INTERIM REPORT

EVALUATION OF THE EFFECT ON AGGREGATE PROPERTIES OF SAMPLES EXTRACTED USING THE IGNITION FURNACE

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ABSTRACT

The Superpave mix design system includes four consensus aggregate properties to ensure aggregate quality: coarse aggregate angularity, flat and elongated particles, fine aggregate angularity, and sand equivalent. In addition to determining these consensus aggregate properties, ascertaining aggregate gradations and specific gravities are also required to complete an optimal mix design.

A method of extracting the asphalt from recycled asphalt pavement (or from quality control/quality assurance samples) that would produce a clean aggregate sample for analysis was needed. VDOT has used the ignition method for determining asphalt content and for the recovery of aggregates for gradation analysis since 1995. This study evaluated the effect on aggregate properties of samples extracted using the ignition furnace.

For the purposes of the study, recycled asphalt pavement was artificially produced by mixing virgin aggregates with asphalt and aging the mixture prior to extraction in the ignition furnace.   Consensus aggregate properties, specific gravity tests, and gradation analysis were performed on three replicates each of the virgin and recovered aggregates.

Only the sand equivalent test and aggregate-specific gravities showed regular significant differences. It was found that the specific gravity values measured for aggregates recovered using the ignition furnace were closer to the measured values for the virgin aggregates than the effective specific gravity method which has been traditionally used for estimating a bulk gravity for recycled asphalt pavement. As a result of this study, recommendations were made to the Virginia Department of Transportation to change testing requirements on recycled asphalt pavement.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) is targeting the year 2000 for the full implementation of the Superpave mix design system. The Superpave mix design system includes specifications for four consensus aggregate properties to ensure aggregate quality: coarse aggregate angularity, flat and elongated particles, fine aggregate angularity (FAA), and sand equivalent. VDOT specifications require the consensus aggregate properties to be determined during the mix design process just prior to production and after each 50,000 tons of aggregate use. In addition to consensus properties, the analysis of aggregate bulk specific gravity (G_{sb}) is required to calculate mixture volumetrics. Determining the proper aggregate gradations is also required to complete a Superpave mix design.

In order to measure the consensus properties and G_{sb} of the recycled asphalt pavement (RAP), the asphalt must first be extracted. In 1995 VDOT adopted the ignition method as an alternative to chlorinated solvent extraction for quality control and acceptance of hot-mix asphalt. In 1997 VDOT mandated the use of the ignition furnace for determining the asphalt content and for the recovery of aggregates for gradation (Prowell & Schreck, 1997).

In 1998 the National Center for Asphalt Technology reported the effects of the ignition furnace on gradation, G_{sb}, absorption, FAA, and fractured face count for four aggregate types. The study indicated that particular aggregate properties were significantly affected, but that the effects appeared to be aggregate-specific (Mallick, Brown & McCauley, 1998). This 1998 study also recommended that user agencies conduct their own studies on commonly available aggregates. Other research looked at changes in gradation and coarse aggregate G_{sb} resulting from the ignition furnace for Arkansas materials (Hall & Williams, 1999). Results from this research concluded that there was little change in gradation and that the changes in coarse aggregate G_{sb} could be attributed to testing variability.

Currently, VDOT excludes RAP from consensus aggregate property testing. This has caused concern among Virginia's aggregate producers, who do not feel they should be held to the Superpave standards if RAP is excluded.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the effect on Superpave consensus aggregate properties, G_{sb}, and gradation of samples extracted using the ignition furnace for typical Virginia aggregates. Ten Superpave mix designs, representing nine aggregate sources, were chosen for the study. Included with the nine sources were aggregates with the two highest ignition furnace mix correction factors in Virginia. Testing was performed on virgin aggregate samples and simulated RAP samples. Simulated RAP was used because materials with known aggregate properties, or ones that could be measured prior to ignition, were required for these tests.

METHODS

Ten mix designs, using nine aggregate sources, were selected for the study. The mix designs included 12.5-, 19.0-, 25.0-, and 37.5-mm nominal maximum size aggregate blends. Since RAP is extensively used in Virginia, it was difficult to find 10 virgin mixtures. Therefore, for mixtures that contained RAP, the RAP was removed from the blend and new blend percentages were calculated so that the virgin aggregates totaled 100 percent. The proportions of the original blend were maintained for each mix design. The aggregate types and blend percentages are shown in Table 1. Six samples, which were of sufficient size to allow all of the tests to be performed from a single sample, were bulk-batched according to the job mix formula for each mixture. Three of the samples were mixed with the optimum asphalt content determined in the Superpave mix design. The mix samples were oven-aged for a short term in accordance with AASHTO PP2-95. These samples were produced to simulate RAP.

The asphalt in the mix samples was extracted in accordance with Virginia Test Method 102 (which is the basis for AASHTO T308-99, Method A). The asphalt in a sample of hot-mix paving material is burned by ignition at 538° C. The asphalt content is calculated from the mass of the ignited aggregate. The ignition method requires that a calibration be performed for each mix design (Brown & Mager, 1996, Prowell, 1996). This accounts for aggregate reactions during the ignition process. The calculation for the corrected asphalt content is shown in Equation 1. The sample size tested is based on the aggregate nominal maximum size (NMS) and ranges from 1200 g for 9.5-mm NMS to 4000 g for 37.5 mm NMS. The American Association of State Highway and Transportation Officials (AASHTO) officially adopted the test procedure *Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method* (AASHTO T308) in 1999.

$$\% \ AC = \left(\frac{M_B - M_A}{M_B} \ x \ 100 \right) - C_F \qquad \text{(Eq. 1)}$$

where

AC = measured asphalt content % by mass of the oven-dried hot-mix asphalt (HMA) sample

