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ABSTRACT

Two important factors for minimizing rutting of hot mix asphalt (HMA) mixtures are: a) the fractured face count of aggregate when gravel is used as coarse aggregate, and b) the use of manufactured sand. Both these factors relate to the shape and texture of the aggregate particles.

One of the objectives of this paper was to study the effect of crushed particle count on the particle shape and texture index (ASTM D3398) of gravel coarse aggregate and to determine if there is an upper limit on the crushed face count above which the particle shape and texture index of the coarse aggregate fraction would not increase significantly. A definite relationship was found to exist between the crushed face count and index of particle shape and texture of the coarse aggregate. Higher percentages of crushed particles increase the index of particle shape and texture significantly.

Highway agencies also limit the amount of natural sand in HMA mixes. This is usually done by generically specifying the maximum allowable percentage of natural sand. A total of 18 fine aggregates (8 natural and 10 manufactured sands) of different mineralogical compositions were used from various sources in Pennsylvania. Particle shape and texture data was obtained using ASTM D3398 and National Aggregate Association (NAA)'s two proposed methods. A particle index value of 14 based on ASTM D3398 appears to divide the natural and manufactured fine aggregates, and can be considered for specification purposes. Corresponding values for NAA's methods A and B are also reported. Test data also suggest that the major fraction particle index can be used in place of the weighted average particle index of the entire gradation when using ASTM D3398.

Good correlations are found to exist between NAA's methods A and B and ASTM D3398 suggesting that the NM methods, which are less time consuming can be adopted as standard test methods in lieu of ASTM D3398. Equations needed to compute ASTM D3398 weighted average particle index values from NAA methods' results are given. The difference between two orifice diameters for the NAA methods was not found to be statistically significant in determining the uncompacted void content of the fine aggregates. However, the 3/8-in. (9.5-mm) dia. orifice resulted in lesser variation compared to the l/2-in. (12.5-mm) orifice.

Natural and manufactured fine sands were blended in various proportions to study the effect using ASTM D3398. The particle shape and texture index decreases as higher percentages of natural sand are blended with the manufactured sand. There is no linear relationship, however.

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INTRODUCTION

Fractured face count of aggregate when natural gravel is used as coarse aggregate and the use of manufactured fine sand are considered important to minimize rutting of hot mix asphalt (HMA) pavements. Many highway agencies specify a minimum percentage of particles with two or more crushed faces when using gravel coarse aggregate in HMA mixtures. This percentage generally varies from 40 to 100 percent. There is a need to correlate the fractured face count with the index of particle shape and texture of coarse aggregate. It is also necessary to determine if there is an upper limit on the percentage of particles with two or more faces crushed above which there is no significant increase in the particle shape and texture index of coarse aggregate fraction. The latter is needed to achieve economy as the cost of increased crushing of the gravel aggregate can be high.

In addition, many highway agencies limit the amount of natural fine aggregate in HMA mixtures for heavy duty pavements. However, the use of generic terms such as *natural sand* or *manufactured sand in* specifications is not rational. There are natural sands which are subangular rather than being completely rounded. Similarly, not all manufactured sands are completely angular. There is a need to quantify the shape and texture of the fine aggregate in order to write the specifications on a more rational basis.

OBJECTIVES

This study was undertaken to achieve the following objectives:

1. Study the effect of crushed particle count on the particle shape and texture index of gravel coarse aggregate.
2. Determine if there is an upper limit on the crushed face count above which the particle shape and texture index of the coarse aggregate fraction does not increase significantly.
3. Study the effect of flat round particles on the index of shape and texture of round coarse aggregate particles.
4. Evaluate the particle shape and texture index of natural and manufactured (crushed) fine aggregates using ASTM D3398 (Index of Particle Shape and Texture), and National Aggregate Association (NAA)'s proposed methods.
5. Study how the particle shape and texture index of the mix varies when natural and manufactured fiie aggregates are blended in various proportions.
6. Study the effect of l/2-in. (12.5-mm) vs. 3/8-in. (9.5-mm) diameter orifices on the uncompacted void contents as determined by NAA's method.

REVIEW OF LITERATURE

Gravel Coarse Aggregate

Herrin and Goetz (*1*) studied the effect of aggregate shape on the strength of HMA mixtures using triaxial-compression test method. They concluded that an increase in the crushed gravel percentage in the coarse aggregate fraction resulted in an increase in strength of one-size mixtures but was of little importance in the dense-graded mixtures.

Significant increases in stability have been reported by Wedding and Gaynor (*2*) when crushed gravel was used in place of uncrushed natural gravel in an HMA mixture. About 45 percent increase in stability has been reported with the substitution of all crushed aggregate (crushed gravel coarse and fine aggregate) for natural sand and gravel.

Field (*3*) studied the influence of the percentage of crushed particles of the coarse aggregate in HMA mixtures. He reported that Marshall stability of an HMA mix changed little for 0 to 35 percent crushed particles and then increased consistently as the percentage of crushed particles was increased to 100 percent. The average stability was reported to be 55 percent higher for 100 percent crushed particles as compared to that with 35 percent crushed particles. Void content and VMA showed very little variation with the change in the percentage of crushed particles in the mix.

Campen and Smith (*4*) have reported an increase in stability of 30 to 190 percent by using crushed aggregate as compared to natural rounded aggregate in HMA mixtures. They measured the stability by Hubbard-Field and Bearing-Index tests.

Gaudette and Welke (*5*) have studied the effect of increasing percent crushed faces of coarse aggregate in an HMA mix. They have reported an increase in Marshall stability of 17 percent for 0 to 50 percent crushed particles, regardless of the number of crushed faces. After the 50 percent crushed point, however, the mixtures containing particles with 3 or more crushed faces continued to increase in stability while those containing one or two fractured faces tended to level off in stability.

The effect of different aggregate types on the aggregate void characteristics of bituminous paving mixtures has been studied by Griffhh and Kallas (*6*). They reported that mixtures containing natural gravel aggregates would generally require less asphalt than those containing crushed stone aggregates. This was attributed to the fact that natural gravels develop lower aggregate voids as compared to the crushed stone mixtures having the same gradation.

Maupin (*7*) has reported a laboratory investigation of the effect of particle shape on the fatigue behavior of an asphalt surface mixture. Three aggregates: round gravel, crushed limestone and slabby slate were used in that study. Constant strain mode fatigue tests were conducted and it was shown that the mixtures containing round gravel had longer fatigue life than those containing the other two type aggregates.

Fine Aggregate

Lottman and Goetz (*8*) have reported the effect of crushed gravel fine aggregate in improving the strength of dense-graded asphaltic surfacing mixtures. Shklarsky and Livneh (*9*) made a very extensive study of the difference between natural gravel and crushed stone aggregates in combination with natural sand and crushed stone fine aggregates. Several variables were studied including the Marshall stability and flow, angle of internal friction and cohesion as measured in triaxial shear, resistance to moving wheel loading resistance to splitting immersion-compression strengths, and permeability. They reported as follows:

> *Replacement of the natural sand with crushed fines improves incomparably the properties of the product, increases its stability, reduces rutting, improves water resistance, reduces bitumen sensitivity, increases the void ratio, and brings the mixture (with gravel coarse aggregate) to the quality level of one with crushed coarse and fine aggregate. Qn the other hand, replacement of the coarse material with crushed coarse aggregate entails no such decisive effect.*

Moore and Welke (*10*) performed Marshall mix designs on 110 sands from throughout the State of Michigan while keeping the coarse aggregate, asphalt content, and mineral filler constant. They have reported that both the angularity of the fine aggregate and the gradation of the mixture are critical for acquiring higher Marshall stabilities. The more angular the fine aggregate, the higher the stability. As for gradation, it has been reported that the closer the gradation was to the Fuller curve for maximum density, the higher was the stability. Rounded sands of relatively uniform size were reported to result in lower stabilities. Moreover, manufactured sands (slag or crusher sands) were found to have highly angular particle shapes and resulted in extremely high stabilities.

