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DISCLAIMER

ABSTRACT

Many highway agencies now limit the amount of natural sand in hot mix asphalt (HMA) when used on heavy duty pavements to minimize rutting. This is usually done by generically specifying the maximum allowable percentage of natural sand. Generally, natural sands tend to be rounded whereas manufactured sands tend to be angular. However, there are some natural sands which are subangular rather than rounded. Also, some manufactured or crushed sands can be subrounded rather than completely angular. There is a definite need to quantify the shape and texture of the fine aggregate so that it can be specified on a rational basis rather than generically.

A total of 18 fine aggregates (eight natural sands and ten manufactured sands) of different mineralogical compositions were sampled 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 generally divide the natural sands and manufactured sands, and therefore, can be used for specification purposes. However, the current ASTM D3398 test procedures are too time consuming because each sieve size fraction needs to be tested individually and results combined. Test data obtained in this study indicates that only the major fraction needs to be tested because its particle index has a fairly good correlation with the average particle index. Moreover both NAA's proposed Methods A and B show very good correlations (R^2=0.97) with the ASTM D3398 method. These methods are straightforward and less time consuming. Equations needed to compute ASTM D3398 weighted average particle index values from NAA Methods' results are given in the paper.

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INTRODUCTION

Natural sand generally has rounded particles and, when used in hot mix asphalt (HMA), tends to lower its resistance to permanent deformation (rutting). As such, many highway agencies now limit the amount of natural sand in HMA for heavy duty pavements in order to minimize permanent deformation. However, the use of generic terms such as natural or manufactured sand in specifications is not rational. It is the shape and texture of these sands which actually determines the resistance of HMA mixes in which they are used to permanent deformation. There are some natural sands which are subangular rather than rounded and, on the other hand, some crushed or manufactured sands are subrounded rather than completely angular. There is a definite need to quantify the shape and texture of the fine aggregate in order to specify in a more rational manner rather than specifying in a generic fashion.

OBJECTIVES

This study was undertaken to achieve the following objectives:

1. Quantify the particle shape and texture of various natural and manufactured (crushed) sands of different mineralogical compositions from Pennsylvania using ASTM D3398 (Index of Particle Shape and Texture) , and National Aggregate Association (NAA) ‘s proposed method using uncompacted void content (both methods A and B).
2. Compare and evaluate the differences between the particle shape and texture of natural sands and manufactured sands obtained by the three methods.
3. ASTM D3398 method is very time consuming because several sieve size fractions have to be tested individually. Examine if this method can be shortened without significantly affecting the particle shape and texture index values.
4. Compare the results from ASTM D3398 method with NAA’s methods A and B, and examine if any of the two NAA’s methods can be used in lieu of ASTM D3398.

REVIEW OF LITERATURE

Aggregate shape is discussed in the literature basically in terms of differences between natural aggregates (gravels) and crushed aggregates and it has been reported that the particle shape of fine aggregate is more important than that of coarse aggregate in improving the stability of HMA mixtures and increasing their resistance to permanent deformation.

Herrin and Goetz (*1*) conducted a study of the effect of aggregate shape on the stability of HMA mixtures and concluded that the addition of crushed gravel in the coarse aggregate fraction resulted in an increase in the strength for one-size mixtures but was of little importance in the dense-graded mixtures.

Lottman and Goetz (*2*) have reported the effect of crushed gravel fine aggregate in improving the strength of dense-graded asphaltic surfacing mixtures. Shklarsky and Livneh (*3*) 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. On the other hand, replacement of the coarse material with crushed coarse aggregate entails no such decisive effect.

Griffith and Kallas (*4*) studied the effect of different aggregate types on the aggregate void characteristics of bituminous paving mixtures. They reported that natural gravel aggregates would generally require less asphalt than the crushed stone mixtures. This was due to the natural gravels developing lower aggregate voids as compared to the crushed stone mixtures having the same gradation.

Significant increases in stability have been reported by Wedding and Gaynor (*5*) when using crushed gravel in place of natural gravel. They concluded that the use of crushed gravel sand in place of natural sand is nearly equal in effectively raising stability as the use of 25 percent crushed gravel in the coarse aggregate.

Maupin (*6*) has reported a laboratory investigation of the effects of particle shape on the fatigue behavior of an asphalt surface mixture. He used three aggregates: round gravel, crushed limestone and slabby slate. Constant strain mode fatigue tests were conducted and it was shown that the mixture containing round gravel had longer fatigue life than the other mixtures.

Marshall mix designs were run by Moore and Welke (*7*) on 110 sands from throughout the State of Michigan while keeping the coarse aggregate, asphalt content, and mineral filler constant. It has been reported that both the angularity of the fine aggregate and the gradation of the mixture are critical for acquiring higher stabilities. The more angular the fine aggregate, the higher the stability. As for gradation, it was found 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 made for extremely high stabilities.

Foster (*8*) conducted tests on two test sections of sand-asphalt mix and of mixes made with two different coarse aggregates and the same fine aggregate used in the sand asphalt. He concluded after observation of the performance of the pavements that the true capacity of dense-graded mixes to resist traffic-induced stresses is controlled by the characteristics of the fine aggregate.

Various methods have been reported in the literature for evaluating particle shape and texture of fine aggregates. These test methods can be divided generally into two 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. A brief summary of the test methods found in the literature follows.

Direct Tests

a) Corps of Engineers' Method CRD-C120-55. Method of Test for Flat and Elongated Particles in Fine Aggregate. In this method, particle shape is evaluated by observing with a microscope. The sample is separated into five sizes and the number of particles having a length-to-width ratio of more than 3 in each group are counted and reported as a percentage. It should be noted that this method evaluates only the particle shape and not surface texture of the particles.
b) Laughlin Method. In this method (*9*), which was basically developed for fine aggregate used in Portland cement concrete, measurements are made using enlarged photographs of particles retained on various sieves. The radii of curvature of the particles and the radius of an inscribing circle are measured. Using these measurements a parameter referred to as the roundness of the particles is then computed. Again, this method only tests the angularity (or roundness) of the particles and not the surface texture.