M_B = total mass of the HMA sample prior to ignition

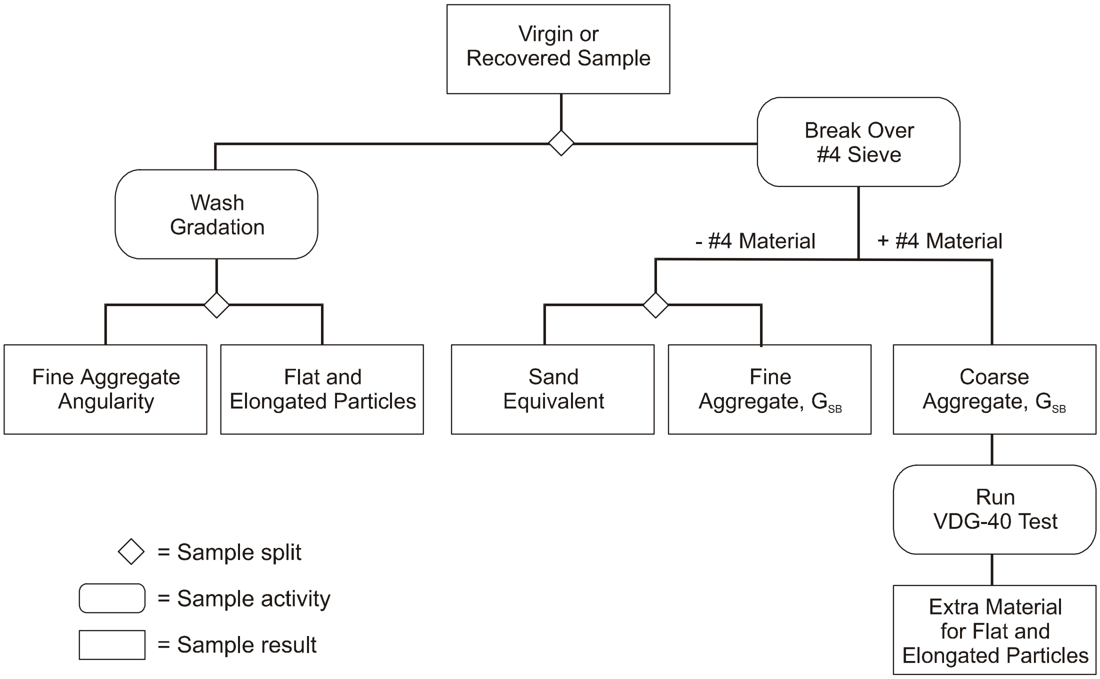
M_A = total mass of aggregate remaining after ignition

C_F = mixture calibration factor for aggregate reaction.

Table 1. Mix Designs by Aggregate Type and Nominal Maximum Size

Dominant Aggregate Type	Aggregate	% of Total	Dominant Aggregate Type	Aggregate	% of Total
Siltstone 12.5 mm	Siltstone #78 Siltstone #10 Granite #10 Natural Sand Baghouse Fines	48 25 11 15 1	Limestone 19.0 mm	Limestone #68 Limestone man. sand Limestone #10	67 19 14
Quartzite 12.5 mm	Quartzite #8 Quartzite #78 Concrete sand Quartzite #10	17 44 11 28	Granite/ Gravel 25.0 mm	9.5 mm Gravel Granite #68 Granite #57 Natural sand	25 30 20 25
Granite 12.5 mm	Granite crusher run Granite #78 Natural sand	55 20 25	Siltstone 25.0 mm	Siltstone #57 Siltstone #78 Siltstone #10 Granite #10 Natural sand Baghouse fines	35 28 11 14 11 1
Diabase Mix 12.5 mm	Diabase #78 Diabase man. sand Natural sand Diabase #10	47 19 16 18	Diabase 25.0 mm	Diabase #5 Diabase #78 Diabase #10	26 30 44
River Gravel 12.5 mm	Gravel #78 Gravel #8 Limestone #10 Gravel #10 Concrete sand	32 29 13 18 8	Granite 25.0 mm	Granite 25.0 mm Granite #78 Granite #68 Natural sand Granite man. sand Bag House Fines	35 25 20 9 10 1

Figure 1. Sample Testing Plan



The samples were split in accordance with the testing plan shown in Figure 1. Fine aggregate-specific gravity (AASHTO T84), coarse aggregate-specific gravity (AASHTO T85), FAA (AASHTO T 304), sand equivalent (AASHTO T 176), flat and elongated particles (ASTM D-4791), and washed sieve analysis (AASHTO T11/T30) were performed on each of the virgin and extracted mixture samples.

The variances of the test results for the virgin and recovered aggregate samples were first compared using the *F* test. Then, the sample means from the virgin and recovered aggregates were compared using the *t* test for either equal or unequal sample variances (Walpole & Myers, 1985). Both tests were performed at the 95 percent confidence level.

RESULTS AND DISCUSSION

The results of the FAA, sand equivalent, and fine aggregate G_{sb} tests are presented in Table 2. The results of each FAA test represents the average of two tests on the same sample. The results of the flat and elongated particle testing at the 5:1 and 3:1 ratios and the coarse aggregate G_{sb} testing are presented in Table 3.

Bulk Specific Gravity

Figure 2 indicates that the fine aggregate G_{sb} was significantly different for 5 of 10 aggregates. G_{sb} of the burnt aggregate decreased in 9 of 10 cases. The average decrease was 0.024. The granite 12.5-mm mixture contained natural sand that was high in organic material. It is believed that the loss of organic material in the ignited sample may have caused the increase in G_{sb}. Figure 3 indicates that the coarse aggregate G_{sb} was significantly different for 6 of 10 aggregates. The G_{sb} of the burnt aggregates decreased an average of 0.039.

G_{sb} is primarily used to calculate voids in mineral aggregate (VMA) in the compacted hot-mix asphalt sample. The actual importance, therefore, is not how much the specific gravity changes, but how much that change affects the determination of VMA. Because of the difficulty and time-consuming nature of determining G_{sb}, some agencies use the effective aggregate-specific gravity (G_{se}) instead of G_{sb} for production testing. G_{se} is used on a widespread basis for the G_{sb} of RAP. In our study, we tested for both G_{se} and G_{sb}.

G_{se} is determined from the theoretical maximum specific gravity and asphalt content of the mixture as follows:

$$G_{se} = \frac{\%\ Aggregate}{\dfrac{100}{Maximum\ Specific\ Gravity} - \dfrac{\%\ AC}{Asphalt\ Specific\ Gravity}}$$

where:

% Aggregate = 100 – AC%

Asphalt Specific Gravity assumed = 1.03.

The blend estimates of G_{sb} were calculated using the fine and coarse G_{sb}, weighted in accordance with the percent passing the 4.75-mm sieve for virgin and burnt mixes. Table 4 shows the virgin blend G_{sb}, the burnt blend G_{sb}, the G_{se} of the RAP sample (an estimate of G_{sb} calculated using the ignition furnace asphalt content), and the G_{se} of the RAP sample (calculated using the actual asphalt content). No absorption was assumed for any of the aggregate types/mixtures when calculating G_{se}. On the average, the burnt values were 0.017 less than the virgin values, and the effective values calculated with the ignition furnace asphalt content and the true asphalt content were 0.080 and 0.057 higher than the virgin values, respectively.

