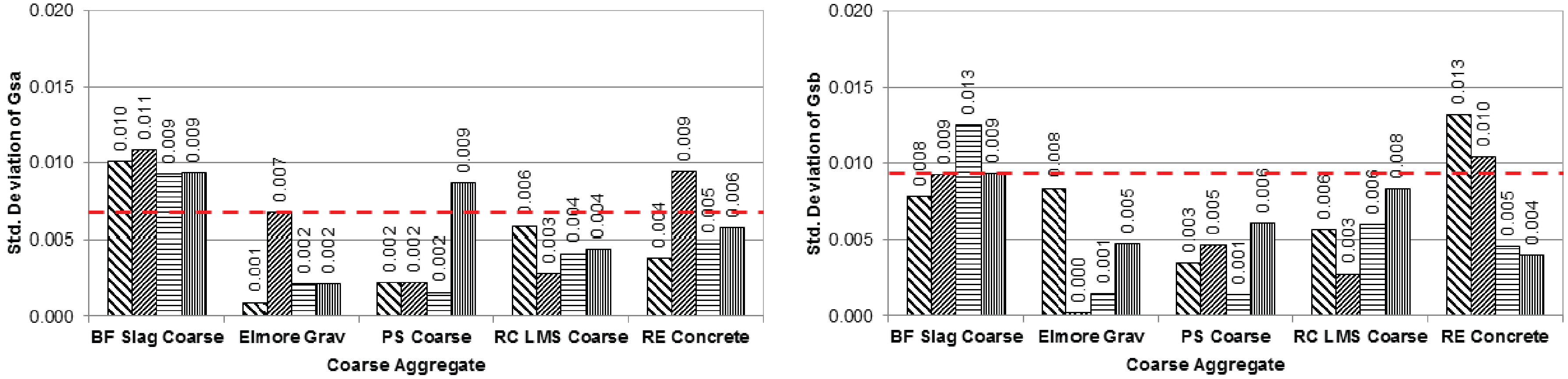
(b) Gsb



(c) Gssd

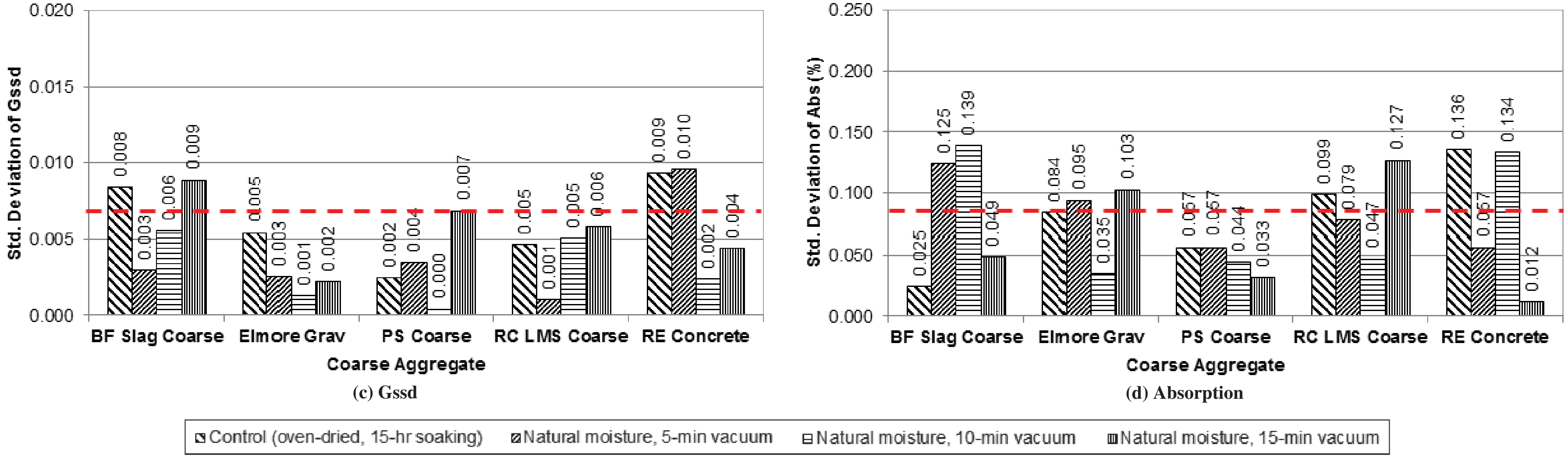
(d) Absorption

Figure 3-27. Effect of soaking methods and use of in-situ moisture samples on AASHTO T 85 test results.



(a) Gsa

(b) Gsb



(c) Gssd

(d) Absorption

Note: Dashed horizontal line = T 85 Single-Operator Std. Deviation

Figure 3-28. Effect of soaking methods and use of in-situ moisture samples on variability of AASHTO T 85 test results.

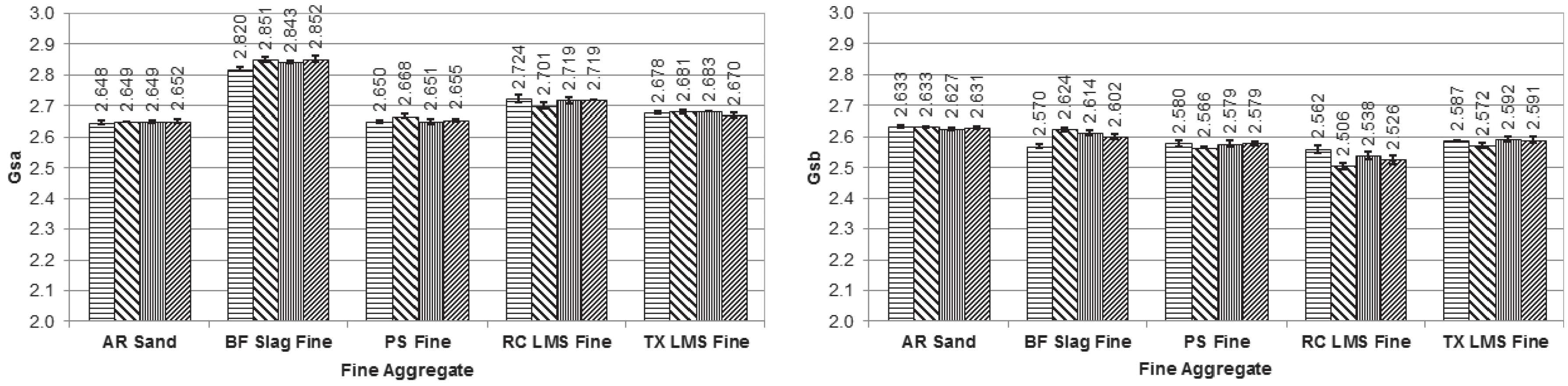
Table 3-30. Results of ANOVA and Tukey's analyses for coarse aggregates.

Results	Materials	ANOVA		Grouping Using Tukey's Method*			
		P-Value	Significant?	Oven-Drying, 15-hr Soak	Natural Moist., 5-min Vacuum	Natural Moist., 10-min Vacuum	Natural Moist., 15-min Vacuum
Gsa	BF Slag Coarse	0.000	Yes	B	A	A	A
	Elmore Grav	0.041	Yes	B	A	A, B	A, B
	PS Coarse	0.113	No	A	A	A	A
	RC LMS Coarse	0.001	Yes	B	A	A	A
	RE Concrete	0.388	No	A	A	A	A
Gsb	BF Slag Coarse	0.140	No	A	A	A	A
	Elmore Grav	0.475	No	A	A	A	A
	PS Coarse	0.096	No	A	A	A	A
	RC LMS Coarse	0.437	No	A	A	A	A
	RE Concrete	0.680	No	A	A	A	A
Gssd	BF Slag Coarse	0.000	Yes	B	A	A	A
	Elmore Grav	0.101	No	A	A	A	A
	PS Coarse	0.095	No	A	A	A	A
	RC LMS Coarse**	0.060	Yes/No	B	A, B	A	A, B
	RE Concrete	0.858	No	A	A	A	A
Abs	BF Slag Coarse	0.000	Yes	B	A	A	A
	Elmore Grav	0.726	No	A	A	A	A
	PS Coarse	0.179	No	A	A	A	A
	RC LMS Coarse	0.013	Yes	B	A	A, B	A
	RE Concrete	0.147	No	A	A	A	A

*For each measured property and material, methods that do not share a letter are significantly different. A and B represent the highest and lowest values, respectively.
**Differences in results of the four methods were not significant in ANOVA but significant in Tukey's method.

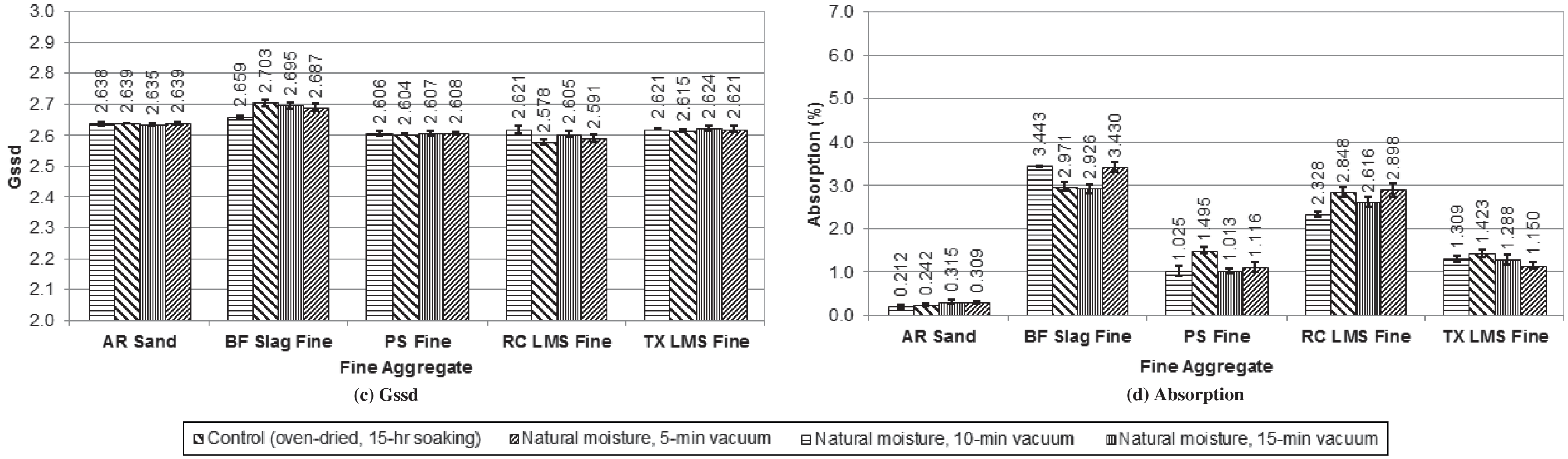
Table 3-31. Results of Bartlett's and Levene's analyses for equal variances.

Results	Materials	Bartlett's Test		Levene's Test	
		P-Value	Significant?	P-Value	Significant?
Gsa	BF Slag Coarse	0.996	No	0.999	No
	Elmore Grav	0.099	No	0.307	No
	PS Coarse	0.091	No	0.550	No
	RC LMS Coarse	0.835	No	0.920	No
	RE Concrete	0.673	No	0.826	No
Gsb	BF Slag Coarse	0.941	No	0.941	No
	Elmore Grav	0.007	Yes	0.185	No
	PS Coarse	0.404	No	0.648	No
	RC LMS Coarse	0.637	No	0.812	No
	RE Concrete	0.375	No	0.668	No
Gssd	BF Slag Coarse	0.573	No	0.774	No
	Elmore Grav	0.330	No	0.414	No
	PS Coarse	0.049	Yes	0.490	No
	RC LMS Coarse	0.310	No	0.836	No
	RE Concrete	0.341	No	0.678	No
Abs	BF Slag Coarse	0.188	No	0.531	No
	Elmore Grav	0.557	No	0.687	No
	PS Coarse	0.893	No	0.946	No
	RC LMS Coarse	0.680	No	0.737	No
	RE Concrete	0.043	Yes	0.473	No



(a) Gsa

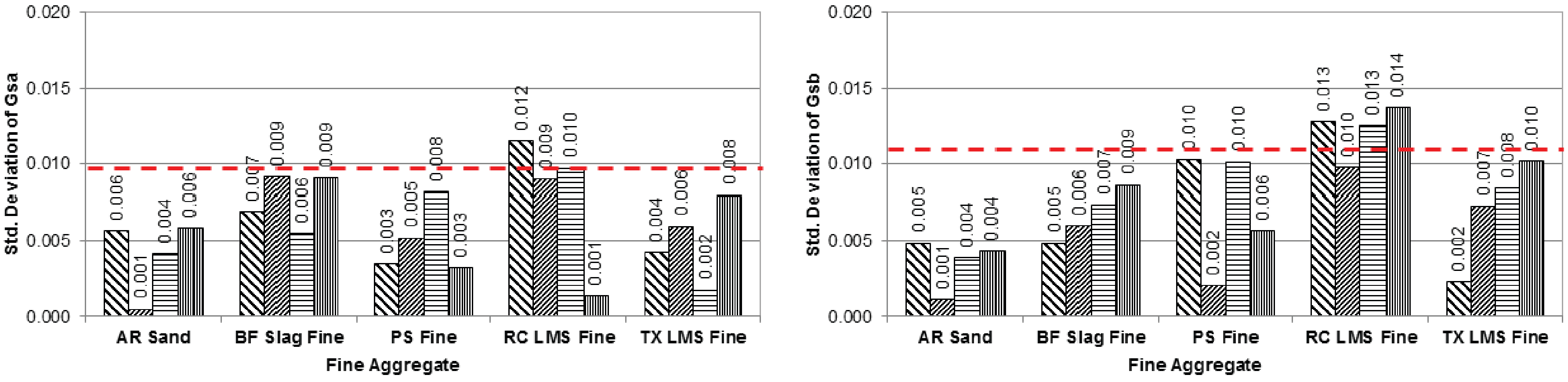
(b) Gsb



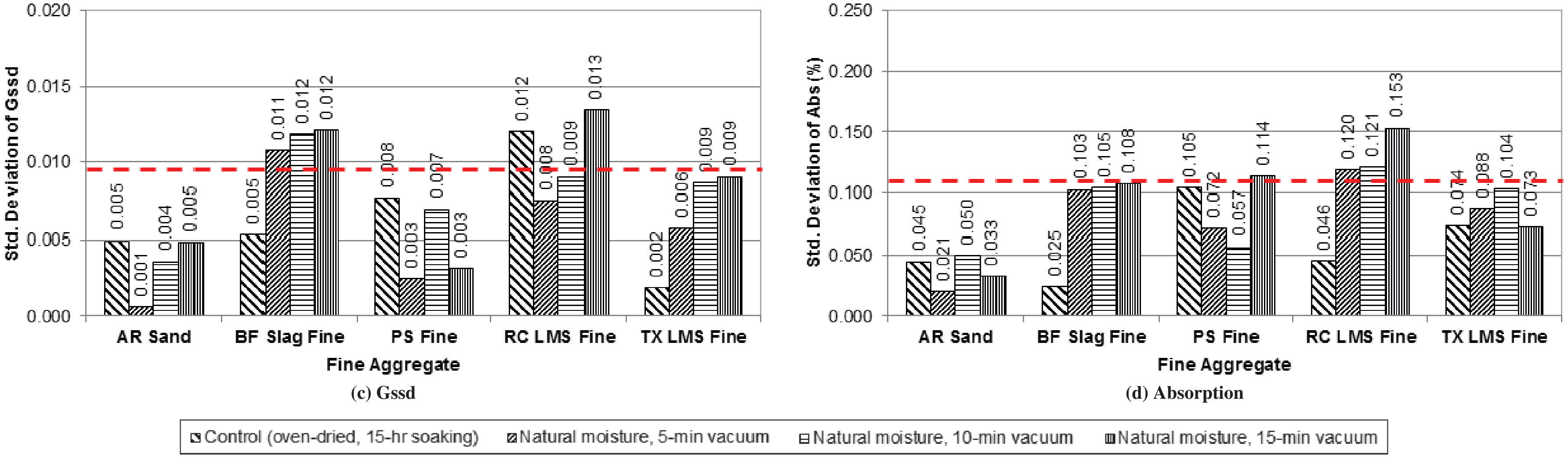
(c) Gssd

(d) Absorption

Figure 3-29. Effect of soaking methods and use of in-situ moisture samples on AASHTO T 84 test results.



(a) Gsa (b) Gsb



(c) Gssd (d) Absorption

Note: Dashed horizontal line = T 84 Single-Operator Std. Deviation

Figure 3-30. Effect of soaking methods and use of in-situ moisture samples on variability of AASHTO T 84 test results.

Table 3-32. Results of ANOVA and Tukey's analyses for fine aggregates.

Results	Materials	ANOVA		Grouping Using Tukey's Method*			
		P-Value	Significant?	Oven-Drying, 15-hr Soak	Natural Moist., 5-min Vacuum	Natural Moist., 10-min Vacuum	Natural Moist., 15-min Vacuum
Gsa	AR Sand	0.680	No	A	A	A	A
	BF Slag Fine	0.003	Yes	B	A	A	A
	PS Fine	0.013	Yes	B	A	B	A, B
	RC LMS Fine	0.056	No	A	A	A	A
	TX LMS Fine	0.094	No	A	A	A	A
Gsb	AR Sand	0.284	No	A	A	A	A
	BF Slag Fine	0.000	Yes	C	A	A, B	B
	PS Fine	0.162	No	A	A	A	A
	RC LMS Fine	0.004	Yes	A	B	A, B	B
	TX LMS Fine	0.038	Yes	A, B	B	A	A, B
Gssd	AR Sand	0.623	No	A	A	A	A
	BF Slag Fine	0.004	Yes	B	A	A	A
	PS Fine	0.826	No	A	A	A	A
	RC LMS Fine	0.007	Yes	A	B	A, B	B
	TX LMS Fine	0.531	No	A	A	A	A
Abs	AR Sand	0.030	Yes	B	A, B	A	A, B
	BF Slag Fine	0.000	Yes	A	B	B	A
	PS Fine	0.001	Yes	B	A	B	B
	RC LMS Fine	0.001	Yes	B	A	A, B	A
	TX LMS Fine	0.028	Yes	A, B	A	A, B	B

*For each measured property and material, methods that do not share a letter are significantly different. A and C represent the highest and lowest values, respectively.

As shown in Table 3-32, the control and 10-minute vacuum methods often had the same letter, which indicated that the difference between these two methods was not significant at the 95 percent confidence interval.

Table 3-33 shows the results of Bartlett's and Levene's statistical tests for equal variances. Based on both the Bartlett and Levene tests, the difference in the test variability was not statistically significant.

Summary

The key findings of Experiment 3 can be summarized as follows:

- The use of an alternative initial drying method can save up to 4 hours, and the use of a vacuum soaking method can save approximately 15 hours. However, they must yield test results comparable to those of the current

Table 3-33. Results of Bartlett's and Levene's analyses for equal variances.

