Evaluation of Test Methods Used To Quantify Sand Shape and Texture

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There are no methods or criteria for determining the acceptability of sands for use in asphalt mixtures in terms of their effects on rutting. Some natural sands perform acceptably while others lead to rutting, shoving, and bleeding. In this study, sands were tested using four methods currently used to quantify particle shape and texture. This was done to determine whether they provide information on how the sands will affect mixture performance, in terms of rutting susceptibility. Each method had at least one poor-performing sand that ranked equal to or higher than a good-performing sand. Therefore, no criteria for acceptability could be developed. The methods cannot account for the gradation of the sand and its effect on the optimal binder content of a mixture. However, it may be possible to eliminate very poor sands using certain methods. The gyratory testing machine (GTM) was used to examine the combined effects of shape and texture, gradation, and quantity of sand on the resistances of mixtures to plastic flow. The GTM was not sensitive to the type of sand.

Aggregate shape and texture are major contributing factors to pavement performance. Research has consistently shown the advantage of using more rough-textured fine and coarse aggregates to minimize tenderness and rutting (*1–6*).

The angularity of the fine aggregate in an asphalt mixture has a substantial impact on the ability of the mixture to resist rutting. In general, mixtures that contain natural sands are more susceptible to rutting than mixtures that contain manufactured, crushed fines. Still, mixtures with some types of natural sands have performed acceptably in the field, and performance can depend on the quantity of sand used. It is believed that an excess amount of rounded sand in an asphalt mixture can result in a mixture that is susceptible to rutting, shoving, and bleeding. FHWA's Technical Advisory T5040.27 (*7*) states the following regarding the quality of sand:

> The quality of natural sand varies considerably from one location to another. Since most natural sands are rounded and often contain some undesirable materials, the amount of natural sand as a general rule, should be limited to 15 to 20 percent for high volume pavements and 20 to 25 percent for medium and low volume pavements. These percentages may increase or decrease depending on the quality of the natural sand and the types of traffic to which the pavement will be subjected.

This recommendation is somewhat vague, but tests that can predict performance and set maximum limits for a particular sand are not available.

There is a need for a test method that can predict how a sand will perform in a mixture before it is used. Poor quality sands can then be rejected, or, the quantity used in the mixture can be reduced. There are several tests available for quantifying the particle shape and texture of sands. However, there are no methods or criteria for determining the acceptability of sands for use in asphalt mixtures.

OBJECTIVES

The objectives of this study are as follows:

1. Quantify the particle shape and texture of good- and poor-performing natural sands and manufactured (crushed) sands using four laboratory testing methods: (a) National Aggregate Association's (NAA) Method A, (b) a direct shear test, (c) ASTM Method D3398, entitled Index of Aggregate Particle Shape and Texture, and (d) a method provided by the Michigan Department of Transportation. (Performance and quality in this paper are based on rutting resistance in the field.)
2. Evaluate the ability of these methods to differentiate good from poor quality sands and develop criteria for their acceptability.
3. Examine the combined effects of shape and texture, gradation, and the quantity of sand on the shear susceptibility of asphalt mixtures using the Corp of Engineers gyratory testing machine (GTM). Determine if the GTM can be used to establish an upper limit on the quantity of sand that can be used.

MATERIALS

Ten natural sands and two manufactured sands with known field performances were tested in this study. (All are called sands as opposed to fine aggregate or some other terminology in this study for convenience.) The type, texture, and source of each sand are listed in Table 1. The performances of the natural sands from New Jersey, Wisconsin, White Marsh, Maryland, and Fredericksburg, Virginia, and the performances of the two manufactured sands were determined through past pavement and laboratory studies conducted by FHWA. The performances of the six other natural sands were based on the experiences of the state highway agencies. These sands were reported to yield consistently poor or good performance. This is important because the same traprock coarse aggregate and screenings were used in all mixtures evaluated. The gra-

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TABLE 1 Type, Texture, and Source of Sands

