A REVIEW OF AGGREGATE AND ASPHALT MIXTURE SPECIFIC GRAVITY MEASUREMENTS AND THEIR IMPACTS ON ASPHALT MIX DESIGN PROPERTIES AND MIX ACCEPTANCE

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Report Prepared by the Specific Gravity Task Group
for the FHWA Mix and Construction Expert Task Group

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EXECUTIVE SUMMARY

Objective and Process of the Review

Volumetric properties are currently used for design and acceptance of hot-mix asphalt (HMA) mixtures. Vital to the calculation of mixture volumetric properties is the conversion of mass percentages to volume proportions/percentages using specific gravity measurements of the mixture and the aggregates in the mixture. The accuracy and reliability of the specific gravity measurements are therefore fundamental to the business of building quality asphalt pavements.

A task group consisting of the authors under the direction of the Federal Highway Administration (FHWA) Asphalt Mix and Construction Expert Task Group was tasked to conduct a critical review of specific gravity measurement methods. The objectives of this review were to summarize problems and issues with current methods, examine possible improvements and/or alternate methods, and identify areas that need further research and development.

This review separately examined three specific gravity determinations, namely, the bulk specific gravity of the aggregates (G_{sb}), the maximum specific gravity of asphalt mixtures (G_{mm}), and the bulk specific gravity of compacted specimens (G_{mb}). The review draws upon information from research studies, state transportation departments, AASHTO and ASTM standards, and the AASHTO Materials Reference Laboratory (AMRL). The view of the task group has been that change(s) to the current specific gravity methods may be motivated by one or more of the following three reasons:
1. The change(s) or new method(s) will provide specific gravity results closer to the truth (i.e., greater accuracy),
2. The change(s) or new method(s) will yield more repeatable results (i.e., better precision), and
3. The change(s) or new method(s) will be faster, easier, and/or less expensive.

Findings

The primary standard test methods for determining the bulk specific gravity of coarse aggregates are AASHTO T 85 and ASTM C127. Disadvantages of these methods include (1) the inconsistency of the visual method for determination of the SSD condition; and (2) the required soak time of at least 15 hours. These disadvantages are addressed in alternative methods for determining G_{sb} of coarse aggregates, including the vacuum sealing procedure (i.e., the commercially available CoreLok device). Recent studies showed that the vacuum-sealing method produced higher G_{sb} values that were significantly different (both statistically and practically) from those determined by AASHTO T 85, especially for highly absorptive coarse aggregates. In addition, the vacuum-sealing and AASHTO T 85 procedures had similar reproducibility.

With respect to the determination of bulk specific gravity of fine aggregates, the primary standard test methods are AASHTO T 84 and ASTM C128. Disadvantages of these test

methods include (1) the inconsistency of the cone and tamp technique used to determine the SSD condition and (2) the required soak time. Several modifications have been made by states to improve the determination of the SSD condition. However, the modifications still require technician judgment. Alternative methods commercially available for determining G_{sb} of fine aggregates include the CoreLok, SSDetect and Phunque procedures. Among the alternative methods, the CoreLok and SSDetect have been evaluated against AASHTO T 84 in several recent studies. Both methods produced significantly different G_{sb} compared to AASHTO T 84. In addition, the SSDetect had better precision indices than AASHTO T 84.

For the measurement of maximum specific gravity of asphalt mixtures, the two primary standard methods are AASHTO T 209 and ASTM D2041. The ASTM multilaboratory precision for non-porous aggregates and the AASHTO/ASTM multilaboratory precision for porous aggregates appeared very high, resulting in an allowable difference of up to two percent in between-laboratory air void values. Alternative methods for determining G_{mm} are the CoreLok and Pressure Meter procedures. Most recent studies have focused on the evaluation of alternative methods but not on the improvement of the accuracy or precision of the current standard test methods. The CoreLok produced similar results for mixtures containing non-porous aggregates and higher G_{mm} values for mixtures containing porous aggregates.

With respect to the determination of bulk specific gravity of compacted HMA specimens, AASHTO T 166 and ASTM 2726 are the primary standard methods. These methods are not accurate for the determination of G_{mb} of coarse-graded and SMA compacted specimens due to the SSD determination. Alternative methods available for determining G_{mb} include paraffin coating, parafilm, vacuum sealing, gamma ray, and dimensional measurement. Recent studies show that the G_{mb} values determined using parafilm, vacuum-sealing, gamma radiation, dimensional measurement, and AASHTO T 166 are different. The differences between results from AASHTO T 166 and the vacuum-sealing or gamma ray devices are greater for coarse-graded and SMA specimens.

An analysis was also performed in this review to assess the effect of specific gravity determinations on the mix design properties and acceptance methods of asphalt mixtures. Based on the precision indices published by the AMRL for G_{mb} and G_{sb}, the acceptable range of two VMA results would be 3.7%, which fall outside VMA specifications, which have a typical range from minimum to maximum of only 2.0 to 2.5%. If the vacuum-sealing method is used instead of the SSD method for determining G_{mb} of coarse-graded compacted specimens, VMA will increase 0.5%, and field density will decrease 1%.

Recommendations

The following recommendations are offered for improving the specific gravity determinations used in hot-mix asphalt mix design, quality control, and acceptance testing:
1. The current standard test methods for determining G_{sb} of coarse aggregate are considered satisfactory with respect to accuracy and precision. No change is

warranted in these methods at this time. Research should explore reducing the soak time.

2. The determination of G_{sb} for fine aggregate suffers from poor reproducibility due to the subjective determination of the SSD condition. The accuracy of the fine aggregate G_{sb} is also questionable for some absorptive materials and those containing highly angular and/or textured particles, or that have high dust contents. Further research is needed to improve the reproducibility and accuracy of the fine aggregate G_{sb} determination. Alternate methods of determining the SSD condition of fine aggregate appear to be promising.

3. For agencies that use VMA or VFA in mix design approval or HMA acceptance testing, the limits for these criteria should be based on well-documented precision information for G_{sb} determinations.

4. The current standard test methods for determination of G_{mm} for HMA mixtures containing aggregate with low absorption are satisfactory. However, the multilaboratory precision estimate for mixtures containing moderately to highly absorptive aggregates is so large that it is not valid to distinguish air voids results for split samples conducted in two laboratories that differ by as much as 2.0 percent. Clearly, further work needs to be conducted to improve the reproducibility of the G_{mm} determination for such aggregate. Another important objective for further research should be to reduce the time to complete the test for mixes containing absorptive aggregate.

5. In order to improve the accuracy of the G_{mb} determination, the SSD method (AASHTO T 166, ASTM D2726) should be limited to specimens with a water absorption of less than or equal to 1.0%. In practice, this will limit the SSD method to use with well-compacted, fine-graded mixtures. For specimens with greater than 1.0% water absorption, the vacuum-sealing method (AASHTO T 331, ASTM D6752) should be used since this method has similar precision estimates to D2726 for these mixtures.

   Note: Agencies should be aware that changing to the vacuum-sealing method will likely have substantial consequences with regard to mix designs for coarse-graded and SMA mixtures and measurement of in-place densities of these mixture when measurements are based on cores:

   ▪ For coarse-graded and SMA mixtures, the vacuum-sealing method will yield higher air voids and VMA than for the same mixtures tested by T 166. Based on available data, the average shifts are about 0.5% for both air voids and VMA for coarse-graded mixtures using mix design compactive efforts. For SMA mixtures, the average shifts in air voids and VMA are 0.9% at a normal mix design compactive effort. These changes will have an effect on future mix designs. Agencies may want to consider adjusting their design VMA criteria so that the resulting mixtures can be expected to perform as well or better than those currently in use. Reasoning was provided in this report to support an increase in VMA by 0.5% for both coarse-graded Superpave mixes and SMA mixtures.

   ▪ Using the vacuum-sealing method in lieu of T 166 for measurement of core densities will shift the results more dramatically than for mix design. Available data shows that in-place air voids are approximately 1.0% and 1.7%

higher on average for coarse-graded mixtures and SMA mixtures, respectively, when using the vacuum-sealing method in place of T 166. Therefore, changing to the vacuum-sealing method for acceptance testing of in-place density will result in one of two scenarios for agencies: either leave in-place density criteria as is and expect contractors to improve their compaction processes to meet the criteria, or adjust the specification criteria for in-place densities to be consistent with the new measurement method so that densities levels are achievable with the current practices for asphalt pavement construction.

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1 INTRODUCTION

Current practices for asphalt mix design and acceptance testing rely on volumetric properties. Vital to the calculation of mix volumetric properties are specific gravity measurements of the mixture and the aggregate in the mixture. In essence, the specific gravity measurements are conversion factors that allow conversion of mass percentages to volume proportions/percentages. The accuracy and reliability of the specific gravity measurements are therefore fundamental to the business of building quality hot-mix asphalt (HMA) pavements.

This paper documents a critical review of specific gravity measurement methods. This review was conducted as part of a task group consisting of the authors under the direction of the FHWA Asphalt Mix and Construction Expert Task Group. The objectives of this review are to summarize problems and issues with current methods, examine possible improvements and/or alternate methods, and identify areas that need further research and development.

The approach to this review has been to separately examine three specific gravity determinations, namely, the bulk specific gravity of the aggregate (G_{sb}), the maximum specific gravity of asphalt mixtures (G_{mm}), and the bulk specific gravity of compacted specimens (G_{mb}). The review draws upon information from recently published research studies, information from state DOTs and equipment manufacturers, and precision information cited in AASHTO and ASTM standards and published on the AASHTO Materials Reference Laboratory (AMRL) website (*1*). This report is organized by discussion of each of these measurements followed by a summary that considers the overall effect of the measurements on asphalt mixture volumetric properties and current criteria for mix design and acceptance. The view of the task group has been that change(s) to the current specific gravity methods may be motivated by one or more of the following three reasons:

1. The change(s) or new method(s) will provide specific gravity results closer to the truth (i.e., greater accuracy),
2. The change(s) or new method(s) will yield more repeatable results (i.e., better precision), and
3. The change(s) or new method(s) will be faster, easier, and/or less expensive.

