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Cement and Concrete Research 35 (2005) 1629–1637

Cement and Concrete Research

Image analysis method for determining 3-D shape of coarse aggregate

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Received 23 December 2003; accepted 1 November 2004

Abstract

A 3-D method for particle shape determination of coarse aggregates using image analysis, IA, is presented. It is based on the measures the axial length of all three axis of every particle in a coarse aggregate sample. Two images of the entire aggregate sample are taken, in lying and standing positions. Since the particle's intermediate axes are measured in both images they can be used to couple the shortest and longest axial dimensions for each particle. The method allows an interpretation of length/thickness, length/width and width/thickness ratios of all the particles and is thus comparable to the flakiness and shape index tests.

Keywords: Particle shape; Image Analysis; Particle size distribution; Physical properties; Aggregates

1. Introduction

Characterization of aggregate quality is important for all areas of usage in engineering. The size, shape and surface texture of aggregates used in asphalt and concrete are important for the quality of the finished product. The ability to characterize aggregates with respect to size, shape and surface texture will result in better management of resources and increase the life of the engineering product and thus result in economic savings.

For decades, sieve analysis has been the main method for size determination and to some extent shape determination of coarse aggregates. However, sieving is just a bulk approximation of the size distribution of an aggregate sample and not a true measure of any of the individual particles in the sample [1–4]. The results of sieving are also dependent upon the shape of the particles [1,4].

Particle shape is important to the suitability of the aggregates with respect to their usage in several engineering materials. Elongated particles compared to cubic particles have a tendency to break along their long axis. Thus particle form affects the strength of the aggregates and life expectancy of the materials such as concrete, asphalt, and railroad aggregate. Spherical particles result in good rheological character in contrast to platy particles that deter the rheological character of concrete paste. Aggregates with a rough surface compared to a smooth surface will bind more securely in both asphalt and concrete.

There are several test methods for characterizing the particle shape, for example the flakiness index and shape index. The test methods are often tedious, subjective and time consuming. Furthermore the results are normally presented as an index for the bulk aggregate sample and do not give specific information concerning the individual particles.

Computers give us the opportunity to develop new image analysis test methods for measuring aggregates. These methods are much more accurate and less time consuming than traditional methods. Image analysis, IA, has been used in numerous studies on aggregate size and shape [5,6]. These deal with laboratory studies of size and shape both on a macro- and microscopic scale [7–16]. There are several other methods that measure the 3-D morphologies of particles. Some methods image individual particles placed in holders [13,14]; each particle is imaged from two orthogonal views. These methods provide a 3-D analysis

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doi:10.1016/j.cemconres.2004.11.017

of the individual particles but require placement of each particle for individual imaging. Still another 3-D method [15] images individual particles from two orthogonal views as they pass on a conveyor belt. This method assumes that the particles will lie in a stable position on the conveyor belt so the thickness of the particle is viewed from the side and the length and width are viewed from above. This assumption is not completely true since particles have several stable positions and the thinnest axis is not necessarily perpendicular to the stable resting position. Furthermore this method requires advanced equipment to feed particles one at a time past the imaging point. A third method allows particles to fall from a rotating cylinder [16]. The particles are imaged as they fall. This method assumes that the thickness of the particles will be oriented parallel to the rotating cylinder. This is not always true since the particles tend to rotate during fall. All of these methods take several individual images of each particle in the sample.

Fernlund's [6] method, 3-D image analysis, IA, for determining the grain-size distribution of coarse aggregate material, evaluates all three dimensions of every particle in the sample from two images of the entire particle population of a sample. In one image all the particles are lying in a stable position and in the second image all the particles are standing up. These two images provide the largest and smallest projected area of the particles, respectively. The results are given in cumulative curves of the size distribution of the 3 axes for all the particles in the aggregate sample. This method can also be used to study the shape of the particles. The aim of this paper is to present how this new 3-D IA method for size distribution can be used to determine the shape of each particle in an aggregate sample.

2. Background

There are several traditional methods for determining particle shape of coarse aggregates. The European Committee for standardization describes various test procedures. Two of which deal with particle shape measurement:
1) flakiness index CEN: EN933-3 (6) part 3: determination of particle shape of aggregates and
2) shape index CEN: EN 933-4 (7) part 4: determination of particle shape of aggregates.

Flakiness index is a method which attempts to measures how thin particles are compared to their sieve size in general. The sample is sieved two times. First using sieves with square apertures and then using bar sieves. The aperture size of the sieves is dependent upon the size of the material. The aperture of the bar sieve is half that of the square sieve aperture size. The flakiness index is the ratio of the mass of the material retained on the two sieves times 100 and is rounded off to the nearest whole number. The flakiness index can be calculated for each fraction in the sample.

Shape index is a measure of the length and thickness ratio of the particles. A special caliper is used to measure the length of the longest 3-D dimension and the thinnest 3-D dimension of the particle. The particles are measured individually by hand. The results present the percent of the mass of cubic versus non-cubic particles.

Several other shape methods exist. The particle shape method called here the "Danish Box", DB, is described by the Danish Standards-DS405.6. With this box the axial lengths of the particles can be determined. The particles are placed into the box and rotated until they fit into the smallest possible box-like volume. The axes of the rectangle are measured using a ruler graded in millimeters. The determination of the position that yields the smallest box-like volume is somewhat subjective. Subjectivity for orientation of particles increases with increased particle irregularity and decreased particle size.

