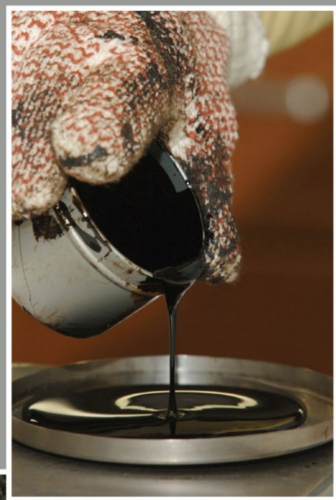

NCAT Report 17-03R

EFFECT OF FLAT AND ELONGATED AGGREGATE ON STONE MATRIX ASPHALT PERFORMANCE

By
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April 2017
(Revised July 2017)

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DISCLAIMER

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ABSTRACT

The importance of this study is driven by asphalt mixture economics since the in-place cost of stone matrix asphalt (SMA) mixtures ranges from 20 to 80% higher than conventional dense-graded mixes. The production of SMA aggregate alone is believed to cost approximately twice that of conventional aggregate production. Therefore, it is essential to determine whether the need for such high quality aggregate products is necessary for satisfactory SMA performance.

European specifications were considered when developing the requirements of AASHTO M325 and typically require SMA aggregates to have no more than 30 percent Los Angeles abrasion loss and no more than 20 percent flat and elongated (F&E) particles when measured at a 3:1 ratio of length to maximum thickness. However, these strict aggregate requirements were primarily developed for use in Europe, where studded tires are used for winter travel, and may not be necessary for other countries or in areas where studded tire use is prohibited or not needed.

The objective of this study was to evaluate the performance of SMA mixes designed with different percentages of flat and elongated aggregate to determine how critical this aggregate property is relative to performance. Quarries that produce both SMA and non-SMA stone and two quarries that do not produce SMA stone (due to high F&E values) were evaluated.

The study concludes that there is generally no significant adverse effect on performance from using high F&E aggregate if that aggregate has low abrasion loss values. This study was conducted with lab-produced, lab-compacted specimens. It is recommended that projects with plant-produced, field-compacted mixtures using high F&E values be evaluated to ensure such SMA mixes meet performance expectations. A recommendation is made to specify the same F&E requirements for SMA mixes as is used for Superpave mixes.

1 INTRODUCTION

1.1 Problem Statement

The importance of this study sponsored by the Georgia Department of Transportation (GDOT) was driven by asphalt mixture economics. The cost of using stone matrix asphalt (SMA) mixtures ranges from 20 to 80% higher than conventional dense-graded mixes. Part of the increase can be explained in that SMA is typically used on high traffic volume routes, which require night time construction with limited work hours. A portion of the higher cost is also due to a higher asphalt binder demand for SMA mixes, which provides increased durability. However, the majority of the increased cost is due to the additional effort and special crushing equipment needed for quarries to produce stone that meets the special requirements for SMA. The production of SMA aggregate alone is estimated to cost approximately twice that of conventional aggregate production. Therefore, it is essential to determine whether such high quality aggregate products are necessary for satisfactory SMA performance.

Since the introduction of SMA from Europe in 1990, there have been questions about aggregate quality requirements needed for these high performance mixtures. European specifications in 1990 required SMA aggregates to have no more than 30 percent Los Angeles (L.A.) abrasion loss and no more than 20 percent flat and elongated (F&E) particles when measured at a 3:1 ratio of length to maximum thickness. These values were adopted as guidelines by a Technical Working Group selected by the Federal Highway Administration (FHWA) in 1991 (*1, 2*). However, as pointed out by Barksdale, these strict aggregate requirements were developed for use in Europe due to degradation resulting from the use of studded tires for winter travel and may not be necessary for other countries (*3*).

A limited study of the effect of F&E aggregate particles on hot mix asphalt performance conducted by the National Center for Asphalt Technology (NCAT) found that the aggregate abrasion value was influenced to some degree by particle shape (*4*). Beam fatigue tests of Superpave mixtures using two aggregate types showed that fatigue resistance characterized by AASHTO T 321 actually improved as the percent 3:1 F&E aggregate particles increased. No significant difference in test results for moisture susceptibility or in aggregate breakdown was observed for the No. 200 (0.075 mm) sieve size. The study did show significant differences in rutting resistance and breakdown on the No. 4 (4.75 mm) sieve size related to percent F&E aggregate particles at the 3:1 ratio. The study concluded that there might be an upper limiting value for F&E aggregate particles at the 3:1 ratio somewhere between 30 to 50 percent. A study by Oduroh found that increases of up to 40% F&E aggregate particles at the 3:1 ratio did not adversely affect performance of Superpave mixes (*5*). The NCAT study further recommended that the upper limiting value for percent F&E aggregate particles should be dependent on L.A. abrasion loss requirements rather than using one threshold for all aggregate and mix types. This recommendation is consistent with Barksdale's comment that the use of a single property as an indication of aggregate degradation is not realistic (*3*). Barksdale related particle breakdown to both particle shape and L.A. abrasion loss.

