Waste Management 45 (2015) 171–179

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Comminution and sizing processes of concrete block waste as recycled aggregates

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ARTICLE INFO

Article history:
Received 26 January 2015
Revised 3 July 2015
Accepted 5 July 2015
Available online 11 July 2015

Keywords:
Recycled concrete aggregate
Comminution
Characterization
Concrete block waste

ABSTRACT

Due to the environmental impact of construction and demolition waste (CDW), recycling is mandatory. It is also important that recycled concrete aggregates (RCA) are used in concrete to meet market demands. In the literature, the influence of RCAs on concrete has been investigated, but very limited studies have been conducted on how the origin of concrete waste and comminution processes influence RCA characteristics. This paper aims to investigate the influence of three different comminution and sizing processes (simple screening, crushing and grinding) on the composition, shape and porosity characteristics of RCA obtained from concrete block waste. Crushing and grinding implies a reduction of RCA porosity. However, due to the presence of coarse quartz rounded river pebbles in the original concrete block mixtures, the shape characteristics deteriorated. A large amount of powder (<0.15 mm) without detectable anhydrous cement was also generated.

1. Introduction

Construction and demolition waste (CDW), which is usually composed of different types of concretes and mortars, ceramic blocks and tiles, and other secondary materials (paper, wood, plastics and metals), represents more than 50% of the total municipal solid waste in Brazil and Europe as well as other countries (Vázquez, 2013). In Brazil, cement-based waste corresponds to approximately 60% of the total CDW. From the 1.3 billion tons of CDW produced in Europe, 325 million tons produced in the United States and approximately 77 million tons produced in Japan, it is estimated that concrete waste can reach up to 80% of the total CDW (Klee, 2009). CDW recycling is extremely important, and it should be used for the predominant fraction of waste (cement-based waste) and most other applications (mortar and concrete) because of the environmental impact of CDW.

The use of coarse recycled concrete aggregates (RCAs) in concrete has been investigated since the end of World War II. Since then, it has been proven to be technically feasible (Hansen, 1992). The porosity of RCAs is responsible for the reduction of the compressive strength and Young's modulus of concrete (Gómez-Soberón, 2002), for the increase of drying shrinkage (Sagoe-Crentsil et al., 2001), and for the loss of concrete workability (Poon et al., 2004). The durability performance of concrete is also lower (de Brito and Alves, 2010) because RCA porosity increases water sorptivity and air permeability (Buyle-Bodin and Hadjieva-Zaharieva, 2002). Such influences have also been investigated for the RCA fine fraction (Evangelista and de Brito, 2010, 2007; Khatib, 2005; Zega and Di Maio, 2011). This fraction is typically more porous than the coarse fraction, resulting in decreased ordinary concrete performance. These negative effects were also observed for recycled dry cast concretes (Poon et al., 2002; Soutsos et al., 2011). Accepting these reductions of performance, different types of concrete can be technically safe-produced when natural aggregates are partially replaced by coarse and/or fine recycled concrete aggregates.

The amount of porous residual cement paste attached to the surface of natural aggregates explains the water absorption of RCA (Belin et al., 2014; de Juan and Gutiérrez, 2009). Comminution by different stages of crushers partially removes the old adhered cement paste from the natural aggregates and thus reduces the porosity of RCA (Kasai, 2006; Nagataki et al., 2004; Pedro et al., 2014; Pepe et al., 2014; Shima et al., 2005; Sui and Mueller, 2012; Tomosawa et al., 2005; Ulsen et al., 2013). Nagataki et al. (2004) showed that using three stages of comminution led to a reduction of the water absorption of coarse RCA of

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http://dx.doi.org/10.1016/j.wasman.2015.07.008
0956-053X/

35–50% when comparing the first and third stages of crushing concrete with different strengths. Pedro et al. (2014) also confirmed that the two stages of crushing result in a water absorption reduction of coarse RCA of approximately 10–20%. Ulsen et al. (2013) compared the use of two and three crushing stages (the third stage by a vertical shaft impactor) and obtained a 40–60% reduction in fine recycled aggregate water absorption. Table 1 summarizes the literature data (the mass balance and water absorption of RCAs) related to the above-mentioned recycling processes. Abrasion is the most efficient technique to reduce the porosity of recycled aggregates, as showed by Kasai (2006). Most processes generate a large amount of fine fraction. RCA powders (<0.15 mm) may have potential residual reactivity due to the presence of anhydrous cement (Arm, 2001; Katz, 2003; Poon and Chan, 2006), and this reactivity depends on the age of the concrete (Katz, 2003).

Other techniques, such as heat treatment before comminution (milling in this case), were also used in processing to remove the cement paste (Shima et al., 2005; Tomosawa et al., 2005), but the energy consumption and generated CO_2 emissions could not be justified with the recycled aggregate improvement (Quattrone et al., 2014).

Choices regarding the comminution process are crucial to establish the most technically and economically feasible conditions for recycling. Thus, the aim of this paper is to investigate the influence of three different comminution and sizing processes on the RCA characteristics obtained from concrete block waste, the fourth most commonly used building component in the Brazilian pre-cast industry.

2. Materials and methods

The experimental procedure involved the following three steps (Fig. 1): (a) concrete block waste sampling, (b) comminution by three different processes and (c) product characterization.

