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Stratification in air jigs of concrete/brick/gypsum particles

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HIGHLIGHTS

- Separation of concrete, brick and gypsum particles from CDW recycled aggregates.
- Separation and concentration of concrete, brick and gypsum particles through gravity concentration.
- Concentrates with high concrete particles and low gypsum contents.
- Gypsum reduction in concrete concentrates of about 25 times.

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ABSTRACT

This work deals with the separation of concrete, brick and gypsum particles from a CDW recycled aggregate mixture. Construction and Demolition Waste materials can be handled as an ore treatment problem. Efficient sorting processes of low quality CDW recycled aggregate could allow the reuse of concrete, brick and gypsum particles. The processes also improve the remaining mixed aggregates for recycling in unbound sub-base materials, by increasing their self-cementing properties and by reducing the sulfate content through the removal of gypsum. All tests were carried out in the size range between 4 and 20 mm using a laboratory air jig. The aim of the work is to concentrate a high amount of gypsum (light material) and concrete (heavy material) particles. Three working parameters are relevant for the jigging processes control such as the sorting duration, the frequency and the expansion ratio. Each of them are studied. It was found that a quadratic model of the number of jig cycles, a product of the frequency and time, accurately predict well the sorting results, if the expansion is large enough. An optimal point seems achieved at about 320 jigging cycles. Concentrates with concrete contents higher than 90% and gypsum contents significantly lower than 1% were possible to be reached and can be an alternative in aggregates for the concrete market. Indeed, gypsum reduction in concrete concentrates was about 25 times. This level of reduction could be satisfactory in sorting real demolition products. On the other hand, contents of over 70% of gypsum concentrates were obtained, increasing the reuse and recycling abilities.

1. Introduction

The basic composition of Construction and Demolition Waste (C&DW) is strongly dependent, among others, on geographical location, type of the construction – commercial or residential [1], or on construction method, conventional or precast [2]. The approximate mean percentage of concrete and ceramics in demolition waste is estimated at 70% [3]. The use of these inert residues is economically feasible [4] but unfortunately, when recycled, the employment of inert waste materials as recycled aggregates is still limited to building materials in public works (embankments, pavements, etc.), or as material for the recovery of degraded areas in quarries. There are also examples of better uses for some of these residues as they have a higher content of concrete and lower content of contaminants like gypsum. They are recovered and used as Recycled Concrete Aggregates (RCA), mainly the coarse RCA fraction (i.e. 4/20 mm), for new concrete

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mix-design. This can provide a net environmental benefit for the concrete recycling method [5]. A more complete reuse is generally hampered by the lack of suitable recycling plants [6].

The success of the off-site construction waste sorting program could be encouraged by government incentive policies [7,8] or by improving the design decisions [9]. For instance the current European and French goal to be achieved by 2020, requires the recovery of 70% by weight of all C&DW from construction and public works [10]. The utilization of a waste management policy on construction sites potentially enables a cost reduction of about 30–40% [11,12]. However, only few building industry players implement the selective demolition and disassembly [13], which is considered time and labor demanding [14]. In fact, the difficulties in implementing in real practice an environmental management system in accordance with ISO Standard 14001 are discussed by Rodriguez et al. [15]. Consequently, improved mechanical sorting systems should be considered to complete the efficiency of the production of high quality recycled aggregates.

Separation methods to treat C&DW are proposed by Tomas and Gröger [16]. Equipment with relatively low separation efficiency is adequate for removing light impurities, such as paper, wood, plastics, etc. Magnetic and eddy current separation can be used to remove ferrous or non-ferrous metals [17]. These kind of sorting systems are included in the advanced industrial mechanical sorting plant as described by Huang et al. [18]. In the current practice, the remaining contaminants are removed, by selective demolition, before the mechanical sorting or after, by manual sorting [19]. Industrial concentration by the use of automatic sorting of recycled aggregates is only embryonic. One can correlate this situation to the marginal utilization of RCA in structural concrete. More sophisticate technologies should be considered for the sorting of ceramic, asphalt, concrete, glass and gypsum particles in order to improve the quality of recycled mixtures up to that of Recycled Concrete Aggregates. In particular, the sorting of the coarse fractions is of first importance, as the reuse of the high quality coarse RCA has become industrially relatively easy, nowadays.

Synergies between mineral processing and recycling of C&DW are obvious, as beneficiation processes of C&DW are similar to those used in the mining industry, after removing contaminants like plastics, paper, iron pieces, etc. However, only a few researches focus on the improving of mechanical sorting in the C&DW plants. It was shown that particular grading classes are more suitable to be re-utilized as first-order material in the building activity [6]. Ulsen et al. [20] had shown the effectiveness of density and magnetic reparability methods in the removal of cement paste and other porous phases from the recycled sand. Montero et al. [21] shows that removing a given density range after segregating fine particles should reduce the amount of gypsum in the total waste mass.

Some researchers have suggested the use of water jigs [19,22] or air jigs [11,12,23] for the density separation of recycled aggregates. Other complementary methods are suggested, like the spirals [11] or the sensor based sorting [23]. A list of available ideas to treat recycled aggregates is also given by Schnellert and Mueller [24], who consider jigging and optical sorting as having a good sorting performance. None of these devices was deeply investigated in the literature for the use in RCA sorting. However, several authors are in agreement about the jigging utilization as a promising method to treat C&DW, characterized by different particles densities [25–29].

In the mineral processing area, there are some size ranges that are used worldwide in processing plants. The classical sizes used are the following [30]:

– 0/0.1 mm – physical-chemistry methods, like froth flotation, agglomeration, floc-flotation, etc.
– 0.1/2 mm – known as fine material – gravity concentrators for fines, like spirals, concentrating tables, jigs for fines, etc.
– over 2 mm – gravity concentrators, like jigs, heavy-media, trommels, etc.

The efficiencies presented by gravity concentrator equipment that use air as a separation medium are quite lower than those which use water [30]. In order to facilitate the processing of minerals by the use of air (for instance air jigs), narrower size ranges are usually used. For instance, air jigs can operate with a size range between 4 and 20 mm.

It is expected that in the near future, air jigs can be efficiently used in the treatment of C&DW. This paper evaluates the potential of a laboratory air jig equipment to separate concrete, brick and gypsum particles aiming at C&DW industrial applications. All tests were carried out in the size range between 4 and 20 mm using a laboratory air jig. The aim of the work is to concentrate a high amount of gypsum (light material) and concrete (heavy material) particles. Three working parameters are relevant for the jigging processes control i.e. the sorting duration, the frequency and the expansion ratio.

