Siliceous Content Determination of Sands Using Automatic Image Analysis

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The characteristics of fine aggregate have a significant influence on the field performance of hot asphalt concrete mixtures. Siliceous and rounded particles, which make up a significant percentage of natural sand, are generally related to rutting and possibly stripping of asphalt mixtures. This study was conducted to develop and verify manual counting and automatic image analysis techniques to evaluate aggregate blends for amount of siliceous sand-size particles. Verification involved preparation of samples with known proportions of siliceous (translucent) and calcareous (opaque) particles. The samples prepared were analyzed manually with the aid of a microscope and automatically with an image analyzer. It was found that automatic image analysis can be used with a higher degree of confidence and accuracy than manual counting techniques in determining percent translucent particles. After the image analysis techniques were developed, extracted fine aggregates from field cores of various highway pavements in Indiana were examined with the image analyzer to determine amounts of translucent particles. The percentages of translucent sand particles, assumed to be natural sand, were evaluated for the effect on the gradation, and it was found that as the siliceous sand content on the field cores increased, humps on the 0.45 power gradation curve were likely to increase. Image analysis was found to be up to four times faster than manual counting techniques.

Rutting is a major type of distress associated with asphalt pavements, resulting in pavement roughness and vehicle hydroplaning and steering control difficulties. Factors that affect tendency for rutting include materials, construction, temperature, and traffic loading. Materials include both the binder and mineral aggregate, and the mineral aggregate consists of blends of coarse and sand sizes. Within the sand size, material may be crushed or uncrushed particles. Uncrushed sand is referred to as natural sand, which, with some exceptions, tends to be rounded and can consist of siliceous sand. The amount and type of natural sand in an asphalt mixture has been shown to influence asphalt mixture stability because of its shape and texture. As a result, specifying agencies have placed limits on the amount of natural sand allowed in asphalt mixtures. The ability to determine the amount of natural sand or siliceous sand in a sand blend is important for specifications and research. Since siliceous sand particles often are translucent in appearance, this study focuses on the ability to detect translucent particles in a sand blend with image analysis.

REVIEW OF LITERATURE

Effects of Natural Sand on Rutting

A combined laboratory and field study by Button et al. (*1*) addressed the effects of natural aggregate on plastic deformation in asphalt concrete pavements. Creep tests were used to determine that 20 percent natural sand resulted in large deformations during long-term loading for low and high air void contents. As a result of observations and tests on in situ pavements, excessive sand-size particles and the rounded shape and smooth texture of natural (uncrushed) aggregate particles were factors associated with rutting. It was recommended that the natural (uncrushed) particle content of asphalt mixes in pavements subjected to a high traffic volume be limited to about 10 to 15 percent.

Ahlrich (*2*) investigated the effects of natural sands on the engineering properties of asphalt concrete mixtures. Compacted specimens were prepared using crushed limestone and 0, 10, 20, and 30 percent natural sand. At the No. 30 sieve size, the gradation, when plotted on a 0.45 power gradation chart, exhibited a slight hump at 20 percent natural sand and a noticeable hump at 30 percent natural sand. In general, as the percent of natural sand increased, a hump at the No. 30 sieve size developed. All laboratory tests indicated that asphalt concrete mixtures containing all crushed aggregates had lower rutting potential than mixtures containing natural sand. Ahlrich recommended a maximum of 15 percent natural sand content for pavements carrying high-pressure-tire traffic.

Classification of Fine Aggregate

Classification methods of fine aggregate particles found in the literature have mostly been by means of particle shape and texture. One method for examining aggregate particle shape is the Corps of Engineers' Method CRD-C120-55, Method of Test for Flat and Elongated Particles in Fine Aggregate. Particle shape is evaluated by observing individual sand particles with a microscope and reporting the percentage of particles in the sample with a length-to-width ratio of more than 3.

Another method of measuring particle shape is ASTM D 3398, which provides an index of relative particle shape to a specified volume of fine aggregate by determining the voids in a standard volume after application of different compactive efforts. This method, however, is long and tedious.

Kandhal et al. (*3*) evaluated the National Aggregate Association's Proposed Method of Test for Particle Shape and Texture of Fine Aggregate Using Uncompacted Void Content. In this test, fine aggregate of a specified gradation flows through a funnel into a calibrated cylinder. The particle index value is computed from the voids in the resulting uncompacted specimen. The particle index is a quantitative way of defining the sand characteristics.

