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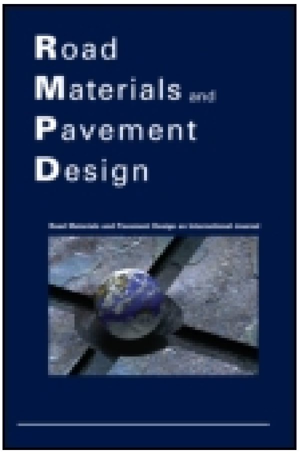

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Recommendations for the characterization of RAP aggregate properties using traditional testing and mixture volumetrics

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Recommendations for the characterization of RAP aggregate properties using traditional testing and mixture volumetrics

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A Federal Highway Administration (FHWA) funded study was conducted to investigate the influence of extraction methods on aggregate properties. The properties of the virgin aggregates were compared with those of aggregates extracted from laboratory-produced recycled asphalt pavement (RAP) from four different aggregate sources. The extracted and actual asphalt binder contents were also compared. The study investigated the influence of the extraction method on tendencies to under- or over-estimated certain mix design properties. The test results were also examined to determine the impact of the RAP aggregate properties on the voids in mineral aggregate (VMA) over different RAP percentages. Recommendations were made for the most appropriate method to estimate the RAP aggregate specific gravities based on acceptable levels of error in VMA for mixtures with varying levels of RAP.

Keywords: extraction; centrifuge; ignition oven; reflux; aggregate; VMA

1. Introduction

As reclaimed asphalt pavement (RAP) usage becomes more common throughout the industry, the differences in handling RAP materials as compared with virgin aggregates are becoming more significant. These differences include RAP aggregate properties, such as specific gravity, absorption, and aggregate gradation, along with other properties of the virgin and RAP aggregate blends. Currently, there are no consistent recommendations for assessing the RAP aggregate properties.

Solvent extraction (AASHTO T164 [AASHTO 2009]) and the ignition oven method (AASHTO T308 [AASHTO 2009]) are currently being used to recover RAP aggregates for specific gravity testing and to determine other properties of the aggregate blend such as gradation and Superpave consensus properties. However, there are limitations with both of these methods. The solvent extraction method may leave a residue on the aggregate while the ignition oven method may cause aggregate degradation. Researchers have evaluated the properties of aggregates extracted using the ignition oven method and found that the specific gravities of some aggregates were significantly affected by the ignition oven (Prowell & Carter, 2000). Others also found that aggregate degradation in the ignition oven can be an issue and concluded that the difference in aggregate properties could affect the VMA (Lynn, James, Wu, & Jared, 2007). Evaluations of multiple solvent extraction methods revealed that asphalt content tended to vary, which may

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be an indication that some methods were not completely removing the asphalt binder from the aggregates (Shultz 1998).

2. Objective

The objective of this study was to investigate three common extraction methods and their influence on the measured properties of the RAP materials, including: binder content, gradation, and specific gravity of the RAP aggregate and how they influence the VMA calculations in typical hot mix asphalt (HMA) mix designs.

3. Research approach

The investigation included four aggregate sources: two limestones (hard and soft), a rhyolite, and a granodiorite. The hard limestone was from Calera, Alabama and the soft limestone was from Brooksville, Florida. The rhyolite was from Reno, Nevada and the granodiorite was from Gonzales, California. Superpave mix designs were developed for each aggregate source in accordance with AASHTO M323 (AASHTO 2009). The mix designs were developed with the virgin aggregates and unmodified asphalt binders. The asphalt binder used for both Alabama and Florida mixes was a PG67-22 supplied by Ergon, Inc. The asphalt binder used for the Nevada and California mixes was a PG64-22 supplied by Paramount Petroleum.

The experimental plan included determining properties of the virgin aggregate blends and contrasting those properties with the laboratory-produced RAP aggregates obtained by extracting the aggregate through the centrifuge, reflux, and ignition oven methods. For the purposes of this paper the reported test properties will include the measured binder content, aggregate gradation and specific gravity of both the coarse and fine aggregates, which all influence the calculated VMA of mixtures containing RAP. The complete data set including the Superpave consensus properties are reported elsewhere (Hajj et al., forthcoming).

The simulated RAP materials were prepared by mixing the samples in the laboratory at the optimum binder content for 3 to 5 minutes following typical mixing procedures as outlined in the Superpave Mix Design Manual (SP-2) (Asphalt Institute, 2001). The mixtures were then subjected to short-term oven aging (4 hours at 135°C) followed by long-term oven aging (5 days at 85°C), in loose condition. To aid in the uniformity of the binder aging, the mixtures were stirred once per hour during the short-term aging and twice per day during the long-term aging.

After the long-term aging, the mixtures were extracted utilizing the three extraction procedures; centrifuge, reflux, and ignition oven. The solvent extractions (i.e. reflux and centrifuge) were all conducted using trichloroethylene (TCE) as the solvent. The centrifuge extractions were conducted in accordance with AASHTO T164, Method A (AASHTO, 2009), while the reflux extractions were conducted in accordance with AASHTO T164, Method B (AASHTO, 2009). The ignition oven extractions were conducted following AASHTO T308 (AASHTO, 2009). Once the extractions were completed, the extracted RAP aggregates were dried and tested in accordance with their respective procedures.

4. Mix design summary

All mixtures were designed following the Superpave volumetric mix design method (AASHTO M323 and R35 (AASHTO, 2009)) for 0.3 to 3 million equivalent single axle loads (ESALs) for the Alabama and California aggregate sources and 3 to 10 million ESALs for the Florida and Nevada sources, which are considered typical traffic levels for those mixtures. Table 1 provides a summary of the mix design data.

Table 1. Mix design summary.

Property	Alabama	Florida	Nevada	California
Nominal Max. Aggregate Size (inch)	0.75	0.50	0.75	0.50
PG Binder	67-22	67-22	64-22	64-22
Design ESALs (millions)	2.5	6	6	2.5
Optimum Binder (% TWM)	5.30	6.00	5.85	4.89
Maximum theoretical gravity, G_{mm}	2.537	2.435	2.424	2.422

5. Extracted asphalt binder contents

Figure 1 and Table 2 illustrate the asphalt binder contents obtained from each extraction method along with their 95% confidence intervals. The properties of the extracted RAP aggregates were compared with the properties of the virgin aggregates using statistical analyses at a significant level of 0.05. The following nomenclatures were used in all the paired mean comparison statistical analysis tables:

- NS – the measured property for the extracted aggregates is not significantly different from the virgin aggregates;
- SL – the measured property for the extracted aggregates is significantly lower than the virgin aggregates;
- SH – the measured property for the extracted aggregates is significantly higher than the measured property of the virgin aggregates.

Overlapping of the confidence intervals indicates the similarities in the extracted binder contents from the various extraction methods. Note that no correction factors were used for the ignition oven results as they are not expected to be available for actual RAP materials from the field. The true asphalt binder contents were assumed to be the designed asphalt binder content for each mix as they were mixed.

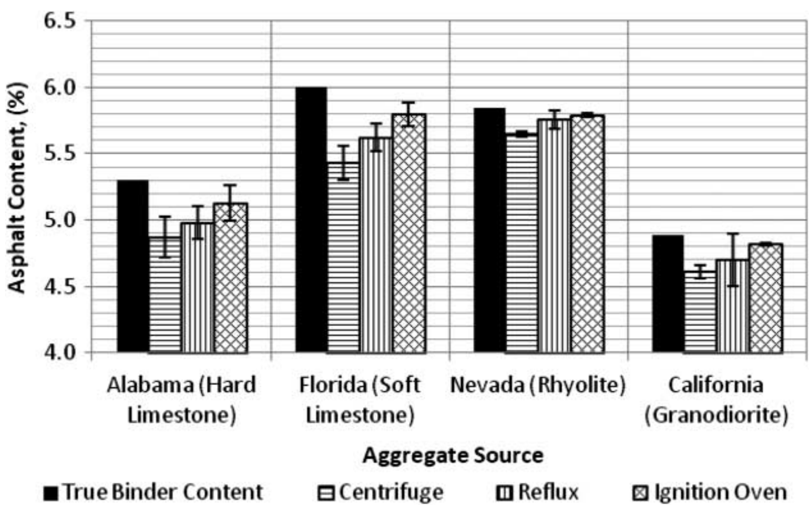

Figure 1. Binder contents (whiskers represent 95% confidence interval).

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Table 2. Extracted asphalt binder contents and t-test results (% TWM).

Extraction method	Aggregate source	Rep	Extracted binder content (%)	True binder content (%)	Difference between extracted and true binder content	Allowable difference (d2s)	p-value $\alpha = 0.05$	95% CI[a]	Sig. level[b]
Centrifuge	Alabama	13	4.87	5.30	0.430	0.520	<0.001	4.70–5.04	SL
	Florida	12	5.43	6.00	0.570[c]		<0.001	5.29–5.57	SL
	Nevada	4	5.65	5.85	0.200		<0.001	5.62–5.68	SL
	California	4	4.61	4.89	0.280		0.002	4.53–4.69	SL
Reflux	Alabama	15	4.98	5.30	0.320	0.520	<0.001	4.85–5.11	SL
	Florida	12	5.62	6.00	0.380		<0.001	5.51–5.73	SL
	Nevada	4	5.76	5.85	0.090		0.082	5.65–5.87	NS
	California	4	4.70	4.89	0.190		0.154	4.38–5.02	NS
Ignition Oven	Alabama	14	5.13	5.30	0.170	0.196	0.024	4.99–5.27	SL
	Florida	14	5.80	6.00	0.200[c]		0.001	5.70–5.90	SL
	Nevada	3	5.79	5.85	0.060		0.001	5.77–5.81	SL
	California	3	4.82	4.89	0.070		0.007	4.80–4.85	SL

[a] Confidence Interval [b] SL: significantly lower, NS: not significant
[c] signifies the measurement is not within the d2s tolerance as compared to the virgin material.

