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Particle shape analysis of coarse aggregate using digital image processing

A.K.H. Kwan*, C.F. Mora, H.C. Chan

Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, People's Republic of China

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Abstract

The particle shape characteristics of the coarse aggregate used can significantly affect the workability, strength, and durability of the concrete produced. However, traditionally, particle shape measurements have to be done in a manual way that is both cumbersome and time-consuming. Herein, digital image processing (DIP) techniques are used to analyze the particle shape characteristics of coarse aggregate. The main particle shape characteristics measured are flakiness and elongation. Twenty-five aggregate samples of different rock type and size have been analyzed and the results are compared to results obtained by the traditional manual method. Strong correlation between the DIP and manual measurement results is achieved and thus the DIP method, which is much faster, may be a better alternative for particle shape measurement. In fact, the DIP method yields more information about the particle shape than the manual method. With the DIP method used, it is possible to measure the mean thickness/breadth and length/breadth ratios of the aggregate directly, rather than just the proportion of flaky or elongated particles according to arbitrary definitions.

Keywords: Characterization; Image analysis; Physical properties; Aggregate; Shape analysis

1. Introduction

Digital image processing (DIP) is a computerized technique by which a scene is captured electronically, digitized into a two-dimensional pixel image, and then processed so that pictorial information about the scene can be extracted [1]. The scene can be captured by means of a video camera or a scanner. Video signals generated in this manner are first digitized using a frame grabber with built-in A/D converters and then stored as an array of pixels. Subsequently, the pixel array is analyzed to extract information from the digital image. Different techniques have been developed for this purpose, depending on the information required. For instance, to find the edge of an object in the scene, an algorithm that looks for sharp changes in color or gray level of neighboring pixels can be employed. Once the objects have been discriminated from the background, they can be measured and analyzed. The parameters that can be measured include particle count, area fraction, size distribution, shape characteristics, spatial distribution, and more. By performing image analysis of successive scenes captured over a period of time, the technique can also be used to measure particle velocity, trace moving objects, and measure deformation.

In recent years, DIP techniques have found widespread applications in many disciplines, including medicine, biology, geography, meteorology, manufacturing, and material science [2]. Relatively, there have been very few applications of DIP in civil engineering [3]. In civil engineering, DIP has been used to analyze the size, shape, and spatial distribution of grains and pores in sandy soil, to study the microstructure of concrete, to detect cracks in road pavement, to measure structural deformations, and to evaluate traffic conditions [4]. However, it is believed that these are just some of the possible applications. If we could exercise more imagination, there could be many more possible applications of DIP in civil engineering.

As part of a research program to explore the possible applications of DIP to concrete technology, the authors are investigating viable means of applying DIP to the size and shape analysis of aggregate particles. This is a topic of practical importance because a concrete mix is constituted largely of aggregate and its quality is hence dependent on the grading, size, and shape of the aggregate used. Applications of DIP techniques to particle size and shape analysis have been attempted by other investigators [5–8]. New techniques and even new approaches are being developed gradually, but it may be a few more years before the full potential of these new methods can be realized or the problems with them completely resolved.

* Corresponding author. Tel.: +852-2859 2647; fax: +852-2559 5337.
E-mail address: khkwan@hku.hk (A.K.H. Kwan)

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One major problem with the DIP technique is that only the two-dimensional projection of the particles is captured and measured. In other words, the third dimension (i.e., thickness) of the particles is not directly obtainable from the DIP results. Due to this problem, the DIP results have to be expressed in terms of area fractions rather than mass fractions [7]. Consequently, they cannot be compared to those obtained by traditional methods and are more difficult to interpret. Another problem is that different researchers are using different shape indexes to describe the shape of aggregate particles and even different definitions for the same shape index. For instance, Barksdale et al. [5] defined the flatness as the ratio of thickness to breadth and the elongation as the ratio of breadth to length while Kuo et al. [8] defined the flatness as the ratio of breadth to thickness and the elongation as the ratio of length to breadth. They also used different definitions for the shape factor and sphericity. There is yet another problem that some of the proposed shape indexes are quite difficult to comprehend because of their high mathematical sophistication. Being engineers by training, the authors have up to now found it difficult to understand the physical significance of the slope density functions and fractal dimensions generated by fractal analysis of the particle shape [6] and how these fractal parameters can be correlated to the common concepts of flakiness, elongation, roughness, etc.

