NCAT Report 00-03

EVALUATION OF THE EFFECT OF FLAT AND ELONGATED PARTICLES ON THE PERFORMANCE OF HOT MIX ASPHALT MIXTURES

By

M. Shane Buchanan

May 2000

National Center for Asphalt Technology
NCAT
AUBURN UNIVERSITY
277 Technology Parkway • Auburn, AL 36830

EVALUATION OF THE EFFECT OF FLAT AND ELONGATED PARTICLES ON THE PERFORMANCE OF HOT MIX ASPHALT MIXES

By

M. Shane Buchanan
Senior Research Associate
National Center for Asphalt Technology
Auburn University, Alabama

NCAT Report 00-03

May 2000

DISCLAIMER

ABSTRACT

Flat and elongated particles have long been considered undesirable in hot mix asphalt (HMA) mixes due to their tendency to break down during construction and traffic. Currently, the Superpave mix design system currently specifies a maximum limit of 10 percent of flat and elongated particles at the 5:1 ratio for the design aggregate blend. Very few coarse aggregate stockpiles will fail the current 10 percent requirement at a 5:1 ratio. Hence, many agencies have expressed an interest in evaluating the particle shape at a more stringent 3:1 ratio. Before the specification is changed to a 3:1 ratio the effect of the particle shape on performance should be evaluated.

Two aggregates (limestone and granite) were evaluated in their “as-received” state and in two other particle shapes (more cubical, less F&E) obtained from Vertical Shaft Impact (VSI) crushing. The laboratory evaluation included volumetric mix designs, wheel tracking, fatigue testing, and aggregate breakdown determination.

The results indicate that the particle shape of the aggregate may influence, to varying degrees, the coarse aggregate breakdown, the rutting susceptibility, and volumetric properties of compacted HMA mixes.

Key Words: Flat and elongated, Superpave mix design, hot mix asphalt, HMA, vertical shaft impact crushing

EVALUATION OF THE EFFECT OF FLAT AND ELONGATED PARTICLES ON THE PERFORMANCE OF HOT MIX ASPHALT MIXES

M. Shane Buchanan

INTRODUCTION AND PROBLEM STATEMENT

Currently, the flat and elongated specification used in the Superpave mix design system is provided in AASHTO MP-2: Standard Specification for Superpave Volumetric Mix Design (*1*) and states that the aggregate shall meet the shape requirements of ASTM D4791: Standard Method for Flat or Elongated Particles in Coarse Aggregate (*2*). The specification states that the value measured shall not exceed 10 percent. In the ASTM D4791 test procedure a particle's elongation is evaluated by comparing its length to width, and its flatness by comparing its width to thickness. With this test procedure it is possible to have aggregate particles which are flat, elongated, flat and elongated, or neither flat or elongated. However, in the Superpave mix design system, an aggregate particle is determined to be flat and elongated if the maximum (length) to minimum (thickness) dimension ratio is greater than five (*3*). This technique of measuring the shape of the particle is known simply as the flat and elongated measurement of an aggregate particle. The Superpave aggregate shape requirements specify that no more than 10 percent of the coarse aggregate retained on the 4.75 mm sieve be flat and elongated at a 5:1 ratio. The inclusion of the 4.75 mm material also differs slightly from ASTM 4791, which requires evaluation of the aggregate retained on the 9.5 mm sieve.

Flat-and-elongated particles are considered to be undesirable in HMA because they have a tendency to break or degrade during the construction process and under applied traffic. Generally, throughout the country, very few coarse aggregates will fail the flat and elongated specification at a 5:1 ratio. Therefore, some agencies believe that the requirement should be changed to an evaluation of the particle shape at a 3:1 ratio. The specification of 3:1 ratio is believed to better define flat-and-elongated particles than the current 5:1 ratio. This has been demonstrated in the recently completed NCHRP Project 4-19, "Aggregate Tests Related to Performance of Asphalt Concrete in Pavement."(*4*). If a change to the current F&E specification is considered in the future to use a 3:1 ratio, the first necessary step is to evaluate the effect of the aggregate's particle shape in HMA. Data should be obtained to determine if there is a significant difference in the performance of HMA mixtures at varying 3:1 ratios. If so, then the maximum allowable percentage of aggregate particles failing the 3:1 ratio requirement should be provided.

Past research conducted by Huber et al (*5*) evaluated a limestone aggregate at two distinct particle shapes. The different particle shapes in the study were obtained through cone and vertical shaft impact crushing operations, which yielded particle shapes of 19.4 percent and 9.0 percent 3:1 F&E, respectively. An evaluation of the volumetric properties showed no significant differences between the 19.4 and the 9.0 percent 3:1 F&E. Further, the authors stated that the Superpave gyratory compactor does not appear to be sensitive to slight to moderate changes in the particle shape of the coarse aggregate in the compacted mixes.

In research evaluating the particle shape for Stone Matrix Asphalt (SMA) mixes, Brown et al (*6*) evaluated a limestone aggregate from Arkansas which was crushed to provided two different particle shapes (A1 and A2, which were the high and low F&E percentage aggregates, respectively). The two aggregate shapes were blended in varying percentages to yield different F&E ratios for the total blend. The evaluated blends are provided in Table 1. Laboratory testing consisted of mix design, aggregate breakdown, and moisture susceptibility testing. The results indicated a slight trend (an increase of 1.2 percent from the 100 % A2 to the 100 % A1 Blend) of increasing VMA as the percent flat and elongated particles increased. Aggregate breakdown testing revealed that there was a significant amount of aggregate breakdown between the varying blends for the 4.75 mm sieve material, but no significant difference was observed for the 0.075 mm sieve material between the blends evaluated. Moisture susceptibility testing showed the varying percentages of 3:1 F&E did not significantly affect the retained tensile strength of the varying mixes. The research concluded that the requirement of a maximum of 20 percent 3:1 F&E aggregate was appropriate for SMA mix design specification requirements.

Table 1. F&E Blends Evaluated by Brown et al (*6*)

Mix Blend	Percent Flat and Elongated		
	2:1	3:1	5:1
100 % A1	67	25	1
100 % A2	38	3	0
75 % A1, 25 % A2	59	20	1
50 % A1, 50 % A2	52	14	0
25 % A1, 75 % A2	45	8	0

OBJECTIVES AND SCOPE

The objective of the study was to evaluate the effect of flat-and-elongated particles (based on a 3:1 ratio) on the mix design volumetric properties, rutting susceptibility, aggregate breakdown, and fatigue cracking potential of HMA mixtures.

TEST PLAN

A description of the test plan is provided in the following pages. In developing the test plan an effort was made to be practical in the research effort. By using commonly used materials and in the proportions often used, a greater confidence can be obtained from the research effort as it relates to everyday production and construction operations. The test plan is shown graphically in Figure 1.

Research Materials

Mineral Aggregate

Two commonly used aggregates in the Southeast were evaluated in the study. These aggregates consisted of an Alabama limestone and a North Carolina granite. Both the limestone and the granite aggregates were evaluated at varying 3:1 flat and elongated (F&E) percentages. This was accomplished by obtaining the “as-received” material (highest percentage of 3:1 F&E material) for each aggregate type and crushing the material in the laboratory to obtain more cubical particles. The crushing of the “as-received” material was accomplished through the use of a vertical shaft impact (VSI) crusher operating at rates of 55 and 65 meters/second (m/s) for the limestone aggregate and at 45 and 68 meters/second for the granite aggregate. A schematic of the VSI crusher similar to the one used for the study is provided in Figure 2. Vulcan Materials Company (VMC) and Svedala personnel are acknowledged for performing the crushing of both aggregates at VMC Technical Services Center located in Birmingham, Alabama.

