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Analysis of Physical Properties of Coarse Aggregates Recovered from Demolished Concrete with a Two-Stage Water Jigs Process for Reuse as Aggregates in Concrete

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Abstract: The present work analyses the physical characteristics of aggregates recovered with the waterjigging process from comminuted concrete. In this work, conventional concrete (C16/20) was crushed to a top size of 20 mm with a jaw crusher and classified in a size range of 5 to 20 mm. The densimetric distribution analysis was carried out in a densimetric range of 2.4 to 2.8 g/cm³, and the cement paste was dissolved from all granulometric ranges to analyze the composition (sand, cement paste, and aggregates) of each part and define the possibilities of materials to recover. A two-stage water jig concentration process was used, generating a cleaner material in the first stage and a re-cleaner material in the second jigging stage. The physical properties of the material inserted in the feed and the material generated in the first and second stages were analyzed to compare them with natural aggregates. The results indicate the viability of recovering 47.8% of the coarse aggregates present in the concrete feed in the re-cleaner material, with 84% of particles having a density higher than 2.6 g/cm³. These characteristics are similar to those found in natural aggregates.

Keywords: concrete; physical proprieties; aggregates; concentration; jigging process



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1. Introduction

Construction and demolition waste (CDW) is the most generated waste when considering the residues generated in all countries in Europe, according to a survey carried out in 2020 by the European Commission [1]. More than a third of the waste generated in economic activities and household waste in the European Union (EU) in 2020 was waste from economic activities linked to construction when comparing all economic activities and households. Waste generation values accounting for all economic activities and households amounted to 2153 million tons or 4813 kg per capita in 2020 [1].

Observing the specific case of Spain, demonstrated by the European Commission [1,2], an even greater portion of waste from construction is observed, which can generate an amount of more than 37% (share of total waste) of solid waste from the construction sector. Looking at the generation of construction waste compared with other types of waste, an aggravating fact comes to light: the generation of CDW occurs in a diffuse and not a centralized manner, which makes the management of this material difficult. Any location with construction, renovation, or demolition of buildings is a potential generator of this material. Research has been carried out within the scope of construction management [3,4] to reduce the volume of material generated. However, it is still at an initial stage and does not have considerable effects on the volume of material generated or on the general quality.

To standardize and develop new guidelines for solid waste management and generation reduction targets, the European Parliament launched the European Directive 2008/98/EC [5], defining parameters and limits for CDW generation and disposal. The Directive defines waste as “any substance or object that the discard holders or intends or is obliged to discard”. Following European guidelines, French legislation [6] regarding CDW recycling aims to recycle 70% of all CDW generated.

The authors researched the economic, environmental, procedural viability, and other aspects surrounding CDW recycling plants [7–11], such as the carbon footprint and the different concentration circuits. This research confirms the viability of the plants. The general method of managing and processing CDW includes the separation (with specific machinery or manually) of large or low-density metallic material (plastic, paper, wood, etc.) and subsequent comminution of the inert material (concrete, bricks, plaster, ceramics, etc.) to separate the fine portion (>5 mm) and obtain the coarse portion of this material (<20 mm and >5 mm), known as “inert CDW” [12–14].

The so-called “inert CDW” contains materials such as bricks, tiles, plaster, concrete, mortar, cement paste, and liberated coarse aggregate [15,16]. Figure 1 shows the average amount of CDW constituents and demonstrates that around 76% of CDW is composed of solidified and inert materials.

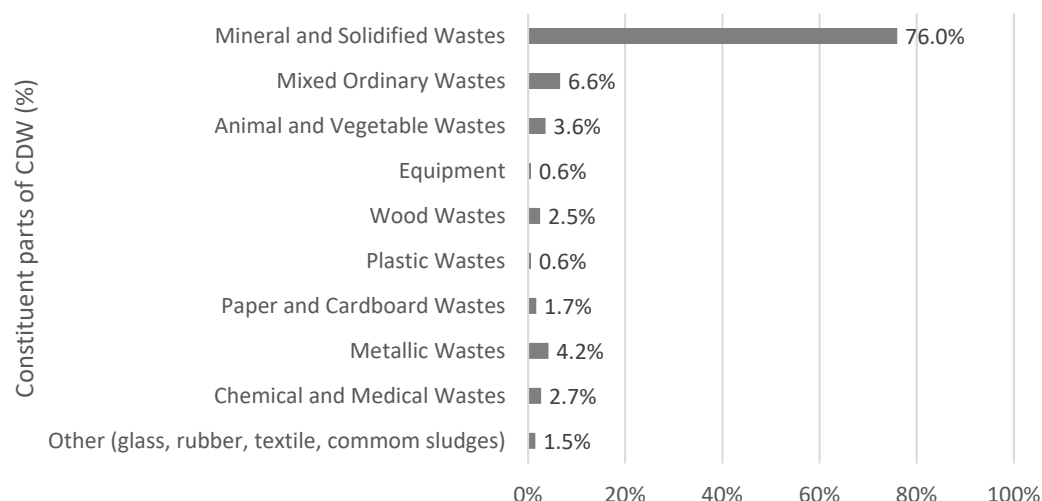


Figure 1. Constituent parts of CDW generated by waste category [16].

Several authors [17–24] studied the use of the inert portion of CDW. The results showed that CDW could be reused in several ways, such as sand production, pavement and roads, direct reuse in the concrete mix as recycled aggregates (RAs), the fabrication of new concrete blocks, and the production of cement. Research was also carried out to analyze the efficiency of CDW as an adsorbent to treat polluted water. However, the researchers also mentioned the difficulties of reuse due to the presence of contaminants and the suitability of material characteristics for uses with greater added value, such as the use of aggregates in new concrete formulations.

The presence of contaminants limits the application of recycled aggregates (RAs) in new concrete formulations. Analyzing the ways of reusing CDW, the authors in [23,25,26] demonstrated that the presence of contaminants is the main factor that influences its possibilities of reinsertion into the supply chain. The contaminants negatively influence the fundamental properties of the aggregates, such as the size distribution, shape index, apparent density, and water absorption. The presence of bricks may make CDW reuse unfeasible due to the reduction in strength inherent to the concrete formulation where the contaminated material is introduced [26–31]. Several standards, BCSJ [32], RILEM [33], and UNE-EN 13242 [34], define the minimum requirements for aggregates so that good-quality concrete can be obtained and define the percentages of their use according to the concrete specifications for which recycled materials can be used and the origin of the CDW. The

adherence of cement paste to aggregates from CDW recycling can modify the characteristics of the material and make their reuse unfeasible. RA concrete formulations, with the addition of cement or water that modify their framework, become economically unviable. Ongoing research [35–37] to reinsert materials into concrete formulations, such as glass and ceramic materials, aims to reduce the generation of CDW, lower the environmental footprint and CO₂ emissions of the construction sector, and provide improvements in formulated concrete.

Some methods to generate an improvement in the characteristics of RA originating from CDW have been investigated, such as separation and classification processes based on the density (water or air) of the materials present in the recycled CDW. The jigging process was also studied by different authors to observe the behavior of the materials present in the inert portion of the CDW to concentrate the denser portion (aggregates) and remove contaminants (plaster, ceramics, and bricks) from the RA [38,39]. This research confirmed the efficiency of the jigging process in concentrating the dense portion of CDW as RA and the efficiency of removing the contaminants, generating a material suitable to reinsert in the market.

Jigging consists of a density concentration process characterized by repeated expansion (dilatation) and contraction (compression) of a bed of particles through a fluid medium (air or water). With the fluidization of the jig bed, the material of similar densities, sizes, and shapes tends to concentrate at either the top or the bottom of the jig. The feed material separates when under the action of the gravity force that allows the separation of materials by density into layers of stratification, with the denser material separating to the bottom of the jig chamber (due to their differential sedimentation velocity) and the lighter material separating to the top of the chamber [40]. Sampaio [41] demonstrates that air jigging, despite having the advantage of not using water to carry out concentration, is less efficient than the water jigging process. Figure 2 demonstrates the expansion and compression process that occurs inside the jig chamber, based on the pulsation of the jig bed.