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Examination of the results indicates that the true asphalt binder contents were consistently higher than the asphalt binder contents obtained from all of the extraction methods. The centrifuge method yielded the lowest asphalt binder content for all four aggregate sources while the ignition oven yielded the highest asphalt binder content.

The asphalt binder contents of each mix for a given extraction method were statistically compared to the corresponding true asphalt binder content using the student t-test at a 0.05 significance level. Table 2 summarizes the results of the t-tests conducted. In almost all cases, the null hypothesis was rejected indicating that all the extracted asphalt binder contents were significantly lower than the true asphalt binder contents except for the Nevada and California aggregates using the reflux method.

Further investigation into the differences of the determined binder contents were considered based upon the precision and bias statements of the respective test methods. The precision statements of the three extraction test methods utilize the d2s parameter as the allowable difference between two replicates of the same sample tested by the same person on the same equipment, which is a significantly smaller allowable margin of error than if the tolerance were corrected for the actual number of replicates following ASTM C670-03. Table 2 indicates that nearly all of the measured binder contents are within the d2s tolerance for their respective extraction procedures. The only exceptions are the centrifuge results from Florida, which are barely out of the tolerance for the centrifuge and ignition oven. Given that the Florida centrifuge results were based upon 12 replicates and the ignition oven results were based upon 14 replicates rather than two, it can be stated that the tested binder contents are generally within the d2s tolerance for all mixes and extraction methods.

Once the extractions were completed, the extracted aggregates were dried and tested in accordance with their respective procedures as if the material had been virgin aggregate. In all cases, three replicates were used to measure the aggregate properties with all the test results falling within the permissible difference between the three results (d3s) for single operator precision considerations.

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6. Sieve analysis

The sieve analyses of the virgin and extracted aggregates were conducted in accordance with AASHTO T27 (AASHTO, 2009). Table 3 shows the gradations for the virgin and extracted RAP aggregates at selected sieve sizes.

In order to distinguish any significant differences in the test results, a one-way (i.e. single factor) analysis of variance (ANOVA) with an alpha level of 0.05 was conducted for each of the aggregate sources to determine if the extraction processes contributed to the variability. Paired mean comparisons were also conducted to determine if there were differences between the means of percentage passing a given sieve of the virgin aggregates and extracted aggregates as shown in Table 3. The acceptable range of two results, d2s, is presented for each source as well. These values are included to further help differentiate the dissimilarities in the measured properties. If, for instance, two results are significantly different, but both are within the allowable tolerance, d2s, then the two results should not be considered significantly different from a practical standpoint. The acceptable ranges vary by the respective sources since the d2s parameters are scaled by the percentage passing each particular sieve being considered.

Based on the results shown in Table 3, the following observations can be made:

- The extracted RAP aggregates using the centrifuge method did not have consistently lower or higher percentage passing a specific sieve size when compared with virgin aggregates. The centrifuge method did not have a significant impact on the extracted aggregate gradation from the Alabama and Nevada RAP mixes, but did have a statistically significant impact on the fine portion (i.e. <2.36 mm sieve) of the extracted aggregates from the Florida and California RAP mixes.
- The extracted RAP aggregates using the reflux method did not have consistently lower or higher percentage passing a specific sieve size when compared with virgin aggregates. Except for the Nevada RAP mix, the reflux method generally had a statistically significant impact on the percentage passing sieve sizes finer than the 4.75 mm sieve.
- The extracted RAP aggregates using the ignition oven method generally created either a significantly higher or significantly lower percentage passing sieve sizes smaller than 4.75 mm, with minor influences on sieve sizes greater than 4.75 mm when compared with virgin aggregates.
- With respect to the acceptable difference between two test results, the majority of the differences fell within the allowable range. Only the ignition oven passing the 0.075 mm sieve from Alabama and several of the Florida gradations did not meet the d2s requirements. Most of the Florida centrifuge sieves, except the 4.75 mm one, were outside the permissible limits, as were the 0.300 and 0.075 mm for the ignition, and the 0.075 mm for the reflux methods.

7. Coarse and fine aggregate bulk dry specific gravities

The specific gravities of the virgin and extracted coarse and fine aggregates were measured in accordance with AASHTO T85 and T84, respectively (AASHTO, 2009). Table 4 summarizes the data for the measured bulk specific gravities and provides the results of the mean comparison analysis that was conducted to determine if the specific gravities of the various extracted aggregates were significantly different from those of the virgin aggregates.

From the data in Table 4, the following observations can be made for the coarse aggregate specific gravities:

- The extracted coarse aggregates using the centrifuge method did not consistently have lower or higher bulk dry specific gravity when compared with the virgin aggregates.

Table 3. Extracted RAP aggregate gradation and paired mean comparison results.

Source	Extraction method	Property	Sieve size (mm) 12.5	4.75	2.36	0.300	0.075
Alabama	None	% passing	93.2	52.1	38.4	11.1	5.44
	Centrifuge	% passing	93.4	51.9	37.8	11.0	5.44
		Difference	+0.2	−0.2	−0.6	−0.1	+0.0
		Significance	NS	NS	NS	NS	NS
	Reflux	% passing	91.8	50.0	36.6	10.7	5.58
		Difference	−1.4	−2.1	−1.8	−0.4	+0.1
		Significance	NS	SL	SL	NS	NS
	Ignition Oven	% passing	92.6	50.8	37.3	12.4	7.66
		Difference	−0.6	−1.3	−1.1	+1.3	+2.2
		Significance	NS	NS	NS	SH	**SH**[d]
	Acceptable d2s		2.3	3.7	3.7	2.8	2.1
Florida	None	% passing	100	54.7	36.9	9.3	5.63
	Centrifuge	% passing	100	50.1	33	6.3	2.4
		Difference	+0.0	−4.6	−3.9	−3.0	−3.2
		Significance	NS	**NS**[d]	**SL**[d]	**SL**[d]	**SL**[d]
	Reflux	% passing	100	52.6	34.5	7.3	2.81
		Difference	+0.0	−2.1	−2.4	−2.0	−2.8
		Significance	NS	NS	SL	SL	**SL**[d]
	Ignition Oven	% passing	100	51.8	33.6	6.9	2.56
		Difference	+0.0	−2.9	−3.3	−2.4	−3.1
		Significance	NS	NS	NS	**NS**[d]	**SL**[d]
	Acceptable d2s		0.9	3.7	3.7	2.1	1.5
Nevada	None	% passing	94.2	58.8	43.1	16.3	5.9
	Centrifuge	% passing	94.6	59	42.9	18.1	5.78
		Difference	+0.4	+0.2	−0.2	+1.8	−0.1
		Significance	NS	NS	NS	SH	NS
	Reflux	% passing	94.1	59.5	42.5	16.8	6.02
		Difference	−0.1	+0.7	−0.6	+0.5	+0.1
		Significance	NS	NS	NS	NS	NS
	Ignition Oven	% passing	94.3	57.9	41.8	16.3	4.68
		Difference	+0.1	−0.9	−1.3	+0.0	−1.2
		Significance	NS	NS	SL	NS	SL
	Acceptable d2s		2.3	3.7	3.7	2.7	1.5
California	None	% passing	86.1	40.7	23.5	9.9	4.3
	Centrifuge	% passing	86.5	40.9	24.9	11.6	5.4
		Difference	+0.4	+0.2	+1.4	+1.7	+1.1
		Significance	NS	NS	SH	SH	SH
	Reflux	% passing	86.3	42.2	25.7	12.2	6.23
		Difference	+0.2	+1.5	+2.2	+2.3	+1.9
		Significance	NS	SH	SH	SH	SH
	Ignition Oven	% passing	86.3	42.2	25.7	12.2	6.23
		Difference	+0.2	+1.6	+2.1	+2.2	+1.7
		Significance	NS	SH	SH	SH	SH
	Acceptable d2s		2.3	3.7	3.7	2.8	2.1

[d] signifies the measurement is not within d2s tolerance of the virgin material.

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Table 4. Coarse and fine aggregates bulk dry specific gravities.

