Evaluation of Natural Sands Used in Asphalt Mixtures

KEVIN D. STUART AND WALAA S. MOGAWER

Five tests for sands were studied to determine whether they could distinguish good-performing from poor-performing natural sands. Performance was based on the effects of the sands on asphalt pavement rutting. The methods were National Aggregate Association Method A, direct shear, ASTM Method D3398, Michigan Department of Transportation Method MTM 118-90, and a flow rate method. The best methods for predicting how the sands would perform in pavements were the flow rate method and ASTM Method D3398. The combined effect of shape, texture, gradation, and quantity of sand on the susceptibility of an asphalt mixture to rutting was evaluated using Marshall stability and flow, the U.S. Army Corps of Engineers gyratory testing machine, Georgia loaded-wheel tester, and the French pavement rutting tester. None of these tests differentiated the poor- from the good-quality sands in the particular mixture tested.

Asphalt paving mixtures containing natural sands are generally more susceptible to rutting, shoving, and bleeding than mixtures containing 100 percent manufactured (crushed) fine aggregates. However, some natural sands have performed as well as manufactured fine aggregates. Natural sands range in shape from very round to angular, depending on their mineralogy and geologic history. The performance of an asphalt mixture can also depend on the quantity of sand used.

The Federal Highway Administration's (FHWA's) Technical Advisory T5040.27 provides the following recommendations regarding natural sands:

> 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. (*1*)

This recommendation is somewhat vague, but tests that can predict the pavement performances of mixtures containing natural sands and set maximum allowable percentages for these sands are not available.

OBJECTIVES

The primary objective of this study was to evaluate the ability of methods that measure the particle shape and texture of sands to distinguish good- from poor-performing sands. Performance was based on the effects of the sands on pavement rutting. By using these tests, poor-quality sands could be rejected or only low percentages used in a mixture. Five methods were evaluated:

- National Aggregate Association (NAA) Method A,
- Direct shear,
- ASTM Method D3398,
- Michigan Department of Transportation Method (MTM) 118-90, and
- Flow rate.

A second objective was to examine the combined effect of shape, texture, gradation, and quantity of sand on the susceptibility of an asphalt mixture to rutting using Marshall stability and flow, the U.S. Army Corps of Engineers gyratory testing machine (GTM), Georgia loaded-wheel tester (GLWT), and the French Laboratoires des Ponts et Chaussées (LPC) pavement rutting tester. Part of this objective was to learn whether the GTM can be used to determine how much natural sand can be incorporated into a mixture.

EVALUATION OF SAND TESTS

Types of Sands

Four good- and five poor-quality natural sands and three good-quality manufactured fine aggregates were tested in this study. (All these materials are called sands in this paper for convenience.) The sands were tested for gradation and specific gravity, washed through a 0.075-mm sieve to remove most of the dust, dried at 110°C, and sieved into the size fractions needed for the methods. Gradations are given in Table 1.

The pavement performances of the Virginia and Maryland manufactured sands, the poor-quality New Jersey and Wisconsin sands, and the good-quality White Marsh and Fredericksburg sands were determined through previous studies conducted by FHWA. The performances of the other sands were based on the experiences of the state highway agencies. These sands consistently performed either poorly or well when used in mixtures subjected to high traffic volumes. This requirement was important because only one coarse aggregate was to be used in the mixture evaluation. The two poor-quality sands received from the Georgia Department of Transportation (GDOT) are no longer used in pavements that carry more than 2,000 vehicles per day. Up to 20 percent sand is allowed when the traffic is 1,000 to 2,000 vehicles per day. The Arkansas State Highway and Transportation Department allows up to 15 percent natural sand in mixtures subjected to high traffic volumes.

K. D. Stuart, Federal Highway Administration, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, McLean, Va. 22101-2296. W. S. Mogawer, Department of Civil Engineering, University of Massachusetts Dartmouth, North Dartmouth, Mass. 02747.

TABLE 1 Gradations of the Sands

	Percent Passing (mm)								
	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075
Poor Quality Natural Sand									
Rheinhart, GA	100.0	100.0	100.0	99.9	99.7	92.2	40.6	4.1	0.6
A. N. Adcock, GA	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, AR	100.0	100.0	100.0	100.0	100.0	100.0	93.4	24.5	11.2
Good Quality Natural Sand									
Anthony Dairy, GA	100.0	100.0	99.0	95.6	85.1	64.5	37.7	20.8	11.0
Oxford Gray, GA	100.0	100.0	99.8	98.5	90.9	68.0	35.9	18.5	10.7
White Marsh, MD	100.0	100.0	97.2	86.8	73.2	52.2	19.0	3.9	1.5
Fredericksburg, VA	100.0	100.0	98.7	93.6	81.7	56.8	21.7	5.4	1.8
Manufactured Sand									
Manassas Traprock, VA	100.0	100.0	96.8	75.5	52.4	38.0	27.4	19.5	13.3
Texas Marble, MD	99.4	98.6	97.1	94.0	86.3	66.1	32.9	15.0	7.0
Donnafill, AR	100.0	100.0	100.0	100.0	99.7	95.3	64.8	40.4	23.6

Microscopic analyses showed that all good-quality sands were angular, whereas all poor-quality sands were rounded, subangular, or subangular to angular.

