

Measurement of Aggregate Shape, Surface Area, and Roughness

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The physical characteristics of aggregates have an important influence on the behavior not only of unstabilized bases but also of asphalt concrete and portland cement concrete mixes. Experimental techniques using modern data acquisition methods for measuring and analyzing aggregate characteristics are described. A Pencept Penpad digitizer accurate to 0.0015 in. together with an IBM-XT microcomputer was used to collect and analyze the necessary data for measuring aggregate shape, surface area, and roughness. Measured coordinates of critical points were stored in an Autocad DXF file. The data were edited using a Basic program and then transferred to Lotus 1-2-3 with which they were analyzed and presented in the form of graphs, tables, and histograms. All data transfer and manipulation were performed electronically. Methods for shape and surface area measurement, classification, and interpretation were reviewed. Two different techniques for measurement of aggregate surface area were compared and demonstrated to yield reasonably similar results. A special shadow technique for studying the characteristics of particles smaller than the No. 8 sieve was described. In addition, the accuracy of the digitizer procedure for measuring surface roughness was assessed.

Asphalt mix designs are based on many factors including the type and amount of asphalt, air voids, aggregate characteristics, aggregate gradation, and mineral filler. In order to investigate the effects of aggregate characteristics, which are usually not fully considered, the Georgia Department of Transportation (DOT) initiated, through the Georgia Institute of Technology, a comprehensive research program. In the final phase of the study, the effects of these variables will be evaluated on the rutting performance of Georgia DOT asphalt mix designs. This paper describes the measurement of aggregate shape, surface area, and roughness using modern digitizing techniques taking advantage of a microcomputer.

PARTICLE SHAPE

Introduction

The shape of the aggregate influences the gradation curve obtained by sieving (1). Flaky particles tend to diagonally pass sieves having square holes. Also, the shape of the particle

has a significant influence on the volume of particles retained on a specific sieve. For material retained on a given sieve size, Lees (1) has shown that rod-shaped particles are about 2.5 times the size of disc-shaped particles. This difference in size affects the ability of the particles to properly fill voids of coarser size aggregate.

Simple Classification Systems

The shapes of fine- and coarse-aggregate particles can be divided into the following four general shape categories (1,2): (a) flaky, (b) cuboidal, (c) blade, and (d) rod. Although British Standard BS 812 (2) separates the aggregate into these four rather broad categories, the method does not define the exact location of an aggregate within each category. A special, simple gauge is used to measure the two indices required for shape classification.

ASTM (3) and the Corps of Engineers (4) also have test methods similar to BS 812 (2) for evaluating flat and elongated coarse particles in aggregates to be used in concrete. These methods use a specially designed caliper to determine particle shape ratios. Measurements are performed by hand to determine if particles have certain length-to-thickness or width-to-thickness ratios; specific particle dimensions are not measured. Although simple, these methods are just classification schemes and do not permit determination of surface area. Different ratios separating aggregate classes have been proposed for describing aggregate particles (1,5).

The four broad categories defined by these methods allow a large range of particle shape characteristics within each classification. For research purposes, these methods might give misleading results, affecting aggregate performance. Also, these classification tests are not suitable for measuring the shape of particles much finer than about the No. 12 sieve, and surface area cannot be determined using the results. Classification systems that use just one aspect ratio are not suitable for defining particle shape.

Generalized Classification Systems

Both fine and coarse aggregate particle shape can be determined by measuring the flatness ratio and elongation ratio (1). The flatness ratio (p) is the ratio of the shortest length (c) divided by the intermediate length (b), and the elongation ratio (q) is the ratio of intermediate length (b) divided by the greatest length (a). By determining the actual flatness and

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elongation ratios, a continuously varying classification can be developed. This approach also permits defining a shape factor $F = p/q$ and sphericity ψ . Sphericity ψ is the ratio of surface area of a sphere of the same volume as the particle divided by the surface area of the particle (I). The proposed method is considerably more flexible for research purposes than the Corps or British classification schemes. The British and Corps classifications can be quickly obtained from the general flatness and elongation ratio method described by Lees.

Also, the surface area and sphericity of the aggregate can be determined using the more general shape classification method. The generalized shape classification concept is a method of tridimensional shape analysis where each grain is approximated by a tetrakaidecahedron (2,6). Three mutually perpendicular particle dimensions (length, width, and thickness) are measured and used to calculate the ratio of surface area of the particle compared to that of an equivalent sphere, or else surface area is directly calculated.

