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DIGITAL METHODS FOR MEASURING GRAIN SIZE PARAMETERS OF AGGREGATE–BINDER MIXTURES

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Abstract

Geometrical parameters of natural and crushed aggregates such as grain length, perimeter, area, etc., underline the shape and flakiness indices definition. The latter indices have a measurable effect on the mechanical properties of aggregates–binder mixtures, e.g. concrete, mortar, bituminous mixtures. In this work, digital methods were developed with the mathematical software Matlab, by applying a statistical method called k-means clustering for the exact separation between background and aggregates to compute the aforementioned properties. The overall code can be applied in real time by analysing quickly a large volume of data with accuracy and significant cost reduction. Currently, only the two dimensions of the grains could be measured. Future work will focus on full three-dimensional measurements by comparing paired images taken from different angles but also aggregate segmentation in case of touching particles.
Key words: *aggregates, shape, flakiness, Matlab.*

Περίληψη

Οι γεωμετρικές παράμετροι χαλικιών, όπως μήκος, περίμετρος, εμβαδόν κλπ., υποδεικνύουν τους δείκτες πλακοειδούς και σχήματος. Αυτοί οι δείκτες έχουν μια σημαντική επίδραση στις μηχανικές ιδιότητες αυτών ως αδρανή υλικά π.χ. στο σκυρόδεμα, το ασβεστοκονίαμα, την άσφαλτο. Στην παρούσα εργασία παρουσιάζονται ψηφιακές μέθοδοι βασισμένες στο μαθηματικό πακέτο Matlab. Εφαρμόστηκε η στατιστική μέθοδος k-means clustering, για τον ακριβή διαχωρισμό φόντου και χαλικιών και με στόχο τον υπολογισμό των προαναφερθέντων ιδιοτήτων. Ο συνολικός κώδικας μπορεί να εφαρμοστεί σε πραγματικό χρόνο αναλύοντας γρήγορα έναν μεγάλο όγκο δεδομένων με μεγάλη ακρίβεια και με σημαντική μείωση του κόστους. Επί του παρόντος μπορούν να μετρηθούν μόνο οι δύο διαστάσεις των κόκκων. Μελλοντική εργασία θα εστιάσει σε τρισδιάστατες μετρήσεις συγκρίνοντας ζεύγη εικόνων που θα παρθούν από διαφορετικές γωνίες αλλά επίσης και διαχωρισμός κόκκων που ακουμπούν μεταξύ τους.
Λέξεις κλειδιά: *χαλίκια, σχήμα, πλακοειδές, Matlab.*

1. Introduction

Limestone aggregates are the major component of hydraulic and asphalt concrete. Aggregate industry requires a precise and reproducible method for measuring their most significant geometrical properties, such as maximum and minimum length, area, and perimeter, as well as other composite properties, such as degree of compaction, circularity, flakiness and elongation index. These parameters affect the packing density of mixtures and consequently the mechanical properties of them as aggregates.

The geometrical properties of aggregates are key parameters for concrete quality, because mechanical properties depend on aggregates and cement paste. Particularity, when the proportion of flat particles is increased, the compressive strength, and workability decrease (Frazao et all, 984). In addition, the use of rounded and smoothed particles increases the workability of concrete. Size distribution of aggregates is also important because it determines the paste's requirements for a workable concrete. Furthermore, the above-mentioned requirements control the construction cost, because cement is the most expensive component and its optimal volume, or mass should be reduced by increasing the mixture packing density. The required amount of cement is dependent upon the amount of void space that must be filled and the total surface area that must be covered. When particles are of uniform size the spacing is the greatest, but when a range of sizes is used, the void spaces are reduced and the paste requirement is lowered.