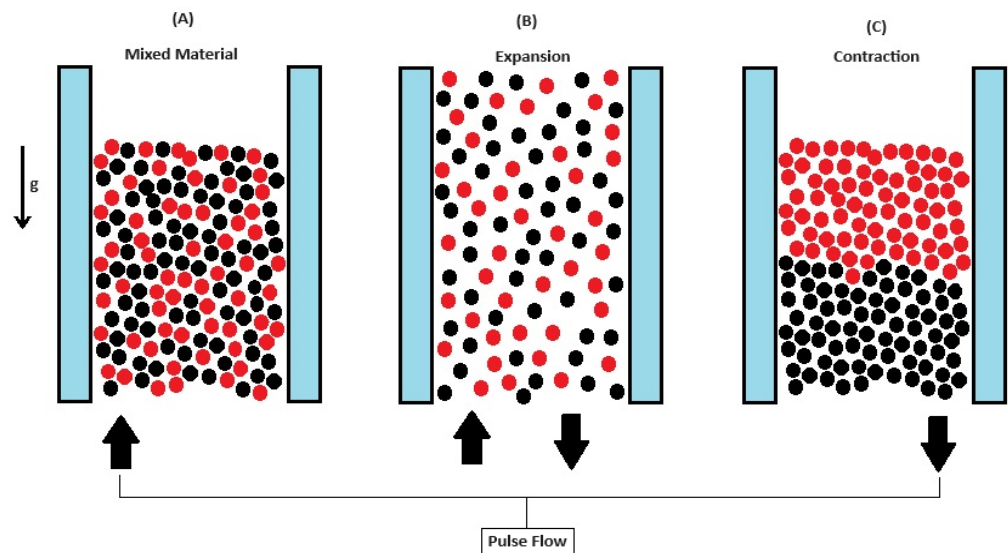


Figure 2. Schematic model of the jig chamber during the jigging process. (A) Jig chamber at the beginning of the process, with light (red) and dense (black) materials mixed; (B) after pulsation, the material fluidizes with the fluid pulse, expanding the bed, allowing the material to differentiate from gravitational forces; (C) after bed contraction, the material stratifies into layers, with the dense material being concentrated at the bottom of the jigging bed and the light material being located at the top of the chamber. The figure was modified from the work of Sampaio et al. [19].

Jigs were and remain widely used mainly because of their low costs. In addition to presenting low operational costs, jigs are robust, have a high capacity, are easy to operate, and benefit relatively large particle distribution, which simplifies mineral processing

flowcharts. In comparison with other beneficiation processes, jigs present a great capacity to absorb large fluctuations of ore contents, feed rates, and solid percentages [19].

Currently, as previously demonstrated, the main use of CDW is where it has a low added value, where it is often not worth processing the material for resale. The use of RA, with a low level of contaminants and desirable characteristics after processing by jiggling, as demonstrated in this work, generates a new perspective for reusing and processing the material. Furthermore, this concept enables new studies on replacing NA with RA, reducing costs, carbon emissions, and energy expenditure on processing and transporting the material.

Observing the proposed context, this article proposes an analysis of the physical characteristics of the aggregates that are recovered from concrete (16/20 Mpa) after their concentration with the jiggling process. Aiming to generate material with characteristics that are equivalent or close to those found in natural aggregates, the paper aims to generate material with desirable characteristics in order to replace natural aggregates in new concrete formulations. After the comminution of the concrete, the aggregates present in the formulation are partially liberated and the analysis of the characteristics is necessary to analyze their possible reuse in new concrete formulations.

2. Materials and Methods

2.1. Material Preparation

In the experiments, conventional structural concretes (16/20 Mpa) were manufactured following Structural Concrete Instruction EHE/08 [42]. The material was initially subjected to manual breaking to adapt to the input capacity of the jaw crusher configured with a top size of 20 mm. After crushing, the material was sieved in a range of 20 to 5 mm (emulating the process carried out in CDW recycling plants) to generate the material used in the tests. The material smaller than 5 mm was separated and will not be used in this study; the material larger than 20 mm was recirculated to the crushing process. Figure 3 demonstrates the crushing process to which the material was subjected to generate the material used in the paper.

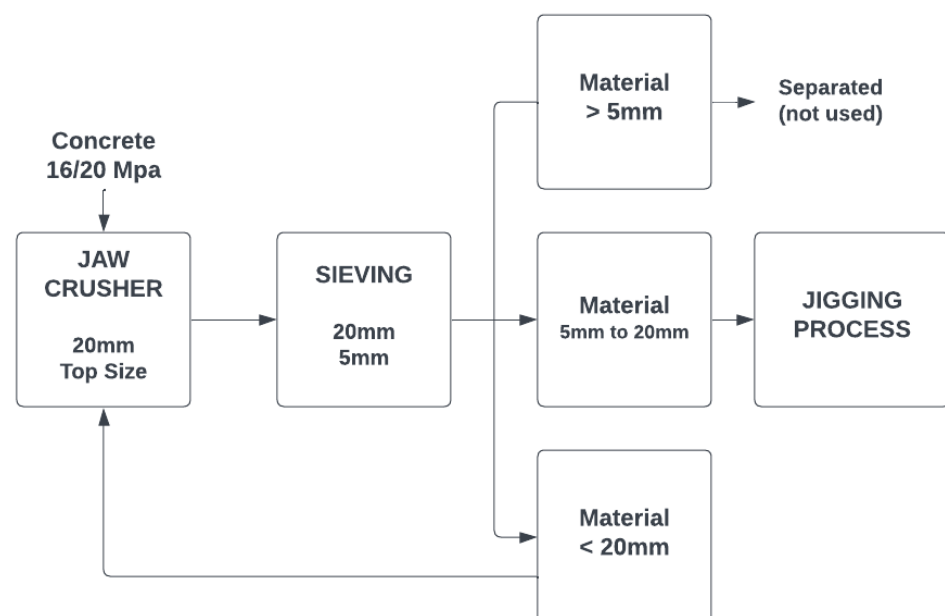


Figure 3. Material generation flowchart before starting the jiggling process.

2.2. Jiggling Process

2.2.1. Jiggling Equipment

The tests were carried out in a water jig designed on a laboratory scale. Figure 4 shows an image of the device that was used in the tests. The device used is a piston jig that

uses water as a dense separation fluid in the concentration process. Powered by the motor (E), the water is pumped from the piston (D) from the water duct (B) to the jig chamber (A—enlarged in the image), where the material is placed. In the jig chamber, the water propelled by the piston comes into contact with the material that provides the expansion and contraction of the bed, enabling the stratification of the material into layers. The energy panel (C) controls the operation. The tests were carried out with a frequency of 35 pulses per minute, a maximum amplitude of 14 cm from the piston, and lasting 3 min.



Figure 4. Jig equipment used in the experiments: (A) jig chamber (enlarged), (B) water passage duct, (C) electric panel, (D) pump chamber, (E) motor. Modified from Teixeira et al. [39].

After each test, the material is manually removed from the top of the jig chamber according to the previously defined layers and placed to dry in an oven at 70 °C for 24 h to remove moisture and subsequently carry out the characterization tests.

2.2.2. Jig Concentration Test

Figure 5 demonstrates the flowchart of the two-stage jigging processes that were carried out to concentrate the concrete. The first stage of jigging was carried out in duplicate, the first (FM1) and second (FM2). During the primary process, two light materials were generated (LM1 and LM2) with 50% of the bulk volume of the batch, which was separated, and a primary concentrate, denser material (DM1 and DM2) was generated representing the other 50% bulk volume of material that was inserted in the jig chamber. The two jig batches were carried out to generate enough material for the second-stage jigging test and to confirm the replicability of the process. In the second jigging stage, DM1 and DM2 were mixed, generating the feed material of the second jigging stage (FM3), and after processing, two materials were generated, the final concentrated material, a dense part (DM3) that represents 33% of the bulk volume, and a lighter material (LM3), which represents 66% of the bulk volume of the jig chamber that was also separated and will not be used in this work.

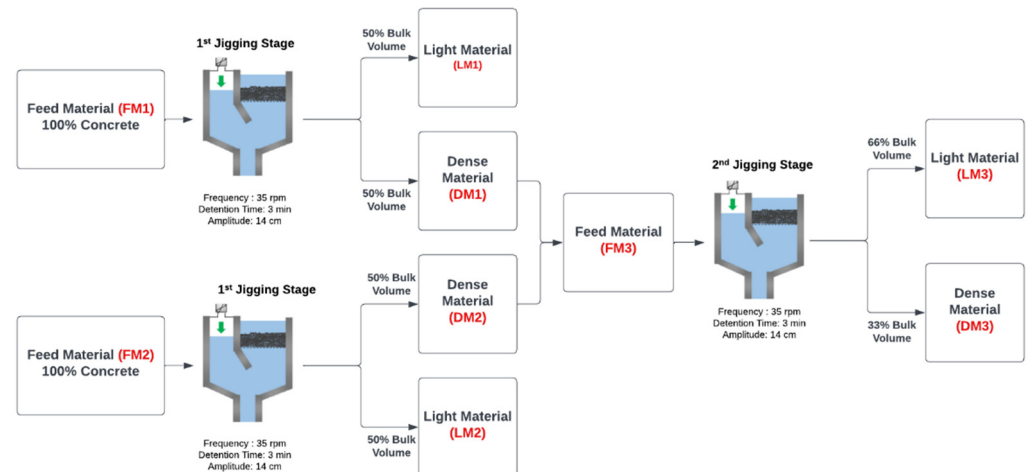


Figure 5. The flowchart of the two-stage jiggling processes is used to concentrate the aggregates from the concrete.