Particle Shape Using a Digitizer

For shape classification, the aggregates studied in this investigation were divided by sieving into the following four size ranges: $\frac{1}{2}$ to $\frac{3}{8}$ in., Nos. 4 to 8, Nos. 8 to 120, and smaller than the No. 120 sieve. These size ranges were selected by a panel of engineers as being appropriate. For the two larger size aggregate ranges (the $\frac{1}{2}$ to $\frac{3}{8}$ in. and Nos. 4 to 8 sizes), an aggregate sample consisted of 150 particles of each size, with the number of particles being counted visually. In the smaller size ranges, microphotographs and special techniques were used to measure the aggregate shape. The number of particles in each sample of smaller particles varied from 50 to 150, on the basis of the number of particles captured in each photograph. At least three different samples were measured for each aggregate type. This approach resulted in the use of a minimum of 450 particles for each of the coarser two sizes studied and a minimum of 150 particles for each of the finer two particle sizes studied; usually 250 or more particles were included. The use of more than 150 particles was desirable but was too expensive to achieve in all cases for the microscopic particles.

Aggregate shape was determined and numerous plots and tables produced without a human hand ever working with the data. The procedure developed for particle analysis is completely automated and uses a relatively inexpensive digitizer that automatically feeds data into an IBM-XT microcomputer.

Aggregate Greater Than No. 8 Sieve in Size

For the aggregate greater in size than the No. 8 sieve, photocopies were made of the flattest profile of the particles. A Savin 7350 copying machine was used to provide images of 50 particles at a time, which were placed in a small box. The box had a clear plastic bottom and dividers so as to give five rows of 10 aggregates each. The copy machine was found not to distort the photocopied image of the aggregate. By providing a profile view of the aggregates, the length and width were easily digitized directly from the photocopy using a Penpad digitizing tablet manufactured by Pencept, Inc. The digitizer had an accuracy of 0.0015 in., which was sufficient,

particularly considering the relatively large observed variation in aggregate shape and dimensions. The length was digitized as the longest dimension of the aggregate, and the width as the average dimension, in the plane of the photocopied image, perpendicular to the length. The coordinates (x, y) of each point representing one end of a dimension were digitized, and the actual dimension was later calculated. If the original ordering of length, width, and thickness was to correct, a computer program later automatically reordered the dimensions correctly.

Shadows were created when trying to photocopy the profile of the aggregate to measure its thickness. Therefore, aggregate thickness was not digitized directly from a photocopy. Instead, vernier calipers were used to measure the average thickness directly from the aggregate. The calipers, open to the proper width, were then laid on the digitizing pad, and the tips of the calipers, representing thickness of the aggregate, were digitized. A pen-type digitizer, as opposed to one with cross-hairs, was used, enabling digitizing of the vernier caliper measurements.

This method of measuring the dimensions proved to be efficient. With experience, an operator can digitize the three dimensions of 150 aggregates in approximately 30 to 45 min. After digitizing the three perpendicular dimensions for all aggregates, the data are saved as an Autocad DXF file in ASCII code.

Aggregate Smaller Than No. 8 Sieve in Size

Aggregates less than the No. 8 sieve in size require the use of specially prepared optical microphotographs. Similar to the large aggregate, aggregate length was digitized directly from the photograph as the longest dimension and the width as the average dimension, in the plane of the photograph, perpendicular to the length.

Because these particles are small, the height cannot be measured directly using calipers. Therefore, a special technique was used relating a shadow length on the photograph to particle height. As the particles were prepared for the microscope, uniform reference spheres were added to establish the scale for vertical height. A thin film of metal was evaporated onto the surface at an angle to the substrate on which the particles set to create a shadow (7). Because the evaporation source is a relatively long distance away, the angles at which it strikes the particles and reference spheres are approximately equal. Therefore, by geometry, a unique ratio exists between the shadow lengths of the reference spheres and the aggregate particles and their heights. A special technique, described subsequently, was used to capture the shadow on the photograph.

Similar to the large aggregate, all digitized dimensions were saved as an Autocad DXF file in ASCII code. A set of microphotograph data can be digitized in 25 to 50 min depending on the number of aggregates in a sample.

Manipulation of Data Using Autocad and Lotus 1-2-3

After digitization, all dimensions were stored in an Autocad DXF file. An Autocad DXF file contains all the formatting,

scaling, size, and other information that Autocad uses when displaying and working with a drawing. A Basic program called DFXTRACT was used to remove all the unwanted formatting information and extract only the coordinates of the ends of lines defining the dimensions of the aggregates. This program then saved the data in a form that Lotus 1-2-3, or other spreadsheets, was able to use readily.

Once the endpoints of the lines representing the dimensions of the aggregates were extracted and stored in the Lotus 1-2-3 PRN file, the PRN file was imported into a Lotus 1-2-3 worksheet using the Lotus 1-2-3 import command. The lengths of the dimensions were then calculated using the coordinates of the end points and stored in a Lotus 1-2-3 worksheet file named "WK1."

The conversion of endpoints to lengths defining the dimensions of the aggregate can be performed faster using Basic as a part of the DFXTRACT program. Using the Basic program requires about 30 sec on an IBM-XT computer, compared with 3 min for the Lotus 1-2-3 macro. However, errors, such as adding a stray line or extra point, are sometimes made using the digitizer and Autocad. The Lotus 1-2-3 worksheet approach allows examination of the data; in most cases the error can be corrected even after general processing of the data has been finished. A Basic program would probably blow up or give useless results in the same situation. Typical results demonstrating how the resulting shape measurement data can be readily presented using a spreadsheet are shown in Figures 1 and 2.