It is evident that methods for characterising the size and the shape of aggregates are necessary. Currently, the assessment of aggregate geometrical properties is carried out by manual methods, such as sieving, including bar sieving for defining their elongation and Danish-box or callipers. Sieving methods are very time consuming and may involve larger statistical errors because of the small sampling volume or because of untrained personnel. In addition various digital methods for 2D (Profitis et al, 2011) but also for 3D (Kim et al, 2003, Fernlund, 2004, Tafesse et al, 2012) aggregate characterization have been used, by using either a digital camera or a laser or even both. Digital methods are expected to be faster, more accurate, also providing more geometrical information while minimizing statistical errors. When automated, they do not require any trained personnel and can be performed in real time.

The performance of digital methods has been investigated by using image processing and by comparing the results with conventional laboratory techniques, such as sieving. For the demonstration of the method limestone aggregates taken from an active limestone quarry in Greece were used.

2. Materials and Methods

2.1. Materials

A representative sample of limestone aggregates was acquired and dried at 110 ± 5 ^{o}C. The sample was sieved into different fractions with square sieves according to the EN 933-3:1997/A1:2003 standard test method. Aggregate grains below 4 mm were discarded. Bar sieves were also used to separate the resulting fractions according to their flakiness (d < $^{1}/_{2}$D, where d and D are the smallest and largest dimension of the grains) in order to define the flakiness index. The bar sieves have the following Di/2 openings in mm: 40, 31.5, 25, 20, 16, 12.5, 10, 8, 6.3, 5, 4, 3.15 and 2.5. Elongation was finally measured with a calliper by measuring the maximum length of the grain and comparing to the minimum. If the minimum dimension (d) was less than 1/3 of the maximum dimension of the grain (D), then grains were characterised as non-cubic, whereas the rest were characterised as cubic. The original total mass of the aggregate sample was 19 kg. The laboratory measurements using sieves and calliper are shown in Table 1.
Pictures were acquired with a rock photography table, stabilising a 6 Mpixel colour camera on a vertical post at a distance of 30 cm. The table is ruled to allow scaling of the images. Ambient diffuse light was used for photography. Images were processed using the Matlab mathematical package, using a custom-made image-processing routines.The algorithm consists of two parts, the first one implements segmentation between the background and the foreground by applying k-means clustering and the second part automatically calculates their most important geometrical properties

measured in pixels. This results to the derivation of a series of important parameters, such as circularity, compactness, elongation and sphericity, shape and form definition. The results are from binary images.

Table 1 - Results of laboratory measurements with sieves and flakiness index calculation.

SQUARE SIEVES				**BAR SIEVES**			**FLAKINESS**
Di (mm)	**di (mm)**	**Fraction di/Di Ri (g)**	**Fraction di/Di Ri (%)**	**Di/2 (mm)**	**Mass of passing fraction mi (g)**	**Mass of passing fraction mi (%)**	**Fli 100*(mi/Ri) %**
80	63	0.00	*0.00*	40	0.00	*0.00*	0
63	50	227.13	*1.20*	31.5	0.00	*0.00*	0
50	40	566.86	*2.98*	25	0.00	*0.00*	0
40	31.5	1388.70	*7.31*	20	158.30	*11.19*	11.40
31.5	25	1697.50	*8.93*	16	200.80	*14.19*	11.83
25	20	1650.20	*8.69*	12.5	166.00	*11.73*	10.06
20	16	1738.50	*9.15*	10	105.20	*7.44*	6.05
16	12.5	1852.10	*9.75*	8	195.85	*13.84*	10.57
12.5	10	1067.00	*5.62*	6.3	116.90	*8.26*	10.96
10	8	1149.60	*6.05*	5	112.90	*7.98*	9.82
8	6.3	1059.20	*5.57*	4	111.00	*7.85*	10.48
6.3	5	781.10	*4.11*	3.15	68.76	*4.86*	8.80
5	4	1191.40	*6.27*	2.5	179.03	*12.65*	15.03
Original Total (g):		19000.00	75.63			100.00	
M1 (Σri) =		**14369.29**		**M2 (Σmi) = 1414.74**			
Fl = (M2/M1)*100= 9.84							

2.2. Methods

2.2.1. Aggregate Size

Aggregate size is often a matter of debate. Because aggregates are shown as two-dimensional images, the length and width represent their size. There are various ways of defining these two axes; the most common are the following:

1. The maximum distance between two points on the perimeter of the grain represents the length, whereas the width is the maximum distance perpendicular to the length (Figure 1a).
2. The dimensions of the smallest rectangle that can be fitted around the grain (Figure 1b). This method is applied when the Danish-box is used.
3. The dimensions of the best-fitted ellipse of the grain. The ellipse should have the same area with the grain.

