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ANALYSIS OF THE GEOMETRICAL PROPERTIES OF FINE RECYCLED AGGREGATES USING DIGITAL IMAGE PROCESSING TECHNIQUE

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Abstract. The acquisition of natural sand and dumping of fine recycled aggregates (FRA) are two serious environmental problems that can be solved simultaneously by using FRA as replacement of natural sand in high-end applications. In the past, FRA has been considered an unwanted by-product of construction and demolition waste (CDW) processing, due to the high levels of contaminations and high content of fines. However, FRA is currently considered as a new secondary raw material with large potential. Due to the increasing interests in FRA it is of utmost importance to extensively examine their characteristics. To date, research has been done on the water absorption, density, chemical and mineralogical composition, and size distribution of the FRA. However, knowledge on the geometrical properties of FRA is limited. In this paper the geometrical properties of several types of FRA are examined using digital image processing (DIP). The effect of processing methods, crusher openings and crushing cycles are considered to gain new insights into the characteristics of FRA.

Keywords: Fine recycled aggregates, geometrical properties, digital image processing.

1. Introduction

In the last decades, climate change has been the most persistent environmental concern. The accelerated urbanization and industrialization pose severe challenges to sustainable development around the world. Depletion of the earth's natural resources is one of these challenges. Over the past five decades, depletion of mineral resources expanded fivefold [1]. Therefore, it is essential to minimize the use of natural resources and replace them with alternative resources. One of the possible solutions is to utilize recycled aggregates, a secondary raw resource derived from processing construction and demolition waste, as replacement of natural aggregates in cement-based materials such as mortar and concrete.

So far, numerous research has been done on the use of coarse recycled aggregates (CRA) in cement-based materials. This has led to an increased use of the CRA in high-end applications. However, the use of FRA as replacement of natural sand in cement-based materials is a subject that is dramatically lagging behind. Today, FRA is mainly used in road construction as foundation and sub-foundation layers. However, this application causes a decrease in the intrinsic value of the secondary raw material and can thus be seen as downcycling [2]. Figures from the MDO (2015) show that 99 % of the produced FRA in Flanders are used in low-end applications such as foundation layers and backfills [3]. Moreover, the current dominant application area, namely foundation layers in road construction, will not remain large enough to meet the production of the RA [2]. FRA has been mainly used in low-end applications due to the high contamination, high content of fines, high water absorption and large variability. Therefore, there is need to extensively examine the FRA to understand their characteristics in order to use it in more value-added applications such as cement-based materials.

Up to now, some research has been done on the water absorption, density, chemical and mineralogical composition and size distribution of FRA [4]. However, there is rather limited knowledge on the geometrical properties of FRA. It is often stated that FRA has a more angular and irregular shape compared to natural sand but there is little research to prove this statement. In literature, nearly no research can be found on the geometrical parameters of FRA and how these parameters are affected by crushing method, size of the crusher opening and amount of crushing cycles. The geometrical properties of FRA can have a major influence on the rheological parameters of the cement-based materials affecting its workability, compactibility and pumpability.

Solyman [6] tested the geometrical properties of FRA using Scanning Electron Microscopy (SEM). It was found that the FRA particles are more angular and irregular in comparison to natural sand. The author also analysed the sphericity of the particles by use of photogrammetric techniques. It was found that the length/width ratio of the natural sand and FRA was similar while the sphericity varies more, confirming the greater angularity of the FRA particles. The increased angularity of the FRA particles can cause a decrease in the workability of cement-based materials.

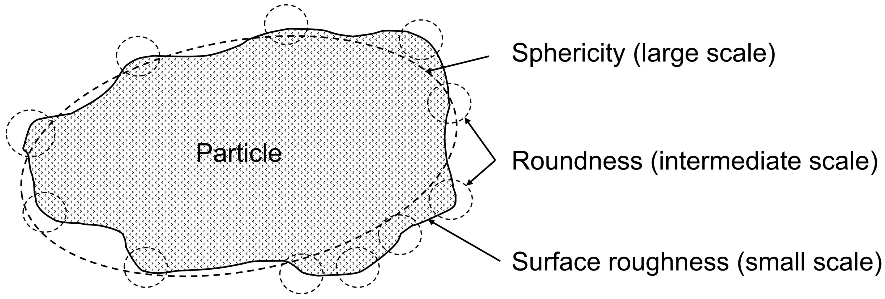


Figure 1. Sub-quantities to describe the geometrical properties of a particle.