A total of three distinctly different 3:1 percentages were obtained for both the limestone and the granite aggregate. All the material for each aggregate type was sampled at the same time; therefore reducing the chance for material variability within the quarry operation. The aggregate obtained was used in the gradation for the 4.75 mm material through the 12.5 mm material.

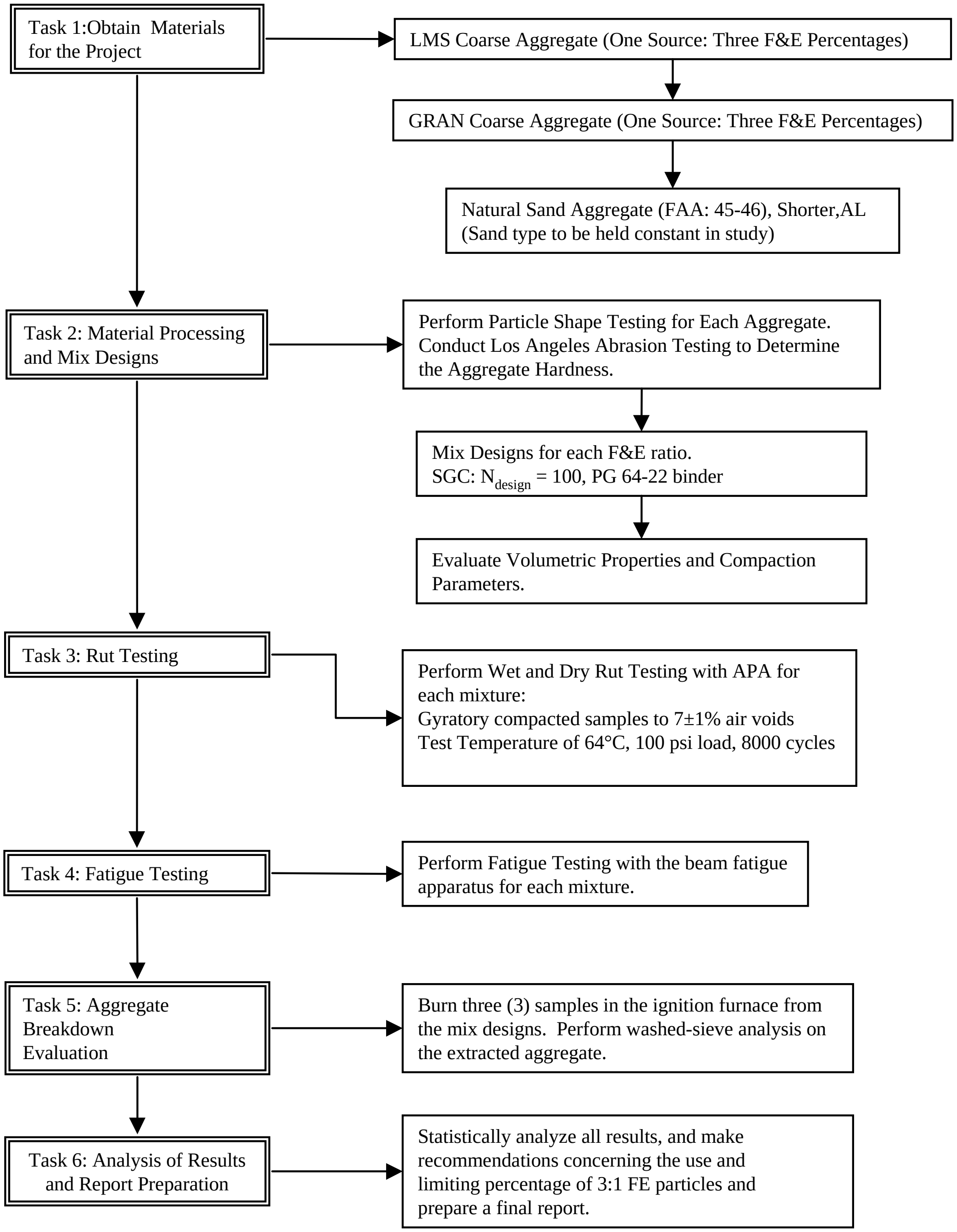


Figure 1. Study Test Plan

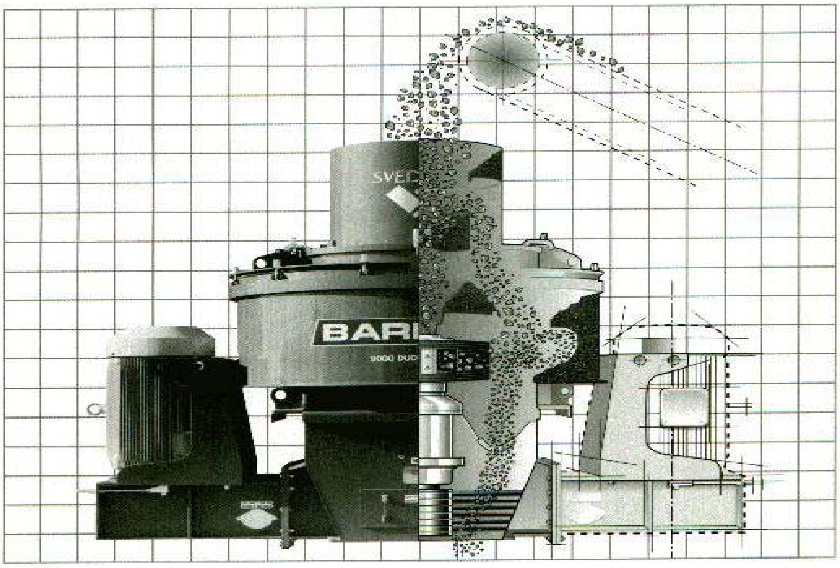


Figure 2. Vertical Shaft Impact (VSI) Crusher

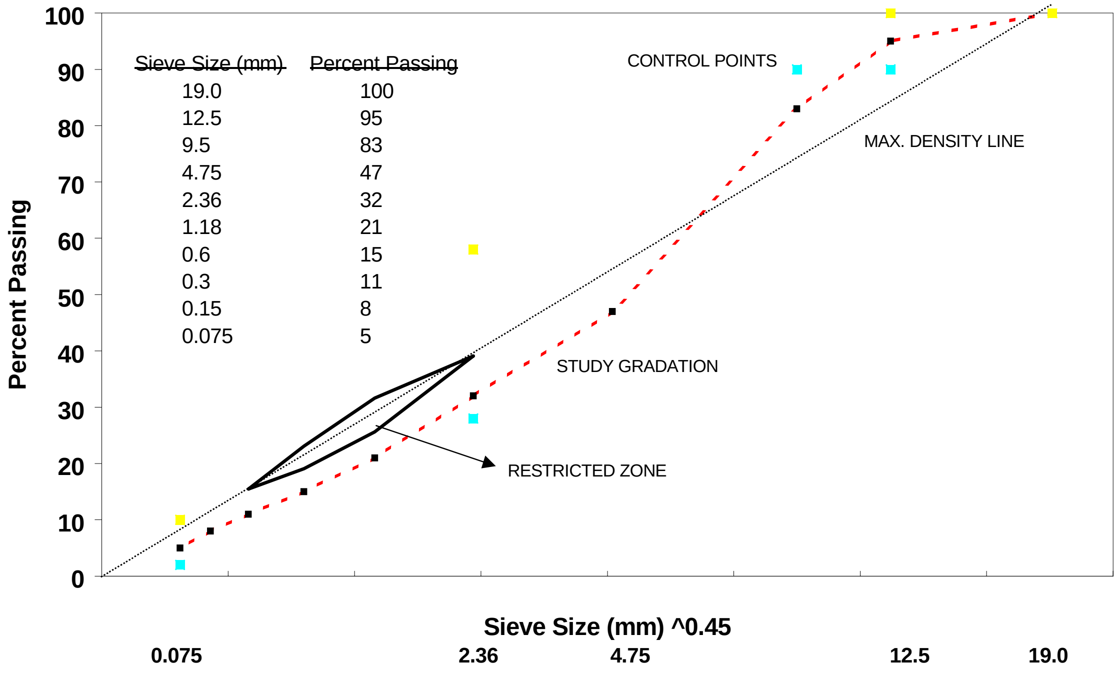
The fine aggregate used in the study was a natural sand from Shorter, Alabama. The sand had a fine aggregate angularity of 45. A material of this nature was used to best represent a material which may be realistically used in mixtures in the field. Using a material with an extremely low fine aggregate angularity value might enhance the effect of the coarse aggregate, but would not represent the majority of field conditions. Additionally, a natural sand was chosen instead of crushed limestone or granite fines in order to provide a neutral fine aggregate, not resulting from either of the parent aggregate types.

