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Effect of Crushing Method on the Properties of Produced Recycled Concrete Aggregates

Julien Hubert [1], Zengfeng Zhao [2,*], Frédéric Michel [1] and Luc Courard [1]

[1] Urban and Environmental Engineering, University of Liège, Allée de la Découverte 9, 4000 Liège, Belgium; julien.hubert@uliege.be (J.H.); frederic.michel@uliege.be (F.M.); luc.courard@uliege.be (L.C.)

[2] Department of Structural Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

* Correspondence: zengfengzhao@tongji.edu.cn

Abstract: Construction and Demolition Waste (C&DW) is generated around the world and its quantity will increase in the future. Recycling has become the favored method of dealing with concrete waste but, to avoid its downcycling, it is important to develop a recycling process which is able to produce high-grade recycled concrete aggregates (RCA). To that end, studying the influence of the production process on the properties of RCA can prove to be a crucial step toward a more circular construction industry. In this study, the influence of the crushing method is investigated. Samples of five laboratory-made concretes have been crushed using the most common mechanical crushing methods (impact crusher and jaw crusher), and the particle size distribution, morphology, hardened cement paste content and water absorption of the produced RCA have been measured and analyzed. The findings indicate that the use of impact crushers results in the production of RCA possessing more spherical geometric characteristics, albeit with a broader particle size distribution and a relatively higher content of fine particles as compared to those obtained from jaw crushers. Additionally, it is observed that the employed crushing technique seemingly exerts no discernible impact on the hardened cement paste content and the water absorption in the context of the studied concretes.

Keywords: construction and demolition waste; recycling; crushing; recycled concrete aggregates; morphology; water absorption

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1. Introduction

The ongoing expansion and replacement of existing real estate leads to the production of important amount of Construction and Demolition Wastes (C&DW). The construction industry is responsible for one of the heaviest and most voluminous waste streams in the EU [1]. It accounts for at least one third of the waste generated in the EU and represents an amount of about 850 Mt (Mt: Megaton). The most widely used building material is concrete with a global production increasing by as much as 25 Gt (Gt: Gigaton) per year [2,3] which means that most of the C&DW are composed of concrete. Due to environmental and economic pressure, recycling has become an increasingly popular method of disposing of C&DW that can provide a sustainable source of aggregates for future concrete production [4–6].

Recycling C&DW starts with the selective demotion of a building to separate the different waste materials [7,8] after which it is transferred to the recycling plant. C&DW recycling plants bear a resemblance to natural aggregate production facilities, as they employ a range of equipment such as crushers, screens, transfer devices and filtering systems to produce granular materials of a predetermined grain size distribution. The degree of processing of the C&DW depends on their intended future application [9]. The recycling plants can be divided into mobile or stationary styles. Considering fixed recycling plants [10,11], the recycling process starts with the reception and storage of the materials to be treated. It is followed by a scalping step where the materials are screened to separate fine particles and soil before crushing. Next, the material is crushed (primary and occasionally secondary crushing), then it goes on a conveyor band equipped with an electromagnet to remove any metallic elements (such as rebars), and through a manual or automatic extraction of impurities. Finally, it is screened for the different desired particle sizes.

The preparation phase is particularly important, specifically for large reinforced concrete elements, as it may impact crushing and purification systems. It is also used to reduce waste dimensions before crushing. The produced aggregates are mainly used in less demanding applications such as bulk fill, fill in drainage, primary foundations, embankments and levelling work [9,12–14] which leads to concrete "down cycling".

A very low percentage of recycled concrete aggregates (RCA) are used for the production of new concrete products because typical state-of-the-art recycling plants usually yield "lower-grade" RCA, presenting a lower density, higher water absorption [15–19], lower resistance to abrasion and higher sulfate content compared to the natural aggregates (NA) [20–27]. These properties of RCA, including its fine content and shape [28–31], have been shown to have a negative impact on the workability, strength and durability of recycled concrete prepared using RCA [32–37]. The lower quality of RCA is attributed to their composition which comprises a mixture of NA and adherent hardened cement paste [38–44]. Some scholars have experimentally studied the mechanical properties of recycled concrete slabs and pointed out the feasible use of recycled concrete in practical engineering applications [20,23–25], whereas the properties of RCA were good enough (this could be improved by updating the crushing procedure).

Given that the recycling of C&DW has become one of the most important topics in concrete research, and because of the correlation between mortar content and RCA properties, many research works have been conducted to identify the factors responsible for the adherent hardened cement paste content. It is mostly influenced by the properties of the parent concrete, the crushing procedure and the final particle size of the RCA produced [45–49].