Results	Materials	Bartlett's Test		Levene's Test	
		P-Value	Significant?	P-Value	Significant?
Gsa	AR Sand	0.109	No	0.758	No
	BF Slag Fine	0.907	No	0.973	No
	PS Fine	0.596	No	0.632	No
	RC LMS Fine	0.188	No	0.607	No
	TX LMS Fine	0.382	No	0.577	No
Gsb	AR Sand	0.432	No	0.560	No
	BF Slag Fine	0.899	No	0.935	No
	PS Fine	0.289	No	0.815	No
	RC LMS Fine	0.978	No	0.994	No
	TX LMS Fine	0.415	No	0.798	No
Gssd	AR Sand	0.197	No	0.572	No
	BF Slag Fine	0.768	No	0.912	No
	PS Fine	0.440	No	0.794	No
	RC LMS Fine	0.881	No	0.918	No
	TX LMS Fine	0.341	No	0.765	No
Abs	AR Sand	0.730	No	0.881	No
	BF Slag Fine	0.397	No	0.644	No
	PS Fine	0.809	No	0.904	No
	RC LMS Fine	0.570	No	0.747	No
	TX LMS Fine	0.964	No	0.988	No

AASHTO T 85 and 84 methods. Testing the aggregate in the natural moisture condition yielded results closer to those of the oven-dried material, but the differences in the test results were still statistically significant for some materials. The vacuum drying method would be promising if it was able to completely dry highly absorptive materials, such as blast furnace slag and recycled concrete.

- For all coarse aggregates, the 10-minute vacuum soaking procedure yielded Gsb and Gssd results that were not statistically different from those measured using the 15-hour hydrostatic soaking method. For all fine aggregates, the 10-minute vacuum soaking procedure yielded all properties that were not statistically different from those measured using the 15-hour hydrostatic soaking method. Since the asphalt mix design process requires only Gsb, aggregate samples can be vacuum soaked for approximately 10 minutes according to the vacuum saturation method described in AASHTO T 209. This would replace the 15-hour soak required in AASHTO T 85 and 84 and substantially reduce the testing time.

Experiment 4: Evaluation of Effects of P200 on AASHTO T 84 Test Results

Experiment 4 was performed to (1) determine the amount of P200 in a fine aggregate sample at which the P200 fraction should be tested separately; and (2) conduct a sensitivity analysis of the impact of P200 on the AASHTO T 84 test results.

Based on the sand equivalent test results shown in Table G-7 (Appendix G, available on the project web page), both the Preston sandstone and RC limestone fine aggregates had low sand equivalent values, which indicated the P200 fractions contained significant amounts of clay-like material. The blast furnace slag and Texas limestone sand had higher sand equivalent values, which indicate that the P200 fines were not clay-like. The natural sand had no clay-like material. The term "clay-like material" is used in AASHTO T 176 for determining the amount of plastic fines in soils and fine aggregate. This term refers to the flocculated material in this test, and this flocculated material may include other materials that are not clay.

The following materials were proposed in the testing plan to assess the sensitivity and breakpoint of the P200 fraction:

- The fractions retained on the No. 200 sieve from the natural sand and RC limestone fine aggregate. These materials have the lowest and highest water absorption, respectively.
- The fine fraction passing the No. 200 sieve from the Texas limestone. This is relatively clean with a minimum amount of clay-like material.
- Clay used to determine the effect of clay present in P200 on the test results. Based on the panel's recommendation, sodium bentonite clay was used this study. The sodium bentonite contains a significant amount of montmorillonite that can absorb a large amount of water and swell 15 to 18 times its dry size. This sodium bentonite material is commercially available and often used as a pond sealer. The Atterberg limits (LL, PL, and PI) were conducted for this material before it was used for testing in this study (Table 3-34). The replacement rate was based on mass.

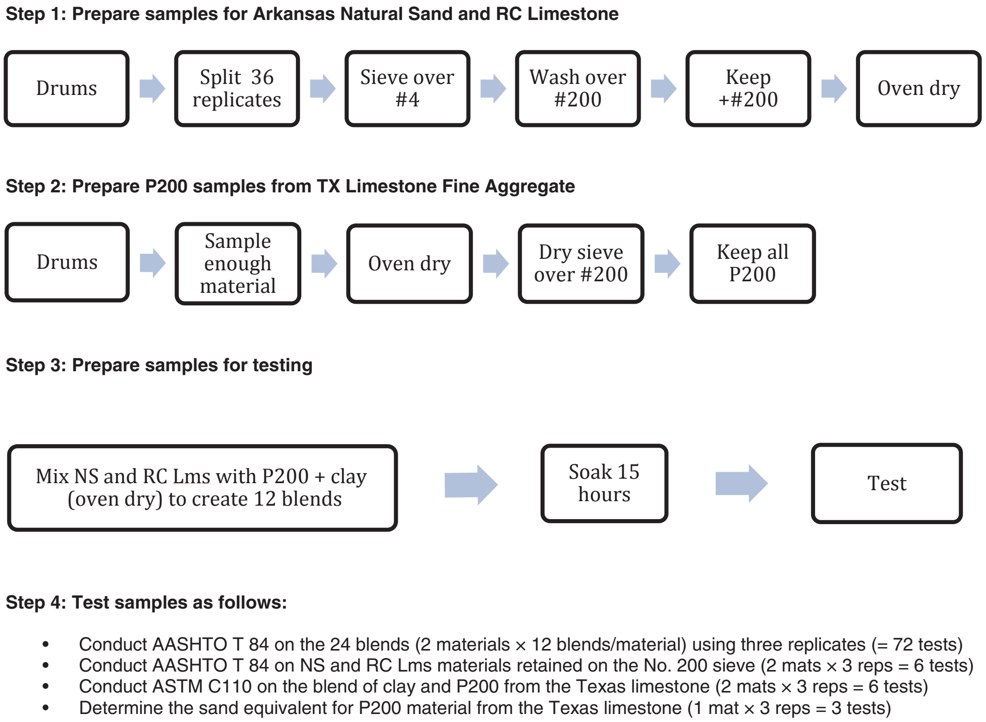
Figure 3-31 shows the laboratory testing plan for Experiment 4. The aggregate materials used in this testing plan are shown in Table 3-35. The testing plan was conducted in the following steps:

- Wash natural sand, RC limestone, and Texas limestone sand over the No. 200 sieve.
- Keep the materials retained on the No. 200 sieve from the natural sand and RC limestone and the P200 material from the Texas limestone sand.
- Discard the P200 materials from the natural sand and RC limestone and the material retained on the No. 200 sieve from the Texas limestone sand.
- Create 12 blends for each of the two materials retained on the No. 200 sieve (Table 3-35).
- Conduct AASHTO T 84 on the 24 blends (2 materials × 12 blends/material) using three replicates.
- Conduct AASHTO T 84 on the two materials retained on the No. 200 sieve (2 materials × 3 replicates = 6 tests).
- Conduct ASTM C110 on the clay and P200 material from the Texas limestone sand (2 materials × 3 replicates = 6 tests).
- Determine the sand equivalent for the P200 material from the Texas limestone sand (1 material × 3 replicates = 3 tests).

A detailed summary of the testing results for Experiment 4 is included in Appendix G, which is available on the project web page. The following analyses were conducted to determine (1) the impact of P200 on AASHTO T 84 test results and (2) the amount of P200 at which the P200 fraction of the fine aggregate should be tested separately.

Table 3-34. Atterberg limits of limestone P200 and clay.

Atterberg Limits	Limestone P200	Clay (Sodium Bentonite, montmorillonite)
Liquid Limit (LL)	18	600
Plastic Limit (PL)	16	98
Plastic Index (PI)	2	502



- Conduct AASHTO T 84 on the 24 blends (2 materials × 12 blends/material) using three replicates (= 72 tests)
- Conduct AASHTO T 84 on NS and RC Lms materials retained on the No. 200 sieve (2 mats × 3 reps = 6 tests)
- Conduct ASTM C110 on the blend of clay and P200 from the Texas limestone (2 mats × 3 reps = 6 tests)
- Determine the sand equivalent for P200 material from the Texas limestone (1 mat × 3 reps = 3 tests)

Figure 3-31. Laboratory testing plan for evaluating effect of P200 on AASHTO T 84 test results.

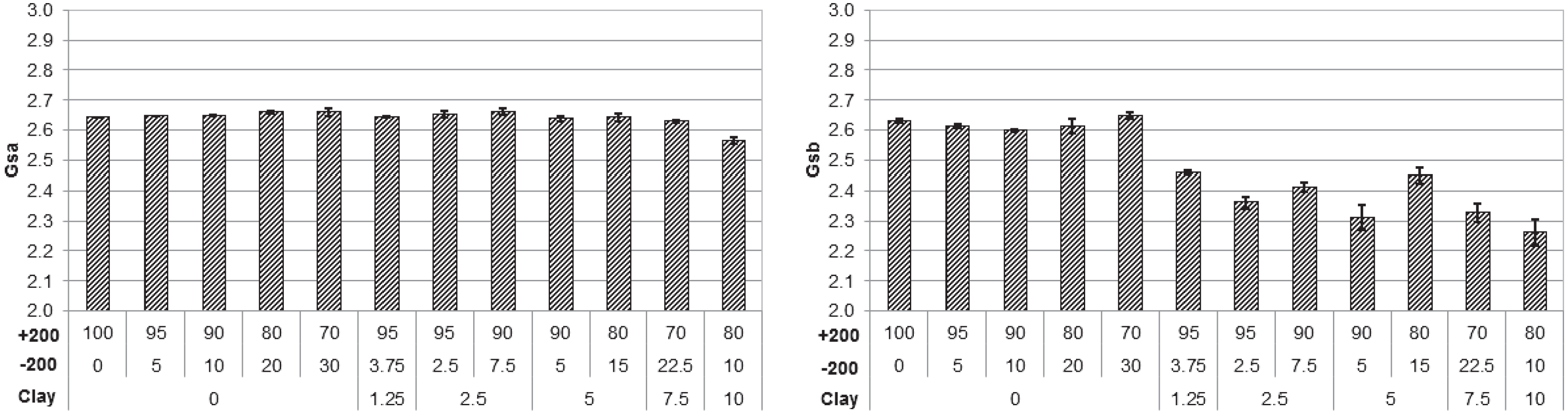
Results and Analysis

Figure 3-32 shows graphical comparisons for 12 blends that included (1) the material retained on the No. 200 sieve from the Arkansas natural sand (shown as "+200" in the graphs); (2) the relatively clean fine material passing the No. 200 sieve from the Texas limestone (shown as "-200" in the graphs); and (3) the sodium bentonite (shown as "clay" in the graphs). Tukey's groupings (significance level = 0.05) of the measured results are included in Tables G-4 through G-7 in Appendix G. For the blends with no clay, the measured results (Gsa, Gsb, Gssd, and absorption) were not statistically different even though these blends included up to 30 percent of the relatively clean P200 material. It should be noted that the absorption capacity for all of these blends was less than 1 percent. The measured results started deviating (statistically different) when even a small amount (1.25 percent) of clay was added to the blend. In addition, the variability of the test results also increased for the blends to which the clay was added.

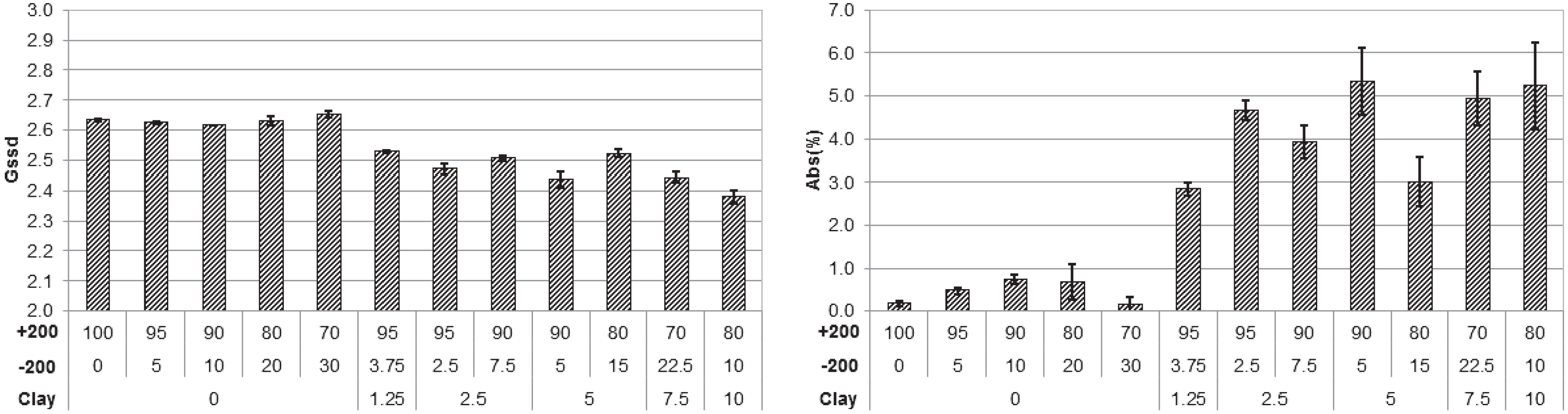
Figure 3-33 compares measured results for the other 12 blends in which the material retained on the No. 200 sieve (shown as "+200" in the graphs) was from the RC limestone. Tukey's groupings of the results are included in Tables G-8 through G-11 in Appendix G. Based on the statistical analysis, the difference in the Gsa results was not significant when the amount of clay added to the blend was less than 7.5 percent. However,

Table 3-35. Materials used in Experiment 4.

Material Fraction	**Material Blend No.**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Plus #200 from natural sand or RC limestone fine aggregate	100	95	95	95	90	90	90	80	80	80	70	70
Minus #200 material from Texas limestone and clay	0	5	5	5	10	10	10	20	20	20	30	30
P200 from Texas limestone	0	5	3.75	2.5	10	7.5	5	20	15	10	30	22.5
% Clay	0	0	1.25	2.5	0	2.5	5	0	5	10	0	7.5
No. of Replicates	3											
No. of Tests	T 84: 2 (+#200 mats) × 12 (blends) × 3 (reps) + 6 = 78 tests C110: 6 tests Sand Equivalent: 3 tests											

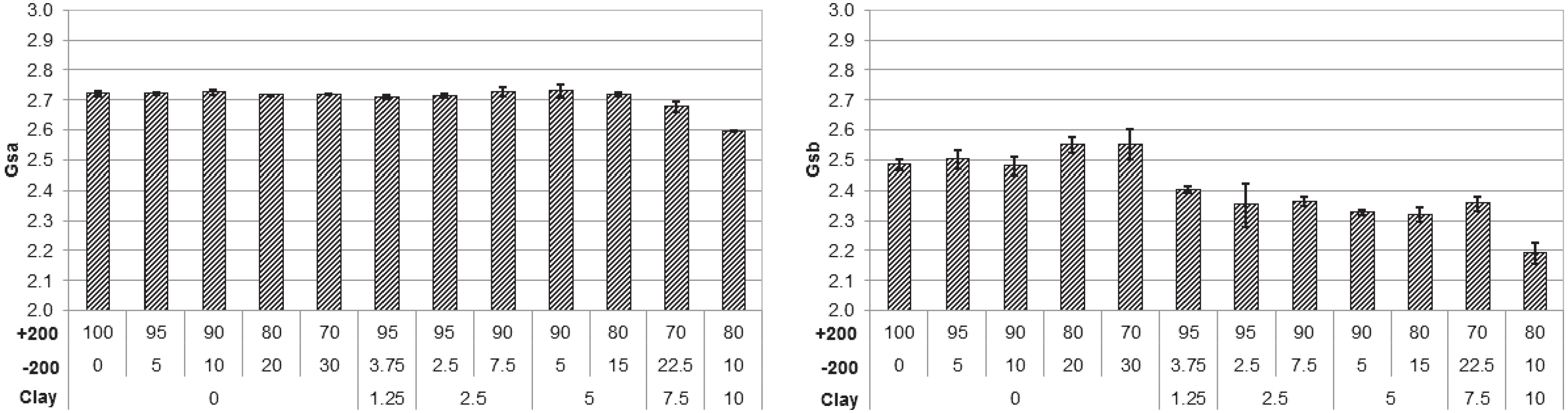


(a) Gsa **(b) Gsb**



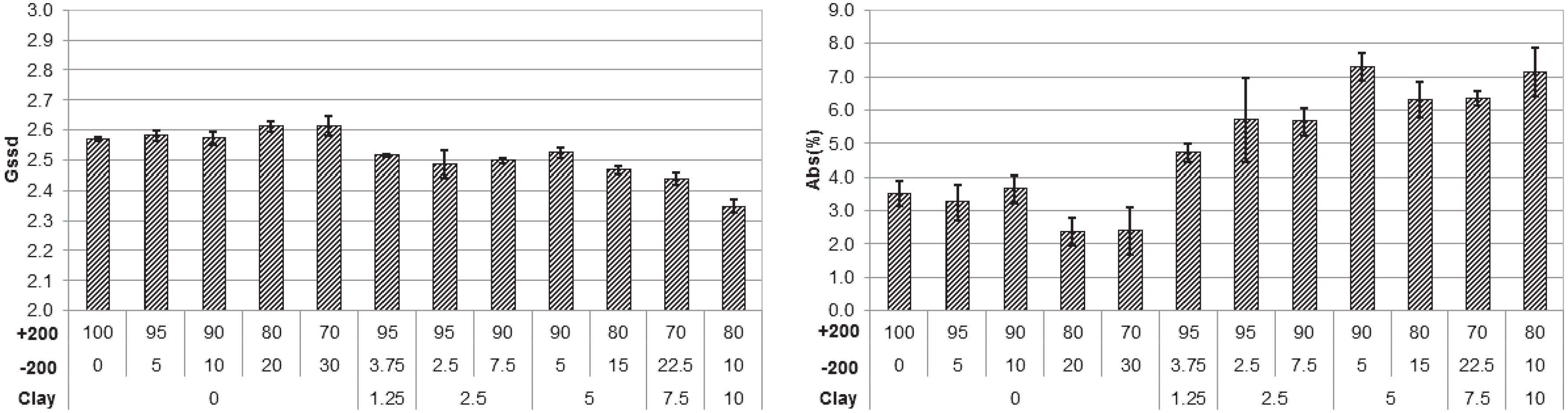
(c) Gssd **(d) Absorption**

Figure 3-32. Effect of P200 materials on AASHTO T 84 test results for natural sand blends.



(a) Gsa

(b) Gsb



(c) Gssd

(d) Absorption

Figure 3-33. Effect of P200 materials on AASHTO T 84 test results for RC limestone blends.

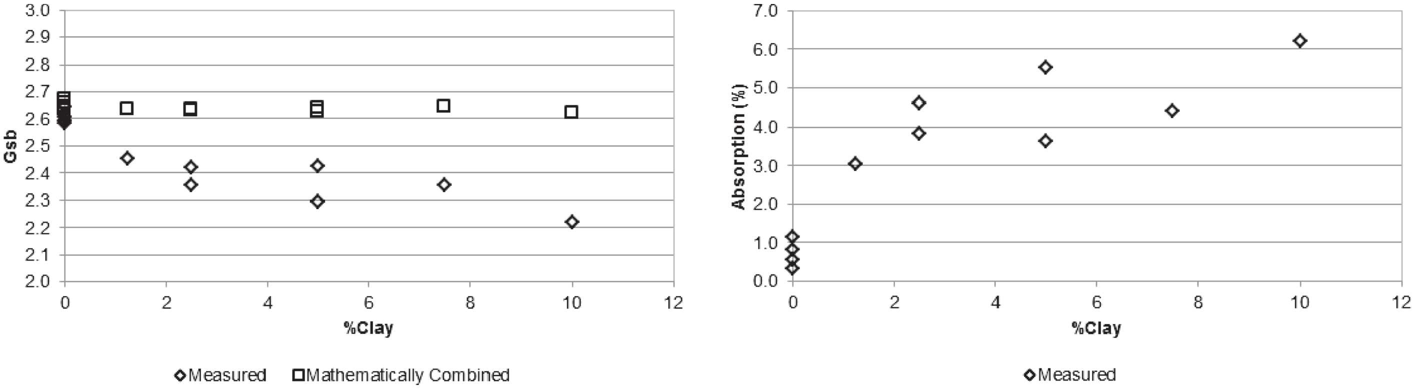
for the other measured results (Gsb, Gssd, and absorption), the differences were statistically significant between two groups of blends—with and without adding the clay.