Poor Quality Natural Sands

Sand name	Type and Texture	State
Rheinhart	Subangular to angular quartz sand.	Georgia
A.N. Adcock	Subangular to angular quartz sand.	Georgia
New Jersey	Subangular quartz sand; some spherical particles.	New Jersey
Wisconsin	Rounded, predominantly quartz sand with a variety of other soils and minerals.	Wisconsin
Graham Pit	Subangular to angular quartz sand with a variety of other soils and minerals. Excessively dirty.	Arkansas

Good Quality Natural Sands

Sand name	Type and Texture	State
Anthony Dairy	Angular quartz sand.	Georgia
Oxford Gray	Angular quartz sand.	Georgia
White Marsh	Angular quartz and quartzite sand with 1 percent mica, garnet, and magnetite. A few rounded pieces.	Maryland
Fredericksburg	Angular quartz and quartzite sand.	Virginia
Donnafill	Angular quartz sand with 10 percent dark minerals including garnet, magnetite, and some mica.	Arkansas

Manufactured Sands

Sand name	Type and Texture	State
Manassas Traprock	100 percent crushed diabase.	Virginia
Texas Marble	100 percent crushed calcitic and dolomitic marble.	Maryland

dations and other physical properties of the sands are shown in Tables 2 and 3, respectively.

For the mixtures tested in this study by the GTM, the natural sand was blended with a 7/16-in. (11.1-mm) maximum size traprock coarse aggregate and No. 10 traprock screenings obtained from Manassas, Virginia. This aggregate is commonly used in northern Virginia asphalt surface courses and has been used in sections tested by the Accelerated Loading Facility (ALF) at the Turner-Fairbank Highway Research Center (TFHRC). The properties of the AC-20 binder used in the mixtures are shown in Table 4.

TEST METHODS

A description of each test method is given in this section. Before testing, all sands were washed on a No. 200 sieve to remove most of the dust, dried at 230°F (110°C), and sieved into individual fractions using ASTM Method C136.

Tests for Sand Shape and Texture

Tests used to evaluate sand shape and texture were as follows:

1. NAA Method A [NAA Method A gradation and as-received gradation (from No. 8 to No. 100)],
2. Direct shear test [NAA Method A gradation and as-received gradation (from No. 8 to No. 100)],
3. ASTM Method D3398 (each fraction was tested separately), and
4. Michigan test method [as-received gradation (from No. 8 to No. 100)].

NAA Method A

NAA Method A evaluates shape and texture in terms of the percentage of voids in a dry, loose uncompacted sample (*8*). High voids usually indicate greater angularity and a rougher

TABLE 2 Gradations of Sands

Sand Type	Percent Passing								
	1/2-in	3/8-in	#4	#8	#16	#30	#50	#100	#200
Poor Quality Natural Sand									
Rheinhart	100.0	100.0	100.0	99.9	99.7	92.2	40.6	4.1	0.6
A.N. Adcock	100.0	100.0	99.3	99.0	98.3	91.2	56.6	12.8	4.8
New Jersey	100.0	100.0	100.0	98.1	89.2	64.5	25.8	5.2	0.6
Wisconsin	100.0	100.0	98.8	84.2	67.9	51.0	22.1	6.4	3.1
Graham Pit	100.0	100.0	100.0	100.0	100.0	100.0	93.4	24.5	11.2
Good Quality Natural Sand									
Anthony Dairy	100.0	100.0	99.0	95.6	85.1	64.5	37.7	20.8	11.0
Oxford Gray	100.0	100.0	99.8	98.5	90.9	68.0	35.9	18.5	10.7
White Marsh	100.0	100.0	97.2	86.8	73.2	52.2	19.0	3.9	1.5
Fredericksburg	100.0	100.0	98.7	93.6	81.7	56.8	21.7	5.4	1.8
Donnafill	100.0	100.0	100.0	100.0	99.7	95.3	64.8	40.4	23.6
Manufactured Sand									
Manassas Traprock	100.0	100.0	92.5	67.4	51.9	43.6	33.5	22.2	13.1
Texas Marble	99.4	98.6	97.1	94.0	86.3	66.1	32.9	15.0	7.0

