Rapid Shape Analysis of Crushed Stone Using Image Analysis†

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Abstract

The shape and texture of construction aggregates are important parameters that have a direct bearing on the strength and durability of their asphalt and concrete end products. Although shape standards may vary throughout the world, nearly every country characterizes shape in terms of elongation and flatness. Typically, a given batch of material is rejected if more than a specific percentage of particles have elongation and flatness ratios which exceed some limit. Present procedures for determining these ratios rely on manual techniques which are tedious and tend to limit the number of samples that can be analyzed.

Researchers at Virginia Tech have recently developed a rapid shape analysis system which can determine elongation and flatness ratios for a standard batch of 100 particles in under 10 minutes. The system consists of an image analyzer constructed around a personal computer. Results obtained indicate an excellent agreement between the rapid analysis system and standard manual techniques. In addition, the system is capable of providing two quantitative measures of particle roughness. The development and validation of the analyzer and its measurement procedures are discussed.

1. Introduction

Over two billion metric tons of aggregate (crushed stone, sand and gravel) are produced annually in the U.S. at a value of nearly $10 billion. Of this tonnage, crushed stone makes up roughly 60% (USBM, 1995). Typically, this material must meet specifications generated by end-users and/or government agencies defining acceptable limits on several material properties including particle size, shape, strength, etc. Of these properties, particle shape may be one of the most important parameters to end-users since poorly shaped particles tend to reduce the strength and durability of road beds, asphalt and concrete.

There are several documented examples indicating the importance of shape and/or product roughness on end-product performance. Barksdale (1989), for example, developed an Aggregate Influence Factor incorporating several shape and roughness parameters to characterize the rutting and resiliency of aggregate bases such as might be used in road beds. Similarly, the use of “well-shaped” material in Portland cement concrete is known to give better workability of the fresh concrete and reduce the quantity of cement and water needed to obtain a given strength. Unpublished work by Rimmer et al. (1986) on the effects of particle shape concludes that the strengths of standard specimens prepared with aggregate samples obtained from different crushers varies so markedly that the use of a well-shaped stone can permit cost reductions of about 15% through the reduced use of cement in concretes of a given compressive strength. Kojovic (1994) and Ramos, Smith and Kojovic (1994) investigated modifications to the crusher models developed at the Julius Kruttschnitt Minerals Research Centre (JKMRC) in order to predict both particle size and shape. They noted that particle shape, a major quality parameter in the construction aggregate industry, has largely been ignored by researchers.

A number of methods have been used and/or proposed over the years to characterize particle shape. These include everything from various qualitative measures to the use of Fourier descriptors and fractal analysis. The most common qualitative measures and shape factors can be found in a variety of classical texts (Allen, 1974; Orr and Dallavalle, 1960). The use of Fourier descriptors has been examined by several authors including Eppler and Meloy (1980) and Beddow (1988). Finally, fractal geometry has been explored since the late 1970’s...

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(Kaye, 1978); although it is only beginning to be investigated for shape analysis in the construction aggregate industry (Carr et al., 1994).

Unfortunately, only a few of these methods are routinely used to characterize construction aggregates. The most common of these methods, and the one now accepted as an ASTM standard (ASTM, 1989), involves the measurement of elongation and flatness ratios. Referring to Figure 1, the elongation ratio is represented by the length-to-width ratio in the plan view, while the flatness ratio is represented by the width-to-height ratio in the end view. According to the standard ASTM procedure, elongation and flatness ratios are measured using a specially designed caliper, shown schematically in Figure 2. This caliper can be set to measure ratios of 2:1, 3:1 or 5:1 depending on various government regulations. Typically, 100 particles are measured and the number and/or weight percent of those particles exceeding a specified limit is recorded. A batch of material is rejected if a certain percentage of particles (e.g., 5%) have elongation or flatness ratios greater than this limiting value. Since this percentage and ratio can vary from state to state, it is possible that a crushed stone product which fails to meet the requirements of one state may be sold in another state. Unfortunately, this would require a second analysis at a different caliper setting. Clearly, even at coarse sizes this is an extremely tedious procedure requiring nearly an hour of analysis time per sample. Thus, the number of samples analyzed is greatly limited in a practical situation.

