Evaluation of Particle Shape and Texture: Manufactured Versus Natural Sands

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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 procedure is usually accomplished 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 that 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. Fine aggregates (8 natural and 10 manufactured sands) of different mineralogical compositions were sampled from various sources in Pennsylvania. Particle shape and texture data were obtained using ASTM D3398, and two proposed methods of the National Aggregate Association (NAA). On the basis of ASTM D3398, a particle index value of 14 appears to divide the natural and manufactured sands, and therefore, can be used for specification purposes. However, because each sieve size fraction needs to be tested individually and results combined, the current ASTM D3398 test procedures are too time consuming. However, test data indicate 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 proposed Methods A and B show 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 two NAA methods are described.

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 to minimize permanent deformation. However, the use of generic terms such as natural or manufactured sand in specifications is not rational. The shape and texture of the sands actually determine the resistance to permanent deformation of HMA mixes in which they are used. Some natural sands 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 to specify sands in a more rational manner rather than specifying them generically.

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 proposed Methods A and B of the National Aggregate Association (NAA) using uncompacted void content.
2. Compare and evaluate the differences between the particle shape and texture of natural and manufactured sands obtained by the three methods.
3. Examine the ASTM D3398 method, which is time consuming because several sieve size fractions have to be tested individually, to see if it can be shortened without significantly affecting the particle shape and texture index values.
4. Compare the results from the ASTM D3398 method with the NAA Methods A and B, and examine if either of the NAA methods can be used in lieu of ASTM D3398.

REVIEW OF LITERATURE

Aggregate shape is discussed in the literature in terms of differences between natural aggregates (gravels) and crushed aggregates. The particle shape of fine aggregate is apparently 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*) studied the effect of aggregate shape on the stability of HMA mixtures and concluded that the addition of crushed gravel in the coarse aggregate fraction increased 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 pav-

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ing mixtures. They reported that natural gravel aggregates would generally require less asphalt than the crushed stone mixtures would, because natural gravels developed lower aggregate voids compared with 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. From constant-strain mode fatigue tests, it was demonstrated 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 in which the coarse aggregate, asphalt content, and mineral filler were held constant. 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, the closer the gradation is to the Fuller curve for maximum density, the higher is the stability. Rounded sands of relatively uniform size result in lower stabilities. Moreover, manufactured sands (slag or crusher sands) have highly angular particle shapes and are made for extremely high stabilities.

Foster (*8*) tested two sections of sand-asphalt mix and of mixes made with two different coarse aggregates and the same fine aggregate used in the sand-asphalt. After observation of the performance of the pavements, he concluded 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 methods 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. (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 methods A and B as ASTM standards.)

Direct Tests

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 observation 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 is counted and reported as a percentage. This method evaluates only the particle shape and not the surface texture of the particles.

Laughlin Method

In this method (*9*), which was 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

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. Thus, the gradation of the sample is determined. Each size of material is then separately compacted in a cylindrical mold using a tamping rod at 10 and 50 drops from a height of 2 in. 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.

National Aggregate Association's Proposed Method of Test for Particle Shape and Texture of Fine Aggregate 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 is 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; in method B the void content is calculated using the void content results of three individual size fractions: Nos. 8 to 16, Nos. 16 to 30, and Nos. 30 to 50.

New Zealand Method

This method (*10*) is a flow test similar to NAA's proposed method. Here the orifice is ½ in. in diameter, and any material larger than the ⁵⁄₁₆-in. sieve is removed. The void content and time required by 1,000 g of the material to flow through the orifice is measured and reported as a basic measure of particle shape and texture.

National Crushed Stone Association (NCSA) Method

In this flow test (*11*), 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. The arithmetic mean of the void contents of the three sizes is computed as the basic measure of particle shape and texture.

Virginia Method

This method (*12*) is basically the same as the NCSA method.

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.

Ishai and Tons Method

In this test (*17*), results from a flow test are related 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.

Specific Rugosity by Packing Volume

This flow test method (*18*) 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 macro- and microsurface voids were computed using the apparent, bulk, and packing specific gravities. The addition of the macro- and microsurface voids thus obtained was done to arrive at the specific rugosity.

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 a known normal stress is applied.

MATERIALS

Fine aggregates used in this study comprised 8 natural and 10 manufactured sands of different mineralogical composition and came from various sources in Pennsylvania. Table 1 presents the source, type of aggregate, and its bulk specific gravity and water absorption data obtained using ASTM C128. Table 2 presents 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).