Foster (*11*) concluded, after observation of the performance of the test sections at the U.S. Army Corps of Engineers Waterways Experiment Station, that the true capacity of dense-graded mixes to resist traffic-induced stresses is controlled by the characteristics of fine aggregate.

Testing Methods

Various methods have been reported in the literature for evaluating the shape and texture of aggregate particles. These test methods can be divided generally into two broad categories: direct and indirect. Direct method may be defined as those wherein particle shape and texture are measured, described qualitatively and possibly quantified through direct measurement of individual particles. In indirect methods, measurement of the bulk properties of the fine aggregate are made separately or as mixed in the end product. The testing methods found in the literature are listed below. Details about each individual method may be found from appropriate references.

Direct Tests

a) Corps of Engineers' Method CRD-C120-55
b) LaughlirI Method (*12*)

Indirect Tests

a) ASTM D3398 - Standard Test Method for Index of Aggregate Particle Shape and Texture
b) National Aggregate Association's (NAA) Proposed Method of Test for Particle Shape and Texture of Fine Aggregate using Uncompacted Void Content
c) New Zealand Method (*13*)
d) National Crushed Stone Association (NCSA) Method (*14*)
e) Virginia Method (*15*)
f) National Sand and Gravel Association (NSGA) Method (*16*)
g) Ishai and Tons Method (*17*)
h) Specific Rugosity by Packing Volume (*18*)
i) Direct Shear Test

It is to be noted that ASTM D3398 is the only test method for determination of particle shape and texture that has been standardized. Efforts are currently underway to propose the NAA's methods A and B as ASTM standards.

MATERIALS

Several different materials were used during the entire study. The coarse aggregate used was a partially crushed natural gravel. The aggregate used was an AASHTO #57 mix. The bulk specific gravity and water absorption of the coarse aggregate as determined by ASTM C127 were 2.515 and 2.22 percent, respectively. Two size fractions were used: a) passing 3/4 in. (19 mm) and retained on 1/2 in. (12.5 mm) and b) passing 1/2 in. (12.5 mm) and retained on 3/8 in. (9.5 mm) sieve. The gravel was separated into uncrushed, l-face crushed and 2-face crushed particles. The crushed particles were colored before blending and then separated for reuse. The crushed and uncrushed gravel aggregates were then blended in the proportions shown in the first three columns of Table 3. Ten percent l-face crushed gravel particles were used in most blends because when any percentage of 2-face crushed particles is attempted there are always some (about 10 percent based on experience) l-face crushed particles produced in the crushing operation. Before reuse all aggregate particles were passed through either l/2-in. (12.5-mm) or 3/8-in. (9.5-mm) sieve, as needed, to remove any particles broken during the test.

In addition to the crushed gravel, a testing program using round and flattened BBs (round steel shots used in air rifles) was also attempted. BB's which originally were approximately 3/16-in. (4.8-mm) metal spheres were flattened by subjecting them to one or two blows of hammer to simulate flat rounded gravel particles which are not uncommon. The flattened BBs were on the average about half the thickness of the original BB's. The bulk specific gravity of the BBs used was 7.70.

A total of 27 different fine aggregates were used in this study. Nine of the fine aggregates were uncrushed natural sands while the rest were all crushed fine aggregates obtained from different stone types. Table 1 shows the source and type of aggregate, and their bulk specific gravity and water absorption data as obtained using ASTM C128. The fine aggregates used were obtained from various sources across Pennsylvania. As received gradations of the fine aggregates used are reported in Table 2.

TEST METHODS

Two test methods were primarily used during this study: a) ASTM D3398 and b) NAA's proposed methods A and B. A brief summary of the test methods and any deviations therefrom is given below.

ASTM D3398

This test method is for determining the Index of Aggregate Particle Shape and Texture. Three different size molds were used during this study. For the -3/4 + 1/2 in. (-19 + 12.5 mm) fraction of coarse aggregate, standard mold B was used while for the -1/2 + 3/8 in. (-12.5+ 9.5 mm) fraction, standard mold C was utilized. All the fine aggregates were tested using standard mold D. All the samples were washed on a No. 200 sieve and dried in the oven at 230±9°F(110±5°C). All the fine aggregates were then sieved to separate into individual size fractions using ASTM C136. The individual size fractions were then compacted in standard molds using 10 and 50 blows of the tamping rod to determine the voids and hence the particle index for each size fraction. For fine aggregates, the weighted particle index was then computed by averaging the particle index data for each size fraction, weighted on the basis of the percentage of the fractions in the original grading of the sample as received. This test method is very time consuming particularly for fine aggregates. If a fine aggregate has 5 fractions, each fraction has to be tested four times (two tests each with 10 and 50 blows) resulting into 20 tests. NAA Method A (which follows) requires only two tests on the combined fine aggregate.

Table 1. General Data for Fine Aggregates Used

No.	County	Type*	Agg. Code	Code Description	Bulk Sp. Gr.	Absorption
1	Crawford	N	GL	Gravel Sand	2.582	1.38
2	Ohio	N	GL	"	2.560	1.24
3	Erie	N	GL	"	2.587	1.26
4	Bucks	N	GL	"	2.556	1.59
5	Bucks	M	LS	Limestone	2.610	1.14
6	Warren	N	GL	Gravel Sand	2.580	0.98
7	Monroe	N	GL		2.570	2.32
8	Wyoming	N	GL		2.593	0.95
9	Westmonland	N	GL		2.564	1.26
10	Westmonland	M	SB	Blast Furnace Slag	2.430	4.33
11	Cumberland	M	SS	Sandstone	2.627	0.40
12	Fayette	M	CS	Calcareous Sandstone	2.670	0.27
13	Westmonland	M	CS-CG	Calcareous Sandstone Conglomerate	2.673	0.60
14	Perry	M	SL	Siltstone	2.648	0.96
15	Berks	M	DO-LS	Dolomitic Limestone	2.728	0.47
16	Northumberland	M	SS-CG	Sandstone Conglomerate	2.664	0.36
17	Bucks	M	AR	Argillite	2.660	0.52
18	Adams	M	BF	Hornfels	2.668	0.58
19	Monroe	M	LS	Limestone	2.722	1.26
20	Monroe	M	DO	Dolomite	2.692	0.58
21	Lycoming	M	LS	Limestone	2.693	0.77
22	Montour	M	BA	Bottom Ash (Cinders)	2.268	0.58
23	Snyder	M	I,S	Limestone	2.668	1.37
24	New York	N	GL	Gravel Sand	2.609	1.46
25	Berks	M	DO-LS	Dolomitic Limestone	2.756	0.45
26	Lancaster	M	DO	Dolomite	2.804	0.33
27	Lancaster	M	SR	Serpentine	2.558	1.56

* N = Natural Fine Aggregate; M = Manufactured Fine Aggregate

Table 2. As-Received Gradations for Fine Aggregates Used

No.	Type	Agg. Code	Percent Passing							
			3/8 in.	#4	#8	#16	30	#50	#100	#200
1	N	GL	100	96	80	63	43	15	4	1
2	N	GL	100	98	78	55	30	6	1	1
3	N	GL	100	95	78	62	46	26	9	3
4	N	GL	100	95	79	69	54	17	3	1
5	M	LS	100	100	78	39	18	8	5	4
6	N	GL	100	96	77	56	38	21	12	4
7	N	GL	100	96	77	58	36	19	8	2
8	N	GL	100	98	73	56	42	15	4	2
9	N	GL	100	98	70	50	37	20	4	1
10	M	SB	100	100	82	58	38	20	10	4
11	M	SS	100	99	86	70	50	26	7	1
12	M	CS	100	100	75	47	31	18	9	4
13	M	CS-CG	100	98	77	46	27	14	4	2
14	M	SL	100	100	73	42	24	14	9	5
15	M	DO-LS	100	100	84	45	26	15	8	3
16	M	SS-CG	100	100	85	50	32	16	8	3
17	M	AR	100	99	79	53	33	17	11	7
18	M	HF	100	100	88	57	31	16	8	5
19	M	LS	100	100	85	53	32	18	11	6
20	M	DO	100	100	81	50	29	15	8	4
21	M	LS	100	93	69	40	28	22	18	12
22	M	BA	100	97	76	51	36	25	15	7
23	M	LS	100	100	85	52	30	16	9	5
24	N	GL	100	99	87	72	55	22	6	2
25	M	DO-LS	100	100	81	50	29	16	8	3
26	M	DO	100	100	78	42	22	13	8	5
27	M	SR	100	100	74	48	32	20	12	6

