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PARTICLE SIZE DISTRIBUTION ANALYSIS OF COARSE AGGREGATE USING DIGITAL IMAGE PROCESSING

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ABSTRACT

An attempt at applying the digital image processing (DIP) technique to analyze the particle size distribution of coarse aggregate is made. Three different types of aggregates have been analyzed, and their grading curves are compared to those obtained by conventional mechanical sieving. Because DIP produces only area gradation and uses a particle size definition different from the square sieve size used in mechanical sieving, direct comparison is not possible unless the gradation basis and particle size definitions of the two methods are aligned. For this purpose, a simple method of converting the area gradation to mass gradation is proposed. Moreover, a size correction factor is used to convert the particle sizes measured by DIP to equivalent square sieve sizes so that comparison between the DIP and mechanical sieving results can be made. The study demonstrates that DIP is a fast, convenient, versatile, and accurate technique for particle size distribution analysis. It is, however, not without limitations, which will be discussed. *© 1998 Elsevier Science Ltd*

Introduction

DIP is a technique by which a scene is captured, digitized into a pixel image and then processed so that information can be extracted from the image. During the past few years, DIP techniques have found widespread applications in many disciplines, including medicine, biology, geography, meteorology, manufacturing, and material science (1). There have been very few applications of DIP in civil engineering (2). DIP has been used to analyze the size, shape, and spatial distribution of grains and pores in soil, study the microstructure of concrete, detect cracks in road pavement, measure structural deformations, and evaluate traffic conditions (3). 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. What is particularly attractive about DIP is that it not only offers a means to augment existing methods but also opens up opportunities of developing innovative methods.

As part of a research program to explore the possible applications of DIP to concrete technology, the authors are investigating practicable means of applying DIP to the size and

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shape analysis of aggregate particles. The size and shape analysis of particles has been a topic of great interest because of its importance in particulate technology, soil mechanics, asphalt pavement construction, and concrete technology, etc. Applications of DIP techniques to particle size and shape analysis have been attempted by Barksdale et al. (4), Li et al. (5), Yue and Morin (6), and Kuo et al. (7). New techniques and even new approaches are being gradually developed, but it may be a few more years before the full potential of these new methods can be realized or the problems with them can be completely resolved. One of the major problems with the DIP technique is that only the two-dimensional projection of the particles is captured and measured. The third dimension, thickness, of the particles is not directly obtainable from the DIP results. A method of estimating the thickness of the particles by creating a shadow of the particles and measuring the shadow length from the captured image has been developed by Barksdale et al. (4). However, this method may fail if the particle spacing is not sufficient to allow for a shadow between adjacent particles. Kuo et al. (7) have developed a technique of measuring the thickness of particles from images of orthogonal projections. As the particles have to be placed and adhered one by one onto an angle-shaped sample tray, this method is more applicable to coarse aggregates rather than fine aggregates because handling the fine aggregate particles one by one is very tedious and time consuming. Due to the difficulties of obtaining the third dimension from DIP, the DIP results have been expressed in terms of area fractions rather than mass fractions and consequently, they cannot be compared directly to those obtained by conventional mechanical sieving.

This paper is on the application of DIP to particle size distribution analysis of coarse aggregates. Unlike previous studies by others, the method developed herein can produce results in terms of mass fractions, and thus the results can be compared to those by conventional mechanical sieving and interpreted more easily, as most engineers are more familiar with mass fraction than area fraction.

DIP Technique

DIP consists of the following basic steps of image acquisition and image analysis.

Image acquisition is the process of capturing a scene and digitizing it into a pixel image. The scene can be captured by means of a charge-coupled device (CCD) camera, a digital camera, or even a 35 mm camera. Digital cameras acquire and digitize the scene in one step, while CCD cameras, which produce analogue signals, require a frame grabber to digitize the signal. Processed films from 35 mm cameras, on the other hand, require the use of a film scanner for image acquisition. The digitized image is stored as an array of pixels. The size of the array depends on the resolution of the hardware used. An array of 250×250 pixels is considered low resolution of a normal size picture. At the high end of the resolution scale, resolutions of 4096×4096 pixels or more are possible.