TEST METHODS

ASTM D3398

This standard is the ASTM Standard Test Method for Index of Aggregate Particle Shape and Texture. Only one size of standard mold was used for this study, a 3-in.-diameter mold (Mold D). The sample was washed on a No. 200 sieve and dried in the oven at 230°F ± 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 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	44
#16 to #30	57
#30 to #50	72
#50 to #100	17
Total	190

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

The samples were dried in the oven at 230°F ± 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 (of 0.375-in.-diameter orifice) from a height of 4.50 in. 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 on the basis of the void contents for individual size fractions.

TABLE 1 GENERAL DATA FOR AGGREGATES USED

S.No.	County	* Type	** Type Agg.	Bulk Sp. Gr.	Water Asborption (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

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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 Aggregate	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 sand

TEST DATA AND DISCUSSION

The test data obtained for particle (shape and texture) index (I_a) using ASTM D3398 are presented 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 shown in Figure 1. The results obtained using the NAA proposed Methods A and B are presented 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.

Differences Between Natural and Manufactured Sands

On the basis of the ASTM D3398 data shown in Figure 1, natural sands appear to exhibit lower I_a values compared with manufactured sands. There is one exception, however, in that one of the manufactured sands (Fine Aggregate No. 5—limestone) falls with the natural sands. Generally, a particle index value of 14 delineates the natural and manufactured sands. As indicated in Table 3, the average particle index for natural sands is 12.3 with a standard deviation of 1.26; thus the 95 percent confidence limits for I_a values of natural sands are 9.8 and 14.8. Similarly, the average particle index for manufactured sands is found to be 18.2 with a standard deviation of 2.72; thus the 95 percent confidence limits of the particle index for manufactured sands are 12.9 and 23.5. On the basis of the 95 percent confidence limits, natural and manufactured sands overlap in the particle index range of 12.9 to 14.8. From trial-and-error procedures, this overlap would cease to exist at a confidence level of 86 percent, yielding a dividing value of the particle index of 14.1. A minimum value of I_a of 14 thus can probably be used in the specifications in lieu of specifying manufactured sand generically.

Similar trends are observed for data obtained using NAA Methods A and B as indicated in Figure 2. The average values, standard deviations, and 95 percent confidence limits for uncompacted void contents obtained using NAA methods are as follows:

Method	*Type of Aggregate*	*Average*	*Standard Deviation*	*95 percent Confidence Limits*
A	Natural	42.5	1.51	39.5–45.5
A	Manufactured	48.1	2.68	42.8–53.4
B	Natural	46.1	1.58	43.0–49.2
B	Manufactured	51.9	2.59	46.8–57.0

Again, on the basis of 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 in the range of 46.8 to 49.2 using Method B. These overlap regions can be avoided at a confidence level of 82 percent for Method A and 84 percent for Method B, yielding delineating values of uncompacted void content separating the natural and manufactured sands as 44.5 (Method A) and 48.4 (Method B), respectively. On the average, the uncompacted void content obtained by Method A is lower than that obtained using Method B. The difference appears to be reasonably uniform as indicated in Figure 2, and, therefore, either Method A or B can be used.

Evaluation of ASTM D3398

Because of the time-consuming nature of ASTM D3398 procedure, alternative approaches were sought during the present study. Correlations were run between the average particle index obtained using ASTM D3398 and the particle indexes for the individual major fraction, and major fraction plus second-major fractions to see whether these could be used instead. These correlations are shown in Figures 4–6. These

TABLE 3 PARTICLE SHAPE INDEX DATA USING ASTM D3398

S. No.	Type*	Type of Aggregate	Sieve Fraction								Weighted Particle Index
			-3/8"+#4	-#4+#8	-#8+#16	-#16+#30	-#30+#50	-#50+#100	-#100+#200	-#200	
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	SB	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 = Manufatured fine aggregate