In a recent paper [9], the authors have applied DIP to size distribution analysis of coarse aggregate and developed a simple method of converting area fractions to mass fractions based on the assumption that aggregate particles from the same source should have more or less the same shape characteristics. After converting to mass fractions, the grading results obtained by DIP were compared to those by mechanical sieving to verify the accuracy of the DIP method. This paper is a follow-up of the previous one, and deals with the application of DIP to particle shape analysis of coarse aggregate. The proposed DIP method is designed in such a way that both flakiness and elongation of the aggregate are measured. As before, the shape analysis results obtained by DIP are expressed in terms of mass fractions rather than area fractions, thus allowing direct comparison with results by the traditional manual method specified in the British Standards. Nevertheless, after comparing with the traditional manual method for the purpose of verification, it is suggested that we need not be bound by the traditional measures of flakiness and elongation. The flakiness and elongation indexes defined in the British Standards, which require manual measurement, are themselves not good measures of flakiness or elongation of the aggregate. The mean thickness/breadth and length/breadth ratios directly obtainable from DIP may be better measures, as will be discussed in the paper.

2. Particle size and shape analysis by traditional method

Traditionally, the size and shape analysis of coarse aggregate are conducted by mechanical sieving and manual gauging, as detailed in the British Standards BS812, Section 103.1 (1985), BS812, Section 105.1 (1989), and BS812, Section 105.2 (1990). For the aggregate sample to be representative, its total mass must be larger than the minimum mass specified in BS812, Section 103.1 (1985).

Basically, the mechanical sieving operation attempts to divide a sample of aggregate into size fractions, each consisting of particles within specific size limits. This is done by forcing the aggregate particles to pass through sieves of successively smaller sizes. Before the sieving operation starts, the sieves are stacked up with the smallest one at the bottom and the largest one at the top. A pan is placed underneath the sieves to collect particles passing through all sieves. To perform sieving, the aggregate sample is placed on the sieve of largest size, covered, and then shaken for a specified period of time. During shaking, the particles pass through the sieves until they are retained on sieves too small for them to pass through. After sieving, the quantity of each size fraction, which consists of particles passing through a sieve of certain size but retained on another sieve of smaller size, is measured by weighing.

The results of sieve analysis are normally presented graphically in the form of grading charts. In the grading chart commonly used, the ordinate represents the cumulative percentage passing by mass of the aggregate and the abscissa the sieve sizes plotted to a log scale. However, the following points should be noted when interpreting the results:

1. Particles passing through a sieve can actually have one dimension that is larger than the size of the sieve apertures. From Fig. 1(a), it can be seen that an elongated particle that has its length greater than the aperture size can pass through the sieve without any difficulties. Therefore, the sieve aperture size is a measure of the lateral dimensions of the particles only.
2. A relatively flaky particle can pass through the sieve aperture, which is square in shape, diagonally as shown in Fig. 1(b). As a result, the breadth of a particle passing through a sieve can also be greater than the sieve size, although it has to be smaller than the diagonal length of the sieve aperture.

Regarding shape analysis of the coarse aggregate, only the flakiness and elongation are measured. The procedures for their measurement are specified in BS812, Section 105.1 (1989) and BS812, Section 105.2 (1990), respectively. These procedures are performed after mechanical sieving because the aggregate sample first needs to be divided into different size fractions, each consisting of particles falling within specific sieve size limits.