Three-Dimensional Measurements of Very Fine Aggregate Samples

The fine aggregate samples studied (smaller than the No. 8 sieve in size) have a broad size range that requires the use both of low- and of high-magnification techniques, which cannot be accomplished using only one instrument. As a result, aggregate varying in size from the No. 8 to the No. 120 sieve was treated differently than aggregate smaller than the 120 sieve. The larger fraction particle size (Nos. 8 to 120 sieve size) is large enough to present difficulties in direct optical measurements and especially in macrophotography because

of the limited depth of field of optical techniques. If measurement of the thickness of these particles is required, a unique sample preparation problem exists.

Large Fraction—Particles of Nos. 8 to 120 Sieve Size

Sample Dispersion The solution for measuring aggregate shape of small particles is to look not at the particles themselves but to create flat silhouette representations of the particles from which measurements can be taken. If a shadow is added to the silhouette directly related to a particle's height, the three dimensions of length, width, and height can easily be measured in one flat plane. The technique of vacuum evaporation of thin metal films, such as that used in the preparation of samples for transmission electron microscopy (TEM), was used to prepare these flat, two-dimensional representations of three-dimensional samples (7). In order to prepare fine aggregates so that silhouettes could be obtained, aluminum was used instead of platinum (which is used in TEM preparation because of its ease of evaporation).

First, a glass microscope slide was cleaned with soap and water to ensure good adherence of the evaporated film. A good dispersion of the sample particles was placed on this slide. Care was exercised to ensure that the particle spacing was sufficient to allow for a shadow between the particles, and that the dispersion was representative of the true size distribution. Obtaining good sample dispersion is perhaps the hardest but most important part of the sample preparation. A wide variety of dispersion techniques can be used depending on the nature of the particulate material being studied.

For the particles used in this study, the dispersion was prepared in the following manner. Each sample was placed in a plastic bag. The sample was then mixed by shaking the bag back and forth while turning it (8). Shaking was carried out for a sufficiently long period of time to thoroughly mix the sample. A number of small subsamples were taken from different areas of the bag and mixed to further ensure a representative sample. Because the mica consisted of relatively large flakes, an antistatic spray was not required to prevent sticking of these particles to the sides of the bag. A number of cleaned glass slides were placed on a flat surface and the extracted sample allowed to drop onto the slides from a height of about 1 ft. This technique was performed in an area that had no air movement. A small quantity of uniform glass spheres was also dropped onto the slides. The size of the spheres was later determined by measuring their diameters on the photograph and calculating sizes knowing the scale of the photograph. One of the slides that visually appeared to have the best dispersion was selected for further processing.

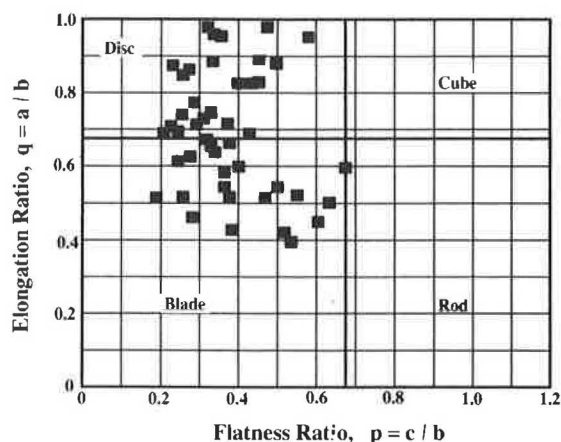


FIGURE 1 Typical shape classification scatter diagram for a selected Georgia specimen.

Evaporation of Aluminum The slide having the best dispersion of particles was placed in a vacuum evaporation unit in which two filaments had been set up for evaporation of aluminum. One filament was located directly above the slide while the other was placed off to the side at an angle of about 30° to the slide surface. The unit was evacuated to a pressure of at least 10^{-4} mm of mercury and the aluminum evaporated. The proper amount of aluminum evaporated was determined experimentally to give the best contrast both for shadow and