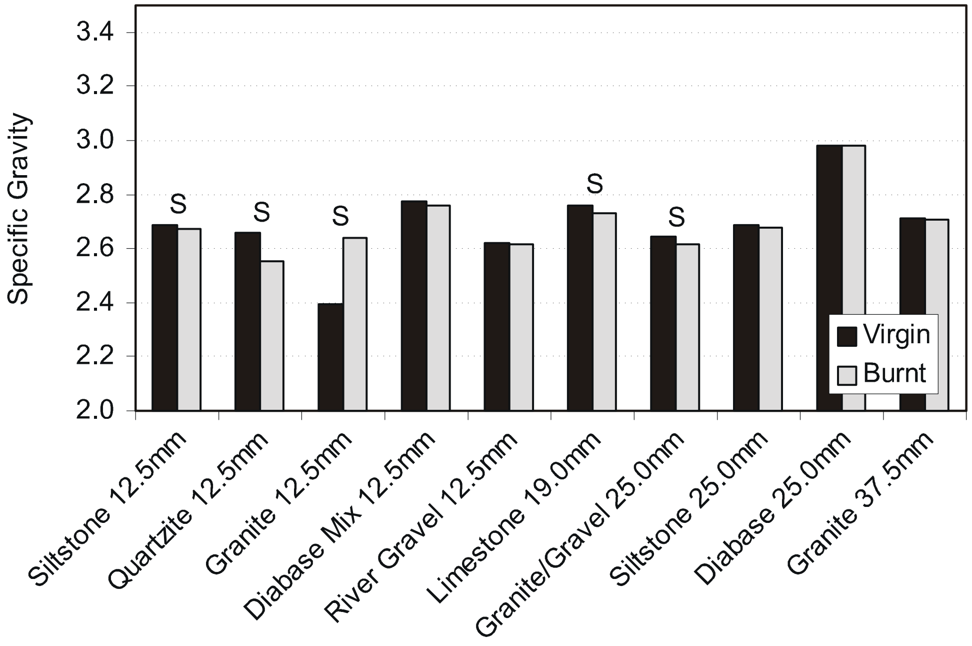
Table 2. Fine Aggregate Properties

Aggregate Type	Sample	Fine Agg. Angularity		Sand Equivalent		Fine Agg. G_{sb}	
		Virgin	Burnt	Virgin	Burnt	Virgin	Burnt
Siltstone 12.5 mm	1	48.1	47.6	71	80	2.684	2.675
	2	47.5	47.1	73	75	2.691	2.672
	3	47.9	47.2	72	74	2.694	2.677
	Avg.	47.8	47.3	72.0	76.3	2.690	2.675
	Std.	0.31	0.26	1.00	3.21	0.0051	0.0025
Quartzite 12.5 mm	1	46.6	45.7	54	45	2.653	2.564
	2	46.4	45.0	57	44	2.655	2.553
	3	46.9	45.2	50	47	2.675	2.546
	Avg.	46.6	45.3	53.7	45.3	2.661	2.554
	Std.	0.25	0.36	3.51	1.53	0.0122	0.0091
Granite 12.5 mm	1	39.3	45.9	53	77	2.368	2.649
	2	40.9	45.3	48	76	2.433	2.634
	3	39.8	45.0	51	76	2.383	2.641
	Avg.	40.0	45.4	50.7	76.3	2.395	2.641
	Std.	0.82	0.46	2.52	0.58	0.0340	0.0075
Diabase Mix 12.5 mm	1	48.7	47.2	77	82	2.779	2.766
	2	48.0	47.4	78	86	2.784	2.755
	3	48.3	48.5	75	85	2.766	2.758
	Avg.	48.3	47.7	76.7	84.3	2.776	2.760
	Std.	0.35	0.70	1.53	2.08	0.0093	0.0057
River Gravel 12.5 mm	1	46.9	47	54	74	2.614	2.621
	2	46.8	46.5	40	78	2.610	2.616
	3	47.5	46.4	47	74	2.637	2.606
	Avg.	47.1	46.6	47	75	2.620	2.614
	Std.	0.38	0.32	7.00	2.31	0.0146	0.0076
Limestone 19.0 mm	1	45.1	44.6	79	79	2.760	2.725
	2	45.2	44.2	74	74	2.757	2.728
	3	45.6	46.3	79	84	2.761	2.743
	Avg.	45.3	45.0	77.3	79.0	2.759	2.732
	Std.	0.26	1.12	2.89	5.00	0.0021	0.0096
Granite/ Gravel 25.0 mm	1	44.2	43.5	43	81	2.642	2.617
	2	44.2	43.1	43	79	2.646	2.611
	3	44.2	43.4	43	77	2.647	2.624
	Avg.	44.2	43.3	43.0	79.0	2.645	2.617
	Std.	0.00	0.21	0.00	2.00	0.0026	0.0065
Siltstone 25.0 mm	1	48.4	47.9	71	78	2.686	2.672
	2	48.1	48.0	74	73	2.688	2.684
	3	47.9	47.7	76	75	2.685	2.679
	Avg.	48.1	47.9	73.7	75.3	2.686	2.678
	Std.	0.25	0.15	2.52	2.52	0.0015	0.0060
Diabase 25.0 mm	1	48.1	47.3	71	77	2.992	2.983
	2	47.5	47.7	76	77	2.951	2.976
	3	48.5	48.1	78	76	3.005	2.989
	Avg.	48.0	47.7	75.0	76.7	2.983	2.983
	Std.	0.50	0.40	3.61	0.58	0.0282	0.0065
Granite 37.5 mm	1	48.2	47.9	80	79	2.707	2.694
	2	48.0	48.2	82	80	2.720	2.706
	3	48.3	48.1	78	78	2.713	2.727
	Avg.	48.2	48.1	80.0	79.0	2.713	2.709
	Std.	0.15	0.15	2.00	1.00	0.0065	0.0167