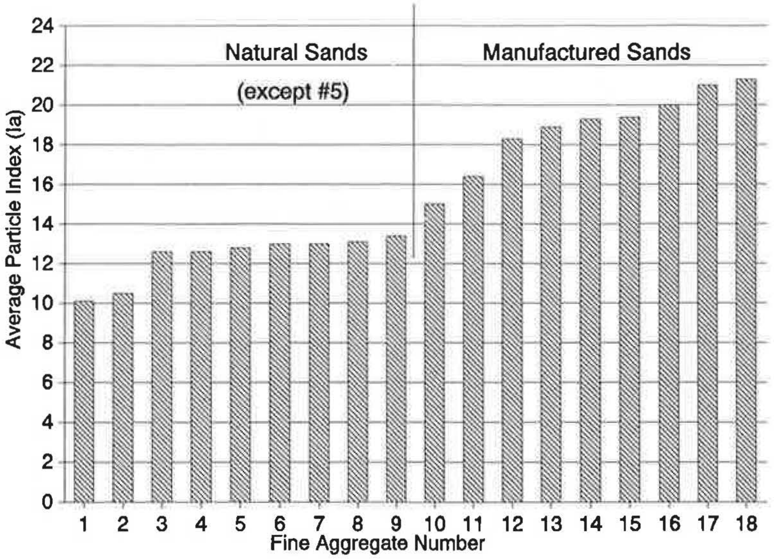

FIGURE 1 Average particle index using ASTM D3398.

TABLE 4 PARTICLE SHAPE AND TEXTURE DATA USING NAA METHODS A AND B

S.No.	* Type	Type Aggregate	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

figures indicate correlations for (a) the whole data including both natural and manufactured sands, (b) natural sands only, and (c) manufactured sands only, respectively. Good correlations exist between the average particle index and particle indexes for major fraction, 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 and 0.98. Natural sands, however, have some scatter and the R^2 values are 0.59 and 0.80 for major-fraction, and major-fraction plus second-major-fraction particle index values, respectively. The equations relating the weighted average particle index (I_a) with major-fraction particle index (I_m) are as follows:

$I_a = 0.92I_m + 1.3$ for combined data

$I_a = 0.82I_m + 2.5$ for natural sands

$I_a = 0.92I_m + 1.4$ for manufactured sands

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

$I_a = 0.93I_{\mathrm{mpsm}} + 1.3$ for combined data

$I_a = 1.08I_{\mathrm{mpsm}} - 0.6$ for natural sands

$I_a = 0.90I_{\mathrm{mpsm}} + 1.8$ for manufactured sands

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.

The particle index may be used for the major fraction of a sand in place of its weighted average particle index. On 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 the major fraction and second-major fraction can be tested and the results combined to yield a weighted average value.

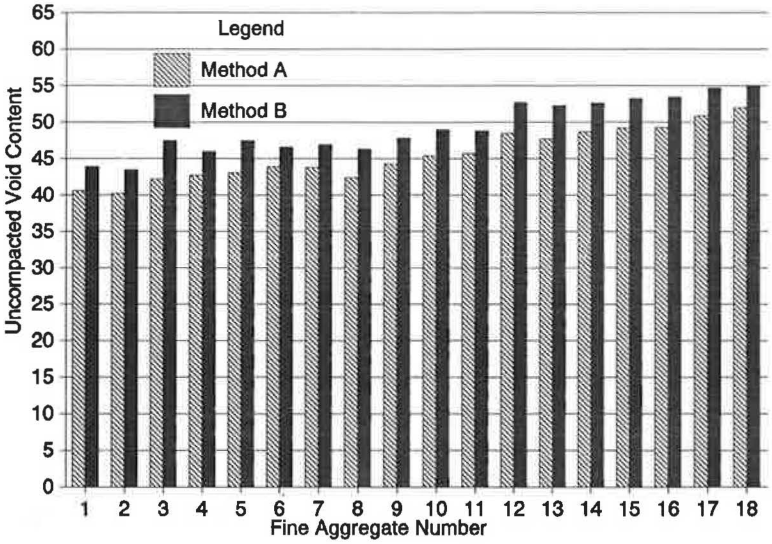

FIGURE 2 Uncompacted void content using NAA proposed Methods A and B.