Extraction Method	Agg. Source	Ave.	STD	Max Difference (Max-Min)	Difference Between Extracted and Virgin Aggregates	Allowable Difference Two-Sigma (d2s)	Paired Mean Comp.
				Coarse Aggregates			
None	Alabama	2.739	0.007	0.013	–	–	–
	Florida	2.419	0.009	0.017	–		–
	Nevada	2.584	0.008	0.018	–		–
	California	2.544	0.004	0.008	–		–
Centrifuge	Alabama	2.728	0.008	0.015	−0.011	0.025	NS
	Florida	2.430	0.005	0.009	0.011		SH
	Nevada	2.569	0.003	0.005	−0.015		SL
	California	2.521	0.007	0.014	−0.023		SL
Reflux	Alabama	2.725	0.002	0.003	−0.014	0.025	NS
	Florida	2.429	0.006	0.010	0.010		SH
	Nevada	2.581	0.004	0.008	−0.003		NS
	California	2.561	0.003	0.006	0.017		SH
Ignition Oven	Alabama	2.683	0.004	0.007	**−0.056**[e]	0.025	SL
	Florida	2.400	0.007	0.013	−0.019		SL
	Nevada	2.564	0.007	0.015	−0.020		SL
	California	2.538	0.006	0.012	−0.006		NS
				Fine Aggregates			
None	Alabama	2.661	0.004	0.007	–	–	–
	Florida	2.585	0.010	0.010	–		–
	Nevada	2.491	0.010	0.019	–		–
	California	2.541	0.009	0.017	–		–
Centrifuge	Alabama	2.711	0.015	0.029	**0.050**[e]	0.032	SH
	Florida	2.583	<0.001	0.010	−0.002		NS
	Nevada	2.486	0.016	0.031	−0.005		NS
	California	2.577	0.010	0.021	**0.036**[e]		SH
Reflux	Alabama	2.718	0.010	0.019	**0.057**[e]	0.032	SH
	Florida	2.622	0.010	0.020	**0.037**[e]		SH
	Nevada	2.522	0.013	0.025	0.031		NS
	California	2.576	0.010	0.021	**0.035**[e]		SH
Ignition Oven	Alabama	2.690	0.004	0.007	0.029	0.032	SH
	Florida	2.521	0.010	0.020	**−0.064**[e]		SL
	Nevada	2.512	0.017	0.032	0.021		NS
	California	2.583	0.008	0.015	**0.042**[e]		SH

[e] signifies the measurement is not within the d2s tolerance when compared to the virgin material.

- The extracted coarse aggregates using the reflux method had bulk dry specific gravities that are either similar or significantly higher than the virgin aggregates specific gravities.
- The extracted coarse aggregates using the ignition oven had bulk dry specific gravities that were significantly lower than the virgin aggregates for three out of four aggregate sources. The bulk specific gravity of the ignition-oven extracted California aggregate was statistically similar to the virgin aggregate specific gravity.
- AASHTO T85 states that the allowable difference between two results by a single operator between true replicates should not exceed 0.025. While the differences between the specific gravities of the virgin and extracted coarse aggregates are not the comparison of true replicates, those differences can provide a good indication of the relative closeness of the obtained results.

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Similarly, the following observations can be made for the fine aggregate specific gravities:

- The centrifuge-extracted fine aggregates had bulk dry specific gravities that are either similar or significantly higher than the virgin aggregates specific gravities.
- The reflux-extracted fine aggregates had bulk dry specific gravities that are significantly higher than the virgin aggregates specific gravities with the exception of the aggregates from Nevada, which had a similar specific gravity.
- The ignition-oven extracted fine aggregates did not have consistently lower or higher fine aggregate bulk dry specific gravities when compared with the virgin materials.
- AASHTO T84 states that the allowable difference between two results by a single operator between true replicates should not exceed 0.032. While the differences between the specific gravities of the virgin and extracted fine aggregates are not the comparison of true replicates, those differences can provide a good indication of the relative closeness of the obtained results and in this case are in close agreement with the statistical comparisons.

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8. Combined aggregate specific gravity

The combined bulk dry specific gravities for the virgin and extracted aggregates of each aggregate source were calculated according to equation (1) using the average values for the measured corresponding coarse and fine bulk dry specific gravities.

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

where, G_{sb} = combined aggregate bulk dry specific gravity,
P_i = percentage of aggregate fraction i,
G_i = aggregate bulk dry specific gravity of fraction i,
n = number of aggregate fractions.

Table 5 shows the data for the combined bulk dry specific gravity for the various aggregate sources. The calculated combined G_{sb} of the centrifuge extracted aggregates was slightly lower than the virgin aggregate combined specific gravity for the Florida and Nevada aggregates and higher for the Alabama and California aggregate. On the other hand, the reflux method resulted consistently in a calculated combined G_{sb} value that is higher than the combined specific gravity of the virgin aggregates. The calculated combined G_{sb} of the ignition-oven extracted aggregates was lower than the virgin aggregate combined specific gravity for the Alabama and Florida aggregates and higher for the Nevada and California aggregates.

9. Effect of RAP aggregate properties on voids in mineral aggregate (VMA)

The specific gravity of the combined gradation of aggregates is required for the volumetric calculations of an HMA mix design. Therefore, the bulk specific gravity of each aggregate stockpile, including the RAP, needs to be determined for the calculation of the bulk specific gravity of the combined aggregate blend. The following three methods have been historically used to estimate the specific gravity of the RAP aggregate (G_{sb}).

- Method A: use the measured specific gravities of the coarse and fine fractions of the extracted RAP aggregate along with the percentage passing the 4.75 mm sieve in the RAP to calculate the combined specific gravity. This would require extracting the RAP aggregate using the centrifuge, reflux, or ignition oven methods.

- Method B: use an assumed asphalt absorption for the RAP aggregate along with the determined theoretical maximum specific gravity (G_{mm}) of the RAP mixture to back-calculate the RAP aggregate bulk specific gravity. This would require a good estimate of the percentage absorbed asphalt in the RAP aggregates.
- Method C: use the RAP aggregate effective specific gravity (G_{se}) in lieu of the bulk specific gravity (G_{sb}). This would require the determination of the RAP binder content and the theoretical maximum specific gravity (G_{mm}) of the RAP.

The impact of the errors associated with the different methods of estimating the RAP aggregate G_{sb} on the calculation of VMA was evaluated for RAP percentages between 10 and 50% in a typical asphalt mixture. For each aggregate source, the measured asphalt binder contents and aggregate properties were used to determine the combined aggregate bulk specific gravities (G_{sb}) (equation (1)), the effective specific gravities (G_{se}) and the percentage absorbed asphalt (P_{ba}). Table 5 summarizes the calculated properties for the virgin and extracted aggregates. The effective specific gravity (G_{se}) was determined for the virgin and extracted aggregates of each source using equation (2) and the maximum theoretical specific gravity (G_{mm}) determined after the long-term oven aging. For each extraction method, the corresponding asphalt binder content (P_b) was used. The percentage of absorbed asphalt (P_{ba}) was determined for the virgin and extracted aggregates from each source using equation (3) and the corresponding combined G_{sb} and G_{se}.

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \tag{2}$$

$$P_{ba} = 100\left(\frac{G_{se} - G_{sb}}{G_{se}G_{sb}}\right) \tag{3}$$

Table 5. Properties of virgin and extracted aggregates.

Source	Extraction Method	Coarse G_{sb}	Fine G_{sb}	% Fines	Comb. G_{sb}	Diff.	Max. Theor., G_{mm}	Percent asphalt TWM, P_b	Eff. specific gravity, G_{se}	Abs. asphalt, P_{ba}	Mix bulk gravity, 4% voids, G_{mb}
Alabama	None	2.739	2.661	52.1	2.698	–	2.537	5.30	2.764	0.89	2.44
	Centrifuge	2.728	2.711	51.9	2.719	0.021		4.87	2.743	0.32	
	Reflux	2.725	2.718	50.0	2.721	0.024		4.98	2.748	0.36	
	Ignition	2.683	2.690	50.8	2.687	−0.011		5.13	2.756	0.93	
Florida	None	2.419	2.585	54.7	2.507	–	2.435	6.00	2.668	2.41	2.34
	Centrifuge	2.430	2.583	50.1	2.504	−0.003		5.43	2.643	2.09	
	Reflux	2.429	2.622	52.6	2.527	0.020		5.62	2.651	1.85	
	Ignition	2.400	2.521	51.8	2.461	−0.046		5.80	2.659	3.02	
Nevada	None	2.584	2.491	58.8	2.528	–	2.431	5.85	2.656	1.90	2.33
	Centrifuge	2.569	2.486	59.0	2.519	−0.009		5.65	2.647	1.92	
	Reflux	2.581	2.522	59.5	2.546	0.017		5.76	2.652	1.58	
	Ignition	2.564	2.512	57.9	2.534	0.005		5.79	2.654	1.78	
California	None	2.544	2.541	40.7	2.543	–	2.427	4.89	2.610	1.01	2.33
	Centrifuge	2.521	2.577	40.9	2.568	0.025		4.61	2.598	0.82	
	Reflux	2.561	2.576	42.2	2.567	0.025		4.70	2.602	0.51	
	Ignition	2.538	2.583	42.3	2.557	0.014		4.82	2.607	0.75	

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where, P_b = percentage of asphalt by total weight of mix,
G_b = asphalt binder specific gravity,
G_{mm} = maximum theoretical specific gravity.