The flakiness and elongation of the aggregate sample are measured in terms of flakiness and elongation indexes, which are defined as the percentages by mass of the aggregate particles classified as flaky and elongated, respectively. The classification is based on the rather arbitrary definitions that a particle is flaky if its thickness (least dimension) is

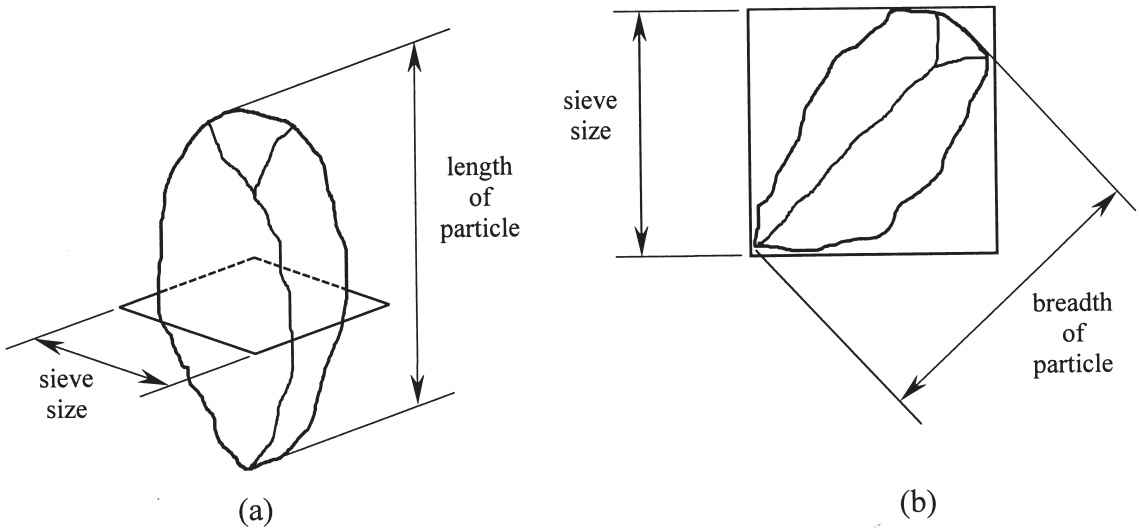

Fig. 1. (a) An elongated particle passing through a sieve aperture. (b) Plan view of a flaky particle passing through a sieve aperture.

smaller than 0.6 times the mean sieve size of the size fraction to which it belongs, and that a particle is elongated if its length (largest dimension) is greater than 1.8 times the mean sieve size (the mean sieve size is the arithmetic mean of the sieve size on which the particle is just retained and the smallest sieve size through which the particle passes).

In actual practice, the thickness and length of the particles are not measured but checked against standard thickness and length gauges to see whether or not the particles are flaky or elongated. Table 1 lists the dimensions of the thickness and length gauges for various size fractions and their respective tolerances. During the test, each particle is gauged manually against the appropriate slot in the thickness gauge or the appropriate gap in the length gauge to identify and separate the flaky or elongated particles. Some particles are both flaky and elongated, and are therefore counted in both categories. For this reason, the flakiness and elongation tests have to be carried out separately.

In the flakiness test, the flaky particles are separated from each size fraction by manual gauging and their quantities measured by weighing. After weighing, the flakiness index is calculated as the ratio of the mass of flaky particles to the total mass of the aggregate sample expressed as a percentage. After the flakiness test, all the flaky particles are put back into the respective size fractions to which they belong for subsequent testing. The elongation test is conducted in a similar manner, after weighing, to determine the quantity of elongated particles. The elongation index is calculated as the percentage by mass of the aggregate particles that are regarded as elongated. During the flakiness or elongation test, if any size fraction of the aggregate sample has a mass smaller than 5% of the total mass of the aggregate sample, the particular size fraction is not included in the test and the total mass of the aggregate sample is adjusted accordingly.

From the authors' own experience, the mechanical sieving takes approximately 1–2 h to complete, while the flakiness and elongation tests, both requiring cumbersome manual gauging of particles one by one, together take about 2–3 h to complete. Hence, it takes about 4 h to perform one set of mechanical sieving and flakiness and elongation tests.

Despite the laborious work required to perform the tests, however, there are a number of shortcomings with the flakiness and elongation tests, as explained below:

1. The definitions used to classify flaky or elongated particles are rather arbitrary. In theory, the shape classification of a particle should be dependent only on its shape, not on its size. However, with the present definitions used, whether or not a particle is flaky or elongated is dependent not only on its shape but also on its sieve size. For instance, a particle having its sieve size equal to the mean sieve size of the size fraction to which it belongs and a thickness equal to 0.6 times its sieve size is regarded as flaky, while another particle of similar shape but slightly larger size would be regarded as not flaky. A similar situation happens with the classification of elongated particles.