2 BACKGROUND

Air voids (V_a), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and volume of effective binder (V_{be}) are calculated from the following well known equations:

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) x100 \tag{1}$$

$$VMA = \left(100 - \frac{G_{mb}P_s}{G_{sb}}\right) \tag{2}$$

$$VFA = \left(\frac{VMA - V_a}{VMA}\right) x100 \tag{3}$$

$$V_{be} = VMA - V_a \tag{4}$$

where:

G_{mb} = bulk specific gravity of the compacted sample
G_{mm} = maximum specific gravity of the asphalt mixture
P_s = percentage (by mass) of aggregate in the total mixture
G_{sb} = aggregate bulk specific gravity

With these equations, the effects of the specific gravity results can be analyzed more closely, and the following approximate relationships can be determined.

- From Equation 1, if G_{mb} is held constant, the following relationship between *Air Voids* and G_{mm} is established:

  when G_{mm} changes by +0.01, V_a changes by +0.4%. (5)

- Likewise, if G_{mm} is held constant in Equation 1, the following relationship between *Air Voids* and G_{mb} is established:

  when G_{mb} changes by +0.01, V_a changes by -0.4%. (6)

- From Equation 2, when G_{sb} and P_s are held constant, the following relationship between VMA and G_{mb} is established:

  when G_{mb} changes by +0.01, *VMA* changes by -0.4%. (7)

- And also from equation 2, when G_{mb} and P_s are held constant, the following relationship between VMA and G_{sb} is established:

  when G_{sb} changes by +0.01, *VMA* changes by +0.3%. (8)

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3 BULK SPECIFIC GRAVITY OF AGGREGATE

Bulk specific gravity is defined as the ratio of the weight of a given volume of aggregate, including the permeable and impermeable voids in the particles, to the weight of an equal volume of water. Bulk specific gravity of aggregate is important information for designing HMA because it is used to calculate VMA and VFA. Since different procedures are used to determine the G_{sb} of coarse and fine aggregate, this section is divided into two parts, one for coarse aggregate and one for fine aggregate.

3.1 Coarse Aggregate Bulk Specific Gravity

3.1.1. Standard Test Methods

The standard test methods used for the determination of specific gravity of coarse aggregate are described in AASHTO T 85 and ASTM C127. The methods are essentially the same, except for the required time in which a sample of aggregate is submersed in water to essentially fill the pores. While the AASHTO standard requires the sample be immersed for a period of 15 to 19 hours, the ASTM method specifies an immersed period of 24 ± 4 hours. After the specimen is removed from the water, it is rolled in an absorbent towel until all visible films of water are removed. This is defined as the saturated surface-dry (SSD) condition. Three mass measurements are obtained from a sample: SSD mass, water submerged mass, and oven dry mass. Using these mass values, the G_{sb} of an aggregate can be determined.

3.1.2. Precision Estimates of Standard Test Methods

Even though the two standard methods require different saturation periods, the precision indices are the same, as shown in Table 1.

TABLE 1	AASHTO T 85 and ASTM C127 Precision Estimates	
	Standard Deviation (1s)	**Acceptable Range of Two Results (d2s)**
Single-operator precision: Bulk specific gravity (dry)	0.009	0.025
Multilaboratory precision: Bulk specific gravity (dry)	0.013	0.038

Precision estimates for the standard coarse aggregate G_{sb} test methods are also determined annually by the Proficiency Sample Programs and reported on the AMRL website (*1*). These precision indices are shown in Table 2. The precision estimates from 1998 through 2005 vary significantly from year to year due partially to the use of different aggregate sources in the program. The precision estimates from the proficiency program are greater than the precision estimates cited in the standard test methods (Table 1). Since 2006, the Proficiency Sample Programs have used a different method of

screening data (*2*) that detects more outliers, resulting in precision estimates that are smaller than those cited in the current standards. Due to these differences, the precision estimates in the standard test methods should be re-established.

TABLE 2   AASHTO T 85/ASTM C127 Precision Estimates Reported by AMRL

Year	Sample No.	No. of Labs		Single Operator		Multilaboratory	
		Participated*	Data Used**	1s	d2s	1s	d2s
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

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

3.1.3. Shortcomings of Standard Test Methods

Problems with the current standard test methods are:
- The visual method of determining when aggregates reach a SSD condition is subjective and therefore is not consistent from operator to operator. Some operators determine the SSD state based on the shine of the water film while others judge based on a slight color change in the aggregate (*3*). Since the determination of the SSD condition is highly operator dependent, the SSD mass and subsequent calculated bulk specific gravity value are less reproducible.
- Both standard methods require almost a full day to perform when aggregate soaking time is included. This makes the test less effective for quality control purposes, where results are needed as quickly as possible.
- The submerged mass may not be determined accurately if the sample is not washed correctly. If adherent fines are not removed prior to testing, they can be removed when the SSD sample is shaken while immersed to remove all entrapped air, resulting in an error in the submerged mass. Consequently, it affects the calculated bulk specific gravity value.

3.1.4. Alternatives to Standard Test Methods

Alternatives to the standard test methods of determining the bulk specific gravity of coarse aggregate are available. Table 3 summarizes the advantages and disadvantages of the alternatives to the standard test methods.

TABLE 3   Advantages and Disadvantages of Alternative Methods for Determining G_{sb} of Coarse Aggregate

Method	AASHTO and/or ASTM Designation	Advantages	Disadvantages
AggPlus / CoreLok System or Vacuum-Seal Method (Instrotek)	None	• SSD weight not required • Result in 30 minutes • Long soaking period not required • Slightly more repeatable • Use for both coarse and fine aggregate	• More complicated to run • More expensive than the standard methods due to equipment and bag costs • More effort to improve reproducibility needed
Rapid Water Displacement (Gilson)	None	• SSD weight not required	• Equipment being developed; no research available at this time

The two alternative methods shown in Table 3 are expected to address the shortcomings of the current standard test methods. A number of investigators have attempted to evaluate the AggPlus system against the current AASHTO method for determining the specific gravity and absorption of coarse aggregate. For the Gilson Rapid Water Displacement method, equipment is currently being developed, so no comparison is available at this time. However, the AggPlus/CoreLok system or vacuum-seal method has been studied by several researchers. The objectives of these studies were to evaluate the reproducibility of the AggPlus system and to determine if it would produce results that are statistically different from those produced by the current standard test methods.

In 2004, Hall (*4*) measured bulk specific gravity of six coarse aggregates from various mineralogy sources in Arkansas using the AASHTO T 85 and vacuum-seal (CoreLok) method. To minimize sources of variability, one operator conducted all testing of five replicates for each aggregate using both test methods. Hall reported that G_{sb} values determined using the two test procedures were significantly different. The AggPlus system tended to produce higher G_{sb} values for coarse aggregate with absorptions of more than one percent regardless of mineralogy. More effort was recommended to improve the test consistency and produce test results comparable to those resulting from the standard test methods if the results are to be used for specification purposes.

In 2005, Mgonella (*5*) evaluated the AggPlus system against the AASHTO T 85 method using eight coarse aggregates representing four basic aggregate types in Oklahoma. The tests were performed by two operators to determine the interaction between the test methods and operators. Mgonella reported that G_{sb} values determined using the two methods were statistically different. The AggPlus system produced higher G_{sb} values. No interactions between G_{sb} values and operators were found for either test method. The AggPlus system and the AASHTO T 85 method had similar reproducibility. The research did not recommend the alternative procedure for replacement of the current AASHTO T 85 method.

Another evaluation of the AggPlus system using the CoreLok vacuum-seal device was performed by Sholar et al. (*6*) and compared to the Florida Department of Transportation FM 1-T 085 procedure, which is similar to the AASHTO T 85 method. The test plan used 11 coarse aggregates from six sources in Florida and Georgia. One operator tested two replicates for individual coarse aggregates using both test methods. Sholar et al. reported that the AggPlus method produced higher G_{sb} values, and the difference was greater for higher absorptive aggregate. The difference was approximately 0.165 for absorptive aggregate, which would result in a VMA change of 5.5%. In most HMA applications, such a difference in VMA would be significant. Influence of aggregate gradation on aggregate G_{sb} was not significant. The repeatability of the AggPlus system was slightly better than the standard test method with respect to bulk specific gravity. The research team did not recommend the AggPlus system for use as a test procedure for determining coarse aggregate G_{sb} in Florida.

In summary, all studies found that G_{sb} values determined using the AggPlus and AASHTO T 85 procedures were significantly different. The AggPlus system produced higher specific gravity values with greater differences for highly absorptive coarse aggregate. In one study, the difference in G_{sb} would result in a VMA change of 5.5%, which would be significant in most HMA applications. Test results using the AggPlus system were not sensitive to nominal maximum aggregate size, gradation, or mineralogy. All studies recommended that the AggPlus system not be used for determining specific gravity and absorption of coarse aggregate in existing specifications.