Sometimes the length and the width are not related to each other. For example, one could take the length as in the first case and the width as in the second case, or just the first case for both (Fernlund et al., 2007). The third case is often used to define the orientation of the grain rather than its dimensions.

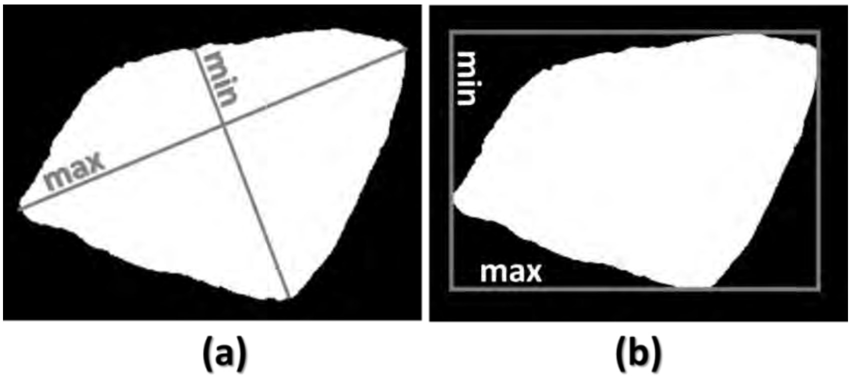

Figure 1 - Maximum (length) and minimum (width) distances as defined in the first two cases.

2.2.2. Shape Characterization

Objects can be categorised in a variety of shapes, or how close to a shape they may look like. Shape is determined by calculating the ratios between various primary dimensions and comparing them to standard shapes (Dunlop,H., 2006). Simple geometrical shapes, such as circle and square, have standard values given in Table 2.

Shape can be divided in three categories: form, roundness, and texture. Here, the first category was examined. Form describes the overall shape, for example, how close to a sphere it is. The following formula scan is used in this task:

- Riley sphericity is defined as:$\text{Riley sphericity} = \sqrt{\frac{d_i}{d_c}}$

where d_i is the diameter of the largest inscribed circle and d_c is the diameter of the smallest circumscribed circle (Figure 3).

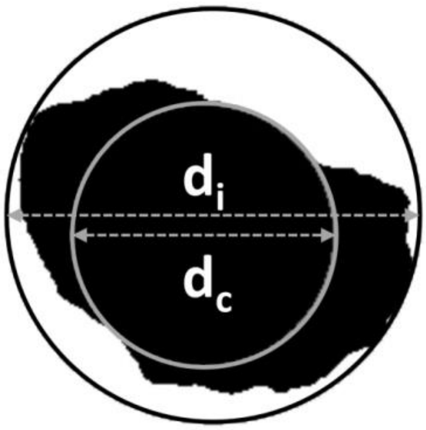

Figure 3 - Circumscribed (black) and inscribed (grey) circle of an object used to define Riley sphericity.

- Elongation is defined as the ratio of the major (M) and the minor (m) length of the object. It is important to mention which of the three cases defined above for maximum length are chosen: Elongation $= \frac{\mathrm{m}}{\mathrm{M}}$
- Compactness is defined as $\frac{\sqrt{\mathrm{Area}}}{\mathrm{Perimeter}}$
- Circularity is defined as $\frac{\mathrm{Perimeter}^2}{4\pi*\mathrm{Area}}$

Table 2 - Standard values of different specific shapes.