Image Analysis Studies on Mineral Aggregates

Perdomo and Button (*4*) conducted a study of coarse and fine crushed limestone and river gravel using grey-level image analysis

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of digitized photographic images. They hypothesized that images of crushed limestone could be distinguished from images of river gravel by the fractal dimension, or "roughness," of the images. They found that the coarse crushed limestone and river gravel had statistically different fractal dimensions, thus distinguishing the two different types of aggregate. However, the two different types of fine aggregate could not be distinguished from one another using the same technique that was used for the coarse aggregate. They suggested that an aggregate classification system could be developed using fractal dimension analysis.

A detailed study by Barksdale et al. (*5*) investigated particle shape characteristics of fine and coarse aggregate particles. The particles were classified by computer programs into different shape categories, thus quantitatively describing the aggregate particles. This method was very labor intensive. However, three dimensions of the aggregate particles were measured, and the study also presented a method for measuring surface roughness.

IMAGE ANALYSIS

Image analysis is "the quantitative measurement of geometrical features that are exposed on two-dimensional images" (*6*). Methods of measurement are manual and automatic (computerized). A microscope can be used for manual image analysis, in which, for example, particles of interest in a specimen are identified and counted. This procedure is laborious and subject to errors, including operator judgment. One technique of automatic image analysis of mineral particles distinguishes one mineral from another by the optical signal strengths emitted from the minerals. This technique can be used to view the whole specimen surface and quantify the area occupied by each type of mineral. This procedure, once calibrated, is fast and eliminates individual operator judgment. The system used at Purdue University is a fully automated area-measuring system that is capable of measuring image characteristics such as area, number, perimeter, shape, and size distribution of aggregate particles. However, this study focused on distinguishing between opaque and translucent particles.

Automatic image analysis technology can be described as being composed of five distinct but related components: image generation and capture, image coding, image reconstruction, image enhancement, and image analysis. These components are discussed below.

Image Generation and Capture

Image generation and capture refers to the process of creating the image and capturing it in such a way that it may be encoded in a digital format. The key objective is to prepare the specimen and the image so that the level of detail and resolution can be captured without losing important information that cannot be reconstructed later. Methods used for image generation tend to be application specific and may encompass a range of specialized techniques.

Image Coding

Image coding refers to techniques used to store the captured image. Regardless of how the image has been captured, data are stored in such a way that each discrete element of the picture (pixel) is uniquely associated with several parameters (e.g., *x*-coordinate, *y*-coordinate, and brightness) (see Figure 1). Good image analysis systems allow for identification of 256 brightness levels. In this study, brightness levels (also called grey levels) are used to discriminate between different minerals in the image on the basis of the optical brightness of the opaque and translucent particles.

Image Reconstruction

Image reconstruction refers to the process of reconstructing an image that has been captured and coded. During the reconstruction, specific algorithms may be used, for example, to correct the image for the effects of distortions as a result of the capturing technique. In most cases, reconstruction is not necessary.

Image Enhancement

Image enhancement or processing refers to a range of techniques used to improve certain aspects of an image before analysis. These "high-level" image-processing activities are also known as morphological transformations. The aim is to minimize the required amount of enhancement required. Common examples of image enhancement include separating overlapping particles, crispening edges, and removing noise. Image reconstruction and enhancement capabilities are the features that distinguish one image analyzer from another.

Image Analysis

Image analysis refers to the actual determination of preselected parameters in relation to the enhanced image and is often referred to as "low-level" image processing. An example for this study

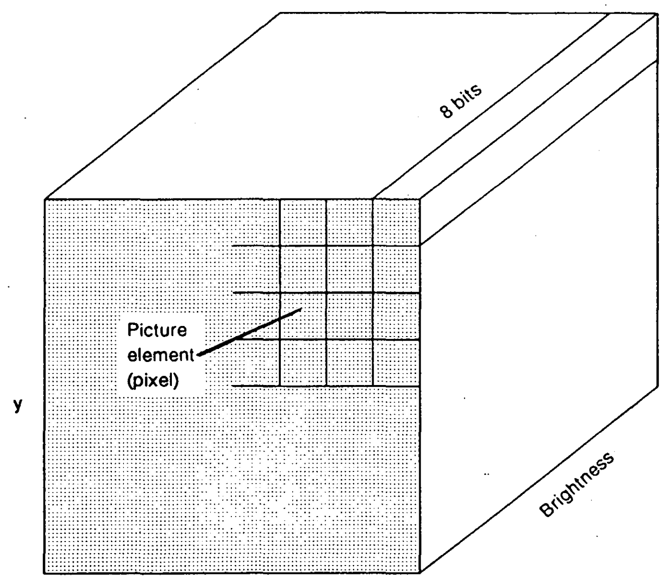

FIGURE 1 Relationship between pixels and brightness.

is calculating the areas of translucent and opaque particles on the basis of brightness level.