Size fractions between the 2.36- and 0.150-mm sieves were tested. The variable performances of natural sands are associated with sizes within this range. The NAA method also specifies this range.

The Michigan method was also performed on the 2.36- to 0.600-mm size fraction because the method specifies this fraction. As reported elsewhere, this size fraction did not provide data that agreed with pavement performance (*2*). One reason for this may be that several sands had very little material retained on the 0.600-mm sieve, and thus the data may not have been representative of the entire sand. The Michigan method discussed in this paper is a modified method because size fractions between 2.36 mm and 0.150 mm were tested.

Data were generated for both as-received and NAA gradations. "As-received gradation" means that the sands were proportioned according to the as-received gradations after removing the plus 2.36-mm and minus 0.150-mm size fractions. "NAA gradation" means that the sands were proportioned as specified by NAA Method A. In this method, a 190-g sample of sand is graded as follows: 44 g of 2.36 to 1.18 mm, 57 g of 1.18 to 0.600 mm, 72 g of 0.600 to 0.300 mm, and 17 g of 0.300 to 0.150 mm. A standard gradation is needed because this method relates shape and texture to void contents. These void contents would be a function of gradation and shape and texture if different gradations were used.

The data for as-received gradations are reported elsewhere (*2,3*). These gradations provided similar results for the ASTM D3398 and direct shear methods but poorer results in the NAA Method A, Michigan, and flow rate methods. A standard gradation should be used in the latter three methods.

Some sands did not contain sufficient material for testing the size fraction above 1.18 or 0.600 mm. NAA Method A does not include an approach for testing sands that do not have all four size fractions. When any of the size fractions were missing, the required masses for these missing fractions were eliminated. The sand was then proportioned according to the masses specified for the remaining fractions. Therefore, all of the sands did not have the same gradation.

The volume of each sand must be determined for the NAA, ASTM D3398, and flow rate methods by dividing the mass of the sand by its bulk-dry specific gravity. The specific gravity of each individual size fraction present in amounts of 10 percent or more by mass was measured as required by ASTM D3398. This is very time-consuming, but it is specified because individual size fractions are tested in this method; the specific gravities of some materials, such as slags, can vary significantly from size fraction to size fraction.

Methods Used To Measure Sand Shape and Texture

NAA Method A

This method evaluates shape and texture in terms of the percentage of voids in a dry, uncompacted sample (*4*). High voids usually indicate high angularity and a rough texture. Low voids usually indicate the sand is rounded and smooth. (NAA Method B, which tests individual size fractions, was not evaluated.)

The blend of sand is poured through a funnel into a weighed, 100-cm^3 calibrated cylinder. Excess sand on top of the cylinder is struck off, and the mass of the collected sand is determined. The volume of the collected sand is calculated by dividing this mass by the bulk-dry specific gravity. The uncompacted void content is the difference between the volume of the cylinder and the volume of the collected sand. The percent uncompacted voids is then calculated on the basis of the volume of the cylinder.

Direct Shear

The resistances of compacted sands to displacement can be measured by the internal friction angle ϕ using the direct shear apparatus (*5,6*). The blend of sand is placed in the apparatus and a normal stress is applied to consolidate it. A shear stress is then gradually applied until it reaches a maximum. Three different normal stresses are used. A graph of normal stress versus maximum shear stress is constructed, and the slope of the plot represents ϕ.

ASTM Method D3398

ASTM Method D3398 calculates a particle index called I_a for each size fraction (*7*). Each fraction is compacted in a calibrated mold in three layers using 10 drops of a standard tamping rod. The percentage of voids in each fraction is the difference between the volume of the mold and the volume of the sand. The volume of the sand is the mass of the sand in the mold divided by the bulk-dry specific gravity. The method is then repeated using 50 drops per layer. The I_a for each size fraction is calculated as follows, using both the percentage of voids at 10 drops (V_{10}) and the percentage of voids at 50 drops (V_{50}):

$$I_a = 1.25V_{10} - 0.25V_{50} - 32.0$$

A weighted average I_a is then calculated on the basis of the percentages of the sand fractions in the grading.