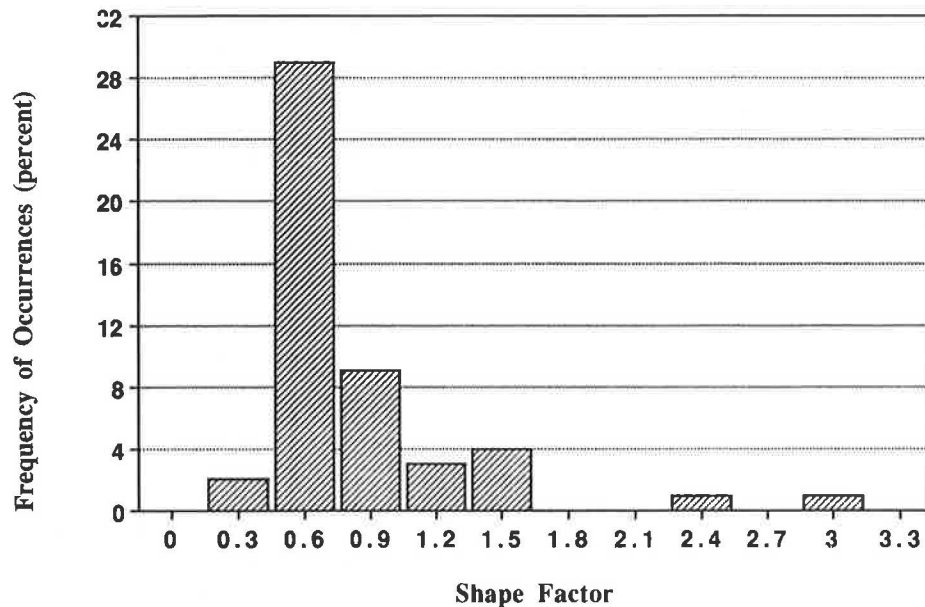


FIGURE 2 Typical shape factor histogram for a selected Georgia aggregate.

silhouette. For a single particle, two areas are present on the slide that may be coated by only one layer of aluminum, the shadow area and an area opposite the shadow if the particle is not square with the surface.

The slide is removed from the coating unit, and the particles are then removed from the slide by blowing them off with air. If the fine particles resist removal by blowing, the slide is placed in a beaker of water containing a small amount of wetting agent and then treated in an ultrasonic bath for a few seconds.

Fine Fraction Smaller Than No. 120 Sieve Size

Particle size measurements of the fine fraction less than the No. 120 sieve in size were made from micrographs taken using the scanning electron microscope (SEM). The particles were dispersed on a plastic substrate and the preparation coated with carbon by evaporation to prevent charging the SEM. The dispersion was then shadowed with aluminum as previ-

ously described. The particles were left in place on the slide because depth of field is not a problem in the SEM. The micrographs were taken using the backscatter signal, which is sensitive to elemental differences. Good contrast was obtained using this technique between the particle, shadow, and background. Uniform glass or latex spheres were included in the dispersion for shadow and thickness determinations.

Estimation of Particle Thickness

After following the previously given procedures for sample preparation, all of the particle information is now represented in the single plane of the slide, which can be photographed at any magnification or viewed on a projection screen where direct measurements can be made. Figure 3 shows the shadowed silhouette of a single particle; *A* is the particle length, *B* the width, and *C* the shadow length. The shadow length of the spheres can be used to convert shadow length of the particles to thickness using the formula

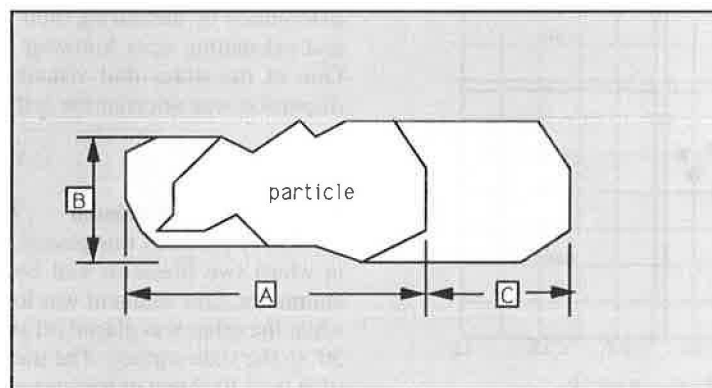


FIGURE 3 Optical presentation of coated and shadowed slide with particle removed.

$$T = \text{Sh}_p \{ \tan[2(\arctan r_{ap}) / (\text{Sh}_{ap} + r_{ap})] \} \quad (1)$$

where

T = particle thickness
 Sh_p = particle shadow length,
 r_{ap} = sphere radius, and
 Sh_{ap} = sphere shadow length.

For low shadowing angles, the simpler formula

$$T = \text{Sh}_p [2r_{ap} / (\text{Sh}_{ap} + r_{ap})] \quad (2)$$

can be used as a close approximation.

SURFACE AREA

Introduction

The surface area of the aggregate for a given quantity of asphalt has a significant effect on the asphalt film thickness and as a result can influence mix performance. Surface area can be determined by a number of methods including (a) the tridimensional approximation described by Aschenbrenner (6), (b) quantitative stereology (9), (c) surface coatings including wax and paint (1,5), (d) air and mercury permeability (10), and (e) gas adsorption. The tridimensional method described by Aschenbrenner (6) has been previously summarized. In addition to this approach, the quantitative stereology and the gas (usually nitrogen) adsorption methods probably offer the best techniques for determining surface area. The gas adsorption method, however, indirectly measures the external surface area of the particle and also any pores greater in size than about 4 Å. This method requires several ideal assumptions to calculate surface area using thermodynamic principles.