Weaker parent concrete has usually been linked to RCA with better densities and thus less adherent hardened paste [50–52], which is due to the mortar in the weaker parent concrete being more easily removed during the crushing process. De Juan and Gutteriez [38] did not directly observe a relation between parent concrete strength and mortar content (they used RCA of unknown origin), but they reported a proportional relationship between mortar content and Los Angeles abrasion resistance, and between Los Angeles resistance and parent concrete compressive strength. It could then be expected that a similar relationship exists between mortar content and parent concrete strength. Grubl and Ruhl [53] have reported, however, that the compressive strength of the original concrete had little to no influence on the cement paste content and that it was only controlled by the crushing procedure. The maximum size of the NA in the parent concrete also affects the properties of RCA. Padmini et al. [51] reported that the water absorption of RCA (closely related to the adherent hardened cement paste content) decreases with increasing NA maximum size.

The effect of the RCA particle size is abundantly present in the literature. Ghorbani et al. [54] have shown that the compressive strength and tensile strength, as well as the workability of concrete made with RCA, all decreased as coarser aggregates were used. In terms of cement paste content, most have reported an increase in adherent hardened cement paste content with decreasing granular fraction. Exteberria et al. [46] have reported that the quantity of adherent mortar increases with a decreasing granular fraction. They observed a variation from 20% to 40% (in mass) in the amount of attached mortar for the granular fractions 10/25 mm and 4/10 mm, respectively. Hansen [55] reported values of attached mortar of up to 60% (in mass) for 4/8 mm coarse RCA and up to 65% for the 0/0.3 mm filler fraction. More recently, Zhao et al. [56] showed variation in hardened cement paste content from 10% to 17% for the granular fractions 14/20 mm and 0/2 mm, respectively. But some authors have also reported contradictory results with mortar content increasing as the grain sizes increased [57].

It was found that most studies on RCA either do not refer to the crushing process at all or only consider the number of crushing steps. Indeed, several authors have indicated that increasing the crushing times results in a reduction in the content of adherent hardened cement paste [38,45,58–62]. However, few results are available related to the influence of the crushing method itself in the literature. This study endeavors to fill this gap. It will clarify the impact of the crushing method on the properties of the produced RCA scientifically, which could play the role of guiding production for the recycling plant. The goal of this research is thus to evaluate the effect of the crushing method on the properties of RCA. Samples of five laboratory-made concretes have been crushed using the most common mechanical crushing methods (impact crusher and jaw crusher). The particle size distribution, morphology, hardened cement paste content and water absorption of the produced RCA have been measured and analyzed.

2. Experimental Program

2.1. Materials Used for the Production of Concrete

In this study, five different compositions of laboratory-made concrete have been crushed using a jaw crusher and an impact crusher at the semi-industrial level. Many studies have demonstrated the correlation between the compressive strength of the original concrete and the quantity of the adherent cement paste [38,50,51]. A different aspect of the parent concrete has thus been chosen for study: its composition. All five compositions are in the same compressive strength range; this study chooses to modify the cement quantity, the type of cement, the nature of the aggregates and the water-to-cement (W/C) ratio selected to investigate the influence of these key parameters on the crushability of concrete and on the properties of the RCA produced. A total of 120 L of each concrete mix was cast and prepared for the production of RCA. In accordance with EN 206 [63], cubes (150 × 150 × 150 mm) were produced and stored in a room with a temperature of 20 ± 2 °C and relative humidity of 90 ± 5% for 90 days before being crushed. The reference concrete was designed using limestone aggregates (2/7, 7/14, and 14/20 mm) and calcareous sand (0/4 mm). The CEM III 52.5 cement based on slag was used for the production of concrete "C2-CEM III" (since slag-blended cement is very often used in the production of cement on the market and the same grade of 52.5 has to be used in this study; thus, CEM III 52.5 was chosen for investigation in this study). CEM I 52.5 produced in the CBR company wasused for the other four types of concrete. The relative proportion between each mix was established according to the standard EN 480-1 [64]. This approach led to the following design for the reference concrete: 35%, 20%, 20% and 25% by mass for the sand 0/4 mm, NA 2/7 mm, 7/14 mm and 14/20 mm, respectively. The quantities of each constituent (expressed in kg/m^3) are given in Table 1. The other concretes only differ from the reference concrete by one parameter. Note that since the sandstone aggregates used present a very close grain size distribution to the limestone aggregates used, the same relative proportions of each constituent have been used. Mixtures with a low cement quantity and low W/C ratio required a superplasticizer to reach the desired slump class (S3/S4). The experimental grain size distribution curve is fitted as much as possible on a theoretical curve linking the mean values defined in the standard EN 480-1 [64]. Concerning the mixing procedure used in the production of concrete, the air-dried coarse aggregates and natural sand were firstly introduced in the mix, and then half of the total water was added and mixed for 1 min. The water compensation was adjusted according to the water content and water absorption of natural sand and coarse aggregates during concrete batching. The other half of the total water was added after the introduction of the cement. In the case of using the superplasticizer, additional mixing of 1 min was carried out to reach the desired slump.