	Circle	Square	Rectangle
Riley sphericity	1	$\sqrt{2}/2$	$<\sqrt{2}/2$
Elongation	1	1	<1
Compactness	$\sqrt{\pi}/2\pi$	0.25	<0.25
Circularity	1	$4/\pi$	$>4/\pi$

2.2.3. Aggregate measurements via conventional laboratory methods

Conventional laboratory methods for measuring the geometrical properties of aggregates include sieving. In addition, bar sieving is applied to evaluate the elongation of coarse aggregates (gravel). The major disadvantage of this method is that it does not measure the axial dimensions of particles and the results are dependent on the particle's shape (Fernlund et al., 2007). Finally, each particle is measured by hand, with the use of Danish-box or calliper. These methods are time-consuming and the particles that have to be measured are quite small, generally over 200 particles per sample. To distinguish the sieving methods from the digital methods, from now on the notation "analogue sieves" for the conventional laboratory sieves and "digital sieves" for the filters made by using the computer algorithms is introduced.

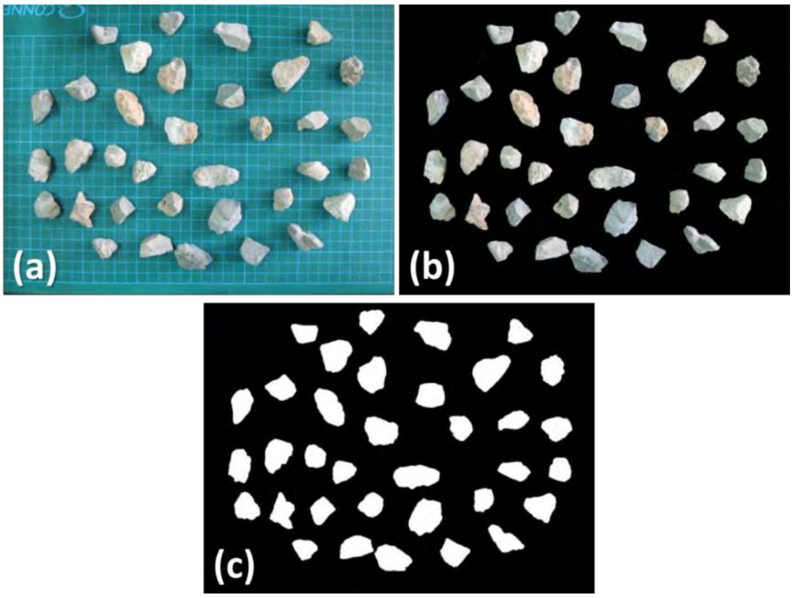

Figure 4 - (a) Original image of aggregates; (b) segmentation between the background and the aggregates; (c) binary image.

2.2.4. Aggregate Measurements via Digital Methods

Digital methods provide measurement of a particle's properties in two dimensions through image processing. The methodology generally depends on the quality and the type of the image and the final purpose of the study. The algorithm must be produced so that any statistical errors minimize and maximize the precision of the results. The whole algorithm consists of two parts. The first one implements segmentation between background and foreground by applying k-means clustering. The segmentation depends on the colour of the object and thus regions with the same colour and/or brightness are plotted separately compared to regions with different colour and/or brightness (Figure 4a-b). The second part consists of the automated calculation of their most important geometrical properties, such as maximum–minimum length, the area and the perimeter, leading to a series of important parameters, such as circularity, compactness, elongation and sphericity, shape and form definition. Finally, the results are derived from binary images (Figure 4c).

3. Results and Discussion

3.1. Reproducibility of Digital Measurements

The assumption that a grain thrown on a flat surface will lay on its flattest surface was tested by performing ten repetitive random throws of certain aggregate clusters. The variances were calculated and compared with analysis of variance (ANOVA). Consequently, the null hypothesis is that the ten throws are similar. When the alpha value is 0.05, the possibility for the null hypothesis to be true is very high, while the F-values stay very low compared to the F-critical value. The test is performed for two different fractions of cubic aggregates and one for non-cubic aggregates (Table 3). Consequently, when either cubic or non-cubic aggregates are thrown and digitally processed for calculating their sizes, the standard error remains low; therefore measurements resulting from image processing are reproducible within approximately 5%. For comparison, the studied aggregates are also separated with analogue sieves.