1.2 Project Objective

The objective of this study was to evaluate the performance of SMA mixes in Georgia designed with different percentages of F&E aggregate particles to determine how critical this aggregate property is. It was suspected that aggregates that meet quality standards for conventional asphalt mixtures would also perform well for SMA mixtures.

The research was initially conducted with a 50/50 blend of fly ash and asphalt plant baghouse dust as mineral filler added to the aggregate blend in order to meet the combined gradation requirements. Filler materials from marble mining and processing waste were also evaluated due to expected shortages of fly ash, which has been the primary mineral filler used in SMA mixes in Georgia.

1.3 Work Plan/Scope

The work consisted of a laboratory study to evaluate the effects of various F&E aggregate particles on compactibility, rutting resistance, and cohesiveness of SMA mixtures. Aggregates were obtained from three sources that produce specially crushed aggregate just for SMA production. A comparison was also made for SMA crushed aggregate versus the typical production stone used for conventional Superpave asphalt mixes from the same sources. Two additional sources of aggregate with high percentages of F&E aggregate particles were also used for comparing mix design and performance testing.

For each of the aggregates selected, SMA mix designs were conducted and Cantabro abrasion loss (for cohesion and resistance to raveling), moisture susceptibility, and rutting performance were evaluated. Mixtures were compacted using the 50-blow Marshall procedure since this is the mix design compaction method used by GDOT.

A comparative degradation of samples from each mixture caused by the compactive effort was determined by placing the combined aggregate without liquid binder into a gyratory mold and gyrating for 100 gyrations. A comparison of before and after gradations was used to determine the effect F&E aggregate particles may have on the amount of aggregate breakdown that occurs during compaction.

Samples from each SMA mix design were prepared for laboratory performance testing. Cantabro abrasion testing was used to evaluate the durability and raveling potential of SMA mixtures with high percentages of F&E aggregate. Samples were also prepared for Asphalt Pavement Analyzer (APA) rut testing using current GDOT test requirements (GDT 115). GDT 115 is similar to AASHTO T340 except that 5.0 ±1.0% air voids are targeted during sample preparation. GDOT targets 5.0% air voids for compaction of SMA and Superpave mixtures with a maximum acceptable level of 7.0% air voids. It is typical for pavements to rut due to low air voids rather than at higher air void levels. Therefore, GDOT has chosen to evaluate rutting susceptibility at the 5.0% air void criteria instead of the higher level of 7.0% recommended in the AASHTO T340 procedure. The test is conducted at 64°C with a 100 lb. vertical load and 100 psi hose pressure for 8,000 cycles. The APA results were compared to the relative rutting susceptibility of the mix designs as related to the percent F&E aggregate.

Moisture susceptibility testing was conducted according to the GDT 66 test procedure. This GDOT procedure is similar to AASHTO T283 with four exceptions:

1. Samples for SMA mixture are prepared at 6.0 ±1.0% air voids.
2. The vacuum saturation period is for 30 minutes and a certain saturation level is not

required.
3. After 24 hours in a hot water bath, freeze-thaw conditioned samples, along with the control samples, are placed in a refrigerator at 55° ±3.6 °F for three hours before testing. The conditioned samples are kept submerged in water.
4. The test loading rate is 0.065 in/min.

Since GDOT targets 5.0% air voids during roadway compaction, and accepts up to 7.0% air voids, it is believed that most in-place pavements have an average of about 6.0% air voids. For that reason, GDOT chose to use 6.0% air voids for moisture susceptibility testing. The remaining GDT 66 requirements are a result of GDOT participation in the original Lottman research in the 1970s and early 1980s. GDOT used criteria from that early research to implement the GDT 66 moisture susceptibility testing prior to the AASHTO T283 procedure being developed. Due to its success with the GDT 66 procedure, GDOT decided to keep the test and related criteria after AASHTO T283 was implemented by other agencies as part of the Superpave technology.

2 LABORATORY TESTS

2.1 F&E Tests

A 1994 study conducted by NCAT included a survey of the state of practice at that time, which revealed that 81% of agencies reported using the 5:1 ratio to determine F&E aggregate particles. The study also found that very few states measured F&E separately as required in ASTM D4791 Method A, but instead used Method B, which is simpler and faster to perform (*6*). Method A is used to separate particles based on whether they are flat (comparing maximum particle width to maximum thickness), elongated (comparing maximum particle length to maximum width), both flat and elongated, or neither flat nor elongated. Method B is used to separate particles into two groups: flat and elongated (comparing maximum length to maximum thickness), or not flat and elongated.