Quantitative Stereology

Fundamentals

An interesting method for measuring surface area of aggregates is by using quantitative stereology (9). Quantitative stereology is a direct measurement method and consists of preparing a random sample of N aggregates placed in a container of known volume. The aggregates are encased in a cementing agent such as an epoxy to form a solid block. The solid block is then sawed into several random pieces with the cuts oriented in different directions. A number of circles of radius R are inscribed on each saw cut surface, and the number (P) of times each circle intersects an aggregate boundary is counted. Now let P_L equal

$$P_L = P/2\pi R \quad (3)$$

where R is the radius of the circle and P is the number of intersections. Next, calculate the average value of P_L (i.e., \bar{P}_L) for all the circles drawn on all sections. The average surface area S of the particles inside the block of aggregate is then equal to

$$S = 2\bar{P}_L V_0 / N \quad (4)$$

where

S = surface area,
 \bar{P}_L = average number of particle intersections per circle,
 V_0 = volume of the sample, and
 N = total number of particles in the sample.

The quantitative stereology approach makes no geometric assumptions concerning aggregate shape (9). This method is statistically exact provided a sufficient number of measurements are performed. However, the sample must be statistically representative of the aggregate, and a sufficient number of circles must be drawn on the cut faces. The best results are obtained if the particles are randomly positioned in the container, with the distribution being homogeneous. If a random distribution does not exist, more sampling planes cutting through the block of aggregates at different angles are required, or more sampling circles must be drawn on the cut faces or both. Even if the aggregates are not randomly oriented, the correct surface area can be obtained if a sufficient number of circles and sections are used together with a sufficiently large number of particles.

Sample Preparation

The procedure used for the quantitative stereology method is considerably more labor intensive than the computer method used to obtain aggregate shape and surface area. Approximately 500 aggregates from the 1/2- to 3/8-in. sieve size were counted for each sample from each of the seven selected quarries for which surface area was measured using this technique. Of these 500 aggregates, 100 were digitized in this study into the computer for analysis by the Aschenbrenner method to compare results. After digitizing was complete, these 100 aggregates were combined with the remaining 400 particles and later placed in a cylinder.

A two-part epoxy glue, which was quick drying and strong, was used to bind the aggregates together. Plastic cylinders 5.25 in. high and 3 in. in diameter were used as molds. This size is convenient to work with and handle, and provides a sufficient volume to produce a representative sample of the size of aggregate studied.

After mixing, a small amount of epoxy was poured into the bottom of the mold. Several aggregates were then dropped into the mold. The mold was tapped for several minutes with a metal rod to move the aggregates into a dense packing and to drive any air bubbles present to the surface. When most of the air bubbles were out, more epoxy and more aggregates were added and the tapping was repeated. This preparation cycle was continued until all the aggregates were placed in the mold. Extra epoxy was also added to top off the mold and to act as a handle to hold the sample when it was cut. The mold was then placed in a warm location and allowed to harden for approximately 24 hr.

The mold was stripped away from the sample after hardening. The sample was then labeled with a permanent marker. Measurements were then taken of the height of the aggregate-epoxy specimen; the total height of the epoxy cylinder was not measured because the volume of actual aggregate is used in the formulas for calculating surface area. Next, the lower

portion of the epoxy-aggregate sample from the bottom up was cut into disks approximately $\frac{1}{2}$ to 1 in. thick. The remaining cylindrical-shaped sample was split down the center, forming two long, semicircular sections. One side of each of the three disks and one of the flat semicircular sides was photocopied. The data were taken from the photocopies and reduced to preserve the integrity of the original samples.

Measurements

Five circles were drawn on each cross section that was photocopied. The long flat side of the semicircular section had 12 circles drawn on it. The number of intersections each circle made with the edges of aggregates was recorded. This large number of circles, 27 in all, was used to achieve a representative sample of the aggregates. The number of intersections per circle was then averaged and entered into Equations 3 and 4 to calculate the surface area. The epoxy cylinder radius, volume of epoxy cylinder containing aggregate, and the total number of aggregates in the sample are also required. Either three or five aggregate-filled specimens were studied from each quarry.

Comparison of Results

Table 1 presents the results of the quantitative stereology method for evaluating surface area with the one described by Aschenbrenner. For the stereology technique, the average standard deviation of the aggregate from the seven granite quarries included in this portion of the study is 0.030 in.², which is 4.3 percent of the average measured value of 0.700 in.² per aggregate. For the Aschenbrenner approach, the average standard deviation is 0.050 in.², which is 6.7 percent of the average measured value of 0.749 in.² per aggregate. The percent differences in average results vary for individual quarries from -10.7 to +9.2 percent. The algebraic average difference in surface area between the two methods for the seven quarries is 2.2 percent. These results appear to indicate that the Aschenbrenner model is probably sufficiently accurate for at least most purposes, particularly considering its simplicity.