A second test involved the investigation of the significance of overlapping grains in estimating the geometrical parameters of interest. To perform this test, an aggregate was randomly thrown and photographed and then rearranged so that there is no overlap between grains, photographed again and compared to the first throw. Overlapping results in decreasing the size of a number of grains, or the wrong estimation of the margins of overlapping grains. It is therefore expected that overestimations of one grain against another can occur, increasing the error. For this purpose, three aggregates were used and tested for cubic grains of different sizes and grains of the same size, but one is cubic and the other is non-cubic. As in all tests, the fractions used are made of aggregates separated with analogue sieves.

Table 3 - Results of the reproducibility test of digital measurement.

		45–31,5 Cubic	**22,4–16 Cubic**	**16-11,2 non-Cubic**
Length (max dimension)	P-value	0.9994	0.9999	0.9999
	Mean ± SE (*% SE*)	54.51 ± 3.00 (*5.50%*)	27.49 ± 0.78 (*2.85%*)	24.45 ± 0.74 (*3.01%*)
Width (min dimension)	P-value of width	0.9983	0.9787	0.8866
	Mean ± SE (*% SE*)	44.96 ±1.97 (*4.38%*)	21.83 ± 0.50 (*2.28%*)	18.33 ± 0.51 (*2.76%*)

SE=Standard Error, P-Value =Probability Value

Table 4 - Results of grain overlapping tests.

	31.5–22.4 Cubic	16–11.2 Cubic	16–11.2 non-Cubic
Length			
Oriented Mean ±Variance (cm)	4.1377 ± 0.6963	2.0179 ± 0.1650	2.2989 ± 0.2275
Random Mean ±Variance (cm)	4.1616 ± 0.7593	2.1222 ± 0.1964	2.3854 ± 0.1992
t	−0.1359	−2.7696	−0.8054
P(T<=t)	0.8922	0.0058	0.4232
t critical, two-sided	1.9861	1.9646	1.9935
Width			
Oriented Mean ±Variance (cm)	3.3342 ± 0.3159	1.6437 ± 0.0563	1.8298 ± 0.0774
Random Mean ± Variance (cm)	3.3036 ± 0.3174	1.7576 ± 0.0751	1.9578 ± 0.1027
t	0.2637	−5.0150	−1.8353
P(T≤t)	0.7926	0.000001	0.0706
t critical, two-sided	1.9861	1.9646	1.9935

To compare between the oriented and random cases, the t-Students statistical test was used and the results are shown in Table 4. From the results, it is made clear that cubic aggregates of large size (31.5–22.4 mm) are less prone to errors due to overlapping and an acceptable separation is performed by using digital methods (e.g., it is highly probable that the two cases, oriented and random, have the same mean and variance). However, this similarity is lost in aggregates of smaller fractions (16–11.2 mm), which show probabilities much less than the alpha value (0.05), therefore the null hypothesis is rejected. It is interesting though to mention that the small-size, non-cubic aggregates show slightly higher possibilities of being similar, possibly because since they are flaky they tend to lay on a preferred orientation and with distinct distribution. It is possible that the problem can be overcome by photographing aggregates with smaller number of grains that are additionally separated by vibrating the photography board, while also using higher resolution photo cameras.

3.2. Digital Sieving

Digital methods can be used to readily estimate the geometrical and shape parameters of aggregate grains. However, because these are measured from two-dimensional images, the third dimension is lost, which in a way it is sensed by the analogue sieves. Here, it is investigated how digital sieves compare with the analogue sieves. This is performed by counting the number of grains that are retained in each sieve, either analogue in the lab, or digital when filtering is performed through computer algorithms. The results are shown in Table 5 and graphically in Figure 5. Digital sieving seems to retain more grains in the consecutive larger in opening sieves, compared to the analogue sieves. In addition, it is observed that the digital histograms present a more structured distribution, with positive anomalies in the middle size sieves, compared to the smoother distributions of the analogue sieves. This observation is more pronounced in the cubic aggregates but less in the non-cubic ones. There is no easy explanation why this occurs; except maybe that, the analogue sieves allow the grains to rotate as they go through them compared to the static grains of the digital sieves. The third dimension that is missing from the digital sieves should not be a reason for that, because only one dimension is responsible for retaining a grain to a certain sieve. It is suggested that for quality control during industrial applications the information provided by the digital processing is more useful, because it describes the general shape of the grain.

