



## Original Article

# Concrete aggregates properties crushed by jaw and impact secondary crushing

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## ABSTRACT

This paper compares the use of jaw and impact secondary crushing for producing coarse recycled aggregates from concrete wastes, obtained from road pavement and demolished building materials. The crushing mechanism interferes directly with recycled aggregate properties at different levels: particle size distribution, aggregate shape, generation of micro-fractures, as well as regarding the detachment of porous hardened cement paste from particle surface in order to recover pure, non-porous natural aggregates. However, crusher selection in the recycling industry is mostly carried out by acquisition and maintenance costs, industry and manufacturer traditional habits, low cost associated with second hand equipment. It also does not consider essential parameters such as the final properties of the desired end-product. Representative samples from two recycling plants were collected after primary impact crusher and secondary crushing were performed in a controlled laboratory condition through jaw and impact crushers. The aggregates attained were characterized, demonstrating similar density, porosity, particle size distribution and content of attached cement paste. Minor observed differences do not justify the common belief in the industry that impact crushers provide an improvement in the quality of recycled aggregates due to the higher detachment of cement paste from aggregates.

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## 1. Introduction

Construction and demolition waste (CDW) is mainly composed of cement-based materials such as concrete and mortar, but often includes other materials. This waste is abundant since concrete is the second most consumed material in all of

society after water according to the World Business Council for Sustainable Development (Report: The Cement Sustainability Initiative, 2009) [1].

Although concrete has the most homogeneous physical properties and the lowest porous inorganic phase in CDW, recycled concrete aggregates (RCA) are more porous, also having lower density and strength when compared to natural

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aggregates, which limit its use as a construction material. While aggregate material used for road bases is widely available, the demand for concrete is currently rising, ultimately emphasizing the importance of substituting natural aggregates for RCA in concrete.

The removal of hardened cement paste attached to recycled aggregates is paramount to enhance the use of RCA in high-strength concrete [2,3]. In typical concrete, cement paste corresponds to less than 30% of its overall mass, the remaining portion being composed of rock forming minerals, mostly quartz and feldspar with a very restricted number of pores. Many mineral processing operations are feasible in recycling processes to achieve the desired content of cement paste in recycled aggregates, ultimately leading toward higher mass recovery rates of up to 70% [4].

Mineral dressing operations can split different material phases in a composite material, including concrete. In this process, it is important to identify phase-specific features to select the most appropriate segregation principles. Thus far, the literature has mostly focused on density separation methods using jigging or air separation, ultimately removing organic materials from CDW. Previous studies evaluating mineral phase segregation indicate different methods for effectively decreasing cement paste content and red ceramic particles in recycled aggregates [4].

In order to remove adhered cement paste from recycled aggregates using mineral dressing operations, two steps are required: liberation and separation. Liberation occurs when dissimilar phases, such as hardened cement paste and natural aggregates, are detached from each other. This segregation is not feasible if a certain degree of particle release has not been previously achieved [5]. Crushing is the first necessary step in the release of usable materials from concrete waste, including gravel, crushed aggregates and sand. In addition, aggregates can be recovered and segregated through subsequent separation and sorting steps starting from the cement paste. The main goal of the liberation comminution concept is to achieve a split across grain boundaries [6].

This paper focuses on comparing crushing systems aiming to reduce the content of cement paste and porosity. A different approach was proposed in the literature for using recycled aggregates with low removal rate of the cement paste at low costs processing technologies for applications at lower mechanical demands [7].

Fig. 1 demonstrates the effect of comminution achieved between attached phases when there is no release across grain boundaries. Specifically, Fig. 1a refers to a particle from a recycled concrete aggregate, while Fig. 1b demonstrates the effect of a coarse comminution on a phase liberation, and Fig. 1c presents the same effect on a finer comminution. This sequence demonstrates that as the recycled aggregate achieves progressive comminution and reduction of particle size, more phases involving mortar matrix or aggregates are detached. For example, Fig. 1b has a greater volume of composite particles than that in Fig. 1c. This detachment promoted by comminution aims at establishing the coarsest comminution possible. A split across the interface is therefore favorable. The liberation process by comminution is well known and daily applicable to the mineral industry; in concrete, it was primarily applied some years ago by German researchers [8].