Table 1
Dimensions of thickness and length gauges according to BS812, Section 105.1 (1989), and BS812, Section 105.2 (1990)

Sieve size limits of aggregate size fraction (mm)	Width of slot in thickness gauge (mm)	Gap between pins of length gauge (mm)
63.0–50.0	33.9 ± 0.30	–
50.0–37.5	26.3 ± 0.30	78.7 ± 0.3
37.5–28.0	19.7 ± 0.30	59.0 ± 0.3
28.0–20.0	14.4 ± 0.15	43.2 ± 0.3
20.0–14.0	10.2 ± 0.15	30.6 ± 0.3
14.0–10.0	7.2 ±0.1	21.6 ± 0.2
10.0–6.30	4.9 ± 0.1	14.7 ± 0.2

2. Classifying particles as either flaky or not flaky and either elongated or not elongated seems a bit too crude. Two particles of similar size but slightly different thickness or length can be classified very differently. Hence, a small change in shape can lead to an abrupt change in flakiness or elongation. On the other hand, two particles of vastly different shape can both be classified into the same category. As a result, changes in shape are not always reflected in the flakiness or elongation measurement. The traditional method simply does not take into account the actual degrees of flakiness and elongation of the particles. It does not provide a proper measure of flakiness or elongation when a single particle is considered because it will give a flakiness/elongation index of either 0 or 100%. Only when a large aggregate sample consisting of many particles is analyzed will the flakiness and elongation indexes become more like continuous variables and acceptable as realistic measures of particle shape.
3. The thickness-to-sieve size ratio used to determine whether or not a particle is flaky is not quite the same as the normal concept of flakiness because the sieve size measurement is not orthogonal to the thickness measurement, as depicted in Fig. 2. Likewise, the length-to-sieve size ratio used to determine whether or not a particle is elongated is different from the normal elongation ratio defined as the length-to-breadth ratio [8]. These differences should be kept in mind when interpreting the flakiness and elongation index results.

3. Particle size and shape analysis by DIP

The DIP system used by the authors is a Quantimet 600 manufactured by Leica Cambridge Ltd. It incorporates a three-chip CCD camera having a resolution of 736 × 574 pixels, a frame grabber with three A/D converters each of 8-bit resolution, a photographic stand fitted with light sources, a Pentium-based computer, and a set of software for image analysis. Fig. 3 shows schematically the setup of the system.

Before any DIP can be performed, it is first necessary to take a high-quality picture of the aggregate particles. The equipment for taking pictures of the aggregate sample is set up by mounting a video camera on a photographic stand, adjusting the height of the video camera to obtain a sufficiently large measurement area on the sample tray, and adjusting the light sources so that there is no shading of any object placed on the sample tray. A sheet of cardboard of suitable color is laid on the sample tray before the aggregate particles are added. When the aggregate particles are placed into the sample tray, they are carefully spread out so that they are not touching or overlapping each other or falling out of the boundary of the measurement area. After the aggregate particles have been properly positioned, the sample tray is placed on the photographic stand under the camera. The focus of the lens is then adjusted to obtain a clear and sharp image of the aggregate sample. When the captured image as seen on the computer screen is checked to be satisfactory, it is stored for image analysis. Other details of the image acquisition process have been reported previously [9].

Having acquired a pixel image of the aggregate sample, image analysis is performed to discriminate the aggregate particles from the background. This involves increasing the contrast between the particles and the background and finding the boundary of each particle. Once the particle boundaries are located, the area, length, and breadth of the particles are measured. The area of a particle is defined as the projected area of the particle in its stable position, while the length and breadth of a particle are defined as the length and breadth of the bounding rectangle that would enclose the projected image of the particle being analyzed. On completion, the measurement results are saved in a spreadsheet file for statistical analysis and postprocessing.

