Bulk Specific Gravity of Reclaimed Asphalt Pavement Aggregate

Evaluating the Effect on Voids in Mineral Aggregate

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Several methods are available for determining the bulk specific gravity (G_{sb}) of reclaimed asphalt pavement (RAP). However, a clear recommendation has not been had for determining this property. In this study, asphalt mixes with known aggregate properties were produced and aged in the laboratory to simulate RAP. The aggregates were recovered, and the aggregate properties, including G_{sb}, were reassessed. The aged mixtures were also tested to determine maximum theoretical specific gravity (G_{mm}), from which estimated G_{sb} values could be calculated. The G_{sb} values from both the extraction and G_{mm} methods were compared with the known or true G_{sb} values for these aggregates. The effects of the RAP G_{sb} errors on voids in mineral aggregate values from the various methods were also evaluated. On the basis of the results of this study, it is recommended that the G_{mm} method be used to determine the RAP G_{sb} when a regional absorption value is known.

One of the key issues accounted for in current mix design procedures is mix durability. Voids in the mineral aggregate (VMA) is the measure used to ensure adequate film thickness to prevent durability issues. VMA quantifies the area between aggregate particles filled with the effective asphalt content and air. One of the inputs for calculating VMA is the bulk specific gravity (G_{sb}) of the combined aggregates; therefore, it is important to obtain an accurate G_{sb}. The G_{sb} of the combined aggregates is determined from specific gravity tests conducted on samples from each aggregate component in the mixture.

When reclaimed asphalt pavement (RAP) is used as a component of an asphalt mixture, the G_{sb} of the RAP aggregate must also be determined. Directly measuring the RAP aggregate properties such as gradation, G_{sb}, or other Superpave® consensus properties, requires the additional step of recovering the RAP aggregate. Two methods can be used to recover the RAP aggregate: solvent extraction (AASHTO T164) and the ignition oven method (AASHTO T308). While both methods are accepted, disadvantages are associated with both. The solvent extraction method may leave a residue of asphalt on the aggregate while the ignition oven method may cause aggregate degradation. Prowell and Carter evaluated the properties of aggregates extracted using the ignition method and found that the specific gravities of some aggregates were significantly affected by the high temperatures (*1*). Lynn et al. also found that aggregate degradation due to the ignition method can be an issue, and the difference in aggregate properties could affect the VMA (*2*). Shultz evaluated several solvent extraction methods and reported that the asphalt content tended to vary, which may be an indication that some methods were not adequately removing asphalt from the aggregate (*3*).

Alternatively, the RAP aggregate G_{sb} can be estimated from the effective specific gravity (G_{se}) of the RAP aggregate, which is calculated from a maximum specific gravity (G_{mm}) test on the RAP sample, the asphalt content of the RAP, and an assumed asphalt absorption. This technique is recommended in *NCHRP Report 452: Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual* (*4*). However, this approach also has three significant disadvantages. The first two disadvantages are associated with determining the asphalt content that must be obtained using one of the extraction methods, either ignition oven or solvent. If the ignition method is employed, the accuracy of the asphalt content may depend on an assumed correction factor. If the solvent extraction method is employed, some of the aged asphalt may be difficult to remove from the aggregate, and the asphalt content may be underestimated. The third potential problem is that the asphalt absorption must be estimated based on a typical value for a location. The assumed value may not adequately represent the absorption that actually exists for the particular RAP.

If the RAP aggregate G_{sb} is incorrect, it will affect the VMA calculated for the mixture. The magnitude of the VMA error will depend on the error of the RAP aggregate G_{sb} and the percentage of RAP used in the mixture. Therefore, the best method for determining the RAP aggregate G_{sb} needs to be identified to prevent overestimating the VMA of a mix, which could result in durability issues.