All aggregates in this study were evaluated for flat and elongated properties using GDT 129, which compares particle length to average thickness. The GDT procedure differs from the ASTM procedure which measures length to maximum thickness. Tests were performed at both 3:1 ratio and 5:1 ratio of length to average thickness for aggregate particles retained on the No. 4 sieve. For comparison, samples were also tested at a 3:1 ratio using the ASTM D4791 Method B procedure for determining flat and elongated particles. All test results were based on a percent of sample mass. The data for comparison, as well as the results of the 5:1 ratio using GDT 129, are given in Table 1.

Table 1 shows the percent F&E aggregate particles for each of the coarse aggregates used in the mixture blend for each quarry source. F&E values ranged from 0 to 6.5% when measured at the 5:1 ratio using GDT 129. For the 3:1 ratio, F&E values ranged from 15.5 to 43.6%. Based on these results, the 5:1 ratio is not able to discriminate the significant differences in aggregate particle dimensions evaluated in this study. In fact, some agencies do not measure F&E because all of their aggregates meet the standard 10% maximum at a 5:1 ratio.

TABLE 1 Flat and Elongated Aggregate Particles by Source and Stone Size

Quarry	Aggregate	F&E 5:1 (GDT 129), %	F&E 3:1 (GDT 129), %	F&E 3:1 (ASTM D4791), %
A	SMA 7	0.5	19.7	8.4
	7	1.4	25.5	17.3
	89	2.2	23.9	13.1
B	SMA 7	0.3	17.0	6.8
	7	0.1	19.9	9.5
	SMA 89	0.0	18.2	7.0
	89	0.0	19.2	10.2
C	SMA 7	0.0	15.5	9.1
	7	0.0	23.3	15.7
	89	3.0	30.4	17.8
D	7	6.5	38.9	26.5
	89	3.8	20.7	20.9
E	7	6.2	43.6	31.5
	89	1.9	31.6	16.8

As expected, the results in Table 1 show that the majority of aggregates will meet the maximum standard of 10% F&E based on the 5:1 ratio used for conventional stone. The 3:1 ratio appears to be much more useful for evaluating F&E aggregate particles (*7*). Although the ASTM results were almost always lower, there was a good relationship (R^2 = 0.82) between the F&E results from GDT and ASTM procedures at the 3:1 ratio, as shown in Figure 1. Generally, the GDT procedure results in F&E values approximately 10% higher than the ASTM method.

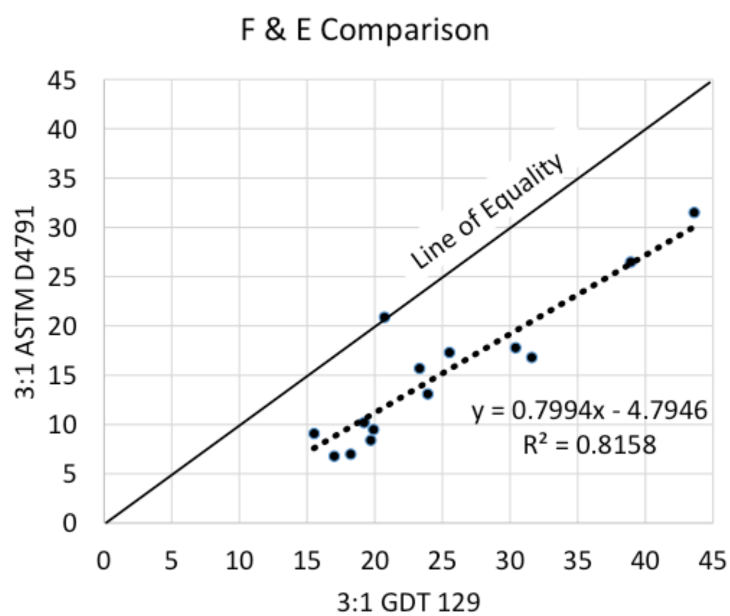

FIGURE 1 Comparison of GDT 129 versus ASTM D4791 for 3:1 Ratio

One concern regarding aggregates with high F&E aggregate particles is that they may be more prone to fracture during mix production, placement, and compaction than those with low F&E

values (*7*). To test the theory, samples of virgin aggregate were placed in a gyratory compactor mold and gyrated for 100 revolutions. Previous work indicated that 100 gyrations resulted in approximately the same amount of aggregate breakdown as could be expected in the field (*8, 9*). The resulting aggregate breakdown does provide a relative comparison between aggregate sources and physical properties. The results reported in Table 2 are the average difference in percent passing each sieve in the gyrated samples minus the average percent passing the same sieve of the control samples. The comparison is for SMA and non-SMA aggregates from the same quarry source, except that quarries D and E do not have SMA stone.