Since the particles are generally anisotropic, it is natural that there is a preferred orientation for a particle to be stable

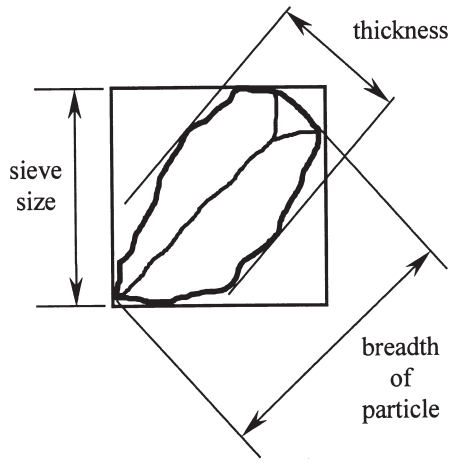

Fig. 2. Plan view of a sieve showing the sieve size and thickness measurements.

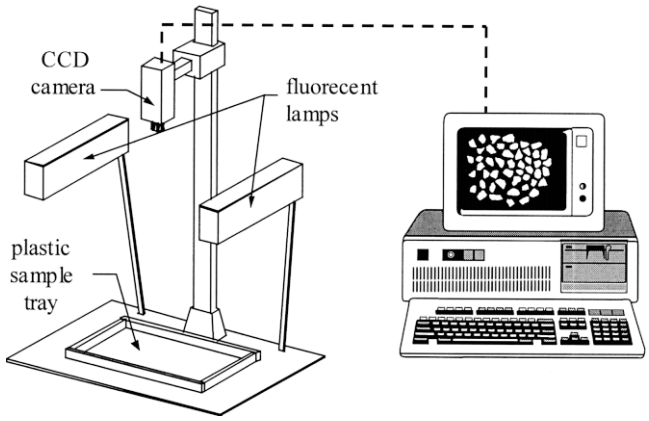

Fig. 3. Setup of the image analysis system.

on a flat surface. If there is only one preferred orientation for a particle to lay stably, then the image measurement results are unique. If, however, there is more than one such preferred orientations for the particle, then at different stable positions, the results can be slightly different, as illustrated in Fig. 4. Nevertheless, if the aggregate sample contains a reasonably large number of particles, such random variations tend to cancel out, and the image measurement results of the aggregate sample as a whole should be quite consistent.

Once the DIP equipment has been properly set up and adjusted, the size and shape analysis of an aggregate sample can be completed in about 10 min of time, which is much shorter than the required time of about 4 h when the traditional method is used.

However, since the image acquired is only a two-dimensional projection of the particles, the thickness and volume of the particles are not directly obtainable from the image. Hence, it is not possible to measure the flakiness of the particles just by using DIP techniques. It is also not possible to measure the quantity of particles in terms of volume or mass. Thus, the quantity of particles can only be measured in terms of their total projected area, as has been done by Yue and Morin [7]. This would cause difficulties in interpreting the quantity of particles measured by DIP because most engineers are used to quantify the amount of aggregate particles in terms of volume or mass. Another problem is that traditionally the size of a particle has been measured in terms of its sieve size, which is not quite the same as the breadth of the particle measured by DIP. As a result, the size measurement results obtained by DIP cannot be compared directly to those obtained by traditional methods. These problems are resolved in the following sections.

4. Converting area fractions to mass fractions

A simple method of converting the quantity of particles in terms of area or area fraction obtained by DIP to mass or mass fraction so that the DIP results can be correlated to those obtained by traditional methods and interpreted more easily has been proposed recently [9]. It is based on the assumption that aggregate particles from the same source should have more or less the same shape characteristics. Using this assumption, the mean thickness of a particle may be estimated from the other dimensions of the particle as shown in Eq. (1):

$$\text{mean thickness} = \lambda \times \text{breadth} \tag{1}$$

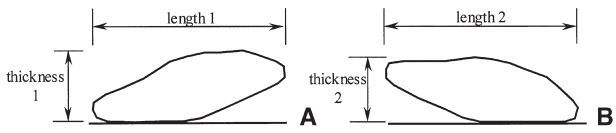

Fig. 4. A particle at different stable positions. (a) Stable position 1; (b) stable position 2.

in which λ is a parameter dependent on the flakiness of the particle. From this equation, the volume of the particle may be estimated by Eq. (2):

$$\text{volume} = \text{mean thickness} \times \text{area} = \lambda \times \text{breadth} \times \text{area} \tag{2}$$