2. Jigging process description

2.1. Jigging process

Jigging is a separation process, which consists of repeated expansion (dilatation) and contraction (compression) of a bed of particles, by the use of a medium, usually water or air. For air jigging, a constant mass flow rate, U_0, is imposed in order to extract the finest particles created by attrition. Its result is a stratification phenomenon of the bed with increasing densities of the particle from the top to the base as represented in Fig. 1. Whatever the jigging method, the pulsations, w, and expansion ratio, A, of the process act on the physical segregation itself governed by the alternation of fluidization and sedimentation.

It is worthwhile mentioning, that jigging pulsation cycles are not always sinusoidal. Over the last years, several jigs, for instance Batac jigs, have presented the possibility of setting different jigging diagrams (pulsation cycles). This makes possible a better optimization of jigging parameters and consequently the Tromp imperfection improvement of the new series of machines [30].

Thus, these characteristics of the fluid pulsation control the fluid velocity that produces the fluidization stage enabling stratification [31].

Jigging is one of the oldest processes used in ore concentration. Its basic principle of operation was already known in Ancient Egypt [32]. It is difficult to prove that jigging was used in antiquity, but a classical text of mineral processing [33] shows that this process has been used for ore concentration in Europe since the 16th century. The jigging process has developed significantly since the days of Georgius Agricola. Jigs pulsed manually and operated discontinuously were used until the 19th century. The ever increasing demand for ores and coals with the beginning of the industrial revolution resulted in great technological advances in jigging. The basket previously used for the retention of ore particles has been replaced by a chamber equipped with a screen (or grid) onto which the material is fed. In this way, the operation also changed from discontinuous to continuous [34]. Modifications were also carried out to the system responsible for particle bed pulsation, which went from manual to mechanical, through the use of pistons with or without rubber seals (diaphragms) [35].

Jigs were and remain widely used mainly because of their low costs. Besides presenting low operational costs, jigs are robust, have a high capacity, are easy to operate and beneficiate relatively

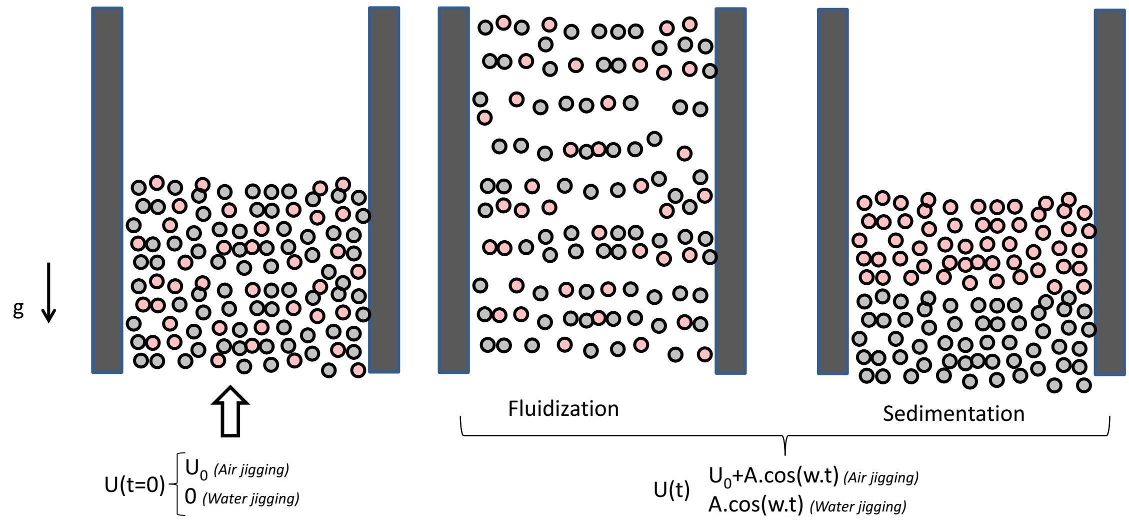

Fig. 1. Jigging process starts with mixed particles. A pulsating mass fluxes (water or air) is delivered through the granular medium at a given frequency (w) and amplitude (A). Successive fluidization and sedimentation cycles enables the segregation phenomenon.

large particle distribution, which simplifies mineral processing flowcharts. In comparison with other beneficiation processes, jigs present great capacity to absorb large fluctuations of ore contents, feed rates and solid percentages.

Besides water, jigs can use air as a medium to promote stratification by particle densities. They are known as air jigs or dry jigs. In contrast with water, the intermittent upward air flow causes significant turbulence when passing through a layer of particles with different sizes, turbulence having large influences on the particle stratification. It was observed that the separation efficiency of equipment using air is lower than the efficiency of those that use water [30]. For instance, the particle size of the material to be processed is slightly higher than the particle size used in water jigs. However, air jigs can efficiently beneficiate particles with sizes over 4 mm [36].

Due to their lower efficiencies, the air concentrators were only used when water is missing near the processing station or when the ore could not be wet [35]. Nowadays, with increasing environmental restrictions on water uses as well as the water price for utilization, equipment such as air jigs are increasingly being installed [37]. A new generation of air jigs has been widely used in coal beneficiation in rougher and/or cleaner stages [38,39].

2.2. Concentration criterion

In mineral processing industry a concentration criterion, CC [40] is largely used to estimate the ease at which materials can be separated by gravity methods. CC is defined by the following formula:

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

where ρ_h – density of heavy particle, in g/cm^3; ρ_f – density of the fluid (used in the equipment, in this case air), in g/cm^3; ρ_l – density of light particle, in g/cm^3.

When CC is a large number (large density difference between particles), it is easy to concentrate (by physical separation) the particles. If CC is a small number, it means that heavy and light particles have almost the same density. In this case, it is considered that the separation is difficult or impossible to be carried out. Obviously, the limit CC between particles easy or hard to be separated is a function of the particle size. The coarser are the particles and shorter the size distribution, the greater is the sorting efficiency [30].

A second driving force for segregation is proposed by Epstein [41] for binary spheres systems of same density ρ_p but different diameters. He considers the reduced bulk densities difference of the two particle species:

$$\gamma = \frac{\rho_{BL} - \rho_{BS}}{\rho_p - \rho_f} \tag{2}$$

where ρ_f – density of the fluid used in the equipment; ρ_{BL} and ρ_{BS} – bulk densities of the large and small particles respectively when each is fluidized separately.

As suggested by Escudié et al. [42], when using non-spherical particles the difference in bulk densities take into account the difference in particle shape between the two particles species.