The effect of crushing on the detachment of hardened cement paste from natural aggregates is associated with a reduction in aggregate water absorption and an increase in its envelop density [9].

From mineral processing knowledge, the finer the comminution, the higher the phase liberation and the purer the aggregates. Specifically, fragile porous hardened cement paste tends to break down into finer particles, accumulating in fractions finer than 0.15 mm. Since the application for ultrafine fractions produced from CDW recycling has not yet been clearly developed, the comminution process should prevent the generation of those particles. Therefore, crushing mechanisms that produce better liberation and lower fines production is recommended.

RCA with higher liberation ratios tends to contain less attached cement paste, therefore reducing its porosity. A higher amount of adhered cement paste on aggregates means that nearly no detachment across the phases grain boundaries has occurred. The result is RCA with higher porosity and water absorption.

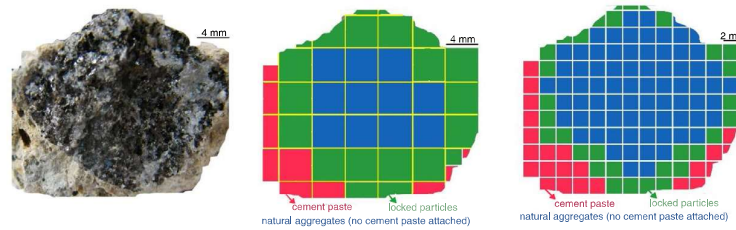
It must be highlighted that the properties of recycled aggregate depend on various factors. A comprehensive study demonstrated that there is an overlapping among the effects of the size of natural aggregates, the compressive strength of parent concrete and the number of crushing stages on the properties of recycled aggregates. The authors stated that “these effects occur simultaneously and interact with one another in varying degrees, rendering it difficult to quantify and to account for them independently” [10]. Nevertheless, the paper did not evaluate the effect of the crushing mechanism.

Crusher choice primarily relies on material size, the desired end product, operating costs, and environmental considerations [11]. A two-crushing process can be found in European recycling plants, while the choice of a secondary crusher often relies on qualitative criteria such as coarse and fine RCA recovery fractions. However, a body of mineral processing literature supports the concept that comminution type might change the properties of the products attained.

Macroscopic models for jaw crusher concrete waste have been previously investigated [12] demonstrating that a rupture zone is formed during load. In addition, fragmentation energy was associated with the amount of coarse natural aggregates in recycled concrete. Recycled concrete aggregates require more energy to crush than recycled mortar aggregates, a finding primarily related to the aggregate size of composite cement particles.

Improvement in the segregation of cement paste tends to enhance the recycled aggregate quality and use under different stress conditions, such as compression, impact and shearing. This process leads to a higher proportion of aggregates with cement content when compared with conventional impact machines [13]. In other words, jaw crushers tend to leave higher levels of cement paste adhered to recycled aggregates, while impact and cone crushers are more effective in removing adhered hardened cement paste [14]. However, these studies were not conclusive regarding the role of crusher type concerning RCA characteristics.

Regardless of the crusher type, the progressive crushing stages are essential in reducing the amount of attached cement paste on RCA. This process generates a higher volume



**Fig. 1 – Simulation of the liberation of recycled concrete aggregated by size reduction.**

of fine aggregates (<4.8 mm), the less used fraction of RCA, and may also cause cracks in natural aggregates [2].

The efficiency of cement paste detachment from aggregates varies in relation to the initial concrete characteristics [10], primarily cement content, as well as its compressive strength [7]. Therefore, the selection of comminution mechanisms has to consider material properties, process costs, power consumption and CO<sub>2</sub> generation [15].

Abrasion crushers generate high quality RCA with an energy consumption which is lower [15] than that of methods involving heating and rubbing [3]. Abrasion is reported to remove most of the attached cement paste, resulting in an RCA with restricted porosity, defined as water absorption below 3%. This process ultimately preserves nearly 50% of the coarse fraction above 4.8 mm from RCA. Thermo-mechanical processes have been reported as being inefficient in relation to energy consumption and CO<sub>2</sub> generation [3], although microwaving might be more efficient [15–17].