The physical characterization tests were carried out on the concrete inserted in the material feed (FM1 and FM2), to obtain the characteristics of the materials that were inserted in the jiggling process after crushing, on the densest materials that were generated after the first stage (DM1 and DM2), and in the dense material (DM3), which is composed of aggregates recovered after the second jiggling stage.

2.3. Materials Characterization

2.3.1. Densimetric Distribution Test

The concrete generated, in the size range of 5 to 20 mm, was submitted to a densimetric distribution with sink and float test in the densities of 2.4, 2.5, 2.55, 2.6, 2.65, 2.7, 2.75, and 2.8. The test was carried out using a solution of sodium polytungstate. The concrete samples were separated in the following density ranges: $\rho < 2.4 \text{ g/cm}^3$, $2.4 < \rho < 2.5 \text{ g/cm}^3$, $2.5 < \rho < 2.55 \text{ g/cm}^3$, $2.55 < \rho < 2.6 \text{ g/cm}^3$, $2.6 < \rho < 2.65 \text{ g/cm}^3$, $2.65 < \rho < 2.7 \text{ g/cm}^3$, $2.7 < \rho < 2.75 \text{ g/cm}^3$, $2.75 < \rho < 2.8 \text{ g/cm}^3$, and $\rho > 2.8 \text{ g/cm}^3$. The density of the solutions was measured with a manual Anton Paar Density Meter (DMA 35).

2.3.2. Analysis of the Concrete Substrate Constitution

To understand the constitution of the concrete used in the experiments, each of the densimetric ranges that were obtained was subjected to a digestion test with sulfuric acid, to quantify the constituent content of fine aggregates (<5 mm), coarse aggregates (>5 mm), and cement paste. The dissolution test was carried out with the methodology defined by Akbarnezhad et al. [43].

The concrete was dried, weighed, and placed in a sulfuric acid solution at a concentration of 3 molar or higher. Using a circular mixer, the concrete was left submerged in the acid for 8 h and washed to remove the cement paste that was dissolved. The procedure was repeated until all the cement paste was dissolved. After the cement paste had been completely dissolved, the remaining aggregates were dried in an oven overnight and sieved through a 5 mm sieve to quantify the remaining weight of coarse aggregates (<5 mm) and fine aggregates (>5 mm). The amount of dissolved cement paste is given by the difference between the amount of aggregates recovered at the end of the process, compared to the weight of material that entered into the process.

2.3.3. Granulometric Distribution Test

The granulometric (particle size) distribution of the material was determined by analyzing the material retained on the sieves with 20 mm, 12.5 mm, 8 mm, and 5 mm sieves, and the fine aggregates with sizes under 5 mm were analyzed.

2.3.4. Form Factor

The form factor test was carried out by the standard EN 933-4 [44]. In total, 200 aggregates are selected proportional to the mass fractions of the ranges 9.5×12.7 mm and 12.7×19.5 mm constant in the sample. The standard is used to perform shape factor analysis for coarse aggregates. To carry out the analysis, a particle size distribution of the material is carried out in the size range of 9.5×12.7 mm and 12.7×19.5 mm, removing materials with particle sizes smaller than 9.5 mm. Subsequently, 200 different particles are selected in proportion to the weight of the materials retained in each granulometric range. The selected grains are measured in their largest longitudinal portion and their smallest thickness with a caliper. The form factor is given by the average of the ratio between the two measurements. The form factor of the materials directly interferes with the bulk apparent density values, which modifies the dynamics of the material's concentration in the jiggling process as well as the physical characteristics of the material's adjustment.

2.3.5. Specific Density (OD), Saturated Specific Density (SSD), Apparent Density (OD), Saturated Apparent Density (SSD), and Water Absorption

Due to the densimetric fractions and the cement paste content present in each of the material concentration stages, the analysis of the material in its saturated state is necessary. Cement paste, due to its porosity and lower density than aggregates, modifies the parameter values according to the saturation of the material. The apparent and specific density values in their water-saturated and oven-dry forms and the water absorption were measured by ASTM C127-07 [45] to understand the influence of the presence of cement paste in the aggregates.

The procedure recommended by the standard is as follows: Dry the test sample in the oven to constant mass at a temperature of 110 ± 5 °C, cool in air at room temperature for 1 to 3 h for test samples of 37.5 mm (1 1/2 in) nominal maximum size, or longer for larger sizes until the aggregate has cooled to a temperature that is comfortable to handle (approximately 50 °C). Subsequently, immerse the aggregate in water at room temperature for a period of 24 ± 4 h.

Remove the test sample from the water and roll it in a large absorbent cloth until all visible films of water are removed. Wipe the larger particles individually. Determine the mass of the test sample in the saturated surface-dry condition. Record this and all subsequent masses to the nearest 0.5 g or 0.05% of the sample mass, whichever is greater. After determining the mass in air, immediately place the saturated surface-dry test sample in the sample container and determine its apparent mass in water at 23 ± 2.0 °C.

Dry the test sample in the oven to constant mass at a temperature of 110 ± 5 °C, cool it in air at room temperature for 1 to 3 h, or until the aggregate has cooled to a temperature that is comfortable to handle (approximately 50 °C), and determine the mass.

The equations used to determine the values are the follows:

- Specific Density (OD) (kg/m^3)

$$997.5 A / (B - C) \quad (1)$$

- Specific Density (SSD) (kg/m^3)

$$997.5 B / (B - C) \quad (2)$$

- Apparent Density (OD) (kg/m^3)

$$997.5 A / (A - C) \quad (3)$$

- Water Absorption (%)

$$[(B - A) / A] \times 100 \quad (4)$$

where

A = mass of oven-dry test sample in air, g;

B = mass of saturated-surface-dry test sample in air, g;

C = apparent mass of saturated test sample in water, g.

3. Results and Discussion

3.1. Granulometric Distribution Test

Table 1 presents the granulometric distribution values of the concrete after the crushing process in the jaw crusher. The majority of the material (67.2% by weight) is coarse aggregates in the particle size range between 5 and 20 mm. After crushing, the concrete turns 32.8% into fine material (0×5 mm). This fine material is composed basically of cement paste and fine aggregates (sand) that separate from the coarse aggregates due to the difference in resistance of the cement paste and the aggregate particles. This material was not analyzed in this paper. The coarse particles are composed of totally liberated aggregates, particles of cement paste mixed with sand that were not comminuted in the crushing process, and aggregates adhered with the cement paste.

Table 1. Size distribution of the concrete (16/20 MPa) comminuted at a top size of 20 mm.

Concrete Size Distribution	<5 mm (%)	5/8 mm (%)	8/12.5 mm (%)	12.5/20 mm (%)	Total (%)
16/20 Mpa Concrete	32.8	14.7	26.6	25.9	100
	32.8		67.2		100

3.2. Densimetric Distribution Test

The following densities were used in the sink-and-flow test: 2.4 g/cm³, 2.5 g/cm³, 2.55 g/cm³, 2.6 g/cm³, 2.65 g/cm³, 2.7 g/cm³, 2.75 g/cm³, and 2.8 g/cm³. Figure 6 demonstrates the mass retained in the different density ranges on the concrete at the particle size range of 5×20 mm.