TEST METHODS

The laboratory-prepared samples used for the microscope evaluation were also used for the image analysis evaluation. Samples were prepared of known proportions by weight of translucent to opaque sand particles. Ottawa sand was used as the translucent sand in this study. Limestone, obtained from stockpiles at Fauber Construction in Lafayette, Indiana, was crushed in the laboratory and used for the opaque sand. The two types of sand particles were sieved separately into four sizes: passing no. 16, retained on No. 30; passing No. 30, retained on No. 50; passing No. 50, retained on No. 100; and passing No. 100, retained on No. 200. Samples were prepared with three levels (percentages) of translucent sand. These percentages were selected on the basis of minimum and maximum amounts of natural sand expected in highway pavements: 10, 20, and 40 percent. The sand particles were blended in these proportions for each individual size. Because of problems with magnification and focusing of different size particles at one time, it was necessary to view the particles in the separate sizes. The percentages of translucent and opaque particles were determined in each sand blend.

As a basis for evaluation, the first part of the study involved using a microscope to manually count the opaque and translucent particles of these prepared samples. The proportion of each was then determined. In the second part of the study, the image analyzer was used to determine the proportions of the same samples by area. The image analysis results were compared with the results obtained from the manual microscopic examination method. In the third part of the study, fine aggregate extracted from pavement cores was analyzed for the percentage of translucent aggregate. The results were evaluated for effects on gradation, assuming that the translucent sand is natural sand.

Sample Preparation

Samples for viewing were prepared in disposable petri dishes, with a volume of particles dependent on the size of the individual particles. Sample preparation was the same for both image analysis and microscope methods for the same particle size. The petri dishes were clear plastic and had a diameter of 3.5 in. It was desired to have the size of the sample approximately the same for each particle size to be viewed. A single layer was also important to avoid overlapping particles, which might have affected the results. Kitchen measuring spoons were found to provide the easiest way to measure out the sand grains on the petri dish. Multiple samples were prepared and viewed until the entire sample, either for the microscope or image analyzer method, was measured.

Manual Testing Procedure

A binocular microscope was used for counting the translucent and opaque particles by moving the prepared sample under the eyepiece of the microscope from top to bottom and then from left to right and counting sand particles at each location of the eyepiece. Magnification was determined for each particle size by considering a reasonable number of particles to view at one time to avoid eyestrain and to make counting easy. A magnification of 40 was used for sieve sizes No. 100 and No. 200 and 10 for sizes No. 30 and No. 50. The number of particles viewed at one time was normally between 15 and 40. The percentage of each type of particle, translucent or opaque, was determined for each sample. Based on a 95 percent confidence limit and a relative error of plus or minus 2 percent, a minimum of 1,111 total counted particles was required for 90 percent opaque, 2,500 for 80 percent opaque, and 6,667 for 60 percent opaque. If the measured percentage was different from the predetermined proportion, a new minimum value was calculated, and if the actual number counted was less, more particles were counted.

Automatic Image Analysis Testing Procedure

The automatic (image analysis) procedure measures translucent and opaque proportions by the area occupied by each mineral. The image processing and analysis system used for this project includes a microscope, solid-state monochrome camera, hardware, and application software packages. The operator console system includes one color monitor to display menus, results, and programming commands and a second color monitor to display camera output or stored images and graphics overlay, a mouse, a keyboard, and a lamp voltage power supply for specimen illumination. Control of the system is with a 20-MHz 386 personal computer with 2 Mbytes RAM, 40 Mbyte hard drive, and high-density 3.5- and 5.25-in. diskette drives.

Camera settings in the image analysis study were adjusted so that the most the sample could be seen while still obtaining a resolution by which the different type of sand particles could be detected. This was not possible with the camera for the No. 200 particles, so these particles were viewed by the image analyzer through the binocular microscope by means of a special camera hookup. Magnification for the No. 30, 50, and 100 sieve sizes was between 1 and 2. Magnification for sieve size No. 200 was 8.

