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Direct estimation of sieve size distributions from 2-D image analysis of sand particles.

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ABSTRACT

Optical image analysis offers several advantages over sieve size distributions in terms of productivity, exactness and automation. In this paper, the authors demonstrate how perfect correlation with sieve size distributions can be achieved for particles in the range between 50 µm and 2 mm when controlling the position and running velocity of particles in front of the video camera and when adopting adequate size measurement algorithms.

Results are shown for sands provided by the European Bureau for Certified Reference together with statistical data for sieve size distributions from five reference labs. Image analysis results without any prior calibration fit perfectly within the dispersion of the five sieve size distributions. The unique underlying hypothesis for perfect correlation is a uniform density as well as a reasonably similar flatness index throughout the size range.

1 INTRODUCTION

It is common practice to distinguish between sieving and non-sieving methods when presenting the large variety of granulometric techniques. The reason for this is the widespread use of sieves in labs and industrial processes but also the very diverse nature of physical principles involved in non-sieving methods (sedimentation, electrical sensing zone, laser diffraction, photon correlation spectroscopy, image analysis, etc.). If one refers to particles in the range between 50µm and 5mm, sieving is still the best method because of its simplicity, its productivity, its accuracy and its widespread availability. Another major reason for relying on sieving results is that many industrial particle separation processes are based on sieving or screening operations.

Despite many efforts for correlating size distributions from other techniques to sieve size distributions results have been disappointing. As a consequence, some authors have argued in favour of polydisperse spherical particle standards [1] whose physical behaviour is easier to understand and correlate, while others, especially manufacturers, suggest a preliminary calibration step. Although there is strong a need for a better reference material, it doesn't appear to be the right solution to rely on synthetic and unrealistic particles such as spheres. On the other hand, calibration protocols based on the anamorphosis of measured size distribution in order to obtain the desired output curve are not acceptable either.

In this paper, the use of image analysis is carefully explored, because it appears to be the only technology capable of giving a direct estimation of the critical sieving diameter, also called the mesodiameter [2]. Hence a natural correlation between image analysis and sieve size distributions should spring up when dealing with particles whose density or flatness ratios are independent of their sieving diameter.

2 METHODOLOGY

It can be shown that the critical diameter for a convex particle to pass through a round mesh is its intermediate diameter. One way of accessing that measurement when no 3-dimensional sensing technique is available is to constrain the particle positioning in such a way that its smallest diameter is made perpendicular to the observation plane. This is easily achieved by dispersing particles and allowing them to rest on a horizontal plane. Such a principle has led to the development of the ALPAGA patented technology [3] wherein a glass slides conveyor belt is continuously running in front of a back-lighted CCD camera. The projected shadow of each particle is taken with a telecentric objective at an optimized shutter speed in order to keep particle displacements during picturing well below the pixel resolution.

Although imaging of particles under controlled position and motion is of critical importance, it is not the only requirement in the search for perfect correlation with sieving.

Classical image analysis [4], be it for free falling particles or static particles imaged under the microscope, relies on a sizing based on the "equivalent disk area diameter":

$$D_O = \sqrt{\frac{4.A}{\pi}} \qquad (1)$$

This measurement takes advantage of a very simple estimation of the projected area (A) by a pixel denumbering algorithm. More sophisticated measurements are available to estimate Feret diameters under a discrete number of orientations [5], but the most accurate technique is the exact estimation of the maximum inscribed disc (D_{IN})[6]. Fig. 1 illustrates how D_O may depart from the true sieving diameter estimated by D_{IN}. Overestimation is evident for very elongated shapes such as the atomized zinc particles, but is still severe with regular sand grains. Fig. 2 gives the relative error of D_O with respect to D_{IN} as computed for perfect ellipses.

Figure 1 Quartz sand particle (left) with D_O = 834µm and D_{IN} = 727µm . Zinc particle (right) with D_O = 417 µm and D_{IN} = 201 µm. Particles are pictured at different magnifications.

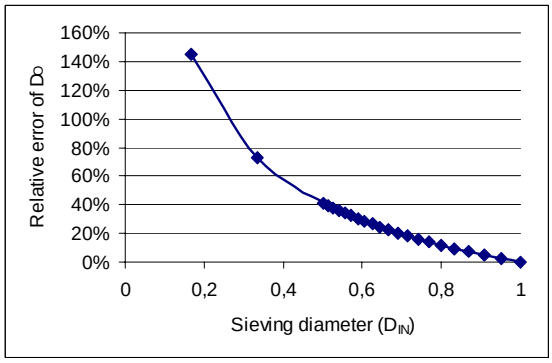

Figure 2 Relative error on estimating the sieving diameter by D_O for ellipses with variable aspect ratios. The major diameter is normalized to one.