Figures 3-34 and 3-35 show the correlations between the clay content and the Gsb and absorption results for the natural sand and RC limestone, respectively. The correlations suggest that the presence of a clay material (even in a small amount) can significantly affect the measured results, especially Gsb, Gssd, and absorption. It should be noted that the clay material (sodium bentonite) used in this study can absorb a large amount of water and swell 15 to 18 times its dry size. As shown in Table 3-34, the Atterberg limits of the clay were very different from those of the limestone P200.

The amount of the relatively clean P200 material also affected the test results, especially Gsb, Gssd, and absorption. Although this effect was less significant for the natural sand, it was more profound for the RC limestone. As shown in Figures 3-32 and 3-33, when the amount of the relatively clean P200 material was 20 percent or more, it affected the measured Gsb, Gssd, and absorption values; however, the differences were not statistically significant based on a 95-percent confidence interval (significance level of 0.05).

Due to the significant effect of clays and P200 on AASHTO T 84 test results, it is desirable to have a test method, such as the sand equivalent test (AASHTO T 176), that can be used to identify fine aggregate materials containing P200 that may have adverse effects on AASHTO T 84 test results. An analysis was conducted to assess the correlation between P200 contents and sand equivalent test results of the fine aggregate blends tested in this study. Figures 3-36 and 3-37 show the correlations for the natural sand and RC limestone blends, respectively. The effect of 1.25 percent of clays was similar to that of 10 percent of relatively clean P200 on the sand equivalent test results, and the effect of 2.5 percent of clays was similar to that of 20 percent of relatively clean P200.

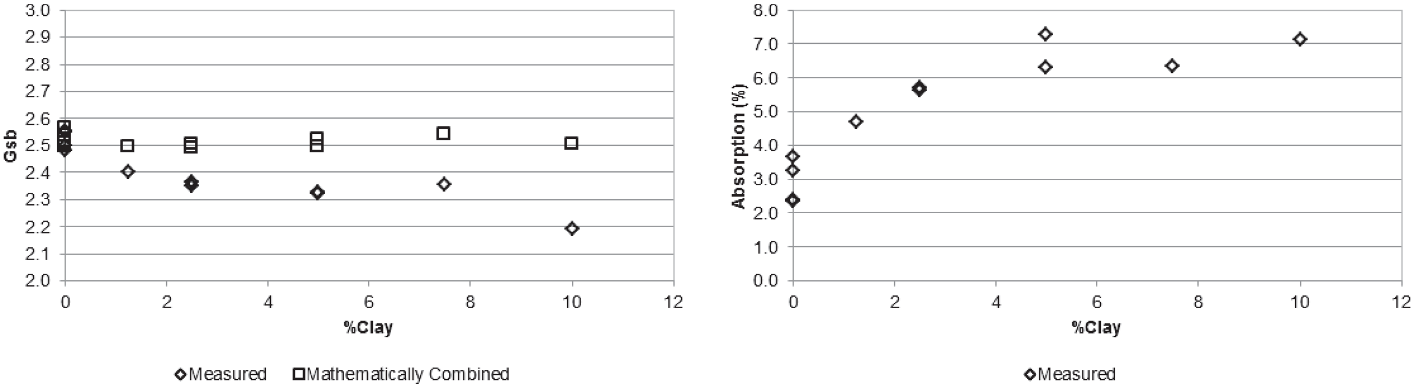
Due to the significant effect of clay on test results, a sand equivalent threshold should be selected so that P200 materials (containing clays) having adverse effects on test results should be tested separately. Based on Figure 3-36, this cut-off sand equivalent value is approximately 75 percent, and it is approximately 65 percent based on Figure 3-37. Thus, it is proposed that a sand equivalent threshold of 75 percent is selected, and it can be used as an option to determine if the "+200" and P200 materials for a fine aggregate should be tested separately.



(a) Gsb vs. Clay Content

(b) Absorption vs. Clay Content

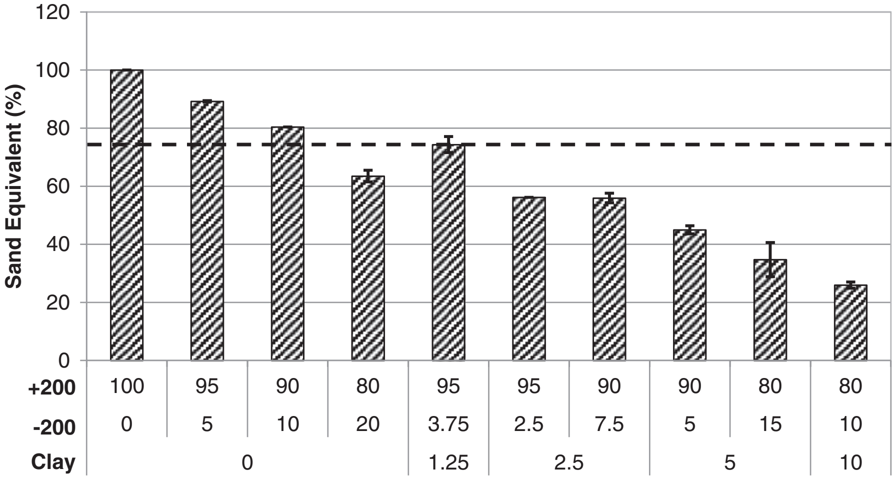
Figure 3-34. Effect of clay content on Gsb and Abs results for natural sand blends.



(a) Gsb vs. Clay Content

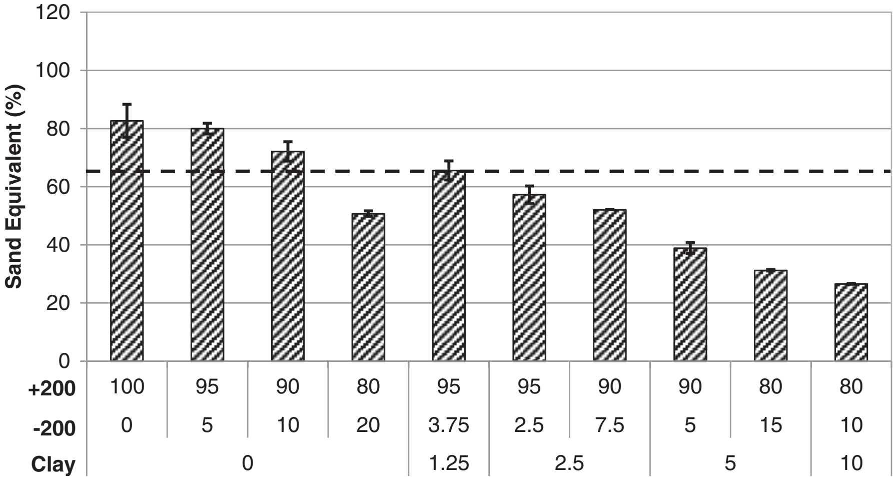
(b) Absorption vs. Clay Content

Figure 3-35. Effect of clay content on Gsb and Abs results for RC limestone blends.



Note: Dashed horizontal line = sand equivalent of 75.

Figure 3-36. ***Correlation of P200 contents and sand equivalent results for natural sand blends.***



Note: Dashed horizontal line = sand equivalent of 65.

Figure 3-37. ***Correlation of P200 contents and sand equivalent results for RC limestone blends.***

However, since the sand equivalent value of 75 percent was determined based on limited data, it should be verified in the future.

Summary

Based on the results of the evaluation of the effect of P200 materials with and without clay, the following observations and proposals are offered:

- If the P200 material does not contain clays, inclusion of the P200 material in the fine aggregate sample will have a minimal effect on AASHTO T 84 test results. If more than 10 percent P200 material is present in the fine aggregate sample, the measured absorption of the fine aggregate sample will be less than that of the "+200" portion. This is due to over-drying of the test sample containing the P200 to determine the SSD condition.
- If the P200 portion contains clays, the clays can significantly affect the AASHTO T 84 test results. In this case, the measured absorption of the "+200" portion will be lower than that of the test sample containing the P200 material because the AASHTO T 84 procedure is sensitive to clays in the P200, causing erroneous measurements.
- Due to the potential error caused by the presence of clays in P200, it is proposed that "+200" and P200 materials of a fine aggregate be tested separately when the sand equivalent of the fine aggregate is lower than 75 percent. The sand equivalent value was determined based on limited data collected in this project, and it should be verified in the future.

CHAPTER 4

Ruggedness Study

Ruggedness Study Plan

The objective of this ruggedness study was to evaluate the sensitivity of the proposed test methods to the changes in levels of operating and environmental factors. The results of ruggedness testing were used to eliminate or reduce the sources of variation, which would ensure better precision of test results and establish appropriate ranges of operating parameters for standardizing the test methods.

This ruggedness study was conducted in accordance with *ASTM C1067*: *Standard Practice for Conducting a Ruggedness or Screening Program for Test Methods for Construction Materials.* The experimental plan involved determination of seven sources of variation, each with potential to influence test results. Each variable factor was assigned high and low values, which represented the tolerance extremes of the variable factor allowed in the test procedure. The experimental plan used in this study was based on the seven-factor Plackett-Burman design presented in ASTM C1067.

Depending on the significance of the interaction between variable factors, the ruggedness experiment can be conducted as a full factorial or fractional factorial. Since the test parameters in the specific gravity measurement were not considered highly interactive, a fractional factorial experiment was considered adequate. Following the ASTM C1067 procedure for a design of fractional factorial, eight determinations (test conditions) were considered sufficient for obtaining valid and objective conclusions with a seven-factor experiment.

The development of a ruggedness study as presented in ASTM C1067 included the following steps:

- Identifying seven variable factors for each test method;
- Determining high and low levels for each factor;
- Setting up 8 combinations of 14 factor levels (7 factors × 2 levels) with 2 replicates for each combination;
- Identifying at least three laboratories to participate in the study; and
- Determining three to five materials that cover the range of materials properties to which the test method is applicable.

Following the above steps, plans for ruggedness testing of revised AASHTO T 85 and T 84 were arranged. Details of each plan are presented in the following sections.

Variable Factors and Their Levels Considered for Ruggedness Study

Variable factors selected for ruggedness testing were based on their probable importance to the final test results. The factors that were most likely to have the greatest effect on the variability of each proposed test method were included in the ruggedness study. The low and high levels of each variable factor were determined based on the allowable tolerance of the factor specified in the test methods. The allowable tolerance of each factor accounted for probable or reasonable variability that was anticipated in practice.

Based on the revised AASHTO T 85 and T 84 procedures, different drying and soaking methods may be used for aggregate with absorption $<$ or $\geq$ 2 percent. Thus, seven variable factors were identified for testing aggregate materials with absorption $<$ and $\geq$ 2 percent.

Tables 4-1 and 4-2 provide seven variable factors and their minimum and maximum levels that were anticipated to have the most influence on results of AASHTO T 85 for coarse aggregate materials with absorption $<$ and $\geq$ 2 percent, respectively. Tables 4-3 and 4-4 provide seven variable factors and their minimum and maximum levels that were anticipated to have the most influence on results of AASHTO T 84 for fine aggregate materials with absorption $<$ and $\geq$ 2 percent, respectively.

The levels included quantitative values, such as soak time, or non-quantitative properties, such as drying the aggregate sample using a dry or damp towel. If testing with the selected levels of a variable factor yielded a significant variation in the

Table 4-1. Seven factors for ruggedness testing of AASHTO T 85 for coarse aggregate with absorption less than 2 percent.

ID	Variable	AASHTO T 85 Requirement	Comments	Low Value	High Value
A	Section 7.2 – Aggregate size	Test materials retained on the No. 4 sieve	Some aggregates contain significant amount of material finer than No. 4	+#8	+#4
B	Section 8.1 – Moisture condition	Dry the sample to a constant mass	Can the sample be tested without initial oven drying?	Oven dried	natural condition
C	Section 8.1 – Cooling time	Cool in air for 1 to 3 hrs until comfortable to handle (~50°C)	Can the sample be soaked immediately without cooling?	0	3 hrs (~50°C)
D	Section 8.1 – Soak time	Vacuum-soak for 10 ± 1 min.	Does this range need to be tighter?	9 min.	11 min.
E	Section 8.1 – Vacuum pressure	3.7 ± 0.3 kPa (27.5 ± 2.5 mm Hg)	Does this range need to be tighter?	3.3 - 3.6kPa	3.8 - 4.1kPa
F	Section 8.4 – Water temperature	23 ± 1.7°C 23 ± 2°C (ASTM)	Does the AASHTO range need to be tighter?	21 - 22°C	24 - 25°C
G	Section 8.5 – Cooling time	Cool in air for 1 to 3 hrs until comfortable to handle (~50°C)	Can the sample be weighed immediately without cooling?	0	3 hrs (~50°C)

Table 4-2. Seven factors for ruggedness testing of AASHTO T 85 for coarse aggregate with absorption greater than 2 percent.

ID	Variable	AASHTO T 85 Requirement	Comments	Low Value	High Value
A	Section 7.2 – Aggregate size	Test materials retained on the No. 4 sieve	Some aggregates contain significant amount of material finer than No. 4	+#8	+#4
B	Section 8.1 – Moisture condition	Dry the sample to a constant mass	Can the sample be tested without initial oven drying?	oven dried	natural condition
C	Section 8.1 – Cooling time	Cool in air for 1 to 3 hrs until comfortable to handle (~50°C)	Can the sample be soaked immediately without cooling?	0	3 hrs (~50°C)
D	Section 8.1 – Soak time	Immerse in water for 15 to 19 hrs (24 ± 4 hrs for ASTM)	Does this range need to be tighter?	15 hrs	20 hrs
E	Section 8.3 – Drying sample	Dry the sample in a large absorbent cloth to SSD	Might need to specify if it is a dry or damp cloth	dry cloth	damp cloth
F	Section 8.4 – Water temperature	23 ± 1.7°C 23 ± 2°C (ASTM)	Does the AASHTO range need to be tighter?	21 - 22°C	24 - 25°C
G	Section 8.5 – Cooling time	Cool in air for 1 to 3 hrs until comfortable to handle (~50°C)	Can the sample be weighed immediately without cooling?	0	3 hrs (~50°C)

Table 4-3. Seven factors for ruggedness testing of AASHTO T 84 for fine aggregate with absorption less than 2 percent.

ID	Variable	AASHTO T 84 Requirement	Comments	Low Value	High Value
A	Section 7.1 – Aggregate size	Removal of P200 if required	Does the P200 content affect test results?	0%	as is
B	Section 7.1 – Aggregate size	Remove material passing the No. 200 sieve	Should P200 be removed using dry sieving or washing?	dry sieving	washing
C	Section 7.1.1 – Moisture condition	Dry the sample to a constant mass	Can the sample be tested without initial oven drying?	oven dried	natural condition
D	Section 7.1.1 – Soak time	Vacuum-soak for 10 ± 1 min.	Does this range need to be tighter?	9 min.	11 min.
E	Section 7.2.1 – Cone test	Apply 25 blows at once or distribute 25 blows in 10, 10, 3, and 2 drops after filling the cone	Do the original and provisional cone tests affect results?	25 blows at once	25 blows in four sets
F	Section 8.2 – Agitation	Manually or mechanically agitate the sample to eliminate air bubbles	Do manual and mechanical methods (AASHTO T 209) yield statistically different results?	manual	mech agitation
G	Section 8.3 – Cooling time	Cool in air for 1 ± 0.5 hrs until comfortable to handle (~50°C)	Can the sample be weighed immediately without cooling?	0	1.5 hrs (~50°C)

Table 4-4. Seven factors for ruggedness testing of AASHTO T 84 for fine aggregate with absorption greater than 2 percent.

ID	Variable	AASHTO T 84 Requirement	Comments	Low Value	High Value
A	Section 7.1 – Aggregate size	Removal of P200 if required	Does the P200 content affect test results?	0%	as is
B	Section 7.1 – Aggregate size	Remove material passing the No. 200 sieve	Should P200 be removed using dry sieving or washing?	dry sieving	washing
C	Section 7.1.1 – Soak type	Immerse or add at least 6% moisture to the sample	Do these methods yield significantly different results?	6% moisture	immerse
D	Section 7.1.1 – Soak time	Immerse in water for 15 to 19 hrs (24 ± 4 hrs for ASTM)	Does this range need to be tighter?	15 hrs	20 hrs
E	Section 7.2.1 – Cone test	Apply 25 blows at once or distribute 25 blows in 10, 10, 3, and 2 drops after filling the cone	Do the original and provisional cone tests affect results?	25 blows at once	25 blows in four sets
F	Section 8.2 – Agitation	Manually or mechanically agitate the sample to eliminate air bubbles	Do manual and mechanical methods (AASHTO T 209) yield statistically different results?	manual	mech agitation
G	Section 8.3 – Cooling time	Cool in air for 1 ± 0.5 hrs until comfortable to handle (~50°C)	Can the sample be weighed immediately without cooling?	0	1.5 hrs (~50°C)

test results, the difference between the minimum and maximum levels of the factor would be reduced.

Experimental Design for Ruggedness Testing

For ruggedness testing, test data were collected for specific combinations of the variable factors and their levels. Each combination resulted from simultaneous changes in the variable factors. Table 4-5 provides the Plackett-Burman design for seven factors and their two levels, which has been found most effective for a seven-factor fractional factorial design as presented in ASTM C1067. The seven factors were assigned letter designations, A to G, and the two levels of each factor were designated with upper and lower cases. Each variable factor changed between two levels to evaluate the effect of the change in factor levels on the test results.

Based on the Plackett-Burman design illustrated in Table 4-5, experimental plans for ruggedness testing of AASHTO T 85 and AASHTO T 84 (Tables 4-6 through 4-9) were developed using the seven factors and their levels provided in Tables 4-1 through 4-4, respectively. Two replicates were tested for each of the eight combinations, resulting in a total of 16 determinants for each material.

Materials for Ruggedness Testing

Table 4-10 shows the materials proposed for use in the testing plans shown in Tables 4-6 through 4-9. Considering two materials for each combination of test method and absorption level, a total of 128 tests (8 combinations × 2 replicates × 4 test method/absorption levels × 2 materials) were conducted in each laboratory.

Participating Laboratories for Ruggedness Testing

As suggested in ASTM C1067, three laboratories participated in the ruggedness study. The laboratories were NCAT, the AASHTO Advanced Pavement Research Laboratory (AAPRL), and the National Institute for Science and Technology (NIST). The test samples were prepared in the Proficiency Sample Program (PSP) facility of the AASHTO Materials Reference Laboratory (AMRL) to ensure that the samples were consistent and

Table 4-5. Ruggedness experimental plan for seven factors and two levels.

Factors	Combination Number							
	1	2	3	4	5	6	7	8
A	a	a	a	a	A	A	A	A
B	b	b	B	B	b	B	B	B
C	C	c	C	c	C	C	C	c
D	D	D	d	d	d	D	D	D
E	e	E	e	E	E	E	E	e
F	F	f	f	F	F	F	f	F
G	G	g	g	G	g	G	G	g

Table 4-6. Experimental design for ruggedness testing of AASHTO T 85 for coarse aggregate with absorption less than 2 percent.

