IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: D Krawczykowski *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **641** 012009

IOP Conf. Series: Materials Science and Engineering **641** (2019) 012009 doi:10.1088/1757-899X/641/1/012009

Evaluation of geometric properties of regular and irregular particles of chalcedonite enrichment products from pulsating laboratory jig by means of dynamic image analysis method (DIA)

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Abstract. The aim of the paper was to evaluate the geometrical properties of regular and irregular chalcedonite particles contained in enrichment products obtained in a laboratory ring jig. Investigative programme included carrying out the tests of aggregate enrichment together with the vision analysis of regular and irregular particles of feed and enrichment products obtained from different layers of the jig bed. Various types of shape coefficients were calculated and the most effective among them for the assessment the particle shape, were selected. The particle size distribution of the feed and their enrichment products according to the minimum Feret's diameter, were also determined. The results obtained by the vision system were discussed in the context of its potential utilization in evaluation of the enrichment process of mineral aggregates in a water jig.

1. Introduction

The quality of mineral aggregates depends on many aspects, concerning their physical and mechanical properties, mineralogical composition and the method of their processing and treatment. Particle size is often regarded as a key parameter, because it preliminary determines an arrangement of technological circuit of their processing, especially in terms of application of specific comminution devices. Such devices operates with different effectiveness, depending the particle size composition of the feed, fines content, material's purity, achieving various technological [5,21], economic [20] and ecological effects [19]. A shape of particle appears to be also a very important feature, that usually classifies particles as regular and irregular ones. The yield of such particles in mineral aggregate products depends, to a large extent, on crushing technology and their geomechanical properties. The aggregate is considered of the highest quality, when it contains cubic particles, i.e. with shape similar to a sphere (regular), while the lower quality aggregate contains flat particles, with a large surface-to-volume ratio (irregular). There are many studies on evaluation of the properties of regular and irregular particles and their impact on the quality of the obtained product aggregates, in particular concretes and asphalt mixtures [4,6,7,12,16,18]. In geomechanics of soils, the shape of particles affects their strength, stability, degree of compaction and other mechanical parameters [3,14]. The particle shape also plays an important role in the technologies of mechanical processing of raw materials, especially in hydraulic classification, gravity beneficiation, and compaction [9,10,15].

At the same time, the shape of a particle is a contractual term, because it can be determined by means of various methods, according to different classification, with using of different shape factors and measurement techniques. One of the oldest methods of particle shape description is the Zingg classification, which divides the particles into cubic, flat, plane-column and column [11]. Currently, two standards: PN-EN 933-3:2012 and PN-EN 933-4:2008 are commonly used [13].

Some video techniques, utilizing computer image analysis for determination the shape of particles, are also available for application. Significant automation of mechanical stages of measurement (i.e. microscopic) allows to increase the representative number of particles in the measurement, however, the methods based on the microscope utilize 2D image analysis, therefore they generate incomplete information because the analyzed particles are always situated in the most stable position [1,2].

The article tries to apply this technique for evaluation of particle's shape by means of commonly known indices like: Aspect Ratio, Convexity and Circularity. Particle size distributions of regular and irregular particles were also determined, utilizing the minimum Feret's diameter as a measure.

2. Materials and Methods

The Analysette 28 ImageSizer vision system, using a dynamic image analysis, was applied in analyses. The analyzer produces a stroboscopic effect utilizing a pulsating light source, and camera records images at high speed and interchangeable optical systems. The vision system records the images of particles in motion with the speed of up to several hundred objects per second. The measurement is performed for dry particles, falling down in front of the camera lens. The recorded particles are then subjected to computer image analysis, on the basis of which their basic geometrical parameters can be determined. The principle of operation of the vision system is similar to the measurement with using a microscope - the camera records the image of particles, and then the computer software analyzes the shape and size of each particle separately. Microscopic measurement, however, is a static measurement and allows for analyzing of only few particles at a time. The DIA method makes it possible to measure particles in motion. Free movement leads to random orientation of particles and actual shape and size of individual particle can be accurately determined. The continuous feeding of dispersed particles results in reliable and representative measurement results, obtained on the basis of large number of registered particles at a high level of statistical confidence. Thanks to such manner of measurement, about ten thousand images per minute can be analyzed, not just a few. The idea of measurement is shown in Figure 1.