3. Experimental method

3.1. Characterization of the materials

The air jig tests were conducted with particles having a size of 4/20 mm, a range considered as typical for the coarse recycled aggregates size. This particle size (4/20 mm) is suitable and largely used for recycling aggregates and it is a size range appropriate for jigging [30].

For each material the skeletal and envelope density [43] were measured. To obtain the skeletal density a helium pycnometer (multipycnometer quantachrome) was used. The envelope density was calculated by weighting and water volume displacement after surface impermeabilization.

Some density definitions used in this work are the following [43]: *Bulk Density* – the mass of the particles divided by the volume they occupied that includes the spaces between the particles; *Skeletal Density* – the ratio of the mass of discrete pieces of solid material to the sum of the volumes of the solid material in pieces and closed (or blind) pores within the pieces; and *Envelope Density* – the ratio of the mass of a particle to the sum of the volumes of: the solid in each piece, that is, within close-fitting imaginary envelopes completely surrounding each piece.

3.2. Jigging process parameters

An AllMineral Company air jig, modell "AllAir S 500®", was used to perform the tests (Fig. 2a). The AllMineral jig is composed of two inputs of the air flow at the bottom of the equipment. The two streams of air simultaneously enter into the machine. The first airflow is responsible for the expansion of the particles bed to be stratified. The second flow vibrates the particle bed. With the entry of the two airflows, the particle bed is expanded and vibrates due to the second inlet airflow. This movement enables the stratification of the particle bed, which presents increasing density from the top to the bottom of the equipment.

Fig. 2. AllMineral jig – (a) modell "AllAir S 500®", used in the tests. (b) Assembly of the jig chambers.

All jigging tests were carried out in batch mode. The equipment simulates stratification that happens inside a continuous jig. An industrial jig promotes along the equipment several expansions and contraction of the particles bed, which can be simulated in the laboratory jig.

It was possible to set some jigging parameters during the tests, which were run in batch mode. The device parameters used are the following:

- Frequency of the jigging pulsation, which is measured in pulsations per min. One pulsation is one expansion (dilatation) and one contraction (compression) of the particles bed; and
- Expansion of the particles bed linked to the amplitude mentioned in Fig. 1. Thus, a percentage of the ventilator capacity (motor generates 6000 Pa) is presently used.

The AllMineral jig is assembled in different sections or boxes (without bottom) one over the other (Fig. 2b), where particles are stratified during the tests. The first section was completely filled with concrete particles. The second vertical section was filled with brick particles, and the third one with gypsum (Fig. 3a).

4. Results and discussions

4.1. Materials and jigging process

Three types of materials – concrete (C25/30), solid clay bricks and gypsum from solid gypsum blocks – were comminuted at a top size of 20 mm. In the size distribution of the particles used in this work (comminuted under 20 mm), the concrete particles in size range 4/20 mm represents 72.40% of the feed (27.60% of the concrete particles are under 4 mm); the brick particles 70.27% (29.73% under 4 mm); and the gypsum particles 66.27% (33.73% under 4 mm). The size distribution of the materials used in tests is given in Table 1. The fraction that is finer than 4 mm of all materials was discarded by sieving and not used in the following tests.

The density results are given in Table 1. In addition, the bulk density of each individual material was determined by simply pouring the dry aggregate in a box of known volume. The bulk densities are also presented in the Table 1 as well as the standard deviation obtained after 10 repetitions.

Table 1
Materials characterization: size distribution (fraction 0/4.75 mm was discarded) – skeletal and envelope density of the materials; Bulk density of dry particles when poured in the box, with the standard deviation.

Material Fraction (mm)	Concrete Mass (%)	Brick Mass (%)	Gypsum Mass (%)
15.9/19.1	3.9	12.6	3.6
9.5/15.9	38.6	43.2	46.4
6.35/9.5	28.8	31.0	38.1
4.75/6.35	28.7	13.2	11.9
Skeletal density (g/cm^3)	2.67	2.59	2.30
Envelope density (g/cm^3)	2.39	2.26	1.86
(Dry) bulk density ± standard deviation (g/cm^3)	1.67 ± 0.037	0.84 ± 0.042	0.61 ± 0.046

Samples of about 39 kg of mixed particles were first obtained from 53% of concrete particles, 27% of brick particles and 20% of gypsum particles, in mass. The mixed particles sample is poured in the assembly of the boxes (Fig. 3a). The amount of each material (concrete, brick or gypsum) was chosen to fill completely one chamber after a hypothetical perfect separation of the three particles species (Fig. 3a).

Once the particles stratified after jigging (Fig. 3c), the boxes were removed separately. The particles inside each layer – Inferior, Middle and Superior – were separated by hand and weighed. For each jigging test, the percentage in weight of concrete, brick and gypsum inside each layer (Inferior, Middle and Superior) was determined. The box or the chamber close to the bottom of the air jig was named the Inferior layer; the box or chamber in the middle, Middle layer; and the box or chamber on the top, Superior layer.

Two sets of tests were conducted. The first one is dedicated to the jigging parameters optimization (frequency, expansion ratio

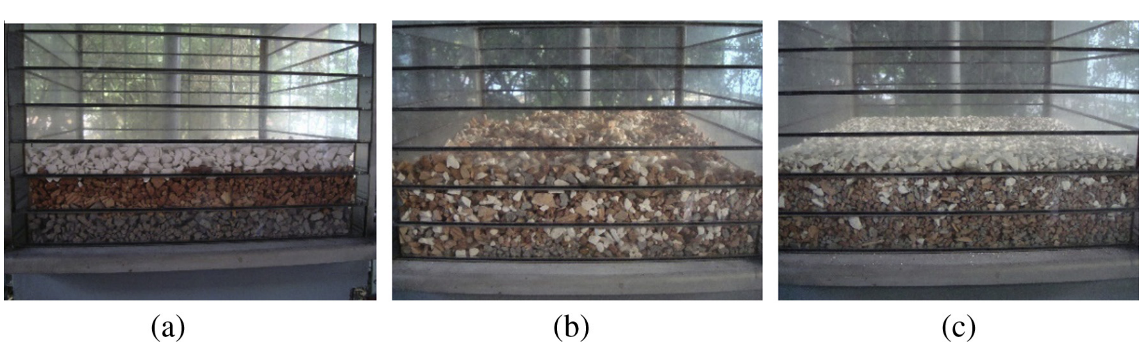

Fig. 3. Jigging bed. (a) Feed, before mixing; (b) feed, after mixing, before sorting; (c) after sorting, stratified particle bed.

and time duration), while the second set of experiments was dedicated to the influence of the amount of mass of gypsum (3%, 5% and 10%) and concrete (59% and 63.5%), as a consequence of the preliminary study based on the CC and reduced density calculations (see Section 2.2). For practical reasons, the content of the mixture slightly evolves from the imposed values. The real content of the mixture is indicated for each test in the next section.