Table 3. Coarse Aggregate Properties

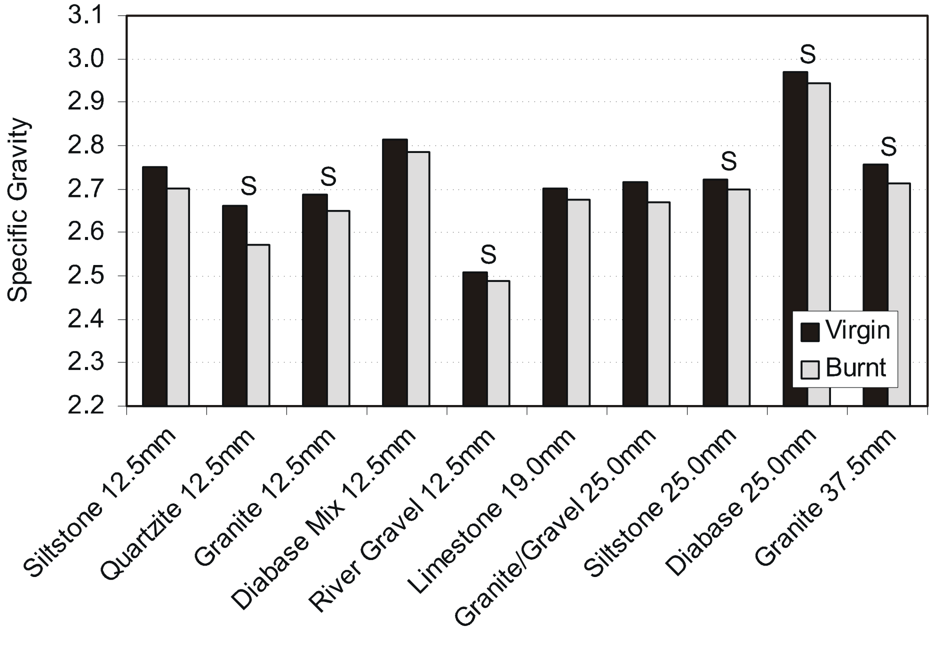
Aggregate Type	Sample	Flat & Elongated, %5:1		Flat and Elongated, % 3:1		Coarse Aggregate G_{sb}	
		Virgin	Burnt	Virgin	Burnt	Virgin	Burnt
Siltstone 12.5 mm	1	4.2	5.3	31.6	30.9	2.753	2.706
	2	5.7	2.6	37.5	34.0	2.664	2.700
	3	6.2	2.7	43.4	21.5	2.838	2.696
	Avg.	5.4	3.5	37.5	28.8	2.752	2.701
	Std.	1.04	1.53	5.90	6.51	0.0870	0.0050
Quartzite 12.5 mm	1	1.7	2.4	27.5	34.5	2.663	2.573
	2	1.7	1.6	12.6	26.3	2.662	2.571
	3	0.6	0.5	16.4	24.9	2.662	2.575
	Avg.	1.3	1.5	18.8	28.6	2.662	2.573
	Std.	0.64	0.95	7.74	5.19	0.0006	0.0020
Granite 12.5 mm	1	1.1	0.0	20.1	30.1	2.690	2.646
	2	1.6	4.4	22.4	35.3	2.684	2.650
	3	4.6	2.6	26.2	33.4	2.691	2.653
	Avg.	2.4	2.3	22.9	32.9	2.688	2.650
	Std.	1.89	2.21	3.08	2.63	0.0038	0.0035
Diabase Mix 12.5 mm	1	7.3	6.6	40.4	39.1	2.832	2.770
	2	8.5	8.7	36.2	48.5	2.802	2.781
	3	7.0	7.8	41.8	33.6	2.811	2.809
	Avg.	7.6	7.7	39.5	40.4	2.815	2.787
	Std.	0.79	1.05	2.91	7.53	0.0154	0.0201
River Gravel 12.5 mm	1	2.0	1.7	20.9	20.3	2.513	2.488
	2	0.6	0.9	18.3	12.3	2.510	2.492
	3	1.2	0.4	11.2	15.0	2.506	2.489
	Avg.	1.3	1.0	16.8	15.9	2.510	2.490
	Std.	0.70	0.66	5.02	4.07	0.0035	0.0021
Limestone 19.0 mm	1	4.2	2.5	21.8	19.7	2.701	2.649
	2	4.5	2.6	25.8	20.6	2.705	2.653
	3	3.3	2.8	24.4	22.5	2.703	2.725
	Avg.	4.0	2.6	24.0	20.9	2.703	2.676
	Std.	0.62	0.15	2.03	1.43	0.0020	0.0428
Granite/ Gravel 25.0 mm	1	2.0	1.4	16.1	19.5	2.772	2.667
	2	0.4	1.3	12.1	15.3	2.693	2.675
	3	0.0	1.5	11.3	19.4	2.685	2.669
	Avg.	0.8	1.4	13.2	18.1	2.717	2.670
	Std.	1.06	0.10	2.57	2.40	0.0481	0.0042
Siltstone 25.0 mm	1	6.9	8.7	35.8	31.3	2.719	2.701
	2	4.1	5.0	36.7	32.6	2.721	2.701
	3	8.5	6.7	35.7	28.0	2.727	2.698
	Avg.	6.5	6.8	36.1	30.6	2.722	2.700
	Std.	2.23	1.85	0.55	2.37	0.0042	0.0017
Diabase 25.0 mm	1	0.0	0.0	6.2	6.8	2.962	2.953
	2	0.2	0.0	10.7	8.2	2.971	2.952
	3	0.0	0.0	8.5	3.0	2.977	2.930
	Avg.	0.1	0.0	8.5	6.0	2.970	2.945
	Std.	0.12	0.00	2.25	2.69	0.0075	0.0130
Granite 37.5 mm	1	0.3	0.5	23.8	27.3	2.756	2.728
	2	1.3	0.2	18.8	24.5	2.761	2.713
	3	0.2	1	27.6	29.2	2.754	2.701
	Avg.	0.6	0.6	23.4	27.0	2.757	2.714
	Std.	0.61	0.40	4.41	2.36	0.0036	0.0135

Figure 2. Comparison of Virgin and Burnt Fine Aggregate G_{sb}



S denotes a significant difference in the sample means at the 95 percent confidence level.

Figure 3. Comparison of Virgin and Burnt Coarse Aggregate G_{sb}



S denotes a significant difference in the sample means at the 95 percent confidence level.

Table 4. Blend G_{sb} and Estimates of G_{sb} for Virgin and RAP Samples

Virgin	Burnt	Gse, Furnace AC%	Gse, Actual AC%
2.716	2.689	2.747	2.745
2.708	2.692	2.746	2.742
2.793	2.772	2.845	2.823
2.724	2.696	2.765	2.751
2.692	2.651	2.698	2.684
2.530	2.646	2.732	2.718
2.976	2.965	3.016	3.007
2.744	2.713	2.893	2.786
2.661	2.563	2.827	2.786
2.557	2.544	2.632	2.632