Indirect Tests

a) ASTM D3398. Standard Test Method for Index of Aggregate Particle Shape and Texture. In this method, the sample is first broken down into individual sieve fractions. The gradation of the sample thus is determined. Each size material is then separately compacted in a cylindrical mold using a tamping rod at 10 and 50 drops from a height of 2 inches. The mold is filled completely by adding extra material so that it just levels off with the top of the mold. Weight of the material in the mold at each compactive effort is determined and the percent voids computed. A particle index for each size fraction is then computed and, using the gradation of the sample, a weighted average particle index for the entire sample is also calculated.
b) National Aggregate Association's Proposed Method of Test for Particle Shape and Texture of Fine Aggre ate using Uncompacted Void Content. In this method, a 100 cm^3 cylinder is filled with fine aggregate of prescribed gradation by allowing the sample to flow through the orifice of a funnel into the calibrated cylinder. Excess material is struck off and the cylinder with aggregate weighed. Uncompacted void content of the sample is then computed using this weight and the bulk dry specific gravity of the aggregate. Two variations of the method are proposed. Method A uses a graded sample of specified gradation while in method B the void content is calculated using the void content results of three individual size fractions: #8 to #16, #16 to #30, and #30 to #50.
c) New Zealand Method. This method (*10*) is also a flow test similar to the NAA's proposed method. Here the orifice is 1/2 in. diameter and any material larger than 5/16 in. sieve is removed. The void content and time required by 1000 g of the material to flow through the orifice is measured and reported as basic measures of

particle shape and texture.

d) National Crushed Stone Association (NCSA) Method (*11*). This is also a flow test in which the material is broken down into three sizes. Void content of each size fraction is determined separately by allowing to flow through an orifice of 1 in. diameter. Arithmetic mean of the void contents of the three sizes is computed as the basic measure of particle shape and texture.
e) Virginia Method (*12*). This is basically the same as the NCSA method.
f) National Sand and Gravel Association (NSGA) Method. This method (*13*) is basically the same test developed by Rex and Peck (*14*) and later used by Bloem and Gaynor (*15*) and Wills (*16*) but with different details. This is also a flow test with the size of an orifice of 0.4 in diameter. Sample is broken down into four size fractions and then recombined in specified proportions. Void content of the sample thus prepared is determined and reported as the basic measure of particle shape and texture.
g) Ishai and Tons Method (*17*). This test attempts to relate results from flow test to more basic measures of geometric irregularity of particles, i.e., macroscopic and microscopic voids in particles. The size of the orifice depends on the size of the particles being tested. The sample may be broken down into as many as six size fractions. One-sized glass beads are needed for each fraction. Flow test performance is reported on one-sized aggregate and corresponding one-sized glass beads.
h) Specific Rugosity by Packing Volume. This method (*18*) is also a flow test and was used for direct measurement of the packing specific gravity of one-sized aggregate particles. Aggregate sample was broken into four sizes and each placed in a cone shaped bin and then poured into a calibrated constant volume container. Packing specific gravity was computed using the weight of this calibrated volume of aggregate. The macrosurface and microsurface voids were computed using the apparent, bulk and packing specific gravities. The addition of the macrosurface and microsurface voids thus obtained was done to arrive at the specific rugosity.
i) Direct Shear Test. This test method is used to measure the internal friction angle of a fine aggregate under different normal stress conditions. A prepared sample of the aggregate under consideration is consolidated in a shear mold. The sample is then placed in a direct shear device and sheared by a horizontal force while applying a known normal stress.

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

A total of 18 fine aggregates were used in this study. The aggregates comprised of 8 natural and 10 manufactured sands of different mineralogical composition and came from various sources all across Pennsylvania. Table 1 shows the source, type of aggregate and their bulk specific gravity and water absorption data obtained using ASTM C128. Table 2 reports the as-received gradations of all the aggregates used in the study. All natural sands were uncrushed and came from pit run or bank run gravel sources while all manufactured sands except one were crushed from different stone types including limestone, sandstone, calcareous sandstone, siltstone, dolomite, argillite, and hornfels. One of the manufactured sands was blast furnace slag (Fine Aggregate No. 10).

Table 1. General Data for Aggregates Used

S. No.	County	Type*	Type Agg.**	Bulk Sp. Gr.	Water Absorption (percent)
1	Crawford	N	GL	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	Bedford	M	LS	2.610	1.14
6	Warren	N	GL	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	2.430	4.33
11	Cumberland	M	SS	2.627	0.40
12	Fayette	M	CS	2.670	0.27
13	Westmonland	M	CS-CG	2.673	0.60
14	Perry	M	SL	2.648	0.96
15	Berks	M	DO-LS	2.728	0.47
16	Northumberland	M	SS-CG	2.664	0.36
17	Bucks	M	AR	2.660	0.52
18	Adams	M	HF	2.668	0.58

* N = Natural fine aggregate M = Manufactured fine aggregate

** GL = Gravel Sand
LS = Limestone
SB = Blast Furnace Slag
Cs = Calcareous Sandstone
Ss = Sandstone
CS-CG = Calcareous Sandstone Conglomerate
SL = Siltstone
DO-LS = Dolomitic Limestone
SS-CG = Sandstone Conglomerate
AR = Argillite
HF = Hornfels