* N = Natural Fine Aggregate; M = Manufactured Fine Aggregate

NAA's Method

In this study, both methods A and B of the proposed NAA's method for determining particle shape and texture of fine aggregate were used. In method A, the specified standard grading was used to make a 190 gram-sample by using the following quantities of dry sand from each size fraction:

Size Fraction	Weight, g
Passing No. 8 retained on No. 16	44
Passing No. 16 retained on No. 30	57
Passing No. 30 retained on No. 50	72
Passing No. 50 retained on No. 100	17
Total	190

For method B, 190 g of dry fine aggregate for each of the size fractions: passing No. 8 retained on No. 16, passing No. 16 retained on No. 30, and passing No. 30 retained on No. 50 was tested individually.

All the samples were dried in the oven at 230±9°F (110±5°C) before determining the void content. A standard 100-cm^3 cylinder was used. Two different orifice diameters were used during different stages of the test. These were 3/8 in. (9.5-mm) and 1/2 in. (12.5-mm), respectively. The sample was allowed to flow freely from the orifice of a conical funnel into the cylinder from a height of 4.5 inches (114 mm) above the base of the cylinder. For the graded sample (Method A), the uncompacted void contents so determined were used directly. For the individual fractions (Method B), the mean uncompacted void content was calculated based on the void contents for the individual size fractions.

TEST DATA AND DISCUSSION

The results obtained from the different phases of the study are discussed below.

Coarse Gravel Aggregate

The particle shape and texture index (I_a) data obtained by ASTM D3398 on coarse gravel aggregate is reported in Table 3. Variation of I_a values with increasing percentage of 2-face

Table 3. Particle Index Data for Coarse Gravel

Percent Uncrushed Particles	Percent 2-Face Crushed Particles	Percent 1-Face Crushed Particles	Average Particle Index for 3/4 + 1/2 in. Fraction	Average Particle Index for 1/2 + 3/8 in. Fraction
100	0	0	6.4	5.7
90	0	10	6.4	5.6
80	10	10	6.9	5.6
70	20	10	8.2	6.3
60	30	10	8.6	6.6
50	40	10	8.7	7.4
40	50	10	9.3	7.8
30	60	10	9.2	8.5
20	70	10	9.4	9.0
10	80	10	9.7	9.5
0	90	10	10.8	10.3
0	100	0	12.0	11.8

crushed particles is shown in Figures 1 and 2. For the larger size aggregate (-3/4+ 1/2 in. or -19+ 12.5 mm), as shown in Figure 1, there is a sharp increase in the value of I_a as the percentage of 2-face crushed particles increase from 0 to about 30 percent. After this there is a plateau till the 2-face crushed percentage of about 80 percent. For percentage of 2-face crushed particles more than 80 percent, the value of the I_a again increases sharply with the increase in percent 2-face crushed particles. Although a cubic polynomial is warranted for the situation, the increase in R^2 from linear (R^2 = 0.93) to cubic polynomial (R^2 = 0.99) fit is only 0.06.

For the smaller size coarse aggregate (-1/2 + 3/8 in.), as shown in Figure 2, the I_a value increases at a constant rate as the percentage of 2-face crushed particles in the blend increases. However, after about 80 percent 2-face crushed particles point there is a sharp increase in I_a value of the blend. The values of R^2 for the linear and second degree polynomial fits are 0.97 and 0.99, respectively.

Based on the data, it appears that the effect of crushed faces is more pronounced in the case of larger size aggregate. Moreover, theoretically, 100 percent crushed particles would be more preferable to use when employing gravel coarse aggregates in an HMA mix. However, the benefits that might be achieved by requiring the 2-face crushed count to be 100 percent should be weighed against the additional cost involved in the crushing operation.

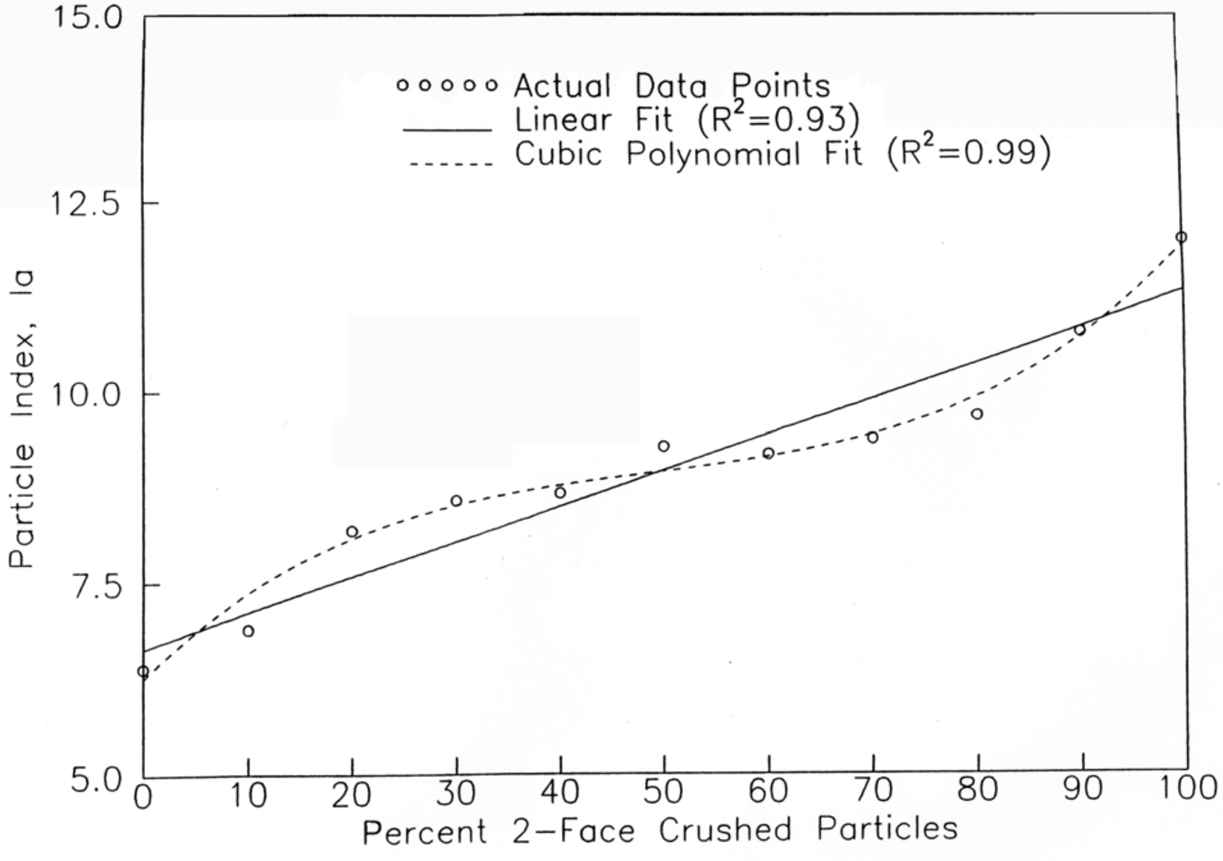

Figure 1. Correlation of Crushed Face Count with Particle Shape and Texture Index (Gravel -3/4 + 1/2 in.)