Gradation

In the project, a 12.5 mm nominal maximum size coarse-graded Superpave mixture, whose gradation is shown in Figure 3, was evaluated. The reason for using a coarse gradation of this type is twofold. First, the vast majority of Superpave mixtures designed to date have been coarse-graded, (below the restricted zone). Secondly, this type of gradation allowed for a greater amount of coarse aggregate to be present in the mixture. This resulted in a greater evaluation of the effect of coarse aggregate F&E particles on the performance properties of HMA. Each aggregate type was processed and then separate aggregate sizes were individually batched to increase the accuracy of the laboratory blend.

Asphalt Binder

The asphalt binder used for all of the study was a Performance Grade (PG) 64-22, which is the most commonly used asphalt binder in the Southeastern states.



Sieve Size (mm)	Percent Passing
19.0	100
12.5	95
9.5	83
4.75	47
2.36	32
1.18	21
0.6	15
0.3	11
0.15	8
0.075	5

Figure 3. Aggregate Gradation for the Study

PROJECT TESTING, RESULTS, AND ANALYSIS

Particle Shape Testing

Particle shape testing (F&E testing) was performed on each aggregate type at each crushing method. All samples tested were proportional to the same gradation as previously shown in Figure 8. The testing consisted of evaluating the flat, elongated, and F&E content at 2:1, 3:1, and 5:1 ratios. The results of the particle shape testing by mass for the limestone and the granite aggregates are shown in Tables 2 and 3, respectively. From Tables 2 and 3, it is seen that as the rotor tip speed of the VSI crusher was increased the limestone and granite aggregate became more cubical in shape. For the limestone the range of 3:1 F&E for the resulting blend ranged from 29.5 percent for the as-received (AR) material to 16.2 percent for the limestone crushed at 65 m/s. A greater difference was obtained for the granite aggregate, with the 3:1 F&E ranging from 57.0 percent for the as received to 2.1 percent for the granite crushed at 68 m/s. The difference in the obtained particle shapes is most likely attributable to the contrasting mineralogies of the two rock types.

Tables 2 and 3 show the differences in the amount of 5:1 F&E percentages for each of the aggregate types. As seen in Table 2, all the limestone aggregate samples evaluated had 5:1 F&E percentages which were less than the currently specified maximum limit of 10 percent. However, for the granite aggregate samples, as seen in Table 3, the “as-received” blend had a 5:1 F&E percentage of 23 percent. The granite crushed at 45 m/s and the 68 m/s had almost no material failing the 5:1 F&E ratio.

The data in Table 2 indicate that for the 2:1 and the 5:1 ratios, the percent F&E for the limestone increased after VSI crushing. This should not be the case in reality and the results are most likely a result of an insufficient number of samples being testing and possibly test variability to some degree.

Table 2. Particle Shape Testing Results for the Limestone Aggregates

Aggregate Type	Aggregate Size	F&E Ratios								
		2:1 Ratio			3:1 Ratio			5:1 Ratio		
		% Flat	% Elongated	% F&E	% Flat	% Elongated	% F&E	% Flat	% Elongated	% F&E
Limestone As-Received	12.5 mm	22.5	0.6	58.7	2.7	0.0	25.6	0.3	0.0	0.6
	9.5 mm	23.6	7.6	68.8	4.8	0.0	27.7	0.0	0.0	0.9
	4.75 mm	20.7	15.8	70.8	3.3	0.0	30.7	0.2	0.0	5.2
	BLEND	*21.5*	*12.5*	*69.2*	*3.6*	*0.0*	*29.5*	*0.2*	*0.0*	*3.8*
Limestone crushed @ 55 m/s	12.5 mm	22.5	0.6	58.7	2.7	0.0	25.6	0.3	0.0	0.6
	9.5 mm	11.0	1.9	53.0	0.2	0.0	17.7	0.2	0.0	0.2
	4.75 mm	23.2	2.1	60.6	1.4	0.0	22.7	0.0	0.0	0.2
	BLEND	*15.4*	*1.9*	*58.6*	*1.3*	*0.0*	*21.8*	*0.1*	*0.0*	*0.2*
Limestone crushed @ 65 m/s	12.5 mm	21.8	1.8	53.0	3.0	0.0	17.6	0.2	0.0	0.6
	9.5 mm	25.0	6.3	66.0	4.8	0.0	15.8	1.0	0.0	3.1
	4.75 mm	27.1	16.8	76.6	3.3	1.7	16.7	0.3	0.0	4.4
	BLEND	*26.1*	*13.0*	*72.0*	*3.6*	*1.2*	*16.2*	*0.5*	*0.0*	*3.7*

Table 3. Particle Shape Testing Results for the Granite Aggregates

Aggregate Type	Aggregate Size	F&E Ratios								
		2:1 Ratio			3:1 Ratio			5:1 Ratio		
		% Flat	% Elongated	% F&E	% Flat	% Elongated	% F&E	% Flat	% Elongated	% F&E
Granite As-Received	12.5 mm	29.0	4.4	56.0	10.0	0.0	16.0	0.4	0.0	1.6
	9.5 mm	47.6	9.4	80.9	13.6	0.8	43.2	1.2	0.0	20.0
	4.75 mm	45.2	32.3	91.8	18.6	2.2	67.2	4.4	0.0	27.0
	BLEND	*44.7*	*24.5*	*85.4*	*16.7*	*1.7*	*57.0*	*3.3*	*0.0*	*23.0*
Granite crushed @ 45 m/s	12.5 mm	29.0	4.4	56.0	10.0	0.0	16.0	0.4	0.0	1.6
	9.5 mm	6.8	0.6	32.2	0.0	0.0	12.4	0.0	0.0	0.0
	4.75 mm	5.6	2.0	44.6	0.0	0.0	14.8	0.0	0.0	0.3
	BLEND	*8.1*	*1.9*	*42.9*	*0.0*	*0.0*	*14.4*	*0.0*	*0.0*	*0.4*
Granite crushed @ 68 m/s	12.5 mm	29.0	4.4	56.0	10.0	0.0	16.0	0.4	0.0	1.6
	9.5 mm	4.0	2.0	20.8	0.0	0.0	0.7	0.0	0.0	0.0
	4.75 mm	7.0	0.0	37.0	0.0	0.0	0.6	0.0	0.0	0.0
	BLEND	*8.4*	*0.9*	*35.1*	*0.0*	*0.0*	*2.1*	*0.0*	*0.0*	*0.1*

Figures 4 and 5 further illustrate the difference in the particle shape of compacted and sawed mix samples comprised of the limestone and the granite aggregates. As mentioned previously, the particle shape of the limestone and the granite aggregate particles tend to become more cubical as the centrifugal velocity of the VSI crusher is increased.