A comparison of the amount of aggregate breakdown for SMA versus non-SMA aggregates was determined based on three samples of SMA and non-SMA stone from each of the three quarries that provide both SMA and non-SMA stone (3 samples x 3 sources = 9 comparisons). Differences in control samples prepared without gyration were compared to samples after 100 gyrations. Test results for the No. 4 (4.75 mm) sieve are summarized in Figure 2. This sieve size was chosen because previous work by NCAT showed that the No. 4 (4.75 mm) sieve was critical in the formation of stone-on-stone contact in SMA mixtures (*7*). For this study, there was also a clear breakpoint in gradation on the No. 4 (4.75 mm) sieve.

TABLE 2 Differences in Percent Passing for Gyrated vs Control Samples

Sieve Size	Agg. A SMA	Agg. A Non-SMA	Agg. B SMA	Agg. B Non-SMA	Agg. C SMA	Agg. C Non-SMA	Agg. D Non-SMA	Agg. E Non-SMA
No. 4	4.0	6.1	4.5	4.5	9.3	9.6	3.0	1.8
No. 8	2.1	3.6	2.9	3.3	6.7	6.4	1.5	2.2
No. 200	0.0	0.6	0.0	0.3	0.6	0.5	0.1	0.3

Studies have also shown a direct relationship between percent F&E aggregate particles and the amount of breakdown on the No. 4 (4.75 mm) sieve (*9, 10, 11*). At low levels of breakdown, the non-SMA stone had a slightly greater difference from the control samples than the specially produced SMA stone; but as the amount of breakdown increased, the differences between aggregates approached the line of equality (Figure 2). Statistical results from an Analysis of Variance (ANOVA) indicates that the differences between breakdown of SMA and non-SMA stone are not significant at the 95% confidence interval (p-value = 0.105).

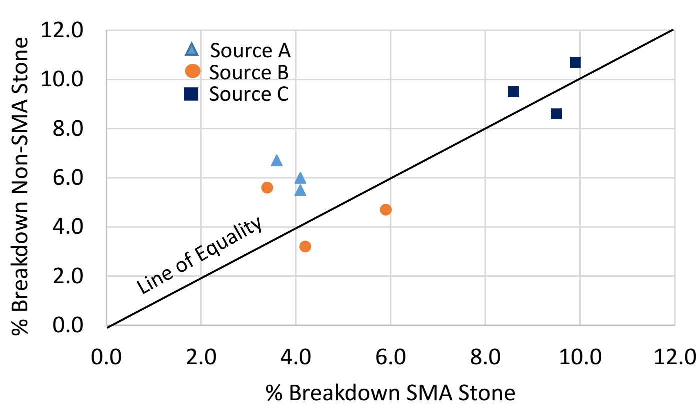

FIGURE 2 Comparison of Aggregate Breakdown on the No. 4 Sieve

An analysis of aggregate breakdown on the No. 8 (2.36 mm) and No. 200 (0.075 mm) sieve was also performed, but as shown previously in Table 2, there was insignificant difference in percent passing for either of the sieves after gyratory compaction. These results seem to verify earlier research findings that aggregate breakdown on the No. 200 (0.075 mm) sieve was not dependent on the percent 3:1 F&E aggregate particles (*4*).

An ANOVA of the breakdown on the No. 4 (4.75 mm) sieve was performed for all eight aggregate sources (three sources with and without SMA stone, and two additional sources without SMA stone). A comparison of aggregate breakdown to the percent flat and elongated particles was conducted. A p-value of 0.000 was obtained, which indicates the breakdown was significantly affected by the flat and elongated property of the aggregate. However, it was anticipated that breakdown would be greater for higher F&E aggregates, as has been the case in other studies (*7, 9, 10, 11*). In this study, the opposite trend was observed; aggregate with higher F&E values actually had less breakdown. For that reason, a comparison was also made of percent F&E aggregate particles to L.A. abrasion loss. The results show that as percent F&E increased, the L.A. abrasion loss decreased (Figure 3). These results show that the toughness of the aggregate in resistance to abrasion explains why breakdown did not increase as the percent F&E increased. The values emphasize the importance of F&E properties and abrasion values being considered together when specifying aggregate properties for SMA performance.