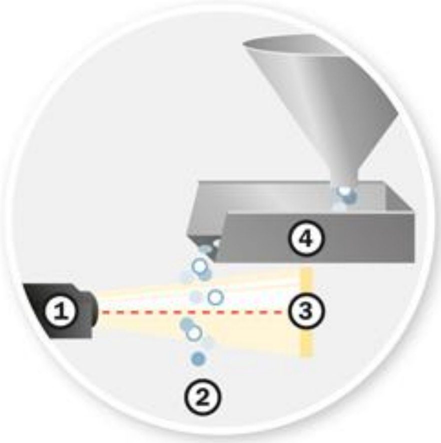

Figure 1. The method of particle size and shape measurement by means of DIA; 1 – camera, 2 – measurement volume, 3 – light source, 4 – feeder (source: www.fritsch.de).

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The feed material was a chalcedonite mineral sample containing regular and irregular particles, the material with some interested properties, especially in terms of densities of individual particles, what determines its wide industrial application [17]. The feed material was initially classified on a slotted bas sieve into narrow size fraction 6.3 – 8 mm, subjected to a vision analysis. The material was then subjected to the enrichment process in a laboratory ring jig, and after 5 minutes of device's operation there were obtained various products located in individual layers of the jig bed [8].

After laboratory experiments involving the enrichment of regular grains and irregular chalcedonite particles in the mentioned particle size class, four products from different layers of the jig bed were obtained. The first product (I) was the bottom one, while the fourth (IV) constituted the upper layer of the material. In addition to the feed, the products of regular and irregular particles enrichment were also subjected to analyzes aimed at determination of differences in geometrical parameters of particles, and thus at examination the effect of aggregate beneficiation. There were specified among others: particle size distributions expressed by the minimum Feret diameter and shape factors: Aspect Ratio AR, Cx (convexity), and C (circularity), according to the formulas:

$$AR = \frac{d_{Fmin}}{d_{Fmax}} \quad (1)$$

$$Cx = \frac{A}{(A+B)} \quad (2)$$

$$C = \frac{4\pi D}{{P_c}^2} \quad (3)$$

where:
d_{Fmin} – minimal Feret's diameter,
d_{Fmax} – maximum Feret's diameter,
A – convex surface of the particle,
B – concave surface of the particle,
D – particle's surface,
Pc –normalized measure of the number of edges of 0, 45, 90 and 135 degrees in the object (Crofton parameter).

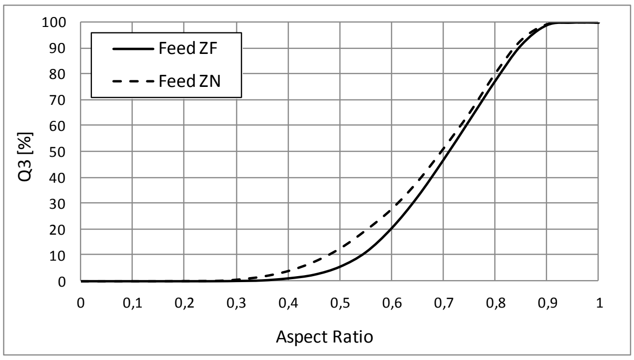
3. Results analysis

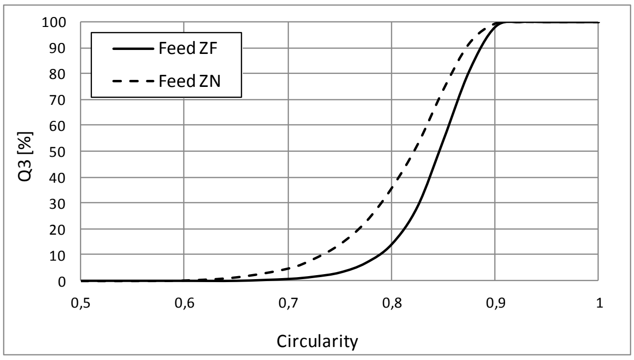
Figures 2 and 3 show exemplary shapes of regular and irregular chalcedonite particles from the feed, generated by means of computerized image analysis. An analysis of the shapes of these particles indicates the visible sharpness and irregularity in shapes of irregular particles comparing to regular ones. Extreme lengthening of size proportions for some irregular particles in relation to regular ones in 2D projection as well as their irregular outline, obtained for the same particle size class but separately for regular and irregular particles, indicates for much higher flatness of irregular particles.