Figure 4. Limestone F&E Blends

Figure 5. Granite F&E Blends

Toughness Determination

The toughness or hardness of each blend of aggregates at each particle shape was determined with the Los Angeles abrasion device. The results of the testing is found in Table 4. It appears from the results that the limestone and the granite materials tested were of approximately the same hardness. Also interesting, is an approximately 27 percent decrease in the abrasion value with the granite material from the “as-received” to the 45 m/s crush rate material. This does indicate that the abrasion value is influenced, to some degree, by the particle shape of the material being tested. A similar trend was evident with the limestone material.

Table 4. Toughness Results for the Study Aggregates

Aggregate Type	Los Angeles Abrasion Value	% 3:1 F&E
Limestone (As Received)	22	29.5
Limestone crushed @ 55 m/s	20	21.8
Limestone crushed @ 65 m/s	19	16.2
Granite (As Received)	26	57.0
Granite crushed @45 m/s	19	14.4
Granite crushed @ 68 m/s	19	2.1

Volumetric Mix Designs

Superpave volumetric mix designs were performed for each aggregate type at each of the 3:1 F&E percentages obtained. The mix designs were completed using the Superpave gyratory compactor at an N_{design} of 100 gyrations. This level of gyration has recently been recommended as the compactive effort for roadways with traffic volumes between 3 million and 30 million equivalent single axle loads (ESALs). Again, the design compactive effort was chosen to be as realistic to possible to real life mix designs and construction practices. The specimens were compacted to N_{design} and their volumetric properties determined. The volumetric properties used as response variables were air voids (Va), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). Additionally, the compaction parameters of $\%G_{mm}$ at $N_{initial}$ and the gyratory compaction slope measured from $N_{initial}$ to N_{design} were obtained for evaluation.

Volumetric Properties

The results of the mix designs for both aggregate types are provided in Table 5. Volumetric properties of the mixes with the limestone “as-received” and the limestone crushed at 65 m/s were found to be approximately the same, while mix properties with the limestone crushed at 55 m/s differed slightly. An explanation of this is not known, since the mix with limestone crushed at 55 m/s had a 3:1 F&E percentage which is between the limestone “as-received” and the limestone crushed at 65 m/s. This amount of difference could be attributed, in part, to the testing variability in the lab. This indicates that for the limestone mixes evaluated there were not significant changes in volumetric properties for 3:1 F&E percentages between 29.5 and 16.2 percent. These results for the limestone mixes show similar results as the past research conducted by Huber et al (5). Other research conducted by Brown et al (6), showed significant differences in the volumetric properties for limestone mixes with varying percentages of 3:1 F&E aggregates. However, the limestone mixes in that study (6) had a broader range of 3:1 F&E percentage (3 to 25 percent), as previously shown in Table 1, than the limestone mixes evaluated in this study.

When the percent 3:1 F&E is very high, significant differences do, however, exist between the granite mixes evaluated. A significant decrease in the optimum asphalt, voids in mineral aggregate, and voids filled with asphalt was seen between the granite “as-received” and the granite 45 m/s mixes.

A significant change in the VMA was observed from the granite “as-received” to the granite crushed at 45 m/s mix. This may be due in part to the orientation of the aggregate particles, which may have resulted in a greater total internal void space, thus requiring more asphalt cement to meet the design air void content. The total amount of surface area present was most likely greater for the "as-received" mix, which would also increase the required asphalt cement content.

Table 5. Volumetric Mix Design Properties and Gyratory Compaction Parameters

Mix Type	Volumetric Mix Design Response Variables				Gyratory Compaction Parameters	
	OAC	VMA	VFA	Dust/AC$_{eff}$	%G$_{mm}$ @N$_{initial}$	Compaction Slope (N$_{initial}$ to N$_{design}$)
Limestone (AR)	4.2	13.7	70.8	1.20	88.1	7.202
Limestone (55 m/s)	4.5	13.9	71.2	1.19	88.4	6.929
Limestone (65 m/s)	4.2	13.7	70.8	1.24	88.1	7.202
Granite (AR)	5.0	14.2	71.8	1.28	87.8	7.476
Granite (45 m/s)	4.6	13.4	70.1	1.25	88.4	6.929
Granite (68 m/s)	4.5	13.4	70.1	1.22	88.7	6.655

No significant difference in the volumetric properties between the mixes with the granite 45 crushed at 45 m/s and the granite crushed at 68 m/s mixes was evident. Based upon these results, it appears that there is an upper limit or value at which the percent of 3:1 F&E particles in a mix causes significant changes in the mix volumetric properties. Recall from Table 3 that the granite "as-received" and the granite crushed at 45 m/s had 3:1 F&E percentages of 57.0 and 14.4 percent, respectively. This is a range of over 40 percent, which makes it extremely difficult to determine what a limiting or upper value of 3:1 F&E should be for this particular aggregate and mix type.

There appears to be little difference between the volumetric properties of the mixes for granite crushed at 45 m/s and the granite crushed at 68 m/s, which had 3:1 F&E percentages of 14.4 and 2.1 percent, respectively.

It should be noted that 5 of the 6 mixes evaluated did not meet current Superpave volumetric criteria. Ideally, all mixes in the study would have met the criteria; however, the relative performance between the mixes with the same gradation was the intent of the study.

Gyratory Compaction Properties

By observation of the gyratory compaction parameters given in Table 5, the effect or non-effect of differing F&E particles can also be determined. For the limestone mixes there appears to be no significant difference between the mixes evaluated.

By observing the gyratory compaction parameters for granite "as-received" and the granite crushed at 45 m/s mixes, there is a increase in percent G$_{mm}$ at N$_{initial}$ from 87.8 to 88.4 percent. This indicates the mix with the granite "as-received" is not densifying as quickly and the mix with granite crushed at 45 m/s, possibly due to the high percentage of 3:1 F&E particles present. Additionally, the slope of the gyratory compaction curve from N$_{initial}$ (8 gyrations) to N$_{design}$ (100 gyrations) is greater for the mix with the granite "as-received" than for the mix with the mix with granite crushed at 45 m/s. Generally, it is thought that mixes with a steeper compaction slope tend to be more harsh or coarser than mixes with flatter slopes. It has been suggested by some that these mixes are slightly more difficult to compact during placement in the field. Thus, this may indicate that the field compaction of mixes comprised of a high percentage of 3:1 F&E particles may be more difficult than for a mix with a low percentage of 3:1 F&E particles.

Rut Testing

Once the optimum asphalt content (resulting in 4 percent air voids) for each of the mix designs was determined, the permanent deformation or rutting potential of the mixes was evaluated using the Asphalt Pavement Analyzer (APA), shown in Figure 6. This evaluation consisted of using gyratory specimens compacted to 7 ± 1 percent air voids at their respective optimum asphalt content and loaded with a 100 lb wheel load and a 100 psi hose pressure for 8000 loading cycles. The test temperature for all testing, both dry and wet, was 64/C, which is the high temperature PG classification of the asphalt binder. It was felt, and has been shown in past research, that testing specimens at lower temperatures would not adequately reflect the aggregate differences which may be present between the various mixtures. In other words, the asphalt binder seems to have the most control over the test results at lower test temperatures.

The testing of each mix type consisted of six gyratory specimens, with two specimens being combined together to form one replicate, thus providing three replicates per mix type for statistical analysis procedures. The Asphalt Pavement Analyzer test results for the limestone and the granite mixtures evaluated can be found in Tables 6 and 7, respectively.