No.	Factor	Determinations (Test Combinations)							
		1	2	3	4	5	6	7	8
A	Section 7.2 – Aggregate size	+#8	+#8	+#8	+#8	+#4	+#4	+#4	+#4
B	Section 8.1 – Moisture condition	oven dried	oven dried	natural	natural	oven dried	oven dried	natural	natural
C	Section 8.1 – Cooling time	3 hrs	0	3 hrs	0	3 hrs	0	3 hrs	0
D	Section 8.1 – Soak time	11 min.	11 min.	9 min.	9 min.	9 min.	9 min.	11 min.	11 min.
E	Section 8.1 – Vacuum pressure	3.3 -3.6kPa	3.8 -4.1kPa	3.3 -3.6kPa	3.8 -4.1kPa	3.8 -4.1kPa	3.3 -3.6kPa	3.8 -4.1kPa	3.3 -3.6kPa
F	Section 8.4 – Water temperature	24 - 25°C	21 - 22°C	21 - 22°C	24 - 25°C	24 - 25°C	21 - 22°C	21 - 22°C	24 - 25°C
G	Section 8.5 – Cooling time	3 hrs	0	0	3 hrs	0	3 hrs	3 hrs	0

Table 4-7. Experimental design for ruggedness testing of AASHTO T 85 for coarse aggregate with absorption greater than 2 percent.

No.	Factor	Determinations (Test Combinations)							
		1	2	3	4	5	6	7	8
A	Section 7.2 – Aggregate size	+#8	+#8	+#8	+#8	+#4	+#4	+#4	+#4
B	Section 8.1 – Moisture condition	oven dried	oven dried	natural	natural	oven dried	oven dried	natural	natural
C	Section 8.1 – Cooling time	3 hrs	0	3 hrs	0	3 hrs	0	3 hrs	0
D	Section 8.1 – Soak time	20 hrs	20 hrs	15 hrs	15 hrs	15 hrs	15 hrs	20 hrs	20 hrs
E	Section 8.3 – Drying sample	dry cloth	damp cloth	dry cloth	damp cloth	damp cloth	dry cloth	damp cloth	dry cloth
F	Section 8.4 – Water temperature	24 - 25°C	21 - 22°C	21 - 22°C	24 - 25°C	24 - 25°C	21 - 22°C	21 - 22°C	24 - 25°C
G	Section 8.5 – Cooling time	3 hrs	0	0	3 hrs	0	3 hrs	3 hrs	0

Table 4-8. Experimental design for ruggedness testing of AASHTO T 84 for fine aggregate with absorption less than 2 percent.

No.	Factor	Determinations (Test Combinations)							
		1	2	3	4	5	6	7	8
A	Section 7.1 – Aggregate size	0%	0%	0%	0%	P200 as is	P200 as is	P200 as is	P200 as is
B	Section 7.1 – Aggregate size	dry sieve	dry sieve	wash	wash	dry sieve	dry sieve	wash	wash
C	Section 7.1.1 – Moisture condition	natural	oven dried	natural	oven dried	natural	oven dried	natural	oven dried
D	Section 7.1.1 – Soak time	11 min.	11 min.	9 min.	9 min.	9 min.	9 min.	11 min.	11 min.
E	Section 7.2.1 – Cone test	25 blows at once	25 blows in 4 sets	25 blows at once	25 blows in 4 sets	25 blows in 4 sets	25 blows at once	25 blows in 4 sets	25 blows at once
F	Section 8.2 – Agitation	mech agitation	manual	manual	mech agitation	mech agitation	manual	manual	mech agitation
G	Section 8.3 – Cooling time	1.5 hrs	0	0	1.5 hrs	0	1.5 hrs	1.5 hrs	0

Table 4-9. Experimental design for ruggedness testing of AASHTO T 84 for fine aggregate with absorption greater than 2 percent.

No.	Factor	Determinations (Test Combinations)							
		1	2	3	4	5	6	7	8
A	Section 7.1 – Aggregate size	0%	0%	0%	0%	P200 as is	P200 as is	P200 as is	P200 as is
B	Section 7.1 – Aggregate size	dry sieve	dry sieve	wash	wash	dry sieve	dry sieve	wash	wash
C	Section 7.1.1 – Soak type	immerse	6% moisture	immerse	6% moisture	immerse	6% moisture	immerse	6% moisture
D	Section 7.1.1 – Soak time	20 hrs	20 hrs	15 hrs	15 hrs	15 hrs	15 hrs	20 hrs	20 hrs
E	Section 7.2.1 – Cone test	25 blows at once	25 blows in 4 sets	25 blows at once	25 blows in 4 sets	25 blows in 4 sets	25 blows at once	25 blows in 4 sets	25 blows at once
F	Section 8.2 – Agitation	mech agitation	manual	manual	mech agitation	mech agitation	manual	manual	mech agitation
G	Section 8.3 – Cooling time	1.5 hrs	0	0	1.5 hrs	0	1.5 hrs	1.5 hrs	0

Table 4-10. Proposed materials for ruggedness testing.

Absorption	Coarse Aggregate (AASHTO T 85)	Fine Aggregate (AASHTO T 84)
Low (< 2%)	1. Granite (abs = 0.5%), Vulcan Materials, Richmond, VA 2. Gravel (abs = 1.4%), Aggregate Industry Rockville, MD (for experiment in Table 4.6)	1. Granite (abs = 0.4%), Vulcan Materials, Richmond, VA 2. Limestone (abs = 1.4%), Aggregate Industry, Rockville, MD (for experiment in Table 4.8)
High (> 2%)	3. Limestone (abs = 2.3%), Vulcan Materials, Tuscumbia, AL 4. BF Slag (abs = 2.7%), Alabaster, AL (for experiment in Table 4.7)	3. Limestone (abs = 2.2%), Vulcan Materials, Tuscumbia, AL 4. BF Slag (abs = 2.2%), Alabaster, AL (for experiment in Table 4.9)

homogeneous. After the samples had been prepared, sample numbers were randomized utilizing the same procedure used for proficiency samples before they were sent to the testing laboratories. A total of 384 tests (128 tests/laboratory × 3 laboratories) were conducted in the three laboratories.

Analysis Method

Test results were analyzed according to ASTM C1067 standard practice. ASTM C1067 contains details about calculations necessary for determining the significance of the variable factors for each test method. The analysis involved the determination of the error variance corresponding to each of the seven factors. The variation in the response variable (specific gravities and absorption) resulted from the low levels and high levels of the seven variable factors and was evaluated using an F-test. To perform an F-test, an F-statistic, which is the ratio of the error variance in test result from one factor to the error variance in test results from all the factors, was calculated using Equation 4-1:

$$F_A = \frac{\sigma_A}{\sigma_{Total}} \tag{4.1}$$

where:

F_A = F-statistic for the effect of Factor A

σ_A = error variance in the test property due to experimental Factor A

σ_{Total} = pooled error variance in the test property due to all main factors (A to G)

For a given variable factor (A to G), the calculated F-statistic was compared to a critical F-value. If the calculated F-statistic was greater than the critical F-value, the main factor was considered to have a significant effect on the measured test property with the main factor being varied between its low and high values. ASTM C1067 recommends the effect of changing a factor between low and high levels to be considered significant at a probability of 5 percent. The critical value determined from the F-distribution table for this level of significance was 5.59. Therefore, the effect of changing a factor between low and high levels was considered significant if the F-statistic of that factor was greater than or equal to 5.59.

Results and Analysis

As discussed in the ruggedness study plan, four coarse aggregates and four fine aggregates were tested. Detailed testing data are included in Appendix I, which is available on the project web page. A summary of the analysis is provided in this section.

Ruggedness Study for Revised AASHTO T 85

The ruggedness study for the revised AASHTO T 85 procedure was conducted in the three laboratories (NCAT, AAPRL, and NIST) using four aggregates (granite, gravel, limestone, and blast furnace slag) that covered a wide range of water absorption. The granite material had the lowest water absorption of 0.5 percent, and the slag aggregate had the highest water absorption of 2.7 percent. A test parameter was found significant in a lab when its F-statistic was greater than $F_{critical}$ (5.59). Tables 4-11, 4-12, 4-13, and 4-14 show F-statistics for Gsb, Gssd, Gsa, and water absorption, respectively, of the four coarse aggregates tested by the three laboratories. In Tables 4-11 through 4-14, NS means "Not Significant," and the shaded cells show the F-values exceeding the critical F-value of 5.59.

Tables 4-15 and 4-16 combine the analysis results shown in Tables 4-11 through 4-14. They show the percentage of times each ruggedness factor was found to be significant in Tables 4-11 through 4-14. ASTM C1067 did not provide a quantitative method for selecting significant test parameters that need to be changed based on the statistical analysis shown in Tables 4-11 through 4-14. Thus, in this analysis, a test parameter or ruggedness factor was considered significant if it was found to be statistically significant in at least two tests (or at least 33 percent of the tests).

Based on the analysis results shown in Tables 4-15 and 4-16, the following observations were made regarding AASHTO T 85:

- Coarse aggregate samples retained on the 4.75-mm (No. 4) sieve or the 2.36-mm (No. 8) sieve prepared according to

Table 4-11. F-statistics for Gsb of coarse aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.5%	NS	NS	NS	NS	NS	8.9	NS
		NCAT	0.5%	NS	NS	NS	NS	NS	NS	NS
		NIST	0.5%	NS	NS	NS	NS	NS	NS	NS
	Gravel	AAPRL	1.4%	6.2	NS	NS	9.9	NS	11.0	NS
		NCAT	1.4%	NS	NS	NS	NS	NS	NS	NS
		NIST	1.4%	13.4	16.3	NS	NS	NS	19.6	NS
≥ 2%	AL-LMS	AAPRL	2.3%	NS	NS	NS	NS	NS	NS	NS
		NCAT	2.3%	NS	NS	NS	NS	NS	6.3	NS
		NIST	2.3%	NS	NS	NS	NS	7.6	NS	NS
	AL-Slag	AAPRL	2.7%	NS	NS	NS	NS	8.8	NS	NS
		NCAT	2.7%	NS	NS	NS	NS	NS	NS	NS
		NIST	2.7%	NS	NS	NS	NS	NS	NS	NS

Table 4-12. F-statistics for Gssd of coarse aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.5%	NS	NS	NS	NS	NS	16.3	NS
		NCAT	0.5%	NS	NS	NS	NS	NS	NS	NS
		NIST	0.5%	NS	NS	NS	NS	NS	NS	NS
	Gravel	AAPRL	1.4%	NS	NS	NS	7.6	NS	6.7	NS
		NCAT	1.4%	NS	NS	NS	NS	NS	NS	NS
		NIST	1.4%	7.4	NS	NS	NS	NS	9.9	NS
≥ 2%	AL-LMS	AAPRL	2.3%	NS	37.7	NS	NS	NS	NS	NS
		NCAT	2.3%	NS	NS	NS	NS	NS	5.9	NS
		NIST	2.3%	NS	NS	NS	NS	NS	NS	NS
	AL-Slag	AAPRL	2.7%	NS	NS	NS	NS	NS	NS	NS
		NCAT	2.7%	NS	NS	13.2	NS	NS	7.0	NS
		NIST	2.7%	NS	NS	9.3	NS	NS	NS	NS

Table 4-13. F-statistics for Gsa of coarse aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.5%	5.9	22.2	NS	NS	NS	17.6	17.3
		NCAT	0.5%	NS	NS	NS	NS	NS	NS	NS
		NIST	0.5%	NS	9.4	NS	NS	NS	NS	14.3
	Gravel	AAPRL	1.4%	NS	NS	NS	NS	NS	NS	6.1
		NCAT	1.4%	NS	6.1	NS	NS	NS	NS	NS
		NIST	1.4%	NS	NS	NS	NS	NS	NS	NS
≥ 2%	AL-LMS	AAPRL	2.3%	NS	203.3	NS	NS	NS	14.1	6.8
		NCAT	2.3%	NS	NS	NS	NS	8.3	NS	NS
		NIST	2.3%	NS	8.2	NS	NS	NS	NS	NS
	AL-Slag	AAPRL	2.7%	NS	NS	6.4	NS	NS	NS	7.4
		NIST	2.7%	NS	NS	19.1	NS	NS	11.6	NS
		NCAT	2.7%	NS	36.7	36.4	NS	NS	40.3	NS

Table 4-14. F-statistics for water absorption of coarse aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.5%	7.2	19.4	NS	NS	NS	NS	34.2
		NCAT	0.5%	NS	NS	NS	NS	NS	NS	6.3
		NIST	0.5%	NS	43.8	10.5	NS	NS	NS	24.6
	Gravel	AAPRL	1.4%	18.8	NS	NS	13.3	NS	23.2	NS
		NCAT	1.4%	NS	NS	NS	NS	NS	NS	NS
		NIST	1.4%	28.2	67.0	7.0	NS	6.0	47.4	NS
≥ 2%	AL-LMS	AAPRL	2.3%	NS	44.1	NS	NS	NS	NS	6.8
		NCAT	2.3%	NS	NS	NS	NS	NS	6.1	NS
		NIST	2.3%	NS	43.9	NS	NS	19.2	NS	7.6
	AL-Slag	AAPRL	2.7%	54.0	NS	NS	NS	49.0	NS	31.6
		NCAT	2.7%	NS	132.6	63.0	12.9	NS	121.9	NS
		NIST	2.7%	NS	NS	49.0	NS	NS	68.3	NS

Table 4-15. Percentages of time each ruggedness factor in AASHTO T 85 was found significant when testing low absorption (<2 percent) coarse aggregates (granite and gravel).

ID	Variable	Low Value	High Value	Gsb	Gssd	Gsa	Abs
A	Section 7.2 – Aggregate size	+#8	+#4	33	17	17	50
B	Section 8.1 – Moisture condition	oven dried	in-situ moisture	17	0	50	50
C	Section 8.1 – Cooling time	0	3 hrs	0	0	0	33
D	Section 8.1 – Soak time	9 min.	11 min.	17	17	0	17
E	Section 8.1 – Vacuum pressure	3.3 - 3.6kPa	3.8 - 4.1kPa	0	0	0	17
F	Section 8.4 – Water temperature	21 - 22°C	24 - 25°C	50	50	17	33
G	Section 8.5 – Cooling time	0	3 hrs	0	0	50	50

Table 4-16. Percentages of time each ruggedness factor in AASHTO T 85 was found significant when testing high absorption (>2 percent) coarse aggregates (AL-LMS and AL-slag).

ID	Variable	Low Value	High Value	Gsb	Gssd	Gsa	Abs
A	Section 7.2 – Aggregate size	+#8	+#4	0	0	0	17
B	Section 8.1 – Moisture condition	oven dried	in-situ moisture	0	17	50	50
C	Section 8.1 – Cooling time	0	3 hrs	0	33	50	33
D	Section 8.1 – Soak time	15 hrs	20 hrs	0	0	0	17
E	Section 8.3 – Drying sample	dry cloth	damp cloth	33	0	17	33
F	Section 8.4 – Water temperature	21 - 22°C	24 - 25°C	17	33	50	50
G	Section 8.5 – Cooling time	0	3 hrs	0	0	33	50

Section 7.2 yield statistically different water absorption results for low absorption (< 2 percent) coarse aggregates.

- The effect of using a coarse aggregate oven-dried sample or in its in-situ moisture condition in Section 8.1 is significant on Gsa and water absorption results.
- Also in Section 8.1, an oven-dried sample can be submerged in water at room temperature immediately, when it is safe, without waiting for the sample to cool to a temperature (approximately 50°C) that is comfortable to handle. However, doing so significantly affects water absorption results for low absorption aggregate, and Gssd, Gsa, and water absorption results for high absorption aggregates.
- In Section 8.1, a low absorption (< 2 percent) coarse aggregate sample can be vacuum soaked in water for a period of 9 to 11 minutes at a residual pressure of 3.4 to 4.0 kPa. Also, a high absorption (≥ 2 percent) coarse aggregate sample can be soaked in water for a period of 15 to 19 hours. The low and high levels of the soak times and vacuum pressure were found to be appropriate.
- The effect of using a dry cloth versus a wet cloth in Section 8.2 was found to be significant on the Gsb and absorption results.
- The water bath temperature in Section 8.3 is a significant test parameter for determining Gsb, Gssd, and absorption of low absorption coarse aggregates and for determining Gssd, Gsa, and water absorption of high absorption coarse aggregates.
- In Section 8.4, the final mass of an oven-dried aggregate sample can be determined immediately after it is removed from the oven when it is safe or after it has been cooled down to a temperature (approximately 50°C) that is comfortable to handle. However, these methods yield statistically different Gsa and absorption results.

Since Gsb and Gssd are used in PCC and AC mix design and production, the test parameters significantly affecting these test properties may need to be tightened. Based on the ruggedness results summarized in Tables 4-15 and 4-16, there are four significant test parameters. Therefore, the following changes are proposed for AASHTO T 85:

- In Section 7.2, testing conducted on aggregate samples retained on the 4.75-mm (No. 4) sieve and on the 2.36-mm (No. 8) sieve would yield significantly different testing results. Since the two test samples have different lower limits of aggregate size, they may have different surface void structures, affecting their absorption capacity and specific gravities. Thus, testing should be conducted on the same aggregate size (retained on either the 4.75-mm [No. 4] sieve or the 2.36-mm [No. 8] sieve) in the agency's and contractor's laboratories.
- In Section 8.1, an oven-dried sample should be allowed to cool to a temperature (approximately 50°C) that is comfortable to handle before being submerged in water at the

Table 4-17. F-statistics for Gsb of fine aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.4%	37.0	NS	NS	16.4	NS	NS	NS
		NCAT	0.4%	52.0	NS	NS	NS	6.0	NS	NS
		NIST	0.4%	7.6	NS	NS	NS	5.7	NS	NS
	LS-105	AAPRL	1.4%	52.4	NS	NS	28.3	NS	NS	NS
		NCAT	1.4%	31.8	NS	NS	13.6	NS	7.9	NS
		NIST	1.4%	111.6	12.1	NS	22.2	6.9	NS	64.2
≥ 2%	AL-LMS	AAPRL	2.2%	80.7	11.8	NS	43.3	NS	NS	NS
		NCAT	2.2%	16.4	NS	NS	6.5	NS	NS	NS
		NIST	2.2%	31.7	10.2	NS	41.9	NS	9.6	1.4
	AL-Slag	AAPRL	2.2%	309.5	47.4	NS	59.4	NS	10.4	19.0
		NCAT	2.2%	71.1	NS	NS	23.7	NS	NS	7.1
		NIST	2.2%	350.7	100.5	NS	91.4	18.2	38.5	237.2

room temperature. This is to avoid thermal shock that may cause differential contraction in the hot aggregate particles. This differential contraction may cause cracks to form, changing the void structure, absorption capacity, and specific gravities of the aggregate.

- In Section 8.3, using a dry towel or a damp towel to dry the surface of soaked aggregate particles to an SSD condition may significantly affect the test results. Depending on the amount of water absorbed in it, the damp towel may absorb water better than a completely dry towel because the skin of a water molecule is polarized, thereby acting like a magnet for other water molecules based on a process known as *capillarity.* Therefore, the agency's and contractor's laboratories should use the same method (either dry towel or damp towel) to dry the surface of soaked aggregate particles to an SSD condition.
- In Section 8.3, the water bath temperature was found to be significant because of thermal effects on the aggregate and the density of water. Thus, it is proposed to change the water bath temperature from 23.0 ± 1.7°C (73.4 ± 3°F) to 23.0 ± 1°C (73.4 ± 1.8°F). The tolerance of ± 1°C is proposed because it can be reasonably controlled in a laboratory.

