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Production of High-Quality Coarse Recycled Aggregates through a Two-Stage Jigging Process

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Abstract: The use of recycled aggregates (RA) to replace natural aggregates (NA) in new concrete production has been pointed out as one of the main strategies to close the loop of construction materials. However, producing RA with properties similar to those of NA has been challenging, since current recycling methods struggle to remove contaminants like ceramics and mortar, whose presence impairs RA properties. In this study, a processing route consisting of a two-stage separation in hydraulic jig was tested, aiming to produce RA from a representative sample of Brazilian construction and demolition waste. All material streams generated in the tests were characterized in terms of composition, size distribution, density, shape index, and water absorption. The results indicated the possibility to produce a high-quality RA, containing more than 99.5% mass of concrete, with adequate properties to replace NA in new concrete production. Also, a conventional RA with suitable properties for downcycling uses (for example, base and sub-base material) could be obtained as a co-product. Finally, the results showed it was possible to recover more than 75% of the original concrete in Construction and Demolition Waste CDW, avoiding its disposal as waste.

Keywords: recycled aggregates; jigging; construction waste; recycling; density-based separation

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1. Introduction

Construction and demolition wastes (CDW), generated during infrastructure construction, building dismantling, and related activities [1] is one of the most voluminous waste streams produced worldwide. Although it is difficult to measure the current CDW global production, it presumably surpasses 3.1×10^9 tons per year [2]. Nowadays, the increase in CDW generation and concern with waste disposal have generated a demand for reuse and recycling, particularly for new concrete production using recycled aggregates (RA) [3–6]. However, as the variability of recycled aggregates composition significantly affects their properties, their adequacy through beneficiation processes becomes indispensable.

Conventional processing of CDW to produce RA does not differ much from the beneficiation of natural aggregates (NA) and consists of crushing followed by screening steps [7,8]. These operations, however, are usually insufficient to deal with the high heterogeneity of typical CDW, a composition which can have distinct materials such as concrete, ceramics, mortar, gypsum, and organics (wood, paper, plastics, etc.). The presence of contaminants limits the application of RAs in new concretes since they negatively influence the fundamental properties of the aggregates such as size distribution, shape index, bulk density, and water absorption [2]. In this sense, the use of additional separation techniques to effectively remove contaminants and thus upgrade the quality of RAs has been the subject of several studies.

For the case of coarse aggregates (−19.1 + 4.75 mm), previous works have shown that gravity separation methods, particularly jigging, stand out as a promising method of RA beneficiation. Jigging is a density-based separation technique consisting of the vertical oscillation of a granular bed, resulting in its stratification followed by separation of light and dense products [9]. The bed motion is driven by water or air pulses, being the first case called hydraulic (or water) jigging and the last case called dry (or air) jigging. In the last decade, dry jigging has prevailed in studies on the field due to its inherent advantage of not using process water. In fact, dry jigging has proven to be able to effectively remove contaminants such as paper, wood, and gypsum [10] as well as significantly decrease the content of undesired ceramics in RAs [11,12].

Nonetheless, despite the positive results, dry jigging has shown operational limitations that have been difficult to overcome. The higher air velocities needed to move the bed (compared to hydraulic jigging) contribute to its remixing, hampering the separation evolution [13]. Also, dry jigging seems particularly prone to the occurrence of wall effects that decrease the separation efficiency near the equipment sidewalls [14]. These factors have restricted the purity of the aggregates, processed through dry jigging, to purities not over 90% in mass concrete. Their properties limit the use in more noble applications like structural concrete [5,15].

Although it requires process water, hydraulic jigging is inherently more efficient than dry jigging since the density of water is much higher than the density of air. The effect of fluid density on separation ease can be better understood by the Concentration Criteria (CC) proposed by Taggart [16] and given by:

$$CC = \frac{\rho_d - \rho_f}{\rho_l - \rho_f} \tag{1}$$

where ρ_d and ρ_l are the densities of the dense and the light constituents and ρ_f is the density of the fluid. The higher the value of CC (Concentration Criteria), the easier the density-based separation of dense and light particles in a fluid. Equation (1) also indicates that the value of CC also depends on the relative difference between the particle and fluid densities, being higher as ρ_l approaches the value of ρ_f. Since water is hundreds of times denser than air, a better separation is expected beforehand in hydraulic systems than in the dry.

The use of hydraulic jigging for CDW processing is not a novelty. Jungmann reported that some recycling plants in Europe and the USA already used the technique in the 1990s, although the focus seemed to be for the removal of fines and organic materials and, to a lesser extent, light mineralized particles [17]. Xing [18] also tested the separation of binary mixtures of concrete (2.4 g/cm^3) and bricks (1.7 g/cm^3), obtaining a heavy concentrate with more than 99% in mass concrete. On the other hand, Peticila et al. [19] tested the separation of mixtures of concrete, ceramics, and mortar, but the separation was considered not satisfactory, since large quantities of mortar and ceramics remained in the product. More recently, Khoury et al. [20] demonstrated that the quality of RAs could be significantly upgraded (higher density and lower water absorption) after processing by hydraulic jigging.

In mineral processing, it is common practice to use multi-stage separation circuits to guarantee the reach of a minimum grade of the target ore. The main idea is to bypass the technical limitations of single separation equipment by exploring the cumulative effect of consecutive separation steps. However, little evidence is available on the impact of beneficiating CDW using more than one density-separation step. Considering this possibility, as well as the need to obtain RAs with properties as close as possible to NAs for new concrete production, in this work, a new beneficiation route of coarse aggregates using double-stage hydraulic jigging is proposed. The results have indicated the possibility of obtaining high-quality RAs with characteristics quite similar to those of natural aggregates.