3. Image analysis method

Image analysis is used to determine the shape of the particles at the same time that the size distributions are determined for all the axial lengths of all the particles. Fernlund's size determination method is described in detail in Ref. [6]. In general the method uses two images of the particles photographed (Fig. 1) in two positions, lying and standing (Fig. 2 and 3). Images of the particles in these two positions gives both the largest and smallest projected areas of the particles, thus all three axes of each particle can be measured. All the particles in the sample are included in one single image; particles are not touching or overlapping thus no preprocessing is necessary which insures high accuracy of results (Fig. 3).

In the lying position particles are placed randomly on a sheet of luminous plastic in a stable position. It is assumed that the photos are of the maximum projected area of the particles (Fig. 2 and 3). This assumption is, however, not completely correct since particles have several stable positions. Fernlund [6] showed that this did not significantly affect the results.

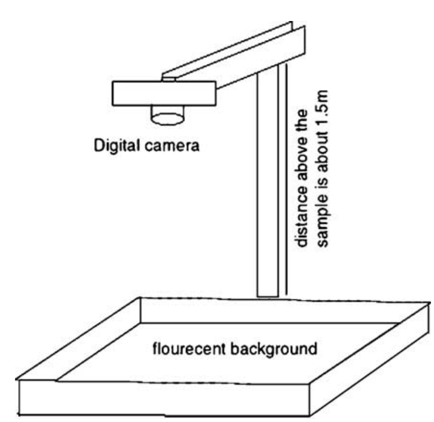

Fig. 1. Setup for photographing the aggregates. The luminous background lights up when the room is dark, resulting in uniform background lighting.

In the standing position particles are pushed down into a layer, 1 cm thick, of luminous beads on top of a layer, about 5 cm thick, of sand (Fig. 2 and 3). Care is taken to insure that they are oriented with the longest axis perpendicular to the plane of view and that the thickest part of the particle is situated above the bead layer. Thus it is assumed the images are of the smallest projected area of the particles.

The image analysis, IA, program "Particles", Procurvision software, was used. The parameter "rectangle" was chosen to represent the axial lengths of the particle. This parameter is defined as the smallest super-scribed rectangle around the particle and is rotational independent. In the image of the maximum projected area, lying particles, the length of the rectangle represents the longest axis of the particle and the width of the rectangle represents the intermediate axis of the particle. For the image of the minimum projected area, standing particles, the length of the rectangle represents the intermediate axis of the particle and the width of the rectangle represents the shortest axis of the particle. The intermediate axis of the particle is measured in both the images, for lying and standing particles, thus it can be used to couple the shortest axis to the longest axis for each individual particle.

The IA data is transferred to Excel, Microsoft software. To construct grain-size distribution curves for all three axial dimensions of the particles the results are sorted independently and cumulative curves of the axial relationships plotted using Kalidagraph, Synergy software [6].

To analyze the shape of the particles the data is sorted with respect to the intermediate axis for both images. Since the size of the intermediate axis, when sorted, will order the particles in increasing size for both images one can assume that the shortest and longest axes coupled to the intermediate axis at any given level will represent a unique particle in the sample. This assumption will not hold for all particles. The order of the intermediate axis in the two images will probably be somewhat varied. It is however suggested that the size relationship between the longest and shortest axis for a given intermediate size position, even if they are not of a unique particle, will be representative of the shape of the particles in the aggregate sample.

Fig. 2. A view of the particles in the standing position (upper part) and lying position (lower part) on the luminous background with the lights on.

a

b

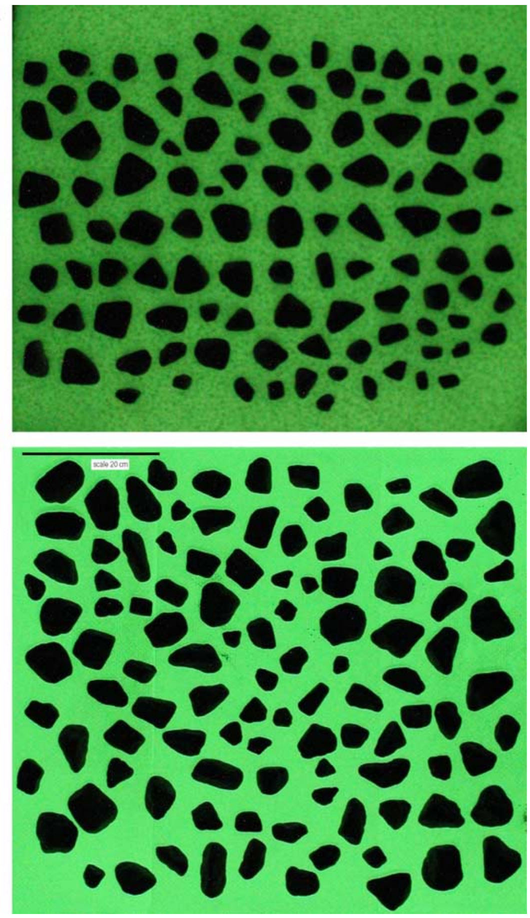

Fig. 3. The luminous background glows when the lights are turned off. (a) Top—particles in the standing position, the longest axis perpendicular to the table consisting of a sand bed covered by luminous beads. (b) Bottom—particles in lying position, on a sheet of luminous plastic in a stable position. The scale is 20 cm.