Using this formulae, the mass of a group of particles is calculated as shown Eq. (3):

$$\text{mass of a group of particles} = \rho \times \lambda \times \sum_{i=1}^{p} (\text{breadth} \times \text{area}) \tag{3}$$

where ρ is the density and the summation is for all particles in the group. Dividing this mass by the total mass of the aggregate sample, the mass fraction of the group of particles is obtained as shown in Eq. (4):

$$\begin{aligned}\text{mass fraction} &= \frac{\rho \times \lambda \times \sum_{i=1}^{p} (\text{breadth} \times \text{area})}{\rho \times \lambda \times \sum_{i=1}^{n} (\text{breadth} \times \text{area})} \\ &= \frac{\sum_{i=1}^{p} (\text{breadth} \times \text{area})}{\sum_{i=1}^{n} (\text{breadth} \times \text{area})}\end{aligned} \tag{4}$$

where the summation in the denominator is for all particles in the aggregate sample. It is noteworthy that λ and ρ are canceled out in the above equation and therefore the actual value of ρ does not affect the conversion of area fraction to mass fraction. Nevertheless, λ may serve as a flakiness indicator and its value can be determined by Eq. (5):

$$\lambda = \frac{M}{\rho \times \sum_{i=1}^{n} (\text{breadth} \times \text{area})} \tag{5}$$

in which *M* is the total mass of the aggregate sample measured by weighing.

5. Converting breadth to equivalent sieve size

As illustrated in Fig. 1(b), the sieve size of a particle is generally smaller than the breadth measured by DIP. The authors have proposed in a previous paper [9] to convert the breadth to an equivalent sieve size using a size correction factor *C* as shown in Eq. (6):

$$\text{equivalent square sieve size} = C \times \text{breadth} \tag{6}$$

The value of *C* is dependent on the shape of the cross section of the particle and therefore has to be determined for each type and source of aggregate. It is determined by a trial and error process of matching the grading curve derived by DIP based on an assumed value of *C* to the corresponding curve obtained by mechanical sieving.

6. Comparison of results by the two methods

Three different types of aggregates (granite, volcanic, and gravel) of maximum sizes ranging from 10–20 mm have been analyzed by both the traditional method and the DIP method. The aggregate samples were first tested by the traditional method and then the same samples were analyzed by DIP again for direct comparison. All together, 25 samples have been tested.

After converting area fractions to mass fractions and breadth to equivalent sieve sizes, the grading analysis results obtained by DIP have been compared to those by mechanical sieving in the previous paper [9]. It was found that with a suitable value of the size correction factor *C* used, very good matching of the grading curves by the two methods can be achieved.

The values of *C* obtained for the aggregate samples analyzed are plotted against the corresponding values of λ in Fig. 5. It is seen that there is a good correlation between *C* and λ and that generally the more flaky the aggregate is, the smaller the value of *C* will be.

The DIP method is unable to yield the flakiness of the aggregate directly. Nevertheless, the parameter λ may be taken as a flakiness indicator because it represents the mean value of the mean thickness-to-breadth ratio. The values of λ obtained by DIP are plotted against the corresponding values of flakiness index measured by manual gauging in Fig. 6. It is seen from this figure that there is a strong correlation between λ and the flakiness index, thus showing that λ may be used as a measure of flakiness in its own right.

Adopting the same definitions used by the British Standards, the DIP method can produce the elongation index of the aggregate in the same way as in the manual gauging method but in a rather clumsy way. First, the breadth measurements by DIP have to be converted to equivalent sieve sizes. Then the size fractions to which the particles belong have to be determined and the corresponding mean sieve sizes evaluated. Having evaluated for each particle the mean sieve size of the size fraction to which it belongs, the particles are classified one by one as either elongated or not elongated. Finally, the mass fraction of the elongated particles is calculated and taken as the elongation index. The elongation indexes evaluated using DIP are compared to those measured by manual gauging in Fig. 7. Very good agreement has been achieved.