Even though electric discharge comminution has been reported as an alternative method [18–20], at this point there is no evidence to support the use of this technology. Crushing mechanisms, concrete porosity induced by cracks, and particle size all have a direct influence on the amount of remaining cement paste as well as on recycled aggregates shape and texture [21]. Importantly, it is not always possible to disrupt the adhesive bond through compressive and impact stresses with targeted crack propagation along grain boundaries.

Finally, a recent body of literature has focused on the mechanical properties of the interfacial thin transition zone (ITZ) in RCA [22–25]. ITZ is defined as the cement paste zone with the highest porosity adjacent to the aggregate-cement paste interface. Characterized as one of the weakest links in the concrete matrix, the ITZ is usually among the first structures reacting to mechanical impact with a bond rupture along the grain boundaries. Promising results have been reported regarding RCA liberation associated with progressive damage of free falling impact or autogenous mill [26,27]. A particularly effective method has been reported with shear-strength crushers [28].

In face of this previous literature, a higher liberation ratio of recycled aggregates may improve its recyclability. With an increased release of aggregate fractions, closed material cycles may be simpler to implement, with properties of newly generated concrete resulting in more efficient recycled aggregates.

Given that crushing is fundamental for phase liberation, this paper compares the use of jaw and impact secondary crushing for producing coarse recycled aggregates from

concrete wastes, obtained from road pavement and demolished building materials.

## 2. Experimental procedure

The investigation involved two case studies:

- Case study A: analyses of properties of RCA made from demolished pavement of structural concrete for application as new concrete for pavements.
- Case study B: analyses of properties of RCA made from demolished building concrete components for application as new concrete for buildings. The concrete waste included other low strength concrete types.

All the concrete samples were composed of natural aggregates (crushed granite/gneiss), homogeneous, without organic materials. Both were primarily crushed at the construction site with top-sizes in between 50 and 75 mm (see item 2.1.1 and 2.1.2), and then secondarily crushed in laboratory to obtain RCAs by changing the combination of crusher types.

Different testing procedures were carried out for each concrete application. Whereas, for road construction materials, the mechanical and abrasion resistance matters, for reuse in concrete, water absorption is more important for concrete technological aspects.

### 2.1. Pre-crushed samples

#### 2.1.1. Case study A: concrete from demolished pavement

Concrete pavement demolished slabs were obtained from the Mario Covas Ring Road in Sao Paulo, Brazil. The slabs were broken into blocks using a hydraulic drill and hauled to a crushing plant, where they were primarily processed by a jaw crusher.

A representative sample of around 1 t of pre-crushed concrete with approximately 3" (75 mm) top-size was homogenized using horizontal elongated piles [29,30]. Steel bars were removed manually after the primary crushing.

#### 2.1.2. Case study B: concrete from demolished building

Demolished building concrete samples were collected and primarily crushed at an impact crusher on site. A pre-crushed concrete sample was obtained with approximately 2" (50 mm) top-size. Steel bars were removed manually after primary crushing. An impact crusher was used in the concretes with

lower strength to check if improvements in cement paste liberation were observed.

To minimize the variability in recycled concrete aggregates, 500 kg of each sample were homogenized by horizontal elongated piles and sampling procedures were used to obtain representative and comparable aliquots of each sample and further products.

## 2.2. Secondary crushing by impact and jaw crusher

A representative aliquot from each sample (about 100 kg each) was obtained from the primary homogenization pile for further laboratory studies.

In laboratory, samples were screened in 25.4 and 4.8 mm sieves. Fractions below 4.8 mm and between 4.8 and 25.4 mm were weighted for mass balance and particle size analysis. Fractions >25.4 mm were split in two similar samples for secondary crushing in jaw and impact crusher.

The particles were crushed in close circuit until most of the material passed the 25.4 mm sieve ( $P_{95} = 95\%$  of the particles passing the 25.4 mm sieve). This size for RCA was oriented for concrete applications rather than the usual pavement sub-bases or bases (<40 mm). Although this refers to a laboratory experiment, the mechanism of cement paste liberation in industrial operations is not higher than that achieved in lab scale. The cement paste liberation results of the study can thus be somehow used to infer about this mechanism in on-site recycling conditions.