4. Test on coarse aggregates

Two samples of coarse aggregates have been studied. The samples have a sieve size of between 10 and 50 mm. The weight of sample 1 is 9976 g and sample 2 is 8429 g. The composition of the aggregates is exclusively gneissic granite, crushed aggregate, from a rock quarry in the Stockholm area, Sweden.

The two samples were analyzed using Fernlund's IA 3-D method [6]. To test the reproducibility of the method the particles were photographed 10 times in both the lying and standing positions [6]. The particles were repositioned for each image.

In order to have a means for evaluation of the IA results the particles in the two samples have been measured using

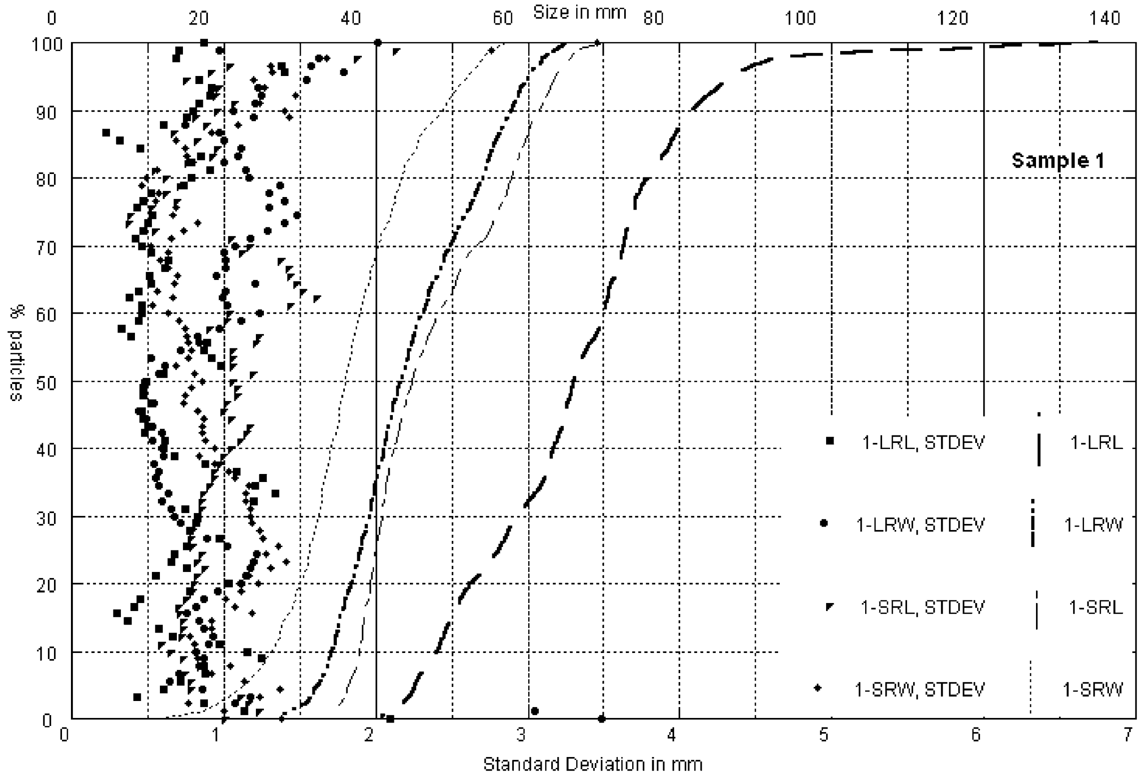

Fig. 4. Sample 1—size distribution curves for all three axes of all the particles. The intermediate axis is measured in both images, lying, LRW, and standing, SRL. It is used to couple the longest, LRL, and shortest, SRW, axes of the particles. The standard deviation is based on 10 images of the same particles.

the "Danish Box", DB, method. Furthermore all the particles were weighed.

5. Results

The size distribution of all three axes can be plotted (Fig. 4) with good accuracy [6]. The placement of the particles in the standing position requires a visual evaluation of the longest axis of the particles and then physical placement of the longest axis perpendicular to the sand bed. As stated above, to test the reliability and variability of this method, each of the samples has been imaged 10 times. The standard deviation of the results from the 10 images is very low (Table 1). Thus the error introduced due to placement is not significant [6]. The lower size limit of particles that can be placed in a standing position has, for this study, been 1 cm. This has in part been due to the size of the luminous beads; they have a diameter of about 4 mm. If finer grained luminous beads were used the lower size limit would be dependent upon the ability to place the particles correctly in the defined standing position; as small as 5 mm may be possible [6].

The shape of the particles can be presented in many ways. Scatter diagrams (Fig. 5) show the spread in size of the longest and shortest axis with respect to increasing intermediate axis size. Cumulative curves (Fig. 6) show the distribution of the individual index and their standard deviation. Cumulative curves of all three indexes for each sample (Fig. 7) are plotted in one diagram allowing comparison between the index relationships. Furthermore the particles can be plotted according to Zingg's [17] classification (Fig. 8) The size distribution of all three axial lengths and the indexes distribution of all three ratios can be plotted on the same diagram (Fig. 9) giving a total analysis of the sample.