A preliminary analysis is possible by a simple calculation of the concentration criterion and the reduced density. In a simplified manner, the reduced bulk density difference can be calculated from the bulk densities of each individual type of aggregate. In addition, the envelope density is considered as the particle density in Eq. (1) and the mean of these values as particle density in Eq. (2). By analyzing the values presented in Table 2, one can observe that the largest level of segregation should be obtained between the concrete and gypsum particles. The segregation between concrete and brick particles is more likely driven by the difference in bulk density while the segregation between brick and gypsum should be driven by the difference in envelope density.

4.2. Assessing of the jigging working parameters

Table 3 presents the percentage in mass of each material type (concrete, brick and gypsum) in the three layers as a function of frequency, jigging time and expansion ratio. These compositions are expressed graphically in the Fig. 4. The initial composition of the mixture is kept similar in all tests. The measured composition of each test is also presented in this table. As explained in Section 4.1, after jigging tests, the jig chambers were removed separately. The particles in each layer, Inferior, Middle and Superior, were separated by hand and weighed. The percentage in weight of concrete, brick and gypsum inside each layer was determined and are presented in Fig. 4.

Six experiments with variable duration (30, 60, 90, 120, 150, and 180 s) of the jigging are carried out at constant frequency (160 cycles per minute – cpm) and expansion ratio (70%). Four experiments is conducted by varying the frequency (150 cpm and 170 cpm) at constant expansion ratio (70%), then by varying the expansion ratio (60% and 80%) at a constant frequency (160 cpm) for 120 s.

The jig is composed of two inputs of air flows at the bottom of the equipment, one constant and another cyclic, described in Section 3.2. The two streams of air enter simultaneously in the machine. Due to the difficulty of estimate the airflow on the top of the jig, a percentage of the ventilator capacity (motor generates 6000 Pa) was used.

In order to facilitate the working parameters evaluation, a criterion based on a Sorting Index is proposed herein:

$$I_c = \frac{C + B + G}{3} \quad (3)$$

where C, B and G indicate the measured mass proportion of concrete in the inferior layer, brick in the middle layer and gypsum in the superior layer, respectively.

Table 2
The concentration criterion and the reduced bulk densities difference for the three pairs of materials.

	Concentration criterion	Reduced bulk densities difference
Brick–Concrete	1.06	0.36
Concrete–Gypsum	1.28	0.50
Brick–Gypsum	1.22	0.11

4.2.1. General segregation trend

Fig. 4 shows that the mixture is stratified according to the following distribution:

- Concrete mainly fills the Inferior layer (about 80–90%), brick the Middle layer (40–60%) and gypsum the Superior layer (about 60–80%). All these concentrations are significantly higher than the mean composition in the corresponding constituents;
- Among these concentrations after jigging, the brick in the Middle layer is characterized by lower concentration. This is explained by the presence of non-segregated brick particles in both Inferior and Superior layers;
- The low amount of gypsum in the Inferior layer as well as the high amount of gypsum in the Superior layer gives good perspective for future industrial application.

4.2.2. Influence of the jigging time

All the elements of the stratification are mostly effective at the shortest tested jigging time, i.e. 30 s (Fig. 4). Indeed, stratification by gravity generally occurs quickly [44]. Also, a perfect stratification will never be reached [44], due to the imperfection of the process (Tromp Curve). However, an equilibrium is reached when stratification and re-mixture have the same influence and the particle bed reaches a balance. Even with an important increasing in jigging time, no significant gain in stratification will be reached, since the stratification error (Tromp Imperfection) depends on the equipment used and not on the material [45–47].

However, a more careful examination shows a slight evolution with longer jigging time. For instance, the proportions of gypsum slightly evolve with an increase in jigging time. The stratification processes along the jigging time is better evidenced by the evolution of the mass ratios in Inferior, Middle and Superior layers (Fig. 5). On average, the mass ratios diminish 25% each time the jigging time doubles, during stratification process progress and follow power laws. A faster evolution is noticeable in each layer characterized by a larger power coefficient. As for example, in the middle layer, the concrete/brick couple is faster than for gypsum/brick. By considering the concentration criterion and the reduced bulk densities difference in Table 2, the evolution in the Middle layer may suggest that the effect of the bulk densities has more pronounced effect than the particle densities.

The Sorting Index increases with the quality of the stratification. It varies between 0.33 for a perfect heterogeneous material to 1 for a perfect stratification. It can be observed that there is a substantial increase in Sorting Index values between 90 and 120 s (Table 3). After this time, the Sorting Index is stable. Consequently, a time of 120 s was fixed for the following jigging tests.

4.2.3. Influence of frequency and expansion ratio

Fig. 6 shows the percentage in mass of Concrete, Brick and Gypsum in the Inferior, Middle and Superior layers for three of jigging frequencies: 150 cpm, 160 cpm and 170 cpm. In these tests all other experimental parameters are kept constant: same mixture composition as in the previous tests, jigging time 120 s, expansion ratio 70%. The effect of the jigging frequency can be well observed in the Superior layer (Fig. 6c), where the proportion of gypsum increases with high frequencies, while both concrete and brick decrease. Indeed, up to a given level, it is expected that the increase in the frequency makes easier the movement of particles up and downwards. For instance, Feil et al. [48] show an increasing concentration of the less dense component in the Superior layer, with increasing frequency.

The behavior in the Middle and Inferior layers seems different from the Superior layer. One can observe, in these layers, that stratification is better at the intermediate frequency value than at the higher frequency (Fig. 6). This concerns all components of the mix-

Table 3
Results of the jigging tests; *f* – frequency of the jigging, *A* – expansion ratio, *T* – jigging time.