2.1. Sampling

Structural masonry concrete blocks with a 28-day characteristic compressive strength ($f_{bk,28}$) equal to 8 MPa were collected from the quality control area of a production plant. After pre-fragmentation by sledgehammers, which simulated primary crushing with pneumatic demolition breakers, the fragmented materials were homogenized by a blending bed technique (Petersen, 2004; Petersen et al., 2005). Then, five samples of approximately 12–15 kg each were collected. To ensure the representativeness of each sample, the mass reduction was carried out using a jones riffle splitter.

2.2. Comminution and sizing

To meet the technical aspects of commonly used aggregates for concrete block production, three different recycling processing strategies were followed:

- *Route 1:* Pre-fragmented concrete block waste samples were screened in a 9.52 mm sieve opening (the cheapest recycling strategy). The material that passed through the 9.52 mm sieve was named RCA-1 (recycled concrete aggregate route 1). The retained material was not considered in this study (approximately 30% in mass).
- *Route 2:* Pre-fragmented concrete block waste samples were crushed by a jaw crusher in a closed circuit with a 4.75 mm sieve aperture until 100% of the passing material was obtained on the circuit (recycling process by conventional operations – crushing and sieving). The passing crushed material in the 4.75 mm sieve was named RCA-2 (recycled concrete aggregate route 2).
- *Route 3:* Pre-fragmented concrete block waste samples were crushed by a jaw crusher with a 4.75 mm sieve aperture and then dry ground in a closed circuit in ball mill so that 90% of the passing aggregates through were obtained on the 1.18 mm sieve (38 min of grinding) (the most expensive recycling strategy). The material originating from grinding was named RCA-3 (recycled concrete aggregate route 3).

Screening (Route 1) is a low-cost process; however, it produces a high porosity coarse fraction (>9.52 mm) that is not normally used in the pre-cast concrete block industry. The comminution in a jaw crusher (Route 2), which is more expensive than screening, is widely used in recycling to set the maximum particle size (<4.75 mm), and it contributes to greater separation of the natural aggregates from the hardened porous cement paste present in RCA (Ulsen et al., 2013). Route 3 causes greater abrasion of the particles and attains finer aggregates (<1.18 mm) and higher liberation between the phases. The latter, despite being a very expensive process, contributes to round RCA particles. Additionally, it might liberate anhydrous cement in powders.

The three investigated comminution processes allow for the production of recycled aggregates with grain size distributions similar to those commonly used in concrete block production (Fig. 2): coarse aggregate (0–9.52 mm) and fine aggregates (0–4.75 mm and 0–2.36 mm), NAT-1, NAT-2 and NAT-3.

2.3. Products characterization

The objective of the characterization of the recycled concrete aggregates (RCA-1, RCA-2 and RCA-3) was to evaluate the particle

Table 1
Mass balance and water absorption of RCAs obtained by recycling processes.

Recycling processes	Recovery of RCA (% in mass)			Water absorption of RCA (% kg/kg)	
	Coarse (>4.75 mm)	Fine (4.75–0.15 mm)	Powder (0.15–0 mm)	Coarse (>4.75 mm)	Fine (4.75–0.15 mm)
Crushers – jaw or impact (0–3 stages) Nagataki et al. (2004) and Pedro et al. (2014)	35–60	40–65	n.i.	3.14–7.80	n.i.
Eccentric rotor crusher or screw abrading crusher (0–4 stages) Kasai (2006)	27–39	61–73	n.i.	1.00–5.61	n.i.
Autogenous grinding Pepe et al. (2014)	~90	~10	n.i.	4.00–6.00	n.i.
2 crushers Ulsen et al. (2013)	50	43	6	–	12.00
2 Crushers + 1 VSI (3 stages) Ulsen et al. (2013)	–	~90	~10	–	7.00–9.00

The cement paste content of RCA tends to increase in fractions below 0.15 mm. Therefore, this particle size was used as the limit between fine aggregates and powders.
n.i. – not informed.