Table 1. Compositions of concrete made in the laboratory.

Name of Concrete	C1-Reference	C2-CEM III	C3-Sandstone	C4-Low Cement	C5-Low W/C
Type of aggregate	Limestone	Limestone	Sandstone	Limestone	Limestone
NA 2/7 mm (kg/m^3)	368.8	368.8	368.8	405.1	367.1
NA 7/14 mm (kg/m^3)	345	345	345	379	343.4
NA 14/20 mm (kg/m^3)	433.5	433.5	433.5	476.2	431.5
Sand 0/4 mm (kg/m^3)	604.9	604.9	604.9	664.4	602.1
Type of cement	CEM I 52.5	CEM III 52.5	CEM I 52.5	CEM I 52.5	CEM I 52.5
Cement quantity (kg/m^3)	400	400	400	320	452
Cement paste volume (dm^3/m^3)	351	358	351	282	351
Efficient water (kg)	224.2	224.2	224.2	180.6	207.1
W/C ratio	0.56	0.56	0.56	0.56	0.46
Superplasticizer (g/kg cement)	0	0	0	6.8	3.3

2.2. Concrete Characteristics

Concretes have been characterized in fresh and hardened states: fresh concrete slump (NBN EN 12350–2 [65]), density (NBN EN 12350-6 [66]) and compressive strengths (NBN EN 12390-3 [67]) were measured. Table 2 shows the properties of the produced concrete.

Table 2. Properties of the produced concrete.

Properties	C1-Reference	C2-CEM III	C3-Sandstone	C4-Low Cement	C5-Low W/C
Slump (mm)	155	176	182	135	146
Slump class	S4	S4	S4	S3	S3
Density (g/cm^3)	2.35	2.31	2.31	2.36	2.31
Compressive strength (MPa) (mean and standard deviation)	56.0 (±2.4)	61.6 (±0.7)	52.7 (±2.5)	56.0 (±6.4)	66.9 (±0.7)

2.3. RCA Production

The crushing mechanism directly impacts the properties of RCA such as grain size distribution, fine content and shape, as well as the adherent hardened cement paste content. Mechanical crushing can be performed with different types of crushers according to a survey conducted in the SeRaMCo project [11]; the most used equipment for C&DW recycling are the impact, jaw and cone crushers. This choice is mainly influenced by acquisition and maintenance costs and does not consider the properties of the end product [68].

Crushing was performed using semi-industrial crushers owned by the CTP (Centre Terre et Pierre asbl) in Tournai (Belgium). Approximately 240 kg of each mix was crushed using the two primary crushers: the impact crusher and the jaw crusher.

A jaw crusher consists of two plates fixed at an angle. One plate remains stationary while the other oscillates back and forth, crushing the material in between. The particle size reduction depends on the maximum and minimum size of the gap between the plates. In an impact crusher, materials fall onto the rotor and are caught by blow bars, which throw them against the impact plates (smashing them into smaller particles).

The crusher's parameters were defined to produce aggregates with a diameter between 0 and 25 mm. For this reason, the jaw spacing was fixed at 22 mm for the jaw crusher. The produced aggregates were sieved at 4/6.3/8/12.5/20/25 mm.

2.4. Characterization of RCA

The particle size distribution was obtained following the European standard method EN 933-1 [69].

The flakiness index was measured on the RCA produced according to the European standard method EN 933-3 [70]. The shape index was also measured on the RCA according to the standard EN 933-4 [71].

There is no standard method to measure the attached mortar content in RCA. In the literature, the following methods are presented:

- The first method consists of a thermal treatment [38]. It is based on several cycles where the aggregates are soaked in water then heated to 300 °C progressively to detach adherent mortar from the surface of NA. This is due to the micro-cracking presented at the interface between aggregates and mortar because of their different thermal dilation coefficients. This method is only suitable for coarse RCA, since mortal removal needs "brushing" of the RCA which is difficult with fine RCA.
- The second method [61,72] involves the dissolution of cement paste in a hydrochloric acid solution. Regrettably, it cannot be utilized when working with limestone aggregates and fillers, as they are susceptible to be dissolved when exposed to hydrochloric acid.
- The third method uses image analysis [61,73] to quantify the amount of residual mortar on a flat polished section, which is efficient with coarse RCA, but the distinction between fine aggregates and cement paste is difficult. Moreover, a statistical approach is needed and it is time-consuming to obtain the reliable results.
- The last method had been developed by Zhao [44] and is based on the dissolution of cement paste in a solution of salicylic acid. This method has been shown not to dissolve calcareous aggregates.