	Mass proportions			Lower layer			Middle layer			Upper layer			Sorting index
	Concrete (%)	Brick (%)	Gypsum (%)	Concrete (%)	Brick (%)	Gypsum (%)	Concrete (%)	Brick (%)	Gypsum (%)	Concrete (%)	Brick (%)	Gypsum (%)	
f = 160 cpm; A = 70%													
T = 30 s	53.6	25.9	20.5	86.5	10.9	2.6	40.1	45.4	14.5	8.7	30.2	61.2	0.64
T = 60 s	52.1	27.7	20.2	88.6	9.1	2.3	32.5	51.9	15.6	6.6	33.9	59.5	0.67
T = 90 s	52.1	27.4	20.5	86.0	11.6	2.4	30.7	55.2	14.1	9.3	26.6	64.1	0.68
T = 120 s	52.3	27.0	20.8	92.3	7.0	0.7	21.7	60.6	17.8	3.1	20.4	76.6	0.76
T = 150 s	54.2	24.2	21.6	90.7	8.4	1.0	30.4	58.5	11.0	3.4	18.1	78.6	0.76
T = 180 s	54.3	28.9	16.9	91.2	7.6	1.3	26.7	60.2	13.1	7.8	29.3	62.9	0.76
A = 70%; T = 120 s													
f = 150 cpm	55.4	24.9	19.7	90.8	7.8	1.4	35.1	52.5	12.4	6.6	25.0	68.4	0.71
f = 170 cpm	52.9	25.7	21.4	89.4	9.5	1.1	28.1	56.1	15.9	2.8	14.9	82.3	0.76
F = 160 cpm; T = 120 s													
A = 60%	54.6	27.8	17.5	83.4	13.0	3.6	46.5	42.2	11.4	4.5	36.9	58.6	0.61
A = 80%	53.1	27.1	19.7	89.1	10.2	0.7	23.9	59.8	16.3	4.7	21.6	73.7	0.74

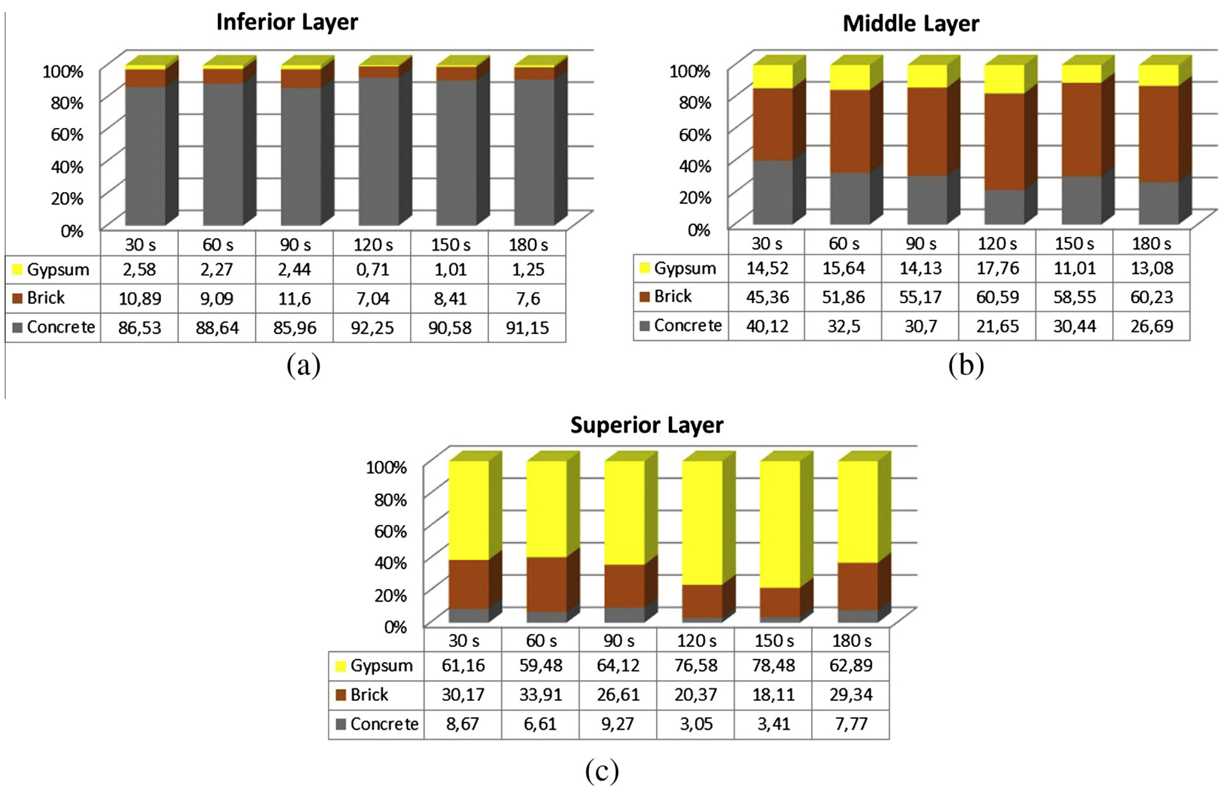

Fig. 4. Percentage in mass of concrete, brick and gypsum in layers Inferior (a), Middle (b) and Superior (c) function of jigging time.

ture: concrete, brick and gypsum. In the Superior layer, the gypsum concentration increases even at the highest frequency. Even if it is difficult to conclude, given the inherent fluctuation of the concentrations during the process, frequencies over 160 rpm seems to increase the re-mixture between the concrete and brick particles. This stratification is driven by the difference in bulk densities. The stratification between brick and gypsum, driven by the difference in particle densities, is amplified at higher frequency than that between brick and concrete.

The influence of the jigging expansion ratio was analyzed by testing three ratios, 60%, 70% and 80%, keeping the other jigging parameters constants: same mixture composition as in the previous tests, jigging time 120 s, frequency 160 cpm (Fig. 7).

Fig. 7 shows the percentage of concrete, brick and gypsum in Inferior, Middle and Superior layers as a function of the expansion ratio. It can be observed that an increase in the expansion ratio from 60% to 70% produces significant improvement of the stratification. The further increase of the expansion ratio to 80% does not produce benefits in stratification. It seems rather that air pressures over 70% increases the re-mixture. This can be observed on all the types of particles in all the layers. Indeed, expansion of the particle layer is carried out through the pressure of inlet air. With high air pressures a very turbulent system is reached, which potentially increase re-mixtures of particles.