Figure 2. Regular particles of chalcedonite feed in particle size fraction 6.3-8mm.

Figure 3. Irregular particles of chalcedonite feed in particle size fraction 6.3-8mm.

Averaged results of the distribution of the three analyzed particle shape coefficients, obtained for the feed with regular and irregular particles, are presented in Fig 4. Analyzing these graphs, it is clearly visible that the coefficient, which apparently indicates differences in chalcedonite particle size, is the circularity (C). Average values of the calculated shape coefficients for feed with regular particles were respectively: ARmean = 0.708, Cxmean = 0.918, Cmean = 0.847, while for irregular ones the results were lower: ARmean = 0.696, Cxmean = 0.914, Cmean = 0.822.





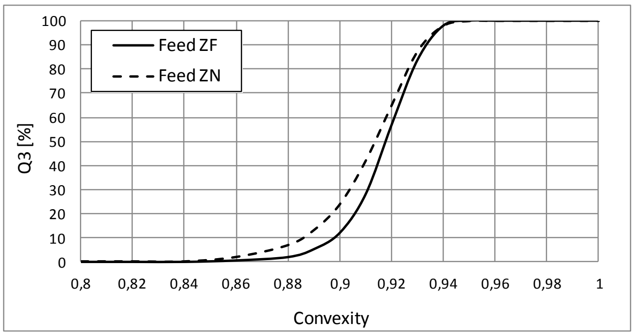


Figure 4. Distribution of selected shape coefficients for regular and irregular particles of chalcedonite feed material .

Analysis of the particle size distribution according to the minimum Feret's diameter d_{Fmin} carried out for the tested feed with regular and irregular particles, prepared on slotted sieves in the particle size class 6.3-8mm, shows the differences in their particle size (Figure 5). The feed material with irregular particles have contained twice as many fine particles (below 5mm). The vision system for these particles has been recording dynamically the smallest third dimension of irregular particles, indicating their flatness, as the minimum Feret's diameter and thus decreased the result of particle distribution. In the area of intermediate particles physically measured on 6.3 mm and 8 mm slot sieves, dynamic image analysis measuring their particle size distribution according to d_{Fmin} underestimates the proportion of irregular particles in the feed. However, it overestimates the yield of these particles in the upper particle size range, close to the size of 8 mm. This is due to the fact that irregular particles are randomly registered by the vision system also in the orientation displaying the two largest dimensions, without capturing the third - the smallest, and that one informs about the flatness (irregularities) of these particles. These two larger dimensions of irregular particles are usually greater than the corresponding dimensions of regular particles within the same particle size class. Differences in the distribution of particles between regular and irregular ones are therefore directly related to differences in their shape. It can be assumed that the differences would be greater by application of the 3D technique, which in each case takes into account the third dimension of the particle, and not only randomly in the case of a convenient orientation of the particle, like in the case of the DIA method.

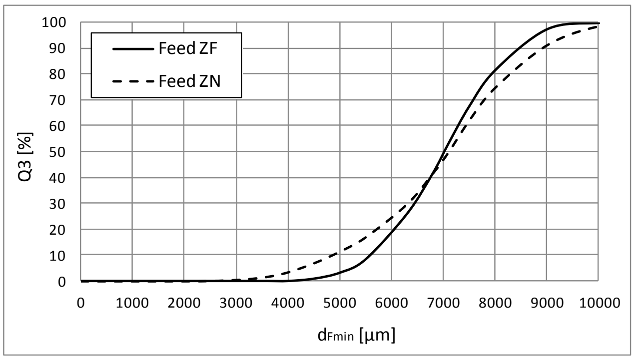


Figure 5. Cumulative particle size distribution functions of chalcedonite feed with regular (ZF) and irregular (ZN) particles.