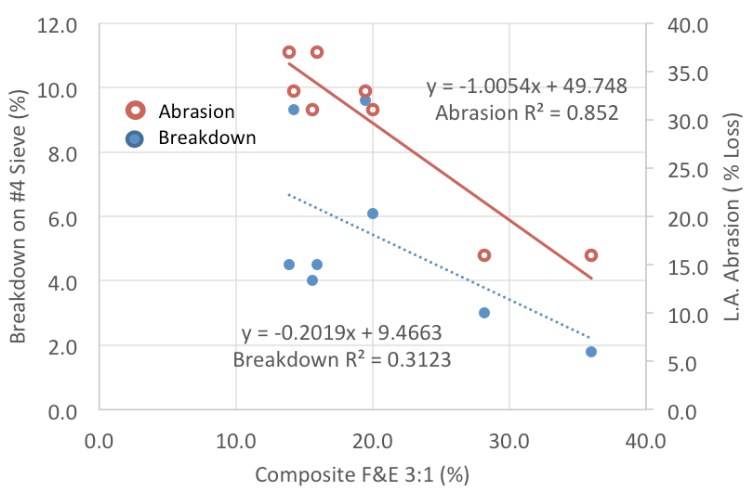

FIGURE 3 Comparison of the Effect of F&E on Aggregate Breakdown and L.A. Abrasion

Barksdale identified that aggregate properties of abrasion resistance and percent F&E must be considered together to identify aggregates that will perform well in an SMA pavement (*3*). As resistance to abrasion loss increases and the aggregate becomes tougher, it will have better resistance to aggregate degradation, and the amount of F&E aggregate particles can be increased. Likewise, as the percent of abrasion loss increases, the proportion of F&E must be reduced accordingly. Table 3 provides a summary of Barksdale's recommendation in relation to L.A. abrasion and F&E properties of aggregate at the 3:1 ratio for use in SMA mixtures. This approach will guard against the possibility of having a source with both high F&E and high abrasion while allowing more economical aggregates that may not meet the 20% maximum F&E generally specified.

TABLE 3 Limits of L.A. Abrasion and Percent F&E at the 3:1 Ratio for SMA Aggregate (*3*)

L.A. Abrasion, % Loss	F&E Limit, (3:1 Ratio)
≤ 45	≤ 20
≤ 40	≤ 25
≤ 35	≤ 35
≤ 30	≤ 40
≤ 25	≤ 45

The amount of F&E particles is important because it relates to the amount of fine dust particles generated during plant production and construction. Generally, as L.A. abrasion increases from 10 to 40%, the amount of material finer than the Number 200 (0.075 mm) sieve varies from 0.5 to 3.5%, respectively. The difference in aggregate breakdown between mix design and field results is due to the heat needed to heat and dry the coarse aggregate for SMA and the abrading action of particles colliding while traveling through the drier drum, silo, and during roadway placement and compaction.

2.2 Mix Designs

Approved SMA mix designs from three aggregate sources used on previous projects were provided by GDOT. All mixes were compacted using the 50-blow Marshall procedure described in AASHTO T245. The optimum asphalt content from the approved mix designs for most mixes was achieved at 4.0 % air voids in this study instead of the typical 3.5% air void target used by GDOT. This difference may be explained by slight changes in mineral filler characteristics since a 50/50 blend of fly ash and baghouse dust was used in this study for most of the mixes. A summary of the mix blends, gradations, and volumetric properties is provided in Table 4.

SMA mix designs were also prepared using non-SMA aggregates from the same three sources. In addition, aggregate from sources D and E that did not meet the current requirements for SMA stone of a maximum of 20% F&E at the 3:1 ratio based on GDT 129 were used. Six trial blends were made for aggregate E material in order to find a combination that would meet the gradation specification as well as the voids in coarse aggregate (VCA) requirements. The most promising blend was used, although it had an optimum asphalt content of 8.3%, which was above the current maximum binder amount allowed by GDOT.

Other research has shown that mixtures with high F&E aggregate particles resist densification and result in higher air voids and increased asphalt demand (*4, 12*). The same trend was observed during the volumetric analysis. Sources D and E, which had the highest percent F&E aggregate particles, also had the highest voids in mineral aggregate (VMA) properties and highest optimum asphalt content as shown in Table 4. It is important to note that Georgia uses the effective specific gravity to calculate VMA. Figure 4 shows that VMA increases as the percent F&E increases. These results are consistent with findings during NCHRP 9-8 research (*8*). All mixes met the recommended minimum VMA threshold of 17% and were within the specification range of 70-90% for voids filled with asphalt (VFA) (*1, 2, 8*). It is possible that the high asphalt demand for mixes with high F&E values may limit their use even if satisfactory mixtures can be designed.