2. Materials and Methods

2.1. Samples Preparation

The samples were selected and prepared to represent the variability possible to be found in Brazilian CDWs, both in terms of composition and of mechanical properties (low and high resistance). For this purpose, the study of Waskow et al. [21] was the main reference, which pointed out that mortar, ceramics, and concrete make up the basis of Brazilian CDW. Thus, it was defined that the initial mixture to be processed would be composed of mortar, low (2 MPa) and high-resistance (7 MPa) ceramics, and low (16 MPa) and high-resistance (54 MPa) concrete.

The ceramics used were commercial ceramic blocks without structural or refractory functions. The following constituents were used for mortar and concrete production: commercial river sand with a density of 2.63 g/cm^3, commercial basalt coarse aggregate (−19 mm) with 2.57 g/cm^3 density (both according to the Brazilian Standard NBR 7225), Portland cement CPIV−32 with 2.76 g/cm^3 density, and type N hydrated lime with 1.6 g/cm^3 density. Colored pigments were used to better distinguish each component. Table 1 shows the complete mixture design for each material.

Table 1. Mix design and characteristics of mortar and concretes.

Material/Characteristic	Low Resistance Concrete	High Resistance Concrete	Mortar
Portland cement	1	1	1
River sand	2.94	1.78	6
Coarse aggregate	3.56	2.56	-
Hydrated lime	-	-	1
Yellow pigment (Lanxess®)	0.017	-	-
Blue pigment (Lanxess®)	-	0.01	-
Brown pigment (Lanxess®)	-	-	0.05
Silica sand	-	0.1	-
Water/cement ratio	0.56	0.5	0.57
Strength after 28 days (MPa)	16	54	7.03

Both concretes and mortar were separately produced in a drum mixer with a conventional mixing method and subsequently molded in 20 cm × 10 cm cylindrical samples. Compressive strength tests were carried out in each 28-day aged cylindrical sample according to Brazilian Standard NBR 5739 (5 samples per concrete recipe). The samples were subsequently crushed in a jaw crusher and classified by screening to produce aggregates with a −19 + 4.75 mm size distribution. Figure 1 shows the appearance of each aggregate type after comminution and classification.

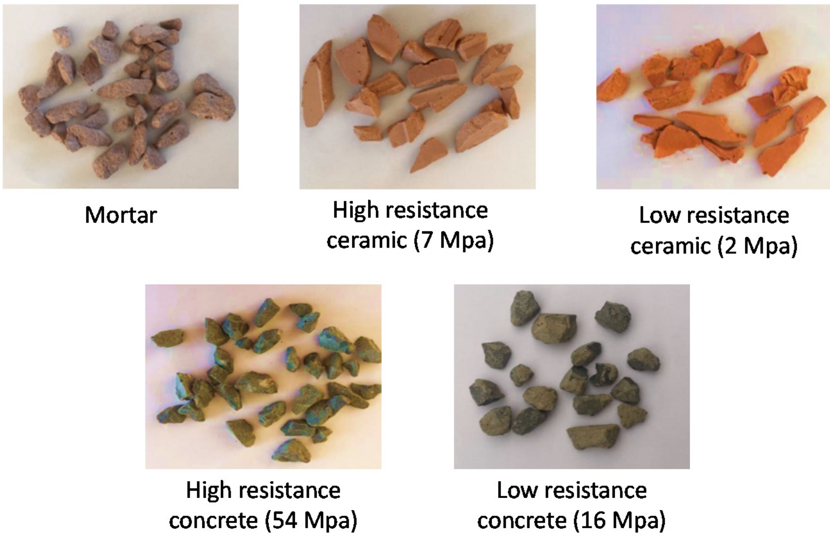

Figure 1. Pictures of aggregates after crushing and classification.

2.2. Jigging Equipment

The tests were carried out in a pilot-scale Baum jig, model AllJig S-400 (Allmineral Aufbereitungstechnik GmbH & Co., Düsseldorf, Germany) (Figure 2a). The jig consists of a tank divided into two sections, one of them containing a container and a sieve (diameter of 1 mm), where the granular samples are placed and another at which an air pulsation mechanism drives the oscillatory motion of water during jigging (Figure 2b). The bed pulsation, caused by vertical pulses of water, opens the bed (increases its porosity), thus allowing the vertical segregation of particles according to differences in density and size. Further details on hydraulic jig operation and the forces driving the stratification phenomenon can be found in literature [9,22–24].

Bed expansion and pulsation frequency are two key parameters affecting jigging. In the jig control panel, these parameters are adjusted by varying the opening of an air inlet valve (gate valve) and the rotation frequency of a rotary piston valve. A direct measure of the bed expansion is performed comparing the bed height at maximum displacement versus the bed height at rest. The jig container consists of overlying layers of Plexiglass $(400 \times 400 \times 50)$ mm^3 assembled that can be individually removed, thus allowing the extraction and the analysis of different vertical strata of the bed (Figure 2c).