An optical image from the camera or microscope is converted by the image analysis system into an analog signal, which is digitized into 256 grey levels. A series of successive images are averaged to filter out noise, and the resulting averaged image is stored in temporary computer memory. Stored images are manipulated by a grey-tone image processor, which performs morphological transformations. In this study, a morphological transformation known as delineation was applied to sharpen the edges of aggregate particles. This transformation improved detection of the particles.

Different types of particles are detected by a process called thresholding. Particles emit an optical brightness. Each pixel has a brightness value, or grey level, from 0 to 255. Many pixels are usually required to represent each sand particle. When the grey level of the pixels is plotted on a histogram, different types of particles can be separated by distinct grey levels. This is the thresholding process. A typical histogram is shown in Figure 2. Threshold values used to separate the two different types of minerals were manually selected at the two "valleys" on the chart. In this example, a grey value of 70 was the separation between translucent and opaque particles. A value of 174 separated the background light from the lightest particles. The area occupied under each portion of the histogram is calculated to determine the percentage of each mineral in the viewed sample. Several meas-

urements were made for each sample, and the average and standard deviation were determined for opaque particles. On the basis of a 95 percent confidence limit and the standard deviations obtained, it was determined that seven or eight measurements were adequate in most cases to satisfy statistical requirements.

RESULTS AND DISCUSSION

Statistical analyses were performed on the data collected from the microscope study and image analysis study. Because of the method with which the data were collected, different analyses were performed.

Microscope Study

A null hypothesis (H_o) was tested to determine if the opaque particle proportion was equal to the weight proportion. The chi-square equation (7) was used to determine if H_o was true. The chi-square equation, corrected for continuity, is

$$X_c^2 = \sum_{i=1}^{k} \frac{(|f_i - F_i| - 0.5)^2}{F_i} \quad (1)$$

where f_i is the number of counts observed in Class i, F_i is the frequency expected in Class i if H_o is true, and the summation is performed over the k categories of data, opaque and translucent particles. A value of 3.84 for the chi-square test statistic was used based on a risk-level alpha of 0.05 and one degree of freedom. The data obtained by manually counting the sand particles using the microscope are shown in Table 1. The volume proportions of the opaque particles were determined to be 89.80, 79.63, and 59.46 compared with the prepared weight proportions of 90, 80, and 60, respectively. These were determined on the basis of the limestone apparent specific gravity of 2.71 and the Ottawa sand apparent specific gravity of 2.65.

On the basis of the data, H_o was rejected in every case except for retained sieve size No. 50 opaque proportion of 60 percent. Some proportions were relatively close to the expected proportion, but because of the certainty guaranteed with the large number of particles counted, H_o was rejected. There are several possibilities for the rejection. The particles may not have been identified correctly. However, they were clearly distinguishable. It was originally assumed that particle proportion was equal to the volume proportion if the particles were of the same shape. It was found, however, that the particles were not of the same shape. The translucent particles, which were obtained from a natural source, were fairly round. An angular particle passing a certain sieve can be several times larger than a round particle passing the same sieve because of shape characteristics such as elongation. This may have resulted in the rejection of H_o.

In conclusion, the method of counting to determine the percentages of different materials by volume in a sand blend resulted in the rejection of H_o in all but one case. In other words, except for one sand blend, the method of counting was not accurate in determining the relative volumes of opaque and translucent particles using this procedure. This is based on two categories of data. If three or more different types of minerals were being counted, it is expected that the accuracy would be much less. The time required using this procedure was significant—about 1 to 4 hr for each sample. An instrument such as the image analyzer was desired for speed and accuracy.

Image Analysis Study

A different method of analysis was used for evaluating the image analysis data. The image analysis results were compared on an area basis, not by weight as in the microscope study. Results of percent opaque particles determined from image analysis are shown in Table 2. It was found, using the t-test and a 95 percent confidence interval, that the percentages of opaque particles measured were not statistically different as the amount present in the