Ruggedness Study for Revised AASHTO T 84

The ruggedness study for the revised AASHTO T 84 procedure was also conducted in the NCAT, AAPRL, and NIST laboratories. Four fine aggregates, including one granite (0.4 percent absorption), two limestones (1.4 and 2.2 percent absorption), and one blast furnace slag (2.2 percent absorption), were tested. A test parameter was found to be significant when its F-statistic was greater than $F_{critical}$. Tables 4-17 through 4-20

Table 4-18. F-statistics for Gssd of fine aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.4%	30.2	NS	NS	6.8	NS	NS	NS
		NCAT	0.4%	54.3	NS	NS	NS	6.2	NS	NS
		NIST	0.4%	NS	NS	NS	NS	6.5	NS	NS
	LS-105	AAPRL	1.4%	26.4	NS	NS	18.6	NS	NS	NS
		NCAT	1.4%	30.2	NS	NS	12.4	NS	8.2	6.5
		NIST	1.4%	136.6	8.5	NS	25.3	6.9	NS	23.3
≥ 2%	AL-LMS	AAPRL	2.2%	59.4	NS	NS	20.4	NS	NS	NS
		NCAT	2.2%	7.6	NS	NS	NS	NS	NS	NS
		NIST	2.2%	51.5	NS	7.3	30.3	NS	17.8	NS
	AL-Slag	AAPRL	2.2%	150.6	20.4	NS	37.4	NS	7.6	NS
		NCAT	2.2%	51.4	NS	6.4	16.6	NS	11.5	NS
		NIST	2.2%	123.7	61.1	NS	25.0	11.4	18.5	69.0

Table 4-19. F-statistics for Gsa of fine aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.4%	17.0	NS	NS	NS	NS	NS	26.0
		NCAT	0.4%	24.0	NS	NS	NS	NS	NS	5.8
		NIST	0.4%	10.3	NS	NS	NS	NS	NS	19.5
	LS-105	AAPRL	1.4%	NS	NS	NS	NS	NS	NS	28.2
		NCAT	1.4%	6.1	NS	NS	NS	NS	NS	19.8
		NIST	1.4%	NS	NS	NS	NS	NS	NS	110.2
≥ 2%	AL-LMS	AAPRL	2.2%	14.1	NS	NS	NS	NS	NS	10.0
		NCAT	2.2%	NS	NS	NS	NS	NS	NS	NS
		NIST	2.2%	33.4	13.3	NS	NS	NS	24.9	NS
	AL-Slag	AAPRL	2.2%	NS	NS	NS	NS	NS	NS	33.3
		NCAT	2.2%	NS	NS	15.4	NS	NS	34.5	17.7
		NIST	2.2%	6.2	NS	NS	5.7	NS	NS	11.8

show F-statistics for Gsb, Gssd, Gsa, and water absorption of the four fine aggregates, respectively. In these tables, NS means "Not Significant," and the shaded cells show the F-values exceeding the critical F-value of 5.59.

The percentage of times each ruggedness factor was found to be significant in Tables 4-15 through 4-18 is summarized in Tables 4-19 and 4-20. As discussed previously, a test parameter or ruggedness factor was considered significant in this analysis if it was found to be statistically significant in 33 percent or more of the tests.

Based on the analysis results shown in Tables 4-19 and 4-20, the following observations were made regarding AASHTO T 84:

- In Section 7.1, testing conducted on fine aggregate samples with and without the P200 yielded statistically different Gsb, Gssd, Gsa, and absorption results.
- Also in Section 7.1, the method of separating the P200 from fine aggregates through dry sieving or washing statistically affected the absorption results for low absorption (<2 percent) fine aggregates and the Gsb, Gssd, and absorption results for high absorption (>2 percent) fine aggregates.
- In Section 7.1.1, testing low absorption (<2 percent) fine aggregate samples in an oven-dried or in-situ moisture condition did not statistically affect the test results. However, for low absorption (<2 percent) fine aggregates, vacuum soaking test samples in water for 9 or 11 minutes at a residual pressure of 3.4 to 4.0 kPa did yield statistically different Gsb, Gssd, and absorption results.
- Also in Section 7.1.1, but for high absorption (≥2 percent) fine aggregates, soaking test samples in water or adding 6 percent moisture yielded statistically different results for Gssd and water absorption. Also, soaking test samples for 15 or 20 hours yielded statistically different Gsb, Gssd, and absorption results.
- For the cone test in Section 7.2.1, dropping the tamper 25 times at once or in four sets yielded statistically different Gsb and Gssd results for low absorption fine aggregates but did not affect the test results for high absorption fine aggregates.
- In Section 8.2, eliminating air bubbles using mechanical agitation or manual agitation significantly affected absorption results for low absorption fine aggregates but significantly affected all the test results (i.e., Gsb, Gssd, Gsa, and absorption) for high absorption fine aggregates.
- In Section 8.3, the final mass of an oven-dried aggregate sample can be determined immediately after it is removed from the oven when it is safe or after it has been cooled down to a temperature (approximately 50°C) that is comfortable to handle. However, these methods yield statistically different Gssd, Gsa, and absorption results for low absorption fine aggregates and Gsb, Gsa, and absorption results for high absorption fine aggregates.

Gsb and Gssd are the two most important test results for AASHTO T 84, as they are used in PCC and AC mix design and production. Based on the ruggedness results summarized in Tables 4-21 and 4-22, there are several significant test parameters for Gsb and Gssd. Changes to these test parameters are proposed as follows:

- The ruggedness study results showed the significant effect of P200 on AASHTO T 84 test results. The cone and tamp method for determining the SSD condition for fine aggregates is based on the observation that the cone of aggregate (~71.6°) is greater than the angle of repose for dry material but less than the angle of repose for aggregate with capillary water between particles. However, the angle of repose of fine aggregate is influenced by several material properties, especially the amount and nature (e.g., plasticity) of the P200 fraction. Thus, in Section 7.1, to simplify the test procedure and improve the test variability, the P200 portion should be tested separately.

Table 4-20. F-statistics for absorption of fine aggregates.

Absorption Level	Material	Lab	Avg. Absorption	A	B	C	D	E	F	G
< 2%	Granite	AAPRL	0.4%	73.8	107.6	NS	184.9	18.7	22.9	231.7
		NCAT	0.4%	21.9	NS	NS	NS	NS	NS	NS
		NIST	0.4%	12.9	NS	NS	NS	NS	NS	9.3
	LS-105	AAPRL	1.4%	240.0	NS	15.2	75.7	NS	0.9	120.8
		NCAT	1.4%	24.1	NS	NS	11.2	NS	NS	NS
		NIST	1.4%	55.3	13.0	NS	12.3	NS	NS	114.8
≥ 2%	AL-LMS	AAPRL	2.2%	95.0	31.5	11.3	124.9	NS	NS	46.3
		NCAT	2.2%	51.7	30.2	6.9	10.2	NS	NS	5.7
		NIST	2.2%	47.1	22.7	NS	52.2	NS	NS	NS
	AL-Slag	AAPRL	2.2%	846.2	150.6	NS	96.7	NS	13.2	193.9
		NCAT	2.2%	98.1	NS	NS	34.6	NS	NS	26.2
		NIST	2.2%	186.3	18.9	NS	63.2	NS	13.6	158.5

Table 4-21. Percentage of times each ruggedness factor in AASHTO T 84 was found significant when testing low absorption (<2 percent) fine aggregates (granite and LS-105).

ID	Variable	Low Value	High Value	Gsb	Gssd	Gsa	Abs
A	Section 7.1 – Aggregate size	with P200	without P200	100	83	67	100
B	Section 7.1 – Aggregate size	dry sieve	wash	17	17	0	33
C	Section 7.1.1 – Moisture condition	oven dried	in-situ moisture	0	0	0	17
D	Section 7.1.1 – Soak time	9 min.	11 min.	67	67	0	67
E	Section 7.2.1 – Cone test	25 drops at once	25 drops in 4 sets	50	50	0	17
F	Section 8.2 – Agitation	mech agitation	manual	17	17	0	33
G	Section 8.3 – Cooling time	0	1.5 hrs (~50°C)	17	33	100	67

Table 4-22. Percentage of times each ruggedness factor in AASHTO T 84 was found significant when testing high absorption (>2 percent) fine aggregates (AL-LMS and AL-slag).

ID	Variable	Low Value	High Value	Gsb	Gssd	Gsa	Abs
A	Section 7.1 – Aggregate size	with P200	without P200	100	100	67	100
B	Section 7.1 – Aggregate size	dry sieve	wash	67	33	17	83
C	Section 7.1.1 – Soak type	immerse	6% moisture	0	33	17	33
D	Section 7.1.1 – Soak time	15 hrs	20 hrs	100	83	17	100
E	Section 7.2.1 – Cone test	25 drops at once	25 drops in 4 sets	17	17	0	0
F	Section 8.2 – Agitation	mech agitation	manual	50	67	33	33
G	Section 8.3 – Cooling time	0	1.5 hrs (~50°C)	67	17	67	83

- If the P200 portion is tested separately, it can be dry-sieved or washed out of the fine aggregate sample. However, the agency's and contractor's laboratories should use the same method for separating the P200 fraction.
- The soak time was found to be a significant test parameter. This suggests that aggregate particles, especially absorptive materials, continue to absorb water beyond the time specified. Thus, the soak time should be changed from 10±1 minutes to 10±0.5 minutes for vacuum soaking. Or, it should be from 15 to 16 hours instead of from 15 to 19 hours for hydrostatic soaking. These ranges are recommended because they can be reasonably controlled in the laboratory.
- To further improve the test variability, the cone test should be conducted by dropping the tamper 25 times at once so that the material within the cone is compacted with the same amount of compaction effort. Also, to eliminate air bubbles, either mechanical agitation or a manual method should be used consistently. In addition, the final mass of an oven-dried aggregate sample should be determined after it is removed from the oven as soon as it is safe to do so.

CHAPTER 5

Practical Significance of Aggregate Specific Gravity Test Results

This chapter discusses the practical significance of the relative accuracy of the specific gravity determinations. The underlying question is, *how close should the result from a revised test method be to that of the current method?* To answer this question, two analyses were conducted. The first analysis was to determine if differences in the results of revised and current methods were within the acceptable range of the current methods. The second analysis assessed the sensitivity of the portland cement concrete and asphalt mixture volumetric properties to aggregate specific gravity values.

Repeatability Analysis

The first analysis was based on the repeatability of the current specific gravity tests. From a practical point of view, it is acceptable if differences in results from different procedures (i.e., alternative methods) are less than differences in results of duplicate specimens tested according to the current methods.

Precision estimates of the current methods are available in AASHTO T 84 and T 85 and also are determined annually by the Proficiency Sample Programs and reported on the AMRL website. The within-lab standard deviations (S_r) and acceptable range of two results (D2S) from AASHTO T 84 and T 85, respectively, are as follows:

AASHTO T 84 Gsb: $S_r = 0.011$; $D2S_r = 0.032$
AASHTO T 85 Gsb: $S_r = 0.009$; $D2S_r = 0.025$

The precision indices for fine and coarse aggregate Gsbs determined annually by the Proficiency Sample Programs are shown in Tables 5-1 and 5-2, respectively. As can be seen, the precision estimates vary significantly from year to year due partially to the use of different aggregate sources in the program. For the fine aggregate precision estimates, data for the last 4 years suggest an improvement in the within-lab and between-lab statistics. However, it should be noted that the Proficiency Sample Program has used a different method of screening data since 2006. The new method detects more outliers, resulting in precision estimates that are smaller than those reported in previous years and those cited in the current standards. The precision estimates for coarse aggregate Gsb shown in Table 5-2 also show lower within-lab and between-lab statistics from 2006 to 2009, but the 2010 results increase to levels more consistent with the earlier 8 years.

For this analysis, the precision statistics from the current standards as shown in Tables 5-1 and 5-2 were used to assess how well the results from alternative methods compared with the results from the standard methods evaluated in Chapter 3. Table 5-3 shows the Gsb results from the experiments to compare testing of the aggregates in the in-situ moisture condition and drying with the CoreDry apparatus to aggregates prepared by the standard oven drying method. Results that differed from the oven drying method by more than the within-lab acceptable range of two results were highlighted in shaded cells. From this table, it was evident that only testing of coarse aggregate in the in-situ moisture condition provides results that are reasonably consistent (based on practical ranges) with the oven drying method.

Table 5-4 shows the Gsb results from the experiment to compare vacuum saturation of different time periods to hydrostatic soaking for 15 hours. From this table, it was evident that for the coarse aggregates, results using vacuum saturation were reasonably consistent (based on practical ranges) with hydrostatic soaking, for each of the three time periods used in the experiment. For the fine aggregates, results using the 15-minute vacuum time were reasonably consistent with the static soaking except for the Preston sandstone. However, this result was close to the within-lab range of 0.032.

Sensitivity Analysis

Another way to view the issue is to ask, *how sensitive are concrete and asphalt mix designs to the values of the aggregate specific gravity?* For this analysis, an asphalt mix design

Table 5-1. AASHTO T 84/ASTM C128 precision estimates published by AMRL.

Year	Sample	No. of Labs		Single Operator		Multilaboratory	
	No.	Participated*	Data Used**	1s	d2s	1s	d2s
2010	167/168	1293	1081	0.006	0.017	0.012	0.034
2009	163/164	1282	1091	0.007	0.020	0.017	0.048
2008	159/160	1189	1001	0.006	0.018	0.015	0.043
2007	155/156	1025	946	0.006	0.018	0.014	0.040
2006	151/152	1044	1016	0.017	0.048	0.029	0.081
2005	147/148	965	939	0.016	0.045	0.033	0.093
2004	143/144	951	936	0.019	0.054	0.041	0.115
2003	139/140	864	850	0.017	0.048	0.037	0.105
2002	135/136	753	739	0.014	0.040	0.034	0.095
2001	131/132	656	642	0.015	0.044	0.033	0.093
2000	127/128	586	579	0.021	0.060	0.041	0.115
1999	123/124	551	540	0.013	0.038	0.028	0.079
1998	119/120	483	475	0.035	0.098	0.045	0.127

Notes:
*Total number of laboratories that participated in the program each year
**Number of laboratories whose data were used to determine precision estimates

having a gradation of 50 percent passing the No. 4 sieve was considered. The standard deviation for the combined Gsb of the blend would be the average of the standard deviations from T 84 and T 85. Likewise, the acceptable range of two Gsb measurements of the combined aggregate should be within the average of the coarse and fine aggregate D2S ranges. Therefore, a reasonable precision estimate for Gsb of the blend is $(0.032 + 0.025) = 0.0285 = 0.029$, which is the practically attainable limit with the current methods. The following calculation illustrates how this acceptable range would affect the calculated VMA for an example asphalt mix.

Table 5-2. AASHTO T 85/ASTM C127 precision estimates reported by AMRL.

Year	Sample	No. of Labs		Single Operator		Multilaboratory	
	No.	Participated*	Data Used**	1s	d2s	1s	d2s
2010	169/170	1384	1246	0.015	0.043	0.034	0.096
2009	165/166	1332	1093	0.003	0.010	0.006	0.017
2008	161/162	1298	1133	0.009	0.025	0.016	0.046
2007	157/158	1198	995	0.005	0.015	0.009	0.025
2006	153/154	1175	956	0.005	0.014	0.009	0.025
2005	149/150	1072	1046	0.012	0.034	0.024	0.067
2004	145/146	1031	991	0.031	0.086	0.019	0.054
2003	141/142	939	919	0.018	0.051	0.044	0.124
2002	137/138	847	838	0.016	0.044	0.026	0.074
2001	133/134	789	766	0.010	0.027	0.019	0.052
2000	129/130	696	693	0.015	0.043	0.027	0.075
1999	125/126	590	579	0.045	0.128	0.029	0.081
1998	121/122	545	542	0.019	0.053	0.031	0.088

Notes:
*Total number of laboratories that participated in the program each year
**Number of laboratories whose data were used to determine precision estimates

Table 5-3. Comparison of Gsb results from oven drying (current standard) to results from in-situ moisture condition and CoreDry methods.

Material	Oven Drying vs. In-situ Moisture Condition			Oven Drying vs. CoreDry Method		
	Oven Drying	In-situ	Difference	Oven Drying	CoreDry	Difference
Coarse Aggregate ($D2S_r = 0.025$)						
BF Slag	2.333	2.337	0.004	2.333	2.360	0.027
Elmore Gravel	2.563	2.565	0.002	2.563	2.566	0.003
PS Coarse	2.489	2.490	0.001	2.489	2.496	0.007
RC Limestone	2.523	2.545	0.022	2.523	2.552	0.029
RE Concrete	2.347	2.333	0.014	2.347	2.396	0.049
Fine Aggregate ($D2S_r = 0.032$)						
Natural Sand	2.619	2.631	0.012	2.619	2.633	0.014
BF Slag Fine	2.715	2.692	0.023	2.715	2.752	0.037
PS Fine	2.531	2.594	0.063	2.531	2.582	0.051
RC Limestone	2.511	2.553	0.042	2.511	2.508	0.003
Texas Sand	2.552	2.599	0.047	2.552	2.595	0.043

Given: Gmb = 2.400, Pb = 5.0, Gsb = 2.650

$$VMA = 100 - \left(\frac{G_{mb} \times (1 - P_b)}{G_{sb}}\right) = 100 - \left(\frac{2.400 \times (100 - 5.0)}{2.650}\right)$$

$$= 14.0\%$$

If the Gsb were changed by 0.029, the new VMA would be as follows:

Given: Gmb = 2.400, Pb = 5.0, Gsb = 2.679
VMA = 14.9%

This clearly shows that VMA is very sensitive to Gsb. This also illustrates one of the serious flaws in using VMA as a mix design or acceptance criterion for asphalt paving mixtures. The test methods for the materials are so variable that it would be easy to design or accept a mixture that appears to be satisfactory but could have too low or too high a VMA.

In the absolute volume method of concrete mix proportioning, the sand (fine aggregate) content is determined last and is based on the volume of the other ingredients subtracted from the total unit volume (e.g., cubic yard). Therefore, when the specific gravity of the coarse aggregate is changed, the net effect is a change in the volume or proportion of sand used in the concrete mixture. Note that ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete* uses "oven-dry relative density (specific gravity)" (i.e., Gsb) of coarse and fine aggregates in the method for determining concrete mix designs. Also note that all specific gravity values used in ACI standards are reported to the hundredths place (e.g., 2.68).

The following mixture constituents are from the example mix design in *Design and Control of Concrete Mixtures*, (*31*, pp 163–166).

Water = 270 lb/(1 × 62.4 pcf) = 4.33 ft^3
Cement = 643 lb/(3.15 × 62.4 pcf) = 3.27 ft^3

Table 5-4. Comparison of Gsb results from 15-hour soak (current standard) to results from vacuum saturation.

Material	15-Hr Soak	5-min. Vacuum	Diff.	10-min. Vacuum	Diff.	15-min. Vacuum	Diff.
Coarse Aggregate ($D2S_r = 0.025$)							
BF Slag	2.333	2.325	0.008	2.334	-0.001	2.328	0.005
Elmore Gravel	2.563	2.561	0.002	2.559	0.004	2.560	0.003
PS Coarse	2.499	2.496	0.003	2.496	0.003	2.492	0.007
RC Limestone	2.523	2.541	-0.018	2.540	-0.017	2.544	-0.021
RE Concrete	2.347	2.365	-0.018	2.365	-0.018	2.351	-0.004
Fine Aggregate ($D2S_r = 0.032$)							
Natural Sand	2.619	2.627	0.008	2.630	-0.011	2.624	-0.005
BF Slag Fine	2.715	2.734	-0.019	2.723	-0.008	2.720	-0.005
PS Fine	2.531	2.591	-0.060	2.578	-0.047	2.567	-0.036
RC Limestone	2.511	2.541	-0.030	2.518	-0.007	2.533	-0.022
Texas Sand	2.552	2.598	-0.046	2.594	-0.042	2.555	-0.003

Air = $(7.0\%/100) \times 27\ \text{ft}^3 = 1.89\ \text{ft}^3$
Coarse Aggregate = $1674\ \text{lb}/(2.68 \times 62.4\ \text{pcf}) = 10.01\ \text{ft}^3$

The weight of coarse aggregate is determined from Figure 9.3 or Table 9.4 (Bulk Volume of Coarse Aggregate per Unit Volume of Concrete) and the dry-rodded unit weight of the coarse aggregate (*31*).