This latter method has been chosen to measure the adherent hardened cement paste content (HCPC) because it is easy to perform and can be applied to RCA obtained by crushing concrete containing natural limestone aggregates. The sample is dried at 105 °C and then ground until it is smaller than 0.2 mm. A small quantity of this dried sample is then immersed into a solution of salicylic acid and methanol and stirred for an hour. The solid fraction is filtered using a glass filter and washed (at least four times) using methanol. The solid residue is then dried at 70 °C for 30 min and weighed. The hardened cement paste content is obtained through:

$$HCPC = \frac{(M_a - M_b)}{M_a} \times 100 \quad (1)$$

where M_a and M_b are the mass of the dried material before dissolution and the mass of the dried filtrate, respectively.

The water absorption of each granular class of RCA has been determined according to the European standard method EN 1097-6 [74], while the details have been also presented in Zhao et al. [44].

3. Results and Discussion

3.1. Particle Size Distribution

Figure 1 shows the variation in the particle size distribution of the RCA produced with the jaw crusher and the impact crusher. It can be seen that the impact crusher curves stop before reaching 100%. The goal of the crushing process was to produce aggregates with a grain size distribution between 4 mm and 25 mm, and this highlights the fact that the impact crusher produces around 30% of aggregates outside the desired range. It also produces more fine particles than the jaw crusher because it crushes mortar and aggregate particles alike; in contrast, a jaw crusher only breaks a small proportion of the original aggregate, thus generating almost half the amount of fine particles for the same maximum size of particle [10,75,76]. These points are in clear favor of the jaw crusher, which is more efficient in terms of material use and produces fewer fine particles which have a high water absorption. Based on these results, we can conclude that the composition (for the formulations considered) has little to no impact on the particle size distribution of RCA.

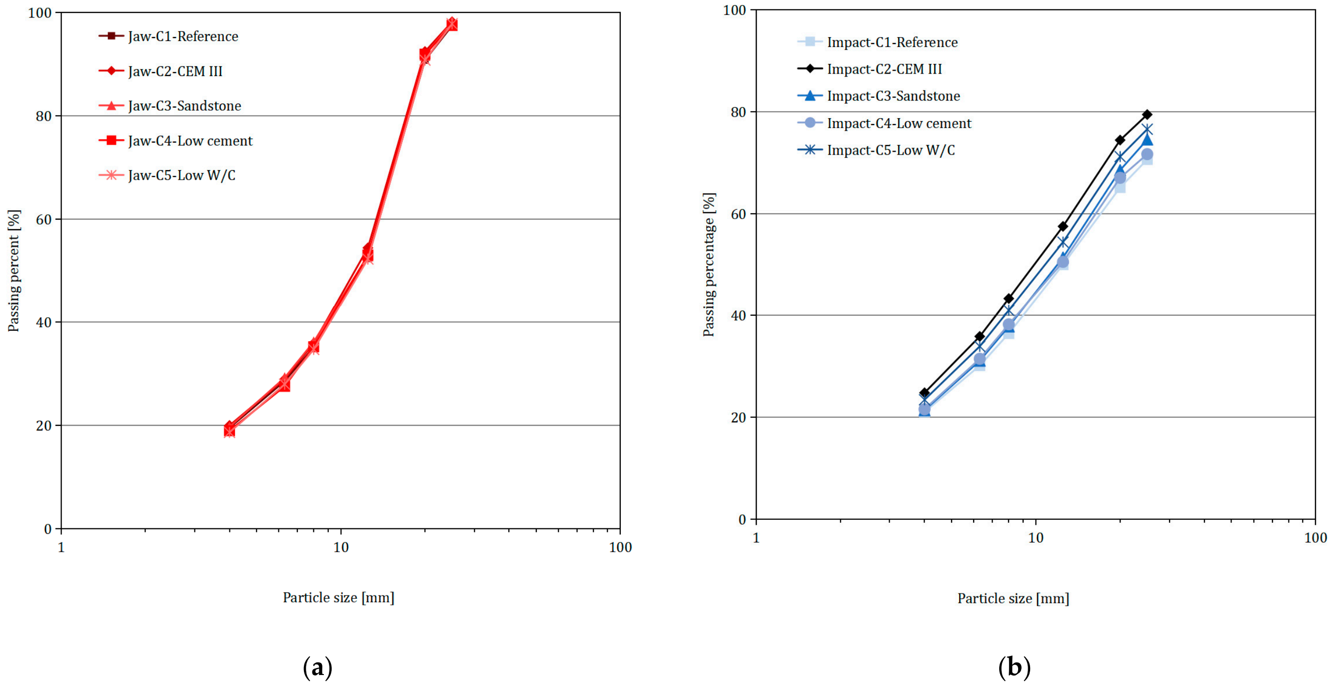

Figure 1. Particle size distribution for all the considered concrete mix processed with a jaw crusher (**a**) and an impact crusher (**b**).