TABLE 4 Mix Design Blend and Volumetric Properties

Aggregate Source	Agg. A SMA	Agg. A Non-SMA	Agg. B SMA	Agg. B Non-SMA	Agg. C SMA	Agg. C Non-SMA	Agg. D Non-SMA	Agg. E Non-SMA
Blend:	79% SMA #7	69% #7	70% SMA #7	75% #7	68% SMA #7	68% #7	66.7% #7	79% #7
	14% M10	10% #89	11% #89	5% #89	12% #89	12% #89	11% #89	5% #89
		13% M10	10% 810	10% 810	11% 810	11% 810	11% M10	6% M10
	5.75% 50/50 Filler	6.75% 50/50 Filler	8.0% 50/50 Filler	9% 50/50 Filler	8% 50/50 Filler	8% 50/50 Filler	10.3% 50/50 Filler	9% 200W Filler
	1.25% H. Lime	1.25% H. Lime	1% H. Lime	1% H. Lime	1% H. Lime	1% H. Lime	1% H. Lime	1% H. Lime
Gradation (Spec):	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing
3/4" (100)	100	100	100	100	100	100	100	100
1/2" (85-100)	98	94	87	91	96	97	95	96
3/8" (50-75)	57	54	54	61	66	70	64	69
No. 4 (20-28)	25	25	24	25	23	23	28	24
No. 8 (16-24)	21	20	18	19	16	16	20	16
No. 16	18	17	16	16	14	14	16	14
No. 30	17	16	14	15	13	13	14	13
No. 50	15	15	13	14	12	12	13	12
No. 100	13	13	12	12	11	11	12	11
No. 200 (8-12)	10.1	10.2	10.1	10.6	9.5	9.5	10.8	8.4
Composite F & E, 3:1	15.6	20.0	13.9	15.9	14.2	19.5	28.2	36.0
L.A.Abrasion Loss, %	31.0	31.0	37.0	37.0	33.0	33.0	16.0	16.0
Opt. AC, % (5.8-7.5)	6.4	6.2	6.5	6.2	6.6	6.6	7.1	8.3
Gmm	2.403	2.410	2.377	2.382	2.378	2.379	2.362	2.405
Gmb	2.306	2.313	2.282	2.287	2.283	2.283	2.268	2.308
Gse	2.644	2.647	2.614	2.615	2.622	2.621	2.623	2.738
Gsb	2.622	2.620	2.590	2.581	2.589	2.592	2.597	2.712
Va,% (3.5 ± 0.5)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
VMA, %	18.4	18.0	18.4	18.0	18.7	18.6	19.7	22.7
VFA, % (70-90)	78.2	77.8	78.2	77.7	78.6	78.5	79.7	82.4
Pbe	6.09	5.82	6.16	5.71	6.13	6.19	6.74	7.97
Dust/Pbe	1.66	1.75	1.64	1.86	1.55	1.53	1.60	1.05
VCAdrc	40.1	39.3	39.4	40.1	40.2	40.6	42.7	42.4
VCAmix	38.6	38.2	37.7	38.3	36.7	36.6	42.1	40.9
VCAmix < VCAdrc	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Georgia uses Gse rather than Gsb to calculate VMA.

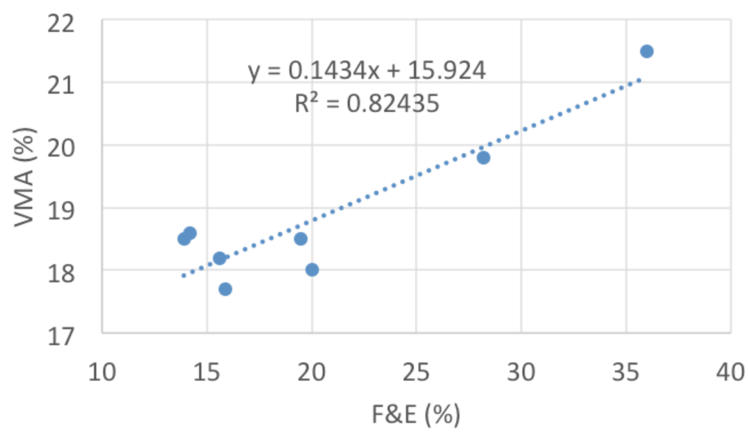

FIGURE 4 Effect of F&E on VMA Values

It is generally possible to reduce VMA and corresponding asphalt demand by changing the gradation. The result may vary depending on the mix, but generally the VMA for SMA mixtures can be reduced by increasing the percent passing the No. 4 sieve or the No. 200 sieve, or both. If the gradation is changed, VCA tests will need to be conducted to ensure stone-on-stone contact still exists for the coarse aggregate portion of the mixture.