9.1. *Impact of Method A on the calculation of VMA*

Method A requires the use of the combined aggregate specific gravity (G_{sb}) that was calculated using the measured corresponding specific gravities for the coarse and fine fractions of the extracted RAP aggregate along with the percentage fine material (i.e. passing the 4.75 mm sieve) in the RAP. The blend aggregate specific gravity is calculated using the virgin aggregate specific gravity and the RAP aggregate specific gravity for different RAP percentages. Additionally, the calculated blend G_{sb} was compared with the G_{sb} of the virgin aggregates (i.e. 0% RAP) and the difference was calculated for RAP percentage between 0 and 50% (Figure 2). Further, VMA is calculated by equation (4) for different RAP percentages using the blend G_{sb} and the mixtures'

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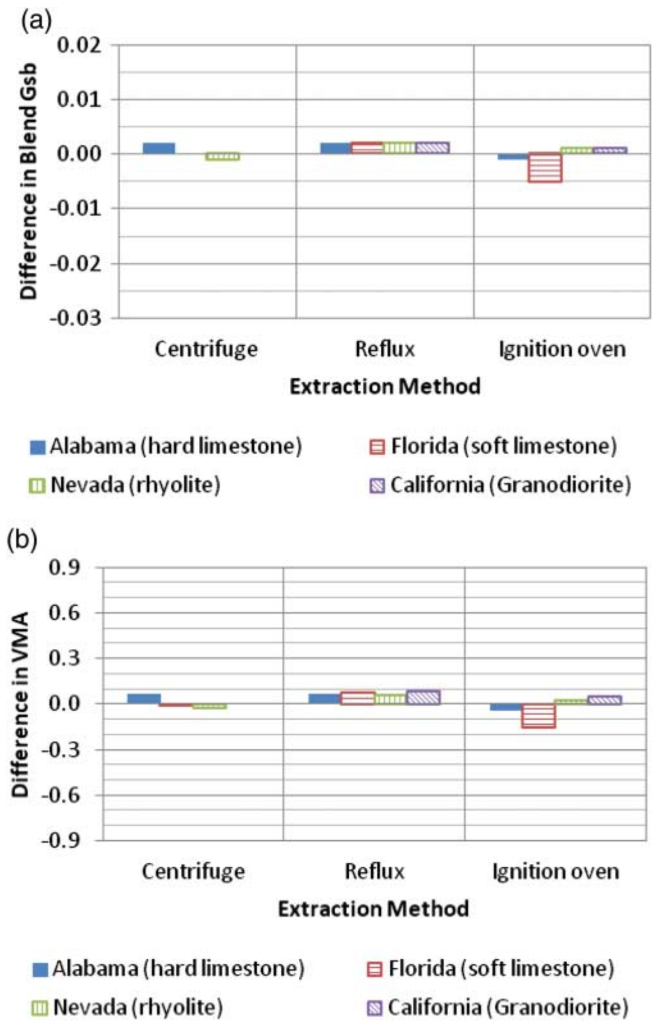

Figure 2. (a) Difference in blend G_{sb} and (b) VMA for 10% RAP content, Method A.

bulk specific gravity (G_{mb}) and percentage asphalt binder (P_b). In this study, the properties of the asphalt mixtures (i.e. G_{mb}, P_b, G_{mm}) before extraction were used to calculate the VMA.

$$VMA = 100 - \frac{G_{mb} \times (100 - P_b)}{G_{sb}} \tag{4}$$

Additionally, the calculated VMA was compared with the VMA of the virgin mix (i.e. 0% RAP) and the difference was considered for RAP percentage up to 50%. Figures 2 through 4 show the differences in blend G_{sb} and VMA for all four aggregate sources at 10, 30 and 50% RAP.

The errors for the calculated blend G_{sb} tended to vary. The impact of the extraction method on the blend G_{sb} can be summarized as follows.

- The centrifuge resulted in an error in the blend G_{sb} between 0.000 and −0.005, with the exception of the Alabama hard limestone aggregate where the error varied from a value of 0.002 at 10% RAP to a maximum of 0.011 at 50% RAP.

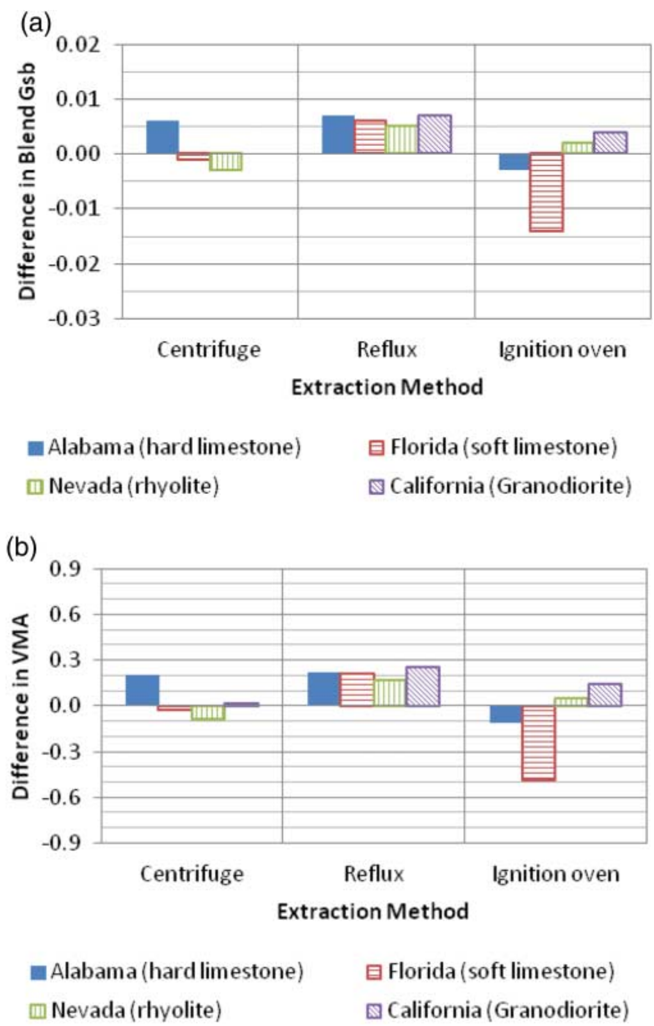

Figure 3. (a) Difference in blend G_{sb} and (b) VMA for 30% RAP content, Method A.

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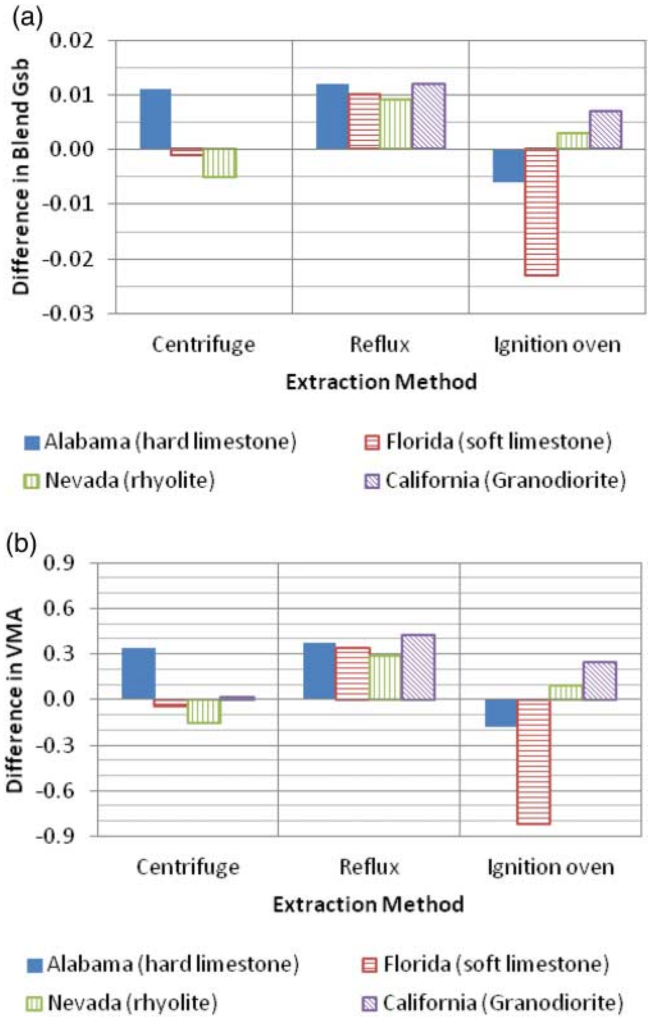

Figure 4. (a) Difference in blend G_{sb} and (b) VMA for 50% RAP content, Method A.

- The reflux consistently overestimated the blend G_{sb}. The error varied from a value of 0.002 at 10% RAP to a maximum between 0.009 and 0.012 at 50% RAP.
- The ignition oven resulted in an error in the blend G_{sb} of maximum between −0.006 and 0.007 at 50% RAP, with the exception of the Florida soft limestone aggregate where the error varied from a value of −0.005 at 10% RAP to a maximum of −0.023 at 50% RAP.

The impact of the extraction method on the VMA can be summarized as follows.

- Using the centrifuge test information resulted in an error in the VMA between −0.16 and 0.01 at 50% RAP, with the exception of the Alabama hard limestone aggregate where the error varied from a value of 0.07 at 10% RAP to a maximum of 0.34 at 50% RAP.
- Using the reflux results led to the consistent overestimation of the VMA values. The error varied from a value of 0.07 at 10% RAP to a maximum between 0.29 and 0.42 at 50% RAP, for all the sources.

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- Using the ignition-oven test information resulted in a maximum error in the VMA between −0.18 and 0.24 at 50% RAP, with the exception of the Florida soft limestone aggregate where the error varied from −0.16 at 10% RAP to a maximum of −0.82 at 50% RAP.