This method uses the same concept as NAA Method A in that shape and texture are based on uncompacted void contents. The equation calculates the voids for an uncompacted state and subtracts the voids for polished, single-sized spheres, which is 32.0 percent (*7*). Testing each size fraction eliminates the need for a standard gradation but makes the method time-consuming.

Michigan Test Method

MTM 118-90 provides an angularity index (AI) (*8*). The concept of determining shape and texture on the basis of uncompacted voids is also used by this method.

The method places 100 mL of distilled water into a 250-mL-capacity graduated cylinder and pours 250 g of sand into it. The volume of the sample in water (solids plus voids filled with water) and the total volume (volume at the water level) are measured to the nearest 1 mL. The volume of the solids is equal to the total volume minus the 100 mL of water. The volume of voids is equal to the volume of the sample in water minus the volume of the solids. The angularity void ratio is the ratio of the volume of voids to the volume of solids. The AI is then calculated as follows:

$$AI = (10.0)(\text{angularity void ratio} - 0.6)$$

This method has an advantage over the NAA, ASTM, and flow rate methods in that the bulk-dry specific gravity of the sand is not needed. The volume of the sand is determined through the displacement of water. However, the volume of any absorbed water will be included in the volume of the voids.

Flow Rate Method

This method was developed by the Bureau of Public Roads (now FHWA) but was later modified (*9–11*). It provides a shape-texture index (STI).

The method was performed according to the NAA procedure using the NAA apparatus with the exceptions that 500 g of sand was used instead of 190 g and the time the sand needed to flow out of the funnel was recorded instead of determining its uncompacted void content (*11*).

The flow rate of the sand is calculated by dividing the volume of the sand (cm^3) by the flow time (sec), which is the time needed by the sand to flow out of the funnel. The volume of the sand is calculated by dividing its 500-g mass by the bulk-dry specific gravity. An STI is calculated by dividing the flow rate for a standard set of round balls by the flow rate for the sand. Therefore, the STI of a sand is proportional to its flow rate. The flow rate for the standard set of balls used in this study was 13.70 (*11*).

Both the STIs and the flow times were used to evaluate the sands. Using the flow time does not account for the variations in the volumes of the sands.

Both individual size fractions and the blends of sands were tested, but testing individual size fractions did not affect the conclusions, required more sand, and was more time-consuming. The data using individual size fractions are reported elsewhere (*2*).

Results and Discussion

The sands were ranked from 1 to 12 according to the average value. A ranking of 1 indicates that the sand was most angular or rough textured according to the method. An analysis of variance and Fisher's least significant difference statistical procedures were used to determine whether any of the poor-quality natural sands ranked better than or equal to any of the good-quality natural or manufactured sands at a 95 percent confidence level. The test results are given in Table 2.

NAA Method A

The poor-quality Graham Pit sand ranked the same as the good-quality White Marsh sand. Thus, NAA Method A was slightly deficient in its ability to determine quality. The Graham Pit sand lacked both size fractions above 0.600 mm. Poor- and good-quality sands will divide at an uncompacted void content around 44.7 percent.

Direct Shear

The poor-quality Wisconsin sand ranked higher than all good-quality natural sands. There was also no significant difference between the poor-quality New Jersey sand and the good-quality Oxford Gray sand. The ability of this method to quantify shape and texture was not as good as the other methods evaluated in this study. This method was also time-consuming.

No reason for the high ranking for the Wisconsin sand was known. This sand had highly rounded particles and was well graded. It was hypothesized that the sand compacted to a high degree during the procedure, causing it to resist shear. Size fractions may have to be tested individually using this method.

ASTM Method D3398

All of the poor-quality sands statistically ranked lower than all of the good-quality sands. Poor- and good-quality sands will divide at a weighted average I_a between 11.7 and 13.9.