Image analysis is the process of extracting information from the digitized image by analyzing the pixel array. Different techniques have been developed for this purpose, depending on the information required. For instance, to find the edge of an object depicted in an image, an algorithm that looks for sharp changes in color or gray level of neighboring pixels can be employed. This kind of process, which detects and isolates objects from the background, is called segmentation. Once the image has been segmented, the discriminated objects can be measured and analyzed. The parameters that can be measured or analyzed

TABLE 1
Minimum mass of sample for sieving analysis according to BS812:Part 103:1985.

Nominal size of material (mm)	Minimum mass of sample to be tested (kg)
63.0	50
50.0	35
40.0	15
28.0	5
20.0	2
14.0	1
10.0	0.5
3.0–6.0	0.2
$<$3.0	0.1

include particle count, area fractions, size distribution, shape characteristics, and spatial distribution, etc. 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.

The DIP system used by the authors is a Quantimet 600 manufactured by Leica Cambridge Ltd. It incorporates a 3-chips CCD camera having a resolution of 736 $\times$ 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. The following accessories are also connected to the system for enhanced DIP capabilities: a film scanner, an M/O disk drive, a CD-ROM writer drive, and a color inkjet printer.

Particle Size Distribution Analysis by Mechanical Sieving

Mechanical sieving is the most commonly used method to determine the grading, i.e., particle size distribution, of an aggregate. Basically, the sieving operation attempts to divide a sample of aggregate into fractions, each consisting of particles within specific size limits. Before the sieving 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 the particles which pass 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 sieves of successively smaller sizes until they are retained on sieves too small for them to pass through. In actual practice, however, after the shaking is done, not all particles retained on a sieve are really larger than the sieve apertures. Particles slightly smaller than the aperture size may sometimes be stuck without passing through the sieve. Manual checking and brief hand sieving are thus required to make sure that all particles retained on a sieve are bigger than the sieve apertures. After sieving, the quantity of each fraction of particles is measured by weighing.

In order for the sample to be representative, there needs to be a minimum sample size for testing, as given in Table 1.

The results of sieve analysis are normally presented graphically in the form of grading

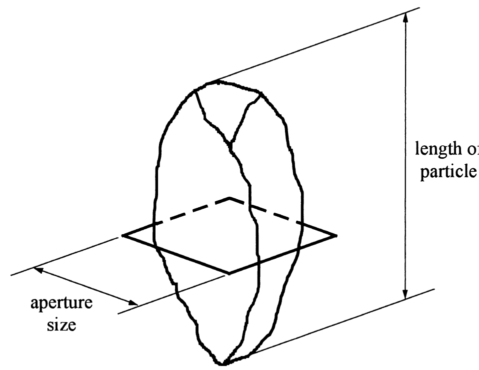

FIG. 1.
An elongated particle passing through a square sieve aperture.

charts. In the grading chart commonly used, the ordinate represents the cumulative percentage passing by mass of the aggregate (mass gradation) and the abscissa the sieve sizes plotted to a log scale. The following points should, however, be noted when interpreting the results of mechanical sieving:

1. Particles passing through a sieve can actually have one dimension larger than the size of the sieve apertures. From Figure 1, it can be seen that an elongated particle having 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 Figure 2. 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.

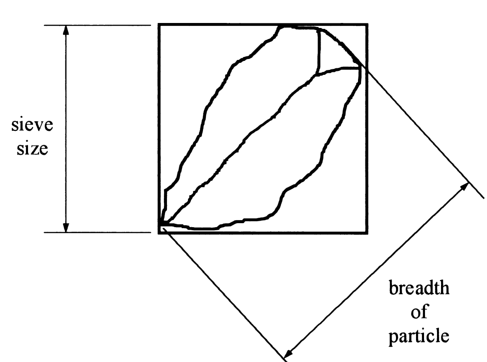

FIG. 2.
Plan view of a flaky particle passing through a square sieve aperture.