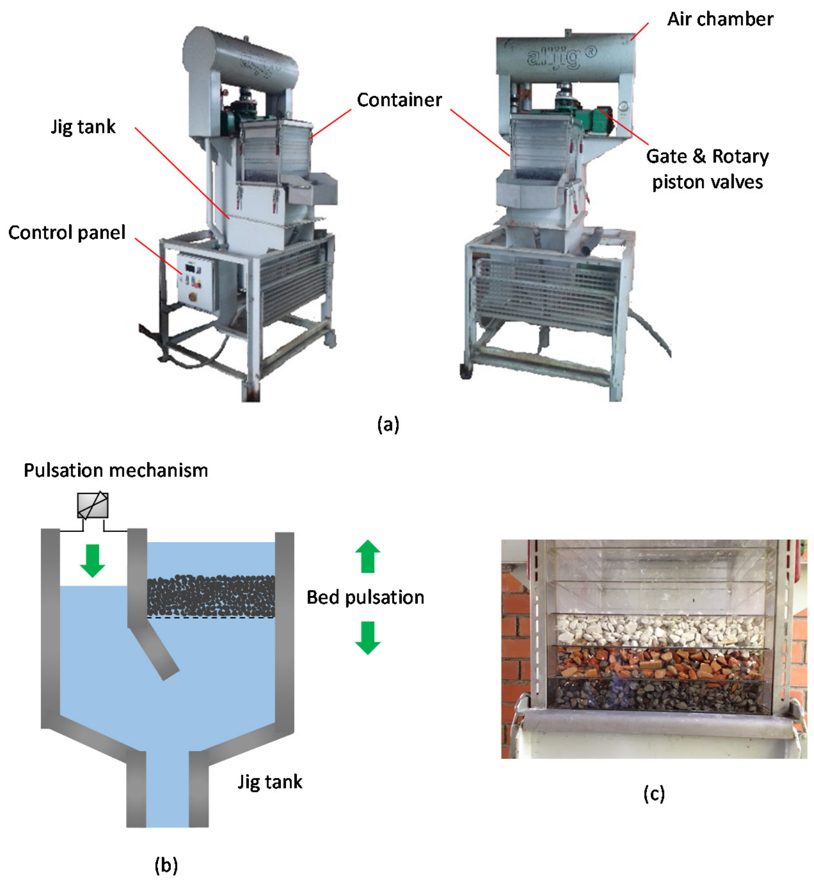

Figure 2. Jigging equipment scheme (**a**); Baum jig operation principle (**b**); Merely illustrative picture of jig container filled with aggregates (**c**).

2.3. Tests Procedure

Initial mixture composition (termed as feed) was set as 33% bulk volume of each material type (mortar, ceramics, and concrete), the same mixture used by Waskow et al. [25]. Table 2 shows the composition of the feed mixture on a mass basis, while Table 3 exhibits the concentration criteria (Equation (1)) calculated for all interactions of aggregates present in the raw mixture. In absolute values, the CC can be considered low in all cases [23], indicating that separation by density may be difficult to carry out. However, previous works reported that the CC tends to underestimate jigging efficacy for aggregates separation [11,12], being a comparative analysis of CC values is more useful. A general analysis suggests that high resistance concrete is more easily separated from mortar and ceramics, whereas separating low resistance concrete from these two constituents might be more challenging. Thus, to enhance the separation of concrete from the other components, the processing route tested envisaged two stages of jigging with a rougher–cleaner configuration. The function of the first jigging stage was to remove as much mortar and ceramics as possible to generate a pre-concentrate aggregate enriched with concrete. As previous tests showed that a significant amount of such materials remained in the product, a second jigging stage was applied seeking the near-total removal of these contaminants. For testing this separation strategy, the essays followed the scheme illustrated in Figure 3.

Table 2. Mass composition of the feed mixture and individual densities of constituents (see Section 2.4 for details about density characterization).

Material	Mass %	Mass % (per Type)	Absolute Density (g/cm^3)	Apparent Density (g/cm^3)	Bulk Density (g/cm^3)	Shape Index
Low resistance ceramic	15.14	29.70	2.43	2.22	1.23	2.94
High resistance ceramic	14.56		2.47	2.35	1.18	2.66
Low resistance concrete	18.83	38.64	2.48	2.46	1.53	1.87
High resistance concrete	19.81		2.77	2.76	1.50	2.00
Mortar	31.66	31.66	2.10	2.04	1.28	2.34
Σ	100.0	100.0	-	-	-	

Table 3. Concentration criteria (CC) in water (see Equation (1)) for interactions of different aggregates.

Light Material	Dense Material	CC
High resistance concrete	Mortar	1.61
High resistance concrete	Low resistance ceramic	1.48
High resistance concrete	High resistance ceramic	1.31
High resistance concrete	Low resistance concrete	1.21
Low resistance concrete	Mortar	1.33
Low resistance concrete	High resistance ceramic	1.08
Low resistance concrete	Low resistance ceramic	1.22
High resistance ceramic	Mortar	1.23
High resistance ceramic	Low resistance ceramic	1.13
Low resistance ceramic	Mortar	1.09

As previously discussed, the separation in the jig stratifies a particle bed generating a segregation profile in which denser particles concentrate in lower layers of the bed whereas lighter particles tend to concentrate in the upper. As concrete was the densest constituent, a higher concentration of it in the bottom layer of the jig bed was expected beforehand. Considering that the initial mixture had 33% in bulk volume of each constituent, the jig feed was prepared so that each constituent (i.e., mortar, concrete, and ceramics) had the bulk volume needed to fill one Plexiglass layer of the jig container (400 × 400 × 50 mm^3). Thus, in the first jigging stage, the stratified bed was sliced into three fractions after jigging: the upper, middle, and lower layers. With that configuration, all concrete should concentrate in the lower layer in case of perfect separation. Therefore, two product streams were collected after the first jigging stage, pre-concentrate recycled aggregates (lower layer), enriched in concrete, and a so-called "Final Waste" (upper and middle layers), with a high content of ceramics and mortar. The total mass of mixture for each jigging test was approximately 20 kg and a total of 3 runs were carried out to generate enough volume of pre-concentrate for the second jigging stage. After each jigging test, the constituents contained in each layer were carefully separated by hand and individually weighed to determine the layer's composition.

The second jigging stage consisted in upgrading the quality of the pre-concentrated generated in the first stage by removing remaining contaminants from concrete. In this case, each collected layer corresponded to a different product stream, namely: mixed aggregates or MA (upper layer), conventional recycled aggregates or CRA (middle layer), and high-quality recycled aggregate or HRA (lower layer). For the sake of clarity, these nomenclatures are summarized in Table 4. All jigging tests were performed under constant operational conditions. Pulse frequency, jigging time, and bed expansion were fixed at 90 pulses per minute, 120 s, and 100 mm, respectively. The first two were the same that were selected by Khoury et al. [20], whereas the bed expansion was greater in the present work due to the larger average size of the used aggregates.