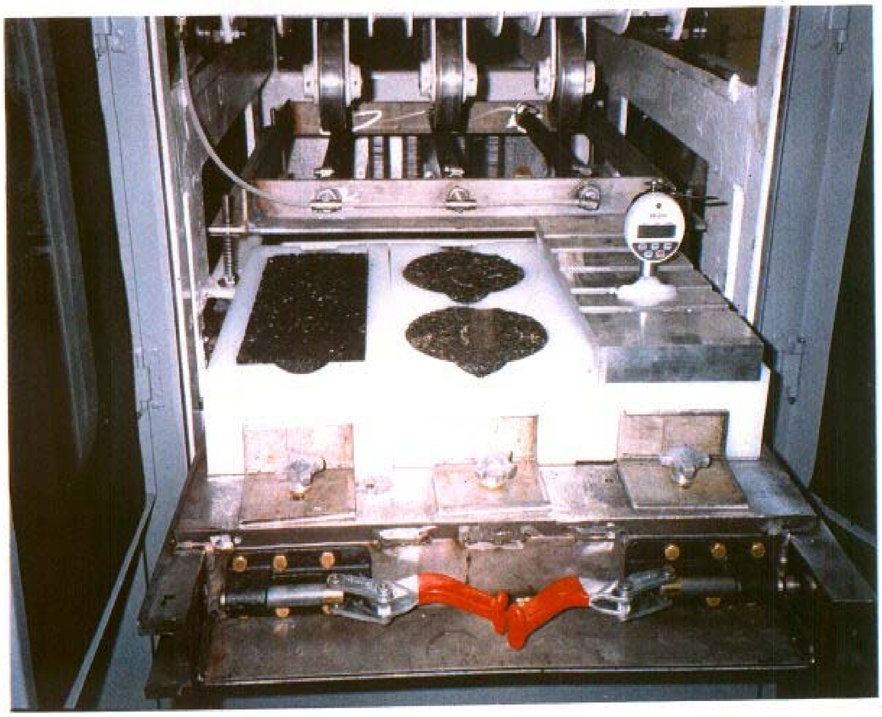


Figure 6. Asphalt Pavement Analyzer

Table 6. Rut Testing Results for the Limestone Aggregate Mixes

Mix Type	Asphalt Pavement Analyzer Average Results							
	Rut Depth, mm[1] (Dry)	Duncan's Statistical Ranking [2]	Slope (Dry) [3]	Duncan's Statistical Ranking	Rut Depth, mm (Wet)	Duncan's Statistical Ranking	Slope (Wet)	Duncan's Statistical Ranking
Limestone As- Received	5.900	A	3.288 E-4	A	5.265	A	2.380E-4	A
Limestone 55 m/s	6.638	A	3.412 E-4	A	5.163	A	2.773E-4	A
Limestone 65 m/s	6.197	A	3.792 E-4	A	5.047	A	2.623E-4	A

Notes: (1) Rut depth after 8000 cycles.
(2) Means with the same letter are not statistically different at a 95 percent confidence level.
(3) Slope (mm/cycles) between 4000 and 8000 cycles.

Table 7. Rut Testing Results for the Granite Aggregate Mixes

Mix Type	Asphalt Pavement Analyzer Average Results							
	Rut Depth, mm[1] (Dry)	Duncan's Statistical Ranking [2]	Slope (Dry) [3]	Duncan's Statistical Ranking	Rut Depth, mm (Wet)	Duncan's Statistical Ranking	Slope (Wet)	Duncan's Statistical Ranking
Granite As- Received	9.169	A	6.501 E-4	A	3.258	A	1.955 E-4	A
Granite 45 m/s	6.248	B	4.568 E-4	AB	3.703	A	1.509 E-4	A
Granite 68 m/s	6.058	B	3.581 E-4	B	3.094	A	1.251 E-4	A

Notes: (1) Rut depth after 8000 cycles.
(2) Means with the same letter are not statistically different at 95 percent confidence level.
(3) Slope between 4000 and 8000 cycles.

Additionally, Figures 7 and 8 illustrate the relationship between the percent 3:1 F&E particles and rut depth. The data from Table 6 and Figure 7 shows that the dry and wet rut depths and slopes for the limestone mixes are not statistically or practically different. This was somewhat expected, since the volumetric and gyratory compaction properties previously mentioned showed no significant difference for the limestone mixes, as well.

The test results for the granite aggregate mixes does show some statistical differences in the rutting characteristics of the mixes. From Table 7, it can be seen that statistical differences in the rut depth exist between mixes with the granite "as-received" and the granite crushed at 45 m/s, and in the rutting slope between mixes with the granite "as-received" and the granite crushed at 68 m/s. Figure 8 show a good relationship between mixes with the granite "as-received" and the granite crushed at 45 m/s and 68 m/s and the amount of rutting. As was the case with the volumetric mix design results, there appears to be an upper value of the percent 3:1 F&E particles in which the rutting susceptibility, as measured by the APA, increases.

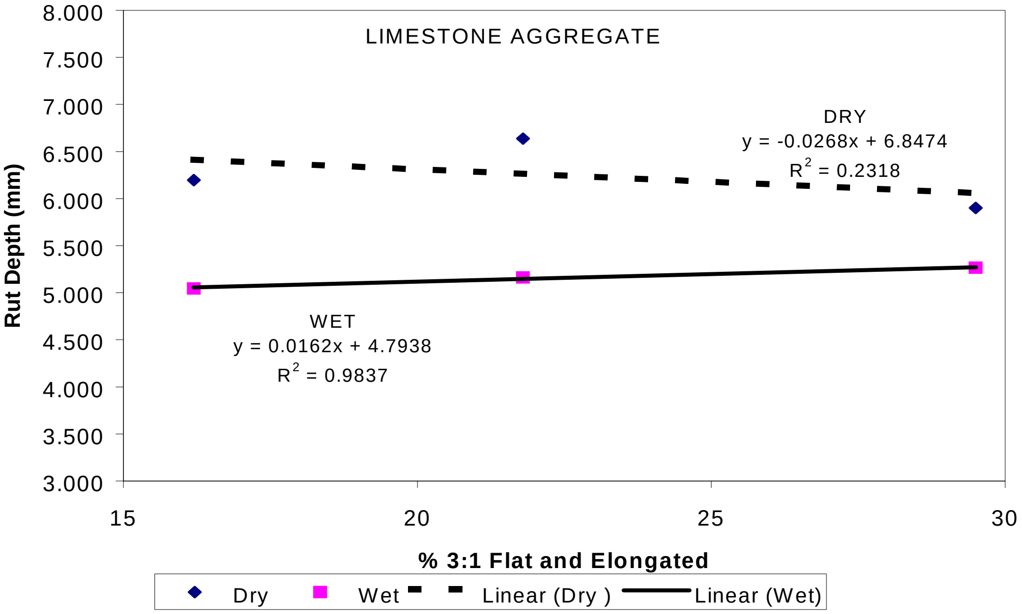


Figure 7. APA Rut Depths versus %3:1 F&E (Limestone Mixes)