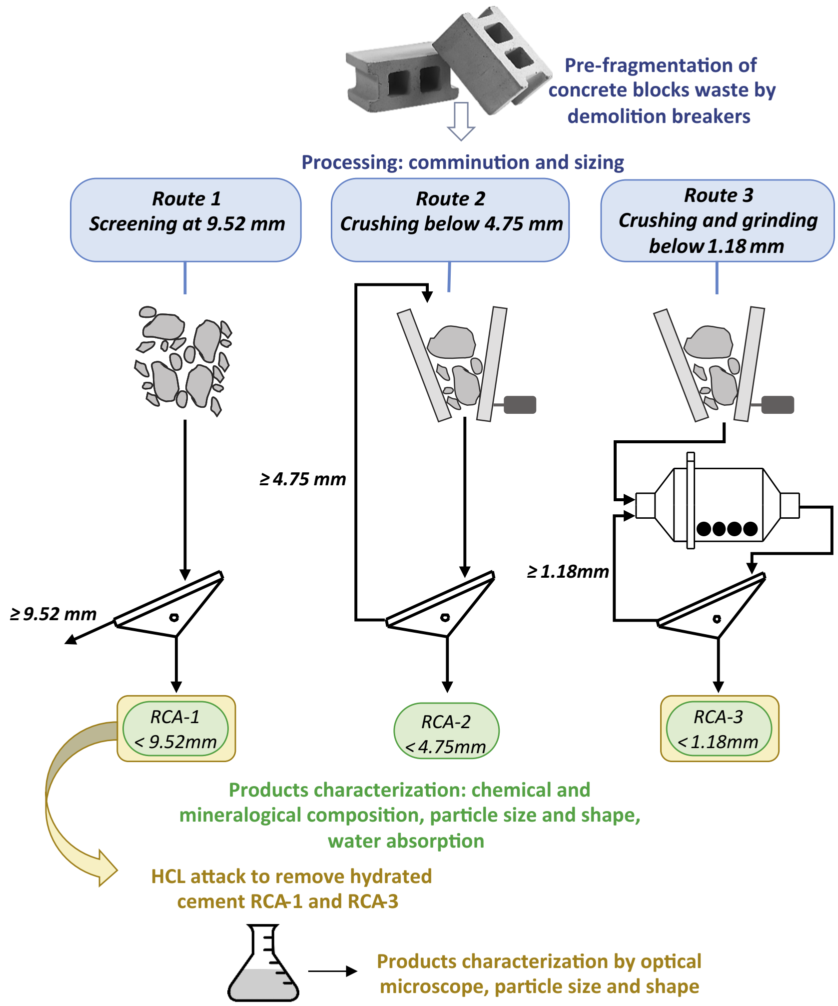


Fig. 1. Flowchart of the experimental procedure.

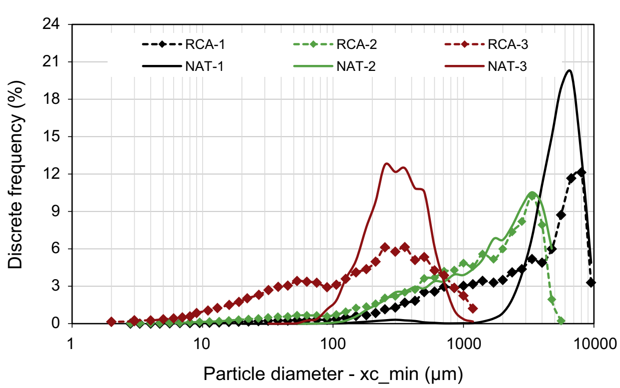


Fig. 2. Particle size distribution (discrete frequency) of the RCAs and natural aggregates used for concrete block production.

size and shape distribution as well as the presence of porous hardened cement paste, according to the procedures detailed below:

a. *Particle size and shape distribution:* An image analysis (Brown et al., 2005; Hawlitschek et al., 2013) was completed using Retsch-branded equipment, model Camsizer and Camsizer XT, according to the methods described in ISO standard 13322-2/2006. Representative mass samples were selected for determinations of approximately 3000 g (RCA-1), 1000 g (RCA-2) and 100 g (RCA-3). Only one sample per RCA type was used.
b. *Chemical composition:* Quantitative chemical analyses were conducted with X-ray fluorescence spectrometry (XRF) in fused beads (Brundle et al., 1992) with anhydrous lithium tetraborate in a fluorescence spectrometer PanAlytical Axios Advance, and loss on ignition was conducted at 1050 °C for 1 h. The chemical analyses were performed according to the standard procedures at the University of São Paulo (Technological Characterization Laboratory), considering systematic control by the analysis of duplicated powdered samples (grain size < 20 μm) and calibration curves for quantitative analyses with the international certified reference materials.
c. *Mineralogical composition:* Powder X-ray diffraction in a PanAlytical X'Pert PRO diffractometer with an X'Celerator detector was completed with only one powdered sample (grain size < 37 μm) per RCA type. The identification of the crystalline phases was obtained by comparing the diffraction pattern of each sample with the PDF2 database of ICDD – International Centre for Diffraction Data (2003) and the PAN-ICSD – PANalytical Inorganic Crystal Structure Database (2007).
d. *Density (D):* The ratio between the dried mass and volume of the solids, excluding open pores but including closed ones (Webb, 2001), was measured by a Micromeritics AccuPyc II

1340 helium pycnometer in the dry samples (40 g each sample) produced by each analysed route. Determinations for each RCA type were conducted in duplicate.

e. *Water absorption:* Water absorption represents the mass of water absorbed by the accessible pores. Water absorption was only determined in fractions above 0.15 mm by analysing and interpreting the drying curves in microwaves in accordance with the procedure of Damineli (2007). This method eliminates the visual and subjective criteria for determining the saturated surface dry condition (SSD) of the aggregates. The author proposed that the determination of this condition is from the ratio of the evaporation of water during drying. Representative mass samples were selected for determinations of approximately 3000 g (RCA-1), 1000 g (RCA-2) and 100 g (RCA-3). Measurements per RCA type were carried out in duplicate.
f. *Acid attack:* To verify the origin of the natural aggregates (quartz and/or granite) inside the RCA samples and the shape changes due to comminution, the hardened cement paste was removed by leaching with a 33% HCl solution (Quarcioni and Cincotto, 2006; Tam et al., 2007). Products from Routes 1 (no comminution) and 3 (two comminution stages) were selected: 1000 g and 100 g, respectively. Assays were completed in batches of 100 g (grain size > 0.15 mm). It is assumed that the aggregates from the HCl attack of RCA-1 (pre-fragmented and sieved) maintained the shape of the original natural aggregates.
g. *Microscopy:* Qualitative analyses were conducted for RCA-1 and RCA-3 in a stereoscopic optical microscope to evaluate the phase associations, surface roughness and particle shapes before and after the acid attack.