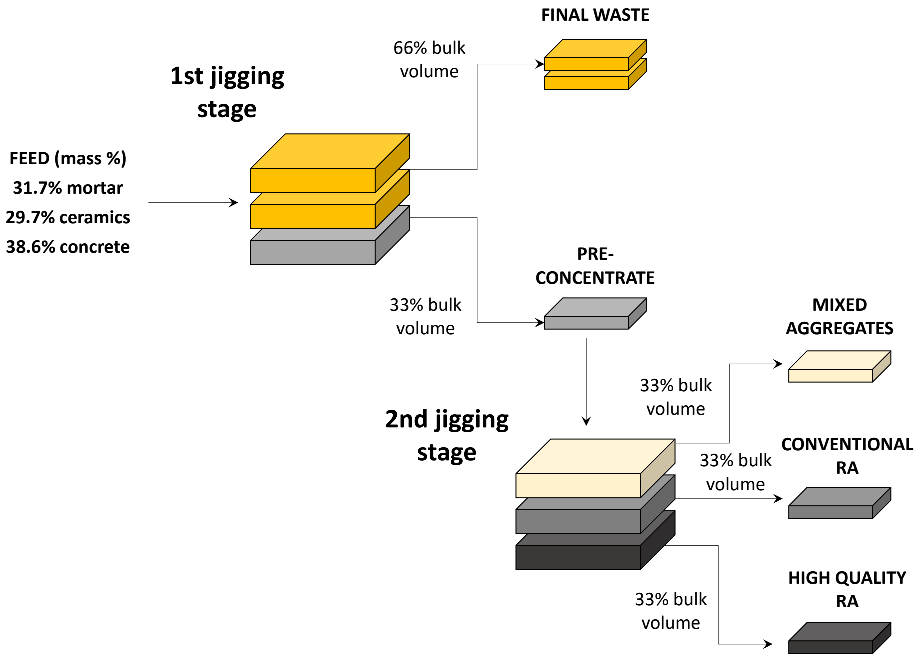

Figure 3. Scheme of jigging tests and product streams.

Table 4. Nomenclatures used for each aggregate type.

Nomenclature	Description
NA	Natural aggregate
RA	Recycled aggregate
MA	Mixed aggregate
CRA	Conventional recycled aggregate
HRA	High-quality recycled aggregate

2.4. Characterization and Analysis

All material streams from the jigging tests were characterized in terms of the main properties of aggregates, namely:

Size distribution (Brazilian Standards NBR 248 and NBR 7211): cumulative retained in 19 mm, 12.5 mm, 9.5 mm, and 4.75 mm.

Shape index (Brazilian Standard NBR 7809): measured by the direct method with the use of a caliper. A total of 200 aggregates were selected proportionately to the mass fraction distributions in the 19–12.7 mm and 12.7–9.5 mm size ranges. The shape index is average of the ratio between the maximum length and the minimum thickness of the grains, weighted by the quantity of grains retained in each size fraction.

The skeletal (absolute) density and the enveloped (apparent) density were determined by water and helium pycnometer (ASTM D5550-06) (Quantachrome Instruments, Odelzhausen, Germany), respectively.

Bulk density (Brazilian Standard NBR NM 45): determining the relationship between mass and volume of bulk material filling a container.

Water absorption: since standard water absorption tests may be difficult to apply for RA due to the cement paste attached [26], the method used here was similar to that proposed by Leite et al. [27]. A mass of 1000 g of material was initially dried in an oven at 105 °C for 4 h. Then, the material temperature should stabilize in an environment at 23 ± 2 °C with relative air humidity of 70 ± 10%. The dry sample was placed on a sample holder with a 0.044 mm opening screen connected to a 0.01 g precision hydrostatic balance (Figure 4). The sample should fill a 3 cm height volume of the sample holder, and it should be covered by a 1 cm water film after water immersion. A lifting platform allowed control of the immersion level of samples. After immersion, readings of the mass gain of aggregates were performed in the following time intervals: 5, 10, 15, 30, 45, 60, 75, 90, 105, 120, 180, 360, and 1440 min (24 h). The overall water absorption (WA) and relative absorption (RA) were calculated according to the respective equations:

$$\text{WA} = \frac{m_{sat} - m_{dry}}{m_{dry}} \tag{2}$$

$$\text{RA} = \frac{m_{w,t}}{m_{w,24}} \tag{3}$$

where m_{sat} is the mass after 24 h of saturation in water, m_{dry} is the mass of dry sample, $m_{w,t}$ is the mass of water absorbed in the time interval t, and $m_{w,24}$ is the total mass of water absorbed.