Table 2. As-Received Gradations For Aggregates Used

S. No.	Type*	Type Agg.	Percent Passing							
			3/8 in	#4	#8	#16	#30	#50	#100	#200
1	N	GL	100.0	96.0	80.1	63.3	43.1	15.4	3.5	1.4
2	N	GL	100.0	97.5	77.9	55.2	29.5	6.1	0.9	0.5
3	N	GL	100.0	95.1	78.2	61.9	45.8	25.7	9.4	3.2
4	N	GL	100.0	94.8	79.3	68.7	53.9	16.6	2.8	1.4
5	M	LS	100.0	99.8	77.9	39.3	18.1	8.2	4.8	3.5
6	N	GL	100.0	95.8	77.2	55.8	38.4	21.2	12.4	3.7
7	N	GL	100.0	96.2	77.4	58.2	36.3	19.4	7.9	2.0
8	N	GL	100.0	98.0	72.6	55.5	42.0	15.3	4.2	1.8
9	N	GL	100.0	98.1	70.2	49.9	36.9	19.6	4.3	0.9
10	M	SB	100.0	99.6	82.0	58.1	37.8	20.0	9.5	4.1
11	M	SS	100.0	99.3	85.9	69.6	49.7	26.4	7.3	1.3
12	M	CS	100.0	100.0	75.3	46.9	31.2	18.0	8.6	4.2
13	M	CS-CG	100.0	98.1	77.0	45.7	27.4	13.5	4.4	2.0
14	M	SL	100.0	99.8	73.3	42.3	24.1	13.7	8.7	5.1
15	M	DO-LS	100.0	99.8	84.0	44.8	25.9	14.5	7.8	3.2
16	M	SS-CG	100.0	100.0	84.5	50.1	32.4	16.4	7.7	3.3
17	M	AR	100.0	99.1	79.4	53.2	33.0	16.8	11.2	6.5
18	M	HF	100.0	99.8	88.1	57.4	31.4	15.7	8.0	4.7

* N = Natural fine aggregate
M = Manufactured fine aggregate

TEST METHODS

The test methods used in the present study were: (a) ASTM D3398 and (b) NAA's proposed methods A and B. A brief summary of these test methods and any deviations therefrom follows.

ASTM D3398

This is the ASTM Standard Test Method for Index of Aggregate Particle Shape and Texture. Only one-size standard mold was used for this study and that was a 3-in. diameter mold (mold D). The sample was washed on a #200 sieve and dried in the oven at 230±9°F. It was then sieved to separate the total material into individual size fractions using ASTM C136. Bulk specific gravity of the material was determined in accordance with ASTM C128. The individual size fractions were then compacted using 10 and 50 drops of the tamping rod to determine the voids and hence the particle index for each size fraction. The weighted average 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.

NAA's Methods

Both Methods A and B were used during this study. In method A the specified standard grading was used to make the sample by using the following quantities of dry sand from each size:

Individual Size Fraction	Weight, g
#8 to #16	444
#16 to #30	57
#30 to #50	72
#50 to #100	17
	Total 190

For Method B, 190 g of dry fine aggregate for each of the sizes: #8 to #16, #16 to #30, and #30 to #50 was used.

The samples were dried in the oven at 230±9°F before determination of voids content. The cylinder used was a standard 100-cm^3 cylinder. Void contents were determined by allowing the sample to flow through a funnel (0.375 in. diameter of the orifice) from a height of 4.50 inches above the top of the cylinder. For the graded sample (Method A) the void content so determined was used directly. For the individual fractions (Method B), the mean void content percent was calculated based on the void contents for individual size fractions.

TEST DATA AND DISCUSSION

The test data obtained for particle shape and texture index (I_a) using ASTM D3398 is reported in Table 3. The results are arranged in order of increasing I_a values. A plot of the weighted average particle index values for various fine aggregates used in this study is given in Figure 1. The results obtained using NAA's proposed methods A and B are reported in Table 4. These results are also shown in Figure 2. A general trend of values obtained by the two methods is shown in Figure 3. A discussion of the results obtained follows.

1. Differences Between Natural and Manufactured Sands

Based on the ASTM D3398 data as shown in Figure 1, natural sands appear to exhibit lower I_a values compared to manufactured sands. There is one exception, however, that one of the manufactured sands (Fine Aggregate No. 5 - limestone) falls with the natural sands. A particle index value of 14 seems to delineate the natural and manufactured sands. As reported in Table 3, the average particle index for natural sands is 12.3 with a standard deviation of 1.26. This gives the 95-percent confidence limits for I_a values of natural sands to be 12.3±2.5 (9.8, 14.8). Similarly, the average particle index for manufactured sands is found to be 18.2 with a standard deviation of 2.72 giving the 95- percent confidence limits of the particle index as 18.2±5.3 (12.9, 23.5). Based on the 95-percent confidence limits, both natural and manufactured sands are found to overlap in the particle index 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, giving the dividing value of particle index as 14.1 which is pretty close to the value of 14 as estimated by just looking at Figure 1. A minimum value of I_a of 14 thus can probably be used in the specifications in lieu of specifying manufactured sand generically.

Table 3. Particle Shape Index Data Using ASTM D3396

S. No.	Type*	Type of Agg.	Sieve Fraction -3/8" + #4	-#4 + #8	-#8 + #16	-#16 + #30	-#30 + #50	-#50 + #100	-#100 + #200	-#200	Weighted Particle Index
1	N	GL	8.9	8.9	9.3	10.5	10.6	11.0	11.0	11.0	10.1
2	N	GL	10.6	10.6	11.2	10.1	9.8	11.2	11.2	11.2	10.5
3	N	GL	11.1	12.0	13.1	13.4	12.7	12.3	12.3	12.3	12.6
4	N	GL	11.7	13.8	13.5	12.2	11.9	13.4	13.4	13.4	12.6
5	M	LS	12.5	12.5	12.7	12.7	13.3	13.3	13.3	13.3	12.8
6	N	GL	9.3	10.0	13.4	13.5	13.2	14.9	15.5	15.5	13.0
7	N	GL	11.7	12.4	12.2	13.0	13.9	13.8	13.8	13.8	13.0
8	N	GL	11.3	11.3	14.8	14.9	12.5	13.8	13.8	13.8	13.1
9	N	GL	11.3	11.3	15.4	15.2	12.8	14.1	14.1	14.1	13.4
10	M	sa	16.1	16.1	15.2	13.1	14.5	16.0	16.0	16.0	15.0
11	M	SS	16.9	16.9	17.1	16.2	15.5	16.5	16.5	16.5	16.4
12	M	CS	0.0	17.8	19.5	20.1	17.2	16.2	16.2	16.2	18.3
13	M	CS-CG	19.7	19.7	19.9	19.0	17.4	16.3	16.3	16.3	18.9
14	M	SL	19.0	19.0	18.8	19.1	19.8	20.8	20.8	20.8	19.3
15	M	DO-LS	20.3	20.3	19.8	18.9	18.6	18.7	18.7	18.7	19.4
16	M	SS-CG	0.0	18.8	19.7	20.2	20.1	21.3	21.3	21.3	20.0
17	M	AR	20.5	20.5	21.6	21.0	20.0	21.6	21.6	21.6	21.0
18	M	HF	19.8	19.8	20.6	22.0	22.1	22.1	22.1	22.1	21.3
							Average for Natural Sands				12.3
							Standard Deviation				1.26
							Average for Manufactured Sands				18.2
							Standard Deviation				2.72