4.2.4. Optimal working point of the air jigging

More objective assessment of the frequency and expansion ratio effects could be obtained by using the Sorting Index (Table 3). It can be observed that the best results are clearly obtained for the test using a frequency of 160 cpm and expansion ratio of 70%. Lowering the expansion ratio or the frequency produces a significant decrease in the Sorting Index. It can be supposed that the stratifi-

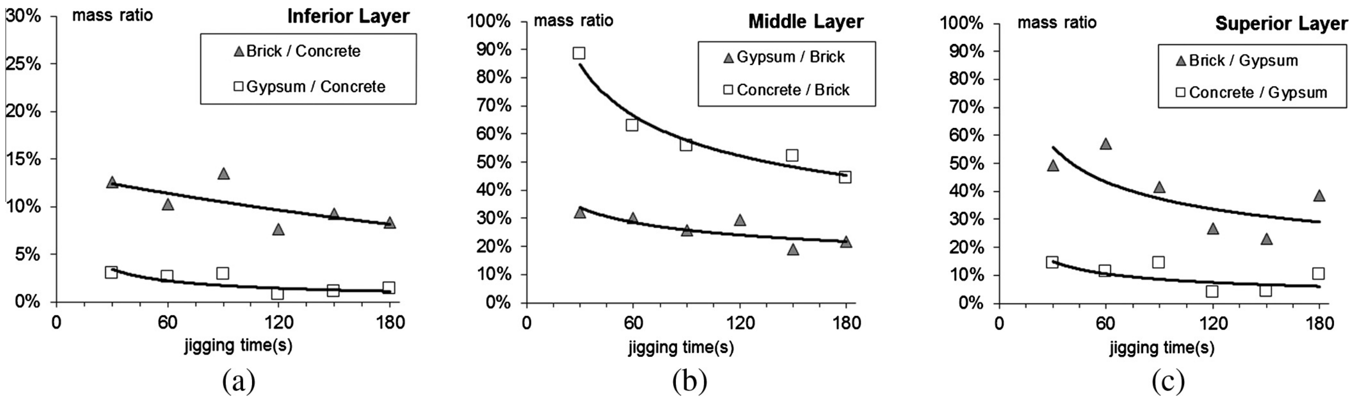

Fig. 5. Evolution of the different mass ratios in the inferior, middle and superior layers along the jigging time.

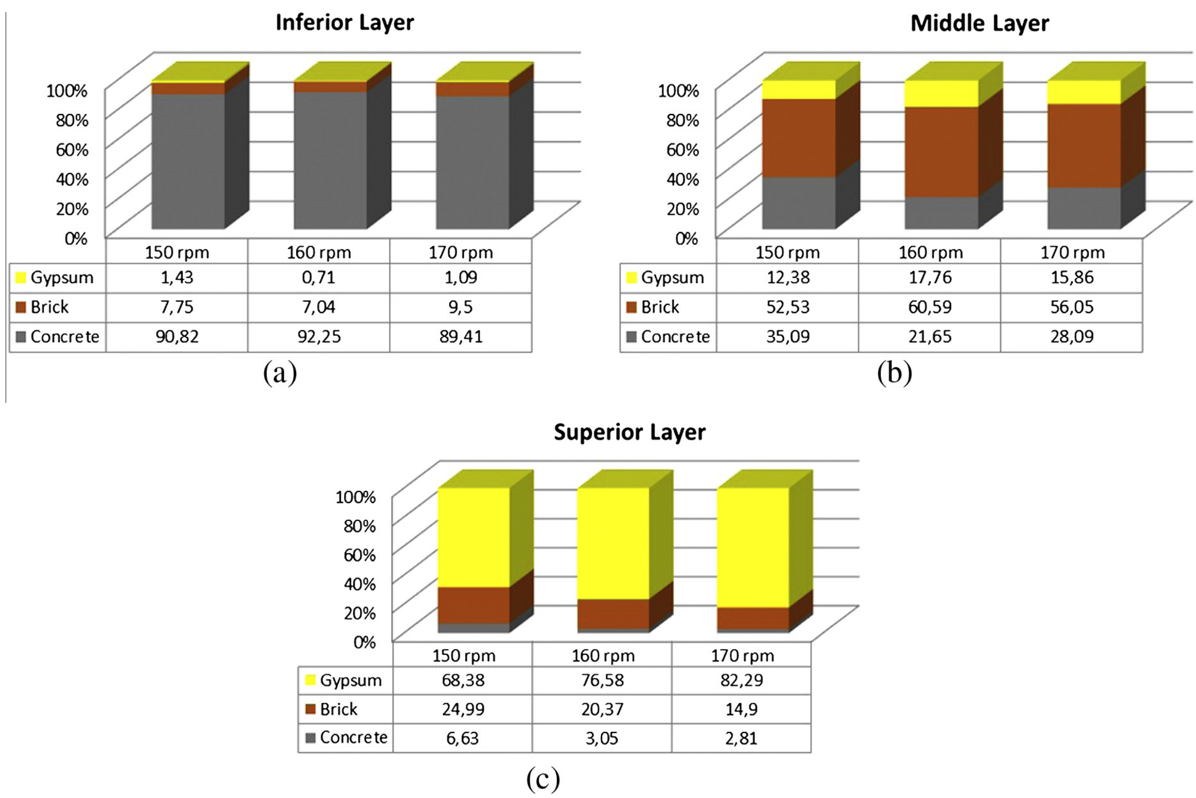

Fig. 6. Percentage of concrete, brick and gypsum in layers Inferior (a), Middle (b) and Superior (c) function of jigging frequency (150, 160 and 170 rpm).

cation mechanism is insufficient for these parameters. For higher expansion ratio or frequency, the Sorting Index also decreases to a lesser extent. It can be supposed that the remixing mechanisms are amplified.

The Sorting Index seems convenient to classify the capacity of jigging parameters to produce adequate stratification. This is also confirmed by the good correlation between the Sorting Index and the gypsum content in the Inferior layer: a linear decrease of the gypsum particles occurs in the Inferior layer with the increase of the Sorting Index. The reduction of the gypsum content is one main justification of this research. One can conclude that the level of gypsum content in the Inferior layer is a good indicator of the degree of achievement for the jigging process, as well.

In order to reduce the number of parameters of the jigging process, it was used the number of cycles defined as the product of the time duration and frequency:

$$N_c = f\ T \tag{4}$$

where f is the frequency and T is the jigging time.

A quadratic model was fitted on the basis of the experiments defined in Table 3, by the use of Sorting Indexes and the numbers of cycles (N_c, ranged between 60 and 480). It was found (Fig. 8) that the quadratic model yields the experimental data with a determination coefficient R^2 = 0.85 and seems to be a relevant prediction of the Sorting Index defined at the beginning of the present section.

The Fig. 8 indicates that the optimal jigging is located around 320 fluidization–sedimentation cycles, whatever the expansion ratio (above 70%) and the time duration (above 30 s). For expansion ratio of 60%, it seems that the sedimentation cannot occur and the jigging result is very imperfect.