3 MATERIALS

The European Community Bureau for Reference Materials distributes a series of crushed quartz sand standards for particle size analysis since 1980. The largest particle size standard, labeled BCR68, ranges from 160 µm to 630 µm and is available as 100 grams samples. It is documented with size distribution curves obtained by five independent reference labs [7], four of them using square mesh sieves and one using round mesh sieves. One such sample has been used in this study for testing against the accuracy of image analysis. The 100 grams sample was carefully subsampled into sixteen 6,25 grams samples which provided enough grains for image analysis and allowed at the same time to test for reproducibility.

Another series of both natural and crushed sand samples has been produced at University of Liège (ULg) for a broader study on "formulation of high durability and high performance concrete". Some of these samples have been used here for investigating the sub-sieve capabilities of image analysis. Shape analysis performed on the same series of samples is presented elsewhere [8].

4 RESULTS

Despite the way diameters are sensed, a major difference still exists between image analysis and sieving, the first method measures thousands of individual particles whereas the second one relies on the weighting of the bulk content of a sieve. This means that the relative importance of size fractions is expressed by number in one method and by weight in the other method. Size distribution by number is of interest to detect anomalous amounts of very fine particles, but it is not standard industrial practice.

In order to correlate image analysis with sieving a weighting factor must be used which can at best be an apparent volume of each individual particle computed from its projection area (A). The authors have chosen to use $A^{1,5}$. It can be proven that this is optimal, provided that all size fractions have identical average densities and flatness indices. Although no data is provided on the granulo-densitometric distribution of BCR68, it is reasonable to assume homogeneity of this crushed sand.

Nevertheless, the attention should be drawn on the fact that there is a need for a future reference standard made of pure quartz or calcite instead of the mineralogical diversity observed in BCR68.

Tab.1 presents the weighted size fractions obtained by image analysis using class limits identical to the ISO sieve set used by the five European reference labs. Fig. 3 presents a

graphical display of the data. It is important to stress the fact that these results are obtained from direct measurements (A and D_{IN}) without any need for a prior calibration step.

Table 1 Size distribution of BCR68 reference sand as obtained by five reference labs (Q3 : median; SR(Q3) : dispersion) and Alpaga image analysis.

	Sieving		Alpaga
µm	Q_3	$S_R(Q_3)$	
160	4.2	0.9	4.2
250	22.9	3.2	23.7
320	44.9	2.4	45.8
400	68.9	2.7	71.2
500	88.8	1.2	90.6
630	97.4	0.9	98.6

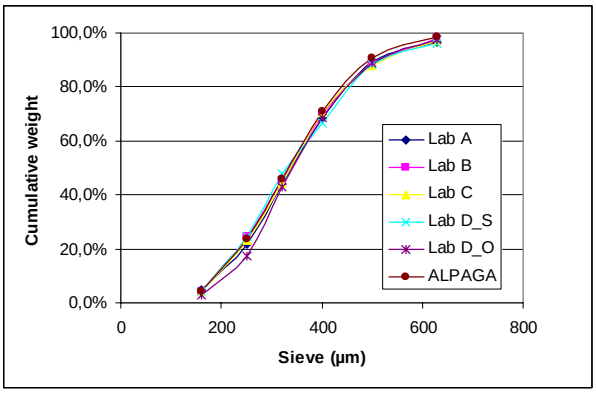

Figure 3 Cumulative size distribution for BCR68 as obtained from five reference labs and ALPAGA.

Sub-sieve size distributions were measured on identical sieve size fractions [250 – 500 µm] obtained from various natural and crushed sands. Fig. 4 displays parallel plots of mean and standard deviations of D_O and D_{IN}.

5 DISCUSSION

The round robin test on sieving BCR68 shows limited dispersion that would probably not have been achieved by comparing results from less experienced labs. Image analysis results are in perfect agreement and fall well within the confidence interval of classical sieving. One would expect image analysis to correlate better with round mesh sieving, but in the present case, because of the non-flaky geometry of the sand grains, the difference between square meshes and round meshes is almost negligible. The only exception is the 250 µm sieve, but no explanation is given for this in the BCR report and it is most probably due to an acceptable analytical error.