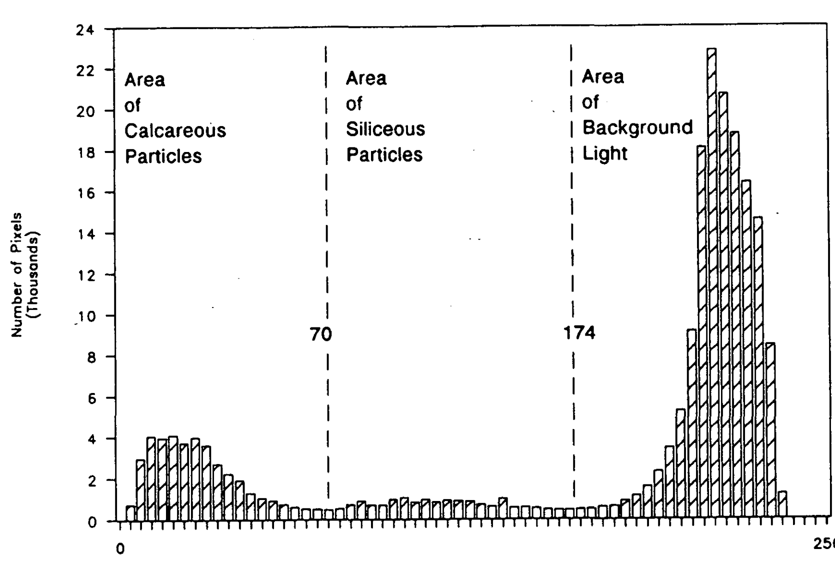

FIGURE 2 Grey level distribution.

TABLE 1 Results of Microscope Study

Sieve Size	Percent Opaque by Weight	Counted Particles Opaque	Counted Particles Transl.	Measured Percent Opaque	Expected Number Opaque	Expected Number Transl.	Chi Square	Decision
30	90	3177	537	85.5	3335	379	72.89	Reject Ho
30	80	3136	1142	73.3	3407	871	105.48	Reject Ho
30	60	5143	4794	51.8	5909	4028	244.6	Reject Ho
50	90	19484	2357	89.2	19613	2228	8.25	Reject Ho
50	80	15808	4474	77.9	16151	4131	35.66	Reject Ho
50	60	13176	8975	59.5	13171	8980	0.0038	Ho
100	90	15512	1574	90.8	15343	1743	18.14	Reject Ho
100	80	15743	2897	84.5	14843	3797	267.6	Reject Ho
100	60	4703	2166	68.5	4084	2785	231	Reject Ho
200	90	2226	193	92.0	2172	247	12.91	Reject Ho
200	80	2677	399	87.0	2449	627	103.68	Reject Ho
200	60	4941	1735	74.0	3970	2706	585.31	Reject Ho

sample for four of the samples, as indicated by a Yes in the last column. A No indicated that the amount measured was statistically different as the amount present in the sample, using a 95 percent confidence interval. Because of problems in producing distinguishable threshold limits for the retained No. 200 particles, no data for this size were collected.

At 95 percent confidence interval, the data from image analysis show that four of the nine specimens displayed measured levels of opaque particles that are not significantly different from levels of particles present in the samples. Overall, the ability of image analysis to determine relative amounts of particles was very good compared with the manual counting techniques. The largest difference from image analysis between measured and actual level was 3.12 percent (for No. 30, 60 percent opaque by weight). The largest difference from manual counting between the measured and actual level was 8.5 percent (for No. 100, 60 percent opaque by weight), not taking into account the No. 200 particles. It should be noted that the standard deviations of the image analysis results are low and resulted in the rejection of H_o in some cases. For example, for No. 100, 90 percent opaque by weight, H_o was rejected, although the difference between measured and actual particle proportion was 0.87 percent. Image analysis resulted in values much closer to actual values than the manual counting technique. The time required for the measurements was 45 min to 1 hr.

Comparisons of Microscope and Image Analysis Methods

The previous statistical analyses compared results with the weight percentages present in the blends. The manual counting and automatic image analysis techniques are also compared. The results are shown in Table 3. The retained No. 50 sizes with opaque proportions of 60 and 80 percent are the only two of the nine in which the microscope method is not significantly different from the automatic image analysis method. This was determined with the standard normal distribution and 95 percent confidence level. In general, the two techniques do not compare well.