TABLE 3 Gravities and Water Absorptions of Sands

Sand Name	Bulk Dry Specific Gravity	Bulk SSD Specific Gravity	Apparent Specific Gravity	Percent Absorption
Poor Quality Natural Sand				
Rheinhart	2.624	2.636	2.653	0.41
A.N. Adcock	2.610	2.627	2.654	0.62
New Jersey	2.646	2.650	2.657	0.16
Wisconsin	2.680	2.706	2.753	0.99
Graham Pit	2.463	2.518	2.604	2.20
Good Quality Natural Sand				
Anthony Dairy	2.564	2.594	2.646	1.20
Oxford Gray	2.524	2.568	2.640	1.75
White Marsh	2.648	2.666	2.697	0.68
Fredericksburg	2.575	2.611	2.669	1.37
Donnafill	2.620	2.629	2.647	0.53
Manufactured Sand				
Manassas Traprock	2.877	2.907	2.963	1.01
Texas Marble	2.807	2.827	2.864	0.71

TABLE 4 Physical Properties of the Binder

Characteristic	Test Method (AASHTO)	Results	AASHTO Requirements
Penetration (100 g, 5 sec, 25 °C)	T-49	83	60 min
Absolute Viscosity (60 °C, Poise)	T-202	2047	2,000±400 P
Kinematic Viscosity (135 °C, cSt)	T-201	444	300 min
Specific Gravity (25 °C / 25 °C)	T-228	1.026	N.S.
Ductility (5 cm/min), 25 °C, cm)	T-51	150+	N.S.
Flash Point, COC, °C	T-48	285	232 min
Thin Film Oven	T-179		
Weight Loss, percent		0.02	0.5 max
Penetration, (100 g, 5 s, 25 °C)		54	N.S.
Absolute Viscosity, (60 °C, Poise)		4308	8000 max
Kinematic Viscosity (135 °C, cSt)		608	N.S.
Ductility (5 cm/min), 25 °C, cm		150+	50 min

Note: N.S. indicates not specified

texture. Low voids usually indicate more rounded sand. This test is easy to perform and provides fast and repeatable results. NAA Method B is more time-consuming and provides similar results; therefore, it was not used in this study (*6*).

For each sand to be tested, four size fractions are weighed, combined, and then tested. The sample consists of 190 g of sand as follows:

Individual Size Fraction	*Weight (g)*
#8 to #16	44
#16 to #30	57
#30 to #50	72
#50 to #100	17

The sample of sand flows through a funnel with a 0.5-in. (1.25-cm) diameter orifice into a 100-cm^3 calibrated cylinder. The funnel orifice is 4.5 in. (11.25 cm) above the top of the cylinder. The void content is calculated as the difference between the cylinder volume and the absolute, or voidless, volume of the sand collected in the cylinder. This method does not give an alternative approach for sands without sufficient material for one or more of the four fractions. The sands were also tested using the as-received No. 8 to No. 100 sieve fraction instead of the proportions given above.

Direct Shear

Compacted angular sand particles become interlocked and exhibit mechanical resistance to displacement (*9*). This resistance can be measured by the internal friction angle (ϕ) using the direct shear apparatus (*10,11*). This test consists of placing sand in the direct shear device, applying a normal stress to consolidate the sample, and then applying a shearing force to shear the sample. The shear stress is applied gradually until it reaches a maximum and then either remains constant or decreases. Three different normal stresses are used. A graph of normal stress versus maximum shear stress is constructed and the slope of the plot represents the internal friction angle. This angle is a function of sand shape and texture. Both the NAA gradation and the as-received No. 8 to No. 100 sieve fraction were tested.