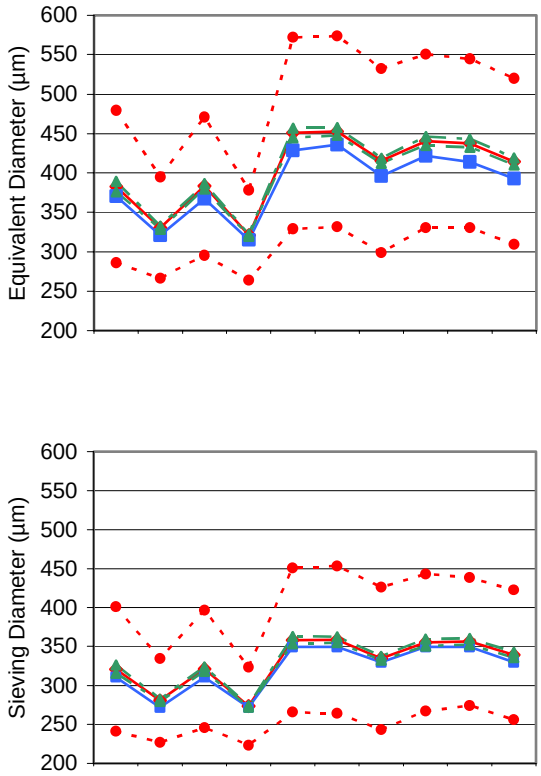

Figure 4 Side by side plot of mean size values with their standard errors and one standard deviation (68 %) confidence intervals (dotted lines). Rows 1 to 4 : ULg river sands; rows 5 to 10 : ULg crushed sands.

The difference between round meshes and square meshes is much more noticeable in the crushed sand fractions of the ULg sands (Fig. 4). When a large amount of flat particles is present, the size estimation by image analysis reveals a significant fraction of particles that are larger then the (square) sieve mesh (500µm) and must have passed in diagonal position.

Fig. 4 also reveals that D_O is more sensitive than D_{IN} in order to discriminate between various sands. Indeed, confidence intervals based on D_O are systematically narrower than those based on D_{IN}.

BCR68 has a limited size range which most probably contributes to the quality of the correlation. It must be stressed that optical image analysis faces different kind of problems at both ends of the size range. At the lower end, if particles smaller than the optical resolution are present, they will be missed, and the whole size distribution curve will be shifted towards the larger fractions. At the upper end, the probability of inclusion within the image frame might drop very severely and the particle might have been deleted or missed. This might provoke a significant underestimation of the larger size fraction. Both

problems are unknown to sieving because ultrafine particles passing the lower sieve or large particles retained by the upper sieve are weighted and accounted for in the size distribution curve.

The lowest resolution of an image analysis device is set by the performance of the optics, the CCD camera and the particle motion during picturing. However, a lower limit of 5 µm is often harder to obtain because of dispersion problems rather than optical problems.

The upper limit of the image analyzer is set by the fixed resolution of the CCD imaging device but also depends on the total number of analysed particles. Considering the Miles-Lantuejoul probability of inclusion of a particle of said diameter within an image frame [9], it must be noted that such a correction becomes very significant for particles reaching about one third of the image width. If the largest particles present very low concentrations, than the problem of inclusion becomes a problem of number of images sampled during the powder flow. The last generation of image analysis systems allows for capturing and measuring of 5000 particles a minute, which means that within a few minutes a representative size distribution curve might be expected. The real-time update of the size distribution curve is an interesting tool for monitoring the quality of the image analysis. But, it must be kept in mind that segregation occurs in the vibrating trough and that stopping the analysis before the whole product has flown in front of the imaging system might bias the result.

6 CONCLUSIONS

Image analysis is unique in that it is capable of predicting the issue of a sieving process. But, virtual sieving can only be achieved if careful particle positioning and adequate image analysis algorithms are used.

Image analysis has proven to give exceptional precision on a reference sample using only but a fraction (1/16) of the whole material. Identical experiences must be conducted on wider size ranges in order to test both the lower and upper limits of the technique.

Image analysis and sieving can only be correlated if all fractions have the same density and the same average flatness index. But interestingly, departure from perfect correlation is a good indication of any variation in 3D (flatness) or density.

There is an urgent need for more standard reference material to be available. Particles with a wide shape range would be of major interest in order to test the robustness of various sizing methods. Image analysis with respect to all other sizing methods has the exceptional advantage of being able to address shape as well as size and eventually other surface properties (colour, texture,…).

Although, image analysis is often considered as being poorly productive, modern systems are capable of measuring very large amounts of particles and achieving representative results within a few minutes, allowing them to rival with laser diffraction in the visible particles range.

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