TABLE 2 Results of Sand Tests and Rankings

	NAA Method A, Percent Uncompacted Voids		Direct Shear, Internal Friction Angle ϕ		ASTM D 3398, Weighted Average Particle Index I_a		Michigan Angularity Index		Flow Rate Method			
									Shape-Texture Index (STI)		Flow Time	
Poor Quality Natural Sand												
Rheinhart	43.6	8	47.0	10	11.7	8	0.4	11	0.99	9	13.8	9
A. N. Adcock	42.7	9	44.5	11	10.7	11	1.2	8	0.98	10	13.6	10
New Jersey	41.5	10	47.2	9	11.6	9	0.8	9	1.04	7	14.4	8
Wisconsin	40.4	11	51.6	3	10.8	10	0.7	10	1.01	8	13.8	9
Graham Pit	44.7	7	47.2	9	10.1	12	1.6	6	0.79	11	12.5	11
Good Quality Natural Sand												
Anthony Dairy	45.0	6	49.9	5	13.9	7	1.6	6	1.12	5	16.2	4
Oxford Gray	45.5	5	48.8	8	14.0	6	2.1	3	1.06	6	15.9	5
White Marsh	44.7	7	49.8	6	14.5	4	1.4	7	1.12	5	15.5	7
Fredericksburg	46.3	3	49.6	7	15.8	3	1.8	5	1.15	4	16.5	3
Manufactured Sand												
Manassas Traprock	47.9	2	59.3	1	17.5	2	2.8	2	1.34	1	17.0	1
Texas Marble	45.8	4	54.7	2	14.3	5	1.9	4	1.21	3	15.6	6
Donnafill	50.6	1	51.5	4	18.9	1	3.5	1	1.22	2	16.8	2

Michigan Test Method

The poor-quality Graham Pit sand ranked higher than the good-quality White Marsh sand and was statistically equal to the good-quality Anthony Dairy sand. This method was not as accurate as the ASTM D3398 and the flow rate methods. The Graham Pit sand lacked both size fractions above 0.600 mm.

Flow Rate Method

All of the poor-quality sands statistically ranked lower than all of the good-quality sands according to the STIs and flow times. Poor- and good-quality sands will divide at an STI around 1.05 and at some flow time between 14.4 and 15.5.

Obtaining the flow times is less time-consuming than obtaining STIs because the bulk-dry specific gravities of the sands are not needed. Even though the flow times do not account for the variations in the volumes of the sands, they differentiated the poor- from the good-quality sands better than the STIs. A reason for this was not apparent.

MIXTURE STUDY

Types of Mixtures

The good-quality Fredericksburg and Oxford Gray sands and the poor-quality A. N. Adcock and Wisconsin sands were tested in mixtures. The A. N. Adcock sand consistently provided poor rankings according to the sand tests, and the Wisconsin sand was the most rounded sand. Each sand was blended with No. 10 traprock screenings and an 11.1-mm traprock coarse aggregate. This aggregate was used in pavements tested by the accelerated loading facility (ALF) machine located at the FHWA Turner-Fairbank Highway Research Center. The No. 10 traprock screenings are the Manassas traprock material that was tested for shape and texture.

Twelve aggregate blends for the four natural sands were prepared by using 10, 20, or 30 percent natural sand by total aggregate mass. These percentages provided natural sand contents of 28, 56, and 77 percent in the 2.36- to 0.150-mm size fraction using the poor-quality A. N. Adcock sand and contents of 27, 50, and 75 percent using the poor-quality Wisconsin sand. One control aggregate blend having no natural sand was also prepared. The gradations of the blends are given in Table 3.

The aggregates were blended by adjusting the percentages of coarse aggregate and screenings according to the percentage of natural sand. This duplicates what is done in practice. However, this provided different gradations, including different dust contents. This could confound the experimental design. For example, the decrease in dust content with increasing natural sand content could itself increase rutting potential. It was assumed that the effects of the natural sands would still be apparent, but if the data were difficult to interpret, other approaches for blending the aggregates would be tried. (Alternative approaches would be to equalize the dust contents or the entire gradation.) The asphalt was an AC-20.

Mixture Tests

Mixture Design

The mixtures were designed by the 75-blow Marshall method. Specimens tested for rutting were prepared at the asphalt contents corresponding to a 4 percent air void level.

GTM

The rutting susceptibilities of the 13 mixtures were evaluated by measuring the gyratory stability index (GSI) and the gyratory elas-