ASTM Method D3398

The index of aggregate particle shape and texture (I_a) (*12*) is determined for four size fractions: No. 8 to No. 16, No. 16 to No. 30, No. 30 to No. 50, and No. 50 to No. 100. Each fraction is compacted in three layers using 10 drops of a standard tamping rod. The percentage of voids in each size fraction is then calculated. The test is then repeated using 50 drops per layer. The index for each size fraction is calculated using a standard ASTM regression equation, which incorporates data from both compactive efforts. A weighted average index is then calculated based on the proportions of the various sand fractions in the original grading. Some sands tested in this study did not have sufficient material for the No. 8 to No. 16 and No. 16 to No. 30 sizes. Therefore, only two fractions were tested to determine the index.

Michigan Test Method (Modified)

The Michigan Department of Transportation developed test method MTM 118-90, *Test Method for Measuring Fine Aggregate Angularity*, which provides an angularity index, or AI (*13*). The test is performed by placing 100 ml of distilled water into a 250-ml capacity graduated cylinder. A 250-g sample of the No. 8 to No. 30 fraction is poured into the 100 ml water from a constant height of 1 in. (2.5 cm) above the water surface. In this study the as-received No. 8 to No. 100 sieve fraction was tested instead of a No. 8 to No. 30 fraction so that the sand was consistent with the other tests. The sample volume is measured to the nearest ml in the cylinder, and the total volume of the sample plus water is also measured. The volume of solids is calculated as the total volume minus the 100 ml volume of water. The volume of voids in the sample is calculated as the difference between the sample volume and the volume of solids. The angularity void ratio is the ratio of volume of voids to the volume of solids. The angularity index developed by Michigan is calculated as follows:

$$\mathrm{AI} = 10 \times (\text{angularity void ratio} - 0.6)$$

Mixture Tests

Mixture Design

After analyzing the test data from the sand tests, two good and two poor quality natural sands were selected. The Fredericksburg and Oxford Gray sands have a good history of field performance, and the A. N. Adcock and the Wisconsin sands have a poor history of field performance. An expected ranking from good to poor is Fredericksburg, Oxford Gray, A. N. Adcock, and Wisconsin. Thirteen aggregate blends were prepared by using 0, 10, 20, and 30 percent sand by total aggregate weight. The remaining aggregate was the ALF traprock. The aggregates were blended so that the gradations met Virginia DOT specifications for S-5 surface mixtures as closely as possible. At the 30 percent level, the gradations and the voids in the mineral aggregate (VMA) did not always meet specifications. The minus No. 200 dust contents could not be kept constant. This follows current practices used in designing mixtures where different aggregate blends are tried in a design. However, it confounds the experimental design of this study.

Marshall mixture designs using 75 blows were performed to determine the optimum asphalt content (OAC) for each mixture based on a 4 percent air void level. Marshall stabilities were generally above 3,000 lbf (13 344 N), and the flows ranged from 9 to 14. The aggregate blends and OAC are presented in Table 5. The gradations of the blends are given in Table 6.

GTM

The effects of sand particle shape and texture on the shear susceptibility of the mixtures were evaluated using the gyratory stability index (GSI) given by the GTM. The GTM is a combination compaction and shear testing machine. The GSI is the ratio of the maximum gyration angle to the minimum gyration angle that occurs during the test. The gyratory angle is a measure of the gyratory strain. The GSI is related to mixture stability and permanent deformation caused by shear (*14*).

A mixture is compacted by the GTM using a chosen gyration angle that is set using two rollers 180 degrees apart. The rollers then gyrate the specimen in the mold as they circle around an upper flanged mold chuck. A shear susceptible mixture will move in the mold when the refusal density is approached in such a way that the angle increases. This increase is due to the shearing movement of the mixture away from the point of highest force under the gyrating action. The gyration angle does not increase significantly for stable mixtures. Typically, for a stable mixture the GSI value is close to 1.0, and for unstable mixtures the GSI is significantly above 1.1 (*14*).