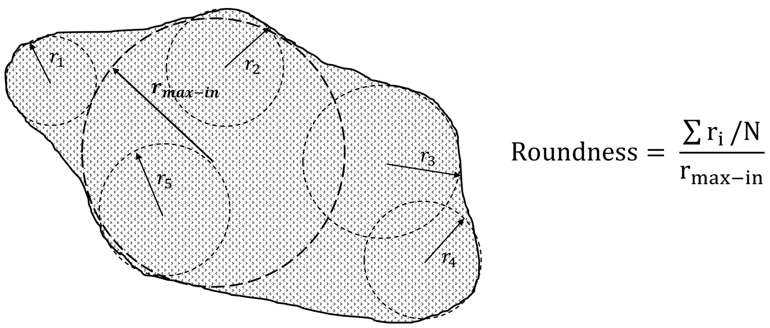


Figure 2. Definition of roundness by Wadel [5].

Fumoto and Yamada [7], examined the geometrical properties of FRA using the BET technique and reported that the greater angularity of FRA is caused by the brittleness of the recycled materials and their production process. In addition, it was found that FRA has a large specific surface area due to the open pores on the surface. The increased specific surface area can cause a loss of efficiency of superplasticisers.

In this study the geometrical properties of several types of FRA is examined using the digital image processing technique. The effect of crushing procedures, crusher opening and amount of crushing cycles on the geometrical properties of the FRA is examined.

2. Materials and methods

2.1. Materials

A total of 25 aggregates are analysed which includes 1 natural aggregate (as reference) and 24 FRA's. The natural aggregates are washed natural riversand 0–2 mm provided by the company Bouwpunt Botha, Belgium. In total 13 fine recycled concrete aggregates (FRCA's) and 11 fine mixed recycled aggregates (FMRA's) are tested. The aggregates were produced with two types of crushers and different crusher openings and crushing cycles are used to determine the effect of the crushing procedure on the geometrical properties of the FRA's.

2.2. Methodology

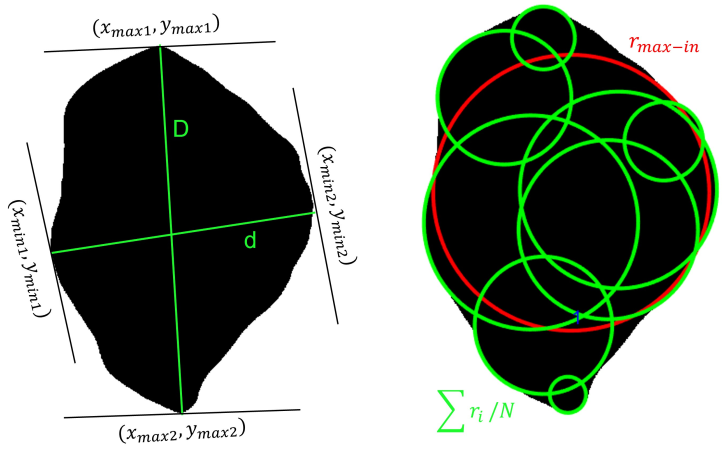
To quantitatively classify the geometrical properties of a particle, a 3D or 2D analyses can be used. A 3D analysis requires sophisticated equipment to establish a 3D model of the particle. The 3D model can be made using 3D scanning or by combining orthogonal images to represent the 3 dimensions. 2D image analyses is easier to perform and can be done using a regular camera or microscope. In a 2D image analysis it is assumed that the particles lay random or over there dominant/stable axis [8]. Due to the complexity of a 3D analysis and the fineness of the particles used in this work, a 2D image analysis is used.

As shown in Figure 1, three parameters can be used to describe the geometrical properties of the aggregates: sphericity, roundness, and roughness. Each of the three sub-quantities describes the geometrical properties of a particle but at a different scale [8, 9].