TABLE 3 Aggregate Gradations (Percent Passing) for the Mixtures

Sieve Size (mm)	0 %	A. N. Adcock Sand 10 %	A. N. Adcock Sand 20 %	A. N. Adcock Sand 30 %	Fredericksburg Sand 10 %	Fredericksburg Sand 20 %	Fredericksburg Sand 30 %	Wisconsin Sand 10 %	Wisconsin Sand 20 %	Wisconsin Sand 30 %	Oxford Gray Sand 10 %	Oxford Gray Sand 20 %	Oxford Gray Sand 30 %
12.5	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
9.5	94.2	94.7	94.2	94.2	95.9	95.7	95.4	94.5	94.6	95.0	94.5	94.3	94.2
4.75	55.3	59.0	55.8	56.0	67.2	66.0	64.2	57.6	58.4	61.4	57.7	56.6	56.2
2.36	34.9	40.6	39.6	41.9	48.2	48.7	48.4	37.8	39.3	42.9	39.2	40.2	41.8
1.18	24.3	31.2	33.4	38.0	35.2	37.2	38.7	27.2	29.2	32.7	29.5	32.4	35.8
0.600	18.1	25.1	28.8	34.1	25.6	26.9	27.8	20.4	22.1	24.7	22.1	24.5	27.1
0.300	13.7	17.7	19.5	22.4	17.0	16.0	14.7	13.8	13.5	13.9	15.2	15.6	16.2
0.150	10.2	10.3	8.9	8.2	11.4	9.7	7.8	9.4	8.2	7.5	10.6	10.2	9.9
0.075	7.2	6.9	5.5	4.7	7.8	6.5	5.0	6.5	5.6	5.0	7.3	6.8	6.5
NAA Method A, Percent Voids (Min = 44.7)		45.6 Pass	43.5 Fail	42.2 Fail				46.1 Pass	44.8 Pass	42.2 Fail			
STI (Min = 1.05)		1.23 Pass	1.17 Pass	1.09 Pass				1.24 Pass	1.17 Pass	1.09 Pass			
Flow Time, s (Min Between 14.4 and 15.5)		16.1 Pass	15.7 Pass	14.8 **				15.8 Pass	15.0 **	14.5 **			

Min = Minimum criterion established in this study.
** = Pass/fail could not be established.

toplastic index (GEPI) using the U.S. Army Corps of Engineers GTM, Model 6B4C. The GTM is a combination compaction and plane strain shear testing machine that applies stresses simulating pavement conditions. The GTM provides a gyratory angle that is a measure of shear strain.

The GSI is the ratio of the maximum angle that occurs at the end of the test to the minimum intermediate angle. It is a measure of shear susceptibility at the refusal, or ultimate, density. The GSI at 300 revolutions is close to 1.00 for a stable mixture and is significantly above 1.10 for an unstable mixture (*12*).

The GEPI is the ratio of the minimum intermediate angle to the initial angle. A GEPI of 1.00 indicates high internal friction. A GEPI significantly above 1.00 indicates lower internal friction due to rounded aggregates. (The manufacturer suggests using an acceptable range of 1.00 to 1.50 and a marginal range of 1.51 to 1.65.) A GEPI below 1.00 indicates that the aggregate is deteriorating.

The GTM was operated in accordance with the National Cooperative Highway Research Program's Asphalt-Aggregate Mixture Analysis System (*13*). The diameter of each specimen was 101.6 mm, and the heights after compaction were approximately 63.5 mm. A vertical pressure of 0.827 MPa, a 0.035-radian gyratory angle, and the oil-filled roller were used.

Specimens were initially compacted to a 6 percent air void level at 143°C. The specimens in their molds were then placed in an oven at 60°C for 3 hr. They were then compacted to refusal density at 60°C using 300 revolutions. A trace of the gyratory angle versus revolutions was obtained to determine the maximum and minimum intermediate angles.

GLWT

Rutting susceptibilities were also evaluated by the GLWT, shown in Figure 1. The control mixture and the four mixtures containing 20 percent natural sand were tested. Twenty percent is the limit recommended for mixtures subjected to heavy traffic by the FHWA advisory (*1*).

The GLWT tests a beam for permanent deformation at 40.6°C. Each beam is 76.2 mm in width and thickness and 381 mm in length. The air voids of the beams ranged from 4.4 to 5.1 percent. These voids were slightly above the target level of 4.0 percent, but the densities were within 97 percent of the Marshall design densities as recommended by GDOT.

The beams were cured for 7 days at room temperature and for 24 hr at 40.6°C. The sides of a beam are confined by steel plates during the test except for the top 12.7 mm. A 690-kPa, pressurized, stiff rubber hose is positioned across the top of the beam and a loaded steel wheel runs back and forth on top of this hose for 8,000 cycles to create a rut. One cycle is two passes of the wheel.

The load was found to vary with the direction of travel. When the wheel was moving from right to left, the load was approximately 740 N at the center of the beam, whereas it was 630 N when moving left to right. Across the central region of the beam

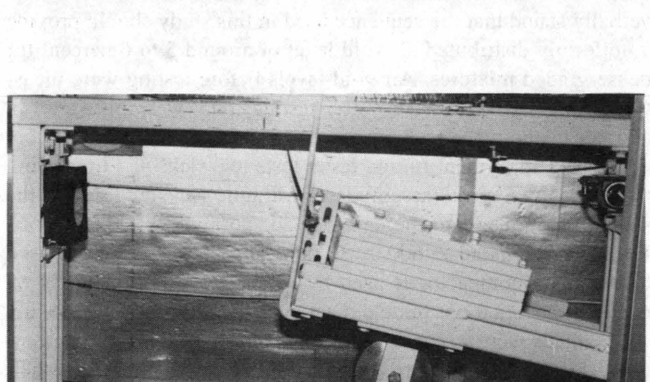

FIGURE 1 GLWT.