The products of chalcedonite enrichment, containing regular and irregular particles, were subjected to further visual analyses. A comparative analysis of irregular particles indicates small differences in the particle size of individual enrichment products, but it points on a significantly finer graining in relation to the feed containing irregular particles, especially in the bottom product (I). Fine particles in enrichment products of irregular particles feed could be generated due to mechanical breaking of flat particles, which are also weaker. Confirmation of this phenomenon can also be seen in the variations of the Circularity and Convexity shape coefficients, especially in relation of the feed material to the enrichment products from the lowest layer (I) (Fig. 6). The fine particles that were formed in this way, have to a large extent the circular shapes. This is confirmed (Fig. 7) by concentration of these particles in the upper left corner of the graph (black dots), which are characterized by high values of the C aspect ratio within the fine particles below 4mm. Analyzing the distribution of Convexity coefficient (Fig. 6), it can be also seen that irregular particles of chalcedonite (flat, often fragile with low strength properties) after the enrichment process in the water jig have a smoother surface (higher Cx coefficient in relation to the feed). This may be due to the washing effect of water.

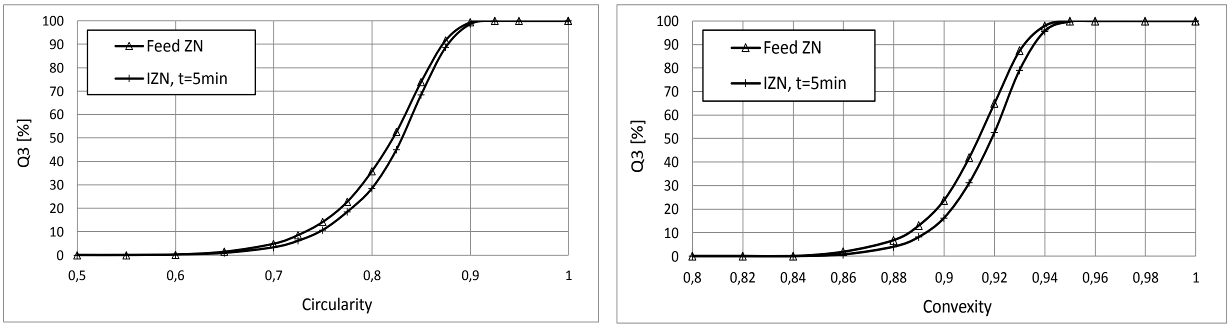


Figure 6. Distributions of the circle and convexity coefficients for the feed particles as well as for enrichment products in the first (I) lowest layer of the jig bed for irregular particles.

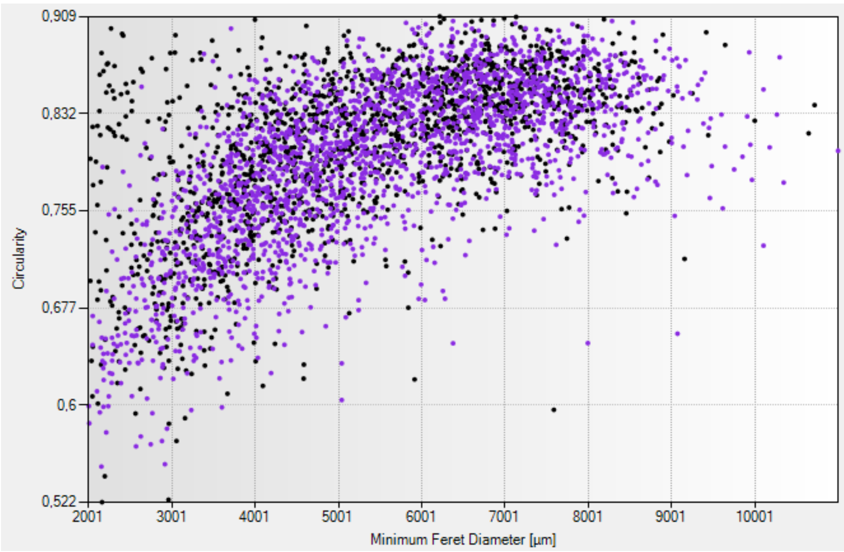


Figure 7. Distribution of circularity coefficient C for the feed with irregular particles and the enrichment product from the lowest layer of the jig, in relationship to the size of particles.