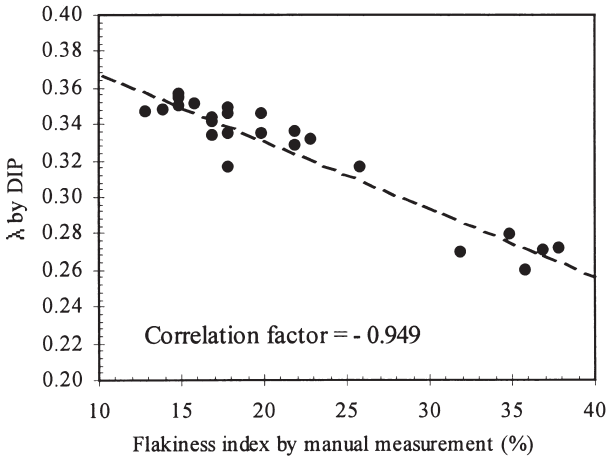

Fig. 6. Comparison of λ to flakiness indexes by manual measurement.

As mentioned before, classifying the shape of a particle according to the mean sieve size of the size fraction to which it belongs is quite misleading. A more rational way is to classify the particle according to its own sieve size. This would change the definition of an elongated particle to one that has a length-to-sieve size ratio greater than 1.8. With the DIP method, the sieve size is not obtained directly; it is converted from the breadth using a size correction factor. To save the trouble of size correction, it is proposed that an even better way of defining an elongated particle is to use the length-to-breadth ratio. Since the sieve size is approximately 0.8 times the breadth, a length-to-sieve size ratio of 1.8 is equivalent to a length-to-breadth ratio of about 1.5. Hence, it is better to define an elongated particle as one hav-

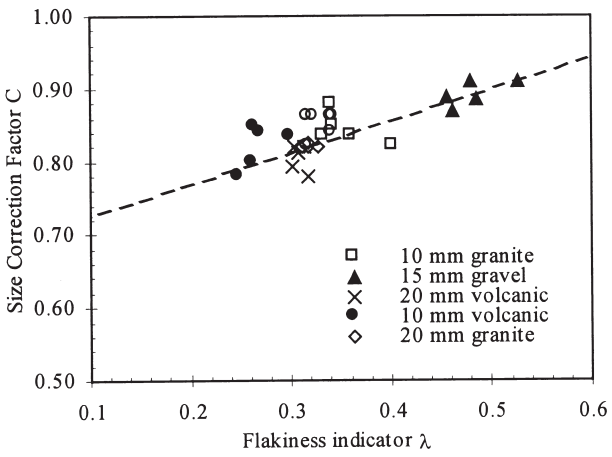

Fig. 5. Relationship between C and λ.

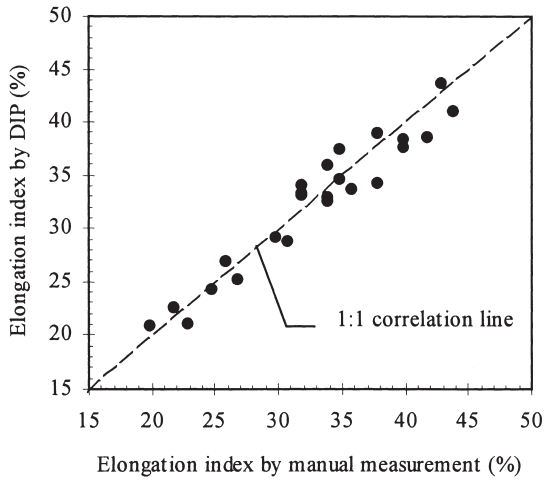

Fig. 7. Comparison of elongation indexes by DIP to those by manual measurement.

ing a length-to-breadth ratio of greater than 1.5. With this new definition adopted, the elongated particles can be identified using the DIP method without any size correction. The elongation indexes evaluated by the DIP method are compared to those by the traditional method in Fig. 8.