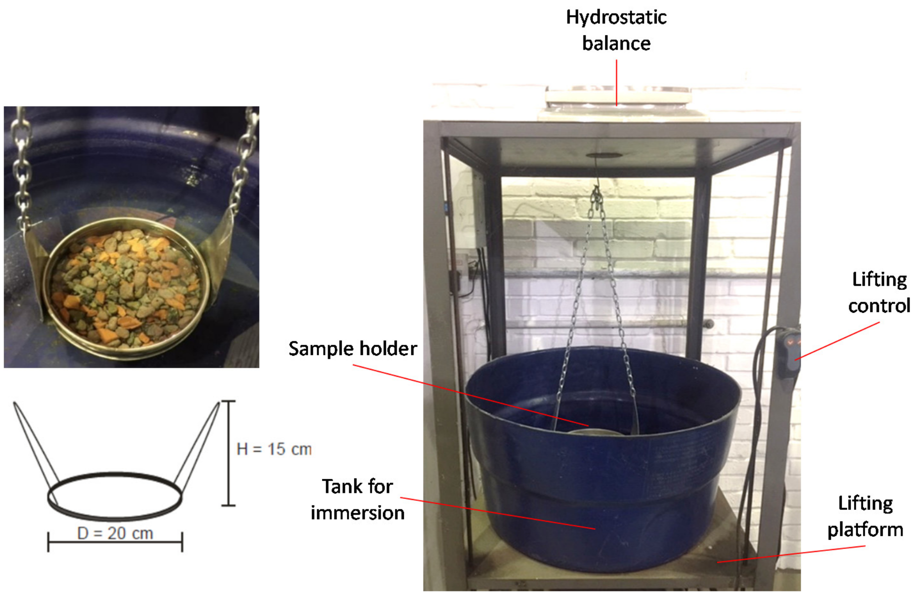

Figure 4. Sample holder (**left**) and experimental apparatus (**right**) used in the water absorption tests.

The properties of all obtained products were compared to those of natural basalt coarse aggregate (NA). Processing efficiency was also measured through the composition of streams and concrete recovery, given by:

$$\text{Recovery} = \frac{m_{concrete}}{M_{concrete}} \tag{4}$$

where $m_{concrete}$ is the mass of concrete in a given process stream and $M_{concrete}$ is the total mass of concrete in the feed stream.

3. Results and Discussion

3.1. Separation Process

Figure 5 shows the mass balance and the overall composition of each material stream after processing. As can be seen, four output streams were produced over the jigging route: a final waste, consisting mainly of a mixture of ceramics and mortar; a high-quality recycled aggregate (HRA), with more than 99.5% mass of concrete; a conventional recycled aggregate (CRA), with low but significant amounts of ceramics and mortar; and a mixed aggregates (MA) stream, constituting of a mixture of the three constituents in mass proportions quite similar to that of the feed stream. Due to that similarity, the possibility to recycle this stream within the circuit (by feeding it back to the first jigging stage) was also considered for analysis purposes.

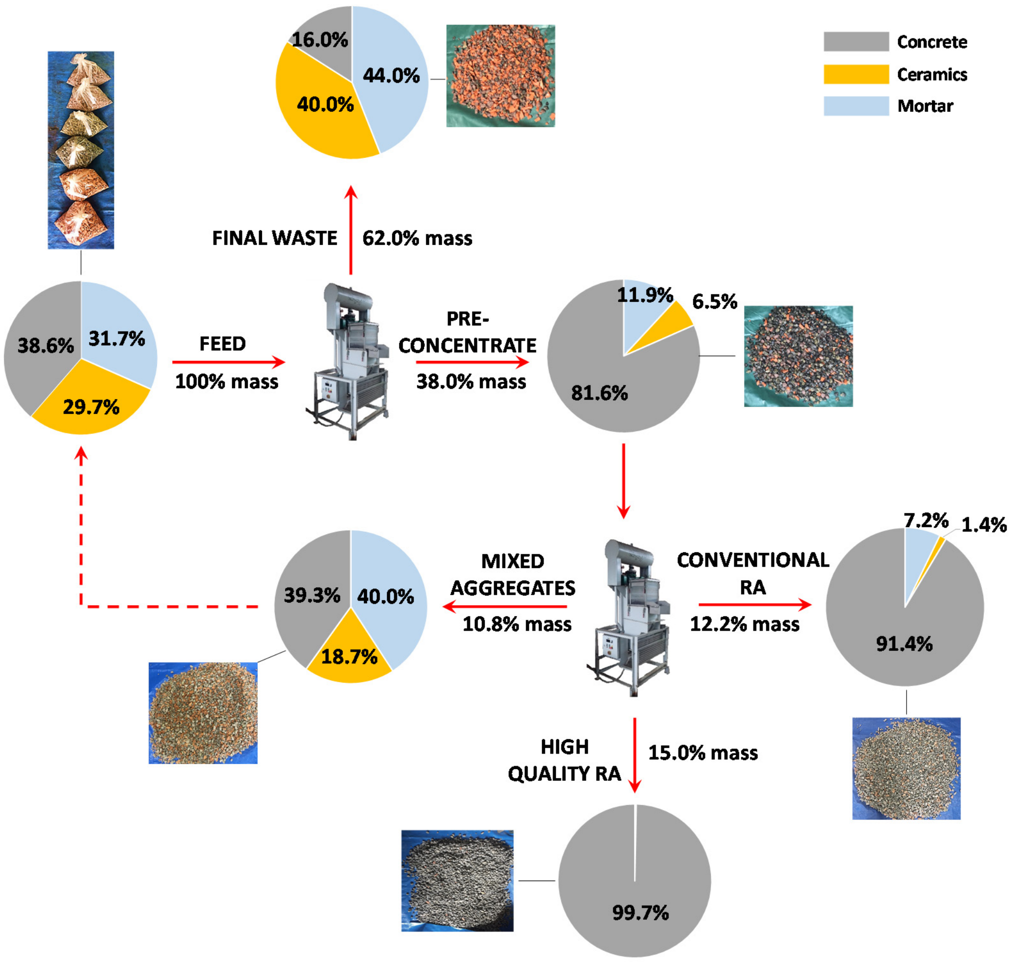

Figure 5. Material balance of the tested route with pictures of products.

The mass balance showed that more than half (62% mass) of the material from the feed stream was separated as final waste in the first jigging stage. Approximately 86% of mortar and 91% of ceramics fed to the system were removed together with this stream (see Table 5 later on). The remaining material, corresponding to the densest fraction, was a pre-concentrate with 81.6% of concrete. In the second jigging stage, the MA stream carried most of the remainder of mortar and ceramics, increasing their overall removal rate (relating to the feed) to 98.2% and 99%, respectively. The CRA stream concentrates the balance of mortar and ceramics, especially the first. The HRA stream, which accounted for 15% of the circuit feed mass, presented only 0.3% of ceramics and no detectable amount of mortar.