OBJECTIVES

The main objective of this study was to identify the best method for determining the RAP aggregate G_{sb}. A secondary objective was to examine the differences and errors associated with the options for determining or estimating the RAP aggregate G_{sb} compared with the true G_{sb}. In this study, asphalt mixes with known aggregate properties were produced and aged in the laboratory to simulate RAP. The G_{mm} values for the aged mixes were determined and were used in calculating the estimated G_{sb}. The aggregates were then recovered, and the aggregate properties were reassessed. Comparisons of the G_{sb}

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TABLE 1 Aggregate Properties Measured

Property	Specification
Sieve analysis	AASHTO T27
Coarse aggregate durability	AASHTO T210
Fine aggregate durability	AASHTO T210
Sand equivalent	AASHTO T176
Los Angeles abrasion	AASHTO T96
Specific gravity and absorption of coarse aggregate	AASHTO T85
Specific gravity and absorption of fine aggregate	AASHTO T84
Coarse aggregate angularity	AASHTO T326
Fine aggregate angularity	AASHTO T304
Fractured faces	ASTM D5821
Soundness	AASHTO T104

values from the extraction methods and the estimated values from the G_{mm} tests were made with the known or true G_{sb} values for these aggregates. The impact of errors on VMA associated with the different methods of determining G_{sb} for the RAP was evaluated for different percentages of RAP in a typical asphalt mixture.

EXPERIMENTAL PLAN

Superpave mix designs were developed in accordance with AASHTO M323 using four virgin aggregate sources. Aggregate properties, including G_{sb} and absorption, were determined for the virgin aggregate blends. Table 1 lists the aggregate properties measured and the procedures that were followed to determine the aggregate properties. The loose Superpave mixes were then aged in the laboratory to produce simulated RAP, and the G_{mm} of each mix was determined after aging. The aggregates were extracted from the simulated RAP using one of three extraction methods, and the aggregate properties were reassessed. The measured and estimated G_{sb} values for each simulated RAP were calculated based on the measured and assumed properties. The measured and estimated G_{sb} values were then compared with the virgin G_{sb} values and used to calculate VMA.

MATERIALS

The four aggregate sources used were two limestones (hard and soft), a rhyolite, and a granodiorite source. The hard limestone was from an Alabama quarry, and the soft limestone was from a Florida quarry. The rhyolite was from a Nevada quarry, and the granodiorite was from a California quarry. Aggregate sources are labeled as follows:

- Hard limestone is labeled Alabama,
- Soft limestone is labeled Florida,
- Granodiorite is labeled Handley, and
- Rhyolite is labeled Lockwood.

Superpave mix designs were developed for each region, consisting of all virgin aggregates and unmodified asphalt binder. The virgin asphalt binder used for both the limestone mixes was a PG 67-22, and the virgin asphalt binder used for the rhyolite and granodiorite mixes was a PG 64-22.

LABORATORY-PRODUCED RECLAIMED ASPHALT PAVEMENT

Superpave mix designs were developed for each aggregate. Once the mix designs and determination of the virgin aggregate properties were completed, laboratory mix was produced and aged to simulate RAP. The aging process was a modification of AASHTO R30. Short-term aging was conducted in accordance with AASHTO R30. The long-term aging process detailed in AASHTO R30 is intended for compacted specimens. However, in this study, the long-term aging was used for loose mix. The loose mixes were spread in thin layers in pans and short-term aged for 4 h at 275°F and stirred every hour. Short-term aging was followed by 5 days of aging at 185°F with the material stirred twice a day.

EXTRACTION METHODS

After 5 days of aging, the material was allowed to cool and then divided into three portions. One portion of the material was extracted following the reflux method (AASHTO T164 Method B). The second portion was extracted following the centrifuge method (AASHTO T164 Method A). The third portion was extracted in the ignition oven (AASHTO T308). The solvent used for the reflux and centrifuge methods was trichloroethylene. The asphalt contents were determined for each sample extracted. Correction factors were not used for the ignition oven results.

RESULTS OF ASPHALT CONTENTS DETERMINED FROM EXTRACTIONS

The asphalt contents were determined using all three extraction methods. The true asphalt content was assumed to be the target asphalt content since the actual asphalt content of a sample could not be determined. The target asphalt content was added during the mixing process; however, asphalt can remain in a mixing bowl, aging pan, and gyratory mold, thus affecting the actual asphalt content. Figure 1 illustrates the asphalt contents obtained from each extraction method as well as the true asphalt content. The true asphalt content was consistently higher than the asphalt contents obtained from each of the extraction methods. The centrifuge method yielded the lowest asphalt content for all four aggregate sources, while the ignition oven consistently yielded the highest of the extraction methods.

Two unequal sample size t-tests were conducted at a level of significance of 0.05 to determine if the mean asphalt content of each mix for a given extraction method was significantly different from the target asphalt content for a given mix. The null hypothesis in each case was that the extracted asphalt content was not significantly different from the target asphalt content. Table 2 summarizes the results of the t-tests conducted. In almost all cases, the null hypothesis was rejected, indicating a significant difference between the target asphalt content and the extracted asphalt contents.