3.2   Fine Aggregate Bulk Specific Gravity

3.2.1.   Standard Test Methods

The standard test methods for determining fine aggregate G_{sb} are presented in AASHTO T 84 and ASTM C128. The two procedures are similar, except for the required period in which a sample of fine aggregate is submersed in water to essentially fill the pores. The AASHTO T 84 procedure calls for immersion of fine aggregate in water for 15 to 19 hours, while the ASTM C128 method specifies a soaking period of 24 ± 4 hours. For both methods, the sample is then spread on a pan and exposed to a gentle current of warm air until approaching a free-flowing condition. Periodically, the aggregate is lightly tamped into a cone-shaped mold with 25 light drops of the tamper. If the fine aggregate retains the molded shape when the mold is removed, the fine aggregate is assumed to have surface moisture, and it is dried further. When the cone of sand just begins to slump upon removal of the mold, it is assumed to have reached the SSD condition. Three masses are determined from the method using either gravimetric or volumetric methods, SSD, saturated sample in water, and oven dry. These are used to calculate G_{sb}.

The precision estimates are the same for both standard methods and are shown in Table 4.

TABLE 4	AASHTO T 84 and ASTM C128 Precision Estimates	
	Standard Deviation (1s)	**Acceptable Range of Two Results (d2s)**
Single-operator precision:		
Bulk specific gravity (dry)	0.011	0.032
Multilaboratory precision:		
Bulk specific gravity (dry)	0.023	0.066

Precision estimates for the current standard test methods for determining G_{sb} of fine aggregate are also published annually on the AMRL website (*1*). Table 5 shows these precision indices. Compared to the precision estimates shown in Table 4, all of the precision indices reported by the AMRL until 2006 are greater, and they also vary significantly from year to year. Since 2007, the new method of screening data has detected more outliers, resulting in smaller precision indices than those shown in Table 4. The precision estimates in the current standard test methods should be re-established.

TABLE 5   AASHTO T 84/ASTM C128 Precision Estimates Published by AMRL

Year	Sample No.	No. of Labs		Single Operator		Multilaboratory	
		Participated*	**Data Used***	**1s**	**d2s**	**1s**	**d2s**
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

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

3.2.3. *Shortcomings of Standard Test Methods*

Problems with the standard test methods for determining fine aggregate G_{sb} are:
- The SSD condition of some fine aggregate may not be determined consistently using the cone and tamp technique because the amount of slump of the fine aggregate is not just dependent on the quantity of surface moisture but also upon the angularity and texture of the fine aggregate (*6*). In addition, it is suspected that the percentage of material passing the No. 100 sieve may also influence the slump condition (*2*). This will result in an inaccurate determination of SSD mass and thereby the calculation of G_{sb}.

- Both standard test methods, including aggregate soaking time, cannot be completed in a working day. It makes the tests less effective for quality control purposes, where results are desired as quickly as possible.

3.2.4. *Modifications for Determining SSD Condition of Fine Aggregate*

Most modifications to the standard test methods have been undertaken in order to better pinpoint the saturated surface-dry condition of fine aggregate and thereby improve the accuracy of G_{sb} test results. The G_{sb} value is used to calculate the amount of asphalt binder absorbed by the aggregate and the VMA of the HMA mixture. These modifications along with their advantages and disadvantages are briefly described in Table 6.

TABLE 6 Modifications of Standard Test Methods for Determining SSD Condition of Fine Aggregate

Method	Description	Advantages	Disadvantages
Provisional Cone Test (AASHTO T 84 Note 2 and ASTM C128)	• Fill cone mold and use 10 drops of tamper • Add more FA and use 10, 3 and 2 drops of tamper, respectively • Level off and lift mold vertically	• Easy and quick to perform	• Same shortcomings as standard test method
Kandhal and Lee Colorimetric Procedure (AASHTO T 84 Note 2 & ASTM C128)	• FA is soaked in water containing special dye that changes color when dry • Upon removal from water, FA has color of wet dye • SSD condition reached when material changes color	• Easy to perform	• Dyes do not show well on dark FA particles • Differential drying on particle size • Technician judgment on color change required
Paper Towel (AASHTO T 84 Note 2 and ASTM C128)	• Use hard-finished paper towels to surface dry FA • SSD condition just achieved when paper towel not picking up moisture from surface of FA	• Easy to perform	• Technician judgment required
California (California Test 225: Option 1)	• Place portion of drying FA in a dry glass jar and shake • SSD condition is when FA ceases to adhere to dry surface	• Easy and quick to perform	• Technician judgment required

TABLE 6   Modifications of Standard Test Methods for Determining SSD Condition of Fine Aggregate (cont.)

Method	Description	Advantages	Disadvantages
Texas (Tex 201-F)	SSD condition is when 2 of 4 criteria below satisfied: • Criterion 1: drying FA slides in same manner as oven-dry FA slides down bottom of 45-deg tilted pan • Criterion 2: drying FA flows freely off a small masonry trowel in same manner as oven-dry FA when trowel tilted slowly to one side • Criterion 3: place water-soluble glue surface of wood block on drying FA for 5 seconds. SSD condition is when no more than 2 particles adhere to water soluble glue after 2 checks • Criterion 4: drying FA has same color as oven-dried FA	• Easy and quick to perform • Easy and quick to perform • Easy and quick to perform • Easy and quick to perform	• Technician judgment required • Technician judgment required • Technician judgment required
Wisconsin (Modified AASHTO T 84)	• Minus No. 200 is removed by rinsing FA over No. 200 screen	• More consistent results	• Technician judgment required • Does not include minus No. 200 fraction
Iowa (IM 380)	• FA is covered with water and placed under 30 mm Hg vacuum for 30 min. and then allowed to stand for another 20 min. Sample is then rinsed over No. 200 sieve. SSD condition achieved when FA grains do not adhere to steel spatula	• Used for both combined and individual aggregate • No soak time required • More consistent results	• Technician judgment required • Does not include minus No. 200 fraction

3.2.5.   Alternatives to Standard Test Methods

Several alternatives to the AASHTO T 84 and ASTM C128 procedures are available to determine fine aggregate G_{sb}. These alternatives, along with their advantages and disadvantages when compared to the standard test methods, are briefly described in Table 7.

TABLE 7   Advantages and Disadvantages of Alternative Methods for Determining G_{sb} of Fine Aggregate

Method	AASHTO and/or ASTM Designation	Advantages	Disadvantages
NCAT / Dana and Peters (*8*) Arizona DOT Procedure	Use with AASHTO T 84 or ASTM C128	• Automated determination of SSD condition	• More expensive than standard methods due to equipment cost • More effort to improve reproducibility needed
AggPlus / CoreLok System or Vacuum-Seal Method (Instrotek)	None	• SSD weight not required • Result in 30 min. • Long soaking period not required • Use for both coarse and fine aggregate	• More expensive than standard methods due to equipment and bag costs • Precision not as good as that of AASHTO T 84
SSDetect (Thermolyne)	None	• SSD condition automatically determined • Result in 1 to 2 hrs. • Long soaking period not required • Improved precision compared with AASHTO T 84 • More scientific/rational approach	• More expensive than standard methods due to equipment cost • Limited research available this time
AASHTO T 84 with Langley De-airing Device	Use with AASHTO T 84 or ASTM C128	• Reproducibility improved • Hand agitation not required	• Equipment cost • Limited research available at this time
Phunque Method (New Mexico DOT)	Requesting for an AASHTO temporary test procedure	• SSD weight not required	• Takes 25 hrs to complete • Specific gravity and absorption very different from AASHTO T 84 • No research available at this time
Rapid Water Displacement (Gilson)	None	• SSD weight not required	• Equipment being developed; no research available at this time

These alternative test methods are expected to address the shortcomings of the standard test methods. A number of studies have been conducted to evaluate the reproducibility of the alternative procedures and to determine if any of the alternatives would produce results statistically similar to those produced by the standard test methods.

In 2000, Kandhal et al. (*7*) conducted a research project to develop a new method using automated equipment for determining the SSD condition of fine aggregate. The work was based on basic principles of thermodynamics that had been studied by Dana and Peters (*8*) of the Arizona Department of Transportation. The equipment measures the temperature gradient of the incoming and outgoing warm air blown into a rotating drum. The SSD condition is achieved when the thermal gradient drops suddenly. While the method shows promise, more effort is needed to improve the repeatability and reproducibility of the test.

Recently, several studies have been conducted to compare the AggPlus system using the CoreLok vacuum-sealing device to the AASHTO T 84 procedure. In 2004, Hall (*4*) conducted an evaluation study in which one operator performed all testing of five replicates for each of five fine aggregate materials using both test methods. He reported that G_{sb} results for some fine aggregates determined using the two methods were significantly different at the 95% confidence level. The AggPlus system was also evaluated in a round-robin study conducted with 12 laboratories by Prowell and Baker (*9*) using six materials, four crushed, and two natural fine aggregate sources. The study found that G_{sb} results using the two methods were statistically different for three of six aggregates, including limestone, washed diabase, and blast furnace slag. The differences were believed to be due to over-drying the aggregate. This lead to inaccurate results for angular materials with high dust contents using the AASHTO T 84 procedure. The precision indices of the CoreLok method were not as good as those of AASHTO T 84, but the authors suggested that the precision would be improved as technicians became more familiar with the CoreLok method.

Another evaluation study was conducted by Sholar et al. (*6*) of the Florida Department of Transportation. One operator tested two replicates for each of seven aggregates using the CoreLok method and AASHTO T 84. The study found that the CoreLok and AASHTO T 84 gave similar G_{sb} results for three low absorptive granite aggregates but different G_{sb} values for four high absorptive limestone aggregates. The CoreLok method produced slightly higher G_{sb} values for the granite aggregate and lower G_{sb} values for limestone aggregate. For the limestone aggregate, the average difference in G_{sb} between the two test methods was 0.040, which would result in a change in VMA of 1.4%. The repeatability of G_{sb} results using the CoreLok was judged to be slightly better than that of AASHTO T 84.