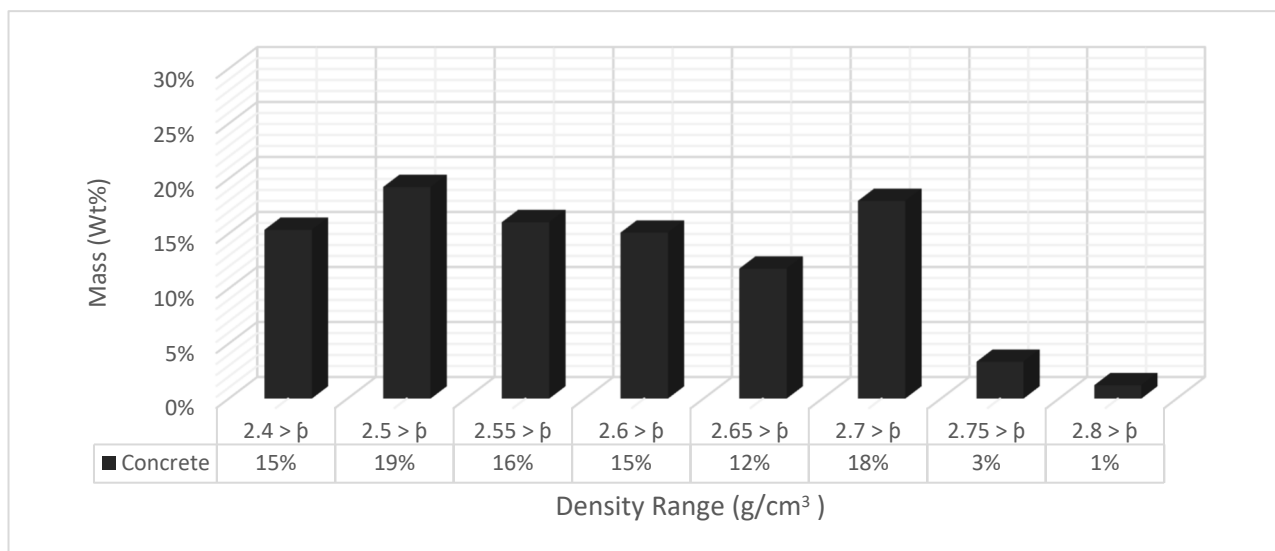


Figure 6. Density distribution of the concrete generated after comminution, material in the granulometric range 5×20 mm.

The concrete studied presents a large density variation, mainly due to the characteristics of the comminution mechanism and the constituent parts of the concrete. Normally, 16/20 Mpa concrete is composed of three parts of coarse aggregates (particles larger than 5 mm and with high density), two parts of fine aggregates (particles smaller than 5 mm,

known as sand), and one part of cement (less dense material which involves particles with higher density, forming concrete in its formulation). Particles with a density lower than 2.6 g/cm^3 are composed of a mixture of cement paste and fine aggregates, or coarse aggregates with cement paste attached. The adhesion of cement paste directly negatively modifies the specific density, porosity, form factor, and water absorption of the material, making it impossible to recirculate it into new concrete formulations.

Accounting for portions $>2.65 \text{ g/cm}^3$, $>2.7 \text{ g/cm}^3$, $>2.75 \text{ g/cm}^3$, and $>2.8 \text{ g/cm}^3$, shown in Figure 6, 34% of the material has a density greater than 2.6 g/cm^3 ; this material is composed of fully liberated coarse aggregates and coarse aggregates with a thin layer of cement paste attached. Due to the difference in resistance between the cement paste and the coarse aggregates, concrete fracture tends to occur in the interface of the materials, which causes liberation of the aggregates. Due to its low cement paste content, this material tends to have characteristics similar to natural aggregates, possibly allowing reuse. In the present work, the objective is to recover the material with a density above 2.6 g/cm^3 and analyze its properties compared to natural aggregates.

3.3. Concrete Substrate Constitution

Concrete formulations (16/20 MPa) normally use a mixture of sand (fine aggregates $> 5 \text{ mm}$), rocks (coarse aggregates $< 5 \text{ mm}$), cement, and water (cement paste). With the aim of understanding the contents of each material existing in each granulometric portion generated, a dissolution test was conducted. The masses retained in each densimetric range were subjected to digestion with hydrochloric acid to understand the composition of each part of the concrete. Figure 7 shows the values obtained for each material in each corresponding density range.

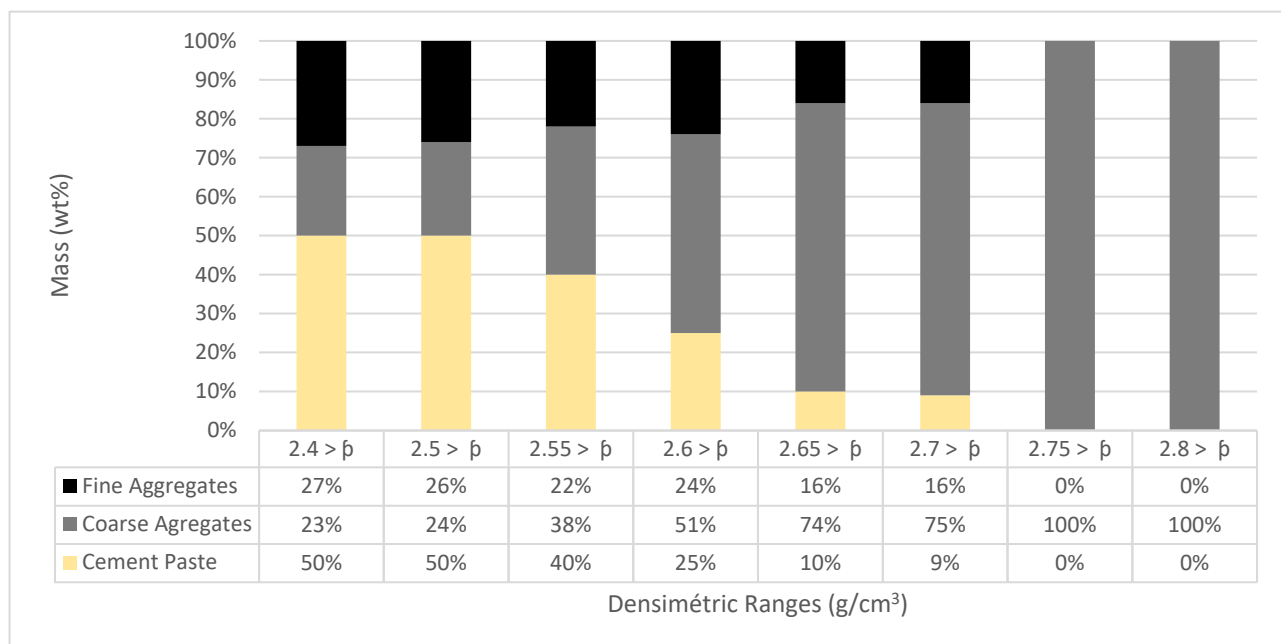


Figure 7. Cement paste, fine aggregates, and coarse aggregates content in different density ranges. Concrete in the $5 \times 20 \text{ mm}$ granulometric range.

The densimetric fractions presented the values of their constituents as expected. Fractions with a density greater than 2.7 g/cm^3 were considered coarse aggregates completely liberated. It is worth mentioning that fine aggregates do not show a degree of liberation due to their complete mixing with the cement paste. Densimetric fractions with densities lower than 2.6 g/cm^3 have a high content of cement paste and fine aggregates, which contributes to reducing the density of the material. The densimetric ranges of $2.6 < \rho < 2.65 \text{ g/cm}^3$ and $2.65 < \rho < 2.7 \text{ g/cm}^3$ have a high content of coarse aggregates, 74% and 75%, respectively;

in addition, the ratio of fine aggregates mixed with cement paste is higher than the less dense fractions, which contributes to increasing the density of the material.

3.4. Jig Concentration Tests

It is worth mentioning that jigging processes (water or air) are devices used around the world and are based on the differentiation by density and size of the materials present in the bed (separation of denser particles from less dense ones). Observing Figure 7 and the basic jigging theory, the jigging tests were dimensioned (height of cuts in the jigging bed) to provide the concentration of materials with a density greater than 2.6 g/cm^3 , to analyze if it is possible to generate material with characteristics similar to the natural aggregates used in industry.

Figure 8 demonstrates the mass flow corresponding to the two-stage jigging process that was proposed in the paper. The figure demonstrates the amount of material that was inserted into the jigging stages and its particle content with a density $> 2.6 \text{ g/cm}^3$. The contents of materials intended for disposal and concentrated materials for aggregate recovery are also demonstrated. The first stage of jigging was carried out in duplicate to verify the replicability of the jigging process in generating materials with similar characteristics and to generate sufficient material for the second jigging stage. The first stage was carried out with two different feed materials FM1 and FM2.