Some properties that may lead to high shear susceptibility and rutting in pavements are using an excessive binder con-

TABLE 5 Blends for Mixtures Tested Using the GTM

Mix No.	7/16-in (11.1-mm) Traprock, percent	#10 Screenings, percent	Natural Sand, percent and type	Optimum Asphalt Content, percent
1	60	40	0	5.0
2	55	35	10 % A.N. Adcock	4.4
3	60	20	20 % A.N. Adcock	4.5
4	60	10	30 % A.N. Adcock	4.9
5	43	47	10 % Fredericksburg	5.1
6	45	35	20 % Fredericksburg	5.5
7	48	22	30 % Fredericksburg	6.3
8	57	33	10 % Wisconsin	4.4
9	56	24	20 % Wisconsin	4.5
10	52	18	30 % Wisconsin	4.6
11	57	33	10 % Oxford Gray	4.3
12	59	21	20 % Oxford Gray	4.2
13	60	10	30 % Oxford Gray	4.3

TABLE 6 Gradations of Mixtures Tested (Percent Passing)

	Sand Type and Mixture Number												
	Control	A.N. Adcock			Fredericksburg			Wisconsin			Oxford Gray		
Sieve	1	2	3	4	5	6	7	8	9	10	11	12	13
1/2in	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8in	94.7	94.7	94.2	94.2	95.8	95.7	95.4	94.5	94.6	95.0	94.5	94.3	94.2
4	58.7	59.0	55.8	56.0	67.2	66.4	64.2	57.0	57.9	60.9	57.1	56.0	55.6
8	38.3	40.6	39.6	41.9	48.2	48.7	48.4	37.8	39.3	42.9	39.2	40.2	41.8
16	26.6	31.2	33.4	38.0	35.2	37.2	38.7	27.2	29.2	32.7	29.5	32.4	35.8
30	19.8	25.1	28.8	34.1	25.6	26.9	27.7	20.4	22.1	24.7	22.1	24.5	27.1
50	14.8	17.7	19.5	22.4	16.9	16.0	14.7	13.8	13.5	13.9	15.2	15.5	16.1
100	11.0	10.3	8.9	8.2	11.4	9.7	7.8	9.4	8.2	7.5	10.6	10.2	9.9
200	7.8	6.9	5.5	4.7	7.8	6.5	5.0	6.5	5.6	5.0	7.3	6.8	6.5

tent, a rounded coarse aggregate, or a natural sand with little roughness. It was hypothesized that the GSI should be influenced by the type of sand because sands affect the shear resistance of a mixture. Dense-graded mixtures do not always have coarse aggregate skeletons that resist rutting only of themselves. The properties of the sand fraction are very important. Rounded sands with little texture often lead to rutting and can have the same effect on performance as using too much binder. Long-term densification in the field using poor natural sands is often greater than in the laboratory when the Marshall hammer is used to design the mixture.

Testing was performed based on the National Cooperative Highway Research Program (NCHRP) Asphalt-Aggregate Mixture Analysis System (AAMAS) procedure (*15*). (The FHWA at TFHRC is currently evaluating this methodology.) Three specimens were fabricated at the OAC for each mixture. All specimens were initially compacted to an air void level representative of in-place field levels after construction (6 to 8 percent) at 275°F (135°C) with a vertical pressure of 120 psi and a 2-degree angle of gyration (*15*). After initial compaction, the specimens were placed in an oven at 140°F (60°C) for 3 hr. The specimens were then compacted to the refusal density, where there is no reduction in air voids with additional gyrations. The same vertical pressure and angle of gyration were used. The GTM oil-filled roller was used; the air-filled roller was not used. Samples were compacted up to 300 revolutions to reach the refusal density. Sample heights were measured at 25, 50, 75, 100, 200, 250, and 300 revolutions to estimate air void levels. These levels were used to verify that the refusal density was reached.

RESULTS AND DISCUSSION

The results obtained using the tests for sand shape and texture are presented in Tables 7 to 10. A multiple comparison procedure, called Fisher's least significant difference (LSD), was performed to rank the sands. The sands were ranked from 1 to 12, where a ranking of 1 represented the best sand, and a ranking of 12 represented the worst sand. This, according to the tests, is a measure of shape and texture. Sands can be ranked as equal by this statistical method. The sands are also divided into in three categories: poor performance natural sands, good performance natural sands, and manufactured sands. Manufactured sands are also good performance sands and can be considered controls.