A scatter diagram shows the relationship of particle shape sorted with respect to the intermediate axis coupled to the longest, respectively the shortest axis (Fig. 5). For comparison the results of the DB are also shown. As expected the results of the IA and the DB methods show similarity although there is a good deal of variation. The

Table 1
Statistics of the standard deviation for sample 1 and sample 2 for both standing and lying images

Sample 1	LRL	LRW	SRL	SRW	Sample 2	LRL	LRW	SRL	SRW
Mean	1.7	1.0	1.0	1.0	Mean	0.5	0.7	0.7	0.7
Standard deviation	0.3	0.5	0.8	0.4	Standard deviation	0.1	0.3	0.3	0.2
Variance	0.1	0.2	0.6	0.2	Variance	0.0	0.1	0.1	0.1

LRL—lying rectangle length; LRW—lying rectangle width; SRL—standing rectangle length; SRW—standing rectangle width; STDEV—standard deviation.

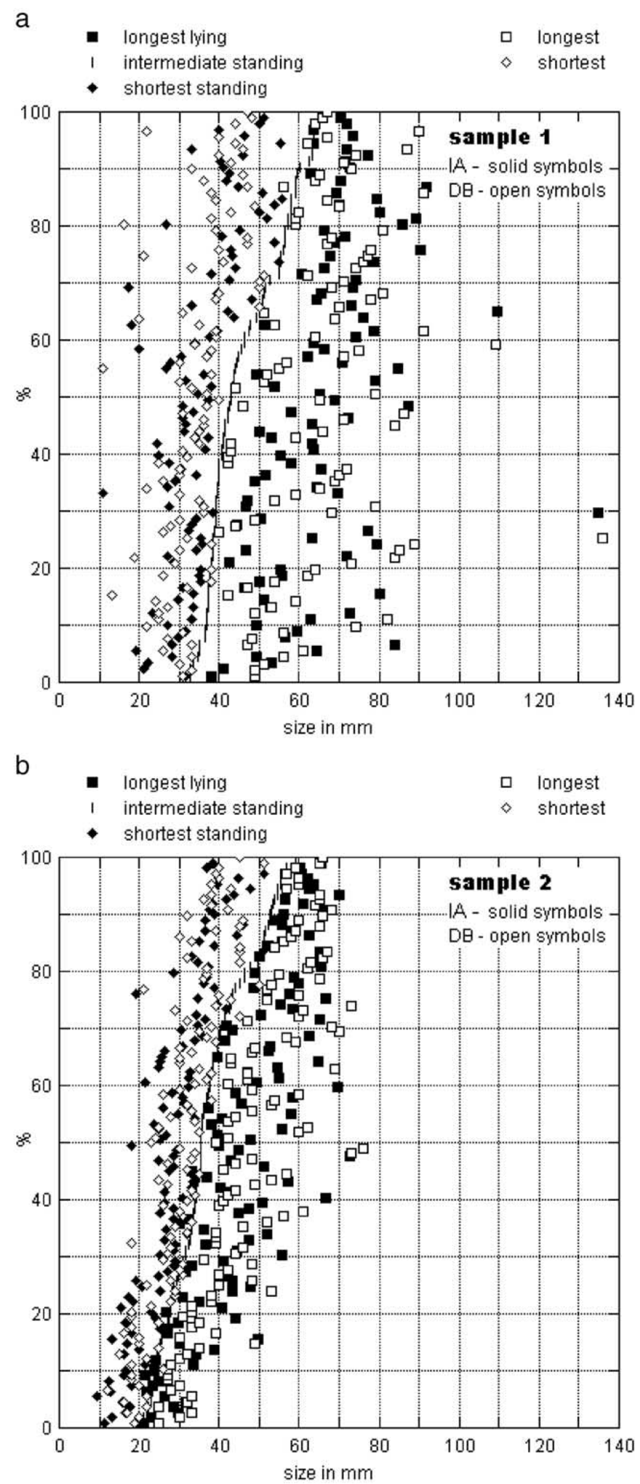

Fig. 5. Scatter diagrams of the IA and DB results for the longest and shortest axis when sorted with respect to the intermediate axis.

reason for the observed variation can be attributed to weaknesses in both methods. The DB method is quite subjective with respect to placement of the particles. Furthermore the measurement scale is graded in millimeters. The IA method makes the assumption that the intermediate axes of the particles sorted in ascending order for both images will allow identification of individual particles. This is not totally correct. Several particles may have similar intermediate axial lengths and thus the order can be slightly different in the two images. Thus the length of one particle can be coupled to the thickness of another. Only when the lengths respective the thicknesses are exceptionally sized, extremely long or short, would this significantly affect the results.

Kwan et al. [2] made the assumption that the shape of the aggregates from one site, rock quarry, would be similar thus it would be possible to estimate the mean thickness of the particles in the sample. They presented a method of estimating the thickness as a function of the breadth multiplied by the area. An evaluation of Fig. 5 reveals that, although there is a limited range in thickness values, they do vary quite a bit thus their assumption [2] is too crude. It is important to actually determine the thickness of particles and not just estimate this property. It is a vital quality governing how aggregates function in different engineering materials and applications.