Table 5 - Comparison between analogue and digital sieving.

Sieves		Analogue sieves			Digital sieves		
Di	**di**	**Number of cubic grains (M1)**	**Number of non-cubic grains (M2)**	**TOTAL (M1+M2)**	**Number of cubic grains (M1)**	**Number of non-cubic grains (M2)**	**TOTAL (M1+M2)**
63	**45**	0	0	**0**	10	1	**11**
45	**31.5**	18	0	**18**	42	11	**53**
31.5	**22.4**	47	9	**56**	77	14	**91**
22.4	**16**	121	15	**136**	242	38	**280**
16	**11.2**	255	37	**292**	453	93	**546**
11.2	**8**	438	96	**534**	408	122	**530**
8	**5.6**	1231	226	**1457**	1716	304	**2020**
5.6	**4**	2605	325	**2930**	1680	120	**1800**
4	**0**	0	0	**0**	87	5	**92**
Sum		**4715**	**708**	**5423**	**4715**	**708**	**5423**

Using the measurements, an effort was made to surpass the lack of the third dimension of each grain with statistical methods. A t-Students test between cubic and non-cubic grains of at least two sizes that we tested resulted in significantly different distributions. Despite this, it was difficult at this stage to precisely estimate the parameters of these two distributions from the distribution of the total sample, in order to predict the number of grains contributing to cubic and non-cubic grain fractions.

3.3. Shape Parameters Acquired with Digital Methods

Shape parameters such as sphericity, elongation, compactness and circularity, as defined in the previous paragraph of this paper, are easily acquired using digital methods. Table 6 demonstrates this, while it also demonstrates that between different size fractions the shapes remain quite similar. Different fractions were tested for similarity with the t-Students test using different combinations if the measured geometrical parameters, such as sphericity; the results seem to vary. However, it is easy to conclude that sphericity values are generally very close to 0.707, which characterises all fractions as cubic, which is true since the fractions belong to the cubic laboratory separate. Similarly, elongation is close to unity as expected for circular cubic grains. Compactness seems to be between cubic and rectangular, whereas circularity values indicate rectangular shapes but not far from cubic.