4.2.5. General considerations

Demolition materials, which are generated in enormous amounts all over the world, can be handled as a simple ore treatment problem, with reasonable separation possibilities. Efficient

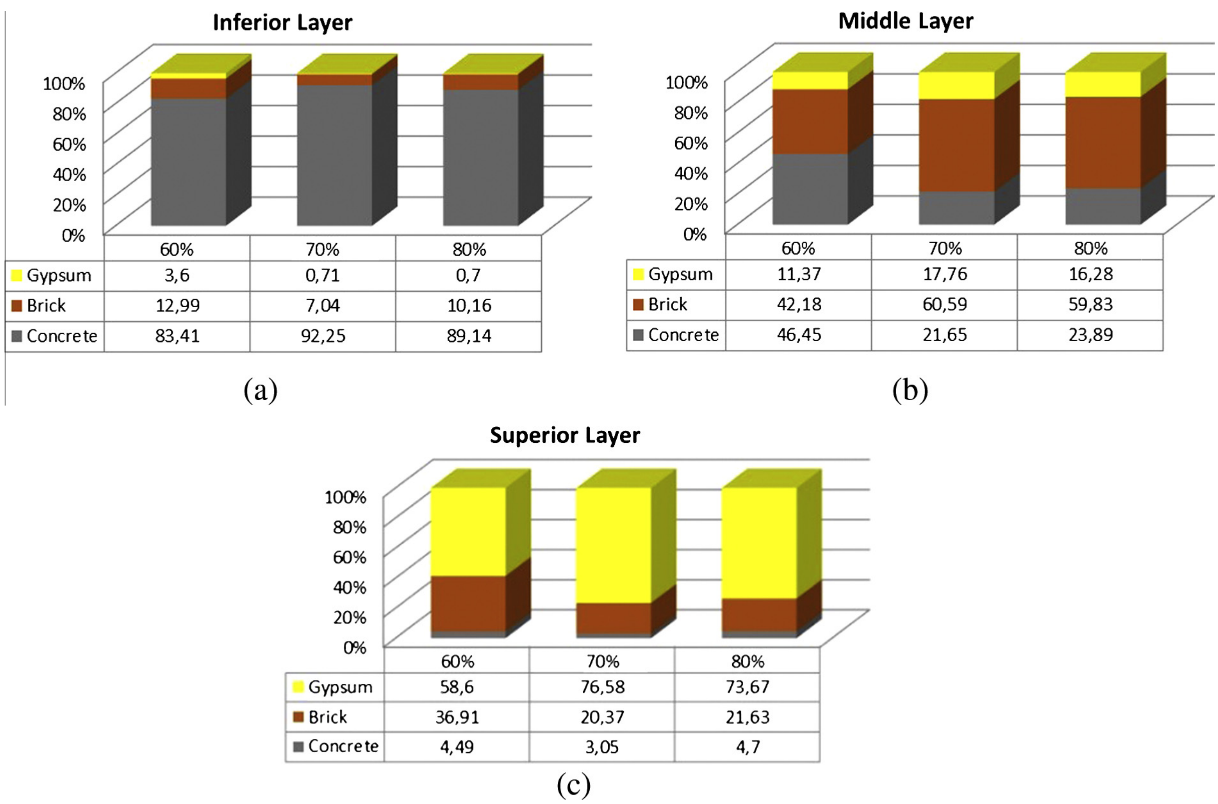

Fig. 7. Percentage of concrete, brick and gypsum in layers Inferior (a), Middle (b) and Superior (c) function of expansion of particles bed (60%, 70% and 80% of the ventilator capacity).

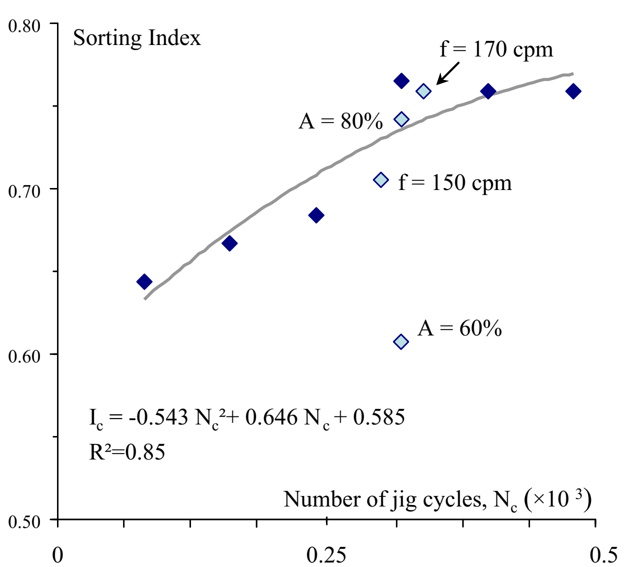

Fig. 8. Sorting Index evolution with the number of jig cycles; experimental points correspond to the reference frequency (160 cpm) and expansion ratio (70%), excepting for the points indicated in the figure.

sorting processes of low quality CDW recycled aggregate could allow the reuse of concrete, brick and gypsum particles. The processes also improve the remaining mixed aggregates for recycling in unbound sub-base materials, by increasing their self-cementing properties and by reducing the sulfate content.

It is possible to separate gypsum from concrete and brick particles, with size range 4–20 mm, in air jigs, due to the difference of bulk densities and particle densities of the materials. In the present tests, using liberated particles, the difference of bulk densities drive the segregation of concrete from brick and gypsum, while the difference of particle densities drive the segregation of gypsum from brick and concrete.

Concentrates (sink products – inferior jig chamber) with concrete contents higher than 90% and gypsum contents lower than 1% were possible to be reached. Products with these gypsum and concrete contents can be inserted in aggregates into the concrete market. For typical gypsum contamination in aggregates, concentrate products with very low gypsum contents are expected.

Gypsum reduction in concrete concentrates was about 25 times. This level of reduction could be satisfactory in sorting real Construction and Demolition Waste aggregates.

Concentrates with lower densities (superior jig chamber) present over 70% of gypsum particles. This level of concentration increases the gypsum reuse and recycling abilities.

For the laboratory equipment used in this research, the best jigging parameters are jigging time 120 s, frequency 160 cpm and expansion ratio 70%. It seems that the number of fluidization–sedimentation cycles can reduce the number of jigging parameters by replacing both jigging time and frequency, for the present flow regime.

Better results as shown in this work can be expected by the use of industrial jigs, which present a smaller wall effect. The jigging wall effect is accentuated in this work and affected the equipment cut imperfection, due to the small dimensions of the laboratory jig (50 × 50 cm).