To make an evaluation of the particles shape based on a scatter diagram (Fig. 5) is somewhat difficult. One can view the spread in the size relationships of the longest and shortest axes with respect to an increasing intermediate axis. However it is more convenient to plot the ratio between the axes, length/thickness (L/T), width/thickness (W/T), and length/width (L/W).

In order to test the accuracy of the IA method the results from the 10 images have been plotted with respect to their axial ratios, length/thickness, width/thickness and length/width (Fig. 6). The standard deviation for the results from the 10 images is very low, usually less than 0.05. However for the particles with larger ration indexes, larger than about 2, the standard deviation increases but never above 0.3. In general the standard deviation is somewhat larger for the L/T index than for the other two indexes. This is interpreted to be due to the fact that this is the index that requires the coupling using the intermediate axial length. The other two indexes are determined from the same image. The DB results are also plotted together with the results of the 10 images (Fig. 7). The agreement is very good. Some deviation occurs in the upper end of the plot. We can conclude that the coupling of the shortest and longest axis using the sorted values of the intermediate axis from the two images yields very good results for the shape determination of the particle.

It is important to determine how the IA method compares to the flakiness index and shape index. These tests have not been made on the aggregates however based on the DB results an approximation of their results can be calculated.

The flakiness index method sieves the particles twice using normal square and bar sieves. The size of the bar sieve aperture is half the normal sieve aperture. The flakiness index is the ratio of the particles mass on the normal sieves with respect to the mass of the particles passing the bar sieve. Since the particles were measured with the DB and weighed individually it is possible make a rough estimation of the results for the flakiness index. This would be about 57% for sample 1% and 21% for sample 2. For IA an L/T index of 2 would represent the particles that would pass the bar sieves. In the plot (Fig. 7) the L/T index would be about 35% for sample 1 and about 20% for sample 2. Theoretically it should be possible to determine a means to correlate the flakiness index to the IA results. A series of tests are planned to evaluate the correlation.