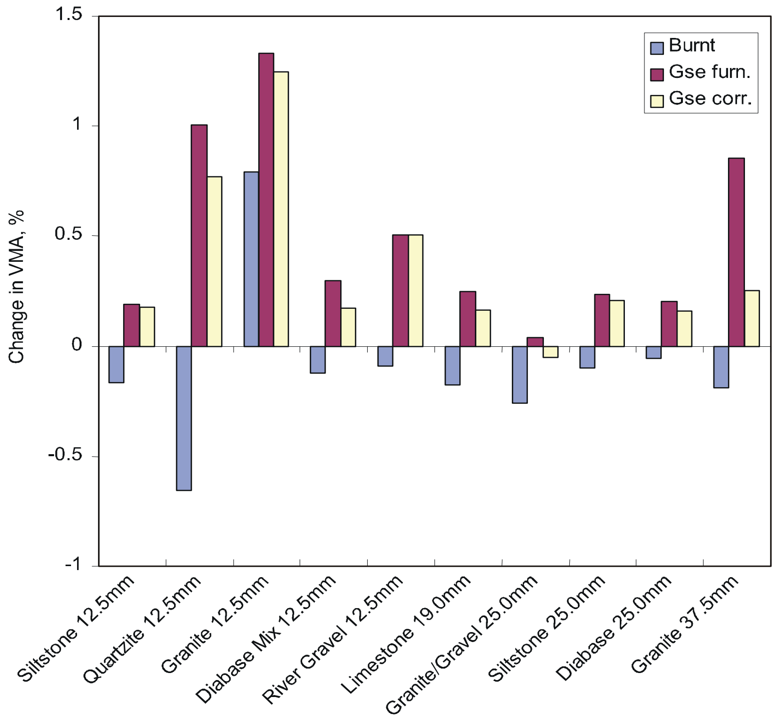
Figure 4 shows the change in VMA attributable to three estimates of the simulated RAP G_{sb} for a simulated mixture. The simulated blend G_{sb} was calculated assuming 80 percent virgin aggregates and 20 percent simulated RAP. The burnt blend G_{sb}, the G_{se} calculated using the uncorrected asphalt content from the ignition furnace, and the G_{se} calculated using the actual asphalt content of the simulated RAP sample were all used for the simulated RAP G_{sb}. The G_{se} calculated using the uncorrected asphalt content from the ignition furnace was included, since the RAP ignition furnace correction factor is generally unknown. The correction factor accounts for aggregate loss or gain during the determination of asphalt content in the ignition furnace. The mixture was assumed to have 5 percent asphalt and a compacted mixture bulk specific gravity of 2.400 for all 10 aggregate types.

For comparison, the VMA was calculated using the G_{sb} of 100 percent virgin aggregate. This represents the case where the specific gravity of the RAP would actually be known. For comparison purposes, this is used as the “true” VMA. The differences in Figure 4 are based on the VMA that was determined by using one of the techniques for estimating the RAP G_{sb} minus the VMA that was determined if the specific gravity had been actually known. In 9 of 10 cases, the VMA calculated using the burnt G_{sb} for the simulated RAP was less than the true VMA. In all cases, the VMA calculated using G_{se} from the uncorrected furnace asphalt content of the simulated RAP was greater than the true VMA.

In 9 of 10 cases, the VMA that was calculated using G_{se} (G_{se} calculated using the true asphalt content) was greater than the actual VMA. The average difference was less for the VMA calculated using the burnt G_{sb} (-0.1 percent) than for the VMAs calculated using G_{se} determined from either the uncorrected ignition furnace asphalt content (+0.5 percent) or the actual asphalt content (+0.4 percent). Therefore, from these data, it appears that more accurate estimates of VMA may be made for mixes containing RAP by using G_{sb} determined from aggregate recovered using the ignition furnace rather than estimates derived from calculations based on G_{se}

The Florida Department of Transportation (1998) uses an alternate procedure to determine the maximum specific gravity and a better estimate of G_{se} for RAP. The Florida DOT procedure is based on the ASTM D2041 supplemental procedure for porous aggregate. Particularly with milled RAP, some of the aggregate surfaces may not be thoroughly sealed by an asphalt film. This allows moisture to enter the aggregate during the vacuuming process. In the Florida procedure, after the sample has been vacuumed and the mass of water displaced by the sample has been determined, the water is then decanted and the sample dried in front of a fan to a constant mass. The constant mass of the sample at this point is used to calculate the volume of the sample. This accounts for any moisture absorbed into the aggregate while vacuuming the sample.

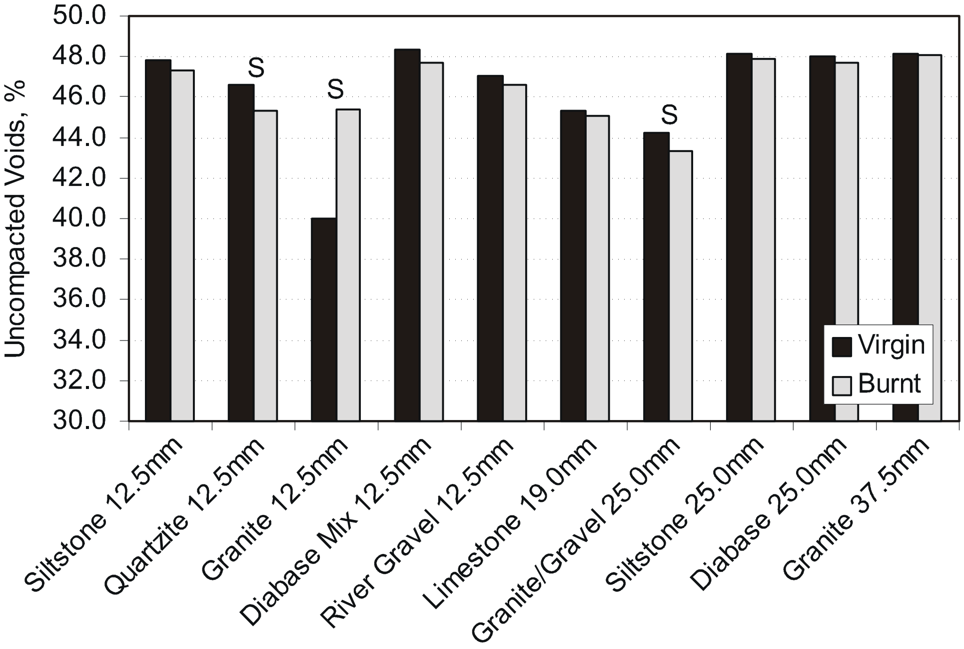
Figure 4. Change in Voids in Mineral Aggregate Based on Various Estimates of Simulated RAP G_{sb}



Fine Aggregate Angularity

The fine aggregate G_{sb} for the particular replicate was used to calculate the fine aggregate angularity (FAA) value. Thus, for the ignition furnace samples, the fine aggregate G_{sb} is based on a burnt sample subject to the significant differences discussed previously. Figure 5 indicates a significant difference between the virgin and burnt aggregates for 3 of 10 cases. With the exception of the granite 12.5-mm mixture, the FAA values of the burnt samples decreased. This was believed to be due to the change in the fine aggregate G_{sb}. It should be noted that the fine aggregate G_{sb} of the granite 12.5-mm mixture increased after ignition, which would in turn increase the FAA value. To test this theory, the fine aggregate G_{sb} of the virgin samples was substituted for the burnt fine aggregate G_{sb} in the FAA calculations for the three significantly different cases. In all three cases, FAA results for the burnt samples using the virgin fine aggregate G_{sb} were still significantly different than the virgin FAA values. The average difference between the virgin and the burnt FAA using their respective gravity was 0.9, 5.4, and 1.3 percent for the granite/gravel 25.0 mm, granite 12.5 mm, and quartzite 12.5 mm, respectively. The average difference when the virgin G_{sb}s were used for both FAA values was 0.3, 1.1, and -0.9 percent, respectively. In all three cases, the FAA values were closer to the values of the virgin material using the virgin G_{sb} rather than the burnt G_{sb}.