The most recent evaluation study was conducted by Cross et al. (*10*) in 2006 using 14 fine aggregates of various types, including limestone, sandstone, granite, rhyolite, and natural sand. They reported that G_{sb} results using the CoreLok and AASHTO T 84 methods were significantly different, and the CoreLok tended to produce higher G_{sb} values.

In summary, studies have shown that G_{sb} results using the CoreLok method are statistically different from those of the AASHTO T 84 procedure for a variety of aggregate sources. Some studies have shown that the precision of the CoreLok is not as

good as that of AASHTO T 84, whereas other studies have shown repeatability of the CoreLok method to be better.

Like the AggPlus system, the SSDetect system does not require the material be immersed in water for at least 15 hours or for the operator to determine SSD condition. The SSDetect system was compared to the AASHTO T 84 procedure in two projects, one conducted by Prowell and Baker (*9*) and the other by Cross et al. (*10*). Materials used and research plans implemented in these studies were previously described. Prowell and Baker (*9*) reported that G_{sb} results using the two methods were significantly different for three aggregates, including washed diabase, rounded natural sand, and angular natural sand. However, these differences were less than those between the CoreLok and AASHTO T 84 G_{sb} results. The precision of the SSDetect method was better than that of AASHTO T 84. Cross et al. (*10*) also found significant differences between G_{sb} results determined by the SSDetect and AASHTO T 84 methods. In addition, the SSDetect method produced the highest G_{sb} results, followed by the CoreLok and AASHTO T 84. However, the SSDetect system has better reproducibility than the other two methods. In summary, the two studies showed the significant differences between G_{sb} results determined by the SSDetect and AASHTO T 84 methods. In addition, the precision of the SSDetect system was better than that of AASHTO T 84. However, the studies had different conclusions on the differences in G_{sb} results using the CoreLok, SSDetect, and AASHTO T 84 methods. These different conclusions may be due to different materials used in the two studies.

For the method using the Langley de-airing device with AASHTO T 84, one study was conducted by Cross et al. (*10*). The study compared G_{sb} results using the AASHTO T 84 procedure with hand agitation and with a Langley de-airing device for 20 minutes to remove air bubbles from the sample in the flask. They reported that the use of the Langley de-airing device improved the reproducibility of the test results; however, the results were not statistically different in most cases.

The Phunque method has been approved for use in New Mexico since July 1, 2006. However, no published evaluation study is available at the time of this writing. A preliminary comparison shown in an electronic presentation received by the authors showed that G_{sb} results using the Phunque method were higher than those using the AASHTO T 84 method.

Equipment for the Gilson Water Rapid Displacement method is currently being developed and therefore no study results are available for the method.

In summary, most recent studies of alternative test methods for determining fine aggregate G_{sb} focus on evaluating two recently developed test procedures, including the AggPlus and SSDetect methods. These methods have been developed to avoid the determination of SSD condition manually and to reduce the aggregate soaking time. The studies show that G_{sb} results determined using alternative test methods are statistically different from those using AASHTO T 84. The differences appear to be greater for more

angular fine aggregate with higher dust contents. Among the alternative methods evaluated, the SSDetect has better precision than AASHTO T 84.

4 MAXIMUM SPECIFIC GRAVITY OF ASPHALT MIXTURES

4.1 Current Standard Test Methods

The test method most often used to determine G_{mm} is AASHTO T 209. Within the method, there are several options for determining the $G_{mm,}$ but all utilize the same basic principle of measuring the mass and volume of the loose mix sample to determine its maximum specific gravity. The options within AASHTO T 209 differ by the type of sample container and whether the container is filled with water or submerged in a water bath. There are three container choices: bowl, flask, or pycnometer.

An outline of the procedure is as follows:

1. The dry mass of the loose mix samples are first determined, and the mix is then placed in a tared container of one of the types previously mentioned.
2. Water is added to the container to completely cover the sample, and a vacuum is applied to remove entrapped air.
3. The container is then filled with water and the mass determined, or it is placed in a water bath and the mass determined.
4. From these mass determinations, the volume of the loose mix and thereby its G_{mm} is determined.

AASHTO T 209 also contains detailed procedures related to the calibration of flasks, bowls and pycnometers, as well as temperature corrections for the asphalt binder in the loose mix and the density of the water used in the test procedure if the test temperature differs from 25°C (77°F).

A survey conducted by the AMRL for the Aggregate Task Group (ATG) shows that out of 34 states that responded to the survey, 22 use AASHTO T209, and 12 states modify the test method to improve between laboratory precision. Most modifications reduce the options allowed in T 209.

The ASTM method for determining G_{mm} is D 2041. D 2041 is nearly the same as AASHTO T 209 with the exception that the calibration and volume correction issues are treated differently between the two methods. Whereas, T 209 provides calibration and volume correction procedures for tests that are conducted at temperatures substantially different than 25C (77F), D 2041 mandates that the test be conducted at temperatures of 25±1C (77±1.8F) to avoid the necessity of using correction factors.

The AASHTO and ASTM methods contain similar procedures for the determination of the G_{mm} for asphalt mixtures containing porous aggregate, commonly referred to as the "dryback" method. Essentially, the dryback procedure is aimed at determining how much water is absorbed into the coated particles during vacuum saturation. The tested sample is dried using a fan to a constant mass. The AASHTO method stipulates that this is only necessary for aggregate with water absorption greater than or equal to 1.5%.

ASTM does not specify an absorption value, nor does it give any other criterion for determining whether a mixture should be tested using the alternate dryback procedure.

4.2. Precision Estimates of Current Standard Test Methods

The AASHTO and ASTM methods provide single operator and multilaboratory precision values for both procedures (non-porous and porous aggregate mixtures). The AASHTO precision values are shown in Table 8, and the ASTM precision values are shown in Table 9. No information is provided regarding the type of container used or whether the container was filled with water or weighed under water for non-porous aggregate mixtures. The ASTM acceptable range of two results for both single operator and multilaboratory conditions for non-porous aggregate mixtures are more than two times greater than the corresponding AASHTO values. The AASHTO and ASTM d2s precision values for both single operator and multilaboratory conditions for absorptive aggregate mixtures shown in Tables 8 and 9 are identical, implying that the same data set was used for the determination of the precision values.

TABLE 8   AASHTO T 209 Precision Estimates for G_{mm}

	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single Operator Precision:		
Without supplemental dryback	0.0040	0.011
*With supplemental dryback for absorptive aggregate mixtures	0.0064	0.018
Multilaboratory Precision:		
Without supplemental dryback	0.0064	0.019
*With supplemental dryback for absorptive aggregate mixtures	0.0193	0.055

* Values only apply to bowl determination of G_{mm}.

TABLE 9   ASTM D 2041 Precision Estimates for G_{mm}

	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single Operator Precision:		
Without supplemental dryback	0.0080	0.023
*With supplemental dryback for absorptive aggregate mixtures	0.0064	0.018
Multilaboratory Precision:		
Without supplemental dryback	0.0160	0.044
*With supplemental dryback for absorptive aggregate mixtures	0.0193	0.055

* Values only apply to bowl determination of G_{mm}.

ASTM D 2041 precision estimates for mixtures containing aggregate with absorption of less than 1.5% or between 4 to 5% were evaluated in NCHRP 9-26 (*2,11*). The precision estimates for D 2041 from NCHRP 9-26 are presented in Table 10 and are much smaller than the corresponding values shown in Table 9.

TABLE 10   Precision Estimates for ASTM D2041 Evaluated in NCHRP 9-26

	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single Operator Precision:		
Without supplemental dryback for aggregate with less than 1.5% absorption	0.002	0.006
With supplemental dryback for aggregate with 4 to 5% absorption	0.005	0.0013
Multilaboratory Precision:		
Without supplemental dryback for aggregate with less than 1.5% absorption	0.004	0.011
With supplemental dryback for aggregate with 4 to 5% absorption	0.010	0.027

The Proficiency Sample Programs also publish precision estimates for AASHTO T 209 and ASTM D2041 annually. These precision indices are shown in Table 11. Information about whether absorptive or non-absorptive aggregate mixtures used and how many laboratories used supplemental dryback for absorptive aggregate mixtures was not published on the AMRL website (*1*) at the time of this writing.

TABLE 11   AASHTO T 209/ASTM D2041 Precision Indices Published by AMRL

Year	Sample No.	No. of Labs Participated*	No. of Labs Data Used**	Single Operator 1s	Single Operator d2s	Multilaboratory 1s	Multilaboratory d2s
2007	21/22	475	430	0.0037	0.0105	0.0057	0.0160
2006	19/20	435	415	0.0060	0.0170	0.0083	0.0234
2005	17/18	405	398	0.0072	0.0203	0.0115	0.0325
2004	15/16	358	352	0.0059	0.0166	0.0086	0.0244
2003	13/14	305	300	0.0041	0.0117	0.0080	0.0227
2002	11/12	281	271	0.0043	0.0123	0.0073	0.0207
2001	9/10	235	230	0.0053	0.0151	0.0070	0.0198
2000	7/8	221	214	0.0048	0.0135	0.0080	0.0225
1999	5/6	152	148	0.0052	0.0148	0.0078	0.0221
1998	3/4	53	51	0.0059	0.0166	0.0077	0.0216

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

Almost all of the annual precision estimates are smaller than the D2041 precision statements shown in Table 9. This suggests that the D2041 precision statements should be re-established.

4.3.   Alternatives to Current Standard Test Methods

There are two additional procedures for the determination of G_{mm} worthy of discussion: 1) the CoreLok and 2) the pressure meter method. The CoreLok is a vacuum-sealing device that has been discussed previously and has been adapted for the determination of G_{mm}. The pressure meter concept for asphalt mixtures is based on the pressure meter used for determining the air content of concrete mixtures. The advantages and disadvantages of each of these alternate methods are shown in Table 12.