Table 5. Detailed composition of product streams.

Stream	Feed	Final Waste	Concentrate	MA	CRA	HRA
Mortar	31.66%	44.00%	11.90%	40.00%	7.20%	0.00%
LS ceramics	15.14%	23.40%	3.10%	13.80%	0.40%	0.30%
HS ceramics	14.56%	16.60%	3.40%	4.90%	1.00%	0.00%
LS concrete	18.83%	7.40%	32.00%	21.10%	32.50%	56.80%
HS concrete	19.81%	8.60%	49.60%	18.20%	58.90%	42.90%
Σ	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Tables 5 and 6 show the detailed composition of each material stream and the distribution of each aggregate type over the products. Some significant differences in distribution can be noted between constituents of the same type. Final waste and MA streams demonstrated a higher concentration of low-strength ceramics than high-strength ones, suggesting that it is easier to separate the first. This was expected beforehand since, as shown in previous studies [11], LS ceramics usually present a flatter particle shape, favoring its concentration in the upper layers of the bed (i.e., with the light product). Similarly, the HRA product was more concentrated with low-strength concrete, whereas the CRA product had more high-strength concrete. The liberation degree of cement paste may have played a role in this trend, as reported in the recent work by Sampaio et al. [28]. In their study, concretes with lower strengths showed a better liberation of aggregates from cement paste, thus facilitating their concentration in denser fractions during density separation. On the other hand, part of the cement paste, with lower densities, accumulates in the final waste. The ceramic particles (low and high strength) accumulate preferentially in the final waste and mixed aggregates because of the lower densities in comparison to concrete particles.

Table 6. Distribution of aggregates (in relation to the feed) over the streams.

Stream	Final Waste	Concentrate	MA	CRA	HRA
Mortar	85.79%	14.21%	11.82%	2.39%	0.00%
LS ceramics	92.49%	7.51%	7.06%	0.17%	0.21%
HS ceramics	88.85%	11.15%	9.07%	0.31%	0.00%
LS concrete	27.41%	72.59%	11.27%	12.32%	41.85%
HS concrete	22.06%	77.94%	9.89%	41.11%	32.15%

Producing recycled aggregate rich in concrete is important to guaranteeing a minimum disposal of concrete as final waste, that is, to ensure the maximum recovery of concrete. Table 7 highlights the distribution of concrete among the product streams and its overall recovery. As mentioned before, the recycling of the MA stream would allow for increasing the recovery of concrete in 10.59% mass, totalizing an overall recovery of 75.24%. Another possibility, not explored in the current work, is making the final waste stream pass by an additional jigging stage (in a rougher–scavenger configuration) to maximize concrete recovery. By assuming the efficiency of this hypothetical separation is the same as the first jigging stage, the total recovery of concrete could be increased to approximately 94%.

Table 7. Concrete distribution and recovery.

Stream	Concrete Recovery (Mass %)	
	Without MA Recycling	With MA Recycling
Conventional RA	27.61%	27.80%
High Quality RA	37.04%	37.29%
MA recycling	-	10.59%
Σ	64.65%	75.24%

3.2. Properties of Aggregates: Size, Density, and Shape

Figure 6 exhibits the size distribution of the obtained products and the commercial NA, including the upper and the lower limits in the range of 9.5 to 25 mm according to NBR 248 and NBR 7211. The lower limit of 9.5 mm was chosen instead of the typical 4.75 mm because of the distribution of NA showed a concentration mostly above the 9.5 mm size. In general, the higher the purity of concrete in a product, the closer its distribution was to that of NA. Thus, HRA presented a curve that most closely approximates the NA curve (100% mass above 9.5 mm), followed by the CRA distribution, whereas the size distribution of the final waste was the most distinct (more than 50% mass below 9.5 mm). The predominance of large particles in the HRA is particularly advantageous since previous studies reported that using larger coarse aggregates could increase the compressive strength of concrete [29].

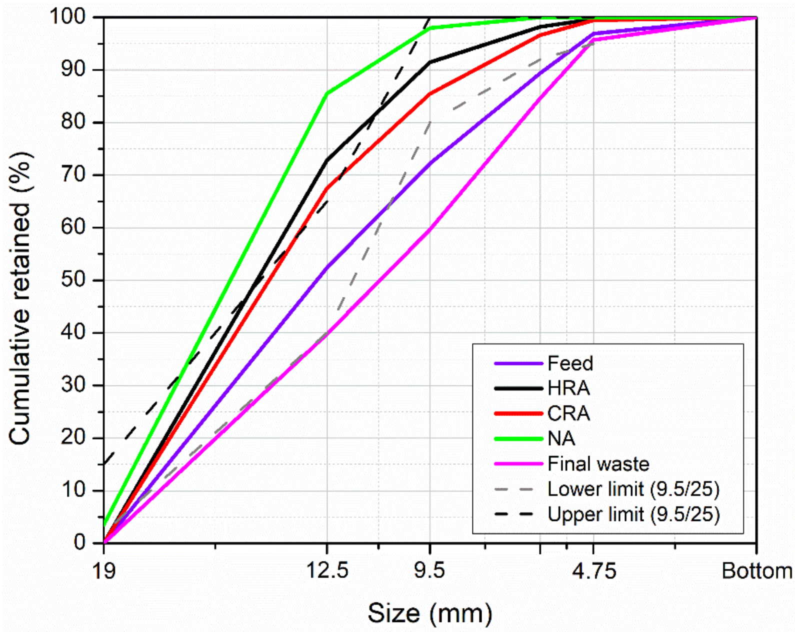

Figure 6. Size distribution curves of products compared to NA.