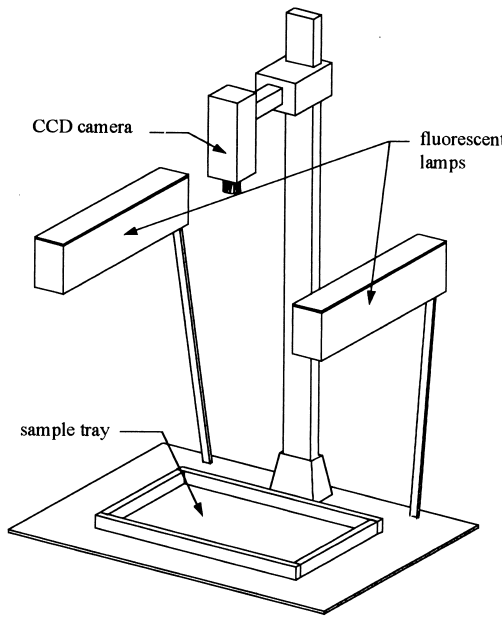

FIG. 3.
Schematic of the photographic stand and camera arrangement.

Particle Size Distribution Analysis by DIP

A high quality picture of the aggregate particles is needed before any DIP can be performed. The equipment for taking pictures of aggregate samples is set up by mounting a camera on a photographic stand as shown in Figure 3, adjusting the height of the 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 card paper of suitable color is laid on the sample tray before the aggregate particles are put in. 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. If the captured image, which can be seen on the computer screen, is checked to be satisfactory, it is stored for image analysis.

Either before or after the picture of the aggregate sample is taken, the image measurement needs to be calibrated by placing a calibrated stage micrometer on the sample tray, taking a picture of it, and then correlating the pixel scale to the linear dimension shown on the stage micrometer in the digitized image. The calibration may also be performed concurrently with the image acquisition process by placing the stage micrometer adjacent to the aggregate sample during the image acquisition process. All settings of the equipment must remain undisturbed between the calibration and the image acquisition process.

The sample tray contains a measurement area of 300 mm $\times$ 240 mm, which is approximately the maximum practical size of the image field of the camera on the stand that guarantees minimum distortion. The number of particles that can be placed within the

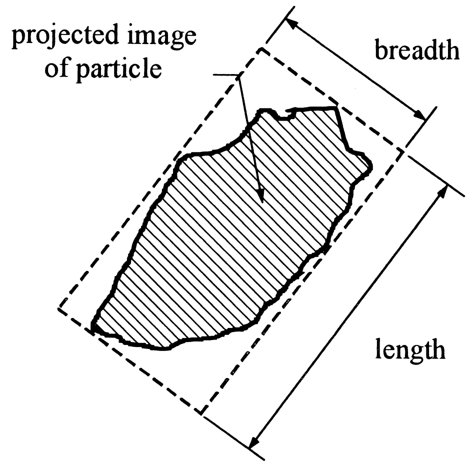

FIG. 4.
Definitions for length and breadth of a particle.

measurement area without touching or overlapping each other ranges from 100 to about 300, depending on the size and shape of the aggregate particles. Because the aggregate sample, which has to be large enough to meet the minimum mass requirement given in Table 1, often contains more than 1000 particles, it cannot be all placed onto the sample tray at one time. Therefore, the aggregate sample has to be divided into several sub-samples whose images are taken successively so that the image of all particles can be captured.

Having acquired a pixel image of the aggregate sample, image analysis is performed to extract the aggregate particles from the background. From the extracted aggregate particles, the following morphological parameters are measured: area, length, and breadth of each particle. Area is defined as the projected area of the particle in its stable position. This involves counting the number of the pixels inside the closed boundary of the particle image and converting the pixel count to an area in real dimensions according to the scale factor determined by calibration. On the other hand, the length and breadth of a particle are defined as the length and breadth of the bounding rectangle that would enclose the particle area being analyzed, as shown in Figure 4. The measurement results are saved in a spreadsheet file for statistical analysis and post-processing.

Once the equipment has been properly set up and adjusted, the sieving analysis by DIP of an aggregate sample can be completed in about 10 min. of time, which is much shorter than the required time of 1 to 2 h for mechanical sieving analysis.