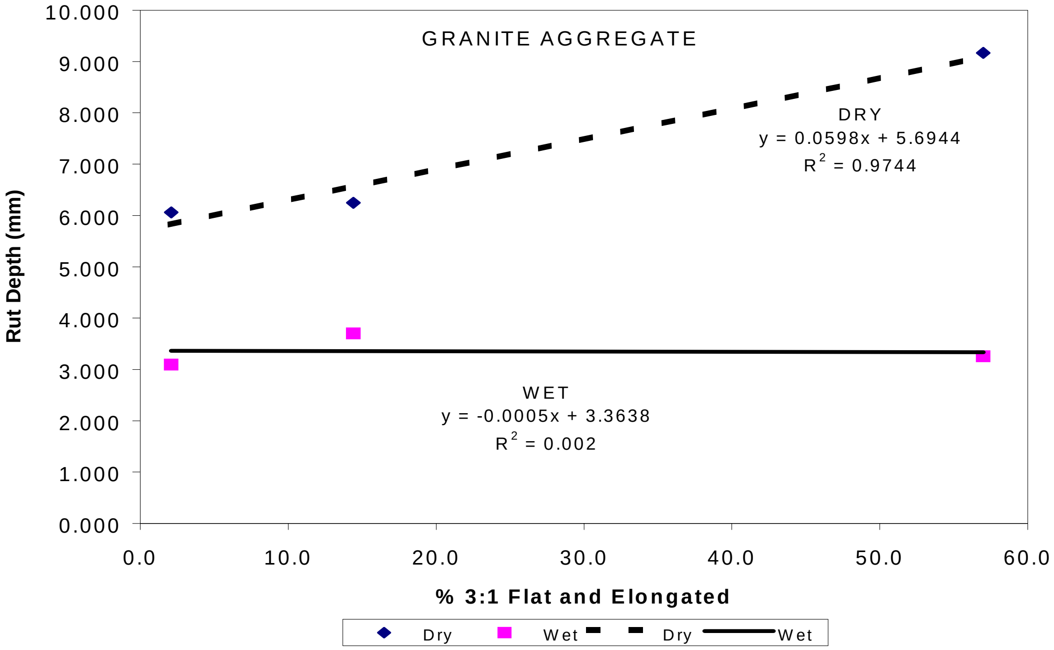


Figure 8. APA Rut Depths versus %3:1 F&E (Granite Mixes)

Interesting to notice is that the dry rut depths for both aggregates types is slightly higher than the wet rut depths. One would expect that by performing the test procedure under water would result in a greater rut depth than in the dry state when the samples are tested at the same temperature; 64/C in this case. An explanation for this occurrence is not readily obvious.

Fatigue Testing

The fatigue resistance of each of the mixes was evaluated by using the four point beam fatigue test procedure, which is described in AASHTO TP8 (*7*). The beam fatigue setup used for the study is shown in Figure 9. In this test procedure, beam specimens which are 380 mm in length, 50 mm in height, and 63 mm in width are tested under high and low strain conditions. High and low strains used in this evaluation were 600 and 300 :strains, respectively. The high and low strain testing was conducted at loading frequencies of 5 and 10 hz, respectively.

In the test procedure a vertical load is applied to the beam sample to achieve the desired testing tensile strain at the bottom of the beam sample. After the load is applied and the beam deflects, the beam is returned to the original position and the process repeated. A loading and returning of the sample to the original position is one loading cycle. At the outset of the test, the beam sample is loaded for 50 cycles and the initial beam stiffness is recorded. Testing continues on the sample until the beam stiffness decreased to 50 percent of the original stiffness value. The number of loading cycles at this point is referred to as the cycles to failure. Obviously, as the number of

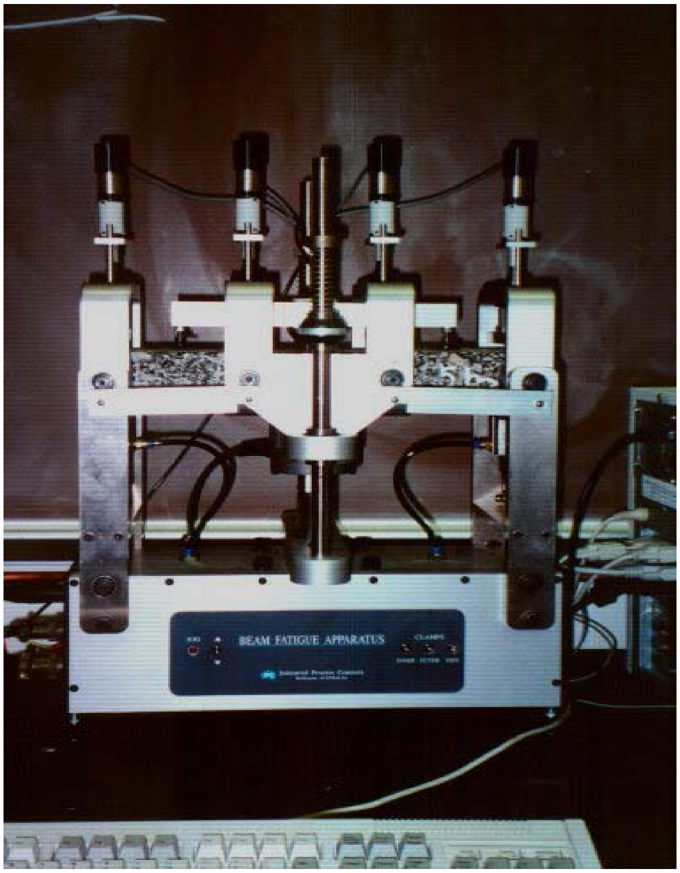


Figure 9. Beam Fatigue Device

cycles to failure increases, the fatigue life of the mix should also be expected to increase accordingly. Test results from the beam fatigue testing are provided in Table 8. Further, the relationship between the percent 3:1 F&E particles for the limestone and granite mixes at low and high tensile strain levels is shown in Figures 10 and 11. The results indicates that for both low and high strain testing the granite mixes exhibited a greater fatigue resistance than did the limestone mixes. This can possibly be attributed to many factors, but is most likely primarily a result of the increased effective asphalt content of the granite mixes. However, there does not appear to be a consistent trend or good relationship between the fatigue resistance of the limestone or the granite mixes with respect to the percent 3:1 F&E particles. Of the four possible relationships observed (two aggregates at high and low strain levels), three showed, in various degrees of confidence, an increase in the fatigue resistance of the mix as the percent 3:1 F&E particles increased.

Table 8. Average Beam Fatigue Testing Results

Mix Type	Strain Level (μs)	Cycles to Failure[1]	Initial Stiffness (MPa)[1]
LMS As-Received	300	175,655	4326
LMS Crushed at 55 m/s	300	226,880	4617
LMS Crushed at 65 m/s	300	147,795	4856
LMS As-Received	600	12,790	3538
LMS Crushed at 55 m/s	600	15,390	3431
LMS Crushed at 65 m/s	600	19,950	3373
GRN As-Received	300	364,290	4292
GRN Crushed at 45 m/s	300	357,895	1903
GRN Crushed at 68 m/s	300	336,095	3761
GRN As-Received	600	38,090	2074
GRN Crushed at 45 m/s	600	20,685	3223
GRN Crushed at 68 m/s	600	39,880	2213

Note: (1) Values shown represent the average of three test replicates.