NAA Method A

Based on the results in Table 7 using the NAA Method A gradation, poor and good sands divided at a compacted void level around 43.4. However, the poor quality Rheinhart sand ranked higher than the good quality Oxford Gray sand. A *t*-test at a 5 percent significance level showed no significant difference between these two sands. Hence, NAA Method A may not always properly distinguish between poor and good quality sands. The microscopic sand shape and texture information in Table 1 was not extensive enough to evaluate this test in this regard.

The good field performance of the Rheinhart sand is most likely related to both the shape and texture of the particles and its gradation. Table 2 indicates that it only has two sieve sizes. The NAA method cannot account for the effects of gradation on mixture properties.

The results from performing the NAA Method A test using as-received gradations from No. 8 to No. 100 did not rank the sands properly. Some poor quality sands had higher rankings than some good quality sands. The NAA method is based on a comparison of voids. It was concluded that the gradations of the sands being tested must be the same when using this method.

Direct Shear Test

Based on the direct shear results in Table 8 using the NAA gradation, the rounded, poor quality Wisconsin sand ranked higher than all good quality natural sands. Also, the difference between the good quality Oxford Gray sand and the poor quality Rheinhart sand was not significant. The direct shear test appears to be a poor guide for evaluating sand shape and texture and the effects on rutting performance. The test is also time-consuming. The results from performing the direct shear test using as-received gradations from No. 8 to No. 100 did not improve the rankings.

The reason for the high ranking for the Wisconsin sand is unknown. This sand had highly rounded particles and was

TABLE 7 NAA Method A Test Results

Sand Name	NAA Gradation, Uncompacted Voids, %	Ranking	As-Received Gradation, Uncompacted Voids, %	Ranking
Poor Quality Natural Sand				
Rheinhart	43.5	7	45.5	4
A.N. Adcock	42.2	9	43.7	6
New Jersey	41.5	10	43.5	7
Wisconsin	40.1	12	38.4	12
Graham Pit	41.2	11	43.1	9
Good Quality Natural Sand				
Anthony Dairy	44.1	6	41.8	11
Oxford Gray	43.3	8	42.0	10
White Marsh	44.5	5	43.3	8
Fredericksburg	45.3	4	45.1	5
Donnafill	50.7	1	52.0	1
Manufactured Sand				
Manassas Traprock	48.1	2	46.4	3
Texas Marble	46.3	3	47.4	2

well graded. The NAA and Michigan methods indicated that it had low uncompacted voids. One hypothesis is that the sand compacts to a high degree in the shear test, which causes it to resist shear, but this could not be verified.

ASTM Method D3398

As shown by Table 9, poor and good sands divided around a weighted particle index of 11.8. However, the poor quality New Jersey sand had an index equal to the good quality Oxford Gray sand. A *t*-test at a 5 percent significance level showed that the New Jersey sand also had an index statistically equal to the good quality Anthony Dairy sand. Hence, the ASTM method may not always distinguish good from poor quality sands. The microscopic sand shape and texture information in Table 1 was not extensive enough to evaluate this test in this regard.

Michigan Test Method (Modified)

As shown by Table 10, this method did not rank the sands properly and was not a good indicator of performance or sand shape and texture. Like the NAA method, this method is

TABLE 8 Direct Shear Test Results

Sand Name	NAA Gradation, Internal Friction Angle, ϕ	Ranking	As-Received Gradation, Internal Friction Angle, ϕ	Ranking
Poor Quality Natural Sand				
Rheinhart	47.0	10	42.4	12
A.N. Adcock	44.5	11	45.0	10
New Jersey	47.2	9	46.6	8
Wisconsin	51.6	3	53.0	3
Graham Pit	47.2	9	44.5	11
Good Quality Natural Sand				
Anthony Dairy	49.9	5	48.2	7
Oxford Gray	48.8	8	45.9	9
White Marsh	49.8	6	54.7	2
Fredericksburg	49.6	7	51.0	4
Donnafill	51.5	4	49.8	6
Manufactured Sand				
Manassas Traprock	59.3	1	55.7	1
Texas Marble	54.7	2	50.2	5