As shown in Table 8, the jigging process was successful in sorting constituents according to their densities. Both absolute, apparent, and bulk densities exhibited a well-defined pattern, with the final residue presenting the lowest densities values and the recycled aggregates (HRA and CRA—see Figure 5) showing higher densities, approaching that of NA. The typical range of apparent density for basalt NA is between 2.62 and 2.8 g/cm^3 [30], and either the values observed for HRA and the reference NA are above such limits. Since the compressive strength of concrete is directly related to the density of the aggregate [31], the results reinforce the potential of HRA as a substitute for basalt NAs. These results highlight the influence of composition on the average densities of aggregates, especially the influence of mortar and ceramics on the lowering of these values. It is reasonable to suppose that the differences of absolute density (−8.1%) and apparent density (−7.0%) of HRA to NA is probably due the existence of residual adhered cement paste on HRA. An increase in compaction (bulk density) is one of the major effects caused by the jigging action, being not by chance that the bulk density of HRA and CRA were relatively higher than that of NA (+24.8% for HRA). In fact, separation in jigs tends to occur in such a manner that the properties of particles in the lower layers (density, size distribution, and shape) are those that result in a greater compaction of the bed compared to the unprocessed material [9].

The increase in bulk density driven by jigging may also have played a role in the average particle shape of the obtained products. As Figure 7 shows, the shape index of CRA and HRA were considerably smaller than that of NA (almost 20% smaller for HRA), indicating that jigging may drive a secondary separation oriented to the concentration of more rounded particles together with those that are denser. Like density, the shape index values are closely related to composition of the aggregates, being the high values associated with the feed and the final waste stream due to the presence of mortar and especially ceramics, which have more flat/elongated particles. The shape of aggregates influences the packing, the cement paste adherence, and, particularly, the cement consumption. Angled, irregular aggregates require more cement due to the higher surface area when compared to rounded particles [32]. Therefore, the shape-based sorting promoted by jigging is beneficial not only for upgrading the shape index of the processed aggregates (compared to NA) but for the potential to help reduce cement consumption in new concrete production.

Table 8. Densities of obtained products and natural aggregate.

Properties	Feed	Final Waste	CRA	HRA	NA
Absolute density (g/cm^3)	2.68	2.59	2.78	2.81	2.93
Apparent density (g/cm^3)	2.51	2.49	2.62	2.71	2.90
Bulk density (g/cm^3)	1.27	1.46	1.60	1.96	1.57

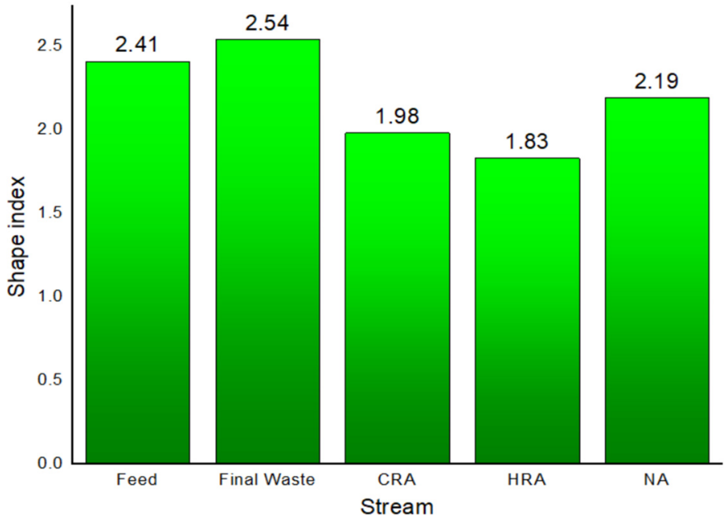

Figure 7. Shape index of different aggregate types, measured through the caliper method (see Section 2.4 for more details).

3.3. Water Absorption

Figure 8 compares the total water absorption (after 24 h) of the different aggregates obtained. The HRA product displayed an absorption value quite close to that of NA (4% larger), as expected, given its composition of near-pure concrete. On the other hand, despite being constituted of more than 90% mass of concrete, the CRA product exhibited an absorption 54% higher than that of NA, emphasizing the negative effect of mortar on this attribute even when in low concentrations. Notwithstanding, it still represented a considerable gain related to the initial aggregate (feed stream), whose water absorption was 4.7 times greater than that of NA.

More detailed insights about differences in water absorption can be seen by observing the absorption rate curves shown in Figure 9. The data indicate that the higher the purity of the aggregate (in terms of concrete content), the faster was the stabilization of water absorption values. For instance, more than 99% of the water absorbed by HRA was absorbed during the first minute of immersion, being the remaining 1% absorbed over the next 120 min. Conversely, aggregates with large contents of mortar and ceramics (like MA and final waste) displayed a slower absorption rate.

Water absorption is a property of pivotal importance when planning to replace NA with RA. High water absorption levels are usually detrimental to the quality of concrete due to its relationship with high porosity and subsequent decrease of density, abrasion resistance, and wear resistance [33,34]. Also, the high variability of RAs (and its difficulty of estimation) may entail different, unknown levels of absorption. This makes the concrete mix design much more challenging than in usual conditions (i.e., with NA), so affecting concrete workability [35,36]. In this sense, besides pointing out the possibility of reducing the absorption level of unprocessed RAs, the results reinforce the potential of using hydraulic jigging for decreasing the normal heterogeneity of RAs, as previously reported by Khoury et al. [20].