Nevertheless, after comparison with the traditional method for the purpose of verification, it is suggested that we need not be bound by the traditional measure of elongation. A much better and more direct way of measuring the elongation of an aggregate is to first determine the length-to-breadth ratios (also called elongation ratios) of all the aggregate particles from the DIP measurement results and then calculate the mean value of the elongation ratios. There is, however, the question of how the mean value should be calculated. Since larger aggregate particles have greater effects on the quality of the concrete produced, it is proposed that the mean value should be calculated as a weighted mean value, given by Eq. (7):

$$\text{weighted mean elongation ratio} = \frac{\sum_{i=1}^{n}\left(\text{volume}\times\frac{\text{length}}{\text{breadth}}\right)}{\sum_{i=1}^{n}(\text{volume})} = \frac{\sum_{i=1}^{n}\lambda\times(\text{breadth}\times\text{area})\times\left(\frac{\text{length}}{\text{breadth}}\right)}{\sum_{i=1}^{n}\lambda\times(\text{breadth}\times\text{area})} = \frac{\sum_{i=1}^{n}(\text{length}\times\text{area})}{\sum_{i=1}^{n}(\text{breadth}\times\text{area})} \quad (7)$$

The weighted mean elongation ratio evaluated based on the DIP measurement results are compared to the elongation indexes obtained by the traditional method in Fig. 9. It is believed that this mean elongation ratio is a better measure of elongation than the elongation index.

7. Conclusions

A method of analyzing the flakiness and elongation of coarse aggregates using DIP technique is developed. Although the thickness and volume of the particles are not measured, this DIP method is capable of producing the mean thickness/breadth ratio of the aggregate and shape measurement results in terms of mass fractions. For the purpose of verification, the shape measurement results obtained by the proposed DIP method have been compared to those obtained by traditional mechanical sieving and manual gauging. Strong correlation between the parameter (mean thickness-to-breadth ratio) derived by the DIP method and the flakiness index measured by the traditional method has been achieved. On the other hand, the elongation indexes obtained by the DIP method agree very closely with those by the traditional method. After such comparison, however, it is suggested that we need not follow the existing definitions of flakiness and elongation indexes, which are suffering from several shortcomings as discussed previously. The parameter λ, which is easily obtainable by the DIP method, can replace the flakiness index. For replacing the elongation index, a new weighted mean elongation ratio, which is believed to be a better measure of elongation, is developed.

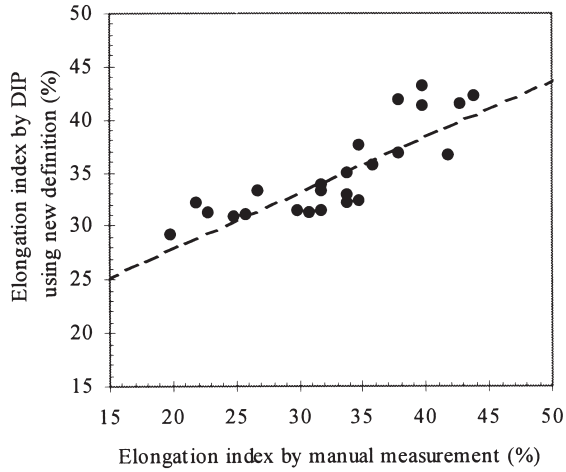

Fig. 8. Comparison of elongation indexes by DIP using new definition to those by manual measurement using existing definition.

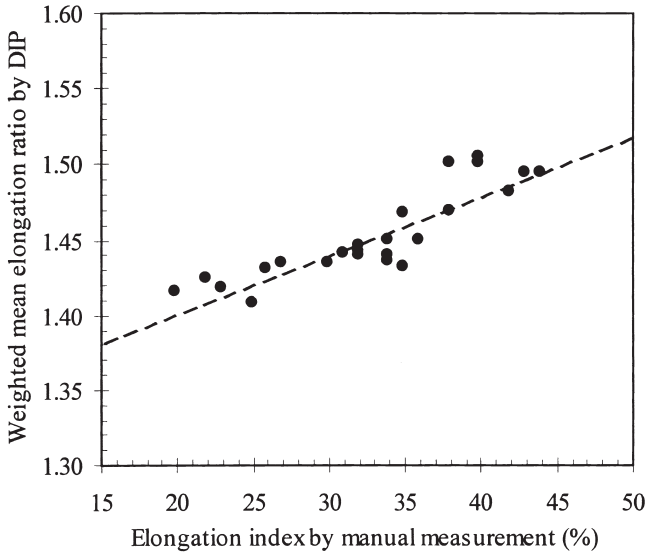

Fig. 9. Comparison of weighted mean elongation ratios by DIP to elongation indexes by manual measurement.

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