Comparison of Results by the Two Methods

Three different types of aggregates, granite, volcanic, and gravel aggregates, have been analyzed by both the mechanical sieving method and the DIP method. The aggregate samples were first analyzed by mechanical sieving and then the same samples were analyzed by DIP again for direct comparison.

Before any comparison between the results obtained by mechanical sieving and those by DIP can be made, the following differences between them need to be addressed:

1. In mechanical sieving, the quantities of aggregate fractions are measured by weighing and thus the gradation is expressed in terms of percentages by mass of the aggregate (mass gradation). In DIP, however, the volume or mass of the aggregate particles are not measured. In fact, because the image acquired is only a two-dimensional projection of the particles, even the thickness of the particles is not measured. Thus, aggregate fractions obtained by DIP can only be presented in terms of percentages by area of the aggregate on a stable horizontal surface (area gradation), as has been done by Yue and Morin (6).
2. In mechanical sieving, the sizes of the particles are measured in terms of the sizes of the square sieve apertures, so that the particles pass through or are retained on. The particle sizes so determined are not the same as the breadth of the particles measured by DIP.

A simple method of converting the area gradation obtained by DIP to mass gradation so that the DIP results can be correlated to conventional mechanical sieving results and interpreted more easily is proposed. It is believed that aggregate particles from the same source have more or less the same shape characteristics. Hence, the mean thickness of a particle may be estimated from the other dimensions of the particle as follows:

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

where λ is a parameter dependent on the flakiness of the particle. From this equation, the volume of the particle may be estimated by:

$$\begin{aligned} \text{volume} &= \text{area} \times \text{mean thickness} \\ &= \lambda \times \text{area} \times \text{breadth} \end{aligned} \tag{2}$$

Using this formula for the volume of a particle, the mass gradation is obtained as:

$$\begin{aligned} \text{percentage by mass passing a sieve} &= \frac{\rho \times \lambda \times \sum_{i=1}^{p} (\text{area} \times \text{breadth})}{\rho \times \lambda \times \sum_{i=1}^{n} (\text{area} \times \text{breadth})} \\ &= \frac{\sum_{i=1}^{p} (\text{area} \times \text{breadth})}{\sum_{i=1}^{n} (\text{area} \times \text{breadth})} \end{aligned} \tag{3}$$

where the summation in the denominator is for all particles while the summation in the numerator is for particles smaller than the sieve size, and ρ is the density. The values of λ and ρ are canceled out in the above equation and therefore the actual value of λ does not affect the mass gradation curve. Nevertheless, λ has a physical meaning and its value may be determined by

$$\lambda = \frac{M}{\rho \times \sum_{i=1}^{n} (\text{area} \times \text{breadth})} \tag{4}$$

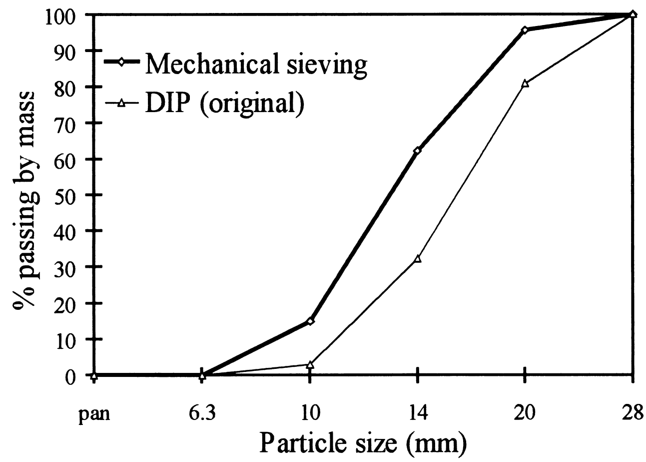

FIG. 5.
Grading curves obtained by DIP and mechanical sieving before size correction.

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

Having converted the area gradation to mass gradation, the grading results obtained by DIP can then be compared to those by mechanical sieving on the same grading chart, as shown in Figure 5. The grading curves obtained by DIP and mechanical sieving do not quite agree with each other, with the curve obtained by DIP being consistently lower than that by mechanical sieving. This is because the particle size definitions used in the two methods are different.