At large scale the particle's morphology is examined. The sphericity is often used to quantify this characteristic [8]. The particle sphericity can be defined in various ways. J. Zheng at al. [10] compared five existing definitions of sphericity based on two-dimensional particle projections and found that the ratio of width to length, often referred to as the aspect ratio, provides the best distribution of sphericity values between 0 and 1 and is also independent of the particle roundness.

At intermediate scale, the corners and edges of the particles are analysed. The roundness is often used as a measure at this scale [8]. Wadel [5] stated that the roundness can be described as the average radius of corners and edges divided by the radius of the maximum inserted circle as shown in Figure 2. At the smallest scale, the term surface roughness is used to describe the texture of the surface.

In this research each aggregate sample is analysed based on sphericity and roundness as mentioned above. A Keyence 3D laser scanning microscope VK-X3000 is used to take images of the aggregate samples. For each



(a). (b).

Figure 3. Analyses of sphericity and roundness with Matlab 2020 – MathWorks.

aggregate sample 400 images of individual particles are taken and analysed.

2.3. Digital image processing technique

Matlab 2020 – MathWorks is used to process the images and analyse them based on the sphericity and roundness. The sphericity is determined using the minimum and maximum Feret diameters, i.e. the distance between two parallel planes restricting the particle perpendicular to that direction as shown in Figure 3a. The roundness of the particles is determined using the Matlab code proposed by Zheng J. and Hryciw, R. [10]. The Matlab code determines the average radius of corners and edges and the radius of the maximum inserted circle of the particle as shown in Figure 3b.

3. Results and discussion

3.1. Fraction

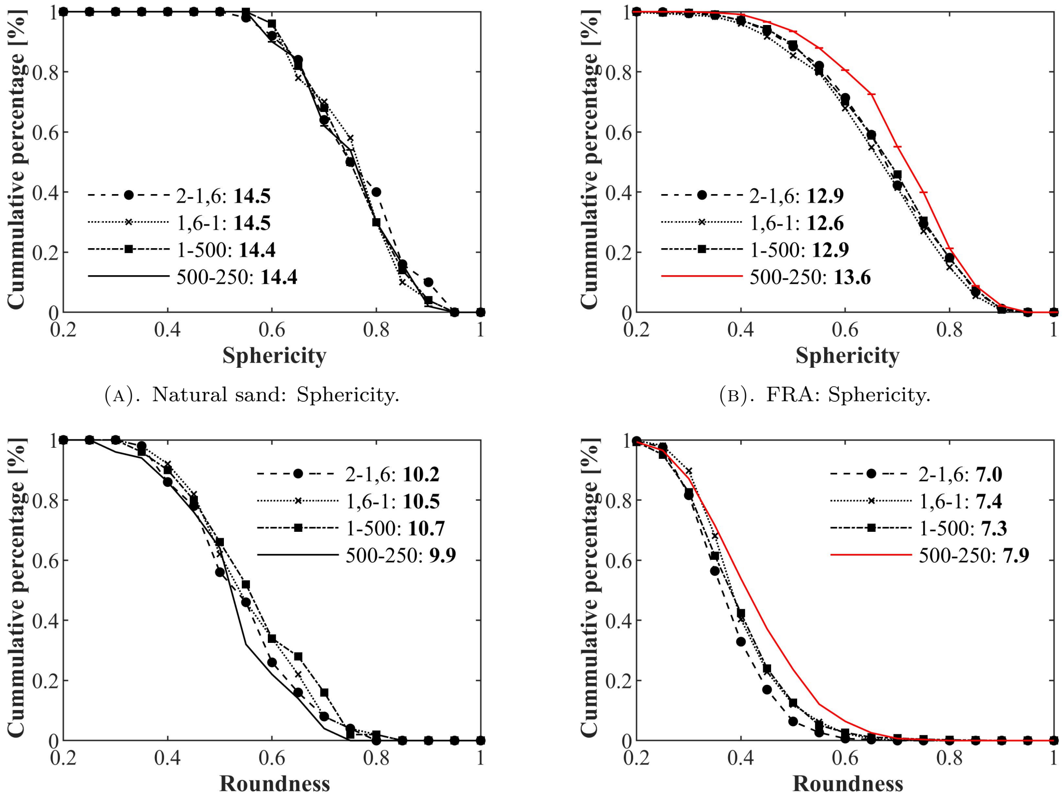
All samples are sieved in 4 different fractions to examine the change in geometrical properties of both the natural sand and FRA's with the fraction sizes. In Figure 4, the sphericity and roundness of the natural sand and all tested FRA's combined are shown. The graphs represent the cumulative percentages of aggregates exceeding a certain sphericity or roundness. In the legenda of the graphs, the sum of the cumulative percentages of each curve is given to further clarify the results. It can be seen from the figures that the sphericity and roundness of the natural sand does not significantly change with the fraction size. However, for FRA's more spherical and rounded particles are found in the fraction 500–250 μm. FRA with fraction 2–1.6 mm show the lowest roundness. It is believed that this phenomenon is caused by a shift in the chemical composition across the different fractions. However, this needs to be verified.