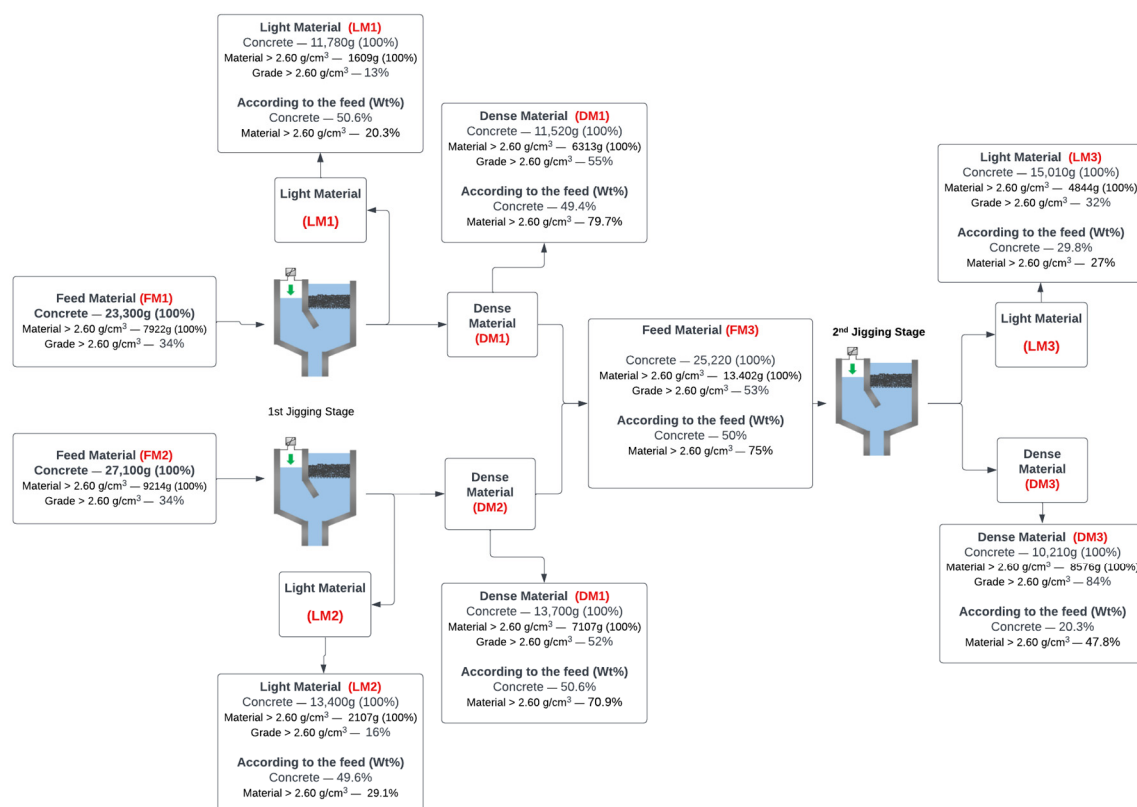


Figure 8. The flowchart of the jig tests and mass balance of the jigging test.

Material Feed 1 (FM1) comprises 23,300 g of concrete with a content of 34% of materials with a density greater than 2.6 g/cm^3 (as shown in Figure 7) presenting 7922 g of this dense material. The process was carried out with a bed height of 18 cm. FM1, after jigging, generated two different materials, a light material (LM1) and a dense material (DM1). LM1 represents 50% (bulk volume) of the jigging bed and has 11,780 g of material with a content of 13% of the material with a density greater than 2.6 g/cm^3 ; the material represents 50.6% (by weight) of the material that was inserted into the FM1 and concentrates 20.3% of the initial FM1 dense material. This material is composed of particles of cement paste and

fine aggregates with cement paste adhered to the material, normally presenting a low density, high porosity, and high water absorption, making recirculation unfeasible. DM1 represents the remaining 50% (bulk volume) of the feed, which separates to the bottom of the jig chamber. With a mass of 11,520 g of concrete, and 55% of it at a density greater than 2.6 g/cm^3 , DM1 represents 49.4% of the material inserted into FM1 and concentrates 79.7% of the dense material inserted into the feed. This material (DM1) is composed of fully liberated aggregate particles and aggregates with a thin layer of cement paste with adhered fine aggregates.

Material Feed 2 (FM2) comprises 27,100 g of concrete with a content of 34% of materials with a density greater than 2.6 g/cm^3 , presenting 9214 g of this dense material. The process was carried out with a bed height of 20 cm. FM2 after jiggling generated two materials, a light material (LM2) and a dense material (DM2). LM2 represents 50% (bulk volume) of the jiggling bed and has 13,400 g of concrete, with a content of 16% of material with a density greater than 2.6 g/cm^3 ; the material represents 49.6% (by weight) of the material that was inserted into the FM2 and concentrates 29.3% of the dense material. DM2 represents the remaining 50% (bulk volume) of the feed, which separates to the bottom of the jig chamber. With a mass of 13,700 g of concrete, and 52% of it at a density greater than 2.6 g/cm^3 , DM2 represents 50.6% of the material inserted into FM2 and concentrates 70.9% of the dense material inserted into the feed. DM1 and DM2 have similar component characteristics.

The light materials (LM1 and LM2) were separated and can later be directed to recirculation, to recover the dense material present. The dense materials (DM1 and DM2) were removed and directed to the second jiggling stage. The physical properties (specific density, bulk density, saturated specific density, saturated bulk density, shape factor, and water absorption) were analyzed of the mixed dense material (FM3) for comparison and analysis of the progression of parameter values during the jiggling process.

Material Feed 3 (FM3) is composed of 25.220 g of pre-concentrated concrete, having a content of 53% of materials with a density greater than 2.6 g/cm^3 , presenting 13.402 g of dense material. The process was carried out with a bed height of 18 cm. FM3 after jiggling generated two materials, a light material (LM3) and a dense material (DM3). LM3 represents 66% (bulk volume) of the jiggling bed and has 15.010 g of concrete with a content of 32% of the material with a density greater than 2.6 g/cm^3 . The material represents 29.8% (by weight) of the material that was inserted into the first jiggling stage and concentrates 27% of the dense material. DM3 represents the remaining 34% (bulk volume), which is separated to the bottom of the jig chamber, has 10.210 g of concrete, and has a content of 84% of material with a density greater than 2.6 g/cm^3 . DM3 represents 20.3% of the material inserted into the first jiggling stage and concentrates 47.8% of the dense material inserted into the test.

The light materials (LM3) were separated and can later be mixed (with LM1 and LM2) for recirculation, to recover the dense material present. The dense materials (DM3) were collected and directed for physical analyses. The physical properties (specific density, apparent density, saturated specific density, saturated apparent density, shape factor, water absorption, densimetric distribution, and cement paste content) were analyzed in DM3 for comparison and analysis of the material generated at the end of the process.

3.5. Material Physical Characterization

After the jiggling process, the materials generated were sent for physical analysis. The physical properties (specific density, apparent density, saturated specific density, saturated apparent density, shape factor, water absorption, and cement paste content) of the concrete used at the beginning of the process (CO), the concentrated dense materials generated from the primary jiggling process (C1), the final material concentrated after the secondary jiggling process (C2), and conventional natural materials (NA) used in the construction industry were analyzed to compare with the materials generated. Table 2 presents each material that was analyzed.

Table 2. Materials analyzed after the jigging process.

Materials	Code
Concrete after the comminution process	CO
Concentrated material generated in the first jig stage (DM1 and DM2)	C1
Concentrated material generated in the second jig stage (DM3)	C2
Natural aggregates used in the industry	NA

Analysis of Physical Properties

Table 3 presents the analyzed values of each of the concentrated materials from the two jigging processes carried out (C1 and C2), as well as the material at the beginning of the process (CO) and natural aggregates (NAs).

Table 3. Analysis of the physical parameters of the materials generated from the jig process (C1 and C2), the concrete used at the beginning of the process for concentration analysis (CO), and the conventional natural aggregates (NAs) normally used in the industry.