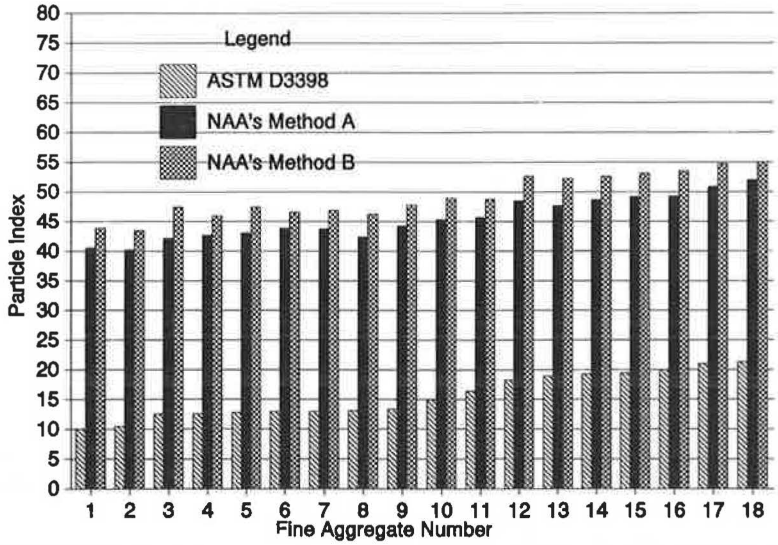

FIGURE 3 Particle index using ASTM D3398 and NAA proposed Methods A and B.

Comparison of ASTM D3398 and NAA Methods

Data obtained using NAA Methods A and B were correlated with the weighted average particle index data obtained using ASTM D3398. These correlations are shown in Figure 7. The coefficient of determination (R^2) for both methods was 0.97. On the basis of the data obtained for the 18 fine aggregates, the NAA methods can successfully be used in place of ASTM D3398. With the slope value of almost one, the data are observed to have only a shift factor for translating NAA method results to ASTM D3398 results. This shift for Method A is −31.2; for Method B, −33.5. The following equations may be used for transforming NAA method results to ASTM D3398 results.

$$I_a = 1.03V_{\mathrm{NAA}} - 31.2 \qquad \text{for Method A}$$

$$I_a = 1.00V_{\mathrm{NAA}} - 33.5 \qquad \text{for Method B}$$

where V_{NAA} is the uncompacted voids content measure of particle shape and texture obtained by NAA methods.

CONCLUSIONS

On the basis of the particle shape and texture index values obtained for the various natural and manufactured sands tested using ASTM D3398 and NAA proposed Methods A and B, the following conclusions can be drawn:

1. A particle index value of about 14 divides 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 Methods A and B as well in which uncompacted void content values of 44.5 and 48.3, divide the natural and manufactured sands, respectively.
2. Correlations between the major-fraction, and major-fraction plus second-major-fraction particle indexes with the weighted-average particle index using ASTM D3398 are fairly good for the overall data. This agreement suggests that a particle index value for the major fraction or major fraction

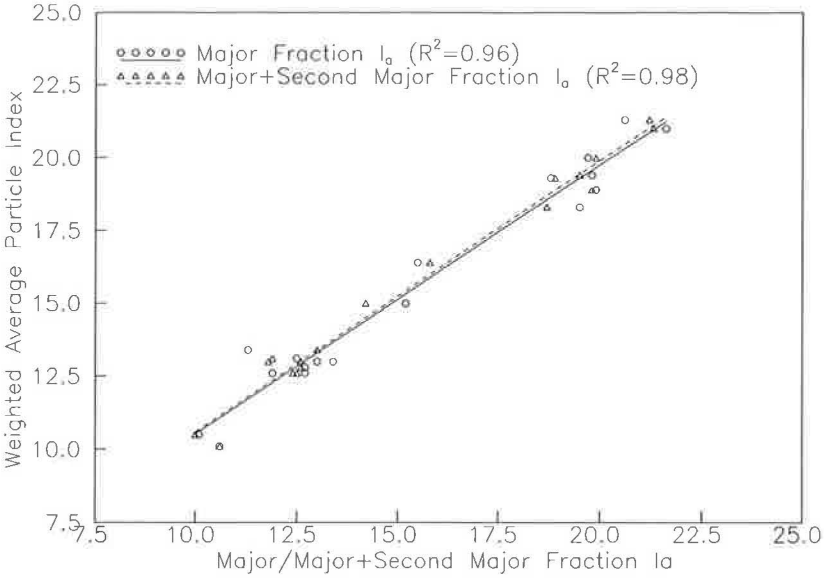

FIGURE 4 Weighted-average particle index versus major-fraction and major-fraction plus second-major-fraction particle indexes (combined data).