Since pre-crushed concretes presented similar top-sizes, they were assumed not to interfere with the mechanism of cement paste liberation. The strength of concrete wastes usually differs in site recycling operations. To orient the study conclusions, the primary crushing mechanism of low strength concrete wastes was tested using an impact crusher to check if cement paste liberation can provide effectively RCAs with superior quality, when compared with that obtained from a primary jaw crusher.

Different configurations of material feed were tested before establishing the crushing conditions and we decided to use the conditions to provide the top-size required for the study. In this sense, variations in opening conditions of jaw crusher were not feasible to be tested, or even the velocity of the lab impact crusher. The material feed was always fully performed, abiding by the most recommended condition for cement paste liberation and usually adopted in real industrial processing conditions. The most purposeful option in the study was considered to make it the most like industrial processing.

The major influence for cement paste liberation is certainly related with the top-size of concrete waste and its strength. Both variables were controlled in this experiment to generalize the conclusions in the present study. Industrial specifications for particle size distribution of crushed aggregates does not consider other variables except materials resistance, feed size and crusher characteristics.

The characterization tests performed in the two case studies were not the same because the studies were performed separately with different purposes; however, this does not interfere with the conclusions that are mostly based on particle size distribution, cement paste content and water porosity (an indirect measurement of porosity). Other results only

enriched the analysis about the effects of secondary crushing on RCAs characteristics.

### 2.2.1. Product characterization – case study A: concrete pavement

For case study A, the products obtained from both crushers were characterized aimed at the following properties: particle size distribution, chemical composition, particle shape and water absorption (oven dry density and porosity were also calculated). In order to obtain representative samples, each product was homogenized and sampled in a horizontal pile or using an open-bin riffle splitter.

Particle size distribution was assessed by wet sieving through screens with nominal apertures from 25.4 down to 0.15 mm.

The chemical composition was determined by quantitative XRF analysis (Axios spectrometer, PANalytical) in fused beads, according to procedures applied in most worldwide mining industries; loss on ignition (LOI) was assayed at 1050 °C for 2 h and represents the weight loss at a certain temperature.

The chemical composition was used to indicate the content of each phase present in the recycled aggregates. Silica is mainly related to the content of quartz, while the sum of  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  has a strong association with the feldspar content [31], for aggregates made of granite/gneiss. Since the chemical analysis was carried out by a quantitative method using international reference materials for the calibration curves, the result deviation is very low (<0.5% relative) and the possible deviations are mostly attributed to the sample representativeness.

The content of cement paste in recycled aggregates is usually assessed by HCl leaching, and the soluble phases correspond to the cement paste content. These results can be correlated to the total content of  $\text{CaO} + \text{LOI}$  [32]. This method comprises a faster and more repeatable analysis, the robustness of which is undoubtable.

Particle shape was measured in aggregates passing the 25.4 mm sieve and retained in the 6.3 mm sieve (particles below 6.3 mm cannot be accurately measured by the caliper method) [33,34]. Three orthogonal measurements were taken by a caliper rule: 'a' (larger dimension), 'b' (intermediate dimension) and 'c' (smaller dimension). The ratios,  $b/c$  and  $c/b$ , were calculated for three different aggregate size ranges (25.4–19.1 mm, 19.1–12.7 mm and 12.7–9.5 mm) and for each product (obtained with the jaw crusher or with the impact crusher). The aggregates were classified according to the particle shapes into cubic, elongated, flat or elongated-flat [35].

The water absorption, envelop density,<sup>1</sup> and porosity of coarse products (from 4.8 to 25.4 mm) were measured as indirect results according to standard procedures [36,37]. The recycled aggregates were immersed in water for 24 h for pore saturation; then, particle surfaces were dried using a towel to determine the saturated surface dry weight and, consequently, the amount of water that penetrates the aggregate

<sup>1</sup> Envelop density is determined for porous materials when pore spaces within the material particles are included in the volume measurement.



pores, which corresponds to the aggregate water absorption capacity.