Materials	Specific Density (OD) (g/cm ³)	Apparent Density (OD) (g/cm ³)	Specific Density (SSD) (g/cm ³)	Apparent Density (SSD) (g/cm ³)	Water Absorption (%)	Form Factor	Cement Paste (%)
CO	2.59	1.37	2.47	1.35	4.73	2.19	46%
C1	2.62	1.38	2.57	1.37	3.2	2.07	30%
C2	2.66	1.38	2.6	1.37	1.2	2.07	15%
NA	2.67	1.47	2.65	1.41	0.72	2.09	0%

Table 2 shows the measured values of the main characteristics defined by Brito and Saikia [23] as the parameters that most influence the fundamental properties of aggregates for use in concrete. According to the concentration of the material with the jigging stages, an increase in the specific and apparent density value observed in both its dry and saturated forms is noted. Density is one of the fundamental parameters of aggregates and is important to designing concrete mixes and controlling several properties of the resulting concrete. The density of the CDW aggregate is lower than that of natural aggregates. This is due to the existence of porous and less dense cement paste in the CDW aggregates. Due to their origin and size, CDW aggregates may have different densities depending on the amount of adhered mortar paste [23]. CO has a specific density of 2.59 g/cm³, while C2 has 2.66 g/cm³, approaching the 2.67 g/cm³ value observed in NA. An increase in density values is observed while the concentration value of the cement paste decreases according to the concentration stages of the jigging process. The jig processing removes less dense particles, basically formed by cement paste. The bulk density of CDW aggregate is also lower than that of normal aggregates. The bulk density of CDW aggregates is generally in the range of 1150–1400 kg/m³ with a few exceptions [23]. Ferreira et al. [28] explain that the lower apparent density value that is observed from RA recycled from CDW compared to NA is due to the greater volume of voids between particles in the CDW aggregate. Water absorption, contrary to what was observed in the density results, is directly related to the cement paste content measured in the materials. The water absorption capacity of the CDW aggregate is higher than that of normal aggregate (which is less than 1% for almost all current aggregates), as the CDW aggregate is composed of cement paste, which is porous by nature and therefore can absorb high amounts of water [23]. The higher the content of the cement paste, the more porous the material is, and consequently it will absorb more water due to its porosity. CO has a water absorption of 4.73%, in C1 3.2% water absorption is observed, while C2 has only 1.2%, a value close to that obtained in NA, which measured 0.72% water absorption. De Juan [46], in a study carried out in Spain, reports that the water absorption of NA can vary between 0 and 4%, while for cement paste that is adhered to the aggregate, it is between 16 and 17%, providing a greater water absorption of RA from CDW, which varies between 0.8 and 13%, with an average of 5.6%. Research [28,47] proposes that

an extra amount of water corresponding to the water absorbed by the RA be added to the concrete mix and describes a method of managing the material to compensate for mixing water by presoaking the RA in order to standardize the water/cement ration in the concrete formulations. The shape factor of the materials is also directly related to the cement mass content, due to the randomness in the fracture of materials with lower density (composed of cement mass and fine aggregates); the shape factor presents higher values in CO when compared to values measured in C1 and C2 and natural aggregates (NAs) that do not have adhered cement mass. Etxeberria et al. [26] reported the shape indices of CDW and stated that the better shape of the CDW aggregates facilitated their use for concrete production. Figure 9 presents the graphs correlating the characteristics tested with the cement paste content and defines the relation between the characteristics.

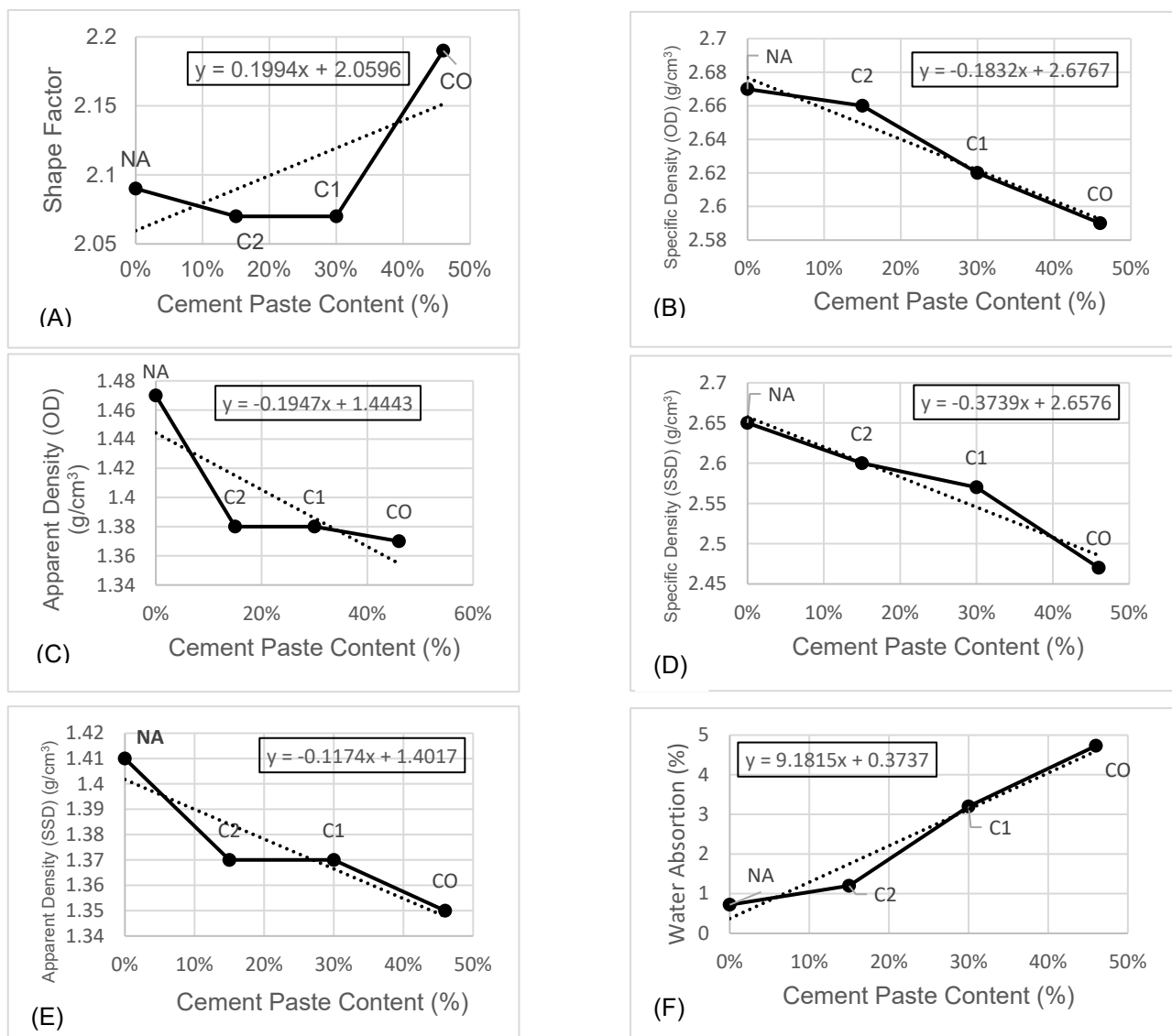


Figure 9. Graphs of the ratio between the analyzed properties of the materials and the cement mass present. (A) Shape Factor $\times$ Cement Paste Content, (B) Specific Density $\times$ Cement Paste Content, (C) Apparent Density $\times$ Cement Paste Content, (D) Saturated Specific Density (SSD) $\times$ Cement Paste Content, (E) Saturated Apparent Density (SSD) $\times$ Cement Paste Content, and (F) Water Absorption $\times$ Cement Paste Content.

Taking into account new concrete formulations, the relationships between materials in their desaturated state are of greater relevance. The analysis of materials in their saturated

state is important due to the modification of proportions and concrete in its fresh state (workability and stiffening of the concrete) and later in its hardened state (durability, resistance, fatigue, and other properties). According to what is observed in Figure 9, the cement paste content directly interferes with the characteristics of the aggregate and consequently with the proportions necessary for the manufacture of concrete, requiring the addition of more water or cement in the formulations to adapt the proportions and characteristics. Figure 10 demonstrates the densimetric distributions of the materials shown in Table 2 to compare the densimetric composition of the generated materials and the similarity of the concentrated material to natural aggregates.

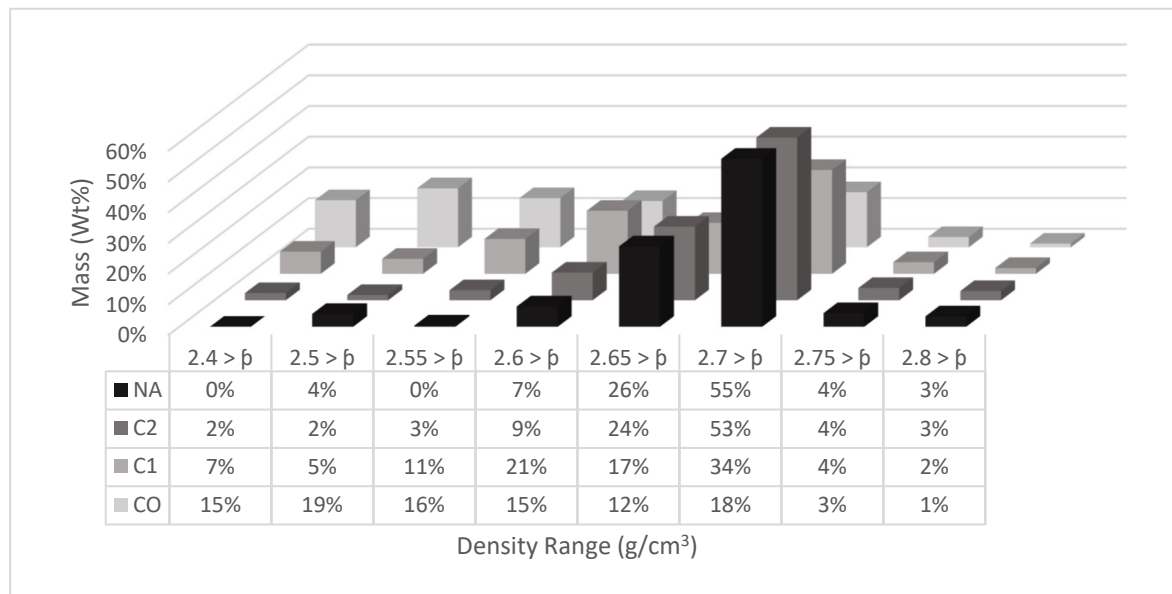


Figure 10. Densimetric distribution of concrete in its initial constitution (CO), the natural aggregates (NAs), and the generated materials in the first (C1) and second jiggling stage (C2).