2.4. Energy consumption estimation

A rough energy consumption estimation for each processing route was completed according to the methodology proposed by Quattrone et al. (2014). The characteristics of the considered electrical equipment are summarized in Table 2.

Eq. (1) calculates the energy consumption per metric tonne of processed material of electrical equipment.

$$E_i = (P_i \cdot \eta_i^{-1}) \cdot C^{-1} \tag{1}$$

E_i is the energy consumption (kW h/t) of the ith machine; P_i and η_i are the mechanical power (kW) and the electric engine efficiency (−) of the ith machine, respectively. C is the production capacity (t/h) set in this estimate as 25 t/h, i.e., the capacity production of the ball mill.

The energy consumption of each route (E_{route}) is calculated by Eq. (2).

$$E_{route} = \frac{\sum_i E_i}{Product} \tag{2}$$

E_{route} is expressed in kW h per metric tonne of product. *Product* represents the percentage (%t/t) of usable materials as aggregates in concrete block production (item 3.6).

Table 2
Characteristics of the equipment used for the energy consumption estimation.

	Vibrating screen	Jaw crusher	Ball mill
Output power (kW)	6	30	30
Production capacity (t/h)	20–80	20–55	25
Efficiency (−)	0.847	0.9	0.9

For the energy consumption estimate, the production capacity was set equal to 25 t/h for all machines.

3. Results

3.1. Particle size distribution and shape analysis

Fig. 2 presents the particle size distribution (discrete frequency) of RCAs and the natural aggregates used for concrete block production. In terms of d_{max}, each RCA fraction matches a natural fraction. The RCA differences are due to the amount of finer particles used.

Fig. 3 shows the cumulative particle size distribution of the recycled concrete aggregates obtained in each route. The RCA-3 aggregate obtained by grinding has a noticeably finer particle size distribution, 42% below 0.15 mm. RCA-2 that passed through the 4.75 mm sieve has an intermediate continuous distribution, as does the RCA-1 generated from screening. The powder contents (grain size < 0.15 mm) of RCA-1 and RCA-2 were 3.7% and 8.1%, respectively.

Fig. 4 shows the results of the particle morphology of the recycled aggregates (grain size > 0.15 mm). Regarding the particle frequencies, the RCA-3 aggregate obtained by grinding has less spherical particles than those obtained by crushing and sieving. This result is similar with respect to particle elongation for RCA-3, which generated the most elongated particles.

Although the results do not indicate a significant difference, they indicate that comminution processes, in this specific case, generate elongated particles, contrary to what is expected of such processes; this will be further explored in the micrograph results.

3.2. Chemical and mineralogical composition

The average chemical composition of the recycled concrete aggregates is presented in Table 3, split for the fractions above and below 0.15 mm. The main constituent oxides are silica (SiO_2), calcium oxide (CaO), alumina (Al_2O_3) and iron oxide (Fe_2O_3), which, together with the loss on ignition (LOI), exceed 90% of the total grade of samples.

The content of CaO + LOI is correlated to the cement paste and carbonate content (when present) in recycled concrete aggregates (Angulo et al., 2009; Ulsen et al., 2013). Considering only the fractions above 0.15 mm, it is observed that crushing reduced the CaO + LOI grades from 6.19% to 5.68% (8% lower), whereas the grinding products were reduced to 3.26% (a 47% relative reduction).

With respect to the powders (grain size < 0.15 mm), there is a noticeable increase in CaO + LOI for the three samples of RCA, indicating an enrichment in the cement paste content. The CaO + LOI content (Table 3) is higher for powders obtained by sieving (RCA-1), followed by crushing (RCA-2) and grinding (RCA-3).

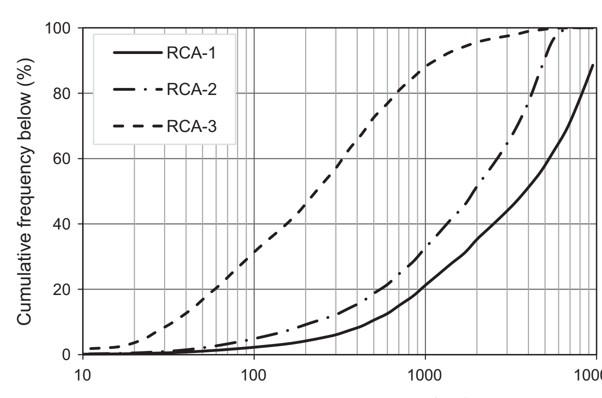
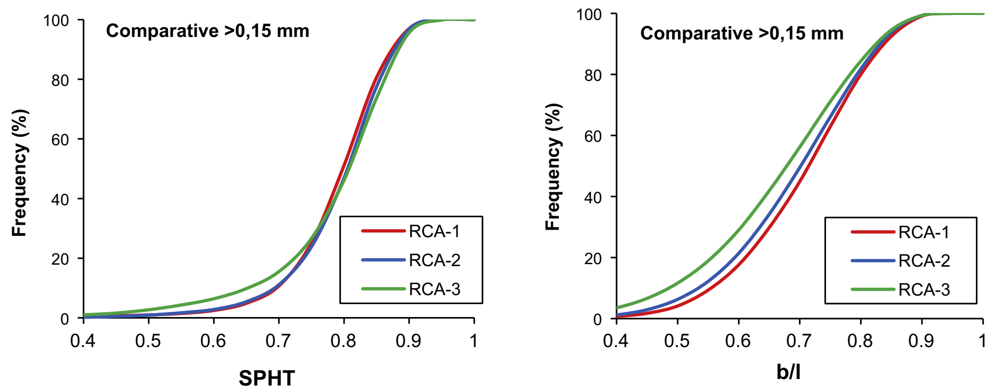


Fig. 3. Particle size distributions of RCA.