3.2. Type of aggregates

In this work, the geometrical properties of both MFRA and FRCA are tested. 4 samples of FRCA and 3 samples of MFRA are crushed with both an impact crusher and a jaw crusher. In Figure 5a and 5c, the sphericity and roundness of the MFRA and FRCA crushed with an impact crusher are shown (M.I and C.I respectively). In Figure 5b and 5d, the sphericity and roundness of MFRA and FRCA crushed with a jaw crusher are shown (M.J and C.J respectively). It can be seen that, for both the samples crushed with a jaw crusher and an impact crusher, the sphericity and roundness are not affected by the aggregate type. Due to the high force used during crushing both MFRA and FRCA are produced under similar failure patterns. Although, it is found that the sphericity and roundness of the particles are not affected by the aggregate type, it still needs to be verified if this is also the case for the particles surface roughness.

3.3. Crushing method

Earlier research has shown that the crushing method affects the geometrical properties of CRA [11]. In this research, the effect of crushing method on the geometrical properties of both MFRA and FRCA are tested. In Figure 6a and 6c, the sphericity and roundness are shown for FRCA crushed with an impact crusher and a jaw crusher (C.I and C.J respectively). In Figure 6b and 6d, the sphericity and roundness are shown for MFRA crushed with an impact crusher and a jaw crusher (M.I and M.J respectively). From the figures, it can be seen that both the roundness and sphericity of the particles are affected by the crushing method. The impact crusher produces rounder and more spherical particles than the jaw crusher. This was also found for CRA by J. Hubert et al. [11]. It is believed that these differences in the geometrical properties are caused by the breakage patterns that occur within the crusher.



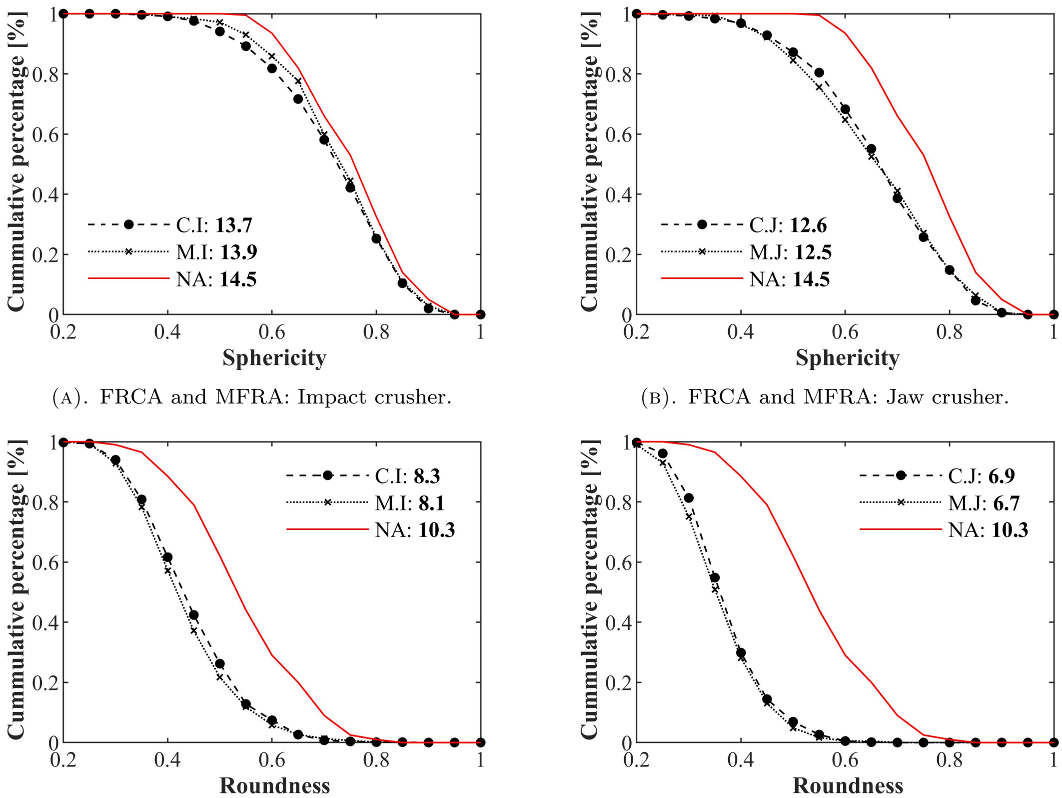
(a). Natural sand: Sphericity.