Over the past several years, researchers at Virginia Tech, under the sponsorship of the U.S. Bureau of Mines Generic Mineral Technology Center for Comminution, have developed a rapid shape analyzer based on the use of image analysis technology. This device replaces the tedious manual techniques currently in use in the aggregate industry and is capable of providing the entire flatness and elongation distribution of a sample in a fraction of the time currently required to obtain a single point on the distribution. In addition, the device provides a direct measure of roughness which is not available with current test procedures. The objective of this paper is to describe the development of the rapid shape analyzer, the test work carried out to validate the measurement procedures, and some preliminary applications of the analyzer in characterizing crusher performance.

2. System Development

Image analysis and computer vision are becoming increasingly common in the world today for identifying and locating objects, analyzing defects and flaws in materials, and positioning robots or robotic arms. In the minerals industry, image analysis has been used for such things as assay determination, particle size analysis and mineral liberation studies. An image analysis system typically consists of a computer, a "frame grabber" board, and a television camera. An image is collected by the television camera and digitized by the frame grabber board. The computer then uses specially designed image analysis software to process the digital image and make measurements on the objects in the image. These measurements can include such things as color, size, area, shape, etc.

A schematic diagram of the rapid shape analysis system is shown in Figure 3. As shown, the system consists of a personal computer and monitor, frame grabber board, video monitor and sample presentation stand with dual camera mounts. Crushed stone samples are placed on the multi-level sample stand and positioned so that all samples can be properly viewed in the video monitor. Two cameras or camera angles are used so that both top and side views can be obtained to provide the necessary.
information for determining elongation and flatness. The camera images are received by the frame grabber board and digitized. The digitized images are then processed, using the OPTIMAS® software package marketed by Bioscan, Inc., to produce measurements of the individual particle dimensions. This information is then used to calculate the flatness and elongation ratios, along with two different roughness parameters, for each particle. The software is compatible with Microsoft Windows® and the data can be displayed in user-friendly tables and plots.

During the course of the system development work, both single- and dual-camera prototypes were tested. In general, it was found that the dual-camera arrangement gave a higher degree of accuracy; however, it is possible that a single camera on a moveable arm may be a cost-effective alternative in future versions. In addition, a multi-level sample stand was incorporated so that more particles would fit within a single field-of-view than would be possible with a flat stand. With the present design, approximately 20-30 particles of Virginia Department of Transportation (VDOT) Designation 57 (90-100% minus 25 mm, 26-60% minus 12 mm, and 0-3% minus 2.4 mm) can be placed in a single image. Assuming a conservative estimate of one minute to load the sample stand, one minute to process the image and one minute to unload the stand, it should be easily possible to complete 100 measurements of both elongation and flatness in under 15 minutes, and probably within 10 minutes. The equipment required for the current prototype analyzer was purchased for approximately $10,000. It is estimated, however, that this cost could be reduced to approximately $5,000 in a commercial version by using less expensive television cameras and by installing an application version of the software as opposed to a developmental version.

3. Testing and Verification

Elongation and Flatness

A sample of crushed limestone (VDOT Designation 57) was obtained from the W.W. Boxley Co. Blue Ridge Operation near Roanoke, Virginia, for use in verifying the accuracy of the rapid shape analysis system. Approximately 150 particles were selected from the sample and each particle was hand measured with a micrometer caliper to determine the elongation and flatness ratios. The same set of particles was then measured using the shape analyzer and the results were compared. These comparisons are shown in Figures 4 and 5 in terms of shape distribution plots (i.e., number percent of particles having elongation or flatness ratios greater than a given value). As shown, the agreement between the caliper measurement and the image analysis measurement is remarkable. The two lines are nearly coincident with,
It is important to note that the rapid shape analyzer is not limited to providing information at a specific value, such as percentage of particles having an elongation greater than 3, but routinely provides information on the entire shape distribution. Thus, from a single measurement, it is possible to determine the percentage of particles having flatness and elongation ratios greater than 2, 3 or 5, as may be required by various state specifications. Further research may also make it possible to correlate the shape distribution to the strength and durability of the final end product. For example, it may be possible that two aggregate samples exhibiting the same percentage of flat and elongated particles at some limiting ratio, may very well produce asphalt or concrete products of different strengths due to differences in the overall shape distribution.