TABLE 12   Advantages and Disadvantages of Alternate Methods for G_{mm}

Method	AASHTO and/or ASTM Designation	Advantages	Disadvantages
Vacuum Sealing or CoreLok (Instrotek) (*6*)	D 6857	• Simple to perform • Less time consuming than current AASHTO or ASTM procedures • Potential for reduced variability with more experience	• Equipment and bag cost • No dryback procedure • Not accurate for mixtures containing porous aggregate
Pressure Meter (Franko and Lee) (*12*)	None	• Similar results to AASHTO T 209 for mean and standard deviation • Fast test	• Cumbersome piece of equipment (large and heavy) • Equipment needs design changes to be more user friendly • Relatively unknown method in asphalt testing • Limited research has been conducted

Recent research related to G_{mm} testing has focused on the evaluation of alternative methods for determining the G_{mm} and not on improving the accuracy or precision of the current AASHTO or ASTM methods. As shown in Table 12, Franko and Lee (*12*) adapted the pressure meter test for asphalt mixtures. This test, similar to that used for the measurement of air content in concrete mixtures, was successful at matching AASHTO T 209 with respect to accuracy and precision. The main drawback is the excessive weight and size of the equipment. The test procedure, with additional refinement, appears to be a viable alternative to the current AASHTO and ASTM procedures.

Sholar et al. (*6*) evaluated a vacuum-sealing device, commercially known as the CoreLok, for the determination of G_{mm} for HMA containing porous limestone aggregate and mixtures containing non-porous granite aggregate. The CoreLok produced results similar to AASHTO T 209 for non-porous aggregate mixtures. However, the CoreLok

consistently determined higher G_{mm} values for asphalt mixtures containing porous aggregate. The researchers determined that this was the result of the CoreLok test method not having a dryback procedure.

As mentioned previously in the *Background* section, if G_{mb} is held constant and the G_{mm} changes by +0.010, the calculated air voids can change about +0.4%. The exact change is dependent on the initial G_{mm}. For example, if the G_{mm} of a mixture is 2.550 and is increased to 2.560, with a constant G_{mb} of 2.450, the air voids will increase from 3.92 to 4.30%, an increase of 0.38%. The AASHTO multilaboratory precision is 0.019 for mixtures containing non-porous aggregate. If the G_{mm} changes by 0.019 (an extreme case not likely to be exceeded more than 5% of the time by definition), then the air voids would change by 0.71%. The ASTM multilaboratory precision is 0.044 for mixtures containing non-porous aggregate. If the G_{mm} changes by 0.044, then the calculated air voids would change by 1.63%. For mixtures containing porous aggregate, the AASHTO and ASTM multilaboratory precision is 0.055. If the G_{mm} changes by 0.055, then the air voids would change by 2.03%.

As can be seen, the ASTM multilaboratory precision for non-porous aggregate and the AASHTO/ASTM multilaboratory precision for porous aggregate can result in between-laboratory air void values that are very different yet still considered valid according to the precision statement. One of the possible reasons for the reduction in precision are the variations allowed when performing the test. One way of addressing this issue is for each agency to conduct an interlaboratory precision study encompassing a representation of contractors, consultants, and agency labs that perform G_{mm} testing. In addition, each agency could further specify the exact types of testing equipment and procedure to be used, such as specifying a particular type of container and method for determining the mass of the container (container filled with water and weighed or weighed under water).

The Florida Department of Transportation, in an effort to improve the precision of the AASHTO T 209 method, has specified the following: 1) flasks will be the only container allowed, 2) the flasks will be filled with water and weighed, and 3) the dryback procedure is required to account for the use of porous aggregate. A precision study was conducted and the following d2s precision values were determined: single operator (0.013) and multilaboratory (0.016). In essence, reducing the options in the test method improved the precision.

5   BULK SPECIFIC GRAVITY OF COMPACTED HMA SPECIMENS

5.1.   Standard Test Methods

The standard test methods for determining G_{mb} of compacted HMA specimens are AASHTO T 166 and ASTM D 2726. The latter differs from the AASHTO standard principally with regard to its precision statement. Both methods calculate the specific gravity of the sample based on the fundamental density equation, mass over volume. It is therefore important that both dry mass and volume of a specimen be accurately determined. These methods base the determination of the volume of a compacted HMA specimen on Archimedes' principle that equates the buoyant force of an object submerged in water to the volume of water displaced by the object. The problem with this technique is that for specimens with large permeable voids, such as with coarse-graded, gap-graded, or open-graded mixtures, some of the water that enters the permeable voids when the specimen is submerged in water drains out of the specimen when the specimen is removed from the water bath and the surface water dried with a damp towel. The problem is amplified when the air voids in a specimen are interconnected or surface connected, which is often the case with field cores and laboratory performance test specimens compacted to target initial relative densities expected to occur in the field. The result of the water drainage is an error in the SSD mass and thereby the volume determination of the specimen. Consequently, a higher specific gravity value than what the specimen actually has is determined.

Current test methods provide an approach to reducing this error by requiring that specimens with water absorption of above two percent be sealed for testing. For T 166, the method cited for sealing is the paraffin coating method, AASHTO T 275. The ASTM method allows either the parafilm method, D 1188, or the vacuum-sealing method, D 6752, when the water absorption exceeds 2%. It is not known why the 2% limit was selected, but it is speculated that this limit was determined for Marshall mixes, which were typically fine-graded.

Note that the definitions of fine-graded and coarse-graded are provided in AASHTO M 323-07, Section 6.1.3.

5.2.   Precision Estimates of Standard Test Methods

As noted above, the precision information from the AASHTO and ASTM methods are different. The AASHTO method, T 166, only includes repeatability information:

"Duplicate specific gravity results by the same operator should not be considered suspect unless they differ more than 0.02."

The precision information for ASTM D 2726 is based on a study conducted by AMRL (*2*) involving 6-inch (150-mm) laboratory compacted specimens with approximately 4.5% air voids. The study included a fine-graded 12.5-mm and a coarse-graded 19.0-mm nominal maximum aggregate size mixture (NMAS) both containing

aggregate with less than 1.0% water absorption. The precision estimates from D 2726 are shown in Table 13 and indicate that the method is less repeatable (i.e. higher within-lab precision) for the coarse-graded specimens compared to fine-graded specimens. Potential sources of variation for the SSD method discussed by AMRL include differences in the dampness of the towel used to blot the surface of the specimen, temperature of the water bath, and differences in the interpretations for achieving the SSD condition as quickly as possible.

TABLE 13   ASTM D 2726 Precision Estimates for G_{mb}

	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single Operator Precision:		
12.5-mm NMAS (fine-graded)	0.008	0.023
19.0-mm NMAS (coarse-graded)	0.013	0.037
Multilaboratory Precision:		
12.5-mm NMAS (fine-graded)	0.015	0.042
19.0-mm NMAS (coarse-graded)	0.015	0.042

NCHRP Project 9-26 (*11*) recently completed a significant study that evaluated the precision estimates for G_{mb}. The study involved more than 22 laboratories that compacted specimens to 100 gyrations in the Superpave Gyratory Compactor in accordance with AASHTO T 312 then tested the compacted specimens in accordance with AASHTO T 166 and ASTM D 6752 (the vacuum sealing method). Materials variables included two aggregate types (low and high absorption) and two NMAS mixtures. The findings of this study were that mixtures with different NMAS and those containing high and low absorptive aggregate yielded similar precision estimates for G_{mb}. This study recommended the precision estimates shown in Table 14 for AASHTO T 166.

TABLE 14   NCHRP 9-26 Recommended Precision Estimates for AASHTO T 166

	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single Operator Precision	0.012	0.033
Multilaboratory Precision:	0.016	0.044

5.3.   Alternatives to Standard Test Methods

Several alternative methods available for determining G_{mb} are listed in Table 14 with their associated advantages and disadvantages.

TABLE 15   Advantages and Disadvantages of Alternative Methods for G_{mb}

Method	AASHTO &/or ASTM Designation	Advantages	Disadvantages
Paraffin Coating	T 275	• Inexpensive	• Sample is un-useable after test • Time consuming • Operator dependent • Wax penetrates large voids • Potential safety issue with handling of hot wax • Difficult to coat specimens with large aggregate
Parafilm	D1188	• Inexpensive	• Time consuming • Operator dependent • Very poor precision • Film tears easily with large aggregate size specimens • Some bridging of surface voids
Vacuum Sealing	T 331 D6752	• Solves problem with specimens having interconnected voids • Method has been thoroughly evaluated vs. other test methods	• Equipment and bag cost • Slightly less precise compared to T 166 • Some bridging of surface voids
Gamma Radiation (Troxler)	none	• Simple	• Limited research available at this time • Equipment cost • Poor precision • Requires calibration
Dimensional measurement	T 269, paragraph 6.2	• Simple	• Works only with specimens with perfect shapes • Under-estimates G_{mb} since surface texture voids are included in volume
Rapid Water Displacement (Gilson SG-4)	none	• Result in less than 2 minutes	• No standard method available at this time • No research available at this time • Measures apparent specific gravity

Several studies have been conducted over the past seven years comparing T 166 to alternate methods for determining G_{mb}. Many of the studies were sparked by the development of the CoreLok device, which is used to vacuum-seal compacted specimens in a special plastic bag for a more accurate volume determination when the specimen has interconnected voids.