The statistical analysis did not reveal an extraction method that resulted in mean asphalt contents that were not significantly different from the target asphalt content; therefore, the recommendation for a method to determine the asphalt content of a RAP source was based on the method that yielded an asphalt content closest to the target asphalt content. Since the ignition oven yielded the asphalt content closest to the true asphalt content, the ignition oven asphalt content was selected to estimate the G_{sb} using the G_{mm} method.

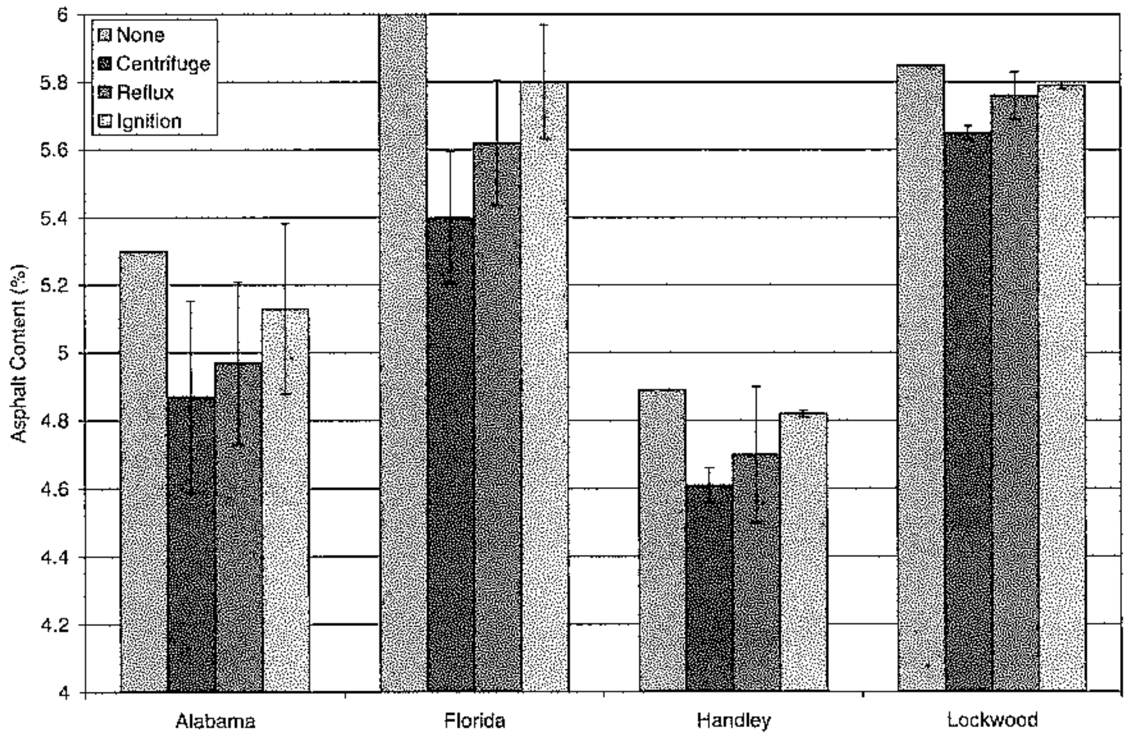

FIGURE 1 Asphalt contents.

VOLUMETRIC CALCULATIONS OF MATERIALS WITH KNOWN PROPERTIES

Measured asphalt contents and aggregate properties were used to determine measured and estimated G_{sb} values for each source. The estimated G_{sb} was also calculated using extraction information from the ignition oven method. After G_{sb} values were determined for each method, the VMA values were calculated. Comparisons between methods of both the G_{sb} and VMA values were made along with comparing to the virgin values. The following section details the calculations completed.

TABLE 2 Results of *t*-Tests Comparing Asphalt Contents

Aggregate Blend	Extraction Method	Reject Null Hypothesis
Alabama	Centrifuge	Yes
Alabama	Reflux	Yes
Alabama	Ignition oven	Yes
Florida	Centrifuge	Yes
Florida	Reflux	Yes
Florida	Ignition oven	Yes
Handley	Centrifuge	Yes
Handley	Reflux	No
Handley	Ignition oven	Yes
Lockwood	Centrifuge	Yes
Lockwood	Reflux	No
Lockwood	Ignition oven	Yes

Specific Gravities

The measured G_{sb} values of the virgin and recovered aggregate were determined in accordance with AASHTO T84 and AASHTO T85. The combined measured G_{sb} of each blend was determined by using the following equation:

$$G_{sb} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} \frac{P_i}{G_i}} \quad (1)$$

where P_i is percentage of aggregate source i and G_i is aggregate bulk specific gravity of source i.