9.2. *Impact of Method B on the calculation of VMA*

Method B represents an alternative approach for estimating the RAP aggregate G_{sb} that was recommended in NCHRP Report 452 (McDaniel & Anderson, 2001) which is based on assuming a value for the asphalt absorption of the RAP aggregate (i.e. P_{ba}). The bulk specific gravity of the RAP aggregate can be calculated based on this assumed absorption using equation (5). This $G_{sb\text{-}est}$ value can then be used to estimate the blend aggregate bulk specific gravity for a different RAP percentage and to calculate VMA.

$$G_{sb\text{-}est} = \frac{G_{se}}{\left(\frac{P_{ba} G_{se}}{100 \times G_b}\right) + 1} \tag{5}$$

In actual practice, the P_{ba} true value for a given RAP source will be unknown; therefore, mix designers will need to estimate the P_{ba} based on the typical values from asphalt mixes where the RAP was obtained. Therefore, this study evaluated the impact of the $G_{sb\text{-}est}$ on VMA for an assumed asphalt absorption equal to the true P_{ba} value and for ±25% variations in the true P_{ba} value. The true P_{ba} was calculated from the properties of the virgin aggregates (i.e. no extraction). P_{ba} values of 0.89%, 2.41%, 1.90% and 1.01%, were calculated for the virgin aggregates from Alabama, Florida, Nevada, and California, respectively.

The blend aggregate specific gravity is calculated using the virgin aggregate specific gravity and the estimated RAP aggregate specific gravity ($G_{sb\text{-}est}$) for different RAP percentages. The VMA was calculated using equation (4) and the determined blend G_{sb} for different RAP percentages. Figures 5 to 7 show the differences in blend G_{sb} and VMA for all four aggregate sources at 10, 30, and 50% RAP and for different levels of P_{ba}.

The following summarizes the impact of the extraction method on VMA when the assumed asphalt absorption was 25% below the true P_{ba}.

- The centrifuge results led to an error in the VMA between −0.01 and 0.09 at 10% RAP and an error between −0.04 and 0.43 at 50% RAP.
- The reflux results consistently overestimated the VMA values. The error in VMA varied between 0.01 and 0.10 at 10% RAP to a maximum between 0.04 and 0.50 at 50% RAP.
- The ignition oven resulted in consistently overestimated VMA values over the different RAP percentages. The error in VMA varied between 0.03 and 0.12 at 10% RAP to a maximum between 0.15 and 0.52 at 50% RAP.

The following summarizes the impact of the extraction method on VMA when the true asphalt absorption (P_{ba}) is used to estimate the specific gravity ($G_{sb\text{-}est}$) of the RAP aggregates.

- The centrifuge results consistently underestimated the VMA values over the considered range of RAP percentages. The error in VMA varied between −0.02 and −0.07 at 10% RAP to a maximum between 0.08 and −0.32 at 50% RAP.
- Using the reflux test information resulted consistently in an underestimation in the VMA values at different RAP percentages. The error in VMA varied between 0.00 and −0.04 at 10% RAP to a maximum between −0.01 and −0.21 at 50% RAP.
- Using the ignition oven test information resulted in a maximum error in VMA of −0.02 at 10% RAP and an error between −0.10 and 0.02 at 50% RAP.

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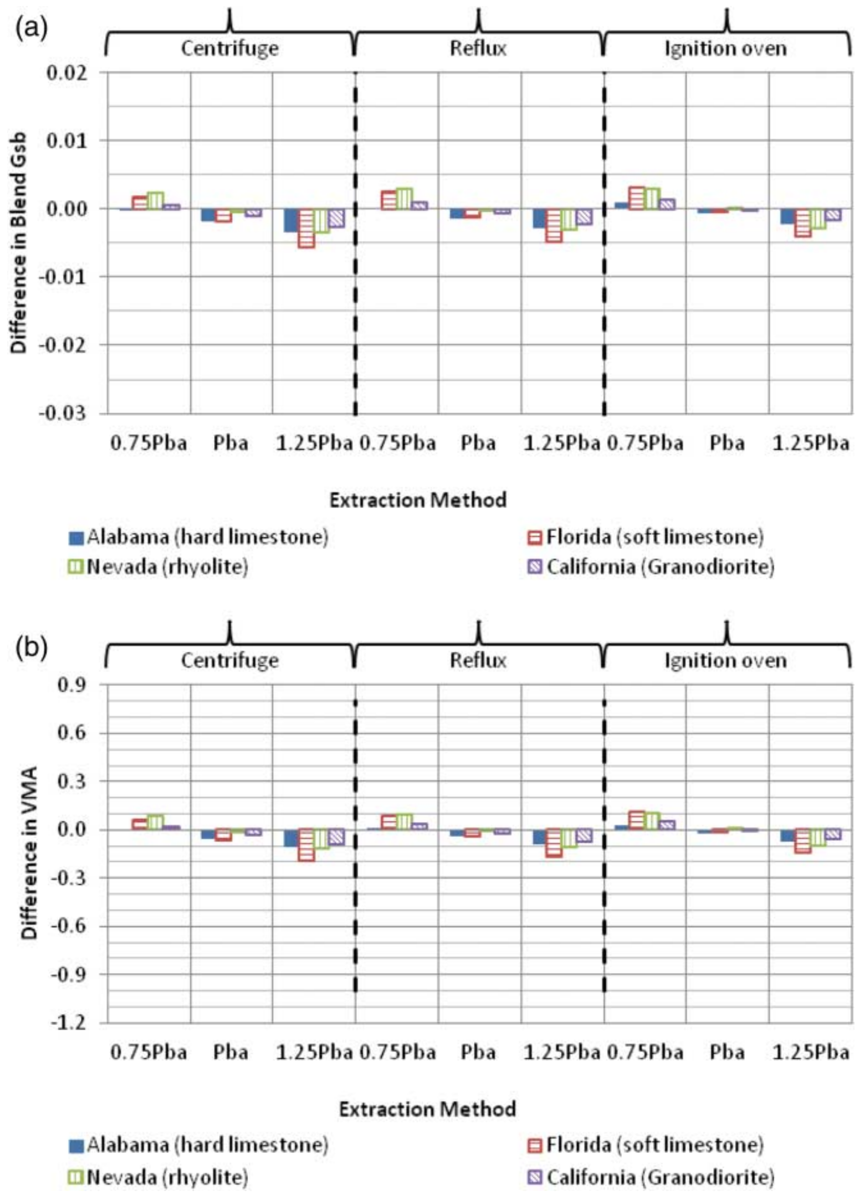

Figure 5. (a) Difference in blend G_{sb} and (b) VMA for 10% RAP content, Method B.

The following summarizes the impact of the extraction method on VMA when the assumed asphalt absorption was 25% higher than the true P_{ba}.

- The centrifuge results consistently underestimated the VMA values at different RAP percentages. The error in VMA varied between −0.09 and −0.19 at 10% RAP to a maximum error between −0.43 and −0.97 at 50% RAP.
- The reflux results consistently underestimated the VMA values at different RAP percentages. The error in VMA varied between −0.07 and −0.17 at 10% RAP to a maximum error between −0.37 and −0.84 at 50% RAP.

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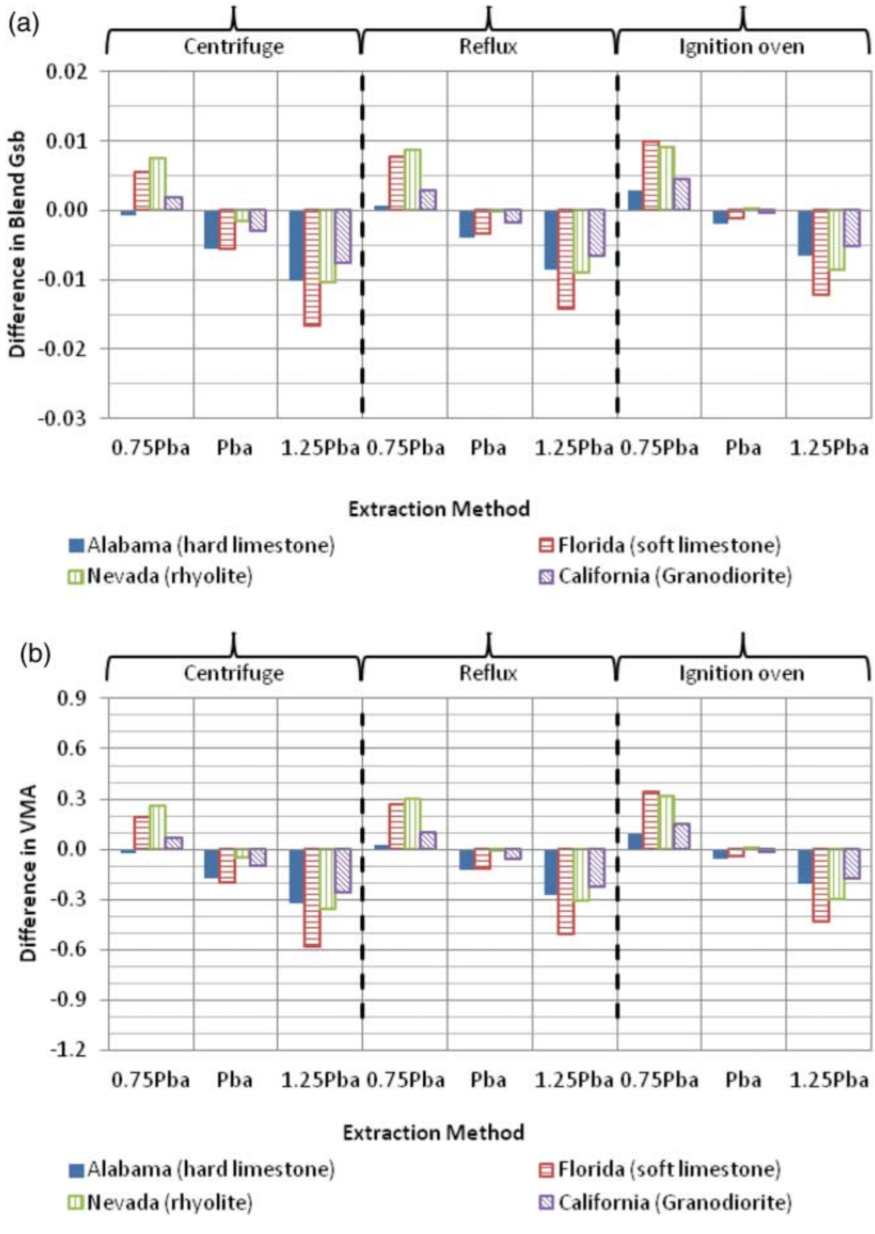