SPHT	RCA-1	RCA-2	RCA-3
mean	0.792	0.796	0.791

(a) sphericity

B/L	RCA-1	RCA-2	RCA-3
mean	0.715	0.706	0.685

(b) aspect ratio

Fig. 4. Shape analysis of the RCA samples.

Table 3
Chemical compositions (average) of RCA.

Sample/products	% wt	Grades (%)									Distribution in the sample (%)				
		SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO + LOI	$Na_2O + K_2O$	CaO	LOI	SiO_2	Al_2O_3	Fe_2O_3	$Na_2O + K_2O$	CaO + LOI
Total sample	100	76.8	8.18	1.93	1.68	2.49	6.89	4.17	3.99	2.90	100	100	100	100	100
RCA-1															
9.52–0.15 mm	96.3	77.8	8.09	1.83	1.68	2.48	6.19	4.16	3.56	2.63	97.0	95.0	91.0	96.0	87.0
<0.15 mm	3.71	52.6	10.6	4.46	1.65	2.8	25.0	4.45	15.03	10.0	3.0	5.0	9.0	4.0	13.0
RCA-2															
4.75–0.15 mm	91.9	78.6	7.96	1.71	1.67	2.49	5.68	4.16	3.32	2.36	94.0	89.0	81.0	92.0	76.0
<0.15 mm	8.10	56.5	10.67	4.42	1.75	2.53	20.7	4.29	11.58	9.12	6.0	11.0	19.0	8.0	24.0
RCA-3															
1.18–0.15 mm	58.0	83.0	6.94	1.22	1.53	2.27	3.26	3.80	1.88	1.38	63.0	49.0	37.0	53.0	28.0
<0.15 mm	42.0	68.2	9.91	2.91	1.89	2.8	11.9	4.69	6.92	5.02	37.0	51.0	63.0	47.0	72.0

Comparing the recycled aggregates RCA-1, RCA-2 and RCA-3, there is an increase in the distribution of CaO + LOI in the powders. The distribution increases from 13% to 72%, indicating that the cement migrates to the powder fraction when crushed and grinded due to its lower hardness. The higher grades and distribution of cement paste (represented by CaO + LOI) in the fine fraction of RCA-3 favours the occurrence of anhydrous cement phases (not hydrated).

The relative reduction in CaO + LOI observed for RCA-3 is due to the migration of natural coarse aggregate particles (feldspar and quartz) from the coarsest to the finest fractions due to comminution. The distribution of $Na_2O + K_2O$ (Table 3), which represents feldspar (Ulsen et al., 2013), increases from 4% (RCA-1) to 47% (RCA-3). The distribution of SiO_2, which represents both quartz and feldspar, increases from 3% to 37%.

Comparative diffractograms of the sample powders (grain size < 0.15 mm) are shown in Fig. 5, and they indicate the presence of quartz, feldspar (albite and orthoclase), mica, minor amounts of calcite, amphibole and, possibly, portlandite (the peaks indicate a possible presence of this phase, which cannot be assured by XRD to the lower content).

In the 28-day-old concrete block waste used in this study, the presence of anhydrous phases, such as belite (C_2S), was not detected.

Comminution led to a successive increase in the quartz contents in powders (grain size < 0.15 mm), as shown in Fig. 6. The increasing grades of SiO_2 in powders (52% for RCA-1, 56% for RCA-2, and 68.2% for RCA-3) were confirmed (Table 3).

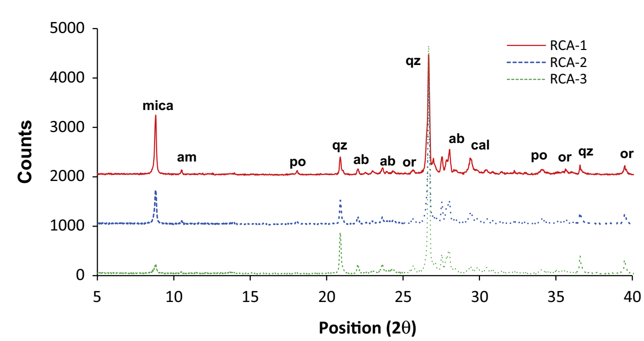


Fig. 5. Comparative XRD patterns of the <0.15 mm RCA fraction (am – amphibole; po – portlandite; qz – quartz; ab – albite; or – orthoclase; cal – calcite).

Likewise, the concentration reduction of $Ca(OH)_2$ related to the presence of hydrated cement was also confirmed (Fig. 6) due to the implementation of the comminution routes (especially crushing and grinding).

Comminution processes reduced the hardened cement paste attached to the recycled concrete aggregates. Therefore, the content of CaO + LOI was reduced by 8% by crushing and by 47% by grinding relative to screening in the fractions above 0.15 mm. In the powders below 0.15 mm, the increasing CaO + LOI distributions corroborate the preferable comminution of low hardness cement paste rather than aggregates (see SiO_2 and $Na_2O + K_2O$ distributions) and the migration to finer fractions.