TABLE 2 Measured Opaque Particles by Image Analysis

Sieve Size	Percent Opaque By Weight	Percent Opaque By Area	Percent Opaque Measured	Number of Observations	Standard Deviation	Significant
30	60	59.46	62.58	13	4.15	No
30	80	79.63	79.81	16	3.54	Yes
30	90	89.80	88.03	12	2.10	No
50	60	59.46	60.19	28	5.68	Yes
50	80	79.63	78.24	27	3.65	Yes
50	90	89.80	88.06	28	1.84	No
100	60	59.46	61.44	27	3.54	No
100	80	79.63	78.89	25	3.28	Yes
100	90	89.80	88.93	25	1.60	No

TABLE 3 Microscope and Image Analysis Comparison

Sieve Size	Percent Opaque Expected (By Area)	Image Analysis	Microscope	Number of Particles	Standard Deviation	Significant
30	59.46	62.58	51.8	9937	0.0025	No
30	79.63	79.81	73.3	4278	0.00299	No
30	89.80	88.03	85.5	3714	0.00203	No
50	59.46	60.19	59.5	22151	0.00162	Yes
50	79.63	78.24	77.9	20282	0.00121	Yes
50	89.80	88.06	89.2	21841	0.00065	No
100	59.46	61.44	68.5	6869	0.0026	No
100	79.63	78.89	84.5	18640	0.00096	No
100	89.80	88.93	90.8	17086	0.00064	No

Field Specimens

Image analysis tests were performed on samples taken from Indiana highway pavements using the same procedure as that for the laboratory-prepared samples. The percentage of translucent particles was then compared with the 0.45 power gradations determined after extraction. Percent translucent contents for the field samples are shown in Table 4. Percent translucent sand for each sieve size by weight is shown. Total translucent content of the material retained on the No. 30, 50, and 100 sieves by weight of the entire sample is also shown, assuming zero percent siliceous content of coarse aggregate. The data are listed in order of increasing translucent sand content (by weight) of the entire sample. Table 4 also summarizes humps observed around the No. 16, 30, and 50 sieves by these categories: no hump, very slight hump, slight hump, hump, large hump, and severe hump. Gradation examples are shown in Figures 3, 4, and 5. The field measurements show that as the percent of translucent material or natural sand increases, a hump is more likely to occur. The reason why translucent contents were lower for the field samples than for the laboratory-prepared samples is that natural sand used in construction is not entirely siliceous. However, it is expected that a relationship exists between translucent content measured and the amount of natural sand placed in the mixtures.

CONCLUSIONS

On the basis of the results and statistical analysis of the data, the following conclusions were drawn:

1. Manual counting techniques to determine relative particle proportions do not produce accurate results. The procedure is time consuming and subject to errors.

TABLE 4 Translucent Contents and Humps on Gradation Curves

Designation	Route	Percent Translucent by Individual Sieve No. 30	No. 50	No. 100	Total Translucent Content (%)	Comments
218B	SR-8	21.1	44.7	44.4	2.659	Very slight hump at 50
711B	I-65	13.2	39.6	39.3	3.479	Very slight hump at 50
821B	SR-37	14.8	32.6	42.0	4.51	Hump at 16
118B	US-24	8.8	33.4	23.4	4.898	No hump
821C	SR-37	15.0	32.0	36.7	5.316	No hump
721C	I-74	17.7	55.7	67.8	5.62	No hump
412B	SR-14	22.7	56.6	74.6	5.993	Severe humps at 30 and 50
721B	I-74	19.7	50.3	65.0	6.458	No hump
318B	I-69	16.0	48.1	56.4	7.176	Very slight hump at 50
321B	US-31	18.0	47.5	53.1	7.341	Severe humps at 30 and 50
128B	US-31	19.0	52.7	63.3	7.68	Slight hump at 50
811B	US-421	27.6	48.4	52.7	7.972	Large humps at 30 and 50
421C	SR-8	16.4	45.4	56.5	9.588	Large humps at 30 and 50
123C	US-31	14.9	49.4	55.4	10.124	No hump
621B	SR-245	29.2	60.0	56.4	10.322	Large humps at 30 and 50
623C	SR-245	26.8	57.9	62.1	10.666	Large humps at 30 and 50
521C	I-64	38.6	66.9	49.7	11.201	Max line at 16, 30, and 50
611B	SR-446	25.2	47.8	48.1	11.202	Large humps at 30 and 50
424B	SR-8	15.4	52.1	68.4	13.603	Severe humps at 30 and 50
521B	I-64	42.7	73.1	60.1	14.335	Large humps at 30 and 50
511B	I-64	29.8	59.3	62.8	14.761	No hump