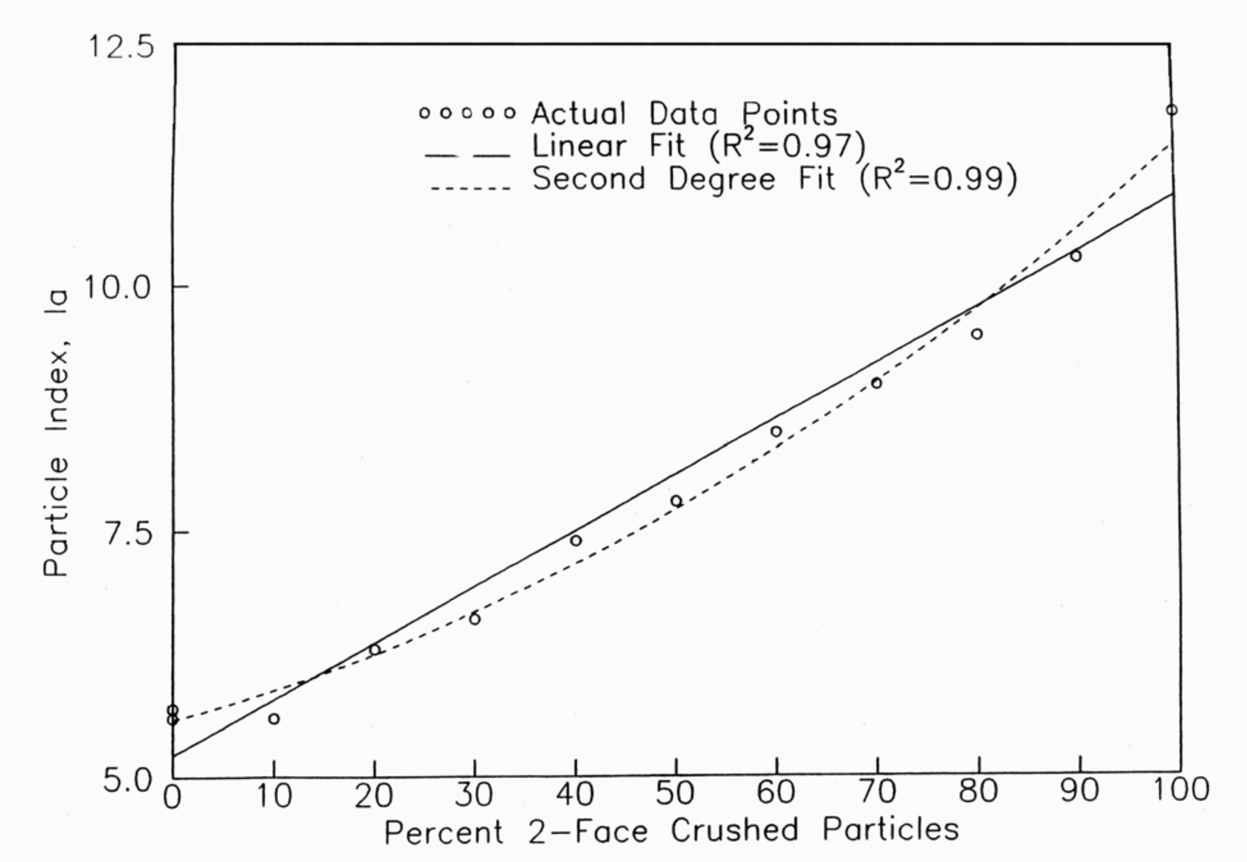

Figure 2. Correlation of Crushed Face Count with Particle Shape and Texture Index (Gravel -1/2 + 3.8 in.)

BBs As Aggregate

In addition to the coarse gravel aggregate, BBs were also used as aggregate to study the effect of particle shape. Original BBs which were spherical in shape were subjected to one or two blows of hammer to create flat rounded shape similar to some uncrushed flat gravel particles. The round and flat BBs were then blended in different proportions to test for particle shape and texture index using ASTM D3398. The results obtained are reported in Table 4. It is interesting to note that the I_a values in this case decrease consistently as the percentage of flat rounded particles in the blend increases. This is just opposite to what was observed for uncrushed and crushed gravel aggregate. No specific reason could be assigned to this behavior. However, the limited data presented here shows that flat round gravel coarse aggregate particles can be even more undesirable in an HMA aggregate blend compared to the almost round particles.

Natural and Manufactured Fine Aggregates

A total of 8 natural and 10 manufactured fine aggregates (first 18 fine aggregates listed in Tables 1 and 2) were tested during this phase of the study using both ASTM D3398 and NAA's methods A and B. The results obtained using ASTM D3398 are arranged in increasing order of 1. values and reported in Table 5. A histogram of the weighted average Ia values is shown in Figure 3. The data obtained for the same fine aggregates using NAA's methods A and B is also reported in Table 5 and the results shown in Figure 3. The findings from this phase of the study are individually discussed below.

Table 4. Particle Index Data for BBs Used as Aggregate

Percent Round BBs	Percent Flattened BBs	Particle Index
100	0	7.2
90	10	7.0
80	20	6.7
70	30	6.7
60	40	6.4
50	50	5.8
40	60	5.6
30	70	5.0
20	80	4.5
10	90	4.4
0	100	3.9

1. Difference between Natural and Manufactured Fine Aggregates

Except for one manufactured fine aggregate (Fine Aggregate No.5: limestone), all manufactured fine aggregates exhibit higher I_a values as compared to those for natural fine aggregates. An I_a value of 14 seems to separate the natural fine aggregates from the manufactured ones. The average I_a value for manufactured fine aggregates is 18.2 with a standard deviation of 2.72 giving the 95-percent confidence interval for I_a as 18.2±5.3 (12.9, 23.5). Similarly, the average I_a value for natural fine aggregates is 12.3 with a standard deviation of 1.26. This gives the 95-percent confidence interval for I_a as 12.3±2.5 (9.8, 14.8). Based on the 95-percent confidence intervals, both natural and manufactured fine aggregates are found to overlap in the I_a range of 12.9 to 14.8. Using trial and error procedures, it can be found that this overlap would cease to exist at a confidence level of 86 percent, resulting in a dividing value of I_a of 14.1 which is pretty close to the value of 14 as estimated by just looking at Figure 3. A minimum value of particle shape and texture index using the ASTM D3398 method can thus be used in specifications in lieu of specifying manufactured fine aggregate generically.

Similar trends are observed for data obtained using NAA's methods A and B as shown in Figure 3. Following the same procedure as for ASTM D3398 data, the values of uncompacted void contents using the NAA's methods A and B are found to be 44.5 and 48.4 at confidence levels of 82 and 84 percent, respectively. The difference between the uncompacted void contents obtained by the two methods appears to be reasonably uniform.

2. Evaluation of ASTM D3398

Because of the time-consuming nature of the ASTM D3398 procedure as mentioned earlier, alternative approaches were sought during this study. Correlations were run between the average particle index obtained using ASTM D3398 and the particle indexes for the individual major, and major plus second major fractions to see if these could be used instead. As shown in Figure 4, very good correlation was found to exist between the average and major fraction 1, values ($R^2 = 0.96$) and average and major plus second major fraction I_a values ($R^2 = 0.98$). This indicates that the major fraction I_a. can be used in place of the average I_a values to save time when using the ASTM D3398 method. If higher accuracy is desired, then both major and second major fractions can be tested and the weighted average I_a used instead of the average I_a for the entire gradation.