**Roughness**

In addition to elongation and flatness, the rapid shape analyzer is capable of conducting other useful particle characterization measurements without the need for additional image processing time. One such measurement that has been incorporated into the current design is roughness. At present, there is no direct method for measuring particle roughness in the aggregate industry. Therefore, two parameters have been identified in this work that directly quantify particle roughness. These two parameters are termed "surface irregularity" and "jaggedness".

Figure 6 illustrates the present implementation of the surface irregularity measurement. The image analysis system begins by locating the centroid of each particle. It then measures the distance, \( R_i \), from the centroid to the edge of the particle in two-degree increments. If these distance measurements are plotted as a function of the angle, \( \theta \), the surface irregularity of the particle is transformed into a linear trace. In order to make the measurement independent of particle size, the distance measurements are normalized by dividing by the average radius, \( R_{\text{avg}} \), of the particle. These normalized radii are then digitally filtered to remove surface variations caused by "noise", and the numerical derivative of the trace is taken to determine the number of peaks and valleys. This number, expressed as a percentage of the total number of possible peaks and valleys (i.e., 179 if every measurement was a peak or valley), represents the surface irregularity of the particle. Mathematically, surface irregularity can be represented using the unit impulse function as:

\[
\text{Surface Irregularity} = \frac{\sum_{i=1}^{179} \left( \frac{d R_i}{d \theta} \right)}{179} \cdot 100
\]  

The jaggedness measurement is used to indicate the amount by which a particle deviates from a perfect sphere. It is calculated using many of the
same parameters used for surface irregularity. In this case, the normalized radius, \( R_i/R_{avg} \), is subtracted from 1. This value provides a measure of the deviation of the radius from the average radius. A perfect sphere should give a value of zero. The individual measurements are then summed over all 180 two-degree increments, and the sum is divided by 180 to give an average measure of the deviation per increment. Mathematically, jaggedness can be represented as:

\[
\text{Jaggedness} = \frac{1}{180} \sum_{i=1}^{180} \left| 1 - \frac{R_i}{R_{avg}} \right|
\]  

(2)

The implementation of the jaggedness and surface irregularity parameters is illustrated in Table 1 using several standard shapes. As can be seen, jaggedness values are typically higher for particles which are elongated or have large projections (i.e., particle types 1, 3, 4, 6 and 7). Surface irregularity values are higher for particles which have many small projections (i.e., particle types 2, 6, 7 and 8). Particles such as the star (particle type 4) are jagged but exhibit a very regular surface, while particles such as the gear (particle type 2) have a high surface irregularity but are not considered jagged. The particle illustrated as type 6 is both jagged and irregular, while a perfect circle (particle type 5) shows no jaggedness or surface irregularity.

Although the rapid shape analyzer makes it possible to quantify particle roughness, the utility of these roughness parameters is yet to be determined.
Table 1. Roughness measurements made on several standard shapes.

| Particle Type | Surface Irregularity | Jaffedness |
|---------------|----------------------|------------|
| 1             | 5.59                 | 61.76      |
| 2             | 24.03                | 6.34       |
| 3             | 3.91                 | 28.26      |
| 4             | 2.79                 | 25.35      |
| 5             | 0.56                 | 0.74       |
| 6             | 11.17                | 26.34      |
| 7             | 9.49                 | 23.30      |
| 8             | 6.70                 | 3.88       |

As shown in Figures 7 and 8, the coarsest particles appear to be more regular in shape, i.e., fewer flat and elongated particles. As size decreases, the percentage of flat and elongated particles increases. Furthermore, the coarsest particles tend to have fewer protrusions as indicated by the jaggedness distribution (Figure 9). These results seem to suggest that the coarse particles appearing in the crusher product are subjected to little breakage and simply have their jagged edges removed. The finer particles, which are freshly produced within the crusher, tend to be less regular in shape and more jagged. In terms of surface irregularity (Figure 10), there is a general tendency for the particle surfaces to become smoother as size decreases. This sug-