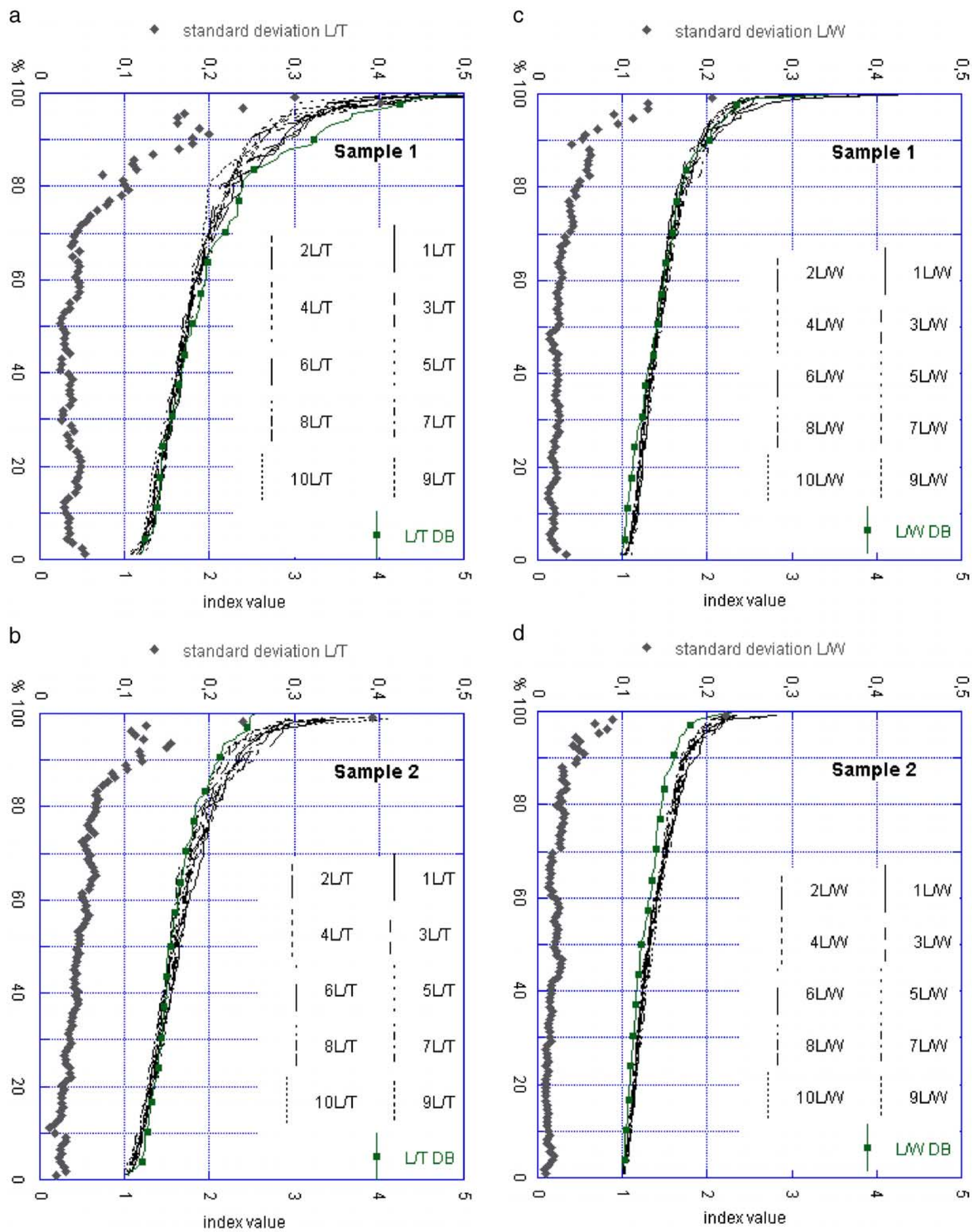

Fig. 6. The index values for length/thickness, width/thickness and length/width, measured with image analysis (ten images) and measured with the Danish Box. Standard deviation of the 10 images is shown.

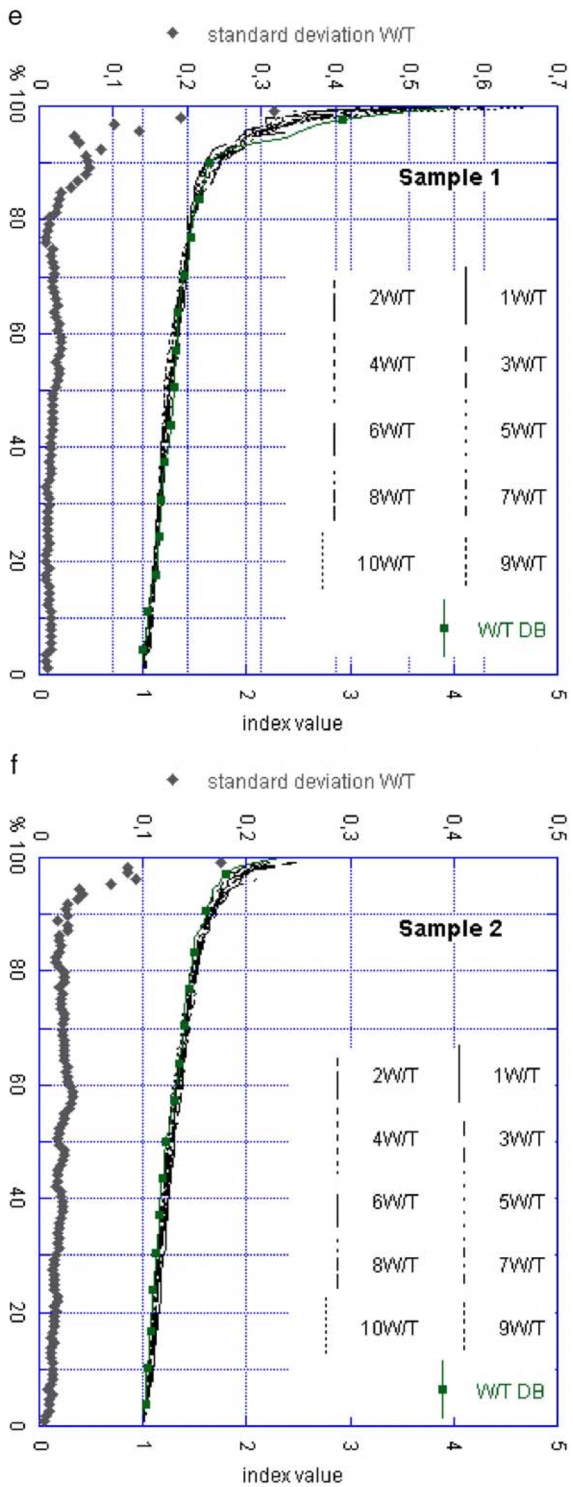

Fig. 6 (*continued*).

The shape index relates the mass of the non-cubic particles divided by the mass of the cubic particles times 100. Where the longest axis divided by the shortest axis is greater than 3, the particles are considered to be non-cubic. Since all the particles were weighed and measured with the DB it is possible to make an estimate of the shape index. For sample 1 it would be 10% where as for sample 2 it would be 0%; there are no particles that are non-cubic in sample 2. The IA *L*/*T* index of 3 would correspond roughly to limit between cubic and non-cubic particles. The amount of non-cubic particles according to the IA results of the 10 images varies somewhat. For sample 1 the results vary between 3% and 10% non-cubic particles and for sample 2 between 0% and 3% non-cubic particles (Fig. 7). This is in very close agreement to the DB estimation. Fernlund [6] discussed this larger variability of results for the largest particles. It was suggested that this is a result of random placement of the particles in the image. Large particles in the outer edges of the image will be distorted more than smaller particles. Thus it is recommended that the largest particles be placed near the center of the images. Theoretically is should also be possible to correlate the IA results with the shape index.