### 2.2.2. Product characterization – case study B: demolished building

Coarse recycled aggregates obtained from demolished building concrete using jaw and impact crushers (in the secondary crushing) were characterized according to the following properties: particle size distribution, estimation of cement paste content by HCl leaching [32], water absorption and apparent porosity as indirect results [36,37].

Particle size distribution was assessed by wet sieving in sieve sizes from 25.4 to 0.15 mm. The content of cement paste was assessed by HCl 33% leaching in fine milled representative aliquots of each sample according to the procedure previously described in the literature [32]. Samples must be weighted before and after leaching; the amount of solubilized material corresponds to the content of cement paste in the sample.

Water absorption was measured according to international standards regarding coarse products (from 4.8 to 25.4 mm), as previously described [36,37].

Density separation was performed in sequential heavy liquid separation for coarse (4.8–25.4 mm) and fine fractions (0.30–4.8 mm) at densities of 2.2 and 2.5 and 2.6 g/cm<sup>3</sup> (bromoform, CHBr<sub>3</sub>, admixtures with ethylic alcohol). The procedure consisted in placing a sample into an organic liquid with the appropriate density, causing the light particles to float and the heavy particles to sink, thereby separating particles with different densities [38]. The liquid density is precisely determined; therefore, possible deviations are mostly attributed to sample representativeness. The porosity and oven-dry density of density-separated aggregates influence the mechanical properties of concrete [39]. Literature data pointed out that recycled aggregates that sink at 2.2 g/cm<sup>3</sup> in heavy liquid density separation have a significantly smaller volume of porous cement paste and lower water absorption [39].

## 3. Results and discussions – case study A: concrete pavement

### 3.1. Particle size distribution

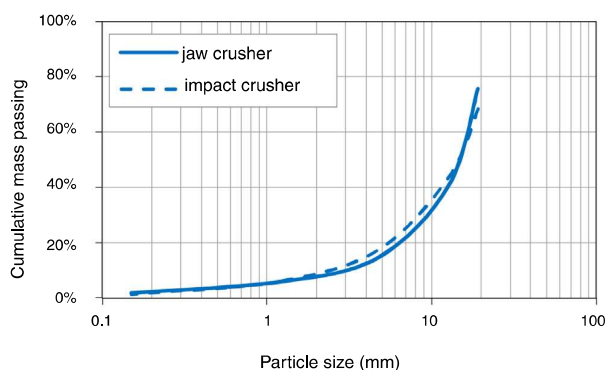
The particle size distribution curves are presented in Fig. 2. Both crushing methods can be observed to result in products with a similar particle size distribution.

The jaw crusher produced 85% coarse aggregates (fraction >4.8 mm), whereas the impact crusher produced 82% coarse aggregates. In both cases, the content of particles finer than 0.15 mm was less than 2% mass.

### 3.2. Chemical composition

The grades of the main oxides attained by XRF and LOI at 1050 °C are shown in Fig. 3, for coarse (a) and fine fractions (b).

The chemical composition of both products is very similar. The content of silica is lower in the fine fractions, while the content of CaO+LOI is higher, indicating a preferential concentration of cement paste in the finer fraction and



**Fig. 2 – Particle size distribution curves of recycled aggregates from concrete pavement crushed by jaw and impact crushers.**

natural aggregates in the coarser fractions. The results between the jaw and impact crusher differ only slightly, which allows assuming there are no significant differences in the liberation ratios of the RCA produced.

The average content of CaO+LOI is around 14% mass.<sup>2</sup> According to data from Angulo et al. (2009) [32], this may represent approximately 23% g/g of binder (cement paste)<sup>3</sup> content, when determined by HCl leaching and admitting the predominant use of quartz/granite natural aggregates (the real context of the case study).

### 3.3. Particle shape

The results from particle shape measurements are presented in Table 1. The difference between recycled aggregates obtained using jaw and impact crushers appears to be insignificant and both were classified as cubical.

### 3.4. Water absorption, porosity and apparent density

The water absorption, porosity and apparent density of coarse fraction (4.8–25.4 mm) from products obtained from jaw and impact crushing are shown in Table 2.