The above volumes sum to 19.50 cubic feet, which is subtracted from 27.0 cubic feet to leave 7.50 cubic feet for the dry fine aggregate. The mass of dry fine aggregate is then determined by multiplying that volume by the Gsb of the fine aggregate and the unit weight of water, 62.4 pcf, as follows:

Fine Aggregate = $7.50\ \text{ft}^3 \times 2.64 \times 62.4\ \text{pcf} = 1236\ \text{lb}$

Trial batch weights are then adjusted to account for the free (surface) water in the aggregates used to prepare the batch. This is where absorption values come into play. In the example, the coarse aggregate has an absorption capacity of 0.5 percent and a moisture content of 2 percent. The fine aggregate has an absorption capacity of 0.7 percent and a moisture content of 6 percent.

The batch weights of the aggregates are increased by multiplying the oven-dried batch weights by 1 plus the moisture contents, as follows:

Coarse Aggregate = $1674\ \text{lb} \times 1.02 = 1707\ \text{lb}$
Fine Aggregate = $1236\ \text{lb} \times 1.06 = 1310\ \text{lb}$

The batch water is then reduced by the amount of free water with each aggregate. The percentage of free water is the difference between the moisture content and the absorption. For the coarse aggregate, the free water percentage is $2.0\% - 0.5\% = 1.5\%$, and for the fine aggregate, the free water percentage is $6.0\% - 0.7\% = 5.3\%$.

The adjusted batch water is $270\ \text{lb} - (1674\ \text{lb} \times 0.015) - (1236\ \text{lb} \times 0.053) = 179\ \text{lb}$

If the aggregate specific gravities changed by the within-lab D2S range, the above example would be recalculated as follows:

Water, cement, and air volumes and batch weights would remain the same. The volume of coarse aggregate would be

$$\text{Coarse Aggregate} = 1674\ \text{lb}/((2.68 + 0.025) \times 62.4\ \text{pcf}) = 9.92\ \text{ft}^3$$

The volume of fine aggregate would be

$$27.00 - (4.33 + 3.27 + 1.89 + 9.92) = 7.59\ \text{ft}^3$$

When the specific gravity of the fine aggregate was changed by the within-lab D2S, the batch weight of fine aggregate would be

$$7.59\ \text{cu. ft} \times (2.64 = 0.032) \times 62.4\ \text{pcf} = 1266\ \text{lb (an increase of 30 lb or 2.4\%)}$$

The within-lab standard deviations (S_r) and acceptable range of two absorption results (D2S) from AASHTO T 84 and T 85 are

AASHTO T 84 Percent Absorption: $S_r = 0.11\%$, $\text{D2S}_r = 0.31\%$
AASHTO T 85 Percent Absorption: $S_r = 0.088\%$, $\text{D2S}_r = 0.25\%$

If the example absorption values for the coarse and fine aggregates were varied by these ranges, the fine aggregate would have an absorption of $0.7\% + 0.31\% = 1.01\%$, and the coarse aggregate would have an absorption of $0.5\% + 0.25\% = 0.75\%$. The free water contents of the coarse aggregates would be $2.0\% - 0.75\% = 1.25\%$, and for the fine aggregate, the free water percentage would be $6.0\% - 1.01\% = 4.99\%$. Thus, the adjusted batch weight for water would be

$$270\ \text{lb} - (1674\ \text{lb} \times 0.0125) - (1266\ \text{lb} \times 0.0499) = 186\ \text{lb}$$

This is a change of 7 pounds (less than 4 percent) in the batch weight for the water. According to the text on Batch Adjustments in *Design and Control of Concrete Mixtures* (*31*, p 165), increasing the mixing water content by 5 pounds will decrease the air content by 1 percent and increase the slump by one-half inch.

Therefore, for concrete mix designs, changes in specific gravities for the aggregates that are less than the repeatability of the Gsb determinations could result in a small change in the proportions of coarse and fine aggregate but are not likely to have a substantial impact on properties of the fresh or hardened concrete.

Changes in aggregate absorption values by the practical range of the within-lab D2S limits will have a small impact on the air content and workability of the concrete. Based on Figure 9.4 in *Design and Control of Concrete Mixtures* (*31*), a loss of 1 percent air could have a moderate impact on the resistance of the concrete to freeze-thaw and deicing chemicals.

In summary, the practical ranges of the within-lab precision estimates for Gsb determinations are reasonable for concrete. However, for asphalt, the Gsb test result has a very large impact on VMA, one of the more critical criteria for asphalt mix design and acceptance. To reduce the impact on VMA to a tolerable level, the acceptable range of differences between within-lab replicates alternative methods would have to be less than 0.010, which is about one-third of what is currently practically attainable.

CHAPTER 6

Conclusions and Recommendations

Current standard test methods for determining the specific gravity and water absorption of coarse and fine aggregates are AASHTO T 85 (or ASTM C127) and AASHTO T 84 (or ASTM C128), respectively. There are also several modified and new test methods for determining these properties; these range from simple modifications to procedures for determining the SSD state in the standard test methods to new test methods with more complex, costly devices. These test methods were reviewed, and comparisons were provided in terms of precision, ruggedness of equipment, ease of use, soaking and testing time, equipment cost, and potential problems or problematic materials. Based on the review results, 10 test methods were selected for further evaluation in this study.

The selected test methods were evaluated through a laboratory testing program. The laboratory program was originally planned in two experiments, but it was later expanded into five experiments. Experiment 1 was a preliminary evaluation to compare results and variability of the selected test methods. Experiment 2 was conducted to further evaluate the test methods selected at the conclusion of Experiment 1 with a broader range of aggregate materials.

At the conclusion of Experiment 1, six test methods were selected for further evaluation in Experiment 2. The other test methods were not further evaluated in this study because of additional costs of the CoreLok equipment and bags, the repeatability of SSDetect not being improved by removing the P200 fraction, and the poor precision of the Phunque method for testing a complete gradation.

Table 6-1 provides a comparison of the six test methods evaluated in Experiment 2. Of the two test methods evaluated for use with coarse aggregate, AASHTO T 85 provided better precision. For the four methods for testing fine aggregate, the SSDetect and Modified AASHTO T 84 methods provided a more reasonable balance of accuracy and precision than the other test methods. Based on the findings of Experiment 2, it was recommended that AASHTO T 85 be used for measuring specific gravity and absorption of coarse aggregate and the Modified AASHTO T 84 and SSDetect methods be used for measuring specific gravity and absorption of fine aggregate.

Among the three test methods, SSDetect is the only one that can be completed within one working day. Ruggedness and round robin studies for SSDetect were completed under a previous study. However, the AASHTO T 85 and Modified AASHTO T 84 (removal of P200) can take up to three working days to complete, which hinders the use of these tests for quality assurance (QA) purposes where results are desired as rapidly as possible. In addition, since the P200 portion of fine aggregate is not tested in the Modified AASHTO T 84, it may be assumed to have the same specific gravity as the other fine aggregate portion, or it can be tested according to ASTM C110 or AASHTO T 133 (with ethyl alcohol).

After reviewing the results of Experiments 1 and 2, Experiments 3, 4, and 5 were added to the laboratory testing program to answer specific questions related to the test procedures previously evaluated. Experiment 3 was conducted to evaluate modifications relative to the drying and soaking methods in AASHTO T 85 and T 84 to reduce the testing time. Experiment 4 was conducted to determine the effect of P200 on AASHTO T 84 test results. The purpose of Experiment 5 was to investigate the time-zero reading for Phunque methods.

In Experiment 3, alternative methods for drying and soaking aggregate to reduce the testing time for AASHTO T 85 and T 84 were evaluated. Instead of using the standard oven-drying method, the aggregate sample can be dried using a vacuum-drying method or tested in its in-situ moisture condition. The vacuum-drying method using the CoreDry device was promising, but it was not able to completely dry highly absorptive materials such as BF slag coarse aggregate and recycled concrete. The results of Experiment 4 showed that testing the aggregate in its in-situ moisture condition was a better alternative to the standard oven-drying method.

The Gsb and Gssd results for the coarse and fine aggregates determined using the 5- and 10-minute vacuum-soaking method (similar to the one described in AASHTO T 209) were

Table 6-1. Comparison of test methods for determining specific gravity and absorption of aggregate.

ID	Test Method	Comments on Accuracy	Equipment Ruggedness	Ease of Use	Time		Eqmt. Cost	Other Comments
					Total	Operator		
I. Test Methods for Coarse Aggregate								
1	AASHTO T 85 and ASTM C127	Yields more accurate measurements of absorption, Gsb, and Gssd	Good	Manual	3 days	30 min.	\$100 ~ \$600	More accurate, repeatable, and reproducible than the Phunque method
2	AASHTO TP 77 (Phunque Method)	Yields less accurate measurements of absorption, Gsb, and Gssd	Fragile in current design	Manual	2 days	2 hrs	\$500	Questionable accuracy for measuring absorption, Gsb, and Gssd, especially for absorptive aggregate
II. Test Methods for Fine Aggregate								
1	AASHTO T 84 and ASTM C128	Yields less accurate measurements of absorption, Gsb, and Gssd for materials with high P200 content	Good	Manual	3 days	1.5 hrs	\$100 ~ \$300	Accuracy, repeatability, and reproducibility are more affected by P200 content and less affected by absorption
2	Modified AASHTO T84 (Removal of P200)	Yields more accurate measurements of absorption, Gsb, and Gssd	Good	Manual	3 days	1.5 hrs	\$100 ~ \$300	Repeatability and reproducibility are affected by absorption; may require another test for P200 material
3	ASTM D 7172 (SSDetect)	Yields more accurate measurements of absorption, Gsb, and Gssd	Good	Auto	1 day	1 hr	\$7,000	Repeatability and reproducibility are affected by absorption; higher equipment cost, faster results
4	AASHTO TP 77 (Phunque Method)	Yields less accurate measurements of absorption, Gsb, and Gssd	Fragile in current design	Manual	2 days	2 hrs	\$500	Low equipment cost, somewhat fragile flasks, questionable accuracy for measuring absorption, Gsb, and Gssd, especially for absorptive aggregate

not statistically different from those measured according to the standard 15-hour soaking method. To reduce the testing time for QA purposes, soaking aggregate samples for 10 minutes should be considered as an alternative to the standard 15-hour soaking method.

The results of Experiment 4 showed the significant error caused by the presence of non-clay fines and clays in P200. Therefore, the fine aggregate portions retained on and passing the No. 200 sieve should be tested separately when the sand equivalent (AASHTO T 176) value of the fine aggregate is less than 75. The portion retained on the No. 200 sieve can be tested according to AASHTO T 84. The P200 can be tested in accordance with ASTM C110, Section 21, ASTM D 854, or AASHTO T 133 (with ethyl alcohol). It is noted that the suggested sand equivalent value (less than 75) was determined based on limited data collected in this project, so it should be verified in the future. In addition, only the sand equivalent test was conducted in this research to determine the presence of clay-like materials in the P200. The hydrometer analysis (AASHTO T 88) and the methylene blue test (AASHTO T 330) also may be used if thresholds similar to the one for the sand equivalent test are developed for these tests in the future.

Based on the results of the laboratory evaluation program, proposed changes to AASHTO T 85 and T 84 were incorporated into the test procedures. The ruggedness study was then conducted to evaluate the sensitivity of AASHTO T 85 and T 84 to the changes in levels of operating and environmental factors.

For AASHTO T 85, the following changes are proposed (see Appendix A):

- The aggregate size (either retained on the 4.75-mm (No. 4) sieve or retained on the 2.36-mm [No. 8] sieve) was found to be significant. Thus, in Section 7.2, testing should be conducted on the same aggregate size in the agency's and contractor's laboratories.
- The temperature of the aggregate (either at approximately 110°C or at approximately 50°C) at the time of being submersed in the water was found to be a significant factor. Hence, in Section 8.1, an oven-dried sample should be allowed to cool to a temperature (approximately 50°C) that is comfortable to handle before being submerged in water at room temperature.
- The method of drying the soaked aggregate sample (using either a dry or wet cloth) also was found to be significant. Therefore, in Section 8.3, the agency's and contractor's laboratories should use the same method to dry the surface of soaked aggregate particles to an SSD condition.
- The water bath temperature was found to be significant. Thus, the water bath temperature specified in Section 8.3 should be changed from 23.0 ± 1.7°C (73.4 ± 3°F) to 23.0 ± 1°C (73.4 ± 1.8°F) to improve the test variability. The tolerance of ± 1°C is recommended because it can be reasonably controlled in a laboratory.

AASHTO T 84 was found to be sensitive to several test parameters. The following changes are proposed for AASHTO T 84 (see Appendix B):

- The P200 portion was found to be the most significant factor and should be tested separately. This suggests that in Section 7.1, only the portion of fine aggregate retained on the No. 200 sieve be tested according to AASHTO T 84.
- The next significant factor was found to be the soaking time; thus, in Section 7.1.1, the soak time should be changed (1) from 10 ± 1 minutes to 10 ± 0.5 minutes for vacuum soaking and (2) from 15 to 16 hours instead of from 15 to 19 hours for hydrostatic soaking. These ranges were proposed because they can be reasonably controlled in the laboratory.
- The variability of the AASHTO T 84 test results also could be improved by using consistent methods for conducting the cone test (dropping the tamper 25 times at once or in four sets), eliminating air bubbles (mechanical or manual agitation), and determining the final mass of an oven-dried aggregate sample as soon as it is safe to do so.

In addition to the statistical significance analyzed above, the practical significance of the aggregate specific gravity test results also was determined for concrete and asphalt mix design methods. The practical ranges of the within-lab precision estimates for Gsb determinations are reasonable for concrete. However, for asphalt, the Gsb test result has a very large impact on VMA, one of the more critical criteria for asphalt mix design and acceptance. To reduce the impact on VMA to a tolerable level, the acceptable range of differences between within-lab replicates alternative methods would have to be less than 0.010, which is about one-third of what is currently practically attainable.

In summary, AASHTO T 85, SSDetect (ASTM D 7172), and Modified AASHTO T 84 were found to provide a better balance of accuracy and precision than the other test methods evaluated in this study. Several changes to AASHTO T 85 and T 84 were proposed to reduce testing time and improve test precision. Although the precision estimates for Gsb are reasonable for concrete proportioning, they are not practically attainable to reduce the impact on VMA required for asphalt mix design to an acceptable level.

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APPENDIX A

Revised AASHTO T 85

Standard Method of Test for

Specific Gravity and Absorption of Coarse Aggregate

AASHTO Designation: T 85-XX
ASTM Designation: C 127-XX

AASHTO
THE VOICE OF TRANSPORTATION

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

Standard Method of Test for

Specific Gravity and Absorption of Coarse Aggregate

AASHTO Designation: T 85-XX
ASTM Designation: C 127-XX

1. SCOPE

1.1. This method covers the determination of specific gravity and absorption of coarse aggregate. The specific gravity may be expressed as bulk specific gravity, bulk specific gravity (saturated surface-dry [SSD]), or apparent specific gravity. The bulk specific gravity (SSD) and absorption are based on aggregate after 15–19 h of soaking in water. This method is not intended to be used with lightweight aggregates.

1.2. The values stated in SI units are to be regarded as the standard.

1.3. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices, and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:
- M 43, Sizes of Aggregate for Road and Bridge Construction
- M 80, Coarse Aggregate for Hydraulic Cement Concrete
- M 92, Wire-Cloth Sieves for Testing Purposes
- M 231, Weighing Devices Used in the Testing of Materials
- T 2, Sampling of Aggregates
- T 19M/T 19, Bulk Density (“Unit Weight”) and Voids in Aggregate
- T 27, Sieve Analysis of Fine and Coarse Aggregates
- T 84, Specific Gravity and Absorption of Fine Aggregate
- T 209, Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)
- T 248, Reducing Samples of Aggregate to Testing Size
- T 255, Total Evaporable Moisture Content of Aggregate by Drying

2.2. *ASTM Standard*:
- C 670, Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials

2.3. *IEEE/ASTM Standard*:
- SI 10, American National Standard for Metric Practice

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. *Absorption*—the increase in the mass of aggregate due to water in the pores of the material, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry mass. The aggregate is considered "dry" when it has been maintained at a temperature of 110 ± 5°C for sufficient time to remove all uncombined water by reaching a constant mass.

3.1.2. *Specific Gravity*—the ratio of the mass (or weight in air) of a unit volume of a material to the mass of the same volume of gas-free distilled water at stated temperatures. Values are dimensionless.

3.1.2.1. *Apparent Specific Gravity*—the ratio of the weight in air of a unit volume of the impermeable portion of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

3.1.2.2. *Bulk Specific Gravity*—the ratio of the weight in air of a unit volume of aggregate (including the permeable and impermeable voids in the particles, but not including the voids between particles) at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

3.1.2.3. *Bulk Specific Gravity (SSD)*—the ratio of the mass in air of a unit volume of aggregate, including the mass of water within the voids filled to the extent achieved by submerging in water for 15–19 h (but not including the voids between particles) at a stated temperature, compared to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

4. SUMMARY OF METHOD

4.1. A sample of aggregate is immersed in water essentially to fill the pores. It is then removed from the water, the water dried from the surface of the particles, and weighed. Subsequently, the sample is weighed while submerged in water. Finally, the sample is oven-dried and weighed a third time. Using the mass and weight measurements thus obtained, and the formulas in the method, it is possible to calculate three types of specific gravity and absorption.

5. SIGNIFICANCE AND USE

5.1. Bulk specific gravity is the characteristic generally used for calculation of the volume occupied by the aggregate in various mixtures containing aggregate, including portland cement concrete (PCC), bituminous concrete, and other mixtures that are proportioned or analyzed on an absolute volume basis. Bulk specific gravity is also used in the computation of voids in aggregate in T 19M/T 19. Bulk specific gravity (SSD) is used if the aggregate is wet, that is, if its absorption has been satisfied. Conversely, the bulk specific gravity (oven dry) is used for computations when the aggregate is dry or assumed to be dry.

5.2. Apparent specific gravity pertains to the relative density of the solid material making up the constituent particles not including the pore space within the particles that is accessible to water.

5.3. Absorption values are used to calculate the change in the mass of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition, when it is deemed that the aggregate has been in contact with water long enough to satisfy most of the absorption potential. The laboratory standard for absorption is that obtained after soaking dry aggregate in water. Aggregates mined from below the water table may have a higher absorption, when used, if not allowed to dry. Conversely, some aggregates when used may contain an amount of absorbed moisture less than the required amount of time to achieve the soaked condition. For an aggregate that has been in contact with water and has free moisture on the particle surfaces, the percentage of free moisture can be determined by deducting the absorption from the total moisture content determined by T 255.

5.4. The general procedures described in this method are suitable for determining the absorption of aggregates that have had conditioning other than the required soak, such as boiling water or vacuum saturation. The values obtained for absorption by other methods will be different than the values obtained by the required soak, as will the bulk specific gravity (SSD).