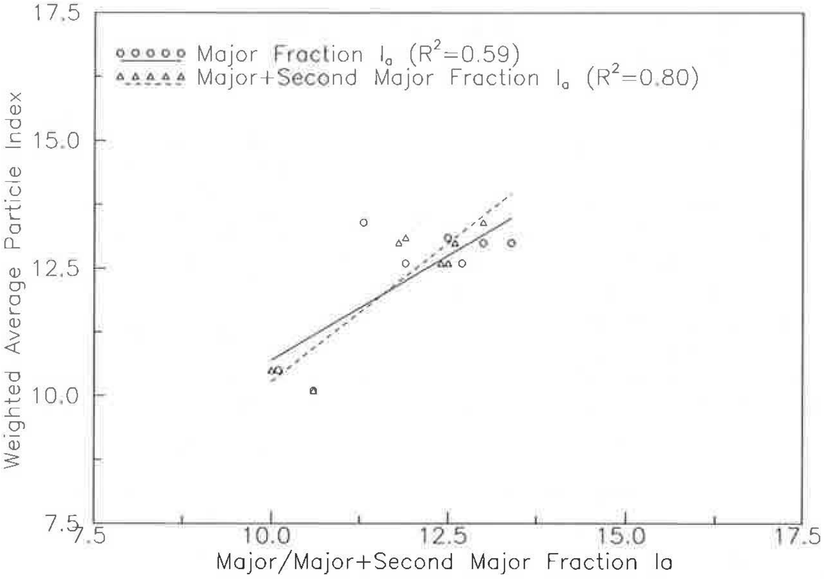

FIGURE 5 Weighted-average particle index versus major-fraction and major-fraction plus second-major-fraction particle indexes (natural sands only).

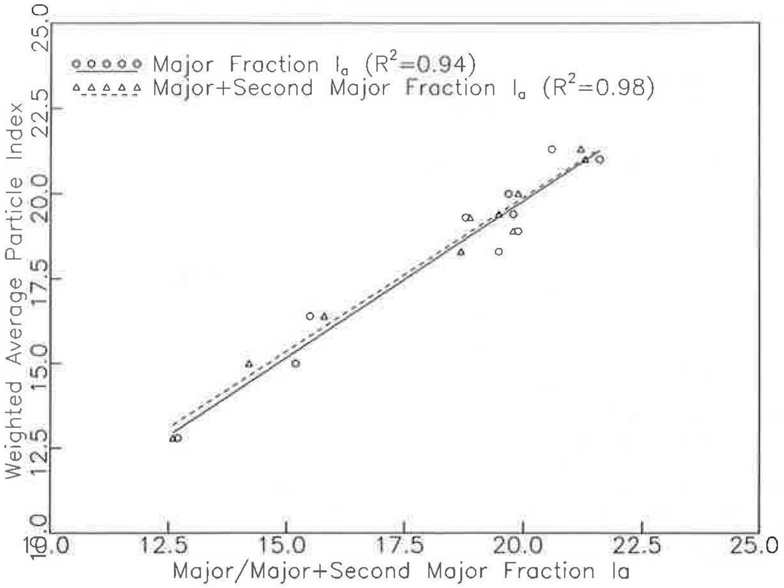

FIGURE 6 Weighted-average particle index versus major-fraction and major-fraction plus second-major-fraction particle indexes (manufactured sands only).

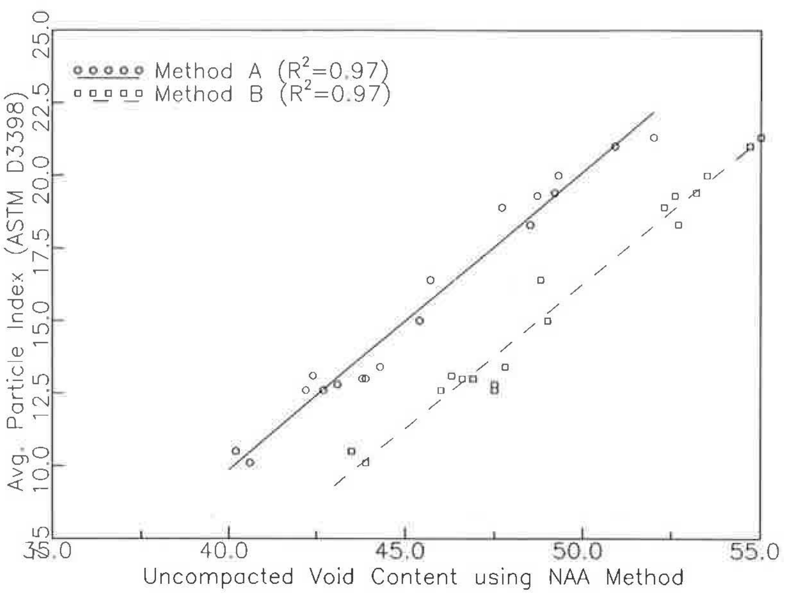

FIGURE 7 Average particle index using ASTM D3398 versus uncompacted void content using NAA Methods A and B.

plus second-major fraction of the fine aggregate may be used as the average particle index for the combined gradation. This result would save time and effort in testing.