SURFACE ROUGHNESS MEASUREMENT

Definition of Surface Roughness

Quantifying surface roughness is not easy, particularly for aggregates that have curved surfaces. Further, the value of surface roughness depends on the magnification at which roughness is examined. Numerous definitions of surface roughness have been proposed (11-13). For this study, the definition developed for surface roughness (R) is as follows:

$$R = L_T/L_p \quad (5)$$

where

L_T = true length of the segment of surface being analyzed, and

L_p = length of the line of best fit for the segment of surface.

This definition, which is slightly different than that used for flat surfaces, was developed because using the line of best fit appears to contribute to the reduction of error caused by the curvature of an aggregate. Coupling this definition with evaluating small sections of the particle, the problems caused by curvature are minimized.

Methods of Measuring Surface Roughness

Most work in measuring microtexture has involved the roughness of flat metal surfaces. Techniques for measuring surface roughness of aggregates include the following (11,12):

1. Stylus. A pen stylus is drawn over the aggregate surface. Optical, mechanical, or electronic magnification is usually used to enhance the profile and process the results.
2. Cut Section. The cut profile surface can be measured of an aggregate embedded in an epoxy. The block of epoxy and aggregate is cut, polished, and photographed at the desired level of magnification such as $15\times$ to $125\times$. The surface profile is then directly measured by automatic measuring techniques.
3. Casting. A casting of the surface is made. The magnified image of the casting is then examined to determine the profile.
4. Oblique Lighting. Illuminating the surface by oblique lighting produces a shadow. A projection microscope is used to observe the shadow.

Stylus-type equipment, which appears at first to be ideal, is made to measure surface roughness along a flat surface; deviation from this plane can cause measurement errors and even instrument damage. Also, a stylus-type instrument cannot follow indentations less than the radius of the stylus and cannot measure roughness where overhangs occur. Flat surfaces on an aggregate particle where measurement is possible are often limited.

Roughness Measurement

The cut section method, previously described, was used to measure surface roughness. Data were collected automatically with the same Pencept Penpad and IBM-XT computer that was used to measure aggregate shape and surface area.

Specimen Preparation

A representative, random sample of 30 aggregate particles was taken from each source. The aggregate sample was then placed in a small plastic cylinder 6 in. high and $1\frac{1}{2}$ in. in diameter. A two-part epoxy was used to bind the aggregate together within the cylinders. Magnolia Plastics Epoxy Compound 2014 and Curing agent 346 were chosen because of their ability to hold the aggregate particles in place while cutting, their good polishing characteristics, and their ability to harden within 24 hr.

Thirty particles $\frac{3}{8}$ to $\frac{1}{2}$ in. in size were dropped one at a time into the cylinder, which was one-half full of epoxy. This

TABLE 1 COMPARISON OF SURFACE AREA BY QUANTITATIVE STEREOLOGY AND COMPUTER SURFACE AREA ANALYSIS FOR SELECTED QUARRIES

| Quarry | Sample | Aggregate Type | SA by Stereology ⁽¹⁾ | Mean | Std. Deviation | SA by Computer ⁽¹⁾ | Mean | Std. Deviation |
|----------------------------------|--------|----------------|---------------------------------|-------|----------------|-------------------------------|-------|----------------|
| | | | (in. ²) | | | (in. ²) | | |
| Dixie Sand Chatt., TN | CA1 | Alluvial | 0.636 | 0.636 | 0.005 | 0.580 | 0.580 | - |
| | CA2 | Alluvial | 0.641 | | | | | |
| | CA3 | Alluvial | 0.632 | | | | | |
| Florida Rock Mt. View, GA | EA1-1 | Granite | 0.767 | 0.816 | 0.042 | 0.752 | 0.738 | 0.015 |
| | EA1-2 | Granite | | | | 0.715 | | |
| | EA2 | Granite | 0.843 | | | 0.733 | | |
| | EA3-1 | Granite | 0.837 | | | 0.747 | | |
| | EA3-2 | Granite | | | | 0.745 | | |
| Florida Rock Tyrone, GA | GA1-1 | Granite | 0.713 | 0.767 | 0.048 | 0.891 | 0.850 | 0.025 |
| | GA1-2 | Granite | | | | 0.833 | | |
| | GA2 | Granite | 0.801 | | | 0.841 | | |
| | GA3-1 | Granite | 0.788 | | | 0.830 | | |
| | GA3-2 | Granite | | | | 0.853 | | |
| GA. Marble Buford, GA | IA1 | Granite | 0.809 | 0.821 | 0.010 | 0.823 | 0.759 | 0.059 |
| | IA2 | Granite | 0.827 | | | 0.747 | | |
| | IA3 | Granite | 0.827 | | | 0.707 | | |
| GA. Marble Cumming, GA | JA1 | Granite | 0.677 | 0.733 | 0.054 | 0.700 | 0.762 | 0.152 |
| | JA2 | Granite | 0.737 | | | 0.935 | | |
| | JA3 | Granite | 0.784 | | | 0.651 | | |
| Vulcan Materials Kennesaw, GA | RA1 | Granite | 0.815 | 0.813 | 0.038 | 0.763 | 0.789 | 0.032 |
| | RA2 | Granite | 0.774 | | | 0.825 | | |
| | RA3 | Granite | 0.849 | | | 0.780 | | |
| Vulcan Materials | UA1 | Granite | 0.759 | 0.774 | 0.013 | 0.770 | 0.763 | 0.019 |
| | UA2 | Granite | 0.781 | | | 0.742 | | |
| | UA3 | Granite | 0.782 | | | 0.777 | | |