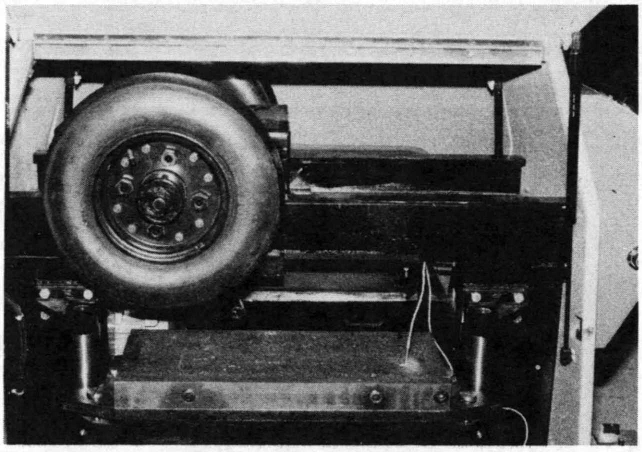

FIGURE 2 LPC pavement rutting tester.

where the deformations are recorded, each of these loads had a variation of less than 5 percent.

Deformations are measured at the center of the beam, 51 mm left of the center, and 51 mm right of the center. The data are averaged. If the average rut depth for three replicate beams exceeds 7.6 mm, the mixture is considered susceptible to rutting (*14*). Testing one beam requires 4 hr.

LPC Pavement Rutting Tester

Rutting susceptibilities were also evaluated by the LPC pavement rutting tester, shown in Figure 2. The machine tests a slab for permanent deformation at 60°C. Each slab had a length of 500 mm, a width of 180 mm, and a thickness of 50 mm.

The slabs were fabricated using the LPC plate compactor. Each slab is compacted in a steel mold using a smooth, reciprocating, pneumatic rubber tire that has a diameter of 415 mm and a width of 109 mm. Various sequences of different compactive efforts, tire pressures, and positions of the tire relative to the width of a slab are used to compact a slab. These parameters depend on the thickness of the slab and the desired air-void level. The manufacturer verbally stated that the sequence used in this study should provide a uniformly distributed air-void level of around 5 to 6 percent for dense-graded mixtures. Air-void levels before testing were measured using the entire slab. After testing, they were measured in and out of the wheelpath after sawing.

The LPC pavement rutting tester tests two slabs at a time using two reciprocating tire assemblies. Hydraulic jacks underneath the slabs push upward to create the load, normally 5000 ± 50 N. Each tire is inflated to 600 ± 30 kPa. The same type of tire used by the plate compactor is used by this tester. Approximately 67 cycles are applied per minute. One cycle is two passes of the tire.

The slabs were cured at room temperature in their molds for 4 days, then placed in the pavement rutting tester and tested in their molds. Initially, 1,000 cycles are applied at 25°C to densify the mixture and to provide a smoother surface. The height of each slab is then calculated by averaging measurements taken at 15 specified positions using a depth gauge with a resolution of 0.1 mm. This average height is considered the initial height, or point of zero rut depth. The slabs were then heated to 60°C for 6 hr. The tester was started, and the average rut depths at 30, 100, 300, 1,000, and 3,000 cycles were measured. To apply 3,000 cycles, 2 to 2.5 hr is needed.

A mixture is acceptable if the average rut depths at 1,000 and 3,000 cycles are less than or equal to 10 and 20 percent of the thickness of the slab, respectively. Slopes for different mixtures taken from log rut depth versus log cycles plots can also be compared. Rut-susceptible mixtures generally have higher slopes.

Results and Discussion

Mixture Design

Mixture design properties are given in Table 4. The Marshall stabilities of 12 out of 13 mixtures were above the minimum stability of 8006 N required for heavy traffic levels (*15*). The mixture containing the poor quality A. N. Adcock sand at a 30 percent level was slightly below 8006 N. (State highway specifications use either a minimum stability of 8006 N or 6670 N.) All flows met the required limits of 8 to 14 (*15*). There was a slight trend of decreasing flow with increasing natural sand content. An opposite trend would be expected, especially since the dust contents also decreased with increasing natural sand content. This anomaly could not be explained from the data collected.