TABLE 9 ASTM Method D3398 Test Results

Sand Name	Weighted Particle Index I_a	Ranking
Poor Quality Natural Sand		
Rheinhart	11.3	8
A.N. Adcock	10.2	10
New Jersey	11.8	7
Wisconsin	10.4	9
Graham Pit	6.0	11
Good Quality Natural Sand		
Anthony Dairy	12.7	6
Oxford Gray	11.8	7
White Marsh	14.0	5
Fredericksburg	14.9	4
Donnafill	19.2	1
Manufactured Sand		
Manassas Traprock	17.8	2
Texas Marble	15.5	3

based on a comparison of voids. It was concluded that the gradations of the sands must be the same in a test where the comparison is based on voids. Using the specified No. 8 to No. 30 fraction may possibly provide better results than the No. 8 to No. 100 fraction used in this study.

GTM Results

The results from testing mixtures using the GTM are presented in Table 11 and Figure 1. The GSI did not agree with expected field performance. It was expected that the GSI for the poor sands would be significantly higher than for the good sands and they would increase with increasing percentage of sand. Based on the data, the GTM method using the oil-filled roller was not sensitive to the type of sand in the mixture evaluated. Hence, the GSI cannot be used to distinguish between poor and good quality sands, at least when using the oil-filled roller.

The GSI for the good quality Fredericksburg sand at a 20 percent level was 1.09. This was the actual mixture used in the ALF pavements at TFHRC. This mixture was not susceptible to rutting when tested by the ALF machine. There was no statistically significant difference between this GSI and the GSI for the poor quality A. N. Adcock and Wisconsin sands. There was also no difference between the GSI for these three sands at a 10 percent level.

The GSI for the good quality Fredericksburg sand at a 30 percent level was 1.18. This GSI was statistically higher than for the poor quality A. N. Adcock and Wisconsin sands. This

TABLE 10 Michigan Test Method Results

Sand Name	Angularity Index	Ranking
Poor Quality Natural Sand		
Rheinhart	2.06	4
A.N. Adcock	1.48	8
New Jersey	1.22	9
Wisconsin	0.24	12
Graham Pit	2.03	5
Good Quality Natural Sand		
Anthony Dairy	0.93	11
Oxford Gray	1.07	10
White Marsh	1.50	7
Fredericksburg	1.89	6
Donnafill	3.73	1
Manufactured Sand		
Manassas Traprock	2.83	2
Texas Marble	2.56	3

TABLE 11 GTM Results

Mixture No.	Natural Sand	GSI	REFUSAL AIR VOIDS, PERCENT
1	0	1.01	3.6
2	10 % A.N. Adcock	1.13	2.2
3	20 % A.N. Adcock	1.10	1.9
4	30 % A.N. Adcock	1.05	2.0
5	10 % Fredericksburg	1.11	2.6
6	20 % Fredericksburg	1.09	2.8
7	30 % Fredericksburg	1.18	1.3
8	10 % Wisconsin	1.17	2.3
9	20 % Wisconsin	1.18	1.7
10	30 % Wisconsin	1.08	2.8
11	10 % Oxford Gray	1.08	2.8
12	20 % Oxford Gray	1.04	3.1
13	30 % Oxford Gray	1.08	3.0

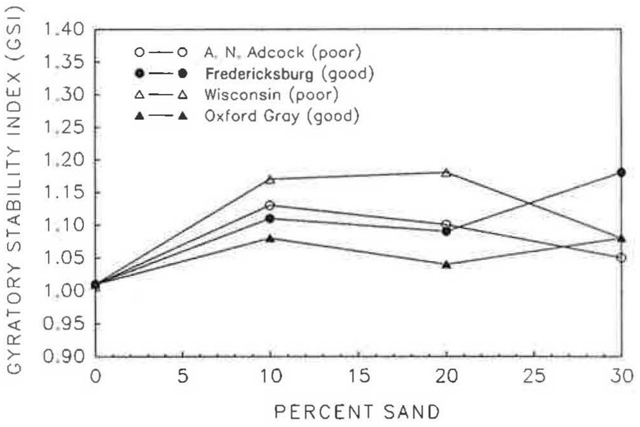

FIGURE 1 GSI versus percent sand.