Table 5. Particle Shape and Texture Data on Natural and Manufactured Fine Aggregates

S.No.	**Type***	**Type of Aggregate**	**Particle Index (I_a) using ASTM D3398 for Sieve Fraction**								**Weighted Average Particle Index**	**Uncompacted Void Content using NAA's Method**	
			-3/8" + #4	**-#4 + #8**	**-#8 + #16**	**-#16 + #30**	**-#30 + #50**	**-#50 + #100**	**-#100 + #200**	**-#200**		**A**	**B**
1	N	GL	8.9	8.9	9.3	10.5	10.6	11.0	11.0	11.0	10.1	40.6	43.9
2	N	GL	10.6	10.6	11.2	10.1	9.8	11.2	11.2	11.2	10.5	40.2	43.5
3	N	GL	11.1	12.0	13.1	13.4	12.7	12.3	12.3	12.3	12.6	42.2	47.5
4	N	GL	11.7	13.8	13.5	12.2	11.9	13.4	13.4	13.4	12.6	42.7	46.0
5	M	LS	12.5	12.5	12.7	12.7	13.3	13.3	13.3	13.3	12.8	43.1	47.5
6	N	GL	9.3	10.0	13.4	13.5	13.2	14.9	15.5	15.5	13.0	43.9	46.6
7	N	GL	11.7	12.4	12.2	13.0	13.9	13.8	13.8	13.8	13.0	43.8	46.9
8	N	GL	11.3	11.3	14.8	14.9	12.5	13.8	13.8	13.8	13.1	42.4	46.3
9	N	GL	11.3	11.3	15.4	15.2	12.8	14.1	14.1	14.1	13.4	44.3	47.8
10	M	SB	16.1	16.1	15.2	13.1	14.5	16.0	16.0	16.0	15.0	45.4	49.0
11	M	SS	16.9	16.9	17.1	16.2	15.5	16.5	16.5	16.5	16.4	45.7	48.8
12	M	CS	--	17.8	19.5	20.1	17.2	16.2	16.2	16.2	18.3	48.5	52.7
13	M	CS-CG	19.7	19.7	19.9	19.0	17.4	16.3	16.3	16.3	18.9	47.7	52.3
14	M	SL	19.0	19.0	18.8	19.1	19.8	20.8	20.8	20.8	19.3	48.7	52.6
15	M	DO-LS	20.3	20.3	19.8	18.9	18.6	18.7	18.7	18.7	19.4	49.2	53.2
16	M	SS-CG	--	18.8	19.7	20.2	20.1	21.3	21.3	21.3	20.0	49.0	53.5
17	M	AR	20.5	20.5	21.6	21.0	20.0	21.6	21.6	21.6	21.0	50.9	54.7
18	M	HF	19.8	19.8	20.6	22.0	22.1	22.1	22.1	22.1	21.3	52.0	55.0

* N = Natural Fine Aggregate; M = Manufactured Fine Aggregate

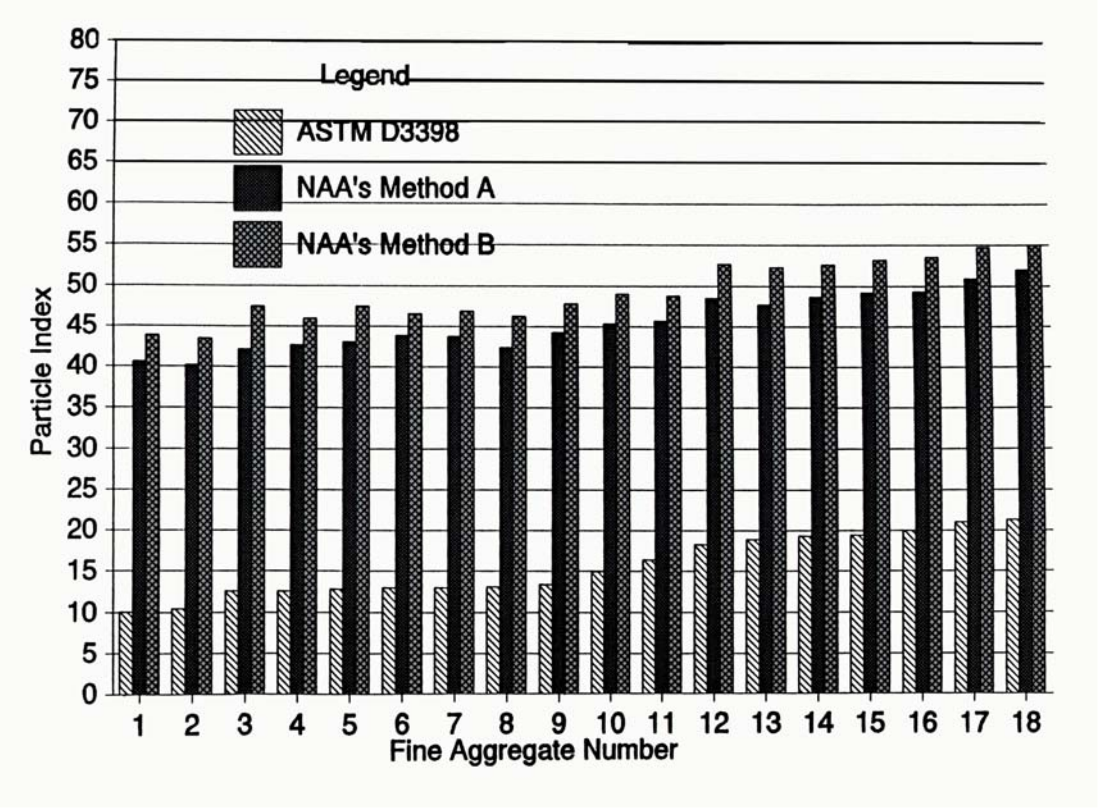

Figure 3. Particle Index Using ASTM D3398 and NAA's Proposed Methods A & B

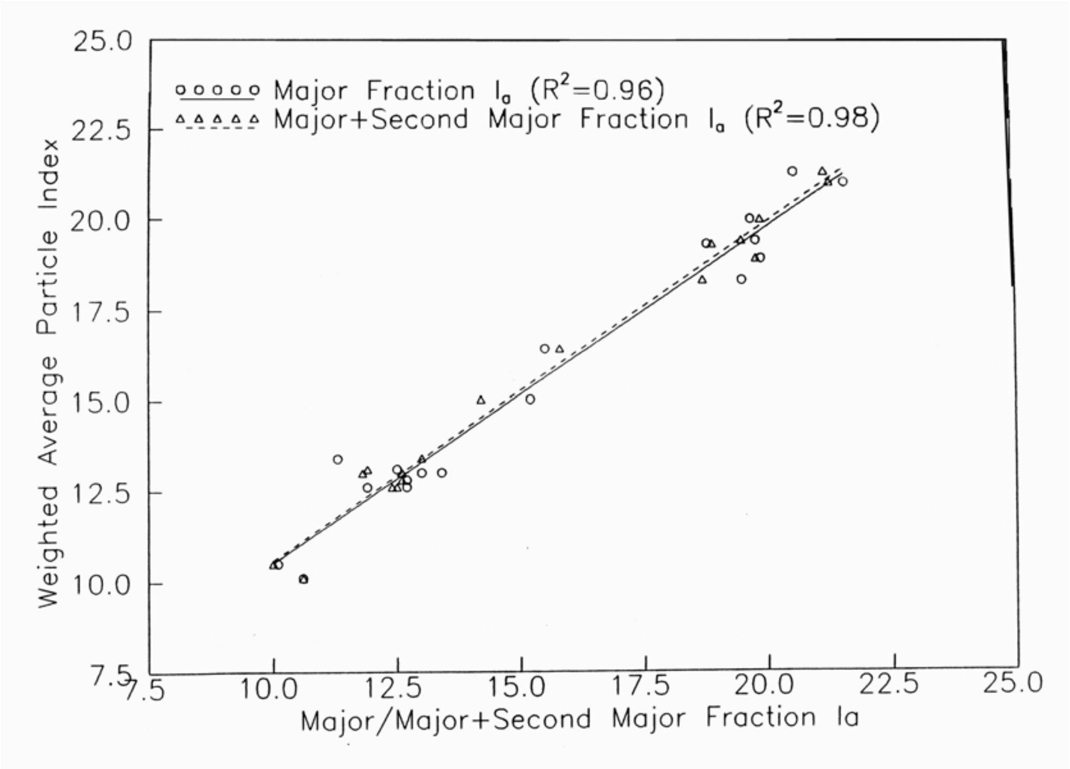

Figure 4. Weighted Average Particle Index vs. Major, Major Plus Second Major Fraction Particle Index