However, the G_{sb} of the RAP aggregate can also be estimated using the recommended methodology in *NCHRP Report 452* (*4*), which would eliminate the need to measure the G_{sb} of extracted aggregate. The estimated G_{sb} values were backcalculated from G_{mm} tests (G_{mm} method). In the G_{mm} method, the RAP G_{mm} is determined, and an asphalt content is calculated from one of the extraction procedures. The asphalt contents from the ignition oven tests were used to estimate G_{sb} since its results were the closest to the true asphalt content of each mixture. The G_{mm} and asphalt content values were used along with an absorbed asphalt specific gravity to determine the RAP aggregate G_{se}. The formula used to calculate the RAP aggregate G_{se} is as follows:

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \quad (2)$$

where P_b is percentage of asphalt and G_b is asphalt specific gravity of the binder (assumed to be 1.028 in this study).

The next step in the G_{mm} method after calculation of the G_{se} was to calculate an estimated G_{sb}. The equation used to estimate the G_{sb} follows:

$$G_{sb_{est}} = \frac{G_{se}}{\frac{G_{se} * P_{ba}}{100 * G_b} + 1} \quad (3)$$

where P_{ba} is percent asphalt absorbed.

In this study, P_{ba} was calculated from the known or true values of G_{se}, G_{sb}, and G_b with Equation 4:

$$P_{ba} = 100\left(\frac{G_{se} - G_{sb}}{G_{se} \times G_{sb}}\right)G_b \quad (4)$$

In actual practice, these true values will be unknown; therefore, mix designers will need to base the asphalt absorption value on typical values from asphalt mixes for the area where the RAP was obtained.

TABLE 4 Results of G_{sb} Mean Comparisons

Aggregate Blend	G_{sb} Determination	Reject H_0
Alabama	Centrifuge	Yes
Alabama	Reflux	Yes
Alabama	Ignition oven	No
Alabama	G_{mm} method	Yes
Florida	Centrifuge	No
Florida	Reflux	Yes
Florida	Ignition oven	Yes
Florida	G_{mm} method	No
Handley	Centrifuge	—
Handley	Reflux	Yes
Handley	Ignition oven	Yes
Handley	G_{mm} method	No
Lockwood	Centrifuge	No
Lockwood	Reflux	No
Lockwood	Ignition oven	No
Lockwood	G_{mm} method	No

NOTE: — = bad test data.

Results of G_{sb} and Voids in the Mineral Aggregate Calculations for Known Materials

The VMA was first calculated using the measured G_{sb} values. Then the VMA was calculated using the estimated G_{sb}. Table 3 lists the measured G_{sb} for the original aggregates (which were considered the true G_{sb}), measured G_{sb} values for the extracted aggregates, and estimated G_{sb} based on the G_{mm} method. The measured G_{sb} from the centrifuge extracted aggregate for Handley was removed from the data set since it was unrealistically low. With the exception of the Handley material, the two solvent extraction methods resulted in measured G_{sb} values that were similar to or slightly higher than the true G_{sb}. The measured G_{sb} of the ignition oven recovered aggregates was either similar to or lower than the true G_{sb}. The estimated G_{sb} values were similar to the true G_{sb} values.

The RAP aggregate G_{sb} results were compared with the true G_{sb} results using Tukey's mean comparisons ($\alpha = 0.05$) to determine if the mean G_{sb} values were significantly different. The null hypothesis in each case was that the RAP aggregate G_{sb} determined from a given method was not significantly different from the true G_{sb}. Table 4 summarizes the results of the t-tests. Eight of the 15 t-tests did not reject the null hypothesis, which indicates that no statistical significant difference was found between the RAP aggregate G_{sb} and the true G_{sb} for the majority of comparisons. Three of the five cases that rejected the null hypothesis were reflux solvent extractions. This indicates that three of the four sets of G_{sb} values from reflux extracted aggregates were significantly different from the true G_{sb}. Two of the four ignition oven mean G_{sb} values were significantly different from the true G_{sb}. Both the centrifuge and G_{mm} methods had one set of G_{sb} values that were significantly different from the true G_{sb}. The Handley centrifuge data were not used in the G_{sb} t-test evaluation since the data were suspect.