higher GSI and the low refusal air voids of 1.3 percent could be due to the higher binder content compared to the other mixtures. Binder contents are given in Table 5. A reason for the slight decrease in GSI and slight increase in refusal air voids for the poor quality Wisconsin sand at the 30 percent level was not apparent. Most likely it is related to differences in the aggregate gradations.

Correlations Between the Tests for Sand Shape and Texture

Correlations were performed between each test and the standard ASTM Method D3398. The coefficients of determination (r^2) are presented in Table 12. NAA Method A was the only method showing a good correlation with ASTM Method D3398. Hence, it might be possible to replace the ASTM method with this method. The NAA method is quick and easy to perform, whereas the ASTM method is very time-consuming. A linear regression model was developed to relate NAA Method A to ASTM Method D3398. The linear regression model is as follows:

$$I_a = -34.7 + 1.08\,(V)$$

where I_a is the weighted particle index and V represents the uncompacted voids.

The shift between the methods is 34.7 when using a slope of 1.0. A linear regression model developed by Kandhal et al. (*6*) is as follows:

$$I_a = -31.2 + 1.03\,(V)$$

The shift between the methods is 31.1 when using a slope of 1.0. Both models have approximately an equal slope. How-

TABLE 12 Coefficient of Determination (r^2) Between ASTM Method and the Other Sand Tests Used in This Study

	r^2
NAA Method A (NAA gradation)	0.83
NAA Method A (As received gradation #8 TO #100)	0.50
Direct Shear (NAA gradation)	0.46
Direct Shear (As received gradation #8 TO #100)	0.36
Michigan Test Method	0.40

ever, the difference of 3.6 between the shifts of the models is significant. Thus the particle indices would be different. Hence, for a reliable model to be developed, more sands should be tested.

CONCLUSIONS

1. Using NAA Method A, with the NAA specified gradation, poor and good sands divided at a compacted void level around 43.4. Using ASTM Method D3398, they divided around a weighted particle index of 11.8. However, neither method properly separated the poor and good quality sands. Both methods were better than the other methods evaluated. The microscopic sand shape and texture information was not extensive enough to evaluate these tests in this regard.

2. The results from performing the NAA Method A test using as-received gradations from No. 8 to No. 100 did not rank the sands properly and was not a good indicator of performance or sand shape and texture. The NAA method is based on a comparison of voids. It was concluded that the gradations of the sands being tested must be the same when using this method.

3. The direct shear method did not rank the sands properly and does not appear to be a good indicator of performance or sand shape and texture. The test is also time-consuming.

4. The modified Michigan Test Method (MTM 118-90), which used as-received gradations, did not rank the sands properly and was not a good indicator of performance or sand shape and texture. Like the NAA method, this method is based on a comparison of voids, and the gradations of the sands being tested must be the same when using this method.

5. The GTM results using the oil-filled roller did not agree with expected field performance. The method was not sensitive to the type of sand. Hence, the GSI cannot be used to distinguish between poor and good quality sands, at least when the oil-filled roller is used. Other tests, such as the creep test or rut testing machines, may aid in understanding the behavior of sands added to asphalt mixtures.

6. NAA Method A, using the NAA specified gradation, is the only method that had a good correlation with the standard ASTM Method D3398. It may be possible to replace the ASTM method with this method. The NAA method is quick and easy to perform, whereas the ASTM method is very time-consuming.

7. Although none of the tests ranked the sands perfectly, it still may be possible to eliminate very poor sands using the NAA and ASTM methods. Like many other tests used in the evaluation of asphalt mixtures and their components, there will be a gray region, where data from some good and some poor performing sands will not rank properly.

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