* N = Natural fine aggregate M = Manufactured fine aggregate

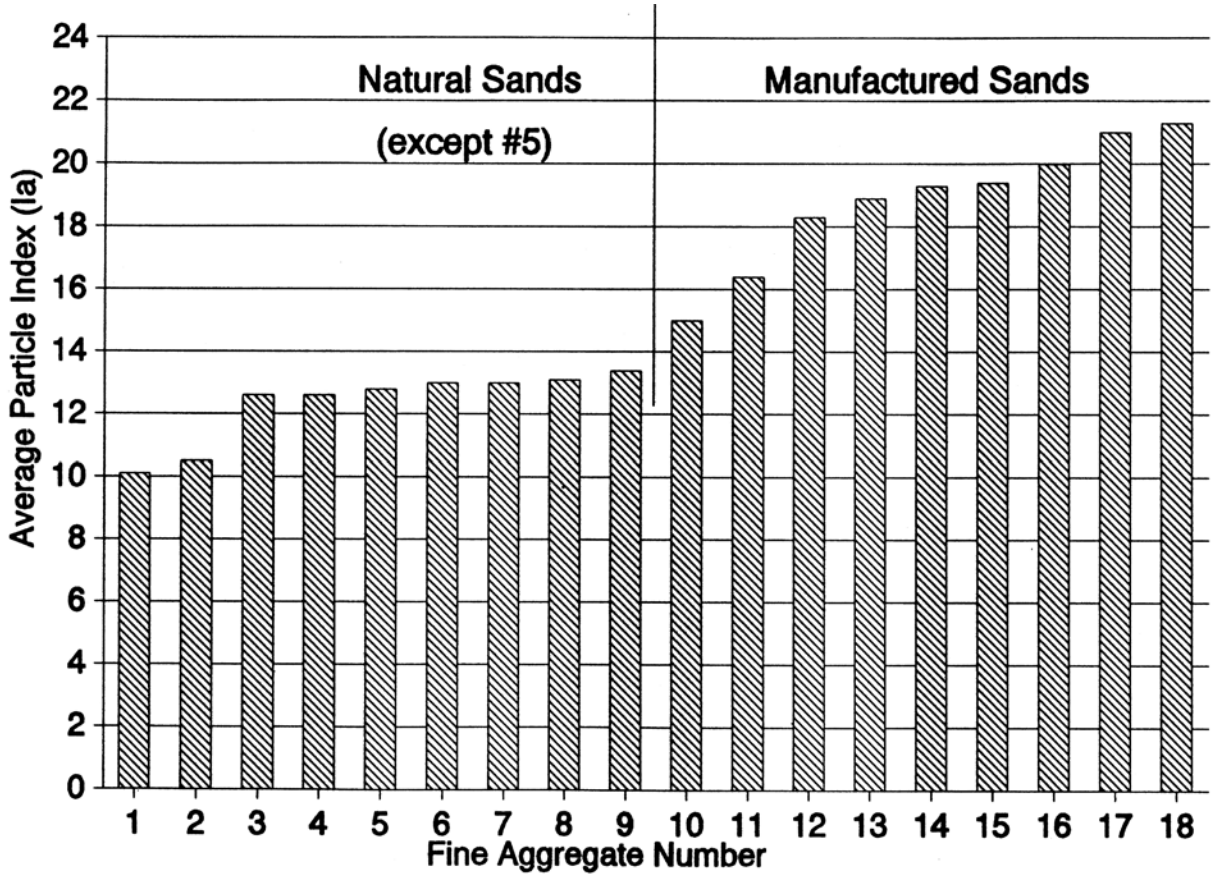

Figure 1. Average Particle Index Using ASTM D3398

Table 4. Particle Shape and Texture Data Using NAA's Methods A & B

S. No.	Type*	Type Agg.	Method A	Method B
1	N	GL	40.6	43.9
2	N	GL	40.2	43.5
3	N	GL	42.2	47.5
4	N	GL	42.7	46.0
5	m	LS	43.1	47.5
6	N	GL	43.9	46.6
7	N	GL	43.8	46.9
8	N	GL	42.4	46.3
9	N	GL	44.3	47.8
10	m	SB	45.4	49.0
11	m	ss	45.7	48.8
12	m	cs	48.5	52.7
13	m	CS-CG	47.7	52.3
14	m	SL	48.7	52.6
15	m	DO-LS	49.2	53.2
16	m	SS-CG	49.3	53.5
17	m	AR	50.9	54.7
18	m	HF	52.0	55.0