3 PERFORMANCE TEST RESULTS

3.1 Cantabro Results for Stone Loss

The Cantabro abrasion test, AASHTO TP 108-14, is used to evaluate the cohesiveness of asphalt mixes and raveling resistance. The procedure requires placing individual compacted samples into an L.A. abrasion machine at 77 ± 2°F and rotating for 300 revolutions at 30-33 rpm. The steel balls normally used in the L.A. abrasion procedure are omitted for the Cantabro test. After the test is completed, the amount of stone loss is determined by comparing the difference in original and final mass. The results from this study show that all of the samples had relatively little stone loss (Figure 5). There is no specific maximum value of Cantabro stone loss for SMA mixes, but the maximum value for open-graded friction courses is typically 20%. Noticeably, the two sources with the highest F&E values also had the lowest Cantabro loss. This may be due to those sources also having the highest asphalt content, which would tend to keep samples more intact. These results follow a trend reported by Aho et al. that stated degradation due to wearing will not occur if the aggregate has less than about 40% F&E at the 3:1 ratio (*9*).

A two sample t-test was conducted to compare the nine compacted specimens made with SMA aggregate to the nine non-SMA aggregate specimens. A p-value of 0.951 was obtained, which indicates there is no significant difference in Cantabro performance for either SMA or non-SMA aggregates.

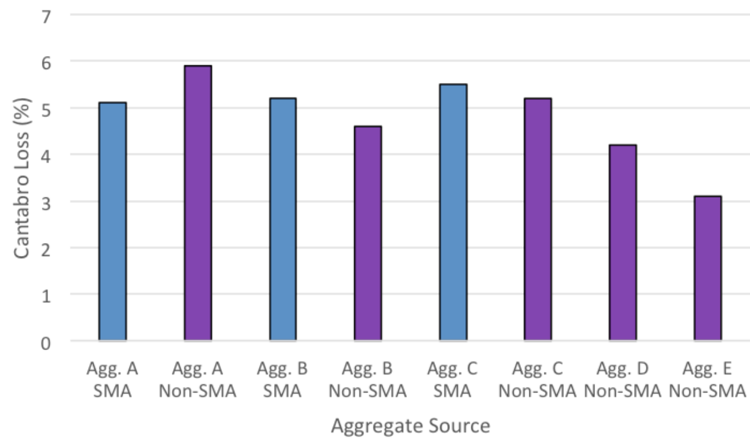

FIGURE 5 Cantabro Stone Loss Based on Aggregate Source

3.2 Rutting Susceptibility

Resistance to rutting was evaluated with the Asphalt Pavement Analyzer (APA) rutting test performed according to GDT 115, which requires samples be prepared at a 75 mm height with a target of 5% air voids. The test is conducted at 64°C and uses 100 lb. wheel load and 100 psi hose pressure. The test is conducted for 8,000 cycles and the maximum rut depth allowed is 5 mm. All results were within the 5 mm maximum specification limit, and a coefficient of determination shown in Figure 6 indicates no correlation between rut depth and percent F&E (R^2 = 0.06).

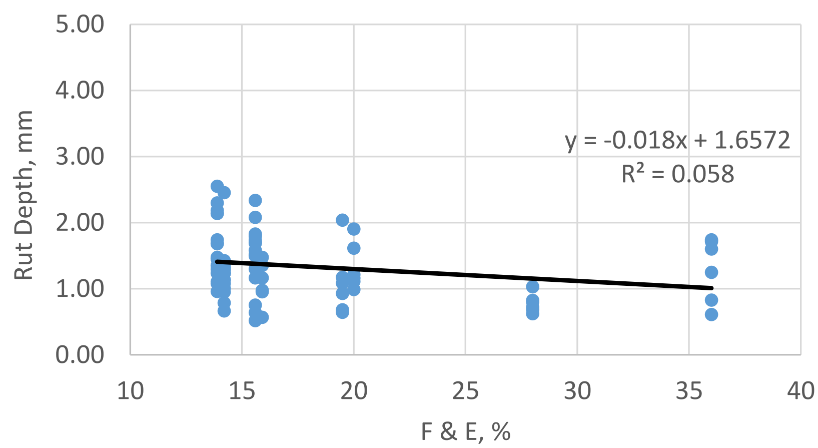

FIGURE 6 APA Rut Depth vs Percent F&E

3.3 Moisture Susceptibility

One concern regarding flat and elongated particles is that they may be detrimental to performance due to a potential for stripping. It has been suspected that F&E particles are more easily broken than cubical particles during production, placement, and compaction. Some agencies do not allow vibratory compactors to be used during the compaction process of SMA mixes for this reason. When aggregate particles are broken during construction, it not only changes the gradation but also exposes two aggregate particles (*13*). The fractured, uncoated particles will make it easier for moisture to penetrate the particle and initiate stripping of the asphalt film.