Comparing the shape coefficients of particles in individual layers of the jig there can be seen differences in their values between the lowest (I) and upper (IV) one. Particles in the bottom layer have smoother surface (higher values of Cx coefficient) and a more circular shape (higher C coefficient values), while particles in upper layers have a more irregular surface and less spherical shapes. The speed of sinking for these particles is therefore lower and for that reason they concentrate in the top layers of the jig bed. This shows that the enrichment effect occur even within the same category of regular and irregular particles. In the mixture of regular and irregular particles, the effect of separation, and thus enrichment of the mixture would be stronger.

An analysis of summary figures with the distributions of the Feret's minimum diameters and convexity and circularity coefficients of both studied populations of particles (Figures 8-10) show the differences in particle size, surface structure and the shape of regular and irregular particles for feed and the products. Samples with irregular particles were characterized by a higher yield of fine grains, they had less circular shape as well as irregular surface.

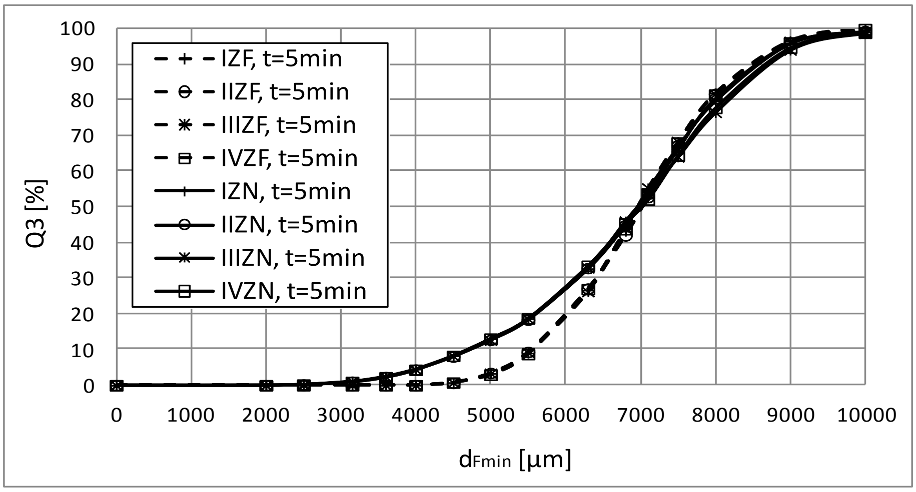


Figure 8. Comparison of particle size distributions of chalcedonite enrichment products for regular and irregular particles.

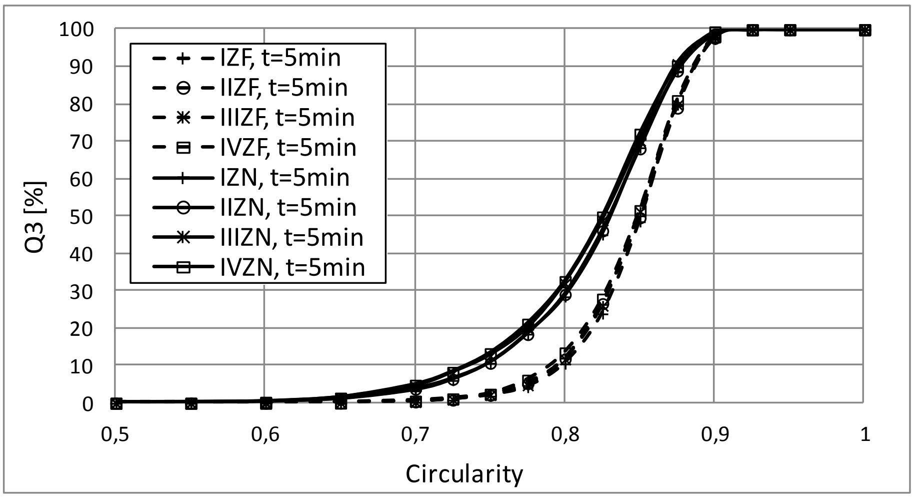


Figure 9. Comparison of Circularity coefficient distributions of chalcedonite enrichment products for regular and irregular particles.