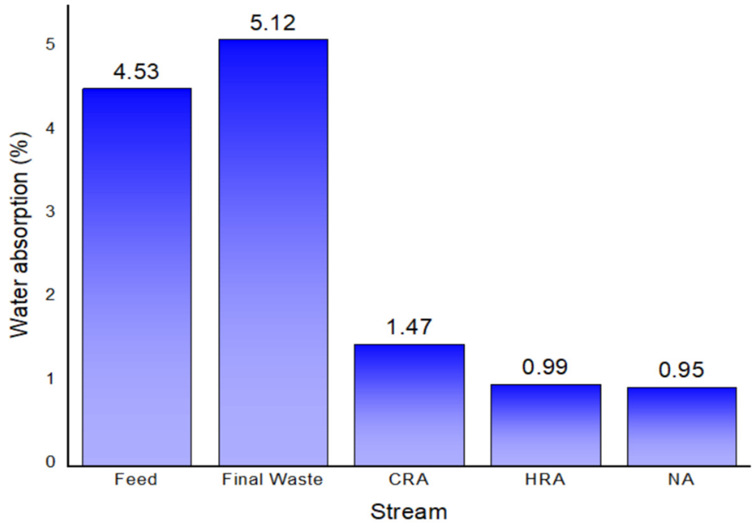

Figure 8. Total water absorption of each aggregate type.

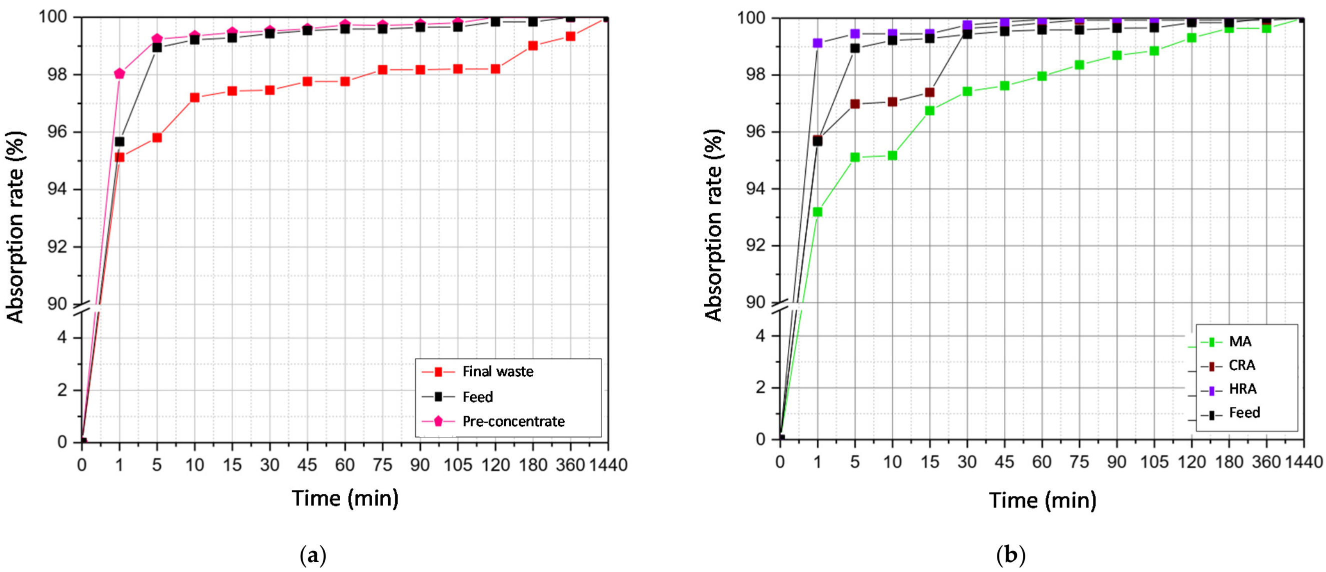

Figure 9. Relative water absorption over time. (**a**) Products from the first jigging stage. (**b**) Products from the second jigging stage.

4. Conclusions

Closing the life cycle of construction materials involves the broad-scale recycling of aggregates, particularly for new concrete production. However, typical recycling methods have so far been unable to adequate the composition and properties of produced RA to suitable levels, making difficult its use as a substitute for natural aggregates. In this work, an effective processing route involving two stages of density separation in hydraulic jigs of CDW was tested, exhibiting unprecedented results regarding the upgrade of RA quality. The main conclusions of this work can be summarized ahead:

After two jigging stages, it was possible to recover high-quality recycled aggregate with more than 99.5% of concrete particles (low and high strength concretes), having properties similar to those of natural aggregates. The jigging separation also generated a subproduct (conventional recycled aggregate) with more than 90% of concrete particles, allowing the recovery of at least 64% of concrete in the feed as recycled aggregate.

The high-quality recycled aggregate presents a higher concentration of low-strength concrete particles, probably due to the higher liberation of coarse aggregates from the cement paste used in the formulation. These coarse aggregates concentrated preferentially in the densest products of each separation stage, whereas mortar and ceramics concentrated more in the lighter fractions, most notably in the final waste stream.

The size distribution curve of the high-quality recycled aggregate presented the pattern that most closely approximated the natural aggregates distribution curve. On the other hand, the shape index of both conventional and high-quality recycled aggregates was considerably smaller than that of natural aggregates, indicating their higher content of rounded particles.

The high-quality recycled aggregate, conventional recycled aggregates, and natural aggregates present lower water absorption in comparison to the feed and the final waste streams. Also, the higher the purity of the aggregate (in terms of concrete content), the faster was the stabilization of water absorption values.

Finally, although analyzing the cost-effectiveness of the proposed process was beyond the scope of this work, it should be the subject of future studies. Despite the consensus that dry beneficiation is cheaper than wet treatment, dry jigging may be notably expensive. Coelho and Brito [37,38] indicated that the air jigging section showed the highest fixed, maintenance, and operational costs of a CDW recycling facility, as well as the highest energy consumption (even surpassing the crushing section) and CO_2 equivalent emissions. On the other hand, previous studies on coal processing have shown that although dry processing may entail shorter payback periods, installations based on wet separation technologies could be more economical in the long-term [39].

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