* N = Natural fine aggregate M = Manufactured fine aggregate

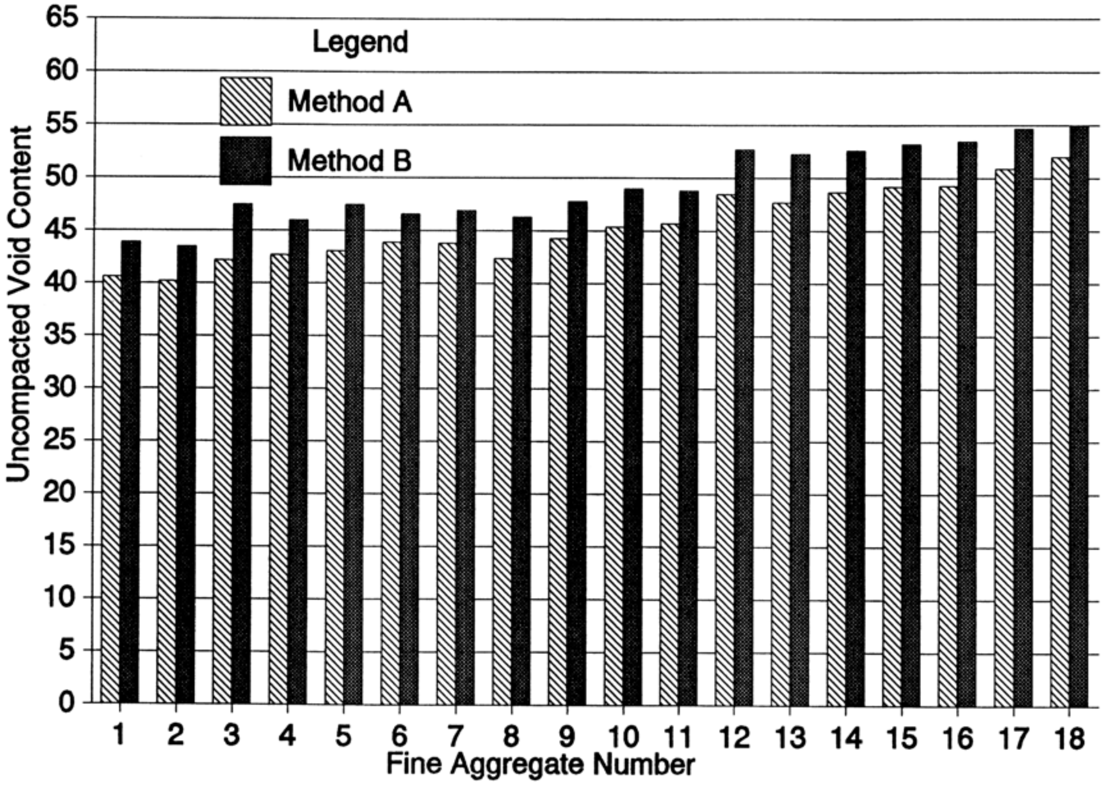

Figure 2. Uncompacted Void Contents Using NAA's Proposed Methods A & B

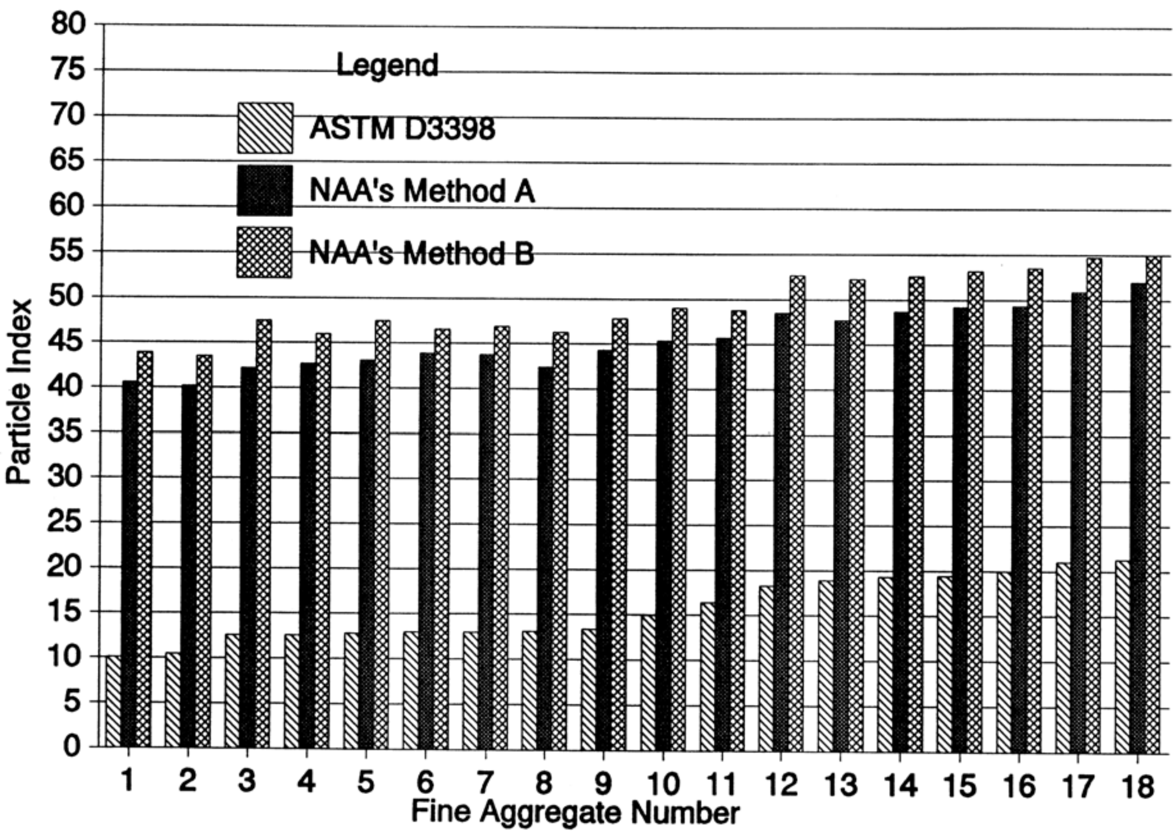

Figure 3. Particle Index Using ASTM D3398 and NAA's Proposed Methods A & B

Similar trends are observed for data obtained using NAA's Methods A and B as can be seen in Figure 2. The average values, standard deviations, and 95-percent confidence limits for uncompacted void contents obtained using NAA's methods are given below.