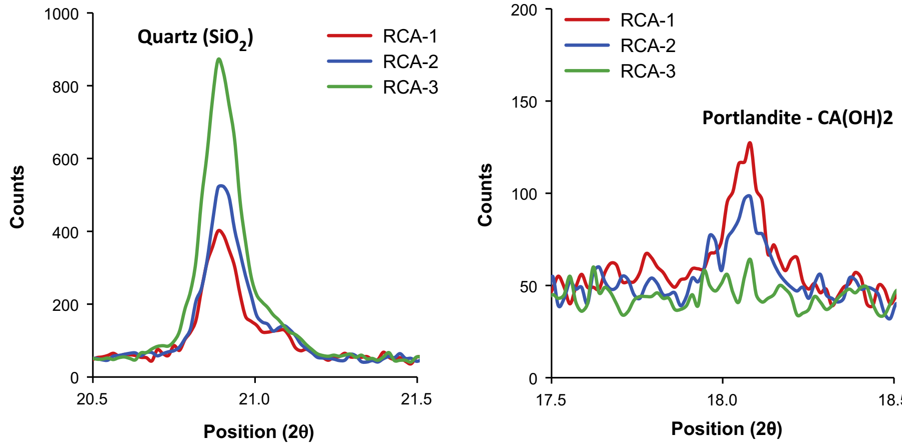


Fig. 6. Main peaks of quartz and portlandite on the <0.15 mm RCA fraction.

Table 4
Physical properties (average) of RCA (grain size > 0.15 mm).

Products	Density (g/cm^3)	Water absorption (%)	Relative density (g/cm^3)	Porosity (%)	Residue Insoluble (%)
RCA-1	2.65	5.98	2.29	13.7	91.8
RCA-2	2.66	5.67	2.30	13.1	n.a.
RCA-3	2.65	3.51	2.42	8.51	97.4

n.a. – not assessed.

Despite the powder content increase in RCA-3 resulting in a higher amount of cement paste, the occurrence of anhydrous (not hydrated) phases was not detected. These results may be related to the low amount of cement commonly used in concrete block production (approximately 150 kg/m^3), to the age of the concrete waste (28 days) or the XDR detection limit (close to 1% depending on phases crystallinity).

3.3. Density, water absorption and insoluble residue

The average density, water absorption, and insoluble residue of the fractions above 0.15 mm from the three samples of RCA are presented in Table 4. The chemical composition of the aggregates is the same, so the density, excluding voids, has similar values. The different processes do not alter the intrinsic chemical and mineralogical composition of the material.

As expected, crushing caused a slight reduction (5% relative) of RCA-2 water absorption in relation to the value of RCA-1 obtained by sieving. This result corroborates the findings of the decreasing CaO + LOI, which represents the content of the hardened cement

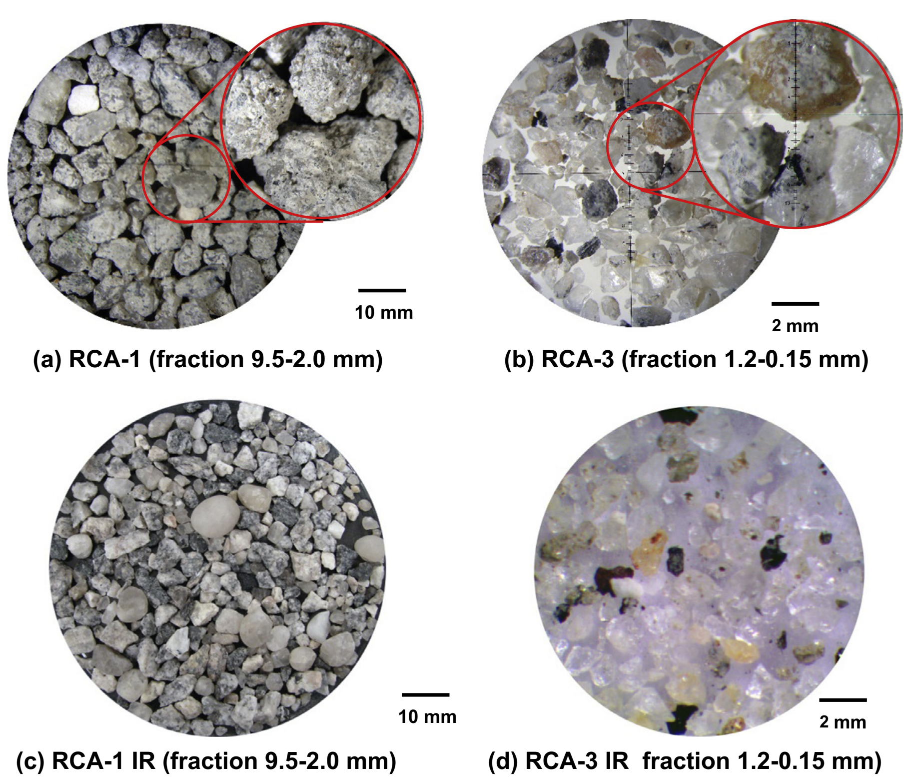


Fig. 7. Microscopic analysis of recycled aggregates samples. Before (a), (b) and after (c), (d) the acid attack.

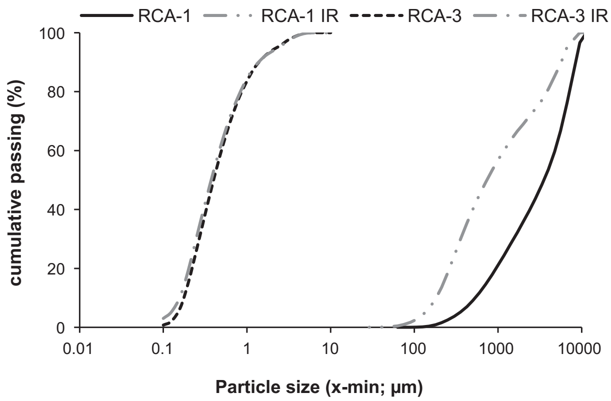


Fig. 8. Comparative particle size distribution of recycled aggregates before and after acid attack.

paste. However, grinding due to the attrition mechanism caused a more significant reduction (41%, relative) of RCA-3 water absorption in relation to RCA-1, confirming a similar trend that was observed by the sum of CaO and LOI.

The results from the acid attack demonstrated that RCA-1 is composed of 91.8% insoluble residues (natural aggregates), i.e., 8.2% of the soluble material in the HCl solution (mainly cement paste). The proportion of insoluble material in the HCl solution increases to 97.4% in RCA-3, confirming the reduction of the hardened cement paste in the grinding product with a grain size above 0.15 mm.

3.4. Micrographs

Illustrative images of the representative aliquots of the products generated by routes 1 and 3 before (RCA-1 and RCA-3) and after leaching in the HCl solution (insoluble residue – IR) (RCA-1 IR and RCA-3 IR) are shown in Fig. 7.

The studied recycled concrete aggregates have porous cement paste adhered to the surface of the natural grains, most notably for the RCA-1 product, because it is not possible to visualize the shape of the natural aggregates used in the original concrete. The presence of a large amount of natural aggregate particles (with none or little adhered hardened cement) is clearly apparent in RCA-3 because of the better phase detachments promoted by comminution.

Images of the insoluble residues (the recycled aggregates after dissolution of the cement paste) show that the natural aggregates used in concrete block waste are composed of fine sand and gravel, e.g. river rounded pebbles (predominant mineral: quartz), with a more spherical and regular (not elongated) shape.

The RCA-3 IR is notable similarity to RCA-3 due to the small content of adhered cement paste on its surface; it is primarily composed of more irregular (elongated) quartz grains (light colour minerals), feldspars and mafic minerals (dark minerals derived from the crushing of rocks).

3.5. Particle morphology

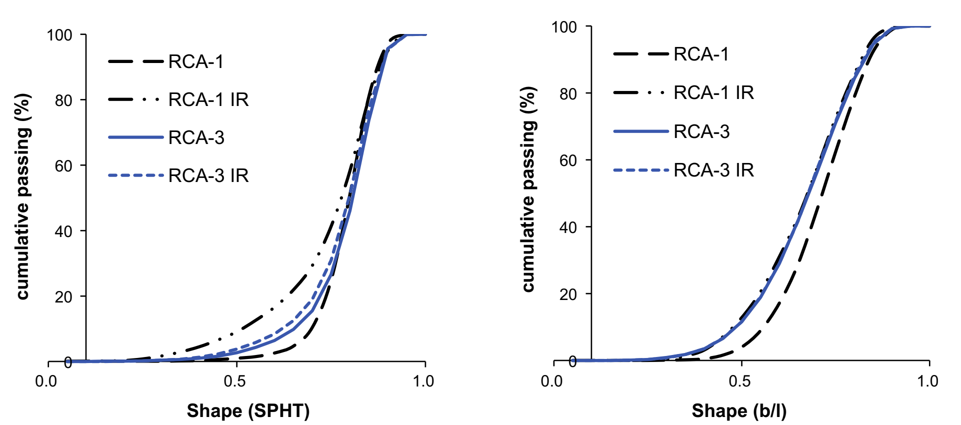
The size and shape distribution of the particles of the recycled aggregates (RCA-1 and RCA-3) and of the insoluble residue after chemical attack (RCA-1 IR and RCA-3 IR) are shown in Figs. 8 and 9.

The aggregates after leaching (RCA-1_IR and RCA-3_IR) have a slightly finer particle size distribution and less spherical and more elongated particle distribution due to the removal of the cement paste adhered to the surface of the particles. These differences are more noticeable in RCA-1, which contains a higher proportion of cement paste adhered to the surface.

Table 5
Mass balance of the processing routes.

Process	Grain size Amount of material (% kg/kg)			Product (% kg/kg)
Route 1	>9.52 mm 30	9.52–0.15 mm 67	<0.15 mm 3	70
Route 2	– –	4.75–0.15 mm 92	<0.15 mm 8	100
Route 3	>1.18 mm 10	1.18–0.15 mm 50	<0.15 mm 40	100

"Product" is the percentage of the material considered to estimate the energy consumption of each processing route.



SPHT	RCA-1	RCA-1 IR	RCA-3	RCA-3 IR
Mean	0.792	0.742	0.791	0.778

B/L	RCA-1	RCA- 1 IR	RCA-3	RCA-3 IR
Mean	0.715	0.682	0.685	0.676

(a) cumulative distribution in sphericity classes

(b) cumulative distribution in aspect relation classes

Fig. 9. Morphological analysis of insoluble residues obtained from RCA-1 and RCA-3; the distributions are in classes of sphericity and aspect relation (fractions above 0.15 mm).

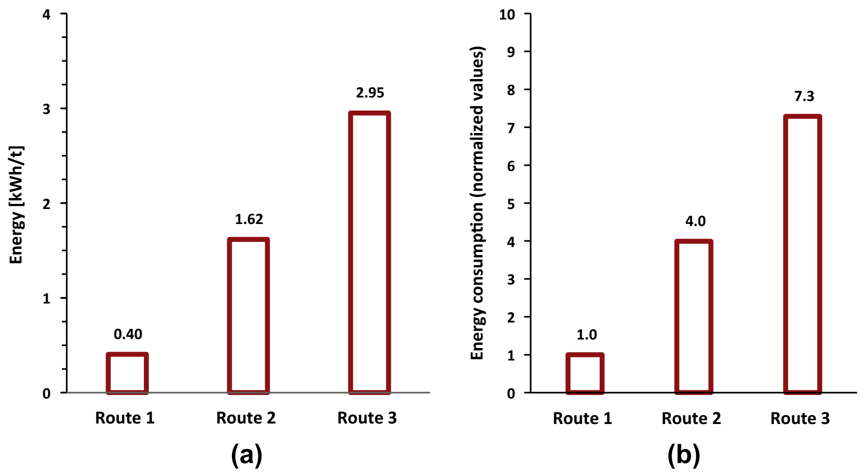


Fig. 10. Energy consumption estimation (a) and normalized values (b) of the three processing routes.

Compared to the screening process, crushing and grinding worsened the shape (the aspect ratio) of RCA due to the presence of quartz rounded river pebbles, which were only assessed by a microscope after the removal of the attached hardened cement paste by the acid attack.

After grinding, the presence of regular pebble particles in the RCA-3 sample is essentially negligible. The comminution process results in more elongated particles of minerals (quartz, feldspar and mica). The quartz pebble shape, acquired by weathering, is the main factor that contributes to a more regular shape (higher b/l – aspect ratio) of the recycled concrete aggregates obtained solely by sieving. Comminution of weathered regular quartz was responsible for the elongation of the RCA obtained by grinding.

3.6. Energy consumption

Table 5 presents the mass balances considered for the allocation of the energy consumption estimated according to item 2.4.

According to the Brazilian standard, "Aggregates for Concrete – Specification" (ABNT NBR 7211: 2009), the powder content (grain size < 0.075 mm) can reach 15% by mass. Route 3 produced a powder percentage slightly higher than the standard limit (Fig. 3). Because of this small difference, all of the processed material was considered to be useable. Therefore, like Route 2, the energy consumption of Route 3 was allocated to all of the processed material that was considered to be product (Table 5). For Route 1, the energy consumption was allocated to 70% of the processed material because 30% of the mass retained in the 9.52-mm sieve was not used in concrete block production, representing, in this case, a useless surplus and not an actual product.

Fig. 10 presents the results of the rough energy consumption estimation of the processing routes.

As expected, Route 3 (crushing, grinding and screening) is the method that requires the most energy: 1.8 times more energy than Route 2 (crushing and screening) and 7 times more energy than Route 1 (screening). Considering the estimated energy consumption of Route 1 as the baseline, Fig. 10b shows the relative energy increase. All of the equipment considered is powered by electricity, so these differences also represent the relative increase of processing costs.

4. Conclusions

The comminution and sizing routes of concrete block waste generated RCAs with different chemical and mineralogical compositions, particle size distributions, particle shapes and porosity.

Preferable comminution of low hardness cement paste of RCAs occurs rather than of quartz and feldspar from natural aggregates. Crushing followed by grinding was effective in reducing the hardened paste attached to RCA. However, a low porosity fine aggregate (water absorption of 3.5%) was produced, and a high mass of powders (<0.15 mm) without detectable anhydrous cement was generated. The low cement content in concrete block waste (approximately 150 kg/m^3) and its age (28 days) caused these results.

In this study, the acid attack of RCA allowed natural aggregates to be recovered and their shape changes to be analysed. Crushing and grinding produced irregular and elongated fine RCA due to the comminution of coarse quartz rounded river pebbles. This change of shape should be considered because this natural aggregate is used worldwide in concrete block mixtures.

The relative increase of energy consumption and processing costs by crushing and grinding was approximately 7 times higher than the more simple recycling process (pre-fragmentation and screening) and roughly 1.8 times higher than ordinary recycling (pre-fragmentation, crushing and screening). Despite the RCA porosity reduction from concrete block waste, no other benefits in terms of shape and anhydrous cement content were observed.

Acknowledgements

The authors thank CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for granting the Procad/Casadinho aid project, Case No. 552300-2011-0, between the USP and UFAL. The work of Dr. Marco Quattrone is supported by FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo (Grant 2012/15195-9). The work of Dr. Sergio Angulo is supported by FAPESP (Research Project 2012/25496-6). The authors also thank the Technological Characterization Laboratory (LCT) and the Laboratory of Microstructure and Eco-Efficiency (LME) of the Polytechnic School of University of Sao Paulo. The information and views presented in this study are those of the authors and do not necessarily reflect the opinion of the associated institutions (CNPq, CAPES and FAPESP).

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