The results of 24 h-water absorption (~4% g/g) and envelope density (~2.3 g/cm<sup>3</sup>) of the RCA studied seems to be coherent with the binder content estimate (23% g/g). The results roughly agreed with the RCA characteristics obtained from concrete C30 (characteristic compressive strength class – fck of 30 MPa) from a previous study [40], which is the real situation of the case study. The concrete waste originated from a structural concrete pavement structure with similar fck.

Both methodologies considered the most appropriate acids to determine cement paste content according to the literature review [40,41]. We here considered HCl as the acid, powder samples, temperature and mechanical stirring, based on direct experimental comparisons of the contents of cement

<sup>2</sup> CaO+LOI (coarse) × coarse fraction content + CaO+LOI (fine) × fine fraction content = 12 × 0.6 + 17 × 0.4.

<sup>3</sup> Binder content = 1.6682 × (CaO+LOI) according to Angulo et al. (2009). Correlation coefficient (R<sup>2</sup> ~ 0.83).

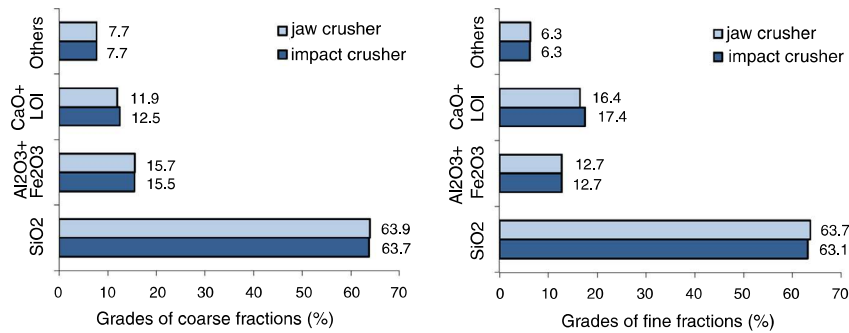


Fig. 3 – Chemical composition of recycled aggregates obtained from concrete pavement crushed by jaw and impact crushers.

Table 1 – Classification of particle shape of products from concrete pavement crushing by jaw and impact crusher.

Fraction (mm)	Jaw crusher products				Impact crusher products			
	Particles	b/a	c/b	Shape	Particles	b/a	c/b	Shape
25.4–19.1	66	0.75	0.68	Cubic	82	0.76	0.71	Cubic
19.1–12.7	87	0.74	0.68	Cubic	65	0.74	0.71	Cubic
12.7–9.5	57	0.73	0.68	Cubic	57	0.74	0.66	Cubic

Table 2 – Water absorption, porosity and envelop density of products from concrete pavement crushing by jaw and impact crusher (fraction 4.8–25.4 mm).

Secondary crushing	Water absorption (%)	Porosity (%)	Envelop density (g/cm <sup>3</sup> )
Jaw	4.00	9.32	2.34
Impact	3.92	9.08	2.32

paste dosed and measured by the insoluble residue in mortars containing quartz aggregates, as reported in literature [41]. Results were reasonably accurate; ~5% of absolute difference or 20–30% of relative error. The experimental procedure adopted in a previous research [40] is quite similar, trying to remove calcium silicates from the surface of natural aggregates and using stronger acid and coarser samples. The accuracy seems to be similar for both methods.

Acid insoluble residue can usually overestimate the cement paste content, even for a weaker acid as HCl, because some constituents of clays or limestone are dissolute in the acid solution. This sulfuric acid attack may be stronger, and it should be taken into consideration. Those compounds may be discounted to improve the overall accuracy.

## 4. Results and discussions – case study B: demolished building

### 4.1. Particle size distribution

The particle size distribution curves of the products obtained using jaw and impact crushers are presented in Fig. 4. The impact crusher led to a finer particle size distribution for the coarse fractions (above 4.8 mm), with little difference in the fine particle sizes.

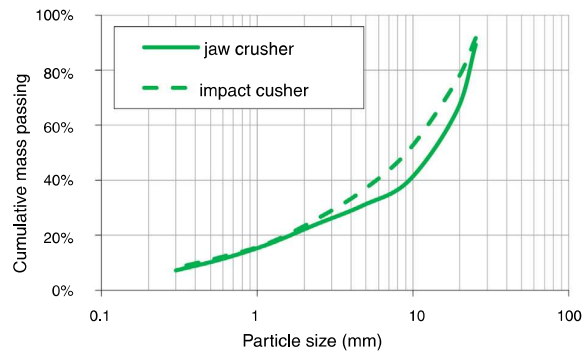


Fig. 4 – Particle size distribution curves of recycled aggregates from building demolition concrete crushed by jaw and impact crushers.