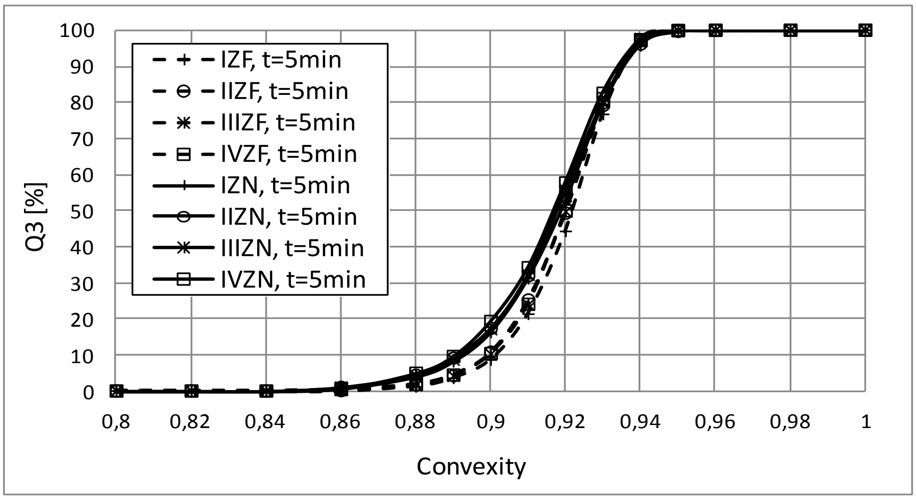


Figure 10. Comparison of Convexity coefficient distributions of chalcedonite enrichment products for regular and irregular particles.

4. Summary and conclusions

The results of investigations show that the shape of particles and a type of measurement method significantly affect the results of particle size measurements by means of vision methods. The dynamic image analysis (DIA) technique gives repeatable and reliable results in terms of the size and shape of chalcedonite particles, differentiating them into regular and irregular grains. The differences in the surface structure and geometry of these particles both for the feed and enrichment products from the individual bed layers of the jig, can be observed. The circularity coefficients C and convexity Cx proved to be the effective coefficients of shape, while the minimum diameter of Feret's Fmin was the effective measure of the size.

These differences could be greater and more visible for a 3D dimensioning technique, which takes into account the particle size distribution and shape of all three dimensions. It seems, therefore, that measurements of the size and shape for irregular (strongly flat) particles should be carried out as far as possible by 3D technique. An application of dynamic image analysis techniques for this purpose, as it was proved in the paper, enables a reliable indication of differences in the geometry of these particles and obtaining representative results, provided, however, a large population of registered particles (minimum few thousand) is used. In such cases, an application of static video measurement technique and the shape of particles, i.e. microscopic image analysis, will be incorrect, because in practice it is difficult to ensure the representativeness of the sample and the registered particles will be placed in the most stable position without the possibility of registering the finest dimension indicating the flatness (irregularities) of these particles. This issue will be a subject of further investigations.

Differences in the structure and geometry of regular and irregular particles between the upper and lower layers of the jig's bed recorded by means of a video measuring system utilizing the DIA technique show that the effect of enrichment of chalcedonite particles occurs even within the same categories of regular and irregular particles.

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Artykuł jest wynikiem realizacji projektu w ramach konkursu NCBiR: konkursu nr 1 w ramach Poddziałania 4.1.4 „Projekty aplikacyjne" POIR w 2017 r., pt.: *Opracowanie i budowa zestawu prototypowych urządzeń technologicznych do budowy innowacyjnego układu technologicznego do uszlachetniania kruszyw mineralnych wraz z przeprowadzeniem ich testów w warunkach zbliżonych do rzeczywistych".* Projekt współfinansowany przez Unię Europejską ze środków Europejskiego Funduszu Rozwoju Regionalnego w ramach Działania 4.1 Programu Operacyjnego Inteligentny Rozwój 2014-2020.

Fundusze Europejskie Inteligentny Rozwój
Rzeczpospolita Polska
Narodowe Centrum Badań i Rozwoju
Unia Europejska