Figure 6. (a) Difference in blend G_{sb} and (b) VMA for 30% RAP content, Method B.

- The ignition oven results consistently underestimated the VMA values at different RAP percentages. The error in VMA varied between −0.06 and −0.14 at 10% RAP to a maximum error between −0.29 and −0.71 at 50% RAP.

In summary, when the true P_{ba} is used, the ignition oven led to the minimal error in VMA, followed by the reflux and the centrifuge. When the assumed asphalt absorption was 25% lower than the true P_{ba}, all three extraction methods led to similar errors in VMA. A significant increase in the VMA error was observed when the assumed asphalt absorption was 25% higher than the

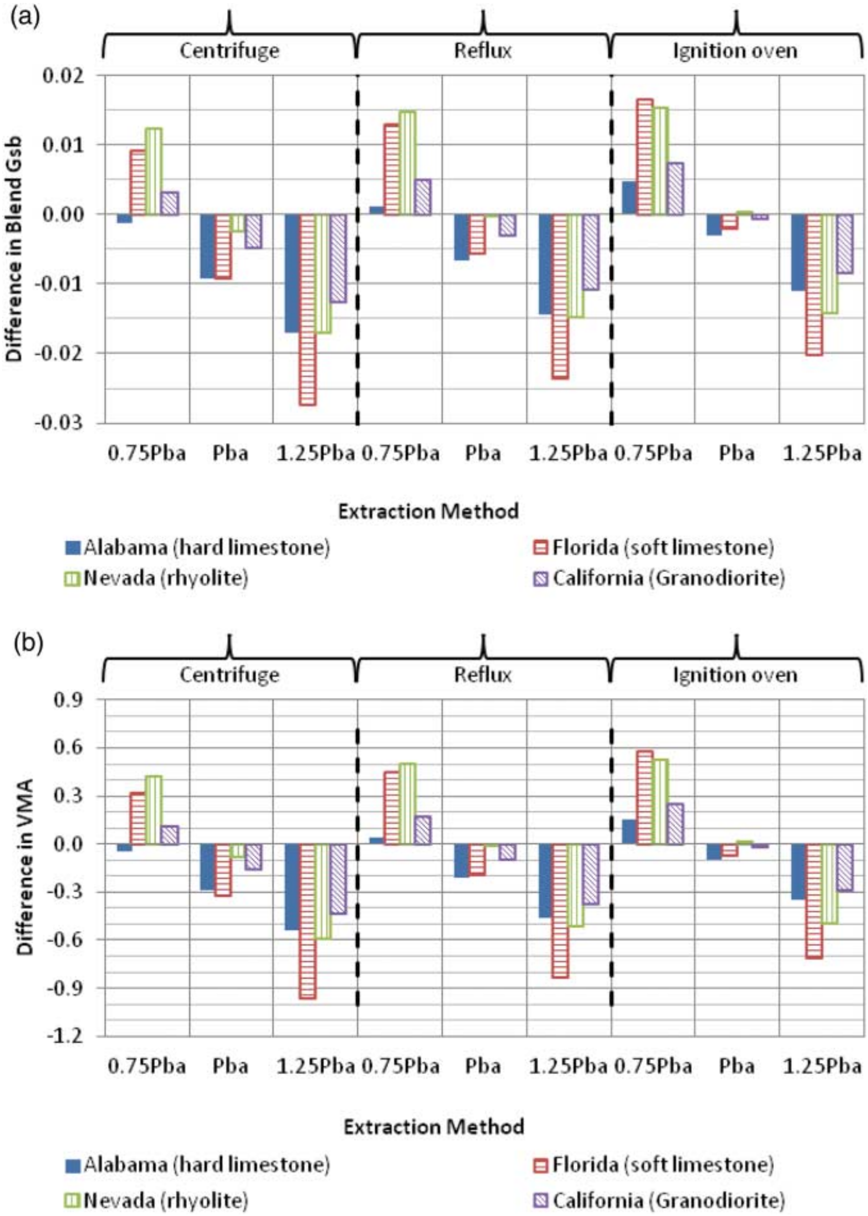

Figure 7. (a) Difference in blend G_{sb} and (b) VMA for 50% RAP content, Method B.

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true P_{ba}. Relatively, the ignition oven led to the least error in VMA, followed by the reflux and the centrifuge with 1.25 P_{ba}.

9.3. *Impact of Method C on the calculation of VMA*

According to NCHRP Report 452 (McDaniel & Anderson, 2001), some states in the past have used the effective specific gravity (G_{se}) of the RAP aggregate instead of its bulk specific gravity (G_{sb}). The effective specific gravity is calculated from the measured RAP maximum specific

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gravity (G_{mm}). Typically, the asphalt binder content of the RAP is determined by extraction or the ignition oven and the binder specific gravity is assumed, the effective specific gravity is then calculated from equation (2). This estimate of the RAP aggregate effective specific gravity is used to calculate the combined aggregate specific gravity, which is then used to calculate the VMA. Figures 8 to 10 show the differences in VMA for all four aggregate sources at 10, 30, and 50% RAP.

In all cases, the blend G_{sb} was overestimated with the error increasing with the RAP percentage. This result was expected since the G_{se} value is larger than the corresponding G_{sb} value. The error in G_{sb} was as low as 0.004 at 10% RAP and as high as 0.074 at 50% RAP. The VMA was calculated using equation (4) and the determined blend G_{sb} for different RAP percentages. The following summarizes the impact of the extraction method on VMA when the effective specific gravity (G_{se}) is used for the RAP instead of the bulk specific gravity (G_{sb}).

- The centrifuge results consistently overestimated the VMA values at different RAP percentages. The error in VMA varied between 0.14 and 0.45 at 10% RAP to a maximum between 0.71 and 2.25 at 50% RAP.

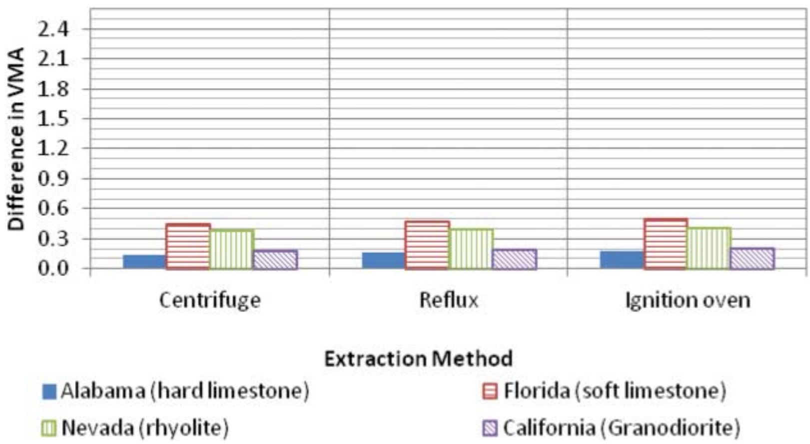

Figure 8. Difference in VMA for 10% RAP content, Method C.

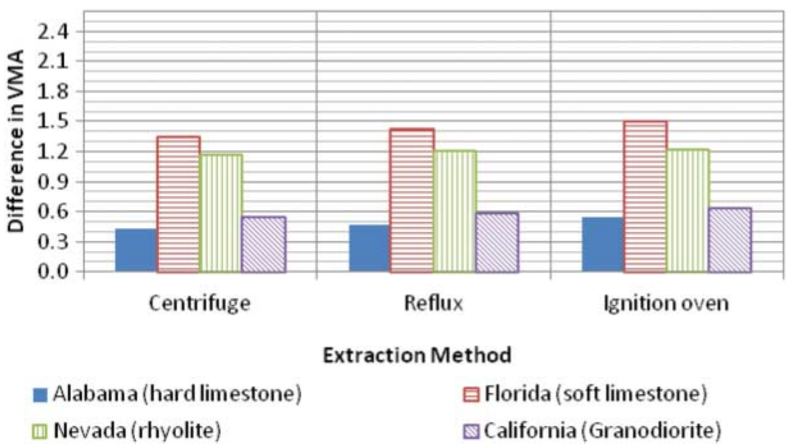

Figure 9. Difference in VMA for 30% RAP content, Method C.