Table 3 – Binder content, water absorption, porosity and envelop density of products from a building concrete crushed by jaw and impact crusher (fraction 4.8–25.4 mm).

Secondary crushing	Binder content by HCl leaching (wt.%)	Water absorption (%)	Porosity (%)	Envelop density (g/cm <sup>3</sup> )
Jaw	26.6	8.76	18.6	2.13
Impact	27.5	9.75	20.2	2.07

The jaw crusher produced 60% of coarse aggregates in weight, whereas the impact crusher produced 49% coarse aggregates. The proportion of particles finer than 0.15 mm is around 7–8% weight for both crushing mechanisms.

### 4.2. Binder content and physical properties

The results of binder content (by HCl leaching), water absorption and apparent porosity tests are presented in Table 3 (for particles between 4.8 mm and 25.4 mm nominal size).

The coarse aggregates obtained by different crushing mechanisms (jaw and impact crushers) show very similar characteristics in terms of binder content assessed by acid leaching (27.5 and 26.6 wt.%), water absorption (8.76 and 9.75 wt.%) and porosity (18.6 and 20.2 vol.%). Thus, it is not

possible to conclude that any of these mechanisms are more efficient in removing the cement paste attached to original aggregate particles. The liberation ratios can also be assumed to differ only slightly. RCA from case study B resulted in more porous aggregates than that from case study A; the cement paste liberation mechanism of the primary crushing was not able to improve the RCA quality significantly.

The water absorption of the recycled cementitious aggregates was systematically higher than that of the recycled concrete aggregates previously reported (and supported by another study [40]). One explanation can be that the recycled cementitious aggregates from this case study may be composed of more porous natural aggregates than the reported ones.

Results in the literature [42] demonstrate that a simple change in granite crushed aggregates to quartz aggregates may systematically increase by ~3% the water absorption of the RCA; this difference may increase the water absorption of the RCA by 6–7%, when the binder content is ~27% g/g [40]. Another possible explanation is that the cement paste content may increase, due to the difficulty of cement paste in becoming liberated in high strength concretes, as reported by a previous article [42]. This may increase the water absorption of RCA in comparison to that obtained from lower strength concrete wastes.

Finally, the water absorption of the cement pastes, estimated by data extrapolation from the literature [40,42] may also change significantly; from 10 to 30% g/g, depending on the concrete strength class. Neither of those studies considered mortar, a possible situation in our case study. The presence of mortars (which may include air-entraining agents) will certainly increase the cement paste porosity and the overall porosity of recycled cementitious aggregates. The results allowed keeping a certain coherence with that reported in the literature [42]. Further investigations are necessary to extrapolate general relations between the cement paste content and porosity, especially in quite different recycling practical situations (waste with high content of porous cementitious materials, or of high strength concretes).

#### 4.3. Density separation

The weight distributions of coarse and fine fractions in different densities are shown in Fig. 5. At first, comparative results of jaw and impact crushing products characterization

demonstrate that both products are quite similar in terms of weight distribution by density, which indicates similar apparent density and porosity as well. However, the differences between coarse and fine fractions must be highlighted. For the coarse fraction, more than 60% of the material sinks at  $2.2 \text{ g/cm}^3$  (Fig. 5a) and only a very small proportion floats at  $1.9 \text{ g/cm}^3$  (less than 1.5%). For the fine fraction, the concentration of dense particles is much higher and more than 90% of the material by weight sinks at  $2.2 \text{ g/cm}^3$ .

The differences observed between coarse and fine fractions are remarkable and emphasize the higher phase liberation for fine fractions and, consequently, greater separation efficiency. A similar statement was previously described in the literature and proved that the production of fine recycled aggregates, despite unusual, it is favored by liberation by comminution and further obtaining low porosity recycled aggregates [4].