Figure 5. Comparison of Virgin and Burnt Fine Aggregate Angularity Values

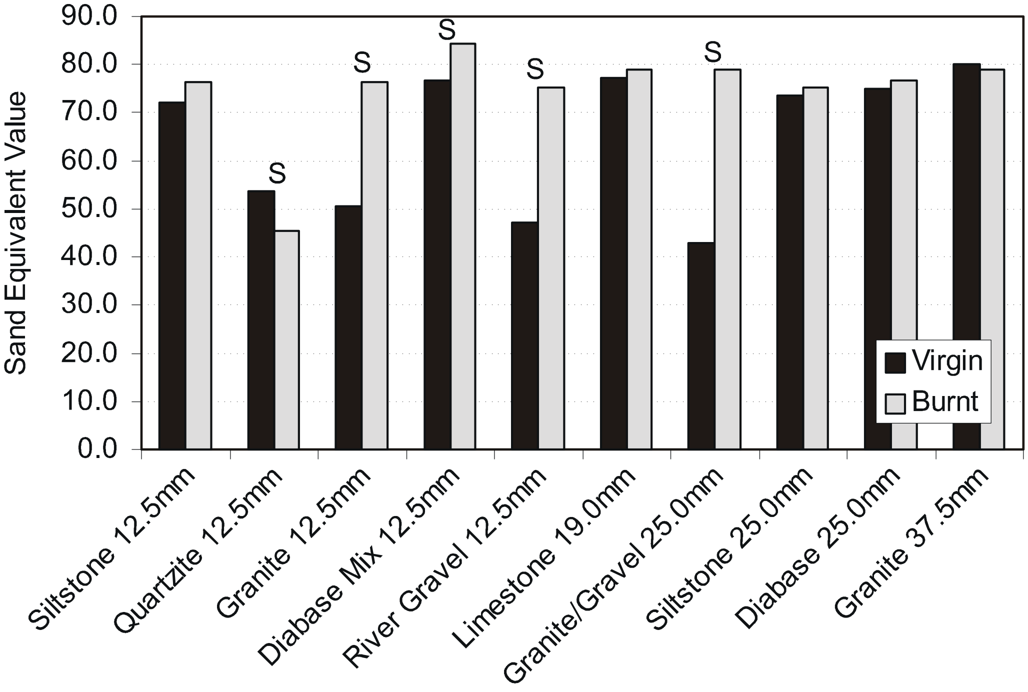


S denotes a significant difference in the sample means at the 95 percent confidence level.

Sand Equivalent

Figure 6 indicates a significant difference between the virgin and burnt sand equivalent values for 5 of 10 cases. The sand equivalent value of the burnt samples was higher than that of the virgin sample for 8 of 10 cases. The significant differences occurred with samples that had relatively low (approximately 50 or less) virgin sand equivalent values. With the exception of the quartzite 12.5-mm mix, the burnt values were higher. Thus, it does not appear that the ignition furnace can be used to recover aggregate for sand equivalent testing.

Figure 6. Comparison of Virgin and Burnt Sand Equivalent Values



S denotes a significant difference in the sample means at the 95 percent confidence level**.**

Flat and Elongated Particles

Figures 7 and 8 indicate a significant difference between the virgin and burnt flat and elongated particles at the 3:1 ratios for the granite 12.5-mm and siltstone 25.0-mm mixes and at the 5:1 ratios for the limestone 19.0-mm mix. The differences between the siltstone 12.5-mm, quartzite 12.5-mm, and granite 12.5-mm mixes appear quite large. A recent round robin determined the acceptable difference between two properly conducted tests by the same operator in the same lab to be 73.9 percent of the mean (Prowell & Weingart, 1999). Thus, the acceptable difference between the average of three properly conducted tests by the same operator in the same lab would be 73.9 divided by √3–or 42.7 percent of the mean. The quartzite 12.5-mm, granite 12.5-mm, and granite/gravel 25.0-mm mixes exceeded this limit. A precision statement was not determined for the 5:1 ratio.

Figure 7. Comparison of Percent 3:1 Flat and Elongated Particles for Virgin and Burnt Samples

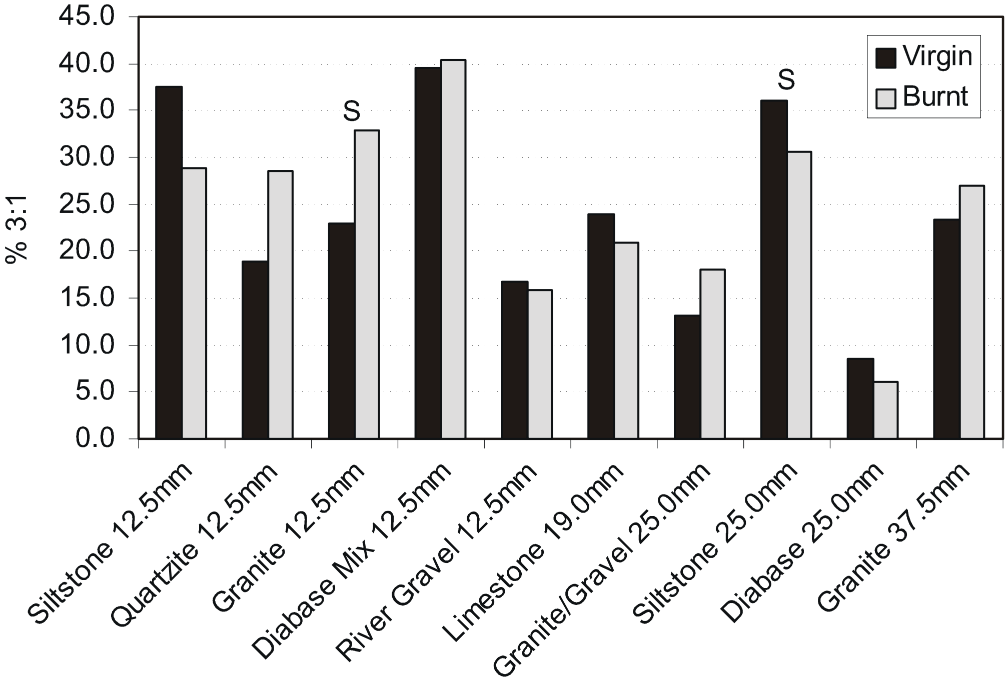
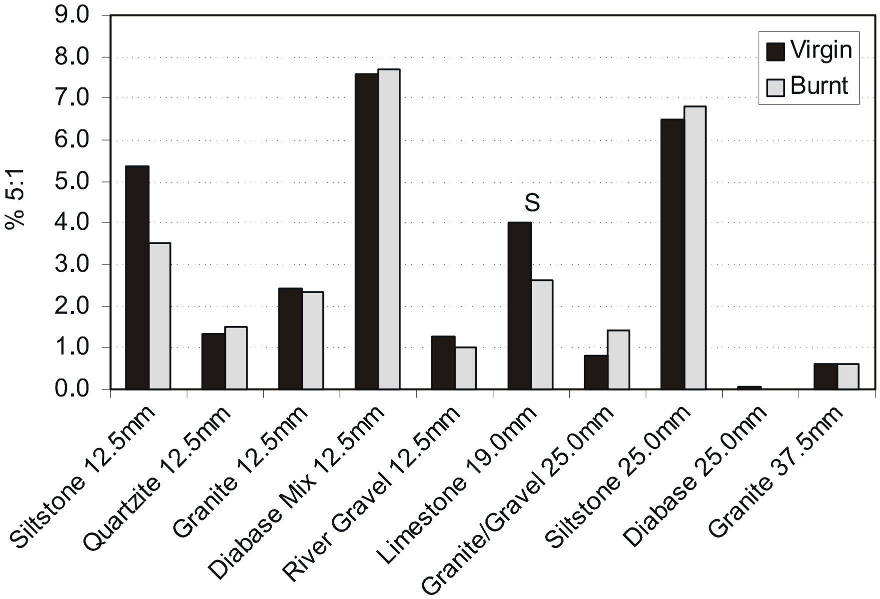


