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Original Article

Management and characterization of concrete wastes from concrete batching plants in Belo Horizonte – Brazil

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A B S T R A C T

This paper aims to evaluate the forms of concrete waste generation in concrete batching plants (CBP) in the metropolitan region of Belo Horizonte, Brazil, and focusing on the reuse of this waste in the productive sector of the CBP. Visits were made to nine dosing centers to collect information related to the production process and waste management. The concrete batching plants in Belo Horizonte use different ways to manage and waste disposal, most of which are inefficient and generate high financial expense and do not added value to waste. This study focusing on the elaboration of proposals to allow the waste reuse in the company itself (reducing costs with the acquisition of new materials), indicating potential reuse of the various types of waste generated. Thereunto, materials were collected in the settling tanks to characterize the wastes, considering the physical (granulometry, specific mass, porosity, SEM) and chemical–mineralogical properties (X-ray fluorescence - XRF, X-ray diffraction - XRD, specific surface area, thermogravimetry - TGA, scanning electron microscopy - SEM and energy dispersive spectroscopy - EDS). This present study demonstrated which management procedures and techniques can be incorporated into concrete batching to reduce waste generation and increase reuse of the generated wastes.

1. Introduction

Concrete is the second most consumed resource in the world. Consequently, the Portland cement industry is responsible for high energy consumption, emission of 4–8% of CO_2 from anthropogenic activities [1], and environmental degradation due to the exploitation of non-renewable natural resources [2].

It is known that in 2018, the ready-mix concrete (RMC) production in countries that are members of the European Ready Mixed Concrete Organization [3] totaled a volume of 250.43 million cubic meter, while in the United States alone the production was 274 million cubic meters. In addition, there was a forecast that in that same year, in Brazil, 72.3 million cubic meters of the product would be produced [4]. According to ERMCO data [3], in 2018, 54.7 and 73% of all cement

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produced member countries and the USA, respectively, were consumed by concrete producers, corresponding to approximately 312 million metric tonnes of binder [3]. In Brazil, this consumption corresponded to 18% of the total cement shipped, approximately 10 million metric tonnes, of the total cement shipped [5].

The generated RMC waste is variable, estimated from 1 to 4% in Europe and 9% in Brazil [6]. Thus, in 2017 in Brazil, approximately 6.5 million cubic meter of waste may have been generated and up to 15.3 million m^3 in ERMCO members in 2016 [3]. Therefore, almost 22 million cubic meters, approximately 48 million metric tonnes, of this residue may have been generated in one year in 22 of the 193 countries that make up the UN [7]. If the generated waste is not reduced or a destination found for its utilization, all this generated volume will be disposed in landfills. However, it is known that, in many countries, the lack of areas destined for this purpose is already a reality [6,8,9]. In addition to generating impacts on the environment [10], they burden the production process due to the cost of proper disposal of this material, which tends to increase with the scarcity of these areas [6,11].