3.2. Morphology

Figure 2 shows the flakiness index increasing with decreasing granular fraction for both crusher types. A smaller value of the flakiness index denotes less elongated ("more cubic") aggregates. The jaw crusher also produces flakier aggregates than the impact crusher. This can be explained by the breakage mechanism involved [11,22]. Composition does not seem to have any significant impact on the flakiness index, since the curves for the different compositions cross each other. It is worth noting that the jaw crusher curves all present a minimum value of the flakiness index for the 16/20 mm granular fraction, which can be explained by the fact that the maximum grain size of the NA used to produce the parent concrete is 20 mm. This means that recycled aggregates of nearly 20 mm in diameter are mostly composed of unbroken NA surrounded by a little cement paste. A similar observation was made by Florea [59], who found a maximum value of RCA densities around 8 mm which corresponds to the D_{max} of the gravel used for the initial concrete. This led them to the same interpretation that RCA with a granular fraction above the D_{max} of the parent concrete most likely contains a larger amount of cement paste than those around the D_{max}. This trend cannot be observed for the impact crusher because of the breakage mechanism. Indeed, impact crushers, contrary to jaw crushers, crush mortar and aggregates alike [76].

The global flakiness index varies from 11% to 14% for the jaw crusher and from 6% to 8% for the impact crusher (Table 3), which is calculated by the percentage of granular fraction and each flakiness index. These values are lower than the maximum value defined in the national standards related to aggregates used for concrete production in a series of North West European countries (maximum overall flakiness index: Belgium, 20%; France and Luxembourg, 35%; Germany, 50%, i.e., varying from 20% to 50% depending on the country).

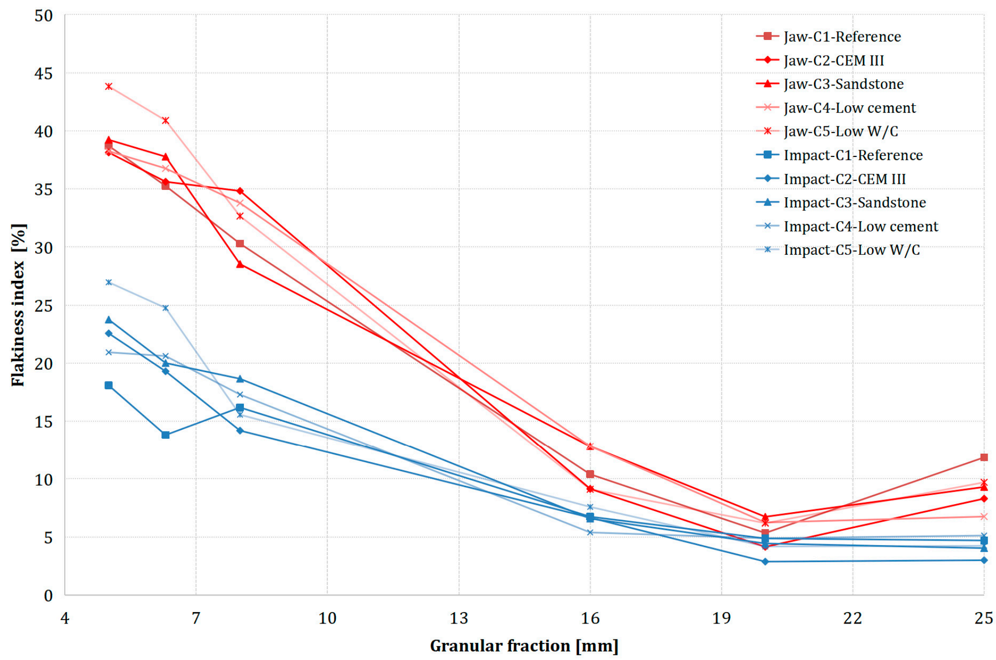

Figure 2. Flakiness index of RCA crushed by jaw and impact crushers.

Table 3. Global flakiness index for the concrete mix crushed by impact and jaw crushers (as a percentage).

	C1-Reference	C2-CEM III	C3-Sandstone	C4-Low Cement	C5-Low W/C
Jaw crusher	14	11	13	11	12
Impact crusher	8	6	6	7	7

The same trend was observed as for the shape index (Figure 3). The shape index increases with decreasing granular fraction (as for the flakiness index, a smaller value of the shape index denotes a more "spherical" aggregate). Once again, the jaw crusher produces more elongated aggregates and the concrete mix does not seem to have any influence for the range investigated. The measured global shape index varies from 34% to 46% for the jaw crusher and from 11% to 18% for the impact crusher.