5.5. The pores in lightweight aggregates may or may not become essentially filled with water after the required soaking period. In fact, many such aggregates can remain immersed in water for several days without satisfying most of the aggregates' absorption potential. Therefore, this method is not intended for use with lightweight aggregate.

6. APPARATUS

6.1. *Balance*—Conforming to the requirements of M 231, Class G 5. The balance shall be equipped with suitable apparatus for suspending the sample container in water from the center of the weighing platform or pan of the balance.

6.2. *Sample Container*—A wire basket of 3.35 mm (No. 6) or finer mesh, or a bucket of approximately equal breadth and height, with a capacity of 4 to 7 L for 37.5-mm ($1^1/_2$-in.) nominal maximum size aggregate or smaller, and a larger container as needed for testing larger maximum size aggregate. The container shall be constructed so as to prevent trapping air when the container is submerged.

6.3. *Water Tank*—A watertight tank into which the sample and container are placed for complete immersion while suspended below the balance, equipped with an overflow outlet for maintaining a constant water level.

6.4. *Suspended Apparatus*—Wire suspending the container shall be of the smallest practical size to minimize any possible effects of a variable immersed length.

6.5. *Sieves*—A 4.75-mm (No. 4) sieve or other sizes as needed (Sections 7.2, 7.3, and 7.4), conforming to M 92.

7. SAMPLING

7.1. Sample the aggregate in accordance with T 2.

7.2. Thoroughly mix the sample of aggregate and reduce it to the approximate quantity needed using the applicable procedures in T 248. Reject all material passing a 4.75-mm (No. 4) sieve by dry sieving and thoroughly washing to remove dust or other coatings from the surface. If the coarse aggregate contains a substantial quantity of material finer than the 4.75-mm (No. 4) sieve (such as for Size No. 8 and 9 aggregates in M 43), use the 2.36-mm (No. 8) sieve in place of the 4.75-mm (No. 4) sieve. Alternatively, separate the material finer than the 4.75-mm (No. 4) sieve and test the finer material according to T 84.

Note 1—The sieve size used to separate the coarse aggregate from the fine aggregate (e.g., 4.75-mm or 2.36-mm) has been found to be a significant factor affecting the final test results. Therefore, the same sieve should be used consistently for a given product to reduce the test variability.

7.3. The minimum mass of test sample to be used is given below. In many instances it may be desirable to test a coarse aggregate in several separate size fractions; if the sample contains more than 15 percent retained on the 37.5-mm ($1^1/_2$-in.) sieve, test the material larger than 37.5 mm in one or more size fractions separately from the smaller size fractions. When an aggregate is tested in separate size fractions, the minimum mass of test sample for each fraction shall be the difference between the masses prescribed for the maximum and minimum sizes of the fraction.

Nominal Maximum Size, mm (in.)	Minimum Mass of Test Sample, kg (lb)
12.5 ($^1/_2$) or less	2 (4.4)
19.0 ($^3/_4$)	3 (6.6)
25.0 (1)	4 (8.8)
37.5 ($1^1/_2$)	5 (11)
50 (2)	8 (18)
63 ($2^1/_2$)	12 (26)
75 (3)	18 (40)
90 ($3^1/_2$)	25 (55)
100 (4)	40 (88)
112 ($4^1/_2$)	50 (110)
125 (5)	75 (165)
150 (6)	125 (276)

7.4. If the sample is tested in two or more size fractions, determine the grading of the sample in accordance with T 27, including the sieves used for separating the size fractions for the determinations in this method. In calculating the percentage of material in each size fraction, ignore the quantity of material finer than the 4.75-mm (No. 4) sieve or 2.36-mm (No. 8) sieve when that sieve is used in accordance with Section 7.2.

8. PROCEDURE

8.1. Dry the test sample to constant mass at a temperature of 110 ± 5°C (230 ± 9°F), cool in air at room temperature for 1 to 3 h for test samples of 37.5-mm ($1^1/_2$-in.) nominal maximum size or smaller. For larger sizes, cool the sample to a temperature that is comfortable to handle (approximately 50°C). Subsequently immerse the aggregate in water at room temperature for a period of 15 to 16 h.

Note 2—Adding water to an oven-dried aggregate sample before it has cooled to a temperature that is comfortable to handle (approximately 50ºC) has been found to significantly affect the final test results, especially for absorptive aggregate. Therefore, the oven-dried sample should be cooled to a temperature that is comfortable to handle before being submersed under water.

Note 3—For aggregate with absorption less than 2 percent, the requirement for initial drying to constant mass may be eliminated, and a vacuum soaking method using the testing apparatus arrangement described in AASHTO T 209 may be used in place of the 15-h soaking. Place the test sample into a vacuum container. Add sufficient water to cover the sample completely. Remove entrapped air and saturate the aggregate surface voids 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 ± 0.5 min. Agitate the container and contents during the vacuum period using a mechanical device or by vigorously shaking at intervals of about 2 min. At the end of the vacuum period, release the vacuum by increasing the pressure at a rate not to exceed 8 kPa (60 mm Hg) per second.

Note 4—When testing coarse aggregate of large nominal maximum size requiring large test samples, it may be more convenient to perform the test on two or more subsamples, and the values obtained combined for the computation described in Section 9.

8.2. As an alternative to Section 8.1, where the absorption and specific gravity values are to be used in proportioning concrete mixtures in which the aggregates will be in their naturally moist condition, the requirement for initial drying to constant mass may be eliminated and, if the surfaces of the particles in the sample have been kept continuously wet until test, the required soaking may also be eliminated.

Note 5—Values for absorption and bulk specific gravity (SSD) may be significantly higher for aggregate not oven dried before soaking than for the same aggregate treated in accordance with Section 8.1. This is especially true of particles larger than 75 mm (3 in.) because the water may not be able to penetrate the pores to the center of the particle in the required soaking period.

8.3. Remove the test sample from the water and roll it in a large absorbent cloth until all visible films of water are removed. Wipe the larger particles individually. A moving stream of air may be used to assist in the drying operation. Take care to avoid evaporation of water from aggregate pores during the operation of surface drying. If the test sample dries past the SSD condition, immerse in water for 30 min, then resume the process of surface drying. Determine the mass of the test sample in the saturated surface-dry condition. Record this and all subsequent masses to the nearest 1.0 g or 0.1 percent of the sample mass, whichever is greater.

Note 6—Using a dry cloth versus a damp cloth has been found to yield significantly different test results. Therefore, either a dry cloth or a damp cloth should be used consistently to reduce test variability.

8.4. After determining the mass, immediately place the saturated surface-dry test sample in the sample container and determine its mass in water at 23.0 ± 1°C (73.4 ± 1.8°F), having a density of 997 ± 2 kg/m^3. Take care to remove all entrapped air before determining the mass by shaking the container while immersed. Maintain the water level in the bath at the overflow depth to obtain a constant water level throughout the test.

Note 7—The container should be immersed to a depth sufficient to cover it and the test sample during mass determination. Wire suspending the container should be of the smallest practical size to minimize any possible effects of a variable immersed length.

8.5. Dry the test sample to constant mass at a temperature of 110 ± 5°C (230 ± 9°F), cool in air at room temperature 1 to 3 h, or until the aggregate has cooled to a temperature that is comfortable to handle (approximately 50°C), and determine the mass. Use this weight for A in the calculations in Section 9.

9. CALCULATIONS

9.1. *Specific Gravity*:

9.1.1. *Bulk Specific Gravity*—Calculate the bulk specific gravity, 23/23°C (73.4/73.4°F), as follows:

$$\text{bulk sp gr} = A/(B-C) \tag{1}$$

where:

A = mass of oven-dry test sample in air, g;

B = mass of saturated surface-dry test sample in air, g; and

C = mass of saturated test sample in water, g.

9.1.2. *Bulk Specific Gravity (Saturated Surface-Dry)*—Calculate the bulk specific gravity, 23/23°C (73.4/73.4°F), on the basis of mass of saturated surface-dry aggregate as follows:

$$\text{bulk sp gr (saturated surface-dry)} = B/(B-C) \tag{2}$$

9.1.3. *Apparent Specific Gravity*—Calculate the apparent specific gravity, 23/23°C (73.4/73.4°F), as follows:

$$\text{apparent sp gr} = A/(A-C) \tag{3}$$

9.2. *Average Specific Gravity Values*—When the sample is tested in separate size fractions, the average value for bulk specific gravity, bulk specific gravity (SSD), or apparent specific gravity can be computed as the weighted average of the values as computed in accordance with Section 9.1 using the following equation:

$$G = \frac{1}{\frac{P_1}{100G_1}+\frac{P_2}{100G_2}+\cdots+\frac{P_n}{100G_n}} \tag{4}$$

where:

G = average specific gravity (all forms of expression of specific gravity can be averaged in this manner);
$P_1, P_2 \ldots P_n$ = mass percentages of each size fraction present in the original sample; and
$G_1, G_2 \ldots G_n$ = appropriate specific gravity values for each size fraction depending on the type of specific gravity being averaged.

Note 8—Some users of this method may wish to express the results in terms of density. Density may be determined by multiplying the bulk specific gravity, bulk specific gravity (SSD), or apparent specific gravity by the density of water (997.5 kg/m^3 or 0.9975 Mg/m^3 or 62.27 lb/ft^3 at 23°C). Some authorities recommend using the density of water at 4°C (1000 kg/m^3 or 1.000 Mg/m^3 or 62.43 lb/ft)^3 as being sufficiently accurate. The density terminology corresponding to bulk specific gravity, bulk specific gravity (SSD), and apparent specific gravity has not been standardized.

9.3. *Absorption*—Calculate the percentage of absorption, as follows:

$$\text{absorption, percent } = \left[(B-A)/A\right] \times 100 \tag{5}$$

9.4. *Average Absorption Value*—When the sample is tested in separate size fractions, the average absorption value is the average of the values as computed in Section 9.3, weighted in proportion to the mass percentages of the size fractions in the original sample as follows:

$$A = \frac{P_1A_1}{100} + \frac{P_2A_2}{100} + \cdots + \frac{P_nA_n}{100} \tag{6}$$

where:

A = average absorption, percent;
$P_1, P_2 \ldots P_n$ = mass percentages of each size fraction present in the original sample; and
$A_1, A_2 \ldots A_n$ = absorption percentages for each size fraction.

10. REPORT

10.1. Report specific gravity results to the nearest 0.001 (coarse aggregate meeting M 80 requirements may be reported to the nearest 0.01), and indicate the type of specific gravity, whether bulk, bulk (saturated surface-dry), or apparent.

10.2. Report the absorption result to the nearest 0.1 percent.

10.3. If the specific gravity and absorption values were determined without first drying the aggregate, as permitted in Section 8.2, it shall be noted in the report.

11. PRECISION AND BIAS

11.1. The estimates of precision of this test method listed in Table 1 are based on results from the AASHTO Materials Reference Laboratory Reference Sample Program, with testing conducted by this test method and ASTM C 127. The significant difference between the methods is that ASTM C 127 requires a saturation period of 24 ± 4 h, while T 85 requires a saturation period of 15-19 h. This difference has been found to have insignificant effect on the precision indices. The data are based on the analyses of more than 100 paired test results from 40 to 100 laboratories.

Table 1—Precision

	Standard Deviation (1s)[a]	Acceptable Range of Two Results (d2s)[a]
Single-operator precision:		
Bulk specific gravity (dry)	0.009	0.025
Bulk specific gravity (SSD)	0.007	0.020
Apparent specific gravity	0.007	0.020
Absorption,[b] percent	0.088	0.25
Multilaboratory precision:		
Bulk specific gravity (dry)	0.013	0.038
Bulk specific gravity (SSD)	0.011	0.032
Apparent specific gravity	0.011	0.032
Absorption,[b] percent	0.145	0.41

[a] These numbers represent, respectively, the (1s) and (d2s) limits as described in ASTM C 670. The precision estimates were obtained from the analysis of combined AASHTO Materials Reference Laboratory reference sample data from laboratories using 15-h minimum saturation times and other laboratories using 24 ± 4-h saturation time. Testing was performed on aggregates of normal specific gravities and started with aggregates in the oven-dry condition.

[b] Precision estimates are based on aggregates with absorptions of less than 2 percent.

11.2. *Bias*—Because there is no accepted reference material for determining the bias for the procedure in this test method, no statement on bias is being made.

APPENDIXES

(Nonmandatory Information)

X1. DEVELOPMENT OF EQUATIONS

X1.1. The derivation of the equation is apparent from the following simplified cases using two solids. Solid 1 has a mass W_1 in grams and a volume V_1 in milliliters; its specific gravity (G_1) is therefore W_1/V_1. Solid 2 has a mass W_2 and volume V_2, and $G_2 = W_2/V_2$. If the two solids are considered together, the specific gravity of the combination is the total mass in grams divided by the total volume in milliliters:

$$G = \left(W_1 + W_2\right) / \left(V_1 + V_2\right) \tag{X1.1}$$

Manipulation of this equation yields the following:

$$G = \frac{1}{\dfrac{V_1 + V_2}{W_1 + W_2}} = \frac{1}{\dfrac{V_1}{W_1 + W_2} + \dfrac{V_2}{W_1 + W_2}} \tag{X1.2}$$

$$G = \frac{1}{\frac{W_1}{W_1 + W_2}\left(\frac{V_1}{W_1}\right) + \frac{W_2}{W_1 + W_2}\left(\frac{V_2}{W_2}\right)} \qquad (X1.3)$$

However, the mass fractions of the two solids are as follows:

$$W_1 / \left(W_1 + W_2\right) = P_1 / 100 \qquad (X1.4)$$

and

$$W_2 / \left(W_1 + W_2\right) = P_2 / 100 \qquad (X1.5)$$

and

$$1 / G_1 = V_1 / W_1 \text{ and } 1 / G_2 = V_2 / W_2 \qquad (X1.6)$$

therefore

$$G = 1 / \left[\left(P_1 / 100\right)\left(1 / G_1\right) + \left(P_2 / 100\right)\left(1 / G_2\right)\right] \qquad (X1.7)$$

An example of the computation is given in Table X1.1.

Table X1.1—Example Calculation of Average Values of Specific Gravity and Absorption for a Coarse Aggregate Tested in Separate Sizes

Size Fraction, mm (in.)	Percent in Original Sample	Bulk Specific Gravity (SSD)[a]	Sample Mass Used in Test, g	Absorption, %
4.75 to 12.5 (No. 4 to $^1/_2$)	44	2.72	2213.0	0.4
12.5 to 37.5 ($^1/_2$ to $1^1/_2$)	35	2.56	5462.5	2.5
37.5 to 63 ($1^1/_2$ to $2^1/_2$)	21	2.54	12593.0	3.0

[a] Average specific gravity (SSD)

$$G_{SSD} = \frac{1}{\frac{0.44}{2.72} + \frac{0.35}{2.56} + \frac{0.21}{2.54}} = 2.62 \qquad (X1.8)$$

Average absorption:

$$A = (0.44)(0.4) + (0.35)(2.5) + (0.21)(3.0) = 1.7\% \qquad (X1.9)$$

X2. INTERRELATIONSHIPS BETWEEN SPECIFIC GRAVITIES AND ABSORPTION AS DEFINED IN METHODS T 85 AND T 84

X2.1. Let:

S_d = bulk specific gravity (dry basis),
S_s = bulk specific gravity (SSD basis),
S_a = apparent specific gravity, and
A = absorption in percent.

Then:

$$S_s = \left(1 + A / 100\right) S_d \qquad (X2.1)$$

$$S_a = \frac{1}{\frac{1}{S_d} - \frac{A}{100}} = \frac{S_d}{1 - \frac{AS_d}{100}} \tag{X2.2}$$

$$S_a = \frac{1}{\frac{1 + A/100}{S_s} - \frac{A}{100}} \tag{X2.3}$$

$$= \frac{S_s}{1 - \left(\frac{A}{100}\left(S_s - 1\right)\right)}$$

$$A = \left(\frac{S_s}{S_d} - 1\right)100 \tag{X2.4}$$

$$A = \left(\frac{S_a - S_s}{S_a\left(S_s - 1\right)}\right)100 \tag{X2.5}$$

APPENDIX B

Revised AASHTO T 84

Standard Method of Test for

Specific Gravity and Absorption of Fine Aggregate

AASHTO Designation: T 84-XX[1]
ASTM Designation: C 128-XX

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

Standard Method of Test for

Specific Gravity and Absorption of Fine Aggregate

AASHTO Designation: T 84-XX[1]

ASTM Designation: C 128-XX

1. SCOPE

1.1. This method covers the determination of bulk and apparent specific gravity, 23/23°C (73.4/73.4°F), and absorption of fine aggregate.

1.2. This method determines (after 15–19 h of soaking in water) the bulk specific gravity and the apparent specific gravity, the bulk specific gravity on the basis of mass of saturated surface-dry aggregate, and the absorption.

1.3. The values stated in SI units are to be regarded as the standard.

1.4. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of whomever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 6, Fine Aggregate for Hydraulic Cement Concrete
- M 231, Weighing Devices Used in the Testing of Materials
- T 2, Sampling of Aggregates
- T 11, Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
- T 19M/T 19, Bulk Density (“Unit Weight”) and Voids in Aggregate
- T 85, Specific Gravity and Absorption of Coarse Aggregate
- T 100, Specific Gravity of Soils
- T 133, Density of Hydraulic Cement
- T 209, Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)
- T 248, Reducing Samples of Aggregate to Testing Size
- T 255, Total Evaporable Moisture Content of Aggregate by Drying

2.2. *ASTM Standards*:

- C 128, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
- C 670, Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials

2.3. *IEEE/ASTM Standards*:

- SI 10, American National Standard for Metric Practice
- D 5550, Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. *Absorption*—the increase in the mass of aggregate due to water in the pores of the material, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry mass. The aggregate is considered "dry" when it has been maintained at a temperature of 110 ± 5°C for sufficient time to remove all uncombined water by reaching a constant mass.

3.1.2. *Specific Gravity*—the ratio of the mass (or weight in air) of a unit volume of a material to the mass of the same volume of gas-free distilled water at stated temperatures. Values are dimensionless.

3.1.2.1. *Apparent Specific Gravity*—the ratio of the weight in air of a unit volume of the impermeable portion of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

3.1.2.2. *Bulk Specific Gravity*—the ratio of the weight in air of a unit volume of aggregate (including the permeable and impermeable voids in the particles, but not including the voids between particles) at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

3.1.2.3. *Bulk Specific Gravity (SSD)*—the ratio of the mass in air of a unit volume of aggregate, including the mass of water within the voids filled to the extent achieved by submerging in water for 15–19 h (but not including the voids between particles) at a stated temperature, compared to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

4. SIGNIFICANCE AND USE

4.1. Bulk specific gravity is the characteristic generally used for calculation of the volume occupied by the aggregate in various mixtures containing aggregate including portland cement concrete (PCC), bituminous concrete, and other mixtures that are proportioned or analyzed on an absolute volume basis. Bulk specific gravity is also used in the computation of voids in aggregate in T 19M/T 19. Bulk specific gravity determined on the saturated surface-dry basis is used if the aggregate is wet; that is, if its absorption has been satisfied. Conversely, the bulk specific gravity determined on the oven-dry basis is used for computations when the aggregate is dry or assumed to be dry.

4.2. Apparent specific gravity pertains to the relative density of the solid material making up the constituent particles not including the pore space within the particles that is accessible to water. This value is not widely used in construction aggregate technology.