Method	Type Agg.	Average	Std. Dev.	95% Conf. Limits
A	Natural Mfg.	42.5	1.51	39.5 - 45.5
		48.1	2.68	42.8 - 53.4
B	Natural Mfg.	46.1	1.58	43.0 - 49.2
		51.9	2.59	46.8 - 57.0

Again, it can be observed that based on the 95-percent confidence limits, the uncompacted void contents for natural and manufactured sands overlap in the range of 42.8 to 45.5 using Method A and 46.8 to 49.2 using Method B. These overlap regions can be avoided with a confidence level of 82 percent for method A and 84 percent for method B giving the delineating values of uncompacted void contents separating the natural and manufactured sands as 44.5 and 48.4, respectively. On the average, the uncompacted void contents obtained by method A are lower than those obtained using Method B. The difference appears to be reasonably uniform as per Figure 2 and, therefore, either Method A or B can be used.

2. Evaluation of ASTM D3398

Because of the time-consuming nature of ASTM D3398 procedure, alternative approaches were sought for during the present 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 we could use these instead. These correlations are shown in Figures 4a to c. These figures respectively show correlations for: a) the whole data including both natural and manufactured sands, b) natural sands only, and c) manufactured sands only. It can be seen that good correlations exist between the average particle index and particle indexes for major, and major plus second major fractions for the whole data as well as for data on manufactured sands. Coefficient of determination (R^2) values are found to range between 0.94 to 0.98. Natural sands, however, show some scatter and the R^2 values are 0.59 and 0.80 for major, and major plus second major fraction particle indexes, respectively. The equations relating the weighted average particle index (I_a) with major fraction particle index (I_m) are:

I_a - 0.92 I_m + l.3	for combined data
I_a - 0.82 I_m + 2.5	for natural sands
I_a - 0.92 I_m + 1.4	for manufactured sands

Similarly, the equations relating weighted average particle index (I_a) with major plus second major fraction particle index (I_{mpsm}) are:

I_a - 0.93 I_{mpsm} + 1.3	for combined data
I_a - 1.08 I_{mpsm} - 0 .6	for natural sands
I_a-0.90 I_{mpsm} + l.8	for manufactured sands

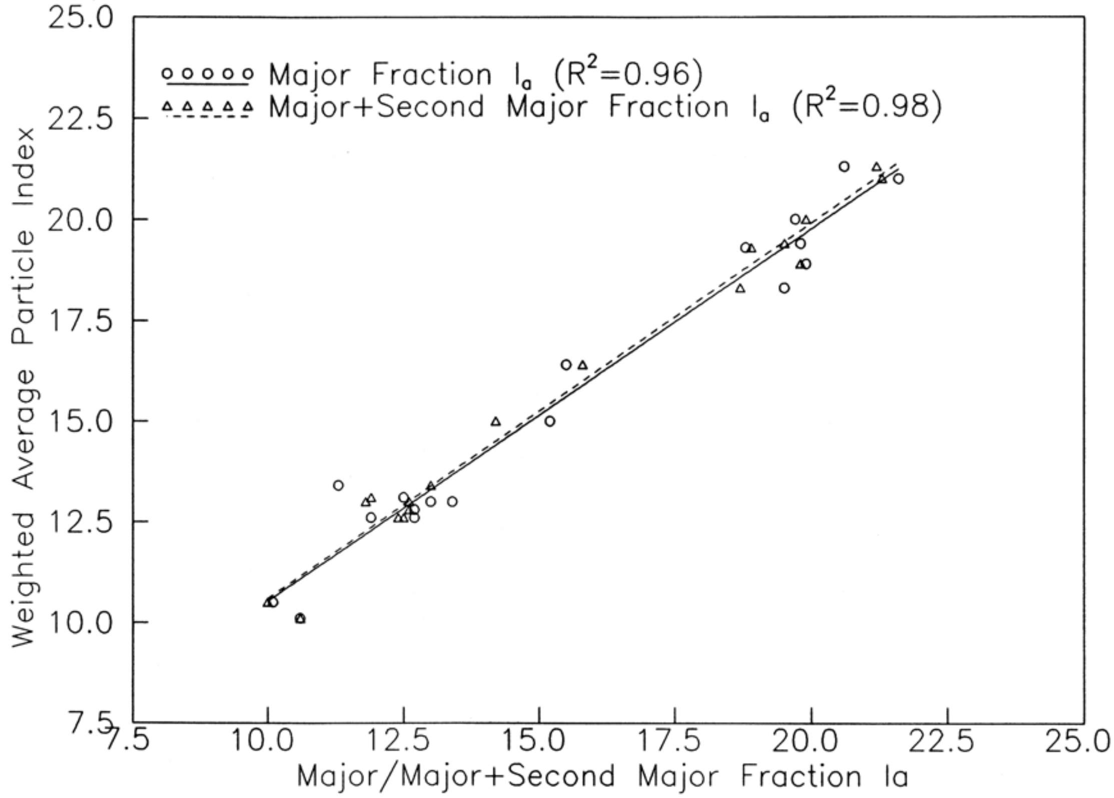

Figure 4a. Weighted Average Particle Index vs. Major, Major Plus Second Major Fraction Particle Indexes (Combined Data)