3.3. Hardened Cement Paste Content

Figure 4 presents the hardened cement paste content (HCPC) for the different granular fractions for the RCA obtained from the reference composition. This shows that a larger granular fraction of RCA presents a lower hardened cement paste content; the HCPC values of RCA obtained in this study are similar to the results given in previous research works [44,56]. This is well correlated with the results obtained on flakiness and shape indexes' variation. Similar trends have also been described by many authors [22,46,55,56].

Based on Figure 4, the HCPC values of RCA obtained by the jaw crusher and impact crusher are similar for each granular fraction (except for the granular fraction 16/20 mm). It can be concluded that the crushing method (whether the jaw crusher or impact crusher) has no clear influence on the hardened cement paste content.

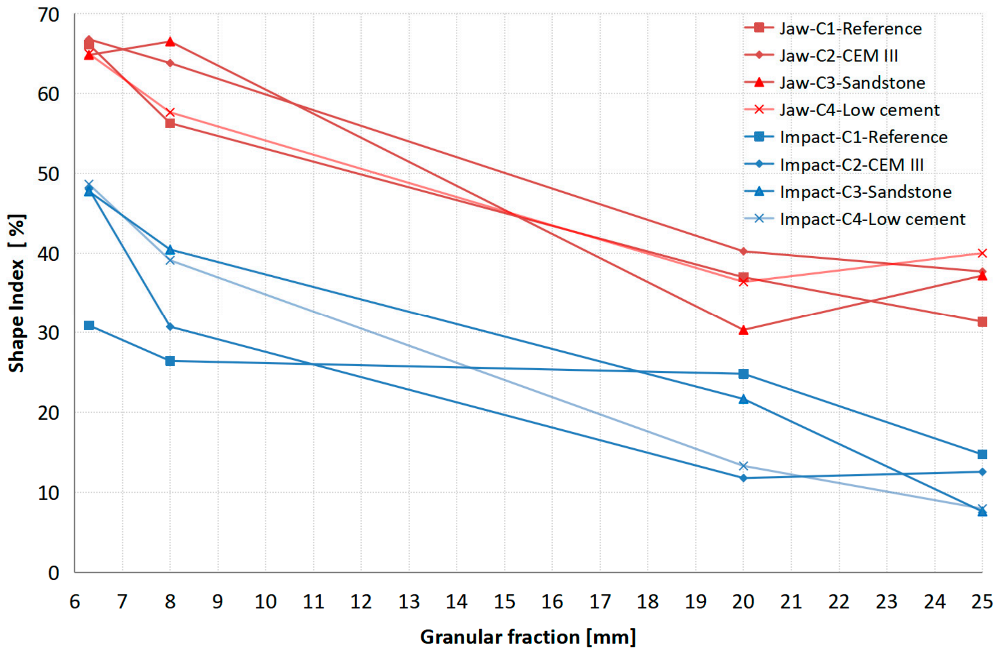

Figure 3. Shape index of RCA crushed by jaw and impact crushers.

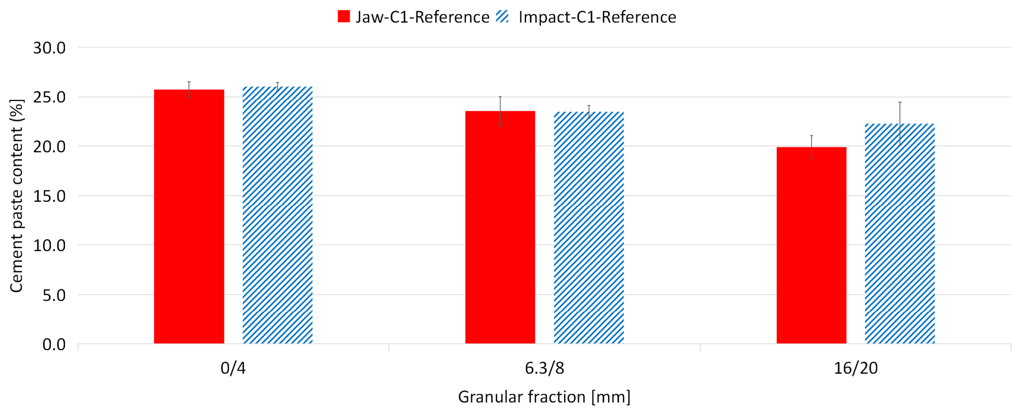

Figure 4. Hardened cement paste content for the RCA obtained from the reference concrete mix.