GTM

The GTM results are given in Table 5. The variation in GEPI from mixture to mixture was small, and all GEPIs were less than 1.50. The GSIs were slightly more variable, but the differences were also low. It was expected that the GSIs or GEPIs for the poor-quality sands would be significantly higher than for the good-quality sands and that they would increase with increasing sand content. This did not occur. The GSI and GEPI did not differentiate the poor- from the good-quality sands. No trends in the refusal air-void levels were found.

The GSIs for the good-quality Fredericksburg sand and the poor-quality A. N. Adcock and Wisconsin sands at a 20 percent level were statistically equal. These mixtures should perform similarly. However, the mixture with the 20 percent Fredericksburg sand did not rut in pavements tested by the ALF machine.

The GSI for the good-quality Fredericksburg sand at a 30 percent level was statistically higher than the GSIs for the poor-quality A. N. Adcock and Wisconsin sands. The higher GSI and the low refusal air-void level of 1.3 percent could be due to the higher asphalt content of this mixture, as shown in Table 4.

GLWT

The GLWT results are given in Table 5. The average rut depths did not correlate with the quality of the sand, and none of the rut depths exceeded the specification level of 7.6 mm. All rut depths were statistically equal.

LPC Pavement Rutting Tester

The LPC pavement rutting tester results are given in Table 6. The percent rut depths did not correlate with the quality of sand, and

TABLE 4 Marshall Mixture Design Properties

	Optimum Asphalt Content (%)	MSG	Density (kg/m³)	Stability (N)	Flow (0.25-mm)	VMA (%)	VFA (%)
0 % Natural Sand	5.0	2.648	2541	14 230	13	14.8	72.9
Poor Quality							
10 % A. N. Adcock	4.4	2.649	2542	11 530	10	13.5	70.4
20 % A. N. Adcock	4.5	2.618	2512	9 820	9	14.2	71.9
30 % A. N. Adcock	4.9	2.578	2474	7 890	8	15.8	74.7
10 % Wisconsin	4.4	2.653	2528	14 670	12	14.3	67.2
20 % Wisconsin	4.5	2.632	2523	15 050	10	14.2	71.3
30 % Wisconsin	4.6	2.616	2506	13 150	10	14.5	71.1
Good Quality							
10 % Fredericksburg	5.1	2.624	2518	12 600	11	14.4	72.2
20 % Fredericksburg	5.5	2.582	2480	12 720	10	15.5	74.2
30 % Fredericksburg	6.3	2.528	2427	10 920	10	17.5	77.1
10 % Oxford Gray	4.3	2.650	2539	17 020	13	13.3	68.9
20 % Oxford Gray	4.2	2.627	2517	15 610	13	13.1	68.6
30 % Oxford Gray	4.3	2.601	2492	14 600	10	13.3	68.9

Marshall Design Blows = 75
Mixing Temperature = 154 °C
Compaction Temperature = 143 °C

MSG = Maximum Specific Gravity of the Mixture
VMA = Voids in the Mineral Aggregate
VFA = Voids Filled with Asphalt

none of them exceeded 10 percent at 1,000 cycles or 20 percent at 3,000 cycles. The poor-quality sands did not have higher slopes.

The initial air voids of the slabs before testing are also given in Table 6. These levels were higher than expected since the compaction procedure used in this study reportedly provides an air-void level around 5 to 6 percent. All levels were above 6 percent.

The data in Table 6 appear to indicate that the air voids in the wheelpath decreased during testing. However, by evaluating the air voids in and out of the wheelpath after testing and by sawing additional untested slabs, it was found that the air voids were lower in the middle of the slabs than at the edges before testing. The air voids decreased very little, if at all, from testing.

Additional Sand Tests

The lack of significant differences in rutting potential was not expected. The differences in gradation, binder content, and sand

TABLE 5 GTM and GLWT Results

	GTM, Average GEPI	GTM, Average GSI	GTM, Average Refusal Air Voids (%)	GLWT, Average Rut Depth (mm)
0 % Natural Sand	1.00	1.00	3.6	3.3
Poor Quality				
10 % A. N. Adcock	1.05	1.15	2.2	
20 % A. N. Adcock	1.05	1.10	1.9	5.2
30 % A. N. Adcock	1.10	1.05	2.0	
10 % Wisconsin	1.05	1.20	2.3	
20 % Wisconsin	1.05	1.20	1.7	3.3
30 % Wisconsin	1.05	1.10	2.8	
Good Quality				
10 % Fredericksburg	1.10	1.10	2.6	
20 % Fredericksburg	1.05	1.10	2.8	4.4
30 % Fredericksburg	1.10	1.20	1.3	
10 % Oxford Gray	1.05	1.10	2.8	
20 % Oxford Gray	1.05	1.05	3.1	3.7
30 % Oxford Gray	1.10	1.10	3.0	