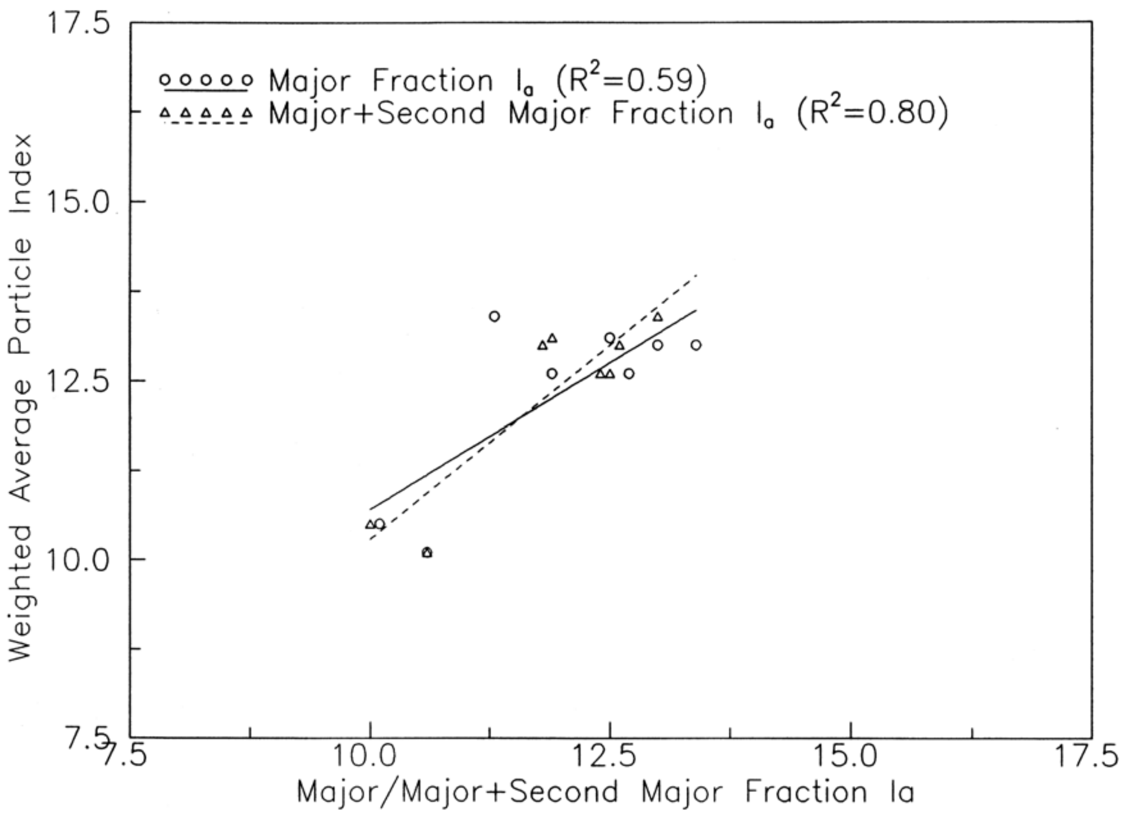

Figure 4b. Weighted Average Particle Index vs. Major and Major Plus Second Major Fraction Particle Indexes (Natural Sands Only)

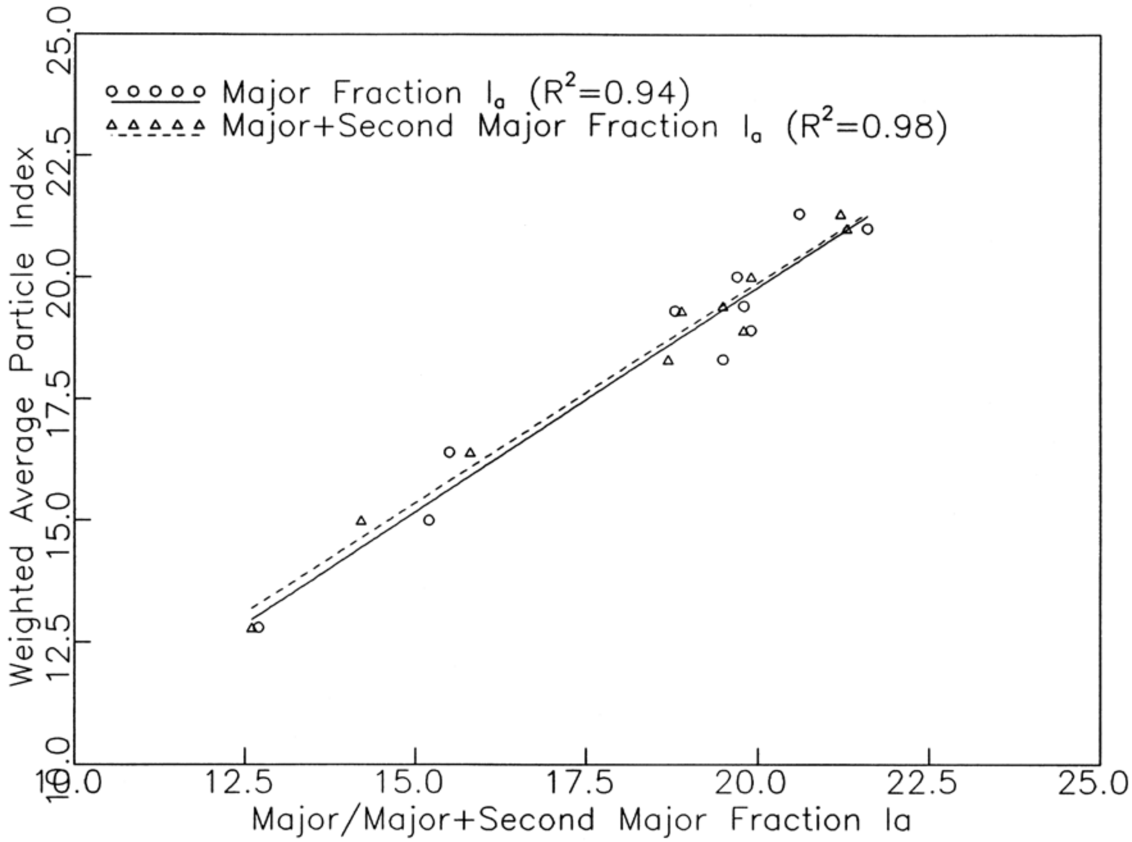

Figure 4c. Weighted Average Particle Index vs. Major and Major Plus Second Major Fraction Particle Indexes (Manufactured Sands Only)

In general, the particle index values within the sieve fraction increase as the sieve size decreases. No general trends can be found as to whether the distribution within the sand is normal or skewed.