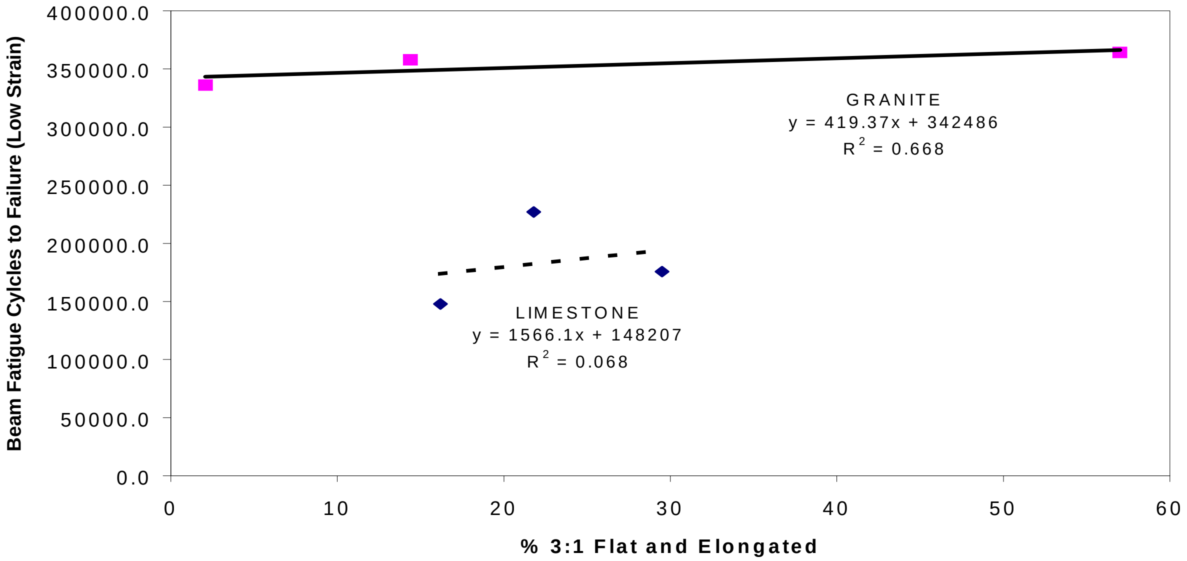


Figure 10. Beam Fatigue at Low Strain versus %3:1 F&E

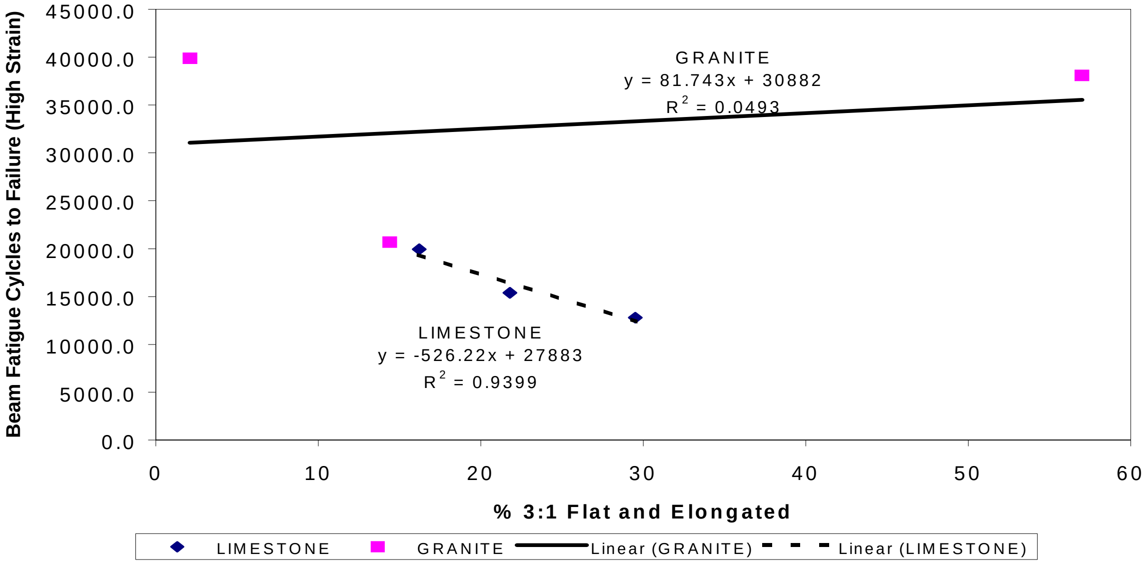


Figure 11. Beam Fatigue at High Strain versus %3:1 F&E

Aggregate Breakdown Determination

It is thought that material which is highly F&E will have a tendency to breakdown during field production and laydown operations. Aggregate breakdown in the laboratory was measured after compaction in the gyratory compactor. The amount of aggregate breakdown was determined for samples of each aggregate type and crush rate from the mix design procedures. Three specimens from each mix design were selected and the gradation of the extracted aggregate, from the ignition furnace, was determined by a washed sieve analysis, then compared to the batched gradation and the breakdown calculated. Some breakdown may be a result of the use of the ignition furnace, but the effect can be considered relative among each of the aggregate types evaluated.

The results of the breakdown testing are provided in Figures 12 and 13. For the limestone aggregate there is approximately three percent breakdown on the 4.75 mm sieve for all the mixes evaluated. There did not appear to be a good relationship for the limestone mixes between the amount of F&E particles and the amount of breakdown on the 4.75 mm sieve, as indicated by Figure 12. Again, this may be possibly attributable to the narrow range of F&E particles evaluated in the study. The amount of breakdown for the 0.075 mm sieve was approximately 0.7 percent for the limestone mixes with the breakdown not apparently dependent upon the varying F&E particles in the mixes evaluated.

More visible differences do exist with granite aggregate as shown in Figures 12 and 13. Figure 12 shows an strong relationship between the amount of F&E particles and the amount of breakdown on the 4.75 mm sieve for the granite mixes. This follows a similar trend reported in past research (6) in which the amount of aggregate breakdown was found to increase significantly with an increase in the percentage of 3:1 F&E aggregate.