Buchanan (*13*) compared AASHTO T 166 with the vacuum-sealing method, the parafilm method, and dimensional volume technique. The experimental plan included specimens compacted in the laboratory with an SGC to yield a range of air void contents. Mixture types included coarse- and fine-graded Superpave mixtures, SMA mixtures, and open-graded friction course (OGFC) mixtures. After the G_{mb} determination was made on the SGC specimens with the four methods, the specimens were saw cut into cube shapes and the G_{mb} determinations were made again. The study concluded that the vacuum-sealing method and AASHTO T 166 provided similar results for fine- and coarse-graded mixtures, but that the two methods gave different results for SMA and OGFC specimens. For these mixes, air void contents with the vacuum-sealing method were higher. A good relationship was found between percent water absorbed in the specimens and the air void difference between the two methods. Buchanan also concluded that significant errors can result even when the water absorbed is less than 2%. The final conclusion was that the vacuum-sealing method appeared to most accurately measure the G_{mb} of all specimens regardless of gradation, aggregate type, or compaction level.

Hall, et al. (*14*) conducted a variability analysis for G_{mb} determinations using AASHTO T 166, dimensional analysis, and the vacuum sealing method. Field produced Superpave mixtures were collected and compacted in an SGC using between 75 and 129 gyrations according to the mix designs for the field projects. Statistical analyses found significant differences in G_{mb} results from AASHTO T 166 and the vacuum-sealing method. The authors noted that substituting the G_{mb} results from the vacuum-sealing method in place of the results from AASHTO T 166 would increase the calculated air voids from 0.36 to 0.9%, and increase VMA from 0.31 to 0.79% for the mixtures in the study. Multi-operator variability was also examined. Compared to AASHTO T 166, the vacuum-sealing method was found to be less variable for 82% of the specimens. Hall et al. concluded that the vacuum-sealing method was a viable alternative for determining G_{mb}. However, agencies were cautioned to consider the shift in G_{mb} results on calculated mix properties.

Malpass and Khosla (*15*) evaluated a prototype gamma ray device for determining G_{mb} and compared the results from this method to those obtained using T 166, the parafilm method, and dimensional analysis. An analysis of variance showed that statistically different G_{mb} results were obtained among the four methods. It was observed that for mixtures with larger maximum aggregate size and higher air voids contents, the differences between results from the gamma ray device and AASHTO T 166 were greater. Conversely, for specimens with low air voids and smoother surface textures, the G_{mb} results from these two methods were similar. The authors explained that the G_{mb} results from AASHTO T 166 were erroneous for coarser, high void specimens due to

inaccurate sample volumes caused by the SSD determination. Analysis also showed that the gamma ray method was the least repeatable, followed by AASHTO T 166, parafilm, and dimensional analysis.

Cooley et al. (*16*) conducted an interlaboratory study to compare test method precision (single operator and multi-lab) of AASHTO T 166 with the vacuum-sealing method. Eighteen laboratories participated in the study. Laboratory-molded SGC specimens were made at the National Center for Asphalt Technology (NCAT) and sent to the participating labs. Sample variables were gradation (three levels) and compactive effort (three levels, which yielded essentially three levels of relative density). Results clearly showed that average G_{mb} results from the two methods were similar for fine-graded specimens, but that AASHTO T 166 yielded significantly higher results for coarse-graded and SMA specimens. The initial analysis showed that a small number of data points were questionable, and the investigation found that some problems could be traced back to the specimen fabrication process and discrepancies of sample masses for a few labs. With the explained outliers removed, the statistical analysis indicated that the vacuum-sealing method was less precise than AASHTO T166 in most cases. The higher within-lab and multilaboratory variability for the vacuum-sealing method were attributed to operator inexperience with this method and leaks in the bags (Note that the current vacuum-sealing method uses a tougher, better sealing bag). The report discusses at length the precision information provided in AASHTO T 166 and ASTM D 2726 and how they compared with their results. The authors found that their precision results closely matched those from ASTM D 2726 and indicated that the AASHTO precision limits may not be valid. The findings suggest that the vacuum-sealing method be used for coarse-graded mixtures when the sample has more than 0.4% water absorption. However, for practical purposes, they recommended the vacuum-sealing method be used for determining G_{mb} of all coarse-graded mixtures, including all laboratory-molded and field-compacted (cored) specimens.

Brown et al. (*17*) also examined four methods of determining G_{mb} as part of a larger study. They compared AASHTO T 166, the vacuum-sealing method, the gamma ray method, and dimensional analysis. In addition to the four test methods, other experimental variables included field cores, lab-molded specimens compacted to three levels of gyration, four gradations, three NMAS, and two aggregate types. Differences among G_{mb} results with the four methods were found to be statistically significant. Differences between AASHTO T 166 and the vacuum-sealing method were small for fine-graded, small NMAS (9.5-mm) mixtures and other mixtures with very low water absorption values. The authors recommended that the water absorption limit for AASHTO T 166 be reduced from 2 to 1%. Although the results suggest that this limit be set even lower, they reasoned that doing so would essentially preclude the use of AASHTO T 166 for most roadway cores. The authors also recommended the vacuum-sealing method add a step to reweigh the sample after determining the submerged weight to check for bag leaks. They also advocated a small correction factor of -0.2% air voids when using the vacuum-sealing method.

Williams (*18*) evaluated four methods for measuring G_{mb}, including the T 166, vacuum-sealing, dimensional, and gamma ray method using coarse-graded 25.0- and 37.5-mm mixtures compacted to approximately 2, 4, and 7% air voids. The results indicated that four methods produced statistically different G_{mb} results. In addition, T166 had the lowest levels of variability, followed by the vacuum-sealing method.

In NCHRP Project 9-26 (*11*), a significant part of the study evaluated the precision estimates for G_{mb} using ASTM D 6752 (the vacuum-sealing method). The findings of this study were that mixtures with different NMAS and those containing high and low absorptive aggregate yielded similar precision estimates for G_{mb}. This study recommended the precision estimates shown in Table 16 for ASTM D 6752. These are greater than the recommended precision estimates for AASHTO T 166 (see Table 14).

TABLE 16   NCHRP 9-26 Recommended Precision Estimates for ASTM D 6752

	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single Operator Precision	0.013	0.036
Multilaboratory Precision:	0.021	0.059

In summary, it has been reported in the existing literature that significant differences in measured G_{mb} using different test methods exist. These differences are more pronounced for coarse-graded HMA mixtures. AASHTO T 166 exhibited the smallest level of variability, followed by the CoreLok, then dimensional method, and finally the gamma ray device.

6   IMPACTS OF SPECIFIC GRAVITY MEASUREMENTS ON MIXTURE PROPERTIES

As stated previously, one motivation for adopting a new test method is reducing the variability of test results. An analysis was performed to assess the relative effect of reducing the variability of aggregate specific gravity and compacted HMA test (G_{mb}) on the VMA of HMA mixtures. The study involved a Monte-Carlo simulation of VMA results calculated using Equation 2. Details of the simulation include the following:

- Values of G_{mb} and G_{sb} were randomly drawn from a population exhibiting a normal probability distribution.
- Each simulation included 50,000 calculated values for VMA.
- Baseline "mean" values for the normal distributions were selected to yield a VMA result of approximately 15.1%, to represent a typical 12.5-mm NMAS hot-mix asphalt mixture.
- The baseline standard deviation for each of the normal distributions was calculated as the average value of all multi-lab standard deviations (1s) reported by the AASHTO Materials Reference Laboratory (AMRL) for the respective specific gravity. The standard deviation values reported for the traditional SSD method for both G_{mb} and G_{sb} were used.

- For G_{sb}, the specific gravity value used in the simulation was calculated using a 50/50 split between coarse (AASHTO T-85) and fine (AASHTO T-84) aggregate.
- To assess the effect of reducing aggregate and HMA bulk specific gravities on VMA results, the standard deviation of each property was reduced from the baseline value in steps of 10 percent to a final value of 50 percent of the baseline.

Each simulation produced a normal distribution of VMA values. Figure 1 shows the overall result from the simulation analysis. The *y*-axis represents the variability of VMA, expressed as the standard deviation of the VMA distribution. The *x*-axis represents the stepwise reduction of the G_{mb} standard deviation. The discrete points arranged vertically represent the stepwise reduction of G_{sb} at each *x*-axis (G_{mb}) reduction step. Thus, the area bounded by the points shown in the figure illustrates the potential reduction in VMA variability (standard deviation) resulting from reductions in constituent specific gravities.

It is possible to compute the percent-reduction in VMA standard deviation as a function of the reductions in standard deviation of both G_{mb} and G_{sb}, as illustrated in Equation 9:

$$VMA_{\text{red}} = 0.4894 \, (G_{mb})_{\text{red}} + 0.4880 \, (G_{sb})_{\text{red}} \tag{9}$$

where:

VMA_{red} = reduction in VMA standard deviation (%),
$(G_{mb})_{\text{red}}$ = reduction in G_{mb} standard deviation (%),
$(G_{sb})_{\text{red}}$ = reduction in G_{sb} standard deviation (%),

It is apparent from Equation 9 that, in general, the improvement in VMA variability is approximately half (in terms of percent from baseline, or original) that of any improvement in compacted HMA and/or aggregate specific gravity.