The particle size measurement obtained by mechanical sieving actually depends on the shape of the apertures of the sieves used. If the sieve apertures are circular, as shown in Figure 6a, then the size of the sieve (diameter of the sieve apertures) that a particle can just pass through is very close to the breadth of the particle. But, if the sieve apertures are square, as shown in Figure 6b, then the size of the sieve (width of the sieve aperture) that a particle can just pass through is generally only about 0.8 times the breadth of the particle. Hence, sieves with circular and square apertures would give different particle size measurement results. According to Bernhardt (8), size measurement results obtained by sieves with circular apertures may be converted to equivalent square sieve sizes by:

$$\text{equivalent square sieve size} = C \times \text{circular sieve size} \tag{5}$$

where C is a size correction factor whose value is dependent on the shape of the cross-section of the particle but is generally within the range of 0.7 to 0.9. Herein, it is proposed that the breadth measured by DIP may also be converted to equivalent square sieve size using such a correction factor, as given below:

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

Because the value of C depends on the shape of the aggregate particles, it has to be determined for each type and source of aggregate. A trial and error process is used to determine the value of C. Different values of C are tried and the grading curves so derived for the DIP results are compared to those obtained by mechanical sieving until the best match

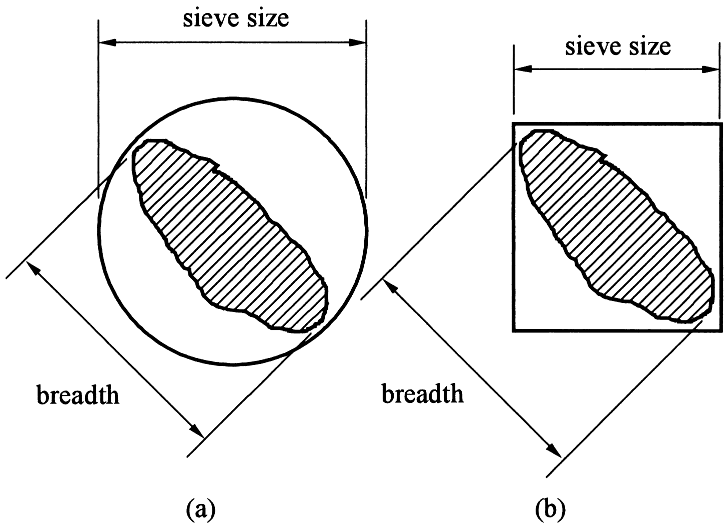

FIG. 6.
Effect of aperture shape on particle size measurement.

between the DIP and mechanical sieving results is obtained. The values of *C* so determined together with the corresponding values of λ are given in Tables 2 and 3. From these results, it is seen that the volcanic aggregates, which are the most flaky among the aggregates studied, have the lowest values of λ. On the other hand, the gravel aggregates, which are rounded in shape, have the highest values of λ. Comparing the values of *C* to the corresponding values of λ, it is seen that generally, the more flaky the aggregate is, the smaller will be the value of *C*.

After the area gradation is converted to mass gradation and the breadth to equivalent square sieve sizes by the methods proposed, the grading curves obtained by DIP are compared to those by mechanical sieving in Figure 7 (due to limitation of space, only the results of some of the samples analyzed are presented). Good agreement between the DIP and mechanical sieving results is obtained.

TABLE 2
Size correction factor *C*.

Aggregate type	Sample S1	S2	S3	S4	S5	Average of 5 samples
20 mm granite	0.82	0.82	0.82	0.82	0.83	0.82
10 mm granite	0.82	0.85	0.88	0.83	0.83	0.84
15 mm gravel	0.91	0.91	0.89	0.89	0.87	0.89
20 mm volcanic	0.80	0.78	0.81	0.82	0.82	0.81
10 mm volcanic	0.80	0.84	0.83	0.78	0.84	0.82

TABLE 3
λ as a flakiness indicator.