Moreover, comparing coarse and fine fractions, it is clear that the two stages of crushing with maximum particle size of 25.4 mm (top-size described in the experimental procedure) were not enough to achieve a satisfactory degree of liberation for the production of coarse recycled aggregates.

### 5. Final remarks and conclusions

Water absorption and porosity are mostly related to the proportion of porous phases, i.e., the remaining hardened cement paste. Impact crushers disrupt particles due to the existing structural weak planes, interfaces, micro-fractures and grain contours. These fractures result in a decreased imperfection percentage within the aggregates. However, jaw crushers also tend to fracture these particles by shearing them across the main tension plane at 45 degrees from the main compression direction. This latter effect can lead to an increase in the number of failure points compared to the particle initial state. Therefore, the current literature reaches a consensus regarding impact crushers being able to generate less porous recycled aggregates. However, to present an appropriate comparison, particle size and liberation particle size should be similar, which necessarily occurs at the 25-mm level.

This comparative study was conducted comparing jaw and impact crushers and demonstrated that end products for both processes are similar in relation to adhered cement paste, density, porosity and particle size distribution. The differences observed do not necessarily justify the widely held belief in the

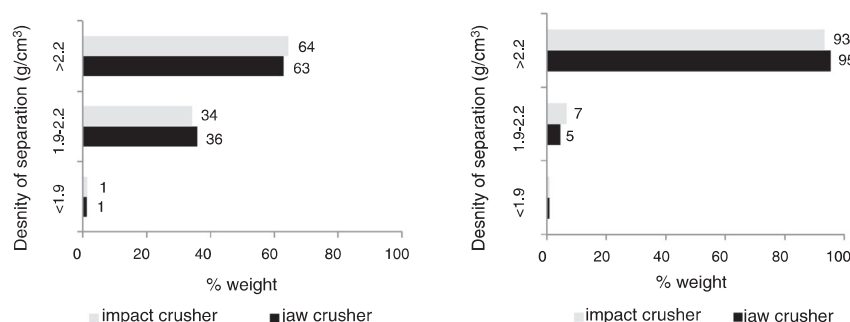


Fig. 5 – Weight distribution in density separation of recycled aggregates from building demolition concrete crushed by jaw and impact crushers.

literature that impact crushers are associated with superior release ratios of RCA. This conclusion is based on two different case studies with crushed concrete samples with different strengths and application (road pavement and building), processed by secondary jaw and impact crusher. This similarity in results may be connected to the release of aggregates and cement paste not occurring at the particle size range about 25 mm. Discussions regarding particle size of the aggregates from parent concrete, the number of crushing stages (one or two) and the RCA properties were previously described in the literature, but not the influence of the crushing mechanism [10].

As a secondary finding, the distribution of coarse and fine products by density separation demonstrated that a two-stage crushing with maximum particle size at 25.4 mm was not enough to achieve a satisfactory degree of release of coarse recycled aggregates. Based on previous studies, the phase release of coarse recycled aggregates increases for comminution levels below 9.5 mm.

The study was limited to comparing the two most used crushing systems by jaw and impact crusher; it did not intent to correlate the properties of the initial concrete and the attained recycled aggregate.

The recycling industry usually selects crushers based on acquisition costs and capacity but very rarely considers essential parameters, such as the desired properties of the end-product. As demonstrated in the literature, the properties of RCA depend on various factors, including crushing mechanics and the number of crushing stages. This work demonstrated that the crushing mechanism does not interfere with aggregates properties if the product top-size is larger than the liberation particle size. In this case, the particle size of crushing is more relevant than the equipment mechanical characteristics. For practical purposes, the industry will be driven to find a balance between the recycling costs and the desired aggregates quality and choose to spend more in processing for obtaining higher quality recycled aggregates, as the Japanese heating and rubbing plants [43] or to spend as the least possible in processing and use the recycled aggregates for low demand applications [7].

Future research should investigate the phase liberation curve by density/porosity to set the most appropriate particle size for comminution. It should also evaluate the influence of aggregates produced by different crushers regarding concrete strength. Costs, maintenance, crusher availability measured as effective working hours, energy consumption and CO<sub>2</sub> emission should also be considered.

## Conflicts of interest

The authors declare no conflicts of interest.

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