The densimetric distribution of the analyzed materials demonstrates a large densimetric variation in the concrete in its initial form (CO) with a homogeneous distribution between the values obtained in lighter materials ($2.4 \text{ g/cm}^3 < p < 2.6 \text{ g/cm}^3$) and denser materials ($2.6 \text{ g/cm}^3 < p < 2.8 \text{ g/cm}^3$). From the first jiggling stage where the first concentrated material (C1) is generated, there is a decrease in the content of light materials and an increase in the content of dense materials. When observing the values obtained from the material generated in the second jiggling stage (C2), the values are similar to the values obtained from natural aggregates, due to the removal of light materials that are located in the upper part of the jig chamber during both stages. In C2, a small presence of light material ($2.4 \text{ g/cm}^3 < p < 2.5 \text{ g/cm}^3$) is observed; the presence of this material is due to the particles that are trapped within the dense material concentrated in the second jiggling stage at the bottom of the jig chamber, which are unable to move to the highest part of the jiggling bed where the light material is located, making it impossible to remove. C2 presents 84% of material with a density $> 2.6 \text{ g/cm}^3$, very close to natural aggregates that present 88% of material in the same granulometric range, and a densimetric distribution similar to the one found in the NA.

3.6. Future Trendings

Analyzing the materials generated and the possibility of recovering aggregates present in concrete with characteristics very similar to natural aggregates, it is necessary to analyze the use of these materials in new concrete formulations to validate the parameters observed in the work. The formulation of concrete test specimens and the analysis of the

characteristics that the insertion of these generated materials can bring to new concretes are of utmost importance for the validation of the concentration method for CDW.

Although the jiggling process is widely used around the world, the method of concentrating aggregates with the jiggling process is a new possibility that is being suggested by this work; thus, a pilot-scale plant is necessary to validate the process at industrial levels.

4. Conclusions

The main conclusions of this paper are the following:

The aggregates recovered from the use of the two-step jiggling process for the processing of CDW as demonstrated in the paper present improvements in their physical properties, and the proposed process is promising for enabling the use of recycled aggregates. The process positively influences the analyzed characteristics of the aggregates and is a fundamental part of the recovery of more than 50% of the coarse aggregates with density $>2.6 \text{ g/cm}^3$ present in the concrete studied.

The comminution of the material via jaw crusher with a top size of 20 mm and the classification of the material in the granulometric range of 5–20 mm demonstrated the generation of more than 32% of fine material (0–5 mm) and more than 67% of coarse material.

It was observed that the concrete presented a large density variation in the coarse particles (5–20 mm), ranging from 2.4 to 2.8 g/cm^3 , allowing the stratification of the material between tailings (cement paste and fine aggregates) and concentrated material (coarse aggregates).

The concrete dissolution analysis, used to observe the composition of the concrete (cement paste, fine aggregates, and coarse aggregates content) in all granulometric ranges, demonstrated the presence of 34% of particles with a density $> 2.6 \text{ g/cm}^3$. Such particles had a low cement paste content and characteristics close to those found in natural aggregates according to the analysis.

The analysis of the properties of the materials that were inserted in the process, as well as the materials that were generated in each of the jiggling stages, positively demonstrate the improvement in the parameters of specific and apparent density, shape factor, water absorption, shape factor, and cement paste content. With cement paste as a contaminant in the CDW recycling process, the reduction in its content is positive for the subsequent analysis of the reuse of this material (DM3).

Due to its proprieties (porosity, density, and water absorption), cement paste content was directly linked to the properties analyzed in the study. A reduction was observed in the 46% content of cement paste that was analyzed in the feed material (CO) of the process to 30% after the first jiggling stage (C1), and to 15% after the second jiggling stage (C2) performed on the final concentrated material.

The densimetric analysis carried out on the materials generated and compared with the natural aggregates provided the verification of the similarity of the densimetric characteristics of the material generated after the second jiggling stage (C2) with the natural aggregates.

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References

1. European Commission. 2011. Available online: http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf (accessed on 15 April 2024).
2. Eurostat. Waste Statistics in Europe. Available online: <http://epp.eurostat.ec.europa.eu/> (accessed on 15 April 2024).
3. Bao, Z.; Lu, W. Developing efficient circularity for construction and demolition waste management in fast emerging economies: Lessons learned from Shenzhen, China. *Sci. Total Environ.* **2020**, *724*, 138264. [\[CrossRef\]](#)
4. López, L.; Roca, R.; Gassó, S. The Circular Economy in the Construction and Demolition Waste Sector: A Review of Initiatives. In Proceedings of the 24th International Congress on Project Management and Engineering, Alcoi, Spain, 7–10 July 2020.
5. Directive, E. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Off. J. Eur. Union* **2008**, *312*, 3.
6. Commissariat Général au Développement Durable. *Waste Managed by the Building Companies: Quantities and Management Methods in 2008, Chiffre et Statistiques nr. 231, Juillet 2011*; Ministère de l'Ecologie du Développement Durable du Transports e du Logement: Paris, France, 2011; p. 5. (In French)
7. Coelho, A.; De Brito, J. Economic viability analysis of a construction and demolition waste recycling plant in Portugal—Part I: Location, materials, technology, and economic analysis. *J. Clean. Prod.* **2013**, *39*, 338–352. [\[CrossRef\]](#)
8. Coelho, A.; De Brito, J. Environmental analysis of a construction and demolition waste recycling plant in Portugal—Part I: Energy consumption and CO₂ emissions. *Waste Manag.* **2013**, *33*, 1258–1267. [\[CrossRef\]](#)
9. Coelho, A.; De Brito, J. Environmental analysis of a construction and demolition waste recycling plant in Portugal—Part II: Environmental sensitivity analysis. *Waste Manag.* **2013**, *33*, 147–161. [\[CrossRef\]](#)
10. Neto, R.; Gastineau, P.; Cazacliu, G.; Guen, L.; Paranhos, R.; Petter, C. An economic analysis of the processing technologies in CDW recycling platforms. *Waste Manag.* **2017**, *60*, 277–289. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Coelho, A.; De Brito, J. Economic viability analysis of a construction and demolition waste recycling plant in Portugal e part II: Economic sensitivity analysis. *J. Clean. Prod.* **2013**, *39*, 329–337. [\[CrossRef\]](#)
12. Hua, K.; Chen, Y.; Naz, F.; Zeng, C.; Cao, S. Separation studies of concrete and brick from construction and demolition waste. *Waste Manag.* **2019**, *85*, 396–404. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Tam, V.; Tam, C.; Le, K. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. *Resour. Conserv. Recycl.* **2007**, *50*, 82–101. [\[CrossRef\]](#)
14. Wu, Z.; Yu, A.T.W.; Shen, L.; Liu, G. Quantifying construction and demolition waste: An analytical review. *Waste Manag.* **2014**, *34*, 1683–1692. [\[CrossRef\]](#)
15. Galderisi, A.; Bravo, M.; Iezzi, G.; Cruciani, G.; Paris, E.; Brito, J.D. Physico-Mechanical Performances of Mortars Prepared with Sorted Earthquake Rubble: The Role of CDW Type and Contained Crystalline Phases. *Materials* **2023**, *16*, 2855. [\[CrossRef\]](#)
16. European Environment Agency. *EU as a Recycling Society—Present Recycling Levels of Municipal Waste and Construction & Demolition Waste in the EU*; European Environment Agency: Copenhagen, Denmark, 2009. Available online: https://web.archive.org/web/20210428083527id_/http://avfallnorge.web123.no/article_docs/EUgjenvinningsstudie.pdf (accessed on 15 April 2024).
17. Reis, G.S.; Quattrone, M.; Ambrós, W.M.; Cazacliu, B.G.; Sampaio, C.H. Current Applications of Recycled Aggregates from Construction and Demolition: A Review. *Materials* **2021**, *14*, 1700. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Gschwenter, V.L.S.; Tubino, R.M.C.; Ambrós, W.M.; Miltzarek, G.L.; Sampaio, C.H.; Moncunill, J.O.; Cazacliu, B.G.; Dal Molin, D.C.C. Production of High-Quality Coarse Recycled Aggregates through a Two-Stage Jigging Process. *Minerals* **2022**, *12*, 532. [\[CrossRef\]](#)
19. Sampaio, C.H.; Cazacliu, B.G.; Miltzarek, G.L.; Huchet, F.; Le Guen, L.; Petter, C.O.; Paranhos, R.; Ambrós, W.M.; Silva Oliveira, M.L. Stratification in air jigs of concrete/brick/gypsum particles. *Constr. Build. Mater.* **2016**, *109*, 63–72. [\[CrossRef\]](#)
20. Sampaio, H.C.; Cazacliu, B.G.; Ambrós, W.M.; Kronbauer, M.A.; Tubino, R.M.C.; Dal Molin, D.C.C.; Oliva Moncunill, J.; Miltzarek, G.L.; Waskow, R.P.; dos Santos, V.L.G.; et al. Characterization of Demolished Concretes with Three Different Strengths for Recycling as Coarse Aggregate. *Minerals* **2021**, *11*, 803. [\[CrossRef\]](#)
21. Salgado, F.D.; Silva, F.D. Recycled aggregates from construction and demolition waste towards an application on structural concrete: A review. *J. Build. Eng.* **2022**, *52*, 104452. [\[CrossRef\]](#)
22. Martinez, P.S.; Cortina, G.M.; Martinez, F.F.; Sanchez, A.R. Comparative study of three types of fine recycled aggregates from construction and demolition waste (CDW), and their use in masonry mortar fabrication. *J. Clean. Prod.* **2016**, *118*, 162–169. [\[CrossRef\]](#)
23. Brito, J.; Saikia, N. *Recycled Aggregate in Concrete—Use of Industrial, Construction and Demolition Waste*; Chapter 3; Springer: London, UK, 2013; p. 81.
24. Caicedo, D.F.; dos Reis, G.S.; Lima, E.C.; De Brum, I.A.; Thue, P.S.; Cazacliu, B.G.; Lima, D.R.; dos Santos, A.H.; Dotto, G.L. Efficient adsorbent based on construction and demolition wastes functionalized with 3-aminopropyltriethoxysilane (APTES) for the removal ciprofloxacin from hospital synthetic effluents. *J. Environ. Chem. Eng.* **2020**, *8*, 103875. [\[CrossRef\]](#)
25. Galderisi, A.; Iezzi, G.; Bianchini, G.; Paris, E.; Brito, E. Petrography of construction and demolition waste (CDW) from Abruzzo region (Central Italy). *Waste Manag.* **2022**, *137*, 61–71. [\[CrossRef\]](#)