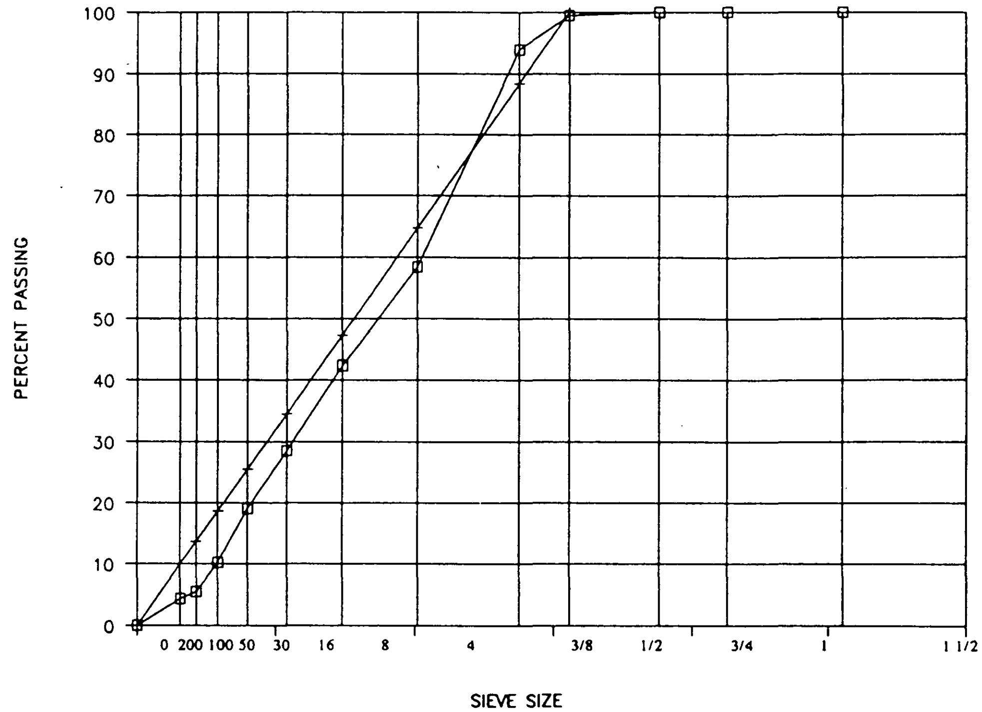

FIGURE 3 Sieve sizes raised to 0.45 power: no hump gradation (118B).

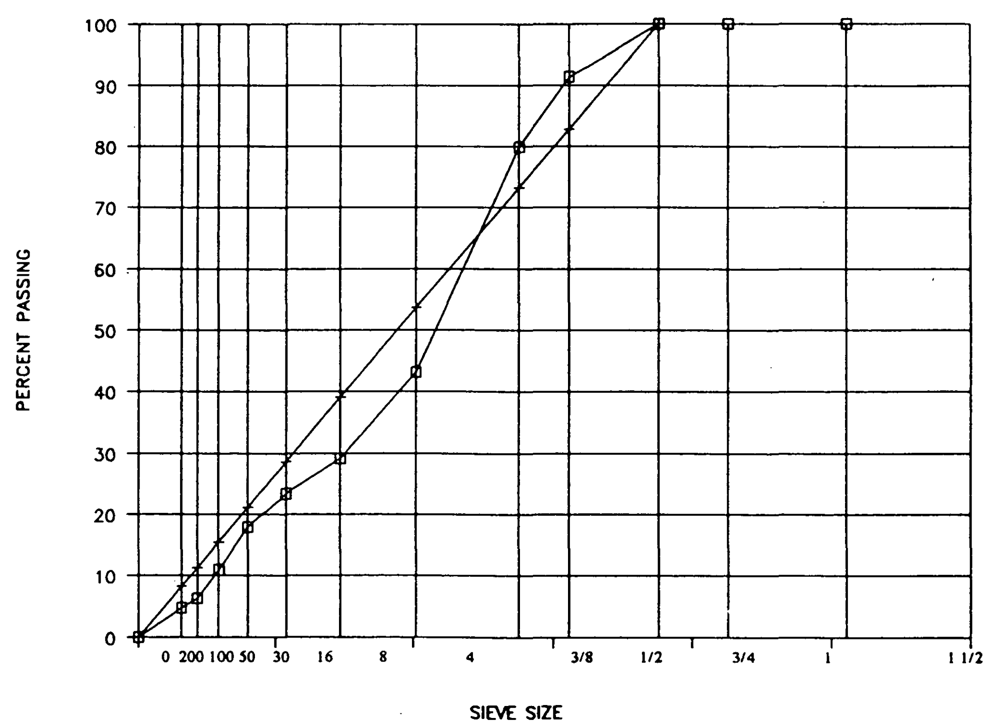

FIGURE 4 Sieve sizes raised to 0.45 power: slight hump gradation (128B).