The focus on variability (standard deviation) is reasonable in the context of the associated range of two test results. Typically, the acceptable range of two test results is calculated using Equation 10.

$$d2s = 2.83 \, \sigma \tag{10}$$

where:

$d2s$ = acceptable range of two test results
σ = standard deviation of test

In the simulation study, the "baseline" standard deviation values for G_{mb} and G_{sb} yielded a distribution of VMA values with a standard deviation of approximately 1.31 percent. Using Equation 10, the acceptable range of two VMA results would be 3.7%. Typical HMA mix design and QA/QC criteria for VMA specifies a total VMA range of only 2.0 or 2.5%. Thus, in this example, two VMA results that should be considered acceptable could in fact fall outside VMA specifications.
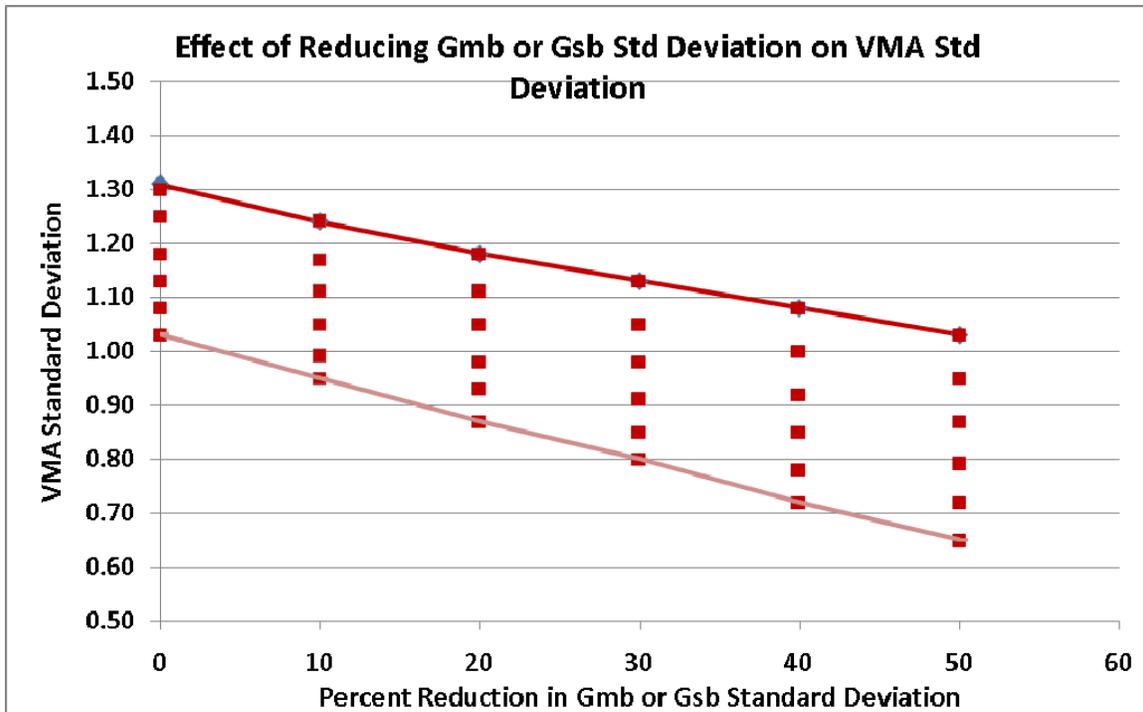
**FIGURE 1 Effect of Reducing G_{mb} or G_{sb} Standard Deviation on
VMA Standard Deviation.**

Changing from T 166 to T 331 (vacuum-sealing method) for G_{mb} determination will also significantly impact several HMA mix properties, including V_a, VMA, VFA, $\%G_{mm}@N_{ini}$, and roadway density, especially for coarse-graded and SMA mixes. Figure 2 shows the relationships betweens G_{mb} determined by the two methods from the NCAT study (*16*). The data are grouped by mix type: fine-graded, coarse-graded, and SMA. The correlation equations between the T 331 and T 166 from this figure are reproduced in Table 17. Using these regression equations, the "corrected air voids" were calculated at two key points in specifications for HMA. According to AASHTO standards, Superpave and SMA mix designs are based on 4.0% air voids. Currently, this criterion is based on G_{mb} determined by T 166. The "corrected air voids" for the three mix types, shown in the third column of Table 17, are the predicted G_{mb} values if the vacuum-sealing method were used. For fine-graded mixes, there is no difference on average between air voids based on T 166 and T 331. For coarse-graded mixes, the data indicate that when specimens have 4.0% air voids based on T 166, the corrected air voids based on the vacuum-sealing method would be 4.5% on average. Likewise for SMA mixes; specimens calculated to have 4.0% air voids based on T 166 would have 4.9% air voids when using T 331. Therefore, when using the vacuum-sealing method for G_{mb} determinations during mix design, the air voids and VMA will increase on average by 0.5% for most coarse-graded trial blends. This could lead to one of three possible adjustments by mix designers: 1) keep the gradation the same and increase the asphalt content (~0.2%) to reduce the air voids to 4.0%, 2) increase the dust content to lower air voids and VMA, or 3) adjust the gradation (shifting finer, toward the maximum density

line). Since it may be more desirable to slightly increase asphalt content of these mixes to improve their durability, the first option may be preferred. To assure that this mix design adjustment is selected, agencies may want to consider increasing the mix design VMA criteria by +0.5% for coarse-graded mixtures. Similarly, for an SMA mixture, the vacuum sealing method will result in 0.9% higher air voids and VMA on average. To bring the target air voids back down to 4.0%, the asphalt content would have to be increased by about 0.4%. This much additional asphalt could cause problems with rutting and flushing of SMA mixtures. Therefore, it is desirable to balance the change in VMA for SMA mixtures with adjustments in the asphalt content and the aggregate gradation. Therefore, increasing the VMA requirement for SMA by only 0.5% will force a more conservative increase in asphalt content and allow gradations to shift to take up the rest of the VMA difference caused by the vacuum-sealing method.

TABLE 17 Average Corrections for Air Voids when Using T 331 Instead of T 166

Mix Type	Regression Equation	Corrected V_a for 4.0% air voids based on T 166	Corrected V_a for 8.0% air voids based on T 166
Fine-Graded	$V_a(\text{T331}) = 0.9884 V_a(\text{T166})$	4.0%	7.9%
Coarse-Graded	$V_a(\text{T331}) = 1.1235 V_a(\text{T166})$	4.5%	9.0%
SMA	$V_a(\text{T331}) = 1.2312\ V_a(\text{T166})$	4.9%	9.8%

Using the vacuum-sealing method will also significantly change roadway density results for coarse-graded mixtures. Since 92.0% of G_{mm} (8% air voids) is a common minimum in-place density requirement in many acceptance specifications for dense-graded mixes, the corrected air void content at this point was also estimated for each mix type. As shown in Table 17, for coarse-graded mixtures, 8.0% air voids using T 166 correlates to 9.0% air voids (91.0% G_{mm}) using the vacuum-sealing method. For SMA mixtures, a minimum in-place density requirement of 92.0% of G_{mm} based on T 166 correlates to a minimum criterion of 90.2% if the vacuum-sealing method is used. Some agencies require a minimum in-place density of 93.0% for SMA mixes to avoid problems with permeability. Adjusting this criterion for the vacuum-sealing method yields a minimum value of 91.4%.
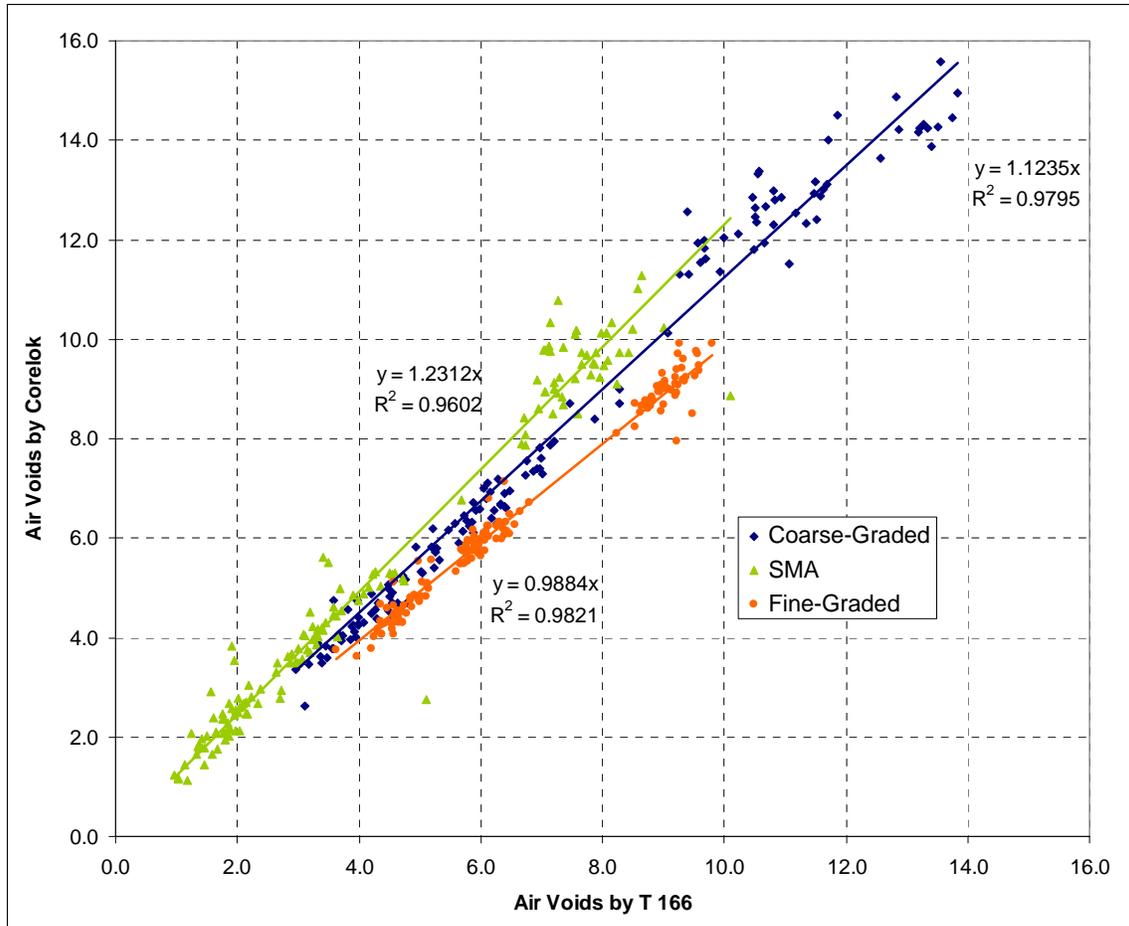
FIGURE 2 Comparison of Air Voids for Field Cores Using G_{mb} determined by AASHTO T 166 and Vacuum Sealing Methods (*17*).