3. Comparison of ASTM D3398 and NAA Methods

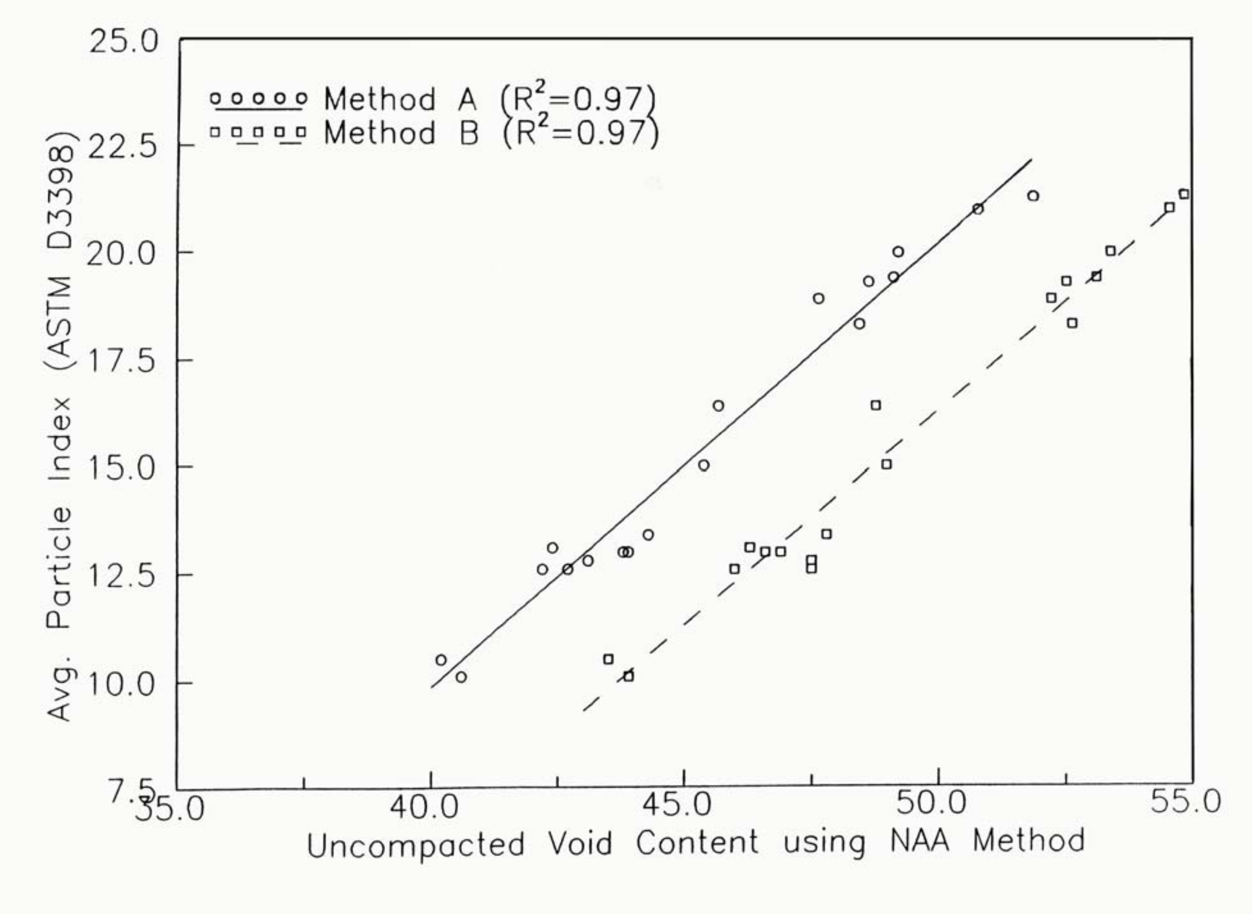

Figure 5. Average Particle Index Using ASTM D3398 vs. Uncompacted Void Contents Using NAA's Methods A & B

Data obtained using NAA's methods A and B were correlated with the weighted average I_a data obtained using the ASTM D3398 method. These correlations are depicted in Figure 5. The R^2 value for both methods A and B is found to be 0.97. The equations for transforming the NAA method results to the ASTM D3398 results are given below.

$I_a = 1.03V_{NAA}-31.2$ for Method A

$I_a = 1.00V_{NAA}-33.5$ for Method B

where V_{NAA} is uncompacted void content obtained by NAA methods.

Aggregate Blends

Eight of the above 18 aggregates were selected to study the effect of blending the natural fine aggregates with the manufactured ones. The aggregates selected for this purpose fall into one of the following four categories:

1. Low I_a natural fine aggregate (LIN)
2. Low I_a manufactured fine aggregate (LIM)
3. High I_a natural fine aggregate (HIN)
4. High I_a manufactured fine aggregate (HIM)

The blending was done according to the following scheme. The aggregates used for each combination are also indicated in parentheses:

1. LIN with HIM (Fine Aggregates No. 1 & 18)
2. LIN with LIM (Fine Aggregates No. 2 & 11)
3. HIN with HIM (Fine Aggregates No. 9 & 17)
4. HIN with LIM (Fine Aggregates No. 8 & 12)

Due to scarcity of the material, the same type material could not be used twice. Moreover, only one size fraction was tested (i.e., passing the No. 8 sieve and retained on the No. 16 sieve). The blending was performed with the following percentages of natural and manufactured fine aggregates, respectively: 0:100, 20:80, 30:70, 40:60, 50:50, 75:25, 100:0. All the blends were then tested using ASTM D3398.

Data from this phase of the study is presented in Table 6. It is observed that as the percentage of natural fine aggregate in the blend increases, the particle index (I_a) of the blend decreases. This is also shown graphically in Figures 6 to 9. It is seen that the variation of I_a with no natural sand in the blend to 100 percent natural sand is not linear. The curves are slightly concave upwards with the intermediate points almost invariably below a line projected from 0 percent natural sand to 100 percent natural sand. This pull down effect is more pronounced at lower percentages of natural sand in the blend. The best combination of the four blends, where the pull down effect is the least, is evidenced when a high I_a natural fine aggregate (HIN) is mixed with a low I_a manufactured fine aggregate (LIM) as shown in Figure 9. On the other hand, the worst of the four is seen to be the blend of a high I_a natural fine aggregate (HIN) with a high I_a manufactured fine aggregate (HIM) with a significant pull down as shown in Figure 8.