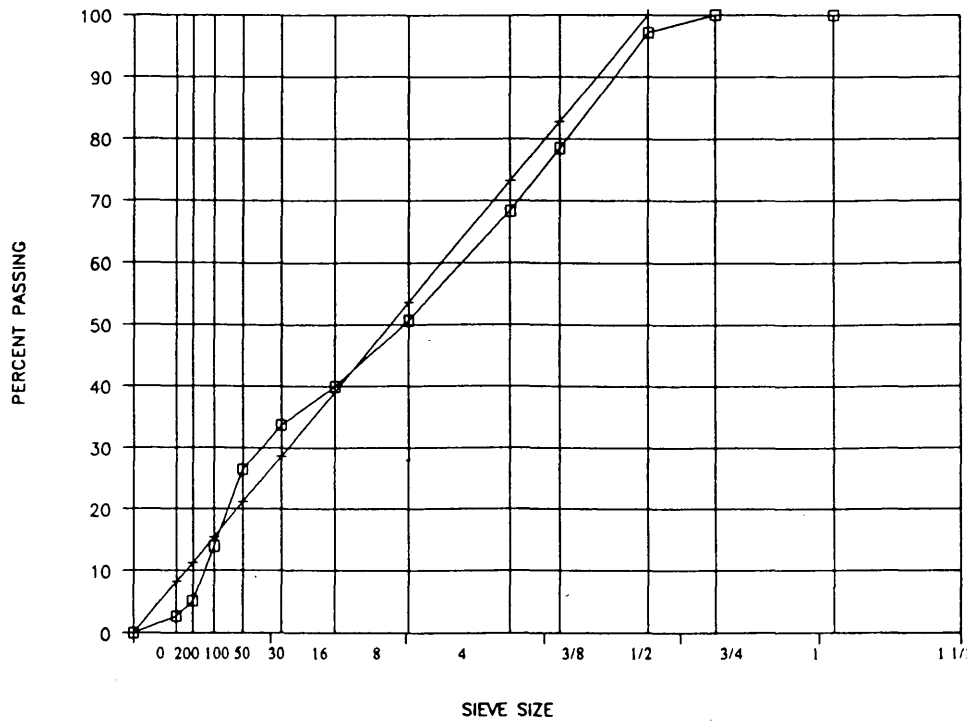

FIGURE 5 Sieve sizes raised to 0.45 power: severe hump gradation (424B).

2. Image analysis techniques to determine relative particle proportions produce results closer to actual proportions than manual counting techniques. Standard deviations are small. Image analysis is faster and subject to less errors than manual counting techniques.

3. The field measurements show that as the percent translucent material increases, it is more likely for a hump to occur. This hump has been found by other researchers to result in a tender mix.

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REFERENCES

1. Button, J. W., D. Perdomo, and R. L. Lytton. Influence of Aggregate on Rutting in Asphalt Concrete Pavements. In *Transportation Research Record 1259*, TRB, National Research Council, Washington, D.C., 1990.
2. Ahlrich, R. C. *The Effects of Natural Sands on Asphalt Concrete Engineering Properties.* Technical Report GL-91-3. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1991.
3. Kandhal, P. S., J. B. Motter, and M. A. Khatri. Evaluation of Particle Shape and Texture: Manufactured Versus Natural Sands. In *Transportation Research Record 1301*, TRB, National Research Council, Washington, D.C., 1991.
4. Perdomo, D., and J. W. Button. *Identifying and Correcting Rut-Susceptible Asphalt Mixtures.* Research Report 1121-2F. Texas Transportation Institute, College Station, Tex., 1991.
5. Barksdale, R. D., M. A. Kemp, W. J. Sheffield, and J. L. Hubbard. Measurement of Aggregate Shape, Surface Area, and Roughness. In *Transportation Research Record 1301*, TRB, National Research Council, Washington, D.C., 1991.
6. Oosthuyzen, E. J. The Application of Automatic Image Analysis to Mineralogy and Extractive Metallurgy. In *ICAM 81, Proceedings of the First International Congress on Applied Mineralogy*, Geological Society of South Africa, Johannesburg, 1983.
7. Zar, J. H. *Biostatistical Analysis.* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1974.