Table 5 lists the average difference between the true G_{sb} value and each respective method for calculating the RAP G_{sb}. For each material, the estimated G_{sb} was the most similar to the true values. However, the assumed asphalt absorption for the G_{mm} method was based on the true asphalt absorption. In practice, an assumed asphalt absorption should be based on typical asphalt absorptions for an asphalt plant. If the typical asphalt absorption for an asphalt plant is not known, another method for determining the RAP aggregate G_{sb} should be considered, such as the measured G_{sb} from one of the extraction methods.

The errors for the measured G_{sb} of the extracted RAP aggregates tended to vary. The measured G_{sb} from the reflux extractions exhibited results that were the most consistent in regard to the error; the reflux consistently underestimated the G_{sb}. The ignition oven tended to yield the lowest difference, with the exception of the Florida limestone, from the true G_{sb} for the measured G_{sb} values. The error for the Florida limestone was the largest error and was most likely due to aggregate

TABLE 3 Average G_{sb} Values

Aggregate Blend	Extraction Method				
	None	Centrifuge	Reflux	Ignition Oven	Estimated G_{sb}
Alabama	2.697	2.719	2.722	2.687	2.689
Florida	2.500	2.508	2.524	2.461	2.504
Handley	2.560	—	2.579	2.574	2.557
Lockwood	2.528	2.518	2.546	2.532	2.525

NOTE: — = bad test data.

TABLE 5 G_{sb} Differences

Aggregate Blend	Extraction Method			
	Centrifuge	Reflux	Ignition Oven	Estimated G_{sb}
Alabama	−0.022	−0.025	0.010	0.008
Florida	−0.008	−0.024	0.039	−0.004
Handley	—	−0.019	−0.014	0.003
Lockwood	0.010	−0.018	−0.004	0.003

NOTE: — = bad test data.

TABLE 6 Combined G_{sb} Criterion for Each Blend

Aggregate Blend	Percentage of Fines	Percentage of Coarse	Combined G_{sb} Criterion
Alabama	52.2	47.8	0.0465
Florida	54.7	45.3	0.0463
Handley	45.9	54.1	0.0470
Lockwood	58.6	41.4	0.0460

degradation. Aggregates such as the Florida limestone emphasize the need to evaluate the effects of an extraction method for a region since some materials are dramatically affected by the method of extraction.

Variability in determining material properties is expected. Since differences in results are expected, an acceptable level of difference was defined to evaluate whether the differences between the true values and the extracted aggregate G_{sb} or estimated G_{sb} were substantial. An established criterion does not exist for a combined G_{sb}. Therefore, one was calculated based on the current coarse and fine aggregate G_{sb} criteria. The criterion developed used the true gradations to establish fine and coarse aggregate percentages and the D2S criterion from AASHTO T 84 and T 85 as input for the G_{sb} values in the combined aggregate equation (see Equation 1). The D2S (difference between two tests) criteria for fine and coarse G_{sb} are 0.043 and 0.051, respectively. Table 6 summarizes the percentages of fine and coarse aggregate and the calculated combined G_{sb} criterion for each blend.

The measured G_{sb} from the ignition oven extracted Florida aggregate was outside this criterion. All other G_{sb} values were within the allowable difference from the true G_{sb}. In other words, by current acceptable tolerances for measuring G_{sb}, all but the ignition oven extracted Florida limestone would be considered similar to the true G_{sb}. The analysis in this study indicated that the G_{mm} method was the most appropriate method for determining the RAP aggregate G_{sb} when a regional absorption is known.

The differences found between the various methods to determine RAP aggregate G_{sb} and the true G_{sb} indicated that, generally, from a practical standpoint, the errors are small. However, these small errors may be magnified when used in VMA calculations. The final evaluation for the study examined the effect of these G_{sb} errors on calculated VMA.

As a RAP percentage increases, the RAP contributes a larger portion of the combined G_{sb}. Small errors in RAP aggregate G_{sb} will be magnified as the RAP percentage increases. Figure 2 illustrates generalized relationships between G_{sb} error, VMA error, and RAP percentage. This plot illustrates the importance of selecting the appropriate method for determining the RAP G_{sb}. Each colored line represents a G_{sb} error and its effect on VMA as the RAP percentage increases. For example, the solid line with triangles represents a RAP G_{sb} that is 0.01 less than the true G_{sb} for that RAP source. At 20% RAP, the VMA error is only 0.06; at 60% RAP, the VMA error increases to 0.2.