4. Applications

The use of the rapid shape analysis system to characterize crusher performance is still in its infancy; however, preliminary results have been obtained on the product from a 1.3-meter short-head cone crusher operating on a basalt-type material at the W.W. Boxley Co. Mt. Athos Plant. This crusher is used as the fourth stage of crushing following a primary jaw crusher, a standard cone crusher and another short-head cone crusher. A belt sample was collected immediately following the crusher discharge point, and the material was sized to produce the distribution shown in Table 2.

Since the bulk of the sample was primarily in the range from 40-5 mm, four size classes within this range were analyzed using the rapid shape analysis system to produce the results shown in Figures 7-10.

Table 2. Product size distribution from 1.3-meter short-head cone crusher.

| Size Class (mm) | Weight Percent |
|-----------------|----------------|
| +38             | 0.9            |
| 38 x 25         | 23.1           |
| 25 x 19         | 27.4           |
| 19 x 12         | 23.5           |
| 12 x 6.4        | 11.6           |
| 6.4 x 3.3       | 4.6            |
| - 3.3           | 8.9            |
5. Summary and Conclusions

1. A rapid shape analysis system has been developed for the aggregate industry. The system uses state-of-the-art image analysis technology to determine elongation, flatness and two measures of roughness.

2. The system is capable of analyzing a standard batch of 100 particles in under 10 minutes and provides information on the entire shape distribution as compared to current manual techniques which provide only a single point of the distribution.

3. Results from the rapid shape analysis system were found to be in excellent agreement with manual measurements of elongation and flatness.

4. Two direct measurements of roughness have been proposed and demonstrated with the rapid shape analyzer. At present, there are no other techniques available for direct measurement of roughness.

5. Preliminary analyses of crusher products indicate that the shape analysis system can serve as a useful tool for quantifying the effect of crusher type and operating conditions on particle shape.

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Nomenclature

$I(\cdot)$ unit impulse function

$R_i$ distance from the centroid of a particle to its edge

$R_{avg}$ average particle radius (average of $R_i$ over 180 two-degree increments)

$\theta$ direction angle for any particle radius, degrees

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Author's short biography

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David A. Broyles obtained his B.S. (1992) and M.S. (1995) in Mining and Minerals Engineering from Virginia Polytechnic Institute and State University. His M.S. thesis focused on the development of an optical analyzer for measuring the shape of crushed stone particles used in the construction aggregate industry. Mr. Broyles is a member of the Virginia Society of Professional Engineers, the National Society of Professional Engineers and the Society for Mining, Metallurgy and Exploration, Inc. He is currently employed as a mineral processing engineer for Engelhard Corp. in Macon, Georgia.

Hugh W. Rimmer

Hugh W. Rimmer is a graduate of Otago (BE, 1963) and Columbia Universities (EngScD, 1972). He taught for several years following graduation, and has worked in process control and metallurgical R&D on the Zambian Copperbelt; comminution/minerals processing with Allis-Chalmers/Svedala; and in coal and minerals processing R&D at Virginia Tech. He is currently self employed, working on process evaluation/optimization and enterprise computing projects in coal, aggregates and minerals processing.

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Gregory T. Adel (Associate Professor, Mining and Minerals Engineering) received his B.S. degree (1978) and M.S. degree (1979) in Metallurgical Engineering from South Dakota School of Mines and Technology. He received his D. Eng. degree in 1982 from the University of California, Berkeley. Following Graduation, he joined the Department of Mining and Minerals Engineering at Virginia Polytechnic Institute and State University as an Assistant Professor. he was promoted to Associate Professor in 1987. Dr. Adel is an active member of the Mineral and Metallurgical Processing Division of the Society for Mining, Metallurgy and Exploration, Inc., serving on a variety of committees. He has approximately 60 publications and 4 patents in areas pertaining to image analysis, optical sensors, mineral and coal characterization, and modeling and simulation of mineral and coal processing operations.