(b). FRA: Sphericity.

(c). Natural sand: Roundness.

(d). FRA: Roundness.

Figure 4. Geometrical properties of natural sand and FRA of different fractions.



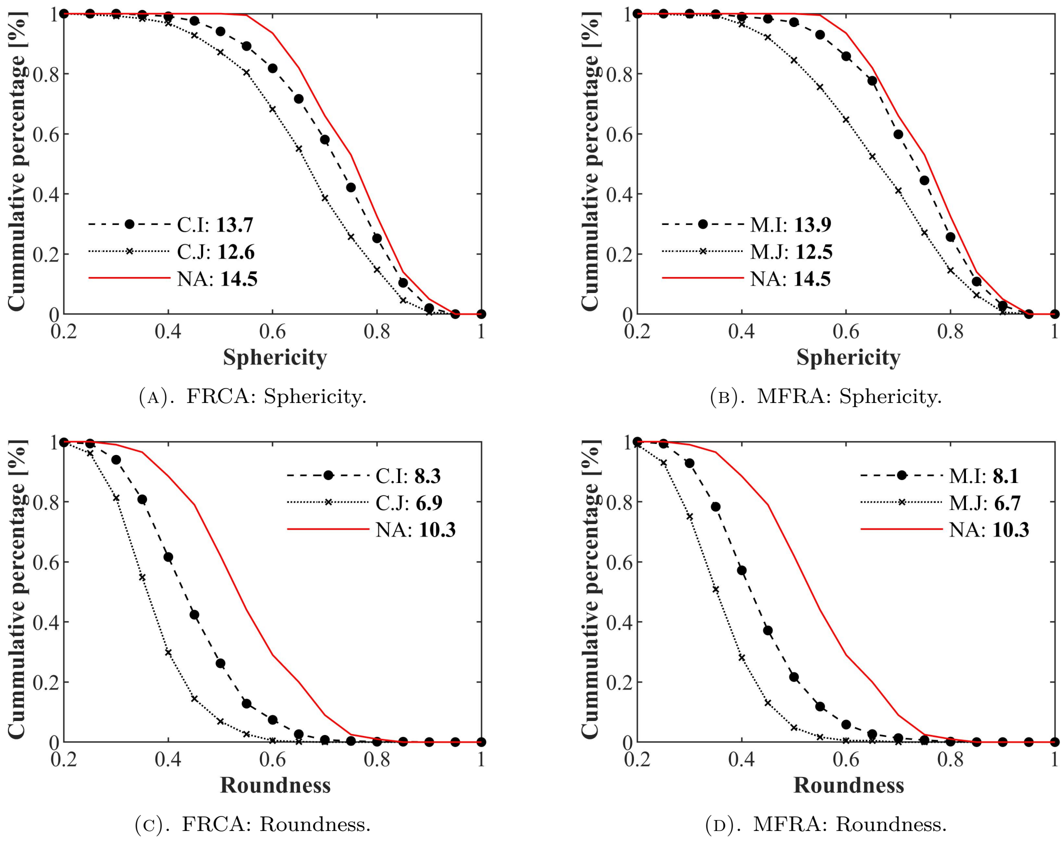
(a). FRCA and MFRA: Impact crusher.