Aggregate type	Sample					Average of 5 samples
	S1	S2	S3	S4	S5	
20 mm granite	0.31	0.31	0.32	0.33	0.32	0.32
10 mm granite	0.40	0.34	0.34	0.36	0.33	0.35
15 mm gravel	0.53	0.48	0.49	0.46	0.46	0.48
20 mm volcanic	0.30	0.32	0.31	0.31	0.30	0.31
10 mm volcanic	0.26	0.26	0.30	0.25	0.27	0.27

Discussions

In the above, the DIP technique has only been applied to the sieve analysis of coarse aggregates. Theoretically, the DIP technique proposed herein can also be applied to fine aggregates. However, there is the major difficulty of spreading the fine particles so that they are not touching or overlapping each other. For coarse aggregate particles, the spreading can be done manually; for fine aggregate particles, manual spreading is cumbersome. A device for gently tapping and vibrating the sample tray so that the particles will be automatically spread out is being fabricated and, if the device works, the results obtained will be presented, together with the results of shape analysis which the authors are working on, in a later paper.

Apart from the above, the DIP technique has the limitation that due to the discrete nature of the pixel image, there is a lower limit for the size of an object that can be accurately represented within the pixel image. Because the coordinates of the particle boundary will be rounded either up or down by half a pixel, there could be a possible error of plus or minus one pixel in the size measurement. To keep the percentage error at less than 10%, it is suggested that the object whose size is to be measured should have a size of at least 10 pixels in the image. Particles whose sizes in the image are less than 10 pixels would not be measured accurately by the DIP technique. Fortunately, due to the random nature of such discretization error, when a large number of particles is analyzed, the net percentage error would be much less because the plus and minus errors tend to cancel each other out. As digital video technology further advances, it is expected that the resolution of the hardware will gradually increase and this discretization error will soon become less of a concern.

Another limitation is that the DIP technique does not produce results directly comparable to those by conventional mechanical sieving, and thus the DIP results, which are in terms of area gradation and breadth, need to be interpreted in a different way. Nevertheless, if all particles of the aggregate are from the same source, the method proposed in this paper may be used to convert the area gradation to mass gradation, which is much easier to understand and interpret. Moreover, the breadth results by DIP may be converted, if so desired, to equivalent square sieve sizes by the size correction factor used herein. However, it may be argued that the breadth is a proper definition of particle size in its own right and it is as easy to interpret as any other definition of particle size. It may even be argued that the square sieve size is quite misleading because particles passing through a square sieve aperture can actually have their length and breadth greater than the sieve size. It is, therefore, suggested that the conversion of breadth to equivalent square sieve size is not really necessary; the conversion