Figure 8. Comparison of Percent 5:1 Flat and Elongated Particles for Virgin and Burnt Samples



S denotes a significant difference in the sample means at the 95 percent confidence level.

Gradation Analysis

Table 5 shows the comparisons between gradations for the virgin and burnt samples. The nominal maximum sieve size is shown for the 12.5-mm and 19.0-mm mixes, one sieve size below the nominal maximum size is shown for the 25.0-mm and 37.5-mm mixes, since many of these mixes had 100 percent passing the nominal maximum size, and the 4.75- and 0.075-mm sieves are shown for all mixes. *F* tests were performed on the results from the virgin and burnt samples to compare sample variances. Table 5 shows the probability that the calculated *F* value exceeds the critical *F* –value. Probabilities less than 0.05 are considered significant and appear in bold type in the table. *T* tests were performed to compare sample means. Table 5 shows that the probability of the calculated *t* value exceeds the critical *T* –value. Probabilities less than 0.05 were considered significant and appear in bold type in the table.

Several materials engineers in Virginia have expressed concern about the accuracy of gradations of samples recovered in the ignition furnace. This concern is based on visual evidence that aggregates have cracked or broken during the ignition test. Generally, this is observed near the top size of the aggregate. Broken aggregate was observed for the siltstone 25.0-mm mix. However, the gradations on the 19.0-, 4.75-, and 0.075-mm siltstone sieves show no significant difference between the sample means [$P(T< = t)$ two-tail > 0.05]. Further, only 4 of 30 gradation samples indicated significant differences between the mean percent passing for the virgin and burnt samples at the 95 percent confidence level. Three of these differences occurred with the 0.075-mm sieve. The average difference between the percent passing the 0.075-mm sieve for the three significantly different aggregates was 0.5 percent. Thus, it appears that the ignition test provides representative gradation for RAP or hot-mix asphalt quality control.

It was felt the ignition furnace correction factor (C_f) for aggregate loss developed for asphalt content determination might be indicative of aggregates whose properties changed when extracted using the ignition furnace. A comparison between C_f and the number of significant differences found with the reported aggregate tests is shown in Table 6. Based on the data, it does not appear that there is any correlation between the ignition furnace correction factor for asphalt content determination and the effect of aggregate properties of samples recovered using the ignition furnace.

Table 5. Comparison of Virgin and Recovered (Burnt) Gradations

Aggregate	Sieve	Virgin Replicate					Burnt Replicate					P(F<=f)	P(T<=t)
	Size	1	2	3	Average	Std.	1	2	3	Average	Std.	two-tail	two-tail
Siltstone	12.5	97.7	97.4	100.0	98.4	1.43	97.2	97.0	94.6	96.3	1.47	0.487	0.153
12.5mm	4.75	39.6	54.8	58.5	51.0	10.03	45.8	54.6	38.6	46.4	8.01	0.390	0.568
	0.075	5.3	5.9	8.0	6.4	1.43	4.5	5.5	4.0	4.7	0.75	0.214	0.141
Quartzite	12.5	98.8	99.3	99.5	99.2	0.33	98.3	99.4	99.5	99.1	0.63	0.213	0.795
12.5mm	4.75	53.4	52.5	54.2	53.4	0.86	58.0	53.5	51.3	54.3	3.39	0.061	0.686
	0.075	6.7	6.7	6.8	6.7	0.07	6.5	6.4	5.8	6.2	0.37	**0.037**	0.137
Granite	12.5	97.6	95.7	97.7	97.0	1.10	96.6	96.4	97.8	96.9	0.77	0.328	0.922
12.5mm	4.75	48.8	51.2	50.7	50.2	1.28	53.1	48.2	43.3	48.2	4.92	0.064	0.522
	0.075	4.3	4.4	4.7	4.5	0.19	4.6	3.9	3.5	4.0	0.58	0.096	0.266
Diabase Mix	12.5	93.2	93.9	91.8	93.0	1.07	96.2	95.3	96.7	96.1	0.71	0.304	**0.014**
12.5mm	4.75	57.9	57.6	56.1	57.2	0.98	55.8	56.3	56.6	56.2	0.38	0.131	0.186
	0.075	4.9	4.5	4.8	4.7	0.20	4.2	4.1	4.3	4.2	0.10	0.189	**0.017**
River Gravel	12.5	99.1	97.8	96.2	97.7	1.45	97.3	97.0	97.1	97.1	0.14	**0.009**	0.595
12.5mm	4.75	46.7	43.9	41.6	44.1	2.56	44.4	44.5	44.7	44.6	0.19	**0.006**	0.779
	0.075	4.3	4.8	4.5	4.6	0.25	4.9	5.1	5.0	5.0	0.10	0.146	**0.043**
Limestone	19.0	98.5	98.1	97.4	98.0	0.54	97.0	98.1	98.9	98.0	0.95	0.243	0.958
19.0mm	4.75	36.9	37.3	39.2	37.8	1.23	37.4	34.8	37.1	36.5	1.41	0.430	0.271
	0.075	4.4	4.5	5.0	4.7	0.29	4.7	4.8	4.5	4.7	0.19	0.308	0.903
Granite/Gravel	19.0	87.0	88.4	85.0	86.8	1.69	82.2	86.0	86.6	85.0	2.41	0.329	0.338
25.0mm	4.75	33.1	35.0	34.4	34.2	0.98	35.9	31.5	37.7	35.0	3.17	0.086	0.676
	0.075	2.2	2.5	2.1	2.3	0.20	1.7	1.9	1.6	1.8	0.16	0.405	**0.027**
Siltstone	19.0	86.5	81.3	85.2	84.3	2.69	83.9	82.1	81.4	82.5	1.28	0.186	0.342
25.0mm	4.75	38.8	37.6	38.4	38.3	0.63	38.2	37.6	38.3	38.0	0.39	0.274	0.623
	0.075	4.5	4.9	4.8	4.7	0.24	4.5	7.2	4.6	5.5	1.53	**0.025**	0.498
Diabase	19.0	86.2	81.8	78.7	82.2	3.74	84.5	77.8	87.1	83.1	4.75	0.382	0.812
25.0mm	4.75	43.3	45.4	46.8	45.2	1.80	53.2	44.3	46.3	47.9	4.67	0.129	0.395
	0.075	5.1	5.5	5.4	5.3	0.18	5.6	5.5	5.8	5.6	0.18	0.493	0.088
Granite	25.0	65.7	71.4	63.4	67.4	5.61	71.8	70.3	71.5	71.2	0.79	**0.036**	0.211
37.5mm	4.75	25.4	30.7	28.1	29.4	1.88	26.5	25.0	27	26.2	1.06	0.137	0.313
	0.075	2.5	2.9	2.5	2.7	0.32	2.3	2.3	2.3	2.3	0.01	**0.001**	0.177