(b). FRCA and MFRA: Jaw crusher.

(c). FRCA and MFRA: Impact crusher.

(d). FRCA and MFRA: Jaw crusher.

Figure 5. Effect of aggregate type on the geometrical properties of FRA's.



(A). FRCA: Sphericity.

(B). MFRA: Sphericity.

(C). FRCA: Roundness.

(D). MFRA: Roundness.

FIGURE 6. Effect of crushing method on geometrical properties of FRCA and MFRA.

3.4. AMOUNT OF CRUSHING CYCLES

During the production process, recycled aggregates are often subjected to several crushing cycles. Therefore, it is examined if the amount of crushing cycles affects the geometrical properties of the FRA's. A sample of FRCA and MFRA was crushed one, two and three times as shown in Figure 7. The sphericity and roundness of the FRCA and MFRA particles are shown in Figure 8.

It can clearly be seen from the figure that for both MFRA and FRCA the geometrical properties are not affected by the amount of crushing cycles. These results are contradictory with the results of CRA since the geometrical properties of CRA are found to be affected by the crusher opening. This can be the result of the breaking processes that occur during the production of the FRA's. CRA is mainly produced under Cleavage failure as shown in Figure 9. This means that CRA will contain mainly elongated particles after an initial crushing cycle. In a second crushing cycle, these elongated particles will mainly break on their short axis, producing more circular particles. After the third breaking process, the sample will again contain more elongated particles due to cleavage failure. However, FRA are not produced under cleavage failure but under compression failure. The geometrical properties of the particles produced under compression failure are not dependent on the number of crushing cycles since the breakage pattern will be similar in each cycle.

3.5. CRUSHER OPENING SIZES

Since different crusher openings are used in practice, this study examined the influence of the crusher opening on the geometrical properties of FRA. A sample of FRCA and MFRA are crushed with crusher openings of 5, 10 and 15 mm. The results are shown in Figure 10. It can be concluded from the results that the sphericity and roundness of the FRA are not affected by the crusher opening. This can be explained by the failure mechanisms of the particles in the crusher. In general, the FRA are produced by compression failure and CRA are produced through cleavage failure. A change in the crusher opening will affect the particles that are produced through cleavage failure i.e. CRA but not the particles produced under compression failure i.e. FRA. Therefore, the crusher opening does not affect the sphericity and roundness of the FRA.

4. CONCLUSIONS

In this research, an extensive analysis is done on the geometrical properties of FRA's. Based on the test results, the main conclusions are:

- The sphericity and roundness of natural sand do not change with fraction. For FRA, fraction 500–250 μm contain more spherical and rounder particles compared to fractions 500 μm–2 mm. FRA particles in fraction 1.6–2 mm show lowest roundness (highest angularity).