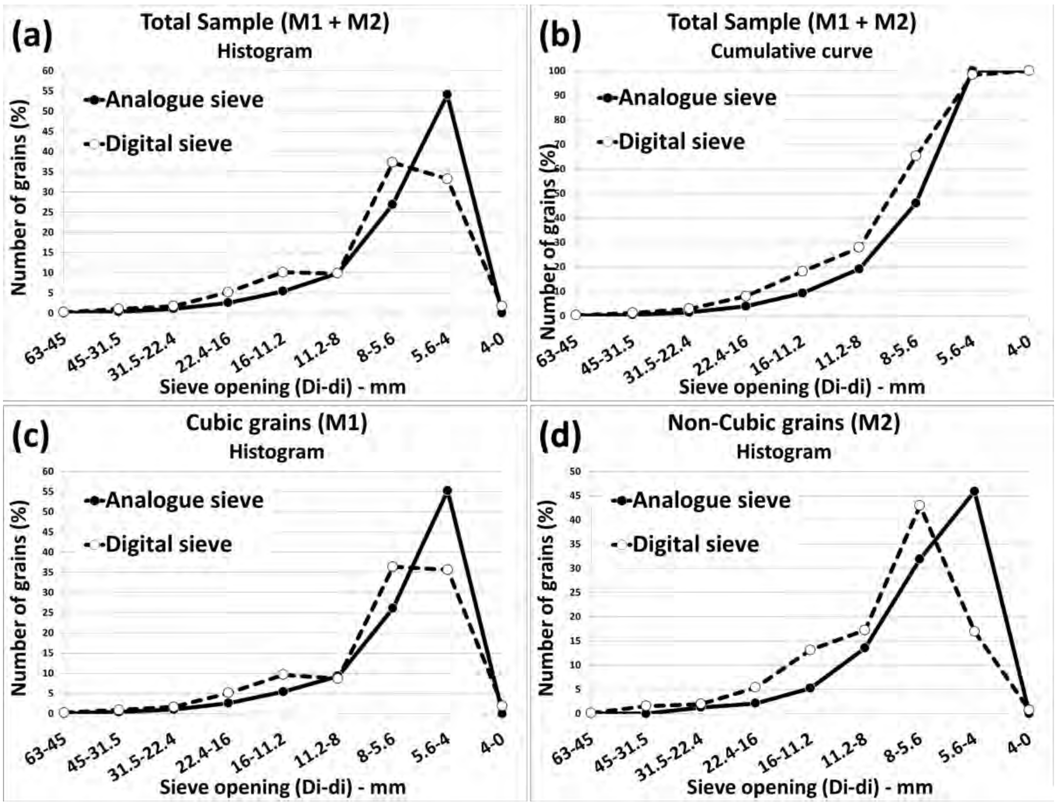

Figure 5 - Allocation of the retained grains (% of number of grains) for analogue (continuous line) and for digital (broken line) sieves, histogram (a) and cumulative (b) plots. Similar histogram plots for cubic (c) and non-cubic grains (d).

Table 6 - Shape parameters measured with digital methods (cubic grains).

Fraction (mm)	**Riley Sphericity**	**Elongation**	**Compactness**	**Circularity**
45–31.5	0.77 ± 0.067	0.860 ± 0.108	0.218 ± 0.013	1.692 ± 0.217
31.5–22.4	0.77 ± 0.070	0.823 ± 0.128	0.225 ± 0.012	1.575 ± 0.191
22.4–16	0.79 ± 0.047	0.854 ± 0.145	0.288 ± 0.050	1.422 ± 0.109
16–11,2	0.77 ± 0.064	0.814 ± 0.128	0.235 ± 0.009	1.396 ± 0.120
11.2–8	0.77 ± 0.061	0.822 ± 0.119	0.234 ± 0.125	1.460 ± 0.161
8–5.6	0.78 ± 0.076	0.815 ± 0.128	0.229 ± 0.018	1.536 ± 0.261
5.6–4	0.77 ± 0.075	0.811 ± 0.122	0.236 ± 0.017	1.547 ± 0.291

4. Conclusions

An effort was made to replace conventional sieves with digital sieves using image processing. It is expected that construction and mining industry would profit from automated equipment, which would improve quality control, as well as it would enable measuring more geometrical characteristics of aggregate grains. Methods were applied to aggregates of certain flakiness, measured with conventional methods.

In the two dimensions, a variety of geometrical parameters can be acquired only with digital methods in high precision. Assuming that aggregates would most often lay with their maximum area, their two maximum dimensions can be computed, while the third dimension, thickness, should be equal or almost equal with the minimum of the two first dimensions when cubic aggregates are considered, or much smaller if flacky aggregates are considered. A statistical check was applied using ANOVA in ten different throws of different size fractions, which shows that indeed different events result to statistically the same distributions. Therefore, digital methods are reliable for shape parameter measurements of aggregates. A second test has shown that digital methods can have the appropriate precision in measuring sizes of aggregates, even during different rearrangements.

Digital sieves are also capable of replacing conventional analogue sieves, performing better in capturing the overall shape of aggregate grains rather than perforations that allow each grain to go through the sieve due to rotational movements. Therefore, digital sieving results in capturing more grains of the larger size fractions compared to analogue sieves. Finally, digital measurements can provide a variety of geometrical information, such as sphericity, elongation, compactness and circularity. However, to fully replace the conventional sieves, the third dimension is required to estimate flakiness and shape indices.

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