3. Both NAA Methods A and B show high correlations ($R^2 = 0.97$) with the ASTM D3398 method. This correlation 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 methods are both straightforward and time saving as compared with ASTM D3398. Equations for computing the ASTM D3398 weighted-average particle index from the NAA method results are described for the aggregates tested in this study.

Currently, research is under way at the National Center for Asphalt Technology, Auburn, Alabama, to correlate the 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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REFERENCES

1. M. Herrin and W. H. Goetz. Effect of Aggregate Shape on Stability of Bituminous Mixes. *HRB Proc.*, Vol. 33, 1954.
2. R. R. Lottman and W. H. Goetz. *Effect of Crushed Gravel Fine Aggregate on the Strength of Asphaltic Surfacing Mixtures.* Circular 63, National Sand Gravel Association, 1956.
3. E. Shklarsky and M. Livneh. The Use of Gravels for Bituminous Paving Mixtures. *Proc., AAPT*, Vol. 33, 1964.
4. J. M. Griffith and B. F. Kallas. Aggregate Voids Characteristics in Asphalt Paving Mixes. *HRB Proc.*, Vol. 36, 1957.
5. P. A. Wedding and R. D. Gaynor. The Effects of Using Crushed Gravel as the Coarse and Fine Aggregate in Dense Graded Bituminous Mixtures. *Proc., AAPT*, Vol. 30, 1961.
6. G. W. Maupin. Effect of Particle Shape and Surface Texture on the Fatigue Behavior of Asphaltic Concrete. In *Highway Research Record 313*, HRB, National Research Council, Washington, D.C., 1970, pp. 55–62.
7. R. B. Moore and R. A. Welke. *Effects of Fine Aggregate on Stability of Bituminous Mixes.* Research Report 78 TB-34-79F, Testing and Research Division, Testing Laboratory Section, Michigan Department of Transportation, 1979.
8. C. R. Foster. Dominant Effect of Fine Aggregate on Strength of Dense-Graded Asphalt Mixes. Special Report 109. HRB, National Research Council, Washington, D.C., 1970, pp. 1–3.
9. G. R. Laughlin. *Limestone Fine Aggregate in Portland Cement Concrete.* Highway Research Laboratory, Lexington, Ky., 1960.
10. *Method of Determining Voids Content, Flow Time, and Percentage Oversize Material in Sand.* Des. C121-69. Central Laboratories, New Zealand Ministry of Works, Wellington, 1969.
11. J. E. Gray and J. E. Bell. *Stone Sand.* National Crushed Stone Association Engineering Bulletin 13, 1964.
12. *Road and Bridge Specifications.* Virginia Department of Highways, Richmond, 1970.
13. *Tentative Method of Test for Uncompacted Void Content of Fine Aggregate.* National Sand and Gravel Association and National Ready-Mix Concrete Association, Washington, D.C., Undated.
14. H. M. Rex and R. A. Peck. A Laboratory Test to Evaluate the Shape and Surface Texture of Fine Aggregate Particles. *Public Roads*, Vol. 29, No. 5, 1956.
15. D. L. Bloem and R. D. Gaynor. Effect of Aggregate Properties on Strength of Concrete. *Journal of American Concrete Institute*, Vol. 60, No. 10, 1963.
16. M. H. Wills, Jr. How Aggregate Particle Shape Influences Concrete Mixing Water Requirement and Strength. *ASTM Journal of Materials*, Vol. 2, No. 4, 1967.
17. I. Ishai and E. Tons. A Concept and a Test Method for a Unified Characterization of the Geometric Irregularity of Aggregate Particles. *ASTM Journal of Testing and Evaluation*, Vol. 5, No. 1, 1977.
18. E. Tons and W. H. Goetz. Packing Volume Concept for Aggregates. In *Highway Research Record 236*, HRB, National Research Council, Washington, D.C., 1968, pp. 76–96.

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