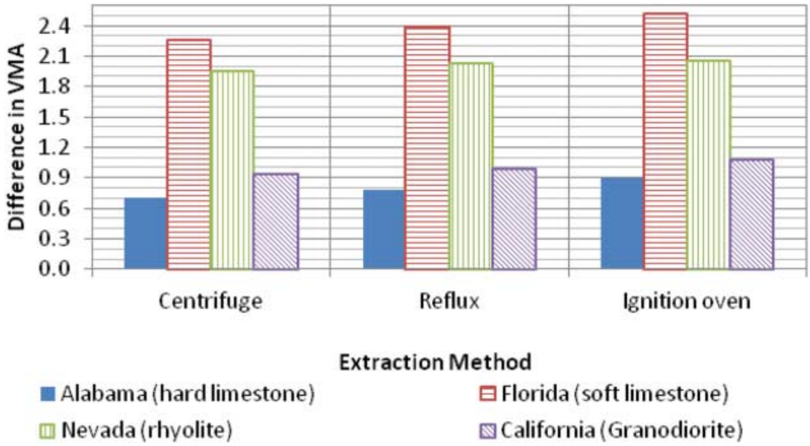

Figure 10. Difference in VMA for 50% RAP content, Method C.

- The reflux results consistently overestimated the VMA values at different RAP percentages. The error in VMA varied between 0.16 and 0.48 at 10% RAP to a maximum between 0.79 and 2.38 at 50% RAP.
- The ignition oven results consistently overestimated the VMA values at different RAP percentages. The error in VMA varied between 0.18 and 0.50 at 10% RAP to a maximum between 0.90 and 2.51 at 50% RAP.

10. Summary of findings

10.1. *Impact of extraction method on RAP properties*

The asphalt binder content of the RAP mix, the gradation, and specific gravities of the RAP aggregate were compared with respect to three extraction methods for each of the four aggregate sources (Hajj et al., 2010). Statistical analyses compared the properties of the extracted RAP aggregates with the properties of the virgin aggregates at a significance level of 0.05 as well as the allowable tolerance between two test results, d2s. Furthermore, the final impact of these changes was evaluated in terms of their impact on the calculated VMA of mixtures containing the RAP.

Table 6 summarizes the combined statistical significance for all four aggregate sources grouped by the evaluated extraction methods. The values in the table indicate how many of the four

Table 6. Comparison of binder content and aggregate properties.

	Centrifuge			Reflux			Ignition oven		
Properties	SL	NS	SH	SL	NS	SH	SL	NS	SH
Asphalt binder content	4	–	–	2	2	–	4	–	–
Sieve analysis									
−12.5 mm sieve	–	4	–	–	4	–	–	4	–
−4.75 mm sieve	–	4	–	1	2	1	–	3	1
−2.36 mm sieve	1	2	1	2	1	1	1	2	1
−0.300 mm sieve	1	1	2	1	2	1	–	2	2
−0.075 mm sieve	1	2	1	1	2	1	2	–	2
−Coarse bulk specific gravity, dry	2	1	1	–	2	2	3	1	–
Fine bulk specific gravity, dry	–	2	2	–	1	3	1	1	2

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aggregate sources correspond to that result for each respective comparison. For example, a '4' under the centrifuge-NS across from the 12.5 mm sieve means that for all four aggregate sources, the centrifuge did not significantly impact on the percentage passing the 12.5 mm sieve.

The data in Table 6 show that the asphalt binder contents measured by all three extraction methods were statistically significantly lower than the true asphalt binder contents except for the Nevada and California aggregates using the reflux method, which showed binder contents statistically similar to the true levels. This similarity was mainly due to the large amount of variability observed in the reflux measurements with Nevada and California RAP mixes.

In the case of aggregate properties, it is clear from Table 6 that, overall, none of the extraction methods consistently impacted the measured properties of the extracted aggregates. While none of the extraction methods had a significant impact on the size distributions of the coarse portion of the aggregates, the effect on the size distribution of the fine portion of the aggregates was aggregate source-dependent.

The impact of the extraction method on the bulk specific gravity of coarse and fine aggregates was method-dependent. The impact of the centrifuge on the coarse aggregate specific gravity of the various sources was also inconsistent. However, the centrifuge led to aggregate properties with either similar or significantly higher fine aggregate specific gravities than the virgin aggregate. The reflux consistently produced aggregates with either similar or significantly higher coarse and fine aggregate specific gravities than the virgin aggregate. The ignition oven produced aggregates with either similar or significantly lower coarse aggregate specific gravities than virgin aggregate. However, the impact of the ignition oven on the fine aggregate specific gravities was inconsistent across the different sources.

The impact of the extraction method on the combined aggregate specific gravity is more critical than their impact on the individual specific gravities, since it is the combined specific gravity that is used to calculate the volumetric properties of the mix. The analysis of this data showed that the impact on the combined specific gravity was method-dependent as well:

- Centrifuge: slightly lower combined specific gravity for the Florida and Nevada aggregates and higher for the Alabama and California aggregates.
- Reflux: consistently higher combined specific gravity for all four aggregates.
- Ignition Oven: lower combined specific gravity for the Alabama and Florida aggregates and higher for the Nevada and California aggregates.

The consequences of using a specific extraction method on the properties of the blend aggregates are summarized in Table 7. The consequences are expressed in terms of the percentage of time that the mix designer may over-estimate or under-estimate a given property and how this may impact the acceptance of the mix.

10.2. *Impact of RAP specific gravity on VMA*

The final step of the analysis investigated the potential for error in VMA caused by the estimated RAP aggregate specific gravity (G_{sb}). The blend G_{sb} was calculated for different RAP contents using the RAP aggregate G_{sb} that was estimated for each RAP material using the traditionally used methods as were previously defined in this study as Methods A, B and C. The blend G_{sb} for different RAP contents was then used to calculate the VMA of the RAP-containing asphalt mixture, which in turns was compared with the true VMA of the same mix. The true VMA was calculated from the blend G_{sb} for different RAP contents using the virgin aggregate specific gravities for the new and RAP aggregates in the mix.

Table 7. Consequences of extraction method on mix design.

Aggregate Property	Centrifuge	Reflux	Ignition oven
Passing 4.75 mm sieve	Close estimate 100% of time.	Close estimate 50% of time and 25% of time over- or under-estimate. *May result in spec violation 50% of time.*	Close estimate 75% of time and 25% of time over-estimate. *May results in spec violation 25% of time.*
Passing 0.075 mm sieve	Close estimate 50% of time and 25% of time over- or under-estimate. *May result in spec violation 50% of time.*	Close estimate 50% of time and 25% of time over- or under-estimate. *May result in spec violation 50% of time.*	Over-estimate 50% of time and under-estimate 50% of time. *May result in spec violation 50% of time.*
Combined bulk specific gravity, dry	Over-estimate 50% of time and under-estimate 50% of time.	Over-estimate 100% of time.	Over-estimate 50% of time and under-estimate 50% of time.

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Figures 11 to 13 summarize, for all four aggregate sources, the impact of the errors associated with the different methods of determining G_{sb} for the RAP aggregate on VMA when the centrifuge, reflux, and ignition oven were used to determine the required properties for the RAP aggregates, respectively. In practice, a VMA error that is within ±0.2% is considered acceptable. Therefore, this level of error was used to assess the appropriateness of the different methods of estimating G_{sb} for the RAP aggregate. Table 8 summarizes this analysis in terms of the percentage of time that the mix designer may over-estimate or under-estimate the VMA and how this action would impact the final mix at the reported RAP contents.

Table 9 shows the overall assessment based on the data generated in this study from the four evaluated aggregates along with the maximum expected error in VMA. The data in Table 9

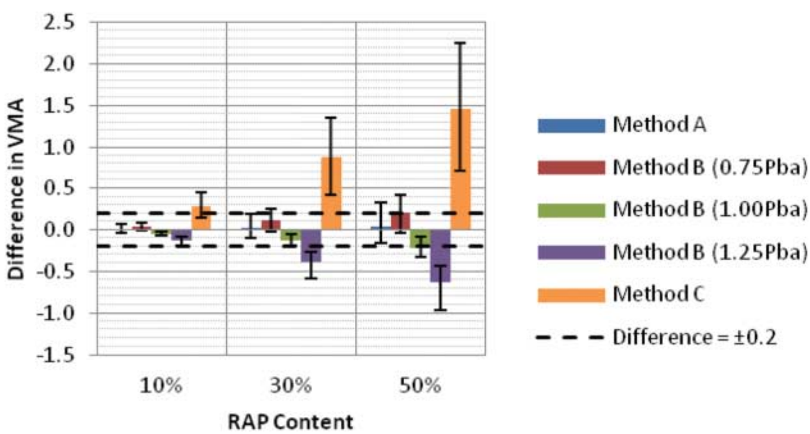

Figure 11. Difference in VMA versus RAP content based on centrifuge (error bars represent minimum and maximum difference in VMA).