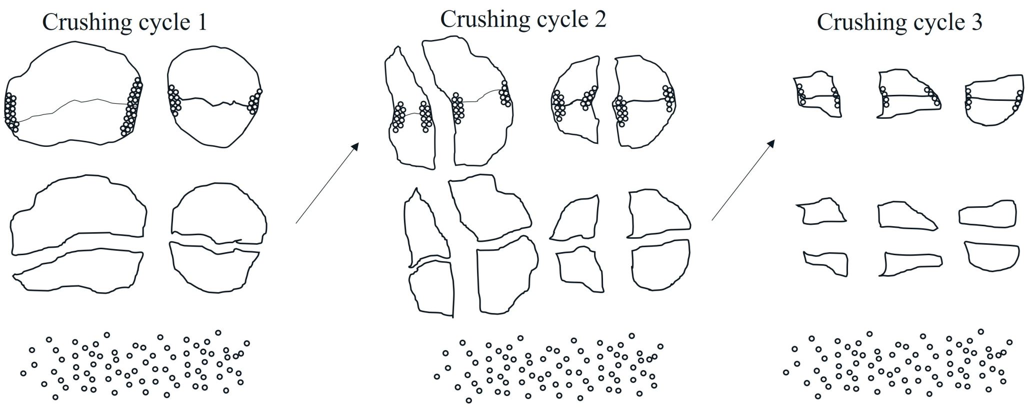
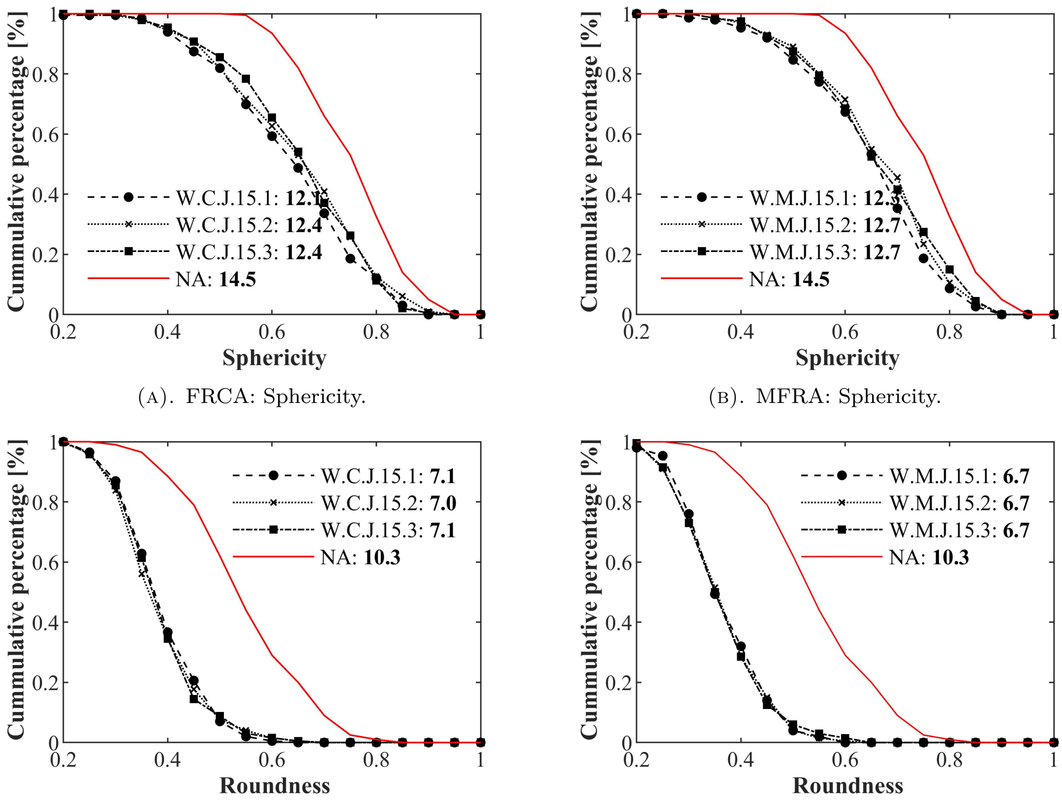


Figure 7. Procedure crushing cycles.



(a). FRCA: Sphericity.

(b). MFRA: Sphericity.

(c). FRCA: Roundness.

(d). MFRA: Roundness.

Figure 8. Effect of crushing cycles on geometrical properties of MFRA and FRCA.