An evaluation of the effects of the errors from the estimated RAP G_{sb} on VMA with increasing RAP percentage was conducted. The VMA errors calculated for each source versus the increasing RAP percentage are illustrated in Figure 3. The Handley aggregate yielded the least difference as the RAP percentage increased, while the Florida VMA difference was the largest.

In practice, a VMA error that is equal to or less than ±0.2% is acceptable. Up to 40% of either limestone RAP sources could be used in a mix without substantially affecting the VMA. The VMA error would by substantially affected for the Lockwood aggregate at RAP percentages greater than 48%. The rate at which the VMA difference increases depends on the aggregate source, as can be seen in Figure 3.

CONCLUSIONS

The methods available for determining the G_{sb} for RAP aggregate were evaluated in this study. Virgin mixes were aged to produce four simulated RAP materials. The asphalt contents determined from the extractions indicated that the ignition method yielded the asphalt content most similar to the actual asphalt content. When the RAP G_{sb} values were compared with the true G_{sb}, the estimated G_{sb} using the G_{mm} method and asphalt contents from the

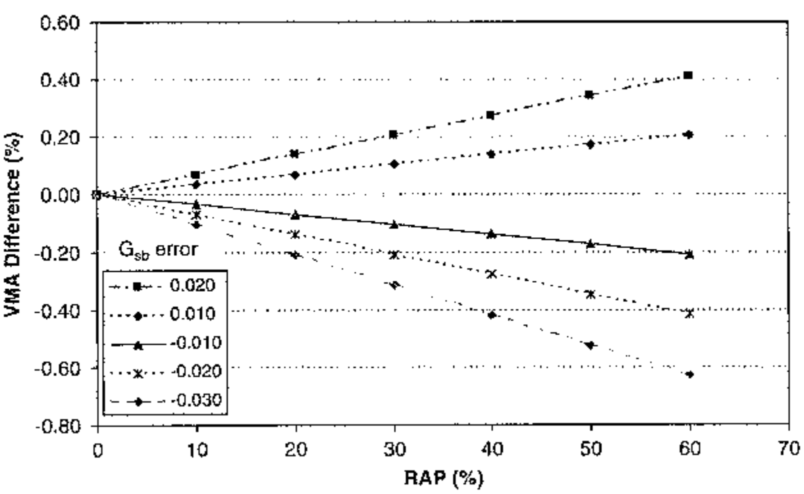

FIGURE 2 VMA error.

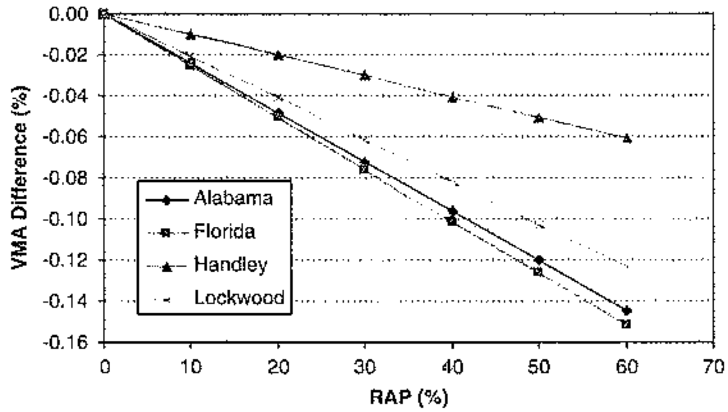

FIGURE 3 VMA difference versus RAP percentage.

ignition oven were the closest to the true G_{sb} for each material. Potential for errors in VMA caused by the estimated RAP aggregate G_{sb} errors was evaluated. The small errors in VMA resulting from the G_{mm} method of estimating G_{sb} were found to be within 0.2%, considered reasonable for high RAP volumetric mixes. The recommendation for determining the RAP G_{sb} is to use the G_{mm} method when a known regional absorption is available. If a regional absorption is not available, then the RAP G_{sb} should be determined from extracted aggregate. The method for extraction employed should be one appropriate for a region. Results of this study confirmed that some extraction methods are not appropriate for certain aggregates.

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