3.4. Water Absorption

Figure 5 shows the variation in water absorption of the RCA produced by the jaw crusher for all of the considered compositions. These results are concordant with the trend observed for the cement paste content. The larger the granular fraction, the lower the water absorption, which is logical given the lower cement paste content. The water absorption of the fraction 0/4 mm presents the highest values (ranging between 8.6% and 12.5% for all five studied compositions), which is consistent with the water absorption of RCA presented in other studies [17,30,38,44]. In addition, the difference in the water absorption values obtained in the fractions 6.3/8, 12.5/20 and 20/25 mm is less than that of the fraction 0/4 mm, which is also confirmed in the previous work [56]. Another trend visible in Figure 5 is the slight increase in water absorption for the granular fraction 20/25 mm when compared to the granular fraction 12.5/20 mm, which validates our previous hypothesis that RCA of a granular size close to the D_{max} of the parent concrete is mostly composed of NA.

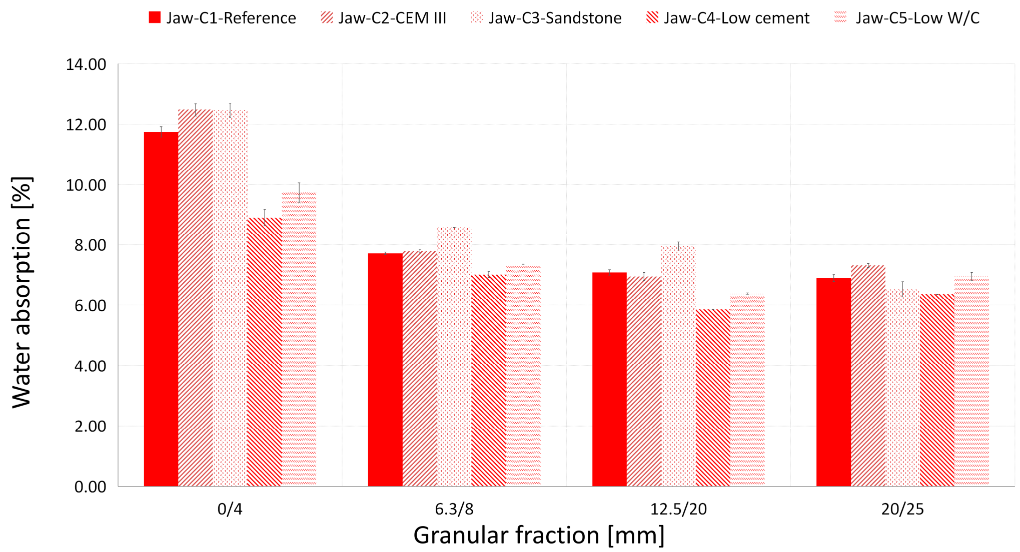

Figure 5. Water absorption for the RCA produced with the jaw crusher.

It is worth noting that, the results obtained for the series of the reference, CEM III and sandstone are very similar. Conversely, the water absorption obtained with all of the granular fractions of RCA produced from the concrete "C4-Low cement" are significantly lower than other RCAs, which can be linked to a low cement content used in the parent concrete, which results in a lower porosity of the hardened cement paste. The lower values obtained for the RCA produced from concrete "C5-Low W/C" can be attributed to the lower W/C ratio of the cement paste in the parent concrete. Both compositions (low cement composition and low W/C composition) produce a lower porosity of the cement paste presented in the parent concrete, leading to the lower absorption of the RCA [27,38,44]. The same trends are observed in Figure 6 for the results obtained by the impact crusher.

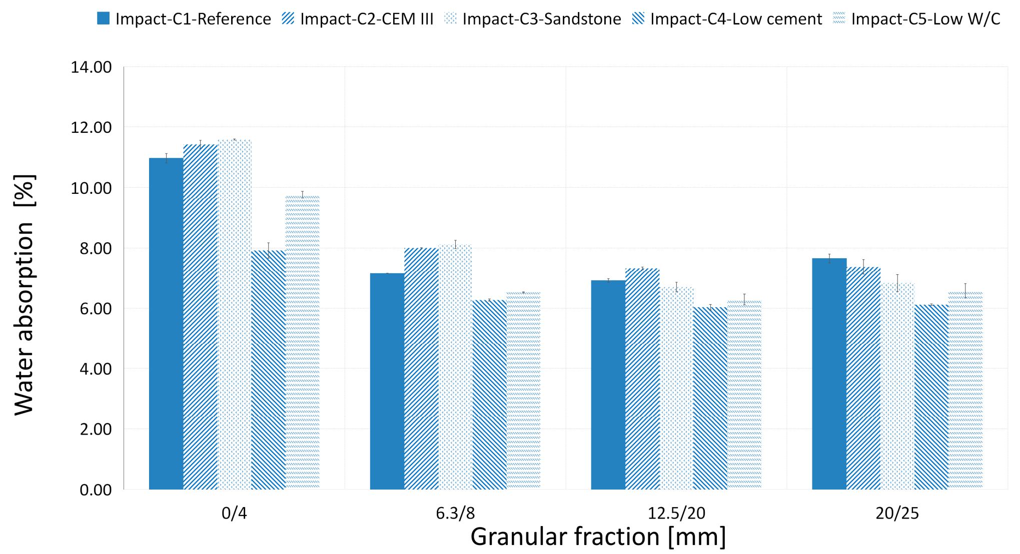

Figure 6. Water absorption for RCA produced with the impact crusher.