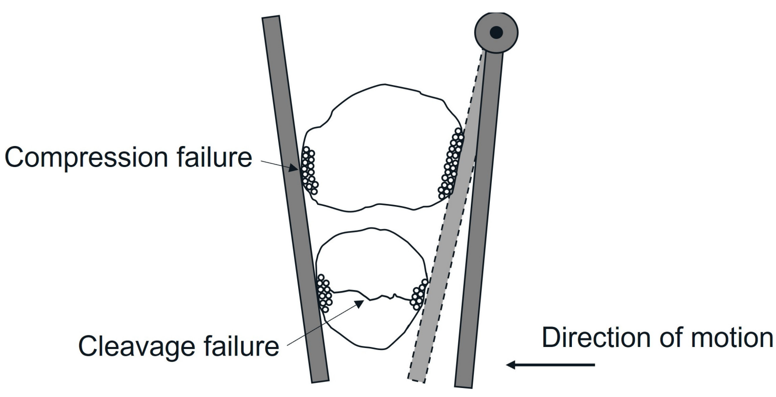
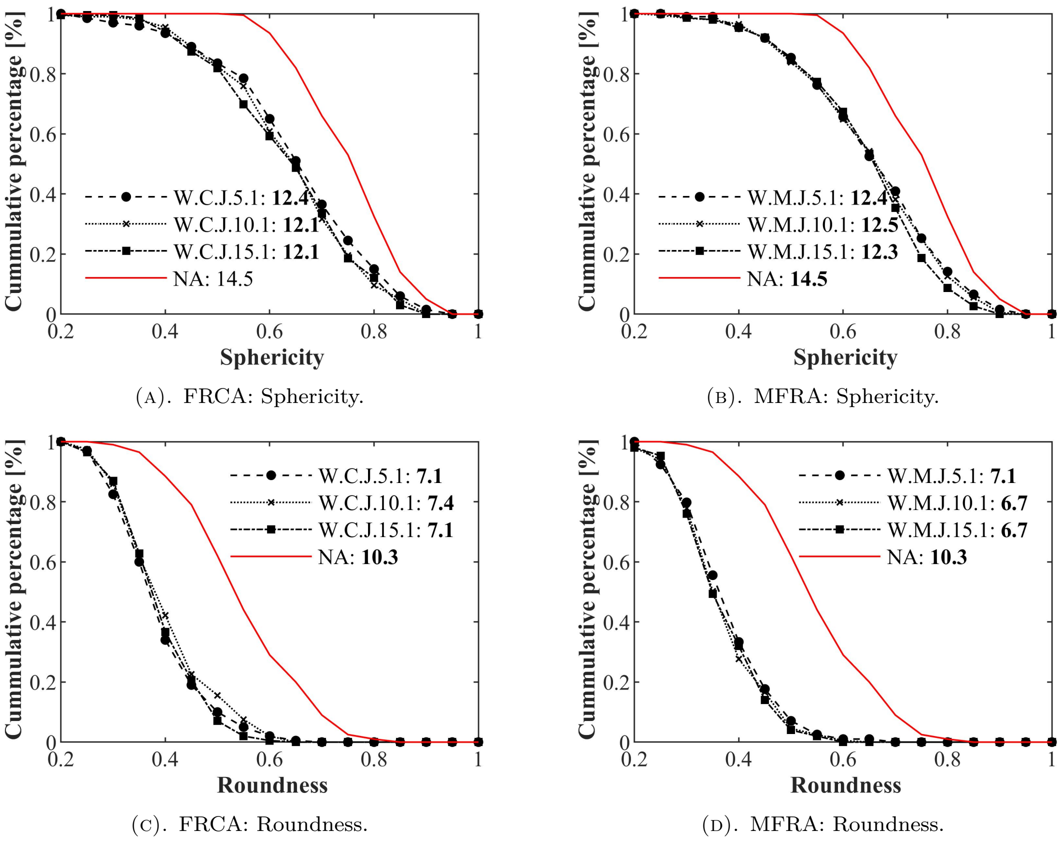


Figure 9. Failure patterns that occur in jaw crusher [12].



(a). FRCA: Sphericity.

(b). MFRA: Sphericity.

(c). FRCA: Roundness.

(d). MFRA: Roundness.

Figure 10. Effect of Crusher opening on geometrical properties of MFRA and FRCA.

- The sphericity and roundness of FRA are not affected by aggregates type. Both MFRA and FRCA showed comparable geometrical properties.
- The sphericity and roundness of the FRA are significantly affected by the crushing method. An impact crusher produces rounder and more spherical particles compared to a jaw crusher.
- The sphericity and roundness of the FRA are not affected by the crusher opening.

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