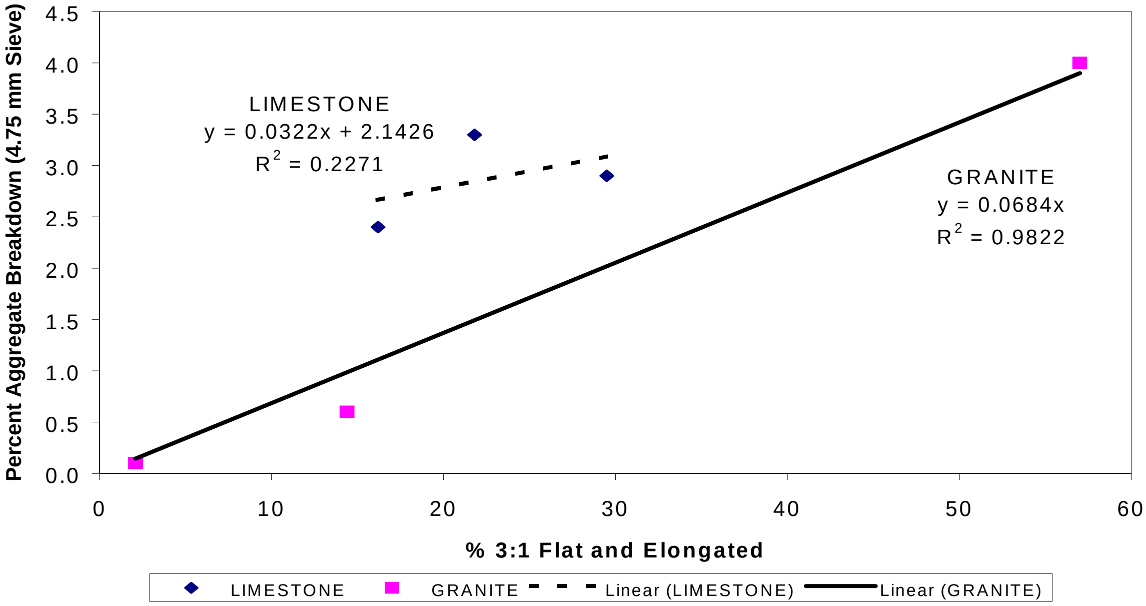


Figure 12. Aggregate Breakdown for the 4.75 mm Sieve

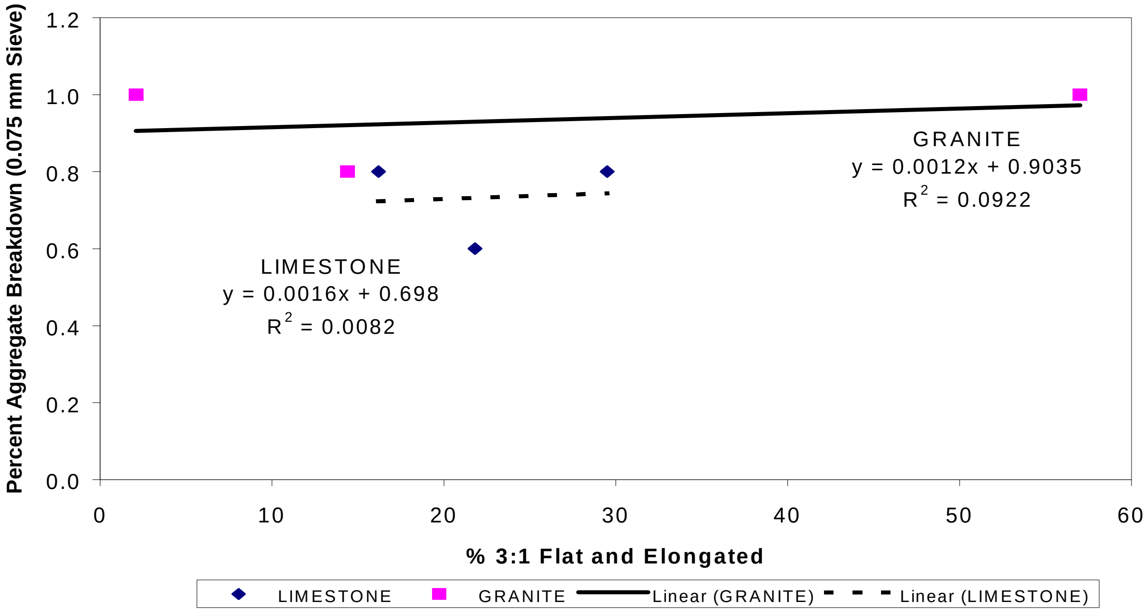


Figure 13. Aggregate Breakdown for the 0.075 mm Sieve

The results in Figure 13, of the breakdown on the 0.075 mm sieve show that there is an average of 0.9 percent for all the granite mixes, and relationship was not apparent. The fact that the amount of aggregate breakdown, for both the granite and the limestone mixes, on the 0.075 mm sieve was not significantly affected by the percentage of 3:1 F&E aggregate agrees with the results reported by Brown et al (6) for limestone mixes.

As with the previous test results the data, as a whole, indicates that there are not significant differences for the limestone mixes prepared with 3:1 F&E aggregates with percentages ranging from 29.5 to 16.2 percent. However, it once again appears that there is an upper limit or value for aggregate in which the mix properties become significantly different.

Recall from Table 4, that the L.A. abrasion values for the limestone and the granite aggregates ranged from the a maximum value of 26 to a low value of 19, which would indicate that both aggregates are high quality in terms of hardness or toughness. However, if the L.A. abrasion values of the aggregate were closer to 40 or 50, the results may have been different. This clearly should be further investigated because not only does the amount of F&E particles present in a mix determine the amount of breakdown, but to a great extent the hardness or toughness of the aggregates also plays a critical role.

OBSERVATIONS AND CONCLUSIONS

The overall objective of the study was to evaluate the effect of varying percentages of 3:1 F&E particles on the laboratory properties of hot mix asphalt mixes. After a review of the results the observations and conclusions provided below can be offered from the study. All conclusions regarding the limestone and the granite aggregate mixes apply to the range of the percentage of 3:1 F&E particles evaluated in the study, which were 29.5 to 16.2 percent and the 57.0 to 2.1 percent for the limestone and the granite mixes, respectively. Any extrapolation or estimation of the performance of the mixes with other 3:1 F&E percentages outside the ranges evaluated is not appropriate.

- The amount of aggregate breakdown on the 4.75 mm sieve was not dependent for either type of aggregate up to approximately 30 percent of 3:1 F&E particles. In the case when the 3:1 F&E was very high (57 percent for the granite "as-received"), the amount of breakdown was also high.
- The aggregate breakdown on the 0.075 mm sieve was approximately the same for the limestone and the granite mixes and was not dependent upon the percentage of 3:1 F&E particles.
- The amount of 3:1 F&E particles may significantly influence the volumetric properties of an HMA mixture if the percentage of 3:1 F&E particles exceeds approximately 30 percent. A limit between 30 and 50 percent may be appropriate, but was not defined by this limited study.
- The amount of rutting in the APA test for the limestone mixes was not significantly influenced by the varying percentages of 3:1 F&E. The amount of measured rutting in the APA test was approximately the same for all limestone mixes evaluated.
- A difference in rutting (dry state) was measured in the APA between the 57 percent 3:1 F&E granite mix and the 14.4 percent 3:1 F&E granite mix, but not between the 14.4 percent 3:1 F&E granite mix and the 2.1 percent 3:1 F&E granite mix.
- The percentage of 3:1 F&E had no significant effect on the fatigue characteristics of the mixes produced with the two aggregate types evaluated.
- The granite mixes showed a greater potential resistance to fatigue cracking than did the limestone mixes at low and high strain levels. This is most likely due to the increased effective asphalt content of the granite mixes.

RECOMMENDATIONS

The results obtained from this study can only be used as a base or starting point for a more extensive evaluation of the effect of particle shape on the HMA performance. If the amount of 3:1 F&E particles is excessive, significant differences in the laboratory properties of HMA mixes may be measured. The amount of 3:1 F&E did appear to influence the laboratory properties of the granite mixes evaluated in the study. However, as mentioned previously this difference existed between the 57 percent 3:1 F&E and the 14.4 percent 3:1 F&E range. This is a relatively broad range. It appears that an upper or limiting value of flat and elongated particles at the 3:1 ratio may be between 30 and 50 percent. However, additional testing will be required to further define this limiting value.

Further research should be conducted on a variety of aggregate types, F&E percentages, and hardnesses. It may be desirable to establish a F & E requirement which is dependent, in part, upon the hardness of the material being utilized for a given application, not just one requirement for all aggregate and mix types.

ACKNOWLEDGMENTS

This study was funded through the Southeastern Superpave Center by its member states.

REFERENCES

1. Standard Practice for *Superpave Volumetric Mix Design,* American Association of State Highway and Transportation Officials, AASHTO Designation: MP2-94, Edition 1A, Gaithersburg, MD, 1996.
2. Standard Method for Flat or Elongated Particles in Coarse Aggregate, American Society for Testing and Materials, ASTM Designation D4791.
3. Cominsky, R., Leahy, R. B., Leahy, and Harrigan, E. T., “Level One Mix Design: Materials Selection, Compaction, and Conditioning.” Strategic Highway Research Program Report No. A-408, National Research Council, Washington, D. C., 1994.
4. Parker, F., and Kandhal, P. S., “Aggregate Tests Related to the Performance of Hot Mix Asphalt,” Final Report for NCHRP 4-19, Transportation Research Board (TRB), 1998.
5. Huber, G. A., Jones, J. C., Messersmith, P. E., and Jackson, M. E., “Contribution of Fine Aggregate Angularity and Particle Shape to Superpave Mixture Performance,” Transportation Research Record 1609, TRB, National Research Council, Washington D.C., (1998), pp. 28-35.
6. Brown, E. R., Cooley, L. A., Haddock, J. E., Hughes, C. S., and Lynn, T. A., “Designing Stone Matrix Asphalt Mixtures Volume IV - Mixture Design Method, Construction Guidelines, and Quality Control Procedures,” Final Report for NCHRP 9-8, Transportation Research Board (TRB), 1998.
7. Standard Method for *Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending*, AASHTO Designation: TP8-97, Gaithersburg, MD, 1997.