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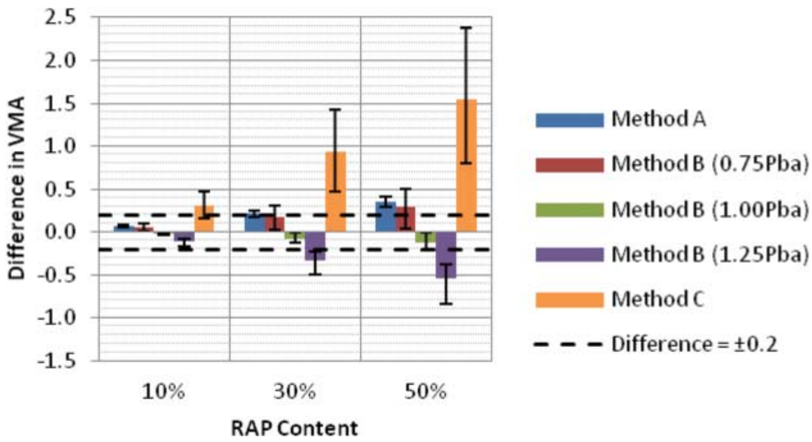

Figure 12. Difference in VMA versus RAP content based on reflux (error bars represent minimum and maximum difference in VMA).

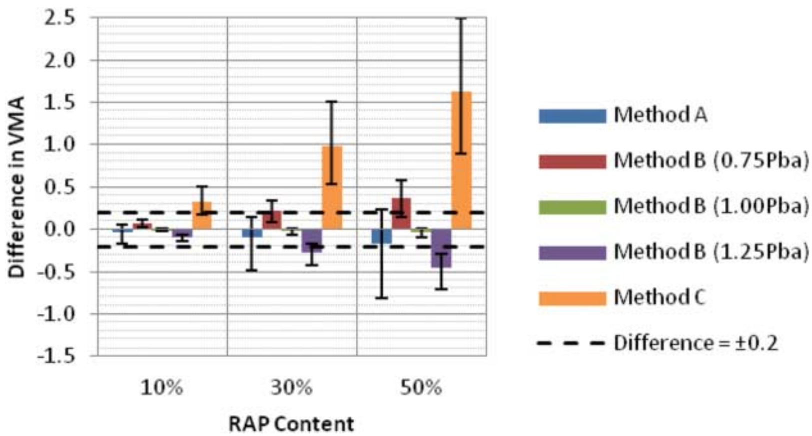

Figure 13. Difference in VMA versus RAP content based on ignition oven (error bars represent minimum and maximum difference in VMA).

show the computed error in VMA calculation depending on the RAP percentage in the mix, the extraction technique and the method used to determine the RAP aggregate specific gravity. For example, for RAP content between 25 and 50%, the computed error in VMA was within ±0.4% if the RAP aggregate specific gravity was directly measured on extracted aggregate (i.e. Method A) using the centrifuge or the reflux.

11. Overall conclusions and recommendations

This study evaluated the impact of extraction methods (i.e. centrifuge, reflux, and ignition oven) on the extracted aggregate properties and binder content of laboratory simulated RAP mixtures with four different aggregate sources: Alabama (hard limestone), California (granodiorite), Florida (soft limestone), and Nevada (rhyolite). The properties of the various extracted aggregates from simulated RAP were compared with the respective virgin aggregate properties. The consequences of using a specific extraction method on the properties of the aggregates that are part of the Superpave mix design method were examined and summarized. Additionally, the impact of the

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Table 8. Impact of extraction method on VMA.

Extraction Method	RAP Content	Method A	Method B (0.75Pba)	Method B (1.00Pba)	Method B (1.25Pba)	Method C
Centrifuge	10%	Close estimate 100% of time[f].	Close estimate 100% of time.	Close estimate 100% of time.	Close estimate 100% of time.	Over-estimate 50% of time. *The design will be un-conservative 50% of time*
	30%	Close estimate 100% of time.	Over-estimate 25% of time. *The design will be un-conservative 25% of time.*	Close estimate 100% of time.	Under-estimate 100% of time.	Over-estimate 100% of time. *The design will be un-conservative 100% of time*
	50%	Over-estimate 25% of time. *The design will be un-conservative 25% of time.*	Over-estimate 50% of time. *The design will be un-conservative 50% of time.*	Under-estimate 50% of time.	Under-estimate 100% of time.	Over-estimate 100% of time. *The design will be un-conservative 100% of time*
Reflux	10%	Close estimate 100% of time.	Close estimate 100% of time.	Close estimate 100% of time.	Close estimate 100% of time.	Over-estimate 50% of time. *The design will be un-conservative 50% of time*
	30%	Over-estimate 25% of time. *The design will be un-conservative 25% of time.*	Over-estimate 50% of time. *The design will be un-conservative 50% of time.*	Close estimate 100% of time.	Under-estimate 100% of time.	Over-estimate 100% of time. *The design will be un-conservative 100% of time*
	50%	Over-estimate 100% of time. *The design will be un-conservative 100% of time.*	Over-estimate 50% of time. *The design will be un-conservative 50% of time.*	Close estimate 100% of time.	Under-estimate 100% of time.	Over-estimate 100% of time. *The design will be un-conservative 100% of time*

Ignition Oven	10%	Close estimate 100% of time.	Close estimate 100% of time.	Close estimate 100% of time.	Close estimate 100% of time.	Over-estimate 75% of time. *The design will be un-conservative 50% of time*
	30%	Under-estimate 25% of time	Over-estimate 50% of time. *The design will be un-conservative 50% of time.*	Close estimate 100% of time.	Under-estimate 50% of time.	Over-estimate 100% of time. *The design will be un-conservative 100% of time*
	50%	Over- or under-estimate 25% of time. *The design will be un-conservative 25% of time.*	Over-estimate 75% of time. *The design will be un-conservative 75% of time.*	Close estimate 100% of time.	Under-estimate 100% of time.	Over-estimate 100% of time. *The design will be un-conservative 100% of time*

[f] *VMA error is within* ±0.2%

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Table 9. Overall summary of expected error in VMA for the evaluated aggregate sources.

Methods for estimating RAP aggregate specific gravity	RAP Percentage			Expected Error in VMA
	Extraction Methods			
	Centrifuge	Reflux	Ignition Oven	
Method A[g]	$\leq 25\%$	$\leq 25\%$	$\leq 10\%$	$\pm 0.2\%$
	25%–50%	25%–50%	10%–25%	$\pm 0.4\%$
Method B[h,i]	$\leq 10\%$	$\leq 10\%$	$\leq 15\%$	$\pm 0.2\%$
	10%–20%	10%–20%	15%–25%	$\pm 0.4\%$

[g] using measured specific gravities of coarse and fine fractions of the extracted RAP aggregate along with the measured percent passing 4.75 mm sieve material in the RAP.
[h] assuming asphalt absorption along with measured theoretical maximum specific gravity and binder content for RAP.
[i] assumed asphalt absorption for the RAP aggregate within ±25% of the true value.

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errors associated with the different methods of determining the RAP aggregate specific gravity on VMA was evaluated for different percentages of RAP in a typical asphalt mixture. Based on the testing with a limited set of aggregates the following recommendations can be made.

- The ignition method appears to give the most accurate results for asphalt content of RAP. Note that in this study, no aggregate correction factors were used for the ignition method results as development of the correction factor is not possible with most RAP sources in the field. The solvent extraction methods do not appear to remove all of the aged binder from RAP, and consequently, RAP asphalt contents using these methods tend to be lower than they actually are.
- One of the most important properties that must be determined for the RAP is the specific gravity of the RAP aggregate. The RAP aggregate G_{sb} is critical to an accurate determination of VMA, which is one of the key mix properties used in mix design and quality assurance. For high RAP content mix designs, the best method for determining the RAP aggregate specific gravities is to use a solvent extraction method (centrifuge or reflux) to recover the aggregate and then test the coarse and fine parts of the recovered aggregate using AASHTO T85 and T84, respectively. The ignition furnace may also be used to recover the RAP aggregate except for some aggregate types that undergo significant changes in specific gravity when subjected to the extreme temperatures used in the ignition method. In this study, the soft Florida limestone was an example of this problem. Note that all of the methods used to recover the RAP aggregate are likely to cause seemingly small errors in the G_{sb} results. As RAP contents approach 50%, the net effect may be an error in the VMA determination of ±0.4%. This magnitude of uncertainty is one of the reasons why it may be appropriate to perform additional performance related tests on high RAP mix designs to assure resistance to rutting, moisture damage, fatigue cracking, and low temperature cracking.
- Another method for estimating the RAP aggregate specific gravity is the approach recommended in NCHRP Report 452. This method was evaluated in this study as Method B and involves determining the maximum theoretical specific gravity (G_{mm}) of the RAP material using AASHTO T 209. From the G_{mm} and the asphalt content of the RAP, the effective specific gravity (G_{se}) of the RAP aggregate can be determined. Although some agencies use the G_{se} for the RAP aggregate in the calculation of VMA, the authors strongly advise against this practice. Other agencies try to correct the G_{se} to an estimated G_{sb} using

an assumed value for asphalt absorption. This correction is only reliable when the asphalt absorption can be assumed with confidence. The correction is very sensitive to the assumed asphalt absorption value and can lead to errors in VMA that are 0.5% or more.

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