Note 1: The surface area (SA) is given for one aggregate.

technique was found to allow settlement of the particles to the bottom minimizing the number of air bubbles trapped during particle placement in the cylinder. No tapping of the cylinder was needed because the samples were small. After curing for 24 hr in a warm location, two to three rock saw cuts across the diameter were performed on each cylinder, giving three or four cut aggregate surfaces suitable for measuring roughness on.

Surface Polishing

Numbers 120, 300, and 600 polishing grits were used to obtain a smooth aggregate surface and sharp contrast between the aggregate surface profile and epoxy. The No. 120 coarse grit was used to take out most of the unevenness caused by the saw cut; at the same time it placed small grooves in the sample. The No. 300 grit was used to polish out the grooves placed by the coarse No. 120 grit. Finally, the No. 600 grit polished out any remaining tiny marks or grooves to provide a smooth, finished surface. The sample was polished a minimum of 5 min with each grit. The samples were washed between grit changes to prevent any contamination of the finer grit with the coarser ones.

Surface Photography

A photograph of the aggregate surface gives the surface profile in a form suitable for digitizing. A scale was also photographed to accurately quantify the level of magnification used. For the purposes of this study, a magnification of approximately $20\times$ was selected for the photomicrograph as being suitable for defining the surface roughness characteristics (Figure 4). The photographs were later blown up 50 percent using a photocopier. This procedure gave a $30\times$ magnification of the surface and resulted in significant savings on printing costs compared with those for blowing the negative up to $30\times$ during printing.

The use of other magnification levels of the surface would be expected to yield different values of surface roughness. Wright, for example, suggested using $125\times$, which perhaps is too much magnification to evaluate surface roughness of the gross surface. The appropriate value of magnification to use certainly deserves further study.

Kodak PX-125 black-and-white film was used for the photographs. Three aggregate particles from each quarry were evaluated for surface roughness. Pictures were taken of two different locations on the surface of each of the three particles, resulting in six photographs per quarry. In determining surface roughness, each photograph was broken into three smaller segments to minimize the curvature effects of the aggregates. This procedure resulted in 18 values of surface roughness from each quarry.

Digitization

A similar scheme of manipulating the data as used for shape analysis was also used for roughness. A macro routine within Lotus 1-2-3 arranged the digitized points, calculated the true

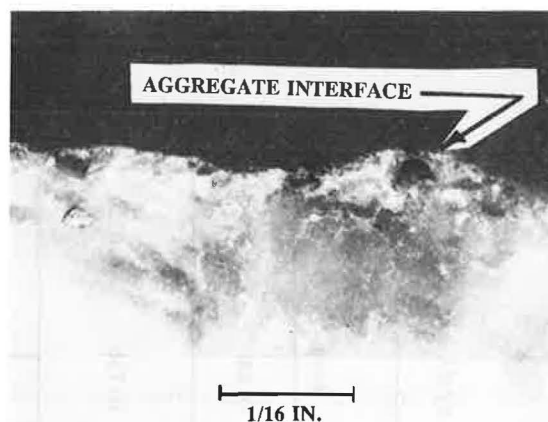


FIGURE 4 Photograph of polished aggregate at surface after $20\times$ magnification.

length of the digitized surface, and calculated the line of best fit of the data. The macro routine also adjusted the length for magnification, calculated the surface roughness, and then created a graph of the real surface and the line of best fit or projected surface. Both the graph and the worksheet were saved on disk.

Calibration of Digitization Procedure

Several calibrations were performed to find any errors, problems, or limitations of the overall digitization methodology used to evaluate surface roughness. Calibrations were obtained from a simple comparison of measured surface roughness with the calculated surface roughness of surfaces having simple, easily defined shapes. The first surface used consisted of two semicircles connected together as shown in Figure 5. For all calibrations, points on the surface were digitized at distances on the photographs varying from 0.01 to 0.1 in.