Table 6. Particle Index Data for Fine Aggregate Blends

Aggregate* Blend	**Percent of Natural Fine Aggregate in the Blend**						
	0	**20**	**30**	**40**	**50**	**75**	**100**
LIN + HIM	20.6	17.8	16.8	15.5	14.6	12.3	9.3
LIN + LIM	17.1	15.4	14.5	14.1	13.8	12.5	11.2
HIN + HIM	21.6	19.0	18.4	17.9	17.5	16.3	15.4
HIN + LIM	19.5	18.5	17.7	17.3	16.9	16.2	14.8

* LIN = Low I_a natural sand
LIM = Low I_a manufactured sand
HIN = High I_a natural sand
HIM = High I_a manufactured sand

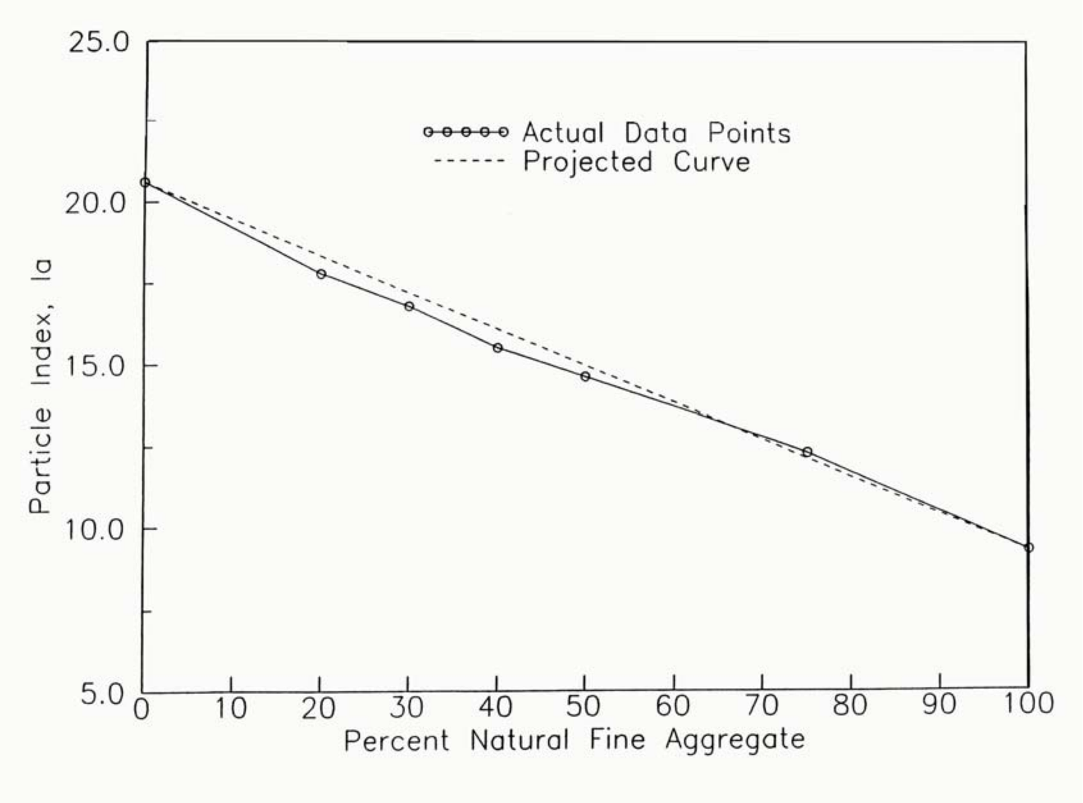

Figure 6. Variation in Particle Shape and Texture of Blend with Increase in Percent Natural Sand (LIN vs. HIM)

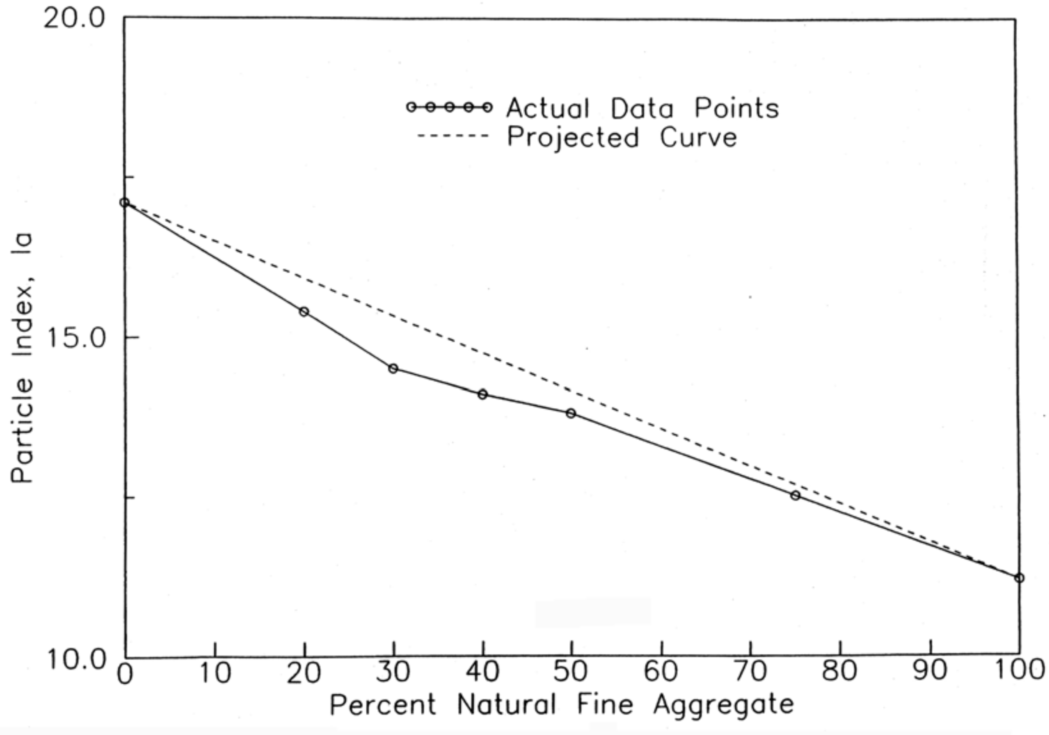

Figure 7. Variation in Particle Shape and Texture of Blend with Increase in Percent Natural Sand (LIN vs. LIM)

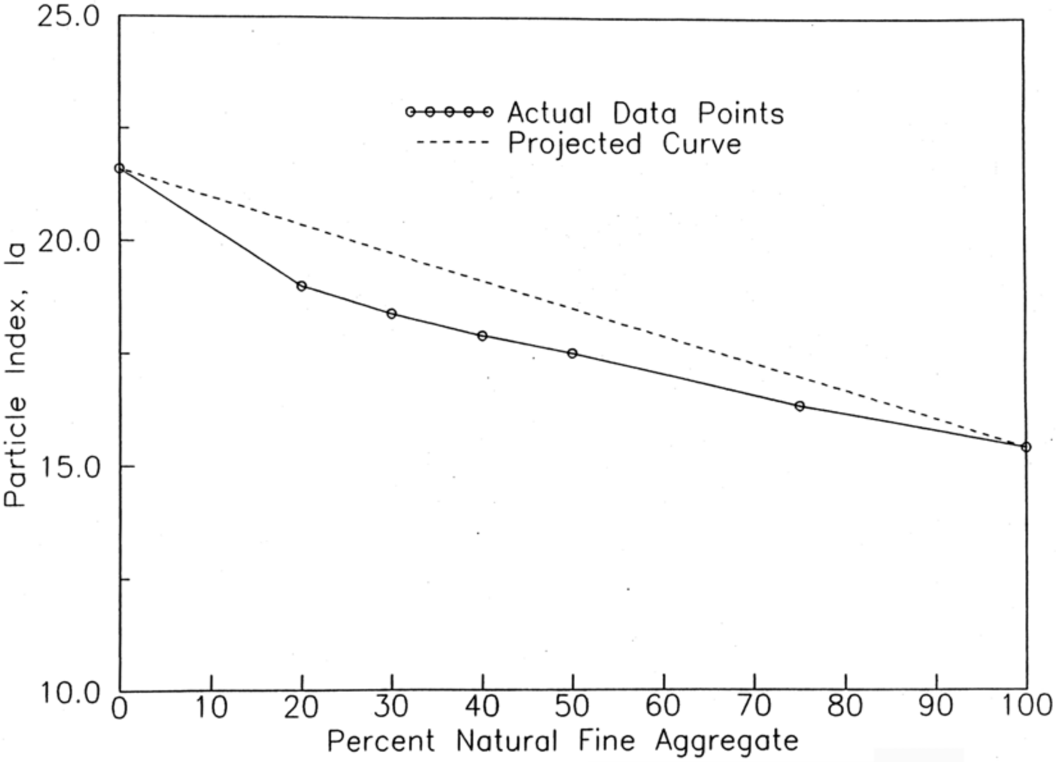

Figure 8. Variation in Particle Shape and Texture of Blend with Increase in Percent Natural Sand (HIN vs. HIM)