7 SUMMARY

This report separately examined three specific gravity determinations, the bulk specific gravity of aggregate (G_{sb}), the maximum specific gravity of HMA mixtures (G_{mm}), and the bulk specific gravity of compacted HMA specimens (G_{mb}). Each specific gravity determination was reviewed in terms of: (1) problems and issues with current standard test methods, (2) modifications and/or alternate methods, and (3) areas that need further research and development. In addition, the impacts of specific gravity measurements on mix design properties and mix acceptance were also investigated. The review draws upon information from current AASHTO and ASTM standards, published research studies, state DOTs, equipment manufacturers, and the AMRL website.

   With respect to the bulk specific gravity of coarse aggregate, the review can be summarized as:
   • In the AASHTO T 85 and ASTM C127 procedures, the visual method of
      determining when aggregates reach a SSD condition is highly operator dependent.

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- Both standard test procedures, including aggregate soaking time, cannot be completed in one work day.
- All of the precision estimates for AASHTO T 85 and ASTM C127 from 1998 through 2005 by the AMRL are much greater than those cited in the standards, and they vary significantly from year to year, which is presumed to be due to the use of different aggregate sources in the proficiency sample program.
- The AggPlus system using the CoreLok device is commercially available as an alternative method for determining G_{sb} of coarse aggregate. Another device, the Gilson Rapid Water Displacement, is being developed.
- Recent studies have evaluated the AggPlus system using the vacuum-seal device against the AASHTO T 85 procedure. The AggPlus system does not require the determination of SSD condition and soaking time. The AggPlus produced higher specific gravity values that were significantly different (both statistically and practically) from those produced by AASHTO T 85. The difference was greater for highly absorptive coarse aggregate. Both methods had similar reproducibility.

For the bulk specific gravity of fine aggregate, the review can be summarized below:
- In AASHTO T 84 and ASTM C128, the SSD condition of various fine aggregates is not consistently determined using the cone and tamp technique.
- Both standard test methods, including aggregate soaking time, cannot be completed in one work day.
- As with the standard test methods for bulk specific gravity of coarse aggregate, most of the precision estimates for AASHTO T 84 and ASTM C128 published annually on the AMRL website are greater than those cited in the standards, and they vary significantly from year to year.
- Several modifications have been made by states to improve the process of determining the SSD condition. However, all modifications still require technician judgment, and the reproducibility improvement is not found in the literature.
- Alternate methods for determining G_{sb} of fine aggregate include the CoreLok, SSDetect, and Phunque. In addition, the Langley de-airing device can be used with AASHTO T 84.
- Recent studies have focused on the CoreLok and SSDetect devices. Both devices do not require the determination of SSD weight and soaking time. However, the G_{sb} values determined using either procedure were significantly different from those produced using AASHTO T 84. Differences were greater for more angular fine aggregate with aggregate having higher dust contents. The SSDetect had the best precision indices, then AASHTO T 84 and the CoreLok.

The review of the maximum specific gravity of HMA mixtures can be summarized as:
- The ASTM multilaboratory precision for non-porous aggregate and the AASHTO/ASTM multilaboratory precision for porous aggregate appeared very high, resulting in an allowable difference of up to 2% in between-laboratory air void values.
- The CoreLok and Pressure Meter procedures are alternatives for determining G_{mm}.

- Recent studies have focused on the evaluation of alternative methods but not on the improvement of the accuracy or precision of the current standard test methods. The CoreLok device shows promise. The CoreLok and AASHTO T 209 produced similar results for non-porous aggregate mixtures. For porous aggregate mixtures, the CoreLok produced higher G_{mm} values.

For the bulk specific gravity of compacted HMA specimens, the review can be summarized as:
- AASHTO T 166 and D 2726 procedures are not accurate for determining bulk specific gravity of many coarse-graded and SMA compacted specimens due to the loss of water from specimen pores during the SSD determination.
- Precision statements for AASHTO T 166 are not complete. However, research by AMRL provides recommendations for new precision statements.
- Alternate methods for determining G_{mb} include paraffin coating, parafilm, vacuum sealing, gamma ray, and dimensional measurement.
- Several recent studies have focused on the comparison of the parafilm, vacuum-sealing, gamma radiation, and dimensional measurement to AASHTO T 166. The G_{mb} values determined using these methods were different. The differences between G_{mb} results from AASHTO T 166 and the vacuum-sealing or gamma ray devices were greater for coarse-graded and SMA specimens. Several studies have recommended reducing the absorption limit for T 166 to 1.0% or less in order to improve the accuracy of the G_{mb} determination for coarse-graded and SMA mixtures.

The impacts of specific gravity measurements on mix design properties were also performed and are summarized:
- Based on the current precision indices for G_{mb} and G_{sb}, the acceptable difference for VMA results performed in two labs on a split sample is 3.7%. This difference is greater than most VMA quality assurance specifications (typically in the range of only 2.0 or 2.5%). This indicates that such specification limits are not valid.
- For G_{mm}, the ASTM multilaboratory precision for mixtures with non-porous aggregate and the AASHTO/ASTM multilaboratory precision for porous aggregate can result in a difference of 2% in between-laboratory air void values.
- When the vacuum-sealing method (AASHTO T 331) is used instead of the T 166 for determining G_{mb} of coarse-graded compacted HMA specimens, air voids, and VMA will increase approximately 0.5%. In effect, this could result in a slight increase in asphalt content for coarse-graded mixtures, thereby making such mixtures more durable and easier to compact.
- Replacing T 166 with the vacuum-sealing method for roadway cores will decrease field-relative densities by approximately 1% for coarse-graded mixtures and approximately 1.75% for SMA mixtures.

Based on the review, the automated test methods offer time savings. In addition, the differences in specific gravity results between the automated test methods and the standard test methods significantly impact the mix design properties for some aggregate or mixture types.

8 RECOMMENDATIONS

Based on the review, the following recommendations are offered for improving specific gravity determinations:

1. The current standard test methods for determining G_{sb} of coarse aggregate are considered satisfactory with respect to accuracy and precision. No change is warranted in these methods at this time. Research should explore reducing the soak time.
2. The determination of G_{sb} for fine aggregate suffers from poor reproducibility due to the subjective determination of the SSD condition. The accuracy of the fine aggregate G_{sb} is also questionable for some absorptive materials and those that contain highly angular and/or textured particles or that have high dust contents. Further research is needed to improve the reproducibility and accuracy of the fine aggregate G_{sb} determination. Alternate methods of determining the SSD condition of fine aggregate appear to be promising.
3. For agencies that use VMA or VFA in mix design approval or HMA acceptance testing, the limits for these criteria should be based on well-documented precision information for G_{sb} determinations.
4. The current standard test methods for determination of G_{mm} for HMA mixtures containing aggregate with low absorption are satisfactory. However, the multilaboratory precision estimate for mixtures containing moderately to highly absorptive aggregate is so large that it is not valid to distinguish air voids results for split specimens conducted in two laboratories that differ by as much as 2.0 percent. Clearly, further work needs to be conducted to improve the reproducibility of the G_{mm} determination for such aggregate. Another important objective for further research should be to reduce the time to complete the test for mixes containing absorptive aggregate.
5. In order to improve the accuracy of the G_{mb} determination, T 166 (and the corresponding ASTM method D 2726) should be limited to specimens with a water absorption less than or equal to 1.0%. In practice, this will limit the T 166 to use with well-compacted, fine-graded mixtures. For specimens with greater than 1.0% water absorption, only the vacuum-sealing method (AASHTO T 331, ASTM D 6752) should be used since this method has similar precision estimates to D 2726 for these mixtures.
    Note: Agencies should be aware that changing to the vacuum-sealing method will have substantial consequences with regard to mix designs for coarse-graded and SMA mixtures, and measurement of in-place densities of these mixtures when measurements are based on cores:
    - For coarse-graded and SMA mixtures, the vacuum-sealing method will yield higher air voids and VMA than for the same mixtures tested by T 166. Based on available data, the average shifts are about 0.5% for both air voids and VMA for coarse-graded mixtures using mix design compactive efforts. For SMA mixtures, the average shifts in air voids and VMA are 0.9% at a normal mix design compactive effort. These changes will have an effect on future mix designs. Agencies may want to consider adjusting their mix design VMA

criteria so that the resulting mixtures can be expected to perform as well or better than those in current use. Reasoning was provided in this report to support an increase in VMA by 0.5% for coarse-graded Superpave and SMA mixtures.

- Using the vacuum-sealing method in lieu of T 166 for measurement of core densities will shift the results more dramatically than for mix designs. Available data shows that in-place air voids are approximately 1.0 and 1.7% higher on average for coarse-graded mixtures and SMA mixtures, respectively, when using the vacuum-sealing method in place of T 166. Therefore, changing to the vacuum-sealing method for acceptance testing of in-place density will result one of two scenarios for agencies: either leave in-place density criteria as is and expect contractors to improve their compaction processes to meet the criteria, or adjust the specification criteria for in-place densities to be consistent with the new measurement method so that densities levels are achievable with the current practices for asphalt pavement construction.

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