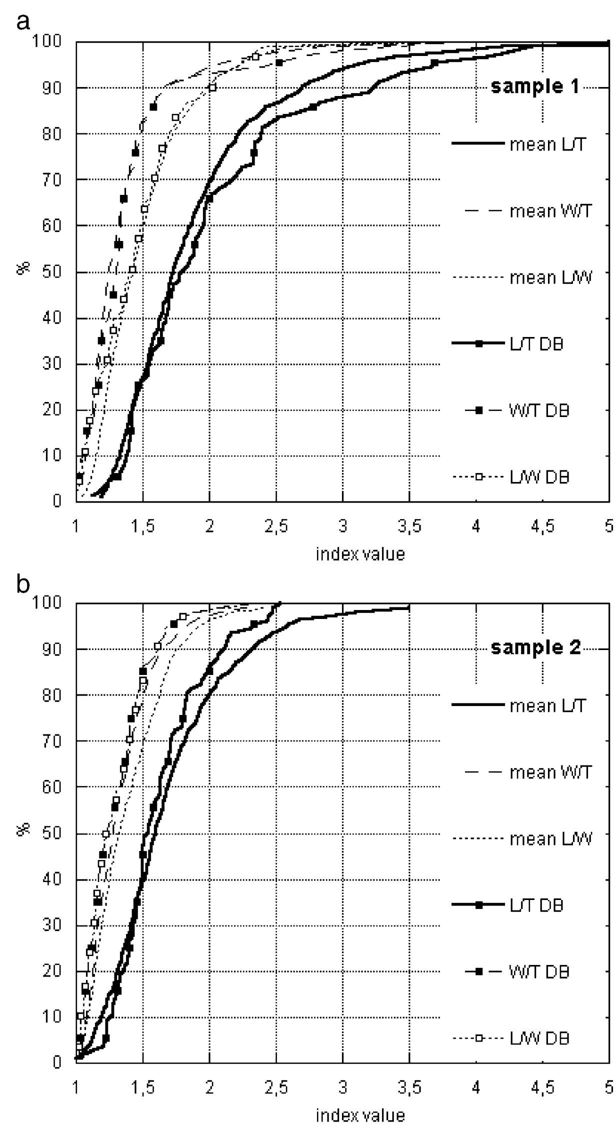

Fig. 7. Index values of both samples, IA compared to the DB. Sample 1 (a)—the *L*/*T* index is larger for the DB than for IA whereas the other two indexes are nearly identical. Sample 2 (b) DB results are somewhat less than IA for the *L*/*T* index. The *W*/*T* index is identical for the two but the *L*/*W* index differs, the DB results are less than the IA.

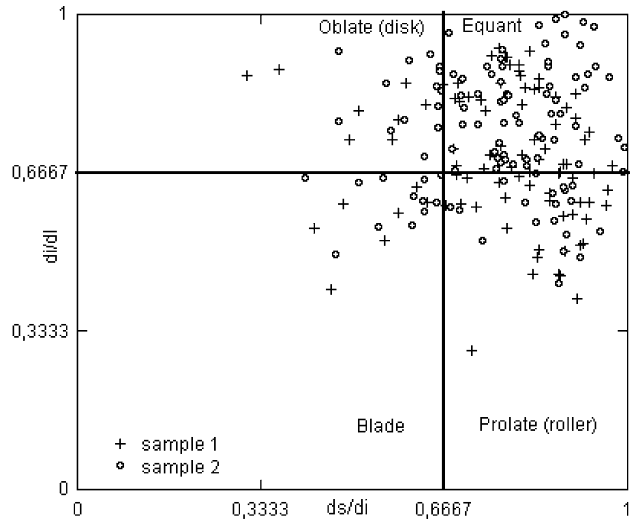

Fig. 8. Plot of the two samples according to Zingg [17].

Further study is needed to evaluate how the IA method is related and can be correlated to the shape index.

The shape of the entire population of particles is presented in a Zingg shape diagram (Fig. 8). Here it is possible to see the entire spectrum of particle shapes. It is clear that sample 2 contains particles that are more extremely equant than does sample 1. Although there are a similar number of oblate, blade and prolate particles in the two samples, it appears that the most extreme shapes are represented in sample 1.

Presentations of the total size and shape distributions are possible using this method (Fig. 9). An exact determination of the percentage of particles in the sample that is "too large" or "too small" with respect to the size that is stipulated for the material for a specific use can easily be determined. The size distribution of the longest axis of sample 1 shows that about 10% of all the particles have a length greater than 80 mm. The size distribution of sample 2 (Fig. 6b) shows that 25% of the particles are thinner than 20 mm. Likewise the percent of elongate and platy particles can be directly determined. In sample 1 there are 33% flaky particles, with a L/T ratio > 2, and 9% extremely flaky particles, L/T ratio > 3. This type of diagram is a dynamic tool for quality control of aggregates with respect to requirement limits for different usages.

6. Conclusions

The 3-D IA method for shape determination gives a very good measure of both the size distribution and shape distribution of all the particles in the aggregate sample. The reproducibility of results is good. As previously stated sieving does not directly measure any particle in the sample. In contrast the IA measures every particle.

The shape determination method of Kwan et al. [2] estimates the thickness as a function of the breadth multiplied by the area based on a crude assumption. In contrast this new method actually measures the thickness of the particles and is thus much more accurate.