TABLE 6 LPC Pavement Rutting Tester Results

	Percent Rut Depth 1000 Cycles	3000 Cycles	Slope	Initial Specimen Air Voids (%)	Air Voids In Wheel-Path After Testing (%)	Air Voids Outside of Wheel-Path (%)
0 % Natural Sand	5.1	6.7	0.27	8.8	7.2	10.5
Poor Quality						
20 % A. N. Adcock	4.6	6.0	0.22	6.1	3.5	7.6
20 % Wisconsin	3.3	4.3	0.23	6.2	4.0	7.7
Good Quality						
20 % Fredericksburg	5.2	7.3	0.32	7.5	5.4	9.0
20 % Oxford Gray	4.2	5.9	0.24	7.5	4.6	8.8

content should more likely produce differences in the data that would be difficult to relate to the percentage of natural sand alone. Possible reasons for the lack of differences were that the characteristics of the poor-quality natural sands were masked by the other aggregates, the mixture tests are not sensitive enough for measuring the effects of natural sands, or a combination of the two.

NAA Method A and the flow rate method were performed on the 2.36- to 0.150-mm size fractions of the aggregate combinations containing the two poor-quality natural sands to determine the quality of the blend of materials. These data are included in Table 3. The results are mixed, but they do not clearly show that the 20 percent level used in the wheel-tracking devices, which provided approximately 53 percent natural sand in the 2.36- to 0.150-mm size fraction, should lead to rutting. However, the data, especially the STIs, introduce a problem with testing blends of sands. The criteria developed in this study were based on testing individual poor- and good-quality sands. Any poor-quality sand with a value slightly under the minimum criterion will pass the method when blended with only a small amount of good-quality material. Some poor-quality sands may always provide a passing value when blended. However, this blend could fail another method. The different methods do not provide the same ranking for poor-quality sands, and field performance data are insufficient to develop a true ranking. Therefore, these methods should only be performed on unblended sands.

CONCLUSIONS

Methods Used To Measure Sand Shape and Texture

1. ASTM Method D3398 differentiated all of the poor-quality sands from all of the good-quality sands. Poor- and good-quality sands will divide at some weighted average particle index (I_a) between 11.7 and 13.9. (All criteria are for heavy traffic pavements.)
2. The STIs and the flow times from the flow rate method differentiated all of the poor-quality sands from all of the good-quality sands. Poor- and good-quality sands will divide at an STI around 1.05 and at some flow time between 14.4 and 15.5.
3. NAA Method A did not differentiate the sands perfectly. One poor-quality sand ranked the same as one good-quality sand. Poor- and good-quality sands will divide at an uncompacted void content around 44.7.
4. The Michigan method did not differentiate the sands perfectly. One poor-quality sand ranked better than one good-quality sand and equal to another good-quality sand.
5. The direct shear method was not as good as other methods evaluated in this study. This test is also time-consuming.
6. The best method was the flow time. The flow times matched the qualities of the sands and was the easiest parameter to obtain.
7. Methods for measuring shape and texture can only be expected to group sands into generalized performance categories, such as high or low potential for rutting. The performance of a sand depends on its quality, the quantity used, the qualities of the other aggregates, and traffic level.
8. Each sand should be tested to determine its rutting potential. The methods are not sensitive enough to evaluate the blend of materials found in a job-mix formula gradation.
9. The discrepancies provided by the NAA and the Michigan methods may be related to gradation. A single, standard gradation should be used in these methods so that the voids they provide are only a function of shape and texture. However, natural sands have widely different maximum particle sizes. Thus, specifying a standard gradation will mean that some sands cannot be tested. Theoretically, a standard gradation should also be used in the flow rate method, even though there were no discrepancies in this study.

Mixture Tests

The Marshall design data, GSI and GEPI from the GTM, and the rut depths from the GLWT and LPC pavement rutting tester did not differentiate the poor- from the good-quality sands. How much natural sand can be incorporated into a mixture could not be established using the GTM data. Reasons for this lack of differentiation could not be established from the information collected.

RECOMMENDATIONS

1. Highway agencies should try both the flow rate method and NAA Method A for evaluating their natural sands using the gradation and apparatus specified by the NAA method.

2. ASTM Method D3398 can also be used. However, this method has not been widely used in the past because it is very time-consuming.

3. The Michigan method is quick and easy to perform. However, this method should only be performed on sands where a single, standardized gradation can be used. This recommendation may also apply to NAA Method A. NAA Method B, which tests individual size fractions, may have to be used when size fractions are missing.

4. Additional mixtures should be tested to determine the validity of the mixture tests used in this study. Other mixture tests, or variations of the tests used in this study, may be needed.

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