Table 6. Summary Comparison of Significant Difference Between Sample Means By Aggregate Type versus Furnace Correction Factor

Primary Aggregate Type	Fine Aggregate Angularity	Sand Equivalent	Fine Aggregate G_{sb}	Flat and Elongated 5:1	Flat and Elongated 3:1	Coarse Aggregate G_{sb}	Gradation			Total Significant Differences	Furnace C_f, %
							Nominal Maximum	4.75 mm	0.075 mm		
Siltstone 12.5mm	-	-	S	-	-	-	-	-	-	1	0.09
Quartzite 12.5mm	S	S	S	-	-	S	-	-	-	4	0.79
Granite 12.5mm	S	S	S	-	S	S	-	-	-	6	0.30
Diabase Mix 12.5mm	-	S	-	-	-	-	S	-	S	3	0.43
River Gravel 12.5mm	-	S	-	-	-	S	-	-	S	2	0.10
Limestone 19.0mm	-	-	S	S	-	-	-	-	-	2	0.28
Granite/ gravel 25.0mm	S	S	S	-	-	-	-	-	S	3	0.30
Siltstone 25.0mm	-	-	-	-	S	S	-	-	-	2	0.09
Diabase 25.0mm	-	-	-	-	-	S	-	-	-	1	0.14
Granite 37.5mm	-	-	-	-	-	S	-	-	-	1	2.02

S denote a significant difference between virgin and burnt sample means at the 95 percent confidence level.

CONCLUSIONS

- Use of the ignition furnace caused significant differences between the mean test values for coarse aggregate G_{sb} in 6 of 10 cases and fine aggregate G_{sb} in 5 of 10 cases. However, the blend G_{sb} values determined from samples recovered in the ignition furnace resulted in a lower error (-0.1 percent) in the VMA estimations than either the G_{se} calculated using the uncorrected ignition furnace or actual asphalt content (+0.5 or + 0.4 percent, respectively).

- *A better estimation of VMA would be obtained using the G_{sb} determined from aggregate extracted in the ignition furnace.*

- *Aggregates recovered using the ignition furnace appear to be unsuitable for sand equivalent testing.* Use of the ignition furnace caused significant differences between the mean test values of virgin and burnt sand equivalent samples in 5 of 10 cases. Four of the 5 cases occurred with samples having relatively low virgin sand equivalent values. This indicates the ignition furnace alters the clay-like particles measured during the sand equivalent test.

- *Though differences between FAA measurements on virgin and recovered samples may occur, it is felt that values for samples recovered using the ignition furnace are reasonable.* The results of the FAA tests were significantly different between the virgin and burnt samples in 3 of 10 cases. The use of the actual G_{sb} in the calculation of the FAA values did not resolve the differences. In only 1 case would the difference have caused a burnt sample to pass the specification value when the virgin sample failed.

- *Accurate results may be obtained for gradation analysis and flat and elongated particle measurements performed on aggregates recovered in the ignition furnace*. The measurements of flat and elongated particles or gradation were not significantly affected by extraction in the furnace. Visually observed changes in aggregate (e.g., fracture) did not correspond with a change in measured gradation.

- *There is no correlation between the ignition furnace correction factor for aggregate loss and the effect of the ignition furnace on aggregate properties*. The effects of the ignition furnace on aggregate properties appear to depend on the aggregate source.

- *With the exception of sand equivalent tests, it appears that consensus aggregate properties measured with samples recovered using the ignition furnace should be viable for both the mix design properties of RAP and the quality control or quality assurance of hot-mix asphalt*.

RECOMMENDATIONS

- *Agencies considering using VMA as an acceptance criterion should carefully consider how they would measure specific gravity in design and production*. Use of G_{se} to calculate VMA during production may result in artificially high estimates of VMA.

- Because of recommendations made from this study, VDOT specifications were changed to include FAA and flat and elongated particle testing on RAP recovered using the ignition furnace for the year 2000 paving season.

RECOMMENDATIONS FOR FURTHER RESEARCH

- Additional research is required to evaluate the effects of the ignition furnace on coarse aggregate angularity. Nine of 10 mixtures had 100 percent two crushed faces in the virgin samples. Sample size precluded testing with the tenth sample. Therefore, coarse aggregate angularity was not evaluated.

- Additional research should be conducted to evaluate the Florida Department of Transportation's procedure for determining G_{se}, as well as assuming different asphalt absorption levels in the calculation of G_{se}. This procedure should be investigated in the future, since the use of the effective gravity would be preferable in terms of testing time. The estimate of G_{sb} using G_{se} can also be improved if an assumption can be made for the asphalt absorption of the aggregate.

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