26. Etxeberria, M.; Vázquez, E.; Marí, A.; Barra, M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cem. Concr. Res.* **2007**, *37*, 735–742. [\[CrossRef\]](#)
27. Xiao, J.Z.; Li, J.B.; Zhang, C. On relationships between the mechanical properties of recycled aggregate concrete—An overview. *Mater. Struct.* **2006**, *39*, 655–664. [\[CrossRef\]](#)
28. Ferreira, L.; Brito, J.; Barra, M. Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Mag. Concr. Res.* **2011**, *63*, 617–627. [\[CrossRef\]](#)
29. De Brito, J.; Pereira, A.S.; Correia, J.R. Mechanical behavior of non-structural concrete made with recycled ceramic aggregates. *Cem. Concr. Compos.* **2005**, *27*, 429–433. [\[CrossRef\]](#)
30. Agrela, F.; Cabrera, M.; Galvín, A.P.; Barbudo, A.; Ramirez, A. Influence of the sulfate content of recycled aggregates on the properties of cement-treated granular materials using Sulphate-Resistant Portland Cement. *Constr. Build. Mater.* **2014**, *68*, 127–134. [\[CrossRef\]](#)
31. Neville, A. The confused world of sulfate attack on concrete. *Cem. Concr. Res.* **2004**, *34*, 1275–1296. [\[CrossRef\]](#)
32. BCSJ. *Proposed Standard for the “Use of Recycled Aggregate and Recycled Aggregate Concrete”*; Building Contractors Society of Japan Committee on Disposal and Reuse of Construction Waste: Tokyo, Japan, 1977.
33. RILEM TC 172-EDM/CIB TG 22; *Environmental Design Methods in Materials and Structural Engineering*. RILEM: Paris, France, 1999.
34. UNE-EN 13242:2003+A1; *Aggregates for Unbound and Hydraulically Bound Materials for Use in Civil Engineering Work and Road Construction*. European Committee for Standardization: Bruxelles, Belgium, 2008.
35. Çelik, A.İ.; Özkılıç, Y.O.; Zeybek, Ö.; Karalar, M.; Qaidi, S.; Ahmad, J.; Burduhos-Nergis, D.D.; Bejinariu, C. Mechanical Behavior of Crushed Waste Glass as Replacement of Aggregates. *Materials* **2022**, *15*, 8093. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Özkılıç, Y.O.; Çelik, A.İ.; Tunç, U.; Karalar, M.; Deifalla, A.; Alomayri, T.; Althoey, F. The use of crushed recycled glass for alkali activated fly ash based geopolymer concrete and prediction of its capacity. *J. Mater. Res. Technol.* **2023**, *24*, 8267–8281. [\[CrossRef\]](#)
37. Çelik, A.İ.; Tunç, U.; Bahrami, A.; Karalar, M.; Othuman Mydin, M.A.; Alomayri, T.; Özkılıç, Y.O. Use of waste glass powder toward more sustainable geopolymer concrete. *J. Mater. Res. Technol.* **2023**, *24*, 8533–8546. [\[CrossRef\]](#)
38. Sampaio, H.C.; Ambrós, W.M.; Cazacliu, B.G.; Oliva Moncunill, J.; Veras, M.M.; Miltzarek, G.L.; Silva, L.F.O.; Kuerten, A.S.; Liendo, M.A. Construction and Demolition Waste Recycling through Conventional Jig, Air Jig, and Sensor-Based Sorting: A Comparison. *Minerals* **2021**, *11*, 904. [\[CrossRef\]](#)
39. Teixeira, A.B.; Barkat, H.; Sampaio, C.H.; Moncunill, J.O. Recovery of Demolished House Rocks from Construction and Demolition Waste with Water Jigs. *Minerals* **2024**, *14*, 39. [\[CrossRef\]](#)
40. Ambrós, M.W. Jigging: A Review of Fundamentals and Future Directions. *Minerals* **2020**, *10*, 998. [\[CrossRef\]](#)
41. Sampaio, C.H.; Tavares, L.M.M. *Beneficiamento Gravimétrico: Uma introdução Aos Processos de Concentração Mineral e Reciclagem de Materiais Por Densidade*; Editora UFRGS: Porto Alegre, Brazil, 2005.
42. Royal Decree 1247/2008; (EHE-08): *Structural Concrete Instruction*. Available online: https://www.mitma.gob.es/recursos_mfom/1820100.pdf (accessed on 12 April 2024).
43. Akbarnezhad, A.; Ong, K.C.G.; Zhang, M.H.; Tam, C.T. Acid Treatment Technique for Determining the Mortar Content of Recycled Concrete Aggregates. *J. Test. Eval.* **2013**, *41*, 441–450. [\[CrossRef\]](#)
44. EN 933-4:2008; *Tests for Geometrical Properties of Aggregates. Part 4: Determination of Particle Shape—Shape Index*. British Standards Institution: London, UK, 2009.
45. ASTM C127-07; *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*. ASTM: West Conshohocken, PA, USA, 2009.
46. De Juan, M.S. Study on the Use of Recycled Aggregates in Structural Concrete Production. Ph.D. Thesis, Polytechnic University of Madrid, Madrid, Spain, 2004. (In Spanish)
47. Santos, J.; Branco, F.A.; de Brito, J. Reinforced concrete beams with recycled aggregates from demolished concrete of a stadium. In *Proceedings of the SB05—3rd International Conference on Sustainable Building*, Tokyo, Japan, 23–29 September 2005; pp. 2011–2018.

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