Figure 7 shows the water absorption of the RCA obtained from the reference composition. As can be seen in this figure, there is no clear influence of the crushing methods on the water absorption, as was the case with the hardened cement paste content. Based on these results, we can conclude that the composition (for the formulations considered) has little to no impact on the water absorption or cement paste content of RCA.

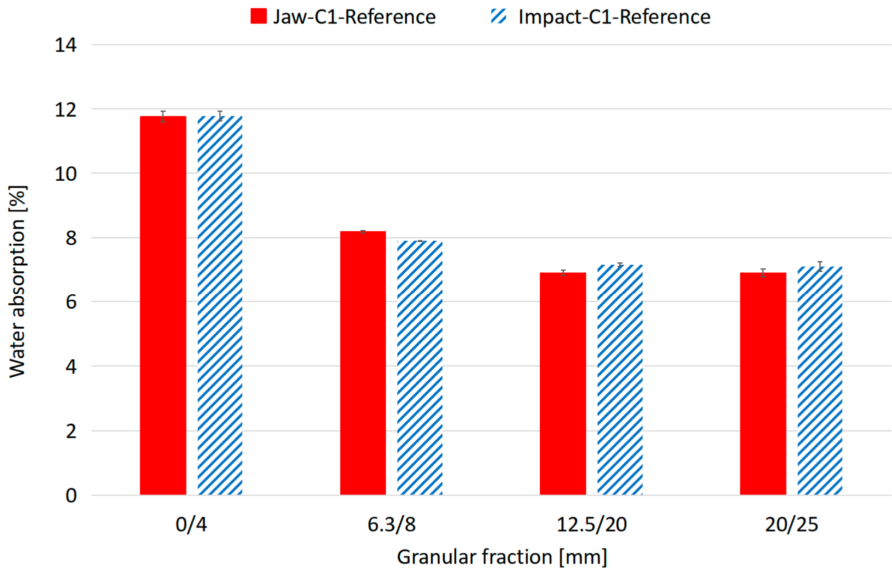

Figure 7. Water absorption for the RCA obtained from the reference concrete by different crushers.

Based on the above discussion, the findings indicate that the use of impact crushers results in the production of RCA possessing more spherical geometric characteristics, albeit with a broader particle size distribution and a relatively higher content of fine particles as compared to those obtained from jaw crushers. Additionally, it is observed that the employed crushing technique seemingly exerts no discernible impact on the hardened cement paste content or the water absorption in the context of the studied concretes.

4. Conclusions

In this study, the impact of the crushing method was investigated. The RCAs obtained by the mechanical crushing of five laboratory-made concretes were characterized. The effect of the parent concrete mix on the properties of the RCA was also investigated. The main conclusions can be drawn as follows:

(a) The impact crusher results in the production of aggregates possessing more spherical geometric characteristics, a broader spectrum of grain sizes and a relatively higher content of fine particles as compared to those obtained from the jaw crusher. In addition, the crushing method exerts no discernible impact on the hardened cement paste content and the water absorption in the context of the studied concretes. The W/C ratio in the range from 0.46 to 0.56, as well as the type of NA in the parent concrete, do not seem to have any influence on the properties of the produced RCA.
(b) The flakiness and shape indexes decrease with the increase in the granular fraction. The larger granular fractions have a lower residual hardened cement paste content and water absorption than the smaller fractions, which indicates that larger fractions of RCA are mostly composed of NA with a bit of adherent mortar.
(c) In the case of using a jaw crusher to produce RCA, the water absorption and morphology indicators of RCA show their minimum values when the granular fraction is close to the maximum diameter of the NA in the parent concrete. This correlation indicates that the breakage mechanism of the jaw crusher does not affect the RCA in a similar manner to the impact crusher.

This study presents the impact of the crushing method on the properties of produced RCA scientifically, which could play the role of guiding production for the recycling plant. Further investigations using more sophisticated morphology measurement techniques (such as laser optical measurements) could potentially discriminate the crushing operating system more appropriately. A wider range of variation in the concrete mix could also affect the the produced RCA, which needs to be investigated in the future. In addition, the properties of concrete based on the RCA produced by different crushers are worth future study.

Author Contributions: J.H.: conceptualization, methodology, writing—original draft preparation, data curation; Z.Z.: writing—review and editing, formal analysis, funding acquisition, validation; F.M.: investigation, visualization, formal analysis; L.C.: writing—review and editing, validation, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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