4.3. Influence of the cut point

Cut point or cut density is the interface where particle separation occurs, in float and sink products (products densities lower and higher than the cut density). In this case, it is the interface of

Table 4
Experiments with different amount of gypsum and concrete; jigging parameters: jigging frequency – 160 rpm, expansion ratio – 70%, jigging time – 120 s.

Test	Feed (kg)			Inferior layer		
	Concrete	Brick	Gypsum	Concrete (%)	Brick (%)	Gypsum (%)
Reference test	20.36	10.51	8.09	92.3	7.0	0.7
More concrete (1.5 kg–7.4%)	21.86	11.67	3.52	91.5	8.3	0.2
More concrete (5.75 kg–28.2%)	26.11	11.38	3.62	92.3	7.4	0.2
Less gypsum (2.9%)	20.39	12.22	0.99	84.8	14.7	0.5
Less gypsum (5.4%)	20.76	11.75	1.84	88.5	11.4	0.1
Less gypsum (9.9%)	20.98	11.64	3.59	88.0%	11.6%	0.4%

2 jig chambers, since particles of different densities completely filled a jig section. Tromp [45] describes the cut point, as the density of a particle that has 50% chance to be in the float or in the sink product. It happens with particles that present a density distribution. In the case of a binary mixture of 2 particles with the same size and different densities, after stratification, on the cut point the interface presents particles completely mixed, due to the stratification imperfection. The same happens in this work, where there are 3 jig chambers, completely filled, before jigging tests, with 3 different particles (3 different densities). After stratification, the region closest to the chambers interfaces presents the most mixed particles.

In order to reach a cleaner sink products (concrete particles), the cut interface between concrete and brick particles was changed, by the addiction of a larger amount of concrete particles. The amount of concrete particles was larger than that required to completely fill the jig chamber close to the bottom. As a consequence, the cut interface between the particles was augmented. In this way, the particle separation through the jig chambers could be carried out in a lower position than the particles cut point, and the sink product (concrete particles) should be cleaner.

Two complementary tests were performed, by increasing the amount of concrete particles. In the first test, 1.5 kg of concrete particles were added (21.86 kg of concrete particles in the feed) and in the second test 5.75 kg (26.11 kg of concrete particles in the feed). The results are presented in Table 4.

The results do not show significant influence of the separation interface on the concrete and brick composition in the Inferior layer after jigging. Despite the advantageous configuration of the tests with larger amounts of concrete, the concrete concentration of the Inferior layer was not improved and remained practically constant, at its highest level.

The concrete particles content however presents values over 90%. These concentrates can be recycled in the construction industry.

One can however observe that gypsum content in the stratified Inferior layer was significantly decreased. This should be associated to the decrease of the gypsum content in the feed and was verified by a second set of complementary tests.

4.4. Influence of the gypsum content

For recycled aggregates, the reduction of gypsum content in the Inferior layer is of main importance. Even small amounts of gypsum in the recycled concrete could introduce difficulties in using the product for new concrete mix-design.

In order to verify the influence of the gypsum content in the feed on the stratification results, a second set of complementary tests was carry out, by reducing the mass of gypsum particles.

Three tests with different gypsum contents (2.9%, 5.4% and 9.9%) were performed (Table 4). The previously reference test presented 20.8% of gypsum content in the feed. The system concrete–brick–gypsum had similar stratification behavior as in the previous

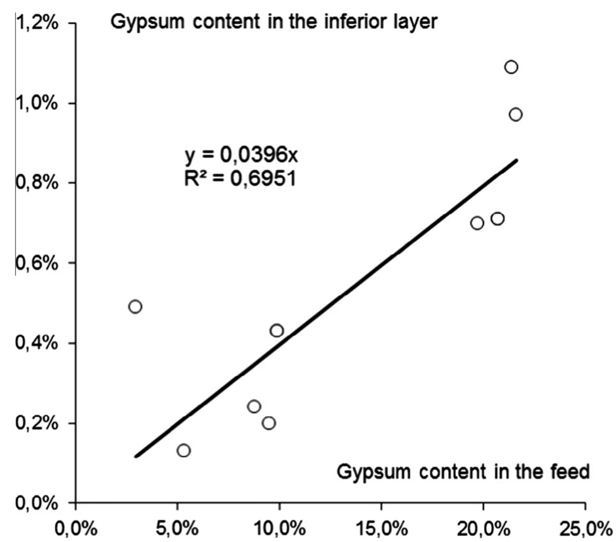

Fig. 9. Evolution of the amount of gypsum in the lower layer with different gypsum proportions in the feed.

experiments. However, one can observe the small amount of gypsum in the Inferior layer, when the total gypsum content in the feed was reduced (Table 4). The low content of gypsum makes possible the concrete particle recycled in new concretes.

Fig. 9 represents the evolution of gypsum content in the Inferior layer as function of the gypsum content in the feed. One can observe that, the lower is the concentration of gypsum in the feed, the easier is to separate it from the other components.

This result corroborates with bibliographic results for water jigging (Müller et al. [29]). However, the level of reduction is much higher in air jig tests, as the gypsum content is reduced in mean 25 times.

5. Conclusions

The main conclusions of the paper are presented below.

Demolition materials can be handled as a simple ore treatment problem, with reasonable separation possibilities.

Efficient sorting processes of low quality CDW recycled aggregate could allow the reuse of concrete, brick and gypsum particles.

The processes also improve the remaining mixed aggregates for recycling in unbound sub-base materials, by increasing their self-cementing properties and by reducing the sulfate content.

It is possible to separate gypsum from concrete and brick particles, with size range 4–20 mm, in air jigs, due to the difference of bulk densities and particle densities of the materials.

Concentrates (sink products – inferior jig chamber) with concrete contents higher than 90% and gypsum contents lower than 1% were possible to be reached.

Gypsum reduction in concrete concentrates was about 25 times. This level of reduction could be satisfactory in sorting real Construction and Demolition Waste aggregates.

Concentrates with lower densities present over 70% of gypsum particles.

All materials (concrete, bricks and gypsum) used in this work were originated by comminuting individual samples. No middlings (particles with different constituents) were used in the tests. With real demolition materials there will be the presence of middlings, which provides new difficulties in physical separation.

Encouraging results were reached in this work, despite problems described in the paper. The results show that the accuracy of the concentration could be improved for lower gypsum contents than tested in the present work, as expected in real demolition products.

Although the tests performed in this work have been made with an air jig, which presents a Tromp imperfection higher than water jigs, it can be observed that the results of gypsum concentration in superior layer (superior jig chamber), or concrete concentration in inferior layer (inferior jig chamber), are quite similar to those presented in the literature.

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