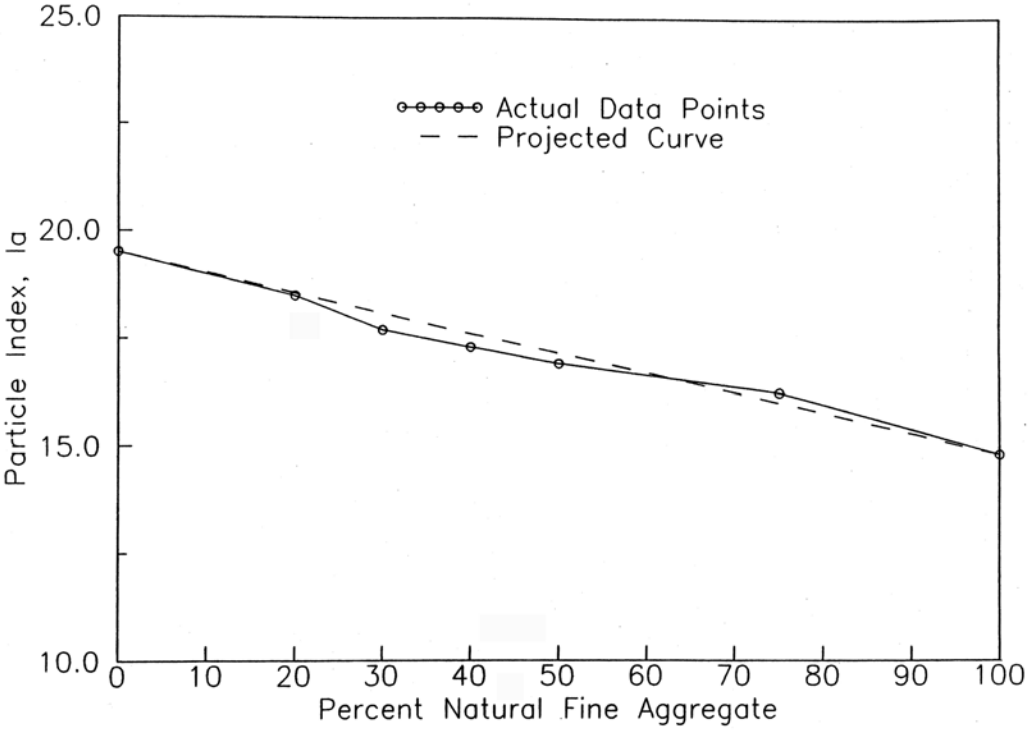

Figure 9. Variation in Particle Shape and Texture of Blend with Increase in Percent Natural Sand (HIN vs. LIM)

Effect of Orifice Diameter on Uncompacted Voids

National Aggregates Association has recently changed the orifice diameter of its apparatus from 3/8 in. (9.5 mm) to 1/2 in. (12.5 mm). This phase of the study was aimed at studying the effect of this change in orifice diameter and whether it is statistically significant or not. Nine different fine aggregates (Fine Aggregates No. 19 through 27) were used in this phase and the uncompacted void contents were determined by the NAA method A using both 3/8-in. (9.5-mm) orifice and l/2-in. (12.5-mm) orifice. Three replicates were used in each case. The design was a completely randomized 2x9 design with 3 replicates. The results are presented in Table 7. An analysis of variance of the data is presented in Table 8. It can be seen that orifice diameter is not statistically significant at "=0.05.

Table 7. Effect of Orifice Diameter on Uncompacted Void Content

S. No.	**Agg. Code**	**3/8 in. Dia. Orifice**			**1/2 in. Dia. Orifice**		
1	DO	48.7	48.9	49.0	48.4	48.2	48.0
2	LS	47.6	47.2	47.4	47.2	47.3	47.4
3	LS	47.2	47.0	47.3	47.5	47.5	47.7
4	BA	56.9	57.1	56.9	57.0	57.8	57.0
5	LS	47.3	47.2	47.6	47.4	47.2	47.2
6	GL	43.6	43.4	43.7	43.9	43.4	43.5
7	DO-LS	49.3	49.2	49.2	49.7	49.4	49.6
8	DO	51.2	51.0	50.8	51.3	51.2	51.1
9	SR	49.1	48.6	48.5	48.6	48.6	48.5

Table 8. ANOVA For Effect of Orifice Diameter on Uncompacted Voids

Source	**df**	**SS**	**MS**	**F_0**
Total	53	652.663	---	---
Orifice Dia. (A)	1	0.009	0.009	0.23
Materials (B)	8	649.901	81.238	2059.55
A x B	8	1.333	0.167	4.22
Error	36	1.420	0.039	---

df = degrees of freedom
SS = sum of squares
MS = mean square

However, since the materials x orifice diameter interaction is significant, pooled variances for data from both orifice diameters were computed. The variances were 0.035 and 0.044 for 3/8-in. (9.5-mm) and l/2-in. (12.5-mm) diameter orifices, respectively. Results from this phase of the study suggest that it might be preferable to use a 3/8-in. (9.5-mm) orifice for the NAA apparatus because of its lower variability.

CONCLUSIONS

Based on the results from the four phases of this study using several natural and manufactured coarse and fine aggregates, the following conclusions can be drawn.

1. There is a significant relationship between the 2-face crushed count and particle shape and texture index of gravel coarse aggregate as measured by ASTM D3398. As the 2-face crushed count increases, the particle shape and texture of the coarse aggregate also increases. The results suggest that there is a sharp increase in the particle shape and texture index when the percentage of 2-face crushed particles in the blend exceed 80 percent. The effect seems to be more pronounced for larger size coarse aggregate.
2. It appears from the laboratory study using blends of BB's (completely round and flattened round shapes) that the flattened round particles (sometimes found in uncrushed gravel) may be more undesirable than almost round particles.
3. A particle index value of 14 seems to be dividing the natural and manufactured fine aggregates when tested using the ASTM D3398 procedure. All manufactured fine aggregates except one were found to exhibit values of particle shape and texture index 4 higher than 14 and all the natural fine aggregates have particle indexes lower than l4. This value should rather be used instead of specifying the use of manufactured fine aggregate generically. Similar trends were observed for NAA's methods A and B also. The dividing uncompacted void contents were observed to be 44.5 and 48.3 for methods A and B, respectively.
4. Considerable time savings could be achieved by testing only the major or the major and second major fractions of a fine aggregate when using the ASTM D3398 procedure. This is concluded from the fact that fairly good correlations exist between the weighted average particle index and particle indexes for the major and major plus second major fractions of an aggregate gradation.
5. Both NAA's methods A and B show very high correlations (R^2 = 0.97) with the ASTM D3398 method. In addition, the NAA methods are fairly straightforward and much less time consuming as compared to the ASTM D3398 procedure. This indicates the viability of substituting the NAA methods for the ASTM D3398 as the standard method for determining particle shape and texture of fine aggregates.
6. The particle index decreases consistently as higher percentages of natural fine aggregate are blended with the manufactured fine aggregate. However, there is no linear relationship. Lower percentages of natural fine aggregate in the blend can decrease the particle index value significantly.
7. The increase in the orifice diameter from 3/8 in. (9.5 mm) to 1/2 in. (12.5 mm) as suggested by the National Aggregate Association does not seem to affect the values of the uncompacted void contents to be statistically significant at a = 0.05. In fact, the 3/8-in. (9.5-mm) diameter ori.fke appears to result in lesser variability as compared to the l/2-in. (12.5-mm) one.

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