4.3. Absorption values are used to calculate the change in the mass of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition, when it is deemed that the aggregate has been in contact with water long enough to satisfy most of the absorption potential. The laboratory standard for absorption is that obtained after soaking dry aggregate in water. Aggregates mined from below the water table may have a higher absorption when used, if not allowed to dry. Conversely, some aggregates when used may contain an amount of absorbed moisture less than that achieved by the required amount of soaking time: For an aggregate that has been in contact with water and that has free moisture on the particle surfaces, the percentage of free moisture can be determined by deducting the absorption from the total moisture content determined by T 255 by drying.

5. APPARATUS

5.1. *Balance*, conforming to the requirements of M 231, Class G 2.

5.2. *Pycnometer*—A flask or other suitable container into which the fine aggregate test sample can be readily introduced and in which the volume content can be reproduced with ±100 mm^3. The volume of the container filled to mark shall be at least 50 percent greater than the space required to accommodate the test sample. A volumetric flask of 500-mL capacity or a fruit jar fitted with a pycnometer top is satisfactory for a 500-g test sample of most fine aggregates. A Le Chatelier flask as described in T 133 is satisfactory for an approximately 55-g test sample.

5.3. *Mold*—A metal mold in the form of a frustum of a cone with dimensions as follows: 40 ± 3 mm inside diameter at the top, 90 ± 3 mm inside diameter at the bottom, and 75 ± 3 mm in height, with the metal having a minimum thickness of 0.8 mm.

5.4. *Tamper*—A metal tamper having a mass of 340 ± 15 g and having a flat circular tamping face 25 ± 3 mm in diameter.

6. SAMPLING

6.1. Sampling shall be accomplished in general accordance with T 2.

7. PREPARATION OF TEST SPECIMEN

7.1. Obtain approximately 1 kilogram of the fine aggregate from the sample using the applicable procedures described in T 248.

7.1.1. 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 comfortable handling temperature. Remove the material finer than 75 µm from the test sample by dry sieving. Subsequently, cover the sample with water, either by immersion or by the addition of at least 6 percent moisture to the fine aggregate and permit to stand for 15–16 h.

Note 1—The removed material finer than 75 µm can be assumed to have the same specific gravity as the fine aggregate. Alternatively, the specific gravity of the material finer than 75 µm may be determined using T 100 (with ethyl alcohol), T 133 (with ethyl alcohol), or D5550; however, these test methods determine the apparent specific gravity and not the bulk specific gravity. The apparent specific gravity of the material finer than 75 µm can be combined with the bulk specific gravity of the material coarser than 75 µm using the weighted average calculation shown in Appendix X.3.

Note 2—As an alternative to Section 7.1.1, for aggregate with absorption less than 2 percent, the requirement for initial drying to constant mass may be eliminated. Also, a vacuum soaking method using the testing apparatus arrangement described in AASHTO T 209 may be used in place of the 15-h soaking. Remove the material finer than 75 µm from the test sample by dry sieving or washing. Place the test sample into a vacuum container. Add sufficient water to cover the sample completely. Remove entrapped air and saturate the aggregate surface voids 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 ± 0.5 min. Agitate the container and contents during the vacuum period using a mechanical device or by vigorously shaking at intervals of about 2 min. At the end of the vacuum period, release the vacuum by increasing the pressure at a rate not to exceed 8 kPa (60 mm Hg) per second.

7.1.2. As an alternative to Section 7.1.1, where the absorption and specific gravity values are to be used in proportioning concrete mixtures with aggregates used in their naturally moist condition, the requirement for initial drying to constant mass may be eliminated and, if the surfaces of the particles have been kept wet, the required soaking may also be eliminated.

Note 3—Values for absorption and for specific gravity in the saturated surface-dry condition may be significantly higher for aggregate not oven dried before soaking than for the same aggregate treated in accordance with Section 7.1.1.

7.2. Decant excess water with care to avoid loss of fines, spread the sample on a flat, nonabsorbent surface exposed to a gently moving current of warm air, and stir frequently to secure homogeneous drying. If desired, mechanical aids such as tumbling or stirring may be employed to assist in achieving the saturated surface-dry condition. As the material begins to dry sufficiently, it may be necessary to work it with the hands in a rubbing motion to break up any conglomerations, lumps, or balls of material that develop. Continue this operation until the test specimen approaches a free-flowing condition. Follow the procedure in Section 7.2.1 to determine whether or not surface moisture is present on the constituent fine aggregate particles. It is intended that the first trial of the cone test will be made with some surface water in the specimen. Continue drying with constant stirring, and if necessary, work the material with a hand-rubbing motion, and test at frequent intervals until the test indicates that the specimen has reached a surface-dry condition. If the first trial of the surface moisture test indicates that moisture is not present on the surface, it has been dried past the saturated surface-dry condition. In this case, thoroughly mix a few milliliters of water with the fine aggregate and permit the specimen to stand in a covered container for 30 min. Then, resume the process of drying and testing at frequent intervals for the onset of the surface-dry condition.

7.2.1. *Cone Test for Surface Moisture*—Hold the mold firmly on a smooth nonabsorbent surface with the large diameter down. Place a portion of the partially dried fine aggregate loosely in the mold by filling until overflow occurs and heaping additional material above the top of the mold by holding it with the cupped fingers of the hand holding the mold. Lightly tamp the fine aggregate into the mold with 25 light drops of the tamper. Each drop should start about 5 mm (0.2 in.) above the top surface of the fine aggregate. Permit the tamper to fall freely under gravitational attraction on each drop. Adjust the starting height to the new surface elevation after each drop and distribute the drops over the surface. Remove loose sand from the base and lift the mold vertically. If surface moisture is still present, the fine aggregate will retain the molded shape. When the fine aggregate slumps slightly, it indicates that it has reached a surface-dry condition. Some angular fine aggregate or material with a high proportion of fines may not slump in the cone test upon reaching a surface-dry condition. This may be the case if fines become airborne upon dropping a handful of the sand from the cone test 100–150 mm onto a surface. For these materials, the saturated surface-dry condition should be considered as the point that one side of the fine aggregate slumps slightly upon removing the mold.

Note 4—The following criteria have also been used on materials that do not readily slump:

1. *Provisional Cone Test*—Fill the cone mold as described in Section 7.2.1 except only use 10 drops of the tamper. Add more fine aggregate and use 10 drops of the tamper again. Then add material two more times using three and two drops of the tamper, respectively. Level off the material even with the top of the mold; remove loose material from the base; and lift the mold vertically.
2. *Provisional Surface Test*—If airborne fines are noted when the fine aggregate is such that it will not slump when it is at a moisture condition, add more moisture to the sand, and at the onset of the surface-dry condition, with the hand, lightly pat approximately 100 g of the material on a flat, dry, clean, dark, or dull nonabsorbent surface such as a sheet of rubber, a worn oxidized, galvanized, or steel surface, or a black-painted metal surface. After 1 to 3 s,

remove the fine aggregate. If noticeable moisture shows on the test surface for more than 1 to 2 s, then surface moisture is considered to be present on the fine aggregate.

3. Colorimetric procedures described by Kandhal and Lee, *Highway Research Record No. 307*, p. 44.
4. For reaching the saturated surface-dry condition on a single-size material that slumps when wet, hard-finish paper towels can be used to surface dry the material until the point is just reached where the paper towel does not appear to be picking up moisture from the surfaces of the fine aggregate particles.

8. PROCEDURE

8.1. Make and record all mass determinations to 0.1 g.

8.2. Partially fill the pycnometer with water. Immediately introduce into the pycnometer 500 ± 10 g of saturated surface-dry fine aggregate prepared as described in Section 7, and fill with additional water to approximately 90 percent of capacity. Manually roll, invert, and agitate or use a combination of these actions to eliminate all air bubbles in the pycnometer (Note 5). Accomplish mechanical agitation by external vibration of the pycnometer in a manner that will not degrade the sample. A level of agitation adjusted to just set individual particles in motion is sufficient to promote de-airing without degradation. A mechanical agitator shall be considered acceptable for use if comparison tests for each 6-month period of use show variations less than the acceptable range of two results (d2s) indicated in Table 1 from results of manual agitation on the same material. Adjust its temperature to 23.0 ± 1°C (73.4 ± 1.8°F), if necessary, by immersion in circulating water, and bring the water level in the pycnometer to its calibrated capacity. Determine total mass of the pycnometer, specimen, and water.

Note 5—It normally takes about 15 to 20 min to eliminate air bubbles by manual methods. Dipping the tip of a paper towel into the pycnometer has been found to be useful in dispersing the foam that sometimes builds up when eliminating the air bubbles, or adding a few drops of isopropyl alcohol, after removal of air bubbles and just prior to bringing the water level to its calibrated capacity, has also been found useful in dispersing foam on the water surface. Do not use isopropyl alcohol when using the alternative method described in Section 8.2.1.

Table 1—Precision

	Standard Deviation (1s)[a]	Acceptable Range of Two Results (d2s)[a]
Single-operator precision:		
Bulk specific gravity (dry)	0.011	0.032
Bulk specific gravity (SSD)	0.0095	0.027
Apparent specific gravity	0.0095	0.027
Absorption,[b] percent	0.11	0.31
Multilaboratory precision:		
Bulk specific gravity (dry)	0.023	0.066
Bulk specific gravity (SSD)	0.020	0.056
Apparent specific gravity	0.020	0.056
Absorption,[b] percent	0.23	0.66

[a] These numbers represent, respectively, the (1s) and (d2s) limits as described in ASTM C 670. The precision estimates were obtained from the analysis of combined AASHTO Materials Reference Laboratory reference sample data from laboratories using 15- to 19-h saturation times and other laboratories using 24 ± 4 h of saturation time. Testing was performed on aggregates of normal specific gravities, and started with aggregates in the oven-dry condition.

[b] Precision estimates are based on aggregates with absorptions of less than 1 percent and may differ for manufactured fine aggregates having absorption values greater than 1 percent.

8.2.1. *Alternative to Determining the Mass in Section 8.2*—The quantity of added water necessary to fill the pycnometer at the required temperature may be determined volumetrically using a buret accurate to 0.15 mL. Compute the total mass of the pycnometer, specimen, and water as follows:

$$C = 0.9975\,V_a + S + W \qquad (1)$$

where:

C = mass of pycnometer with specimen and water to calibration mark, g;
V_a = volume of water added to pycnometer, mL;
S = mass of saturated surface-dry specimen, g; and
W = mass of the pycnometer empty, g.

8.2.2. *Alternative to the Procedure in Section 8.2*—Use a Le Chatelier flask initially filled with water to a point on the stem between the 0- and the 1-mL mark. Record this initial reading with the flask and contents within the temperature range of 23.0 ± 1°C (73.4 ± 1.8°F). Add 55 ± 5 g of fine aggregate in the saturated surface-dry condition (or other mass as necessary to result in raising the water level to some point on the upper series of graduation). After all fine aggregate has been introduced, place the stopper in the flask and roll the flask in an inclined position, or gently whirl it in a horizontal circle so as to dislodge all entrapped air, continuing until no further bubbles rise to the surface (Note 6). Take a final reading with the flask and contents within 1°C (1.8°F) of the original temperature.

Note 6—When using the Le Chatelier flask method, slowly adding a small measured amount (not to exceed 1 mL) of isopropyl alcohol, after removal of air bubbles, has been found useful in dispersing foam appearing on the water surface. The volume of alcohol used must be subtracted from the final reading (R_2).

8.3. Remove the fine aggregate from the pycnometer, dry to constant mass at a temperature of 110 ± 5°C (230 ± 9°F), cool in air at room temperature for 1.0 ± 0.5 h and determine the mass.

Note 7—In lieu of drying and determining the mass of the sample that has been removed from the pycnometer, a second portion of the saturated surface-dry sample may be used to determine the oven-dry mass. This sample must be obtained at the same time and be within 0.2 grams of the mass of the sample that is introduced into the pycnometer.

8.3.1. If the Le Chatelier flask method is used, a separate sample portion is needed for the determination of absorption. Weigh a separate 500 ± 10 g portion of the saturated surface-dry fine aggregate, dry to constant mass, and reweigh. This sample must be obtained at the same time as the sample that is introduced into the Le Chatelier flask.

8.4. Determine the mass of the pycnometer filled to its calibration capacity with water at 23.0 ± 1°C (73.4 ± 1.8°F).

8.4.1. *Alternative to Determining the Mass in Section 8.4*—The quantity of water necessary to fill the empty pycnometer at the required temperature may be determined volumetrically using a buret accurate to 0.15 mL. Calculate the mass of the pycnometer filled with water as follows:

$$B = 0.9975\,V + W \qquad (2)$$

where:

B = mass of flask filled with water, g;
V = volume of flask, mL; and
W = mass of the flask empty, g.

9. BULK SPECIFIC GRAVITY

9.1. Calculate the bulk specific gravity, 23/23°C (73.4/73.4°F), as follows:

$$\text{bulk sp gr} = A/(B + S - C) \tag{3}$$

where:

A = mass of oven-dry specimen in air, g;
B = mass of pycnometer filled with water, g;
S = mass of saturated surface-dry specimen, g; and
C = mass of pycnometer with specimen and water to calibration mark, g.

9.1.1. If the Le Chatelier flask method was used, calculate the bulk specific gravity, 23/23°C, as follows:

$$\text{bulk sp gr} = \frac{S_1(A/S)}{0.9975(R_2 - R_1)} \tag{4}$$

where:

S_1 = mass of saturated surface-dry specimen used in Le Chatelier flask, g;
R_2 = final reading of water level in Le Chatelier flask; and
R_1 = initial reading of water level in Le Chatelier flask.

10. BULK SPECIFIC GRAVITY (SATURATED SURFACE-DRY BASIS)

10.1. Calculate the bulk specific gravity, 23/23°C (73.4/73.4°F), on the basis of mass of saturated surface-dry aggregate as follows:

$$\text{bulk sp gr}(\text{saturated surface-dry basis}) = S/(B + S - C) \tag{5}$$

10.1.1. If the Le Chatelier flask method was used, calculate the bulk specific gravity, 23/23°C, on the basis of saturated surface-dry aggregate as follows:

$$\text{bulk sp gr}(\text{saturated surface-dry basis}) = \frac{S_1}{0.9975(R_2 - R_1)} \tag{6}$$

11. APPARENT SPECIFIC GRAVITY

11.1. Calculate the apparent specific gravity, 23/23°C (73.4/73.4°F) as follows:

$$\text{apparent sp gr} = A/(B + A - C) \tag{7}$$

12. ABSORPTION

12.1. Calculate the percentage of absorption as follows:

$$\text{absorption, percent} = \left[(S - A)/A\right] \times 100 \tag{8}$$

13. REPORT

13.1. Report specific gravity results to the nearest 0.001 (Fine Aggregate meeting M 6 requirements may be reported to the nearest 0.01) and absorption to the nearest 0.1 percent. The appendix gives mathematical interrelationships among the three types of specific gravities and absorption. These may be useful in checking the consistency of reported data or calculating a value that was not reported by using other reported data.

13.2. If the fine aggregate was tested in a naturally moist condition other than the oven dried and 15-h soaked condition, report the source of the sample and the procedures used to prevent drying prior to testing.

14. PRECISION AND BIAS

14.1. The estimates of precision of this test method (listed in Table 1) are based on results from the AASHTO Materials Reference Laboratory Reference Sample Program, with testing conducted by this test method and ASTM C 128. The significant difference between the methods is that ASTM C 128 requires a saturation period of 24 ± 4 h, and T 84 requires a saturation period of 15–19 h. This difference has been found to have an insignificant effect on the precision indices. The data are based on the analyses of more than 100 paired test results from 40 to 100 laboratories.

14.2. Because there is no accepted reference material suitable for determining the bias for the procedure in T 84 for measuring specific gravity and absorption of fine aggregate, no statement on bias is being made.

APPENDIX

(Nonmandatory Information)

X1. POTENTIAL DIFFERENCES IN BULK SPECIFIC GRAVITY AND ABSORPTION DUE TO PRESENCE OF MATERIAL FINER THAN 75 μM (NO. 200)

X1.1. It has been found that there may be significant differences in bulk specific gravity and absorption between fine aggregate samples tested with the material finer than 75 μm (No. 200) present and not present in the samples. Samples from which the material finer than 75 μm is not removed usually give a higher absorption and a lower bulk specific gravity compared with testing the same fine aggregate from which the material finer than 75 μm is removed following the procedures of T 11. Samples with material finer than 75 μm may build up a coating around the coarser fine aggregate particles during the surface drying process. The resultant specific gravity and absorption that is subsequently measured is that of the agglomerated and coated particles and not that of the parent material. The difference in absorption and specific gravity determined between samples from which the material finer than 75 μm have not been removed and samples from which the material finer than 75 μm have been removed depends on both the amount of the material finer than 75 μm present and the nature of the material. When the material finer than 75 μm is less than about 4 percent by mass, the difference in specific gravity between washed and unwashed samples is less than 0.03. When the material finer than 75 μm is greater than about 8 percent by mass, the difference in specific gravity obtained between washed and unwashed samples may be as great as 0.13.

X1.2. The material finer than 75 μm, which is removed, can be assumed to have the same specific gravity as the fine aggregate. Alternatively, the specific gravity of the material finer than 75 μm may be further evaluated using T 100; however, this test determines the apparent specific gravity and not the bulk specific gravity.

X2. INTERRELATIONSHIPS BETWEEN SPECIFIC GRAVITIES AND ABSORPTION AS DEFINED IN T 84 AND T 85

X2.1. Let:

S_d = bulk specific gravity (dry basis),
S_s = bulk specific gravity (SSD basis),
S_a = apparent specific gravity, and
A = absorption in percent.

Then:

$$S_s = \left(1 + A/100\right) S_d \qquad (X1.1)$$

$$S_a = \frac{1}{\frac{1}{S_d} - \frac{A}{100}} = \frac{S_d}{1 - \frac{AS_d}{100}} \qquad (X1.2)$$

Or:

$$S_a = \frac{1}{\frac{1 + A/100}{S_s} - \frac{A}{100}} = \frac{S_s}{1 - \frac{A}{100}\left(S_s - 1\right)} \qquad (X1.3)$$

$$A = \left(\frac{S_s}{S_d} - 1\right) 100 \qquad (X1.4)$$

$$A = \left(\frac{S_a - S_s}{S_a\left(S_s - 1\right)}\right) 100 \qquad (X1.5)$$

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[1] This method is technically equivalent to ASTM C 128-12.

X1. X3. AVERAGE SPECIFIC GRAVITY VALUES

X3.1. *Average Specific Gravity Values*—When the sample is tested in separate size fractions (retained on and passing the No. 200 sieve), the average value for bulk specific gravity, bulk specific gravity (SSD), or apparent specific gravity can be computed as the weighted average of the values as computed in accordance with Sections 9 through 11 using the following equation:

$$G = \frac{1}{\frac{P_1}{100G_1} + \frac{P_2}{100G_2} + \cdots + \frac{P_n}{100G_n}} \qquad (4)$$

where:

G = average specific gravity (all forms of expression of specific gravity can be averaged in this manner);
$P_1, P_2 \ldots P_n$ = mass percentages of each size fraction present in the original sample; and

$G_1, G_2 \ldots G_n$ = appropriate specific gravity values for each size fraction depending on the type of specific gravity being averaged.

Note 8—Some users of this method may wish to express the results in terms of density. Density may be determined by multiplying the bulk specific gravity, bulk specific gravity (SSD), or apparent specific gravity by the density of water (997.5 kg/m^3 or 0.9975 Mg/m^3 or 62.27 lb/ft^3 at 23°C). Some authorities recommend using the density of water at 4°C (1000 kg/m^3 or 1.000 Mg/m^3 or 62.43 lb/ft^3) as being sufficiently accurate. The density terminology corresponding to bulk specific gravity, bulk specific gravity (SSD), and apparent specific gravity has not been standardized.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation