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Separability studies of construction and demolition waste recycled sand

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ABSTRACT

The quality of recycled aggregates from construction and demolition waste (CDW) is strictly related to the content of porous and low strength phases, and specifically to the patches of cement that remain attached to the surface of natural aggregates. This phase increases water absorption and compromises the consistency and strength of concrete made from recycled aggregates. Mineral processing has been applied to CDW recycling to remove the patches of adhered cement paste on coarse recycled aggregates. The recycled fine fraction is usually disregarded due to its high content of porous phases despite representing around 50% of the total waste.

This paper focus on laboratory mineral separability studies for removing particles with a high content of cement paste from natural fine aggregate particles (quartz/feldspars). The procedure achieved processing of CDW by tertiary impact crushing to produce sand, followed by sieving and density and magnetic separability studies. The attained results confirmed that both methods were effective in reducing cement paste content and producing significant mass recovery (80% for density concentration and 60% for magnetic separation). The production of recycled sand contributes to the sustainability of the construction environment by reducing both the consumption of raw materials and disposal of CDW, particularly in large Brazilian centers with a low quantity of sand and increasing costs of this material due to long transportation distances.

1. Introduction

The construction industry is a major solid waste generator around the world (Agency, 2010; Kartam et al., 2004; Meyer, 2009; Poon et al., 2001; Rao et al., 2007). Construction and demolition waste (CDW) is generated through the construction, renovation, and demolition processes of residential or commercial buildings, roads, bridges, etc. If CDW is not recycled, this material will aggravate landfill shortage problems.

On the other hand, the demand for cement-based materials is expected to increase by a factor of 2.5 within the next 40 years, especially in developing countries (Müller and Harnisch, 2008). This implies a growing demand for aggregates, especially in large metropolitan areas, leading to greater transportation distances and impacting costs and environmental loads and therefore increasing the attractiveness of turning CDW into recycled aggregates.

Concrete recycled aggregates differ from natural aggregates in that they contain patches of attached porous cement paste from previous construction projects, and this negatively affects the workability and mechanical properties of the concrete (De Juan and Gutierrez, 2009; Etxeberria et al., 2007). Different mineral dressing operations have been proposed to remove the cement paste from coarse recycled aggregates (Linss and Mueller, 2004; Nagataki et al., 2004; Shima et al., 2005; Tateyashiki et al., 2001).

Studies about the use of fine CDW fractions are rare (Miranda, 2005; Poon and Chan, 2007; Silva et al., 2008) even though this fraction represents about half of the CDW weight. In large Brazilian centers, the shortage of sand deposits and the increasing prices (100% over the last 4 years in the city of Sao Paulo) due to long transportation distances is significant. In addition, the fine fraction of CDW represents around half of its weight. Both of these factors have contributed to a construction boom that has generated more construction and demolition waste (more than 70 million tons per year in Brazil, of which more than 40% is from the Sao Paulo metropolitan area), encouraging the development of technologies for the production of high quality recycled sand for cement-based materials.

The separation of enriched cement paste particles through mineral processing can be attained only if a reasonable degree of liberation between this material and natural aggregates has been achieved through a previous treatment. Liberation is a condition for good separation (Gaudin, 1932). With the purpose of evaluating

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the potential separation between natural aggregates (quartz and/or feldspar) and cement paste, this paper investigates mineral separability of CDW crushed sand (or CDW recycled fine aggregates) by density and magnetic separations.

2. Experimental

2.1. Field sampling and production of recycled sand

The CDW sample was collected at Urbem Tecnologia Ambiental, a private recycling plant located in the city of Sao Bernardo do Campo in the Sao Paulo metropolitan region. A total of 4 tons was collected twice a week for 60 randomly selected days following impact crushing. The laboratory procedure involved the comminution of the entire sample by secondary crushing below 19 mm with a jaw crusher, along with tertiary crushing with a vertical shaft impactor (VSI – Metso Barmac 3000) on closed circuit with a 3 mm aperture screen. The production process and operational conditions are discussed by Ulsen et al. (2012b).

The goal was to produce recycled sand from the processing of the total CDW obtained from the recycling plant and establish the best operational conditions for the removal of attached cement paste.

The metropolitan area of Sao Paulo was selected for the studies due to its significance in the country: the economy of the state represents 30% of the total Brazilian GNP, there are more than 20 million people living in the Sao Paulo metropolitan area, the generation of CDW exceeds 30 million tons per year (almost 50% of total generated in the entire country). Moreover, the maximum recycling plant capacity in the country can process at most 5% of the total CDW generated (Miranda et al., 2009).

2.2. Separability studies

The separability studies were carried out at narrow sieve fractions for two main reasons: (a) the aggregate plants have a classification process for delivering graded sand, something that is also underway in Europe and promises to be an international trend, especially for mortar applications; and (b) there is higher separation efficiency. It is therefore appropriate that the classification of recycled sand precede the mineral dressing.

The procedure comprised density separations by heavy liquid media, elutriation and magnetic separation on the Frantz barrier field separator. The experiment is described below.

Wet screening: the VSI recycled sand was sieved in wet media on screens with nominal apertures of 2.0; 1.2; 0.60; 0.30 and 0.15 mm.

Heavy liquid separation: the heavy liquid separation was carried out for each sieve fraction (>0.15 mm) at densities of 2.2, 2.5 and 2.6 g/cm^3 (bromoform admixtures with ethylic alcohol). The procedure consisted of placing a sample into an organic liquid with the appropriate density, causing the light particles to float and the heavy particles to sink and thereby separating particles with different densities (Burt, 1984). The porosity and

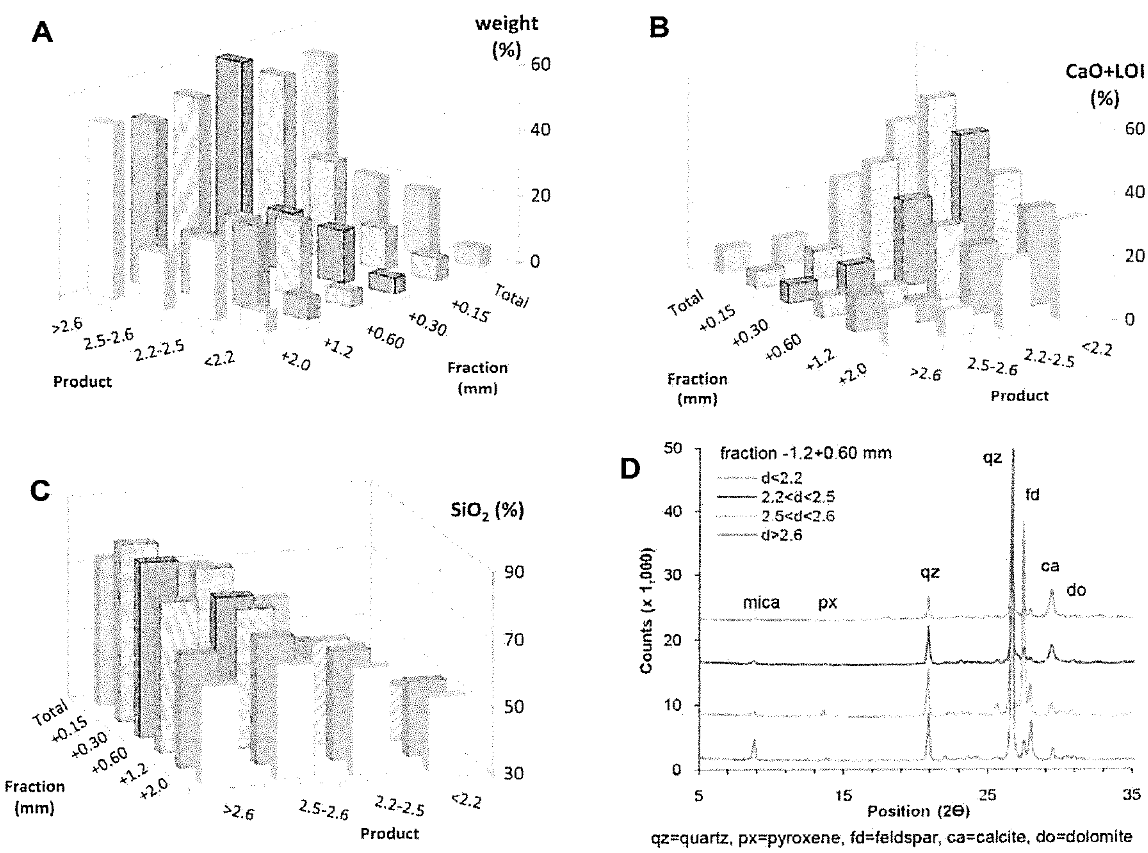

Fig. 1. Weight and grades of the main compounds in the heavy liquid separation products (A–C) and XRD patterns (D).

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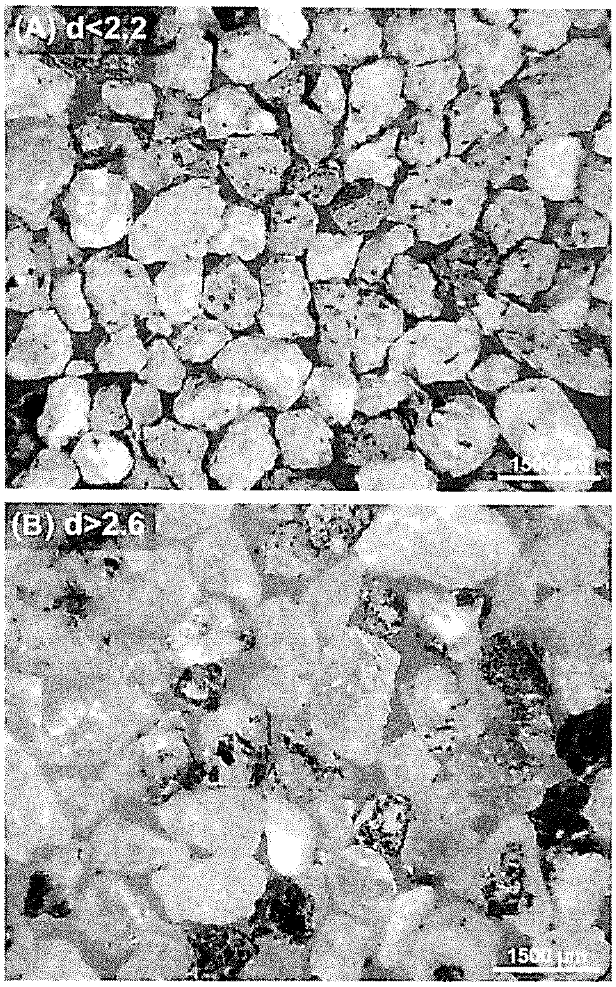

Fig. 2. Representative images of heavy liquid separation products, (A) $d < 2.2$ and (B) $d > 2.6$.

oven-dry density of density separated coarse aggregates influence the mechanical properties of concrete (Angulo et al., 2010) and the same is expected for fine CDW aggregates.

Elutriation: the separation of recycled sand through upward water flow (Taggart, 1944) was evaluated by elutriation of the narrow screened fractions employed one by one (>0.15 mm). The water flow was controlled by a rotameter and set to obtain a mass partition on light and heavy products of around 20% and 80% respectively, and a density cut of close to 2.4 g/cm^3 (based on heavy liquid separation results).

Magnetic separation on the Frantz barrier model: the Frantz magnetic separation was first conducted on the heavy liquid separation products at the fraction size of between 0.60 and 0.30 mm in order to evaluate magnetic susceptibility (Kelly and Spottiswood, 1982; Wills and Napier-Munn, 2006) by density class. The magnetic field was 0, 3.3, 4.8, 6.2, 7.5 and 8.9 kG. The separability study was then performed by sieve fraction products at the same conditions: side inclination of feed of 15° and magnetic field of 1.1, 4.0 and 8.9 kG.

2.3. Product characterization

The attained products were characterized as follows:

a. Chemical composition: quantitative X-ray fluorescence (Axios spectrometer, PANalytical) in fused beads and the loss in ignition (LOI) at 1050 °C. The chemical composition was used to indicate the content of each phase present in the recycled aggregates. The silica is mainly related to quartz; the sum of Na_2O and K_2O has a strong association to the content of feldspar (Ulsen et al., 2012a); the sum of CaO and LOI essentially indicates the content of cement paste and calcareous aggregates (Angulo et al., 2009).
b. Mineralogical composition: X-ray diffraction (XRD, powder method) of each product (PANalytical X'Pert with Cu Kα radiation and X'Celerator detector). Calcite is both related to the cement paste and calcite from calcareous aggregates.
c. Texture characterization: qualitative analysis at stereoscopic microscope to evaluate the associations between the cement paste and the aggregates.

3. Results and discussion

3.1. Mineral separability by density

The results of particle size analysis through wet sieving show that 79% of the total sample weight is above 0.15 mm, corresponding to the fractions focused in mineral separability studies.

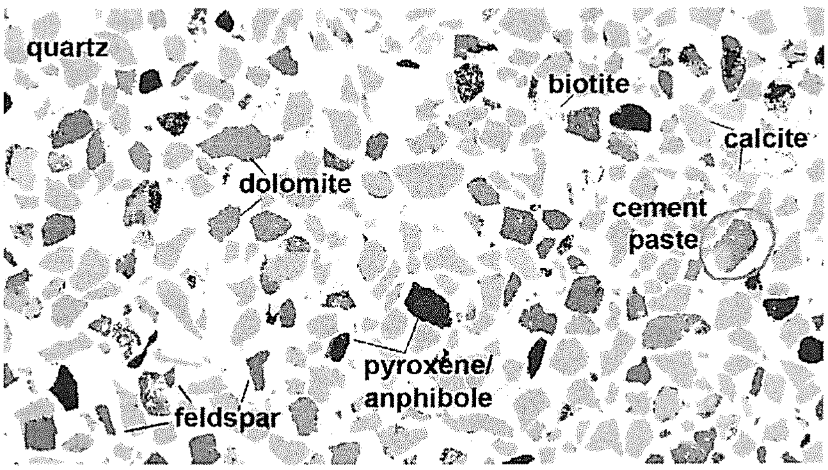

Fig. 3. Image from SEM/BSE colored according to phase discrimination showing the very low content of cement paste on sink product at 2.6 g/cm^3.

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Table 1
Cumulative results for the sink fraction of heavy liquid separation, total calculated −3.0 + 0.15 mm.

Product (mm)	w/w (%)	Grades (%)									Distribution (%)				
		SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	CaO	LOI	CaO + LOI	SiO_2	Al_2O_3	Fe_2O_3	$Na_2O + K_2O$	CaO + LOI
d > 2.6	53.9	75.6	8.22	3.18	1.78	1.87	1.16	4.85	3.32	8.17	58.0	52.5	64.3	51.2	32.5
d > 2.5	74.6	74.7	8.79	2.85	1.66	2.63	1.02	4.81	3.48	8.29	79.3	77.7	79.7	82.8	45.6
d > 2.2	94.2	71.8	8.49	2.69	1.43	2.57	1.15	6.87	4.99	11.9	96.3	94.8	95.0	97.5	82.5
Head	100.0	70.3	8.44	2.67	1.37	2.50	1.22	7.87	5.68	13.5	100	100	100	100	100

Grades mean the content of each phase (% weight); distribution indicates the proportion of some compound in such a fraction or product in relation to the total content of the whole sample.

Table 2
Summary of separability by elutriation, total calculated −3.0 + 0.15 mm.

Fraction (mm)	w/w (%)	Grades (%)									Distribution (%)				
		SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	CaO	LOI	CaO + LOI	SiO_2	Al_2O_3	Fe_2O_3	$Na_2O + K_2O$	CaO + LOI
Heavy	79.7	73.1	7.99	2.55	1.48	2.48	1.02	6.26	4.58	10.8	82.9	75.5	76.1	81.3	63.8
Light	20.3	59.2	10.2	3.15	0.97	2.57	2.02	14.2	10.0	24.2	17.1	24.5	23.9	18.7	36.2
Head	100	70.3	8.44	2.67	1.37	2.50	1.22	7.87	5.68	13.5	100	100	100	100	100

Grades mean the content of each phase (% weight); distribution indicates the proportion of some compound in such a fraction or product in relation to the total content of the whole sample.

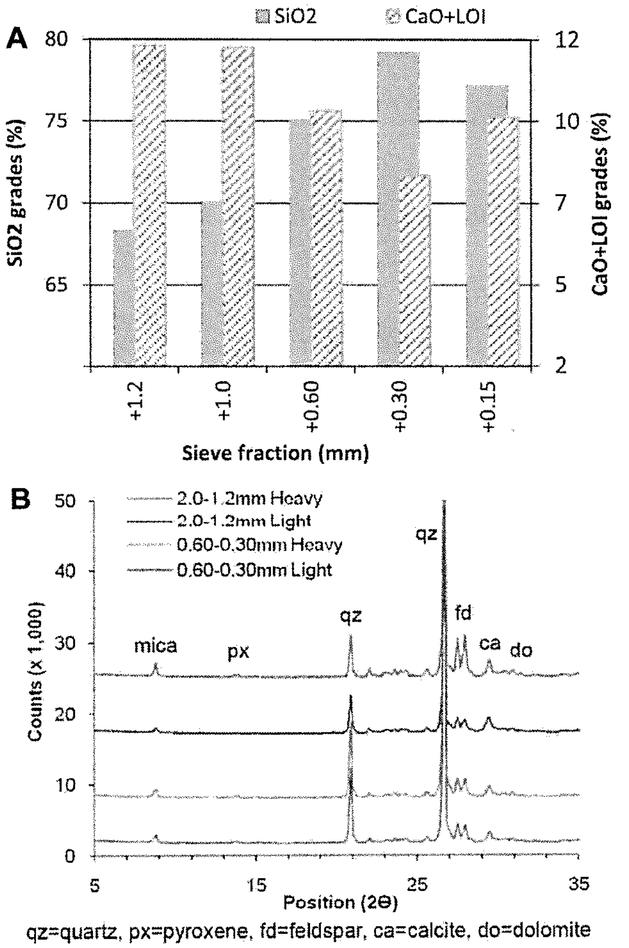

Fig. 4. Grades of the main compounds (A) and XRD patterns (B) of the heavy elutriation product.

3.1.1. Heavy liquid separation

The products at densities below 2.5 g/cm³ represent 25% of the total weight for fractions above 0.15 mm (Fig. 1A) and present higher content of cement paste (from 25% to 40% of CaO + LOI on average) (Fig. 1B). As expected, the consequence is lower silicate content (quartz and feldspar, Fig. 1C and D). Stereomicroscope imaging confirms that CDW aggregate particles are surrounded by porous cement paste (Fig. 2A).

Regarding the cement paste content, the decrease in the amount of CaO and LOI in products with densities greater than 2.5 g/cm³ is notable (Fig. 1B) and there is an increase in silicates content (Fig. 1C and D), mainly quartz and feldspar. Images from the stereomicroscope show that the sink product at 2.6 g/cm³ is composed basically of quartz, feldspar and mafic minerals (mica, pyroxene, amphibole) in free particles or with small patches of attached cement paste in mineral particles (Fig. 2B).

From the coarser to the finer fractions, the grades of silica increase for the denser products while the content of CaO + LOI increases for the lighter products. This behavior indicates that there is a better liberation between cement paste and the aggregates at the finer grain size fractions. Therefore, the cement paste

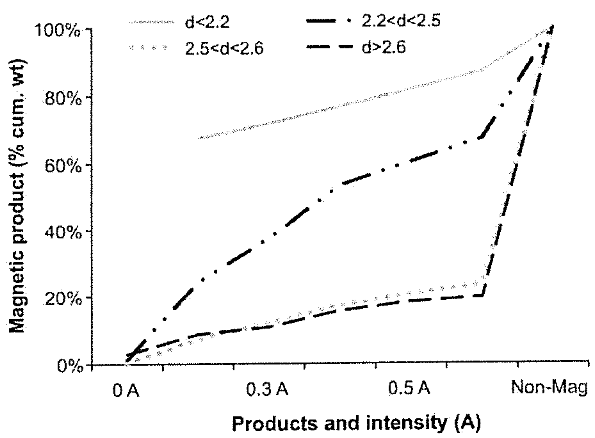

Fig. 5. Magnetic separability curves (w/w) for density classes, fraction −0.60 + 0.30 mm.

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tends to be removed in the lower density products while the aggregates are rather concentrated in denser products.

The evaluation of cement content based on the sum of CaO and LOI is overestimated for sink products at 2.6 g/cm^3 due to the higher content of calcium bearing phases (around 50%) such as calcite from calcareous aggregate and mafic minerals (Ulsen, 2011) compared to cement paste (Fig. 3).

From the point of view of mineral separations, the removal of light phases will result in a product with lower cement paste content (Table 1). The removal of product float at 2.5 g/cm^3, which represents 25% weight (fractions > 0.15 mm) and 55% of the total CaO + LOI generates a product with high recoveries of silica, alumina, iron oxide and alkalis (about 80%). Increasing the density of the separation to 2.6 g/cm^3, the grades of CaO + LOI decrease from 13.5% on head sample to 8.17% (calcareous aggregates and cement paste) at sink product at 2.6 g/cm^3; as well, the distribution of weight and the main oxides also decreases.

3.1.2. Elutriation

The results of the elutriation are shown in Table 2. The grades and distribution of the main chemical compounds of the heavy product for each sieve fraction and XRD patterns of selected fractions are summarized in Fig. 4.

The elutriation applied to narrow sieve fractions of the recycled fine aggregates indicates that the cement paste (represented by CaO + LOI) decreases significantly in heavy products (10.8% on

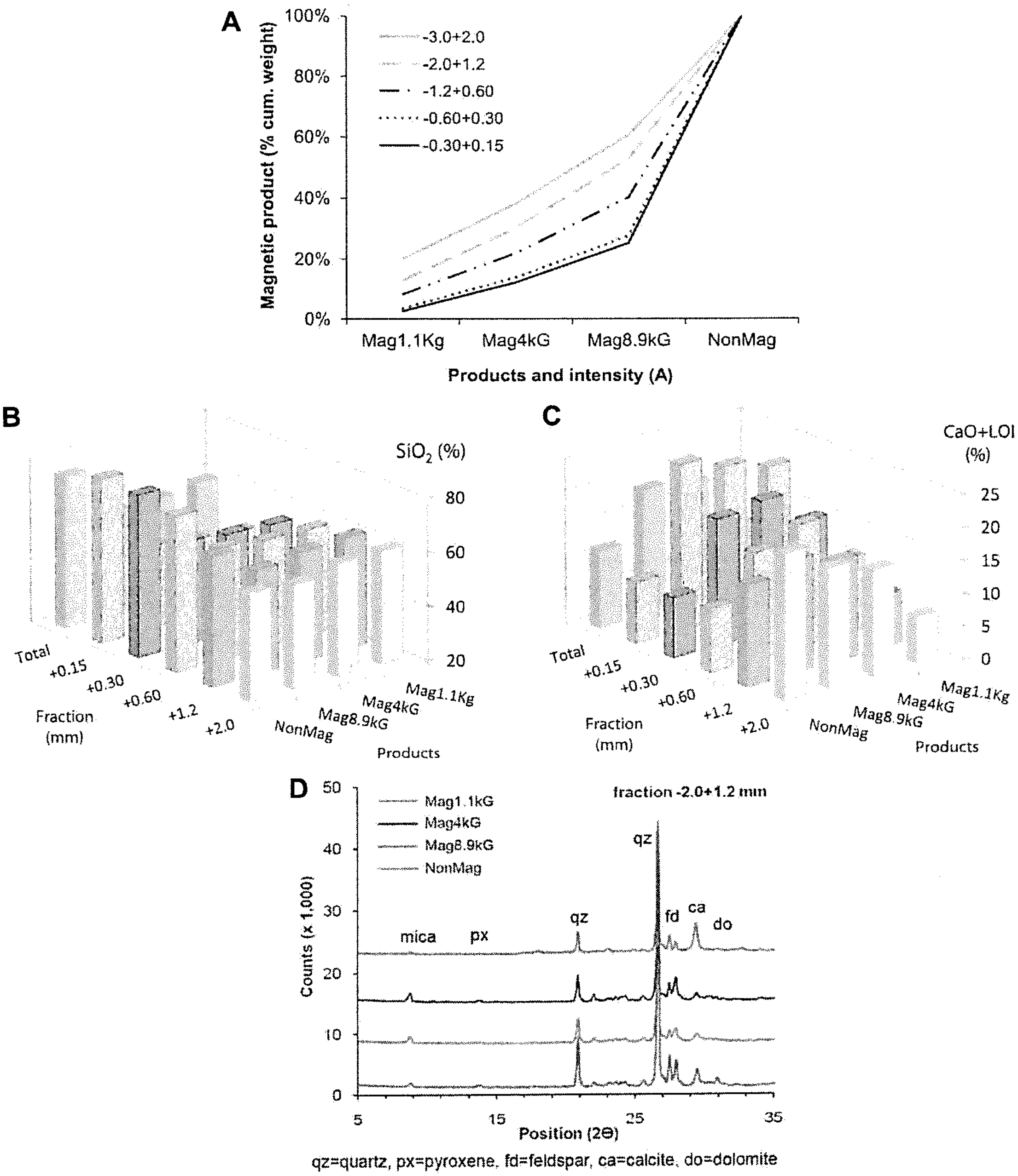

Fig. 6. Weight distribution (A), SiO_2 grades (B), CaO + LOI content (C), XDR patterns (D) in magnetic separation products.

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average) when compared to light ones (24.2% on average). Considering that in heavy products the sum CaO + LOI is also attributed to the calcareous aggregates and other mafic minerals, the content of cement paste in this product is lower than estimated, and so the elutriation is more efficient in the removal of porous cement paste in light products than estimated by the sum CaO + LOI.

Regarding sieve fractions, there is a notable increase in silica and a decrease in CaO + LOI (Fig. 4A) content at the fine fractions, which once more indicates better liberation of cement paste from the aggregates at the finer grain size fractions. The silica increased due to the presence of quartz in sand aggregates (confirmed by XRD analysis, Fig. 4B); the lessening of CaO + LOI content indicated liberation of the cement paste and the natural aggregates at the finest fractions, while the enrichment of $Na_2O + K_2O$ at coarser fractions was associated with the presence of feldspar (confirmed by XRD).

The distribution indicated that around 60–70% of CaO + LOI is associated with the light product despite representing only 20% of the weight. On the other hand, around 75–85% of the total silica as well as alumina, iron oxide and $Na_2O + K_2O$ were associated with the heavy product. K_2O is also present in the float product since it is related to both feldspar (microcline/orthoclase) and mica (biotite/muscovite), which tends to float due to its plate-like shape.

The chemical composition of the products clearly demonstrates that the light and heavy products are different and reflect the same behavior observed in the heavy liquid separations. Considering the separation principles and the fact that elutriation was performed in narrow sieve fractions, the density separation in water media has a great potential to separate particles with a high content of cement paste from those more liberated from the paste.

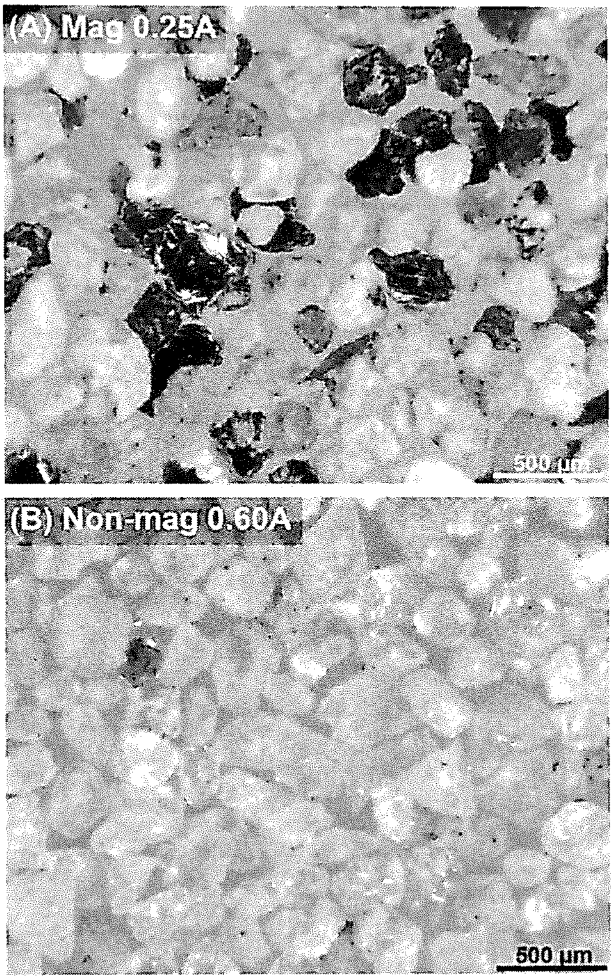

Fig. 7. Representative images of magnetic separation products, (A) magnetic at 1.1 kG, and (B) non-magnetic at 8.9 kG.

3.2. Mineral separability by magnetic susceptibility

The results of the initial evaluation of magnetic separability tests on a Frantz barrier field magnetic separator using the products from heavy liquid separation (fraction −0.60 + 0.30 mm) are shown in Fig. 5.

The graphs clearly demonstrate a very distinct behavior for product float at 2.5 g/cm^3. The lighter the product, the higher the content of cement paste and the higher the magnetic susceptibility. So it is possible to conclude that magnetic susceptibility is a differential property between enriched cement paste particle and recycled sand.

The product float at 2.2 g/cm^3 ($d < 2.2$) had 68% w/w magnetic at 3.3 kG and 87% w/w at 8.9 kG. The $2.2 < d < 2.5$ g/cm^3 product displayed 68% w/w for the magnetic product at 8.9 kG. By increasing the separation density and thus reducing the attached cement paste content, a systematic decrease in the content of the magnetic products is observed.

Magnetic separability curves, comparative grades of SiO_2, CaO + LOI and XRD patterns of selected fractions are shown in Fig. 6.

The magnetic separability curves indicate that the finer the fraction size, the lower the content of magnetic material (from 39% to 75% weight, Fig. 6A), due to the liberation of cement paste from the aggregates at the finer grain size fractions.

The grades of CaO + LOI in the non-magnetic product decreased noticeably and approached the finer fractions, while the grades of SiO_2 increase, principally below 1.2 mm due to the greater liberation of the cement paste and natural aggregates at finer fractions (Fig. 6B and C). The XRD confirms the enrichment of quartz in the non-magnetic product (Fig. 6D). In magnetic products, it is possible to identify mica and other mafic minerals, pieces of ceramic and particles with patches of attached cement paste (Fig. 7A), especially at coarser fractions.

Table 3
Cumulative results for the non-magnetic products, total calculated −3.0 + 0.15 mm.

Fraction (mm)	w/w (%)	Grades (%)									Distribution (%)				
		SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	CaO	LOI	CaO + LOI	SiO_2	Al_2O_3	Fe_2O_3	$Na_2O + K_2O$	CaO + LOI
Non-magnetic 8.9 kG	59.6	77.5	6.10	1.51	1.05	2.20	0.77	6.36	5.24	11.9	65.7	43.1	33.7	45.5	52.4
Non-magnetic 4.0 kG	77.5	73.3	7.40	1.99	1.14	2.32	1.01	7.47	5.80	12.6	80.8	68.0	57.9	64.1	71.9
Non-magnetic 1.1 kG	91.0	71.2	7.90	2.36	1.20	2.38	1.17	8.02	5.92	12.9	92.3	85.2	80.4	79.6	86.9
Head	100	70.3	8.44	2.67	1.37	2.50	1.22	7.87	5.68	13.5	100	100	100	100	100

Grades mean the content of each phase (% weight); distribution indicates the proportion of some compound in such a fraction or product in relation to the total content of the whole sample.

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Regarding mineral separations, the removal of magnetic phases generates a product with lower content of cement paste composed essentially of quartz and feldspar (Fig. 7B). The grade and recoveries of the attained products are shown in Table 3.

The removal of the magnetic product at 8.9 kG generates a non-magnetic product representing almost 60% of the total sample weight, enriched in silica (grade of 77.5% and 65.7% distribution) with lower grades of alumina, iron oxide, alkalis and CaO + LOI. The increasing relative proportion of quartz is notable (Fig. 7B). Considering the separation at lower magnetic intensities (1.1 and 4.0 kG), weight recovery increases significantly.

Thus, magnetic separation appears to be an alternative for separating particles with different cement paste contents, with the advantage of being a dry separation method. Although, compared to density separation, the reduction of CaO + LOI grades is lower for a similar weight recovery, indicating that magnetic separation is less selective than density separation.

4. Conclusions

The production of recycled sand from the comminution of the entire CDW by tertiary crushing represents an alternative for obtaining sand in a low-income consumer market where the generation of waste is significant.

The separability studies performed at laboratory scale indicate that both density and magnetic separation were effective at reducing the content of cement paste and residual red ceramic particles since the cement paste and natural aggregates have achieved a proper degree of liberation; efficiency was greater for fractions below 1.2 mm due to the greater mineral liberation. The removal of cement paste and other porous phases is important to improve the quality of the recycled sand and enlarge the market for recycled aggregates.

The mass recovery was 80% for density separation ($d > 2.5$ and heavy elutriation products) and 60% for magnetic separation (non-magnetic 8.9 kG).

Magnetic susceptibility is a differential property between enriched cement paste particles and recycled sand (mainly quartz and feldspar particles). As an advantage, separation does not require water and so contributes to the sustainability of the recycling process.

The suggestion for future studies is to evaluate the separability performance of recycled sand on pilot or semi-industrial scale operations. The circuit should consider the comminution below 1.2 mm (due to the liberation results), removal of fractions below 0.15 mm enriched in cement paste and mineral separation at the above fractions. Density separation could be conducted on spirals or up-current water separators or shaking tables, and dry magnetic separations could consider rare-earth separators, such as ReRoll. Reductions in the porosity of the attained products have to be evaluated and energy consumption and CO_2 balance should also be considered in the feasibility studies.

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