The moisture susceptibility of mixes produced with low and high F&E properties was determined based on GDT 66. The test varies slightly from AASHTO T283 as discussed earlier in the report. GDOT requires a minimum tensile splitting ratio (TSR) of 80% after conditioned samples have been vacuum saturated, subjected to a freeze/thaw cycle, and conditioned in a hot water bath. The freeze-thaw cycle is an accelerated aging procedure to simulate several years of environmental conditioning. A provision is made that the TSR value may be as low as 70% so long as all six specimens used in the moisture susceptibility testing have a minimum tensile strength of at least 100 psi. GDOT also requires a minimum average tensile strength of 60 psi for both wet and dry subsets.

A statistical evaluation of results showed that there was a significant difference in control tensile strength but not for conditioned strength or TSR values. However, the control strengths were higher for the non-SMA stone mixes and explain why the three highest F&E non-SMA aggregate sources had the lowest TSR values. The results, shown in Table 5, indicate that the tensile strength of SMA mixes is not adversely affected by aggregate F&E values. Similar results were reported in NCHRP 425, which showed that F&E variations had no effect on moisture susceptibility (*8*). A study of the effect of F&E aggregate particles on asphalt mix performance also indicated that there was no clear trend or relationship in respect to fatigue resistance based on F&E values; however, it was not unusual for fatigue resistance of mixes to increase as the percent F&E particles at the 3:1 ratio increased (*4*).

For each of the SMA aggregate mixes and one of the non-SMA aggregate mixes, the conditioned tensile strength was higher than the control strength. However, these results are not unusual when hydrated lime is used as an anti-strip additive with granite aggregate sources.

TABLE 5 Tensile Strength Results

Aggregate Source	**Agg. A SMA**	**Agg. A Non-SMA**	**Agg. B SMA**	**Agg. B Non-SMA**	**Agg. C SMA**	**Agg. C Non-SMA**	**Agg. D Non-SMA**	**Agg. E Non-SMA**
TS-Conditioned (psi)	88.3	89.9	78.3	92.6	85.1	84.7	76.4	77.1
TS-Control (psi)	79.4	104.8	72.5	93.7	78.8	77.6	85.2	86.4
TSR, % (≤ 80)	111.3	85.8	108.0	98.8	108.0	109.1	89.6	89.3

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This study did not have a source of aggregate with a combination of high F&E aggregate particles and high L.A. abrasion loss. For the limited aggregate sources evaluated, several conclusions can be made from this research, many of which support previous findings.

1. The 5:1 ratio of F&E particles did not discriminate well between the differences in F&E properties of various aggregates. The 3:1 ratio was much more sensitive to such differences.

2. Previous recommendations of no more than 20% F&E aggregate particles based on a 3:1 ratio were taken from European requirements for use with studded tires during winter operations. Those limitations appear to be unnecessarily restrictive based on satisfactory performance of mixes with high F&E aggregate particles in this study.
3. F&E aggregate properties should be considered with other properties, such as L.A. abrasion, in order to evaluate aggregate acceptability. Aggregates with high F&E values may perform well if they have low abrasion loss.
4. Aggregate breakdown on the No. 4 (4.75 mm) and No. 200 (0.075 mm) sieves is not significantly different between SMA and non-SMA stone and is thus not dependent on the percent F&E particles.
5. Aggregates with high F&E aggregate particles generally have higher VMA properties and may require higher binder content. The economics of producing mix with high asphalt content may limit the use of sources that have high F&E aggregate particles. Changes in gradation are typically used by designers to reduce VMA and asphalt demand.
6. There is no significant difference in Cantabro abrasion loss between SMA and non-SMA aggregate.
7. There is no correlation between rut depth and percent F&E particles. However, the differences in APA rut depth were statistically significant, with the non-SMA stone showing the greatest rutting resistance. All rutting values for both SMA and non-SMA stone were well within the 5 mm tolerance allowed by GDOT.
8. There was a statistically significant difference in control tensile strength values based on percent F&E. However, the control strengths were higher for non-SMA aggregates. Generally, the tensile strength of SMA mixes is not adversely affected by aggregate F&E values.

4.2 Recommendations

The maximum F&E limit (≤ 20% F&E at a 3:1 ratio) that is a standard threshold used by most agencies for SMA aggregate should be reconsidered based on satisfactory performance results of high F&E aggregates in this study. Similar research is needed for quarry sources that may have both high L.A. abrasion loss and a high proportion of F&E aggregate particles to determine if such sources can also provide satisfactory performance. It is recommended that Superpave F&E criteria required in AASHTO M323 at a 5:1 ratio be specified for SMA mixtures as well.

The results of this study were determined from laboratory-mixed and laboratory-compacted samples. Performance test results from plant-produced, field-compacted specimens may be different. It is recommended that field projects using SMA stone with higher proportions of F&E aggregate be evaluated for performance.

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