Figure 5 shows that an optimum spacing of digitized points of about 0.05 in. exists, which gives the minimum error for a surface consisting of two semicircles. A closer spacing of digitization points, which intuitively would be thought to be more

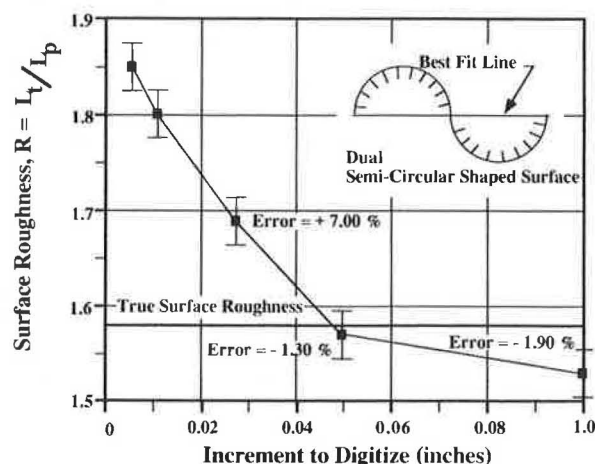


FIGURE 5 Calibration of surface roughness digitization using a sine wave surface.

accurate, was actually found to be less desirable. The loss in accuracy was apparently caused by small levels of shaking of the hand (referred to as hand vibrations). A surface with saw-tooth shape was also used for calibration. The optimum digitization spacing was found to be 0.04 in., which was close to that found for the circular surface.

The calibration studies indicated that a digitization increment of 0.05 in. yielded good results. An average correction factor of +2.0 percent was used to correct calculated surface roughness to increase the accuracy on the basis of the calibration studies.

Reproducibility of roughness measurements on aggregate surfaces obtained by a single experienced operator was found to be good. In comparing the results from three digitizer operations (only one having a high level of experience), the standard deviation of roughness was found to be 0.023 for three quarries in a supplementary study. This study indicated that the operator should become experienced using the digitizer on reference surfaces such as the one shown in Figure 5.

Results

As presented in Table 2 and found by Wright (11), surface roughness varies greatly both over the surface of a single particle and from one particle to another for the same quarry. Therefore, only general trends of surface roughness should be considered and as many measurements as practical should be performed. Observed variations in surface roughness were as follows: 1.16 to 1.26 for 15 granite gneiss quarries; 1.13 to 1.15 for 3 limestone quarries; 1.16 for an injection quartz; and 1.13 for an alluvial gravel.

CONCLUSIONS

The use of modern data acquisition procedures, which include a relatively low-cost digitizer and microcomputer, makes possible the accurate and rapid acquisition of large quantities of data. These devices were used together with Autocad and Lotus 1-2-3 spreadsheet, to acquire and process large quan-

TABLE 2 ROUGHNESS DATA ILLUSTRATING VARIABILITY FOR A STREAM DEPOSIT—
DIGITIZATION INCREMENT OF 0.05 in., AGGREGATE $\frac{3}{8}$ TO $\frac{1}{2}$ in.

| SAMPLE | ROUGHNESS PER SAMPLE | CORRECTED ROUGHNESS | AVG. RGH PER GROUP | AVG. RGH PER AGG. | AVG. RGH PER QUARRY |
|--------|-------------------------|------------------------|-----------------------|----------------------|------------------------|
| CA1051 | 1.16 | 1.18 | | | |
| 2 | 1.10 | 1.12 | 1.14 | | |
| 3 | 1.09 | 1.11 | | 1.12 | |
| CA2051 | 1.09 | 1.11 | | | |
| 2 | 1.07 | 1.09 | 1.10 | | |
| 3 | 1.07 | 1.09 | | | |
| CA3051 | 1.07 | 1.09 | | | |
| 2 | 1.12 | 1.14 | 1.12 | | |
| 3 | 1.09 | 1.11 | | 1.15 | 1.13 |
| CA4051 | 1.23 | 1.25 | | | |
| 2 | 1.08 | 1.10 | 1.18 | | |
| 3 | 1.16 | 1.18 | | | |
| CA5051 | 1.10 | 1.12 | | | |
| 2 | 1.10 | 1.12 | 1.11 | | |
| 3 | 1.06 | 1.08 | | 1.13 | |
| CA6051 | 1.20 | 1.22 | | | |
| 2 | 1.10 | 1.12 | 1.16 | | |
| 3 | 1.10 | 1.12 | | | |
| Mean | 1.13 | Standard Deviation | 0.50 | | |

Roughness per Sample - True Length/Projected Length

Corrected Roughness - (1.0199) + Roughness per Sample

Avg. Rgh. per Group - Average roughness of samples from same picture

Avg. Rgh. per Agg. - Average roughness of 2 groups (pictures) taken from same aggregate

Avg. Rgh. per Quarry - Average roughness of 3 agg. from each quarry sample, A or B

tities of data without ever touching the data after digitization. The use of a spreadsheet makes possible easy interpretation and presentation of the data. Sample preparation and data acquisition have been described for shape, surface area, and roughness of aggregates. These techniques can, however, also be applied to many other materials applications.

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