In view of the above, it seems that we can use the particle index for the major fraction of a sand in place of its weighted average particle index. On an average, the major fraction particle index differs from the weighted average particle index by 0.1 which is practically insignificant. If increased accuracy is desired then both major plus the second major fractions can be tested and results combined to get a weighted average value.

3. Comparison of ASTM D3398 and NAA Methods

Data obtained using NAA's Methods A and B was correlated with the weighted average particle index data obtained using ASTM D3398. These correlations are shown in Figure 5. The coefficient of determination (R^2) for both methods is found to be 0.97. Based on the data obtained with the 18 fine aggregates used in the present study, it can be concluded that NAA's methods can successfully be used in place of ASTM D3398. With the slope value of almost one, the data is observed to only have a shift factor for translating NAA method results to ASTM D3398 results. This shift for method A is -31.2 and for method B it is -33.5. The following equations may be used for transforming NAA method results to ASTM D3398 results.

I_a - 1.03 V_{NAA} - 31.2 for Method A
I_a - 1.00 V_{NAA} - 33.5 for Method B

where V_{NAA} is uncompacted void content (measure of particle shape and texture) obtained by NAA methods.

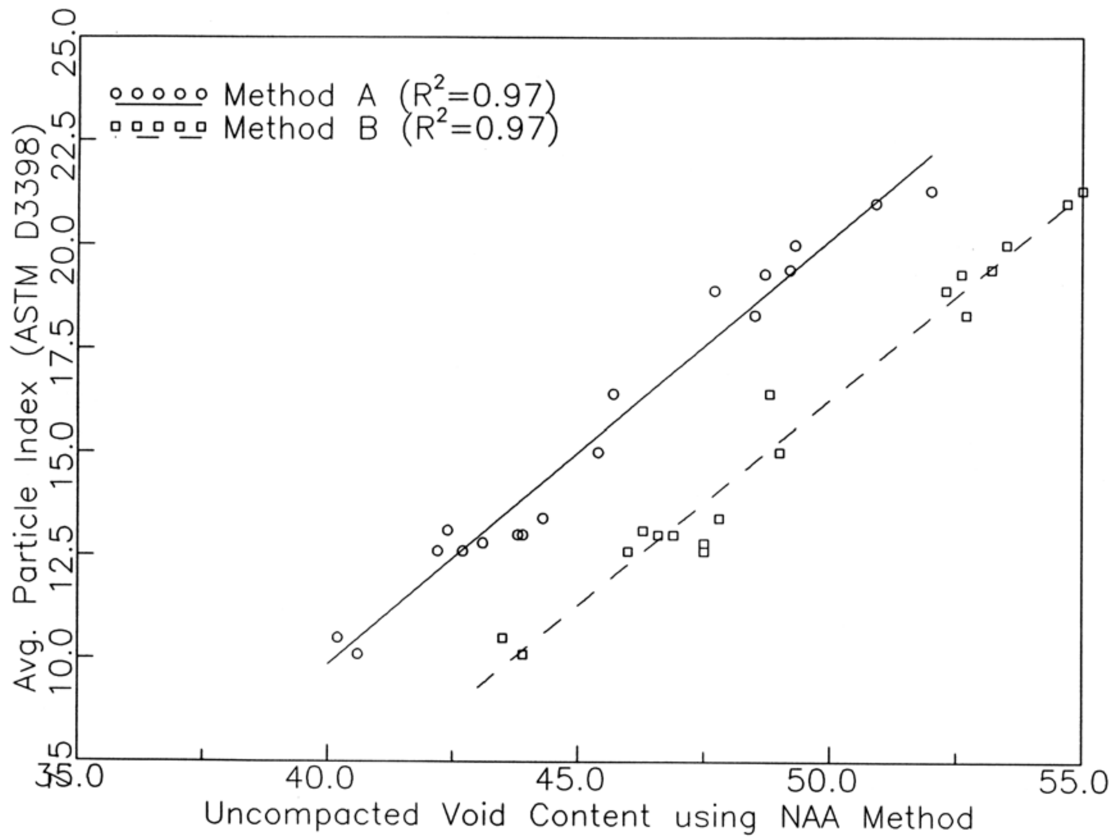

Figure 5. Average Particle Index Using ASTM D3398 Versus Uncompacted Void Contents Using NAA's Methods A & B

CONCLUSIONS

Based on the particle shape and texture index values obtained for the various natural and manufactured sands tested using ASTM D3398 and NAA's proposed methods A and B, the following conclusions can be drawn.

1. A particle index value of 14 seems to be dividing the natural and manufactured sands when using ASTM D3398. This value can probably be used for specification purposes when ASTM D3398 is used. All manufactured sands except one exhibit higher particle index values and all natural sands have lower particle index values. A similar trend is observed for NAA's methods A and B as well where uncompacted void contents of 44.5 and 48.3, respectively, divide the natural and manufactured sands.
2. Correlations between the major, and major plus second major fraction particle indexes with the weighted average particle index using ASTM D3398 are fairly good for the entire data viewed as a whole. This suggests that particle index values for the

major or major plus second major fractions of the fine aggregate may be used as the average particle index for the combined gradation. This would result in considerable savings of time and effort in testing.

3. Both NAA's Methods A and B show very high correlations ($R^2 = 0.97$) with the ASTM D3398 method. This indicates the viability of substituting the NAA methods for ASTM D3398 as the standard methods for determining particle shape and texture of fine aggregates. NAA's methods are both straightforward and time-saving as compared to ASTM D3398. Equations needed to compute ASTM D3398 weighted average particle index from NAA method results are given based on the aggregates tested in this study.

Currently research is underway at the National Center for Asphalt Technology, Auburn, Alabama to correlate fine aggregate particle index with the permanent deformation (rutting) behavior of the HMA mixes so that minimum values of particle index can be specified for heavy duty pavements.

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