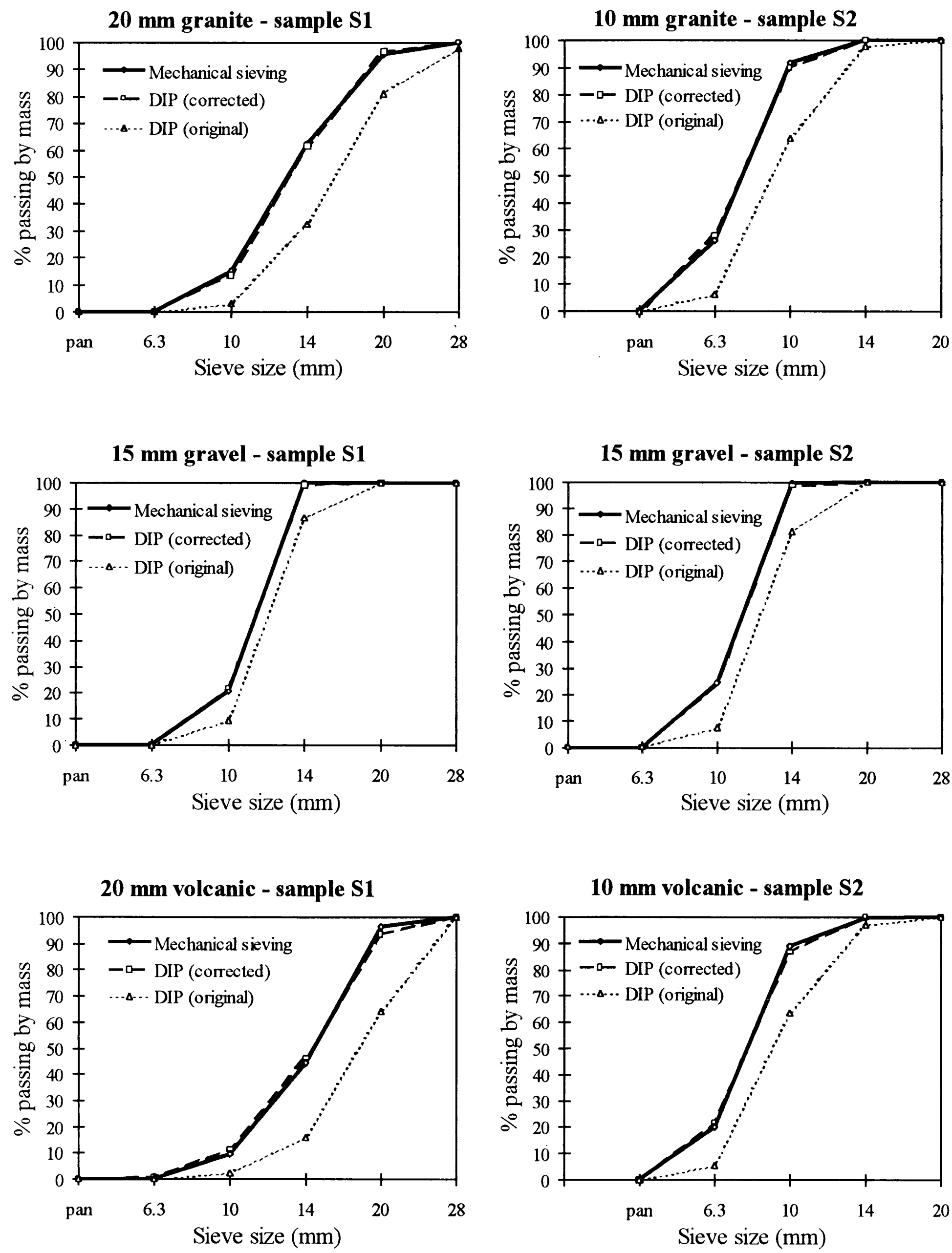

FIG. 7.

Grading curves obtained by DIP and mechanical sieving after size correction.

performed in this study was only for the purpose of comparing the results of DIP to those by mechanical sieving so that the accuracy of the DIP method may be verified.

All in all, the experience gained from this study indicates that the DIP method is fast, convenient, versatile, and yet sufficiently accurate for engineering purposes. In fact, the DIP method yields a lot more information than the conventional mechanical sieving method. For instance, the DIP method can produce continuous grading curves that are not possible with the mechanical sieving method. In fact, from the same captured image, the shape characteristics of the aggregate may also be obtained. Because the DIP method also produces length results, the elongation of the aggregate may be determined simply as the mean length/breadth ratio of the aggregate particles. In addition, the [lamba] factor obtained by the DIP method may also be interpreted as the ratio of the mean thickness to the breadth and hence taken as a measure of flakiness.

Conclusions

A method of analyzing the particle size distribution of coarse aggregates using DIP technique is developed. Unlike other DIP methods, which yield only results in terms of area gradation, the method developed herein has the capability of converting the area gradation to mass gradation, provided all particles of the aggregate sample are from the same source. During the process of converting area gradation to mass gradation, a shape parameter λ, which may be taken as a measure of flakiness, is generated and hence flakiness is also measured. Good agreement is achieved when the DIP results are compared to those by conventional mechanical sieving.

Apart from being fast, convenient, and versatile, the DIP method has the major advantage that it yields a lot more information than the mechanical sieving method. In fact, from the same captured image of the aggregate, detailed shape analysis of the particles may also be carried out. However, the DIP method has the difficulty that the particles must be carefully spread out to avoid touching or overlapping. There is also the limitation that the particles must not appear to be too small in the pixel image or otherwise their pixel representations would be inaccurate.

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