The 3-D methods by Kuo et al. [13], Frost and Lai [14], Maerz [15] and Weingart and Prowell [16] differ from Fernlund's method in that they measure one particle at a

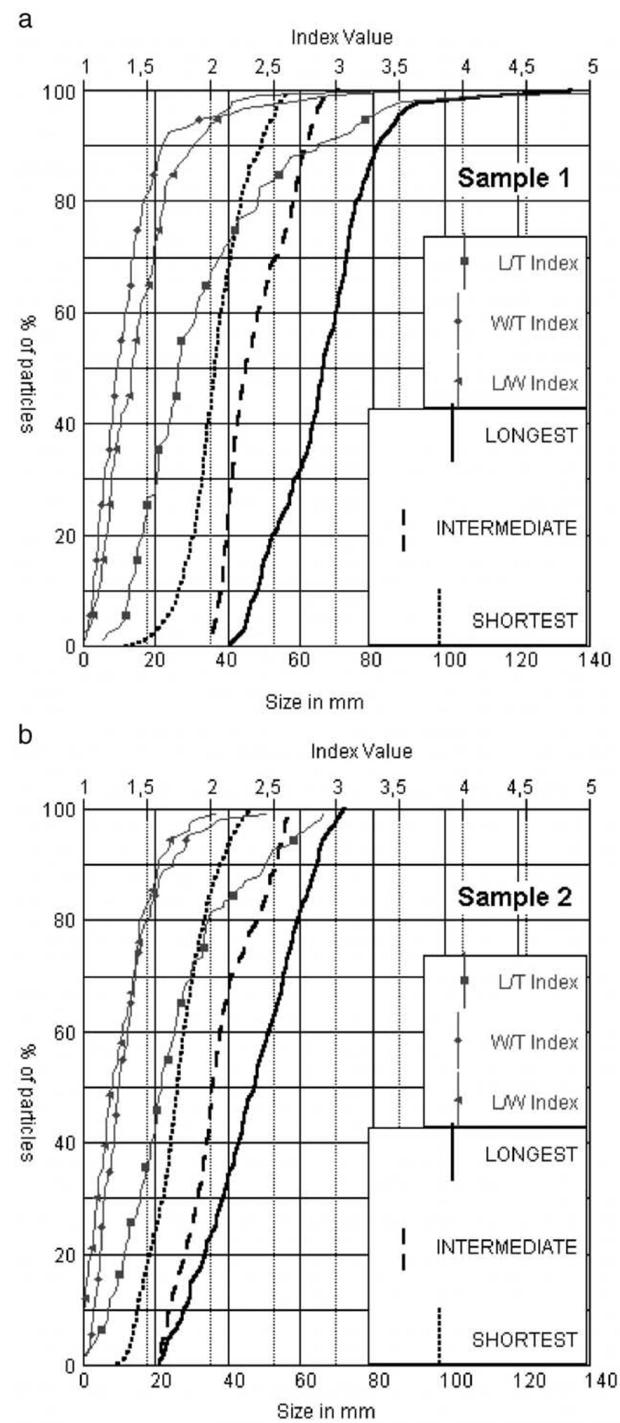

Fig. 9. The size distribution and shape indexes distribution for sample 1 (a) and sample 2 (b). Sample 1—particles are much longer than they are thick and only slightly thicker than they are thin. Sample 2—particles are smaller overall, and much more equal in dimension especially the smallest particles.

time whereas all the particles in the sample are imaged in only two images in Fernlund's method. Kuo et al. [13] and Frost and Lai [14] place each particle individually in a holder and image it from several sides. Maerz's [15] method has a mechanical conveyor belt that transports each particle past two cameras. These are somewhat time consuming methods. The fact that each individual particle is imaged separately ensures that the 3-D shape is unique for the individual particle. This is not the case in Fernlund's method; it is based on the assumption that the particle's intermediate axis is sorted in the same order in each of the images. The results suggest that this is a reasonable assumption since the standard deviation for the 10 images is very low and there is good agreement with the results of the Danish Box measurements [6]. Fernlund's method is an easy method requiring no mechanical equipment and only one camera and it is quick since it only requires two images. Fernlund's method requires that each particle be placed in a standing position. This is a very quick and easy procedure and is shown to produce accurate results [6]. Furthermore the method can easily be adapted for use in the field.

This new IA method can be used to evaluate the results of other aggregate tests that use sieving in the methodology. An example is the Los Angeles Drum test [18]. This is only one of numerous test methods that are dependent upon sieving for which the evaluation could be made in a much more efficient and accurate way if this IA method was employed.

There are several advantages with this IA 3-D shape determination method compared to the traditional methods such as flakiness index and shape index;

- it provides a very accurate measure of all 3 axes of each individual grain in the aggregate sample;
- the axial relationships of all the particles are determined and plotted giving the possibility to evaluate the range of shapes in the sample; this is not possible with either the flakiness index or shape index;
- much more information about the aggregates quality is determined than with conventional methods;
- size and shape distribution can be determined from one simple analysis that requires only two images of the particles in the sample. This allows an evaluation of both size and shape of the total population of the sample;
- results can be presented for the size distribution as well as the shape distribution from the same analysis and in the same plot (Fig. 9);
- it is quick, easy, versatile, very accurate and user friendly.

Traditional methods require several tests to obtain similar information obtained from one image analysis test. Plus the accuracy of the IA method is much better than the traditional methods. For coarse aggregates this new IA 3-D method can singularly replace both sieving tests for size distribution and shape tests such as the flakiness index, shape index and Danish Box. This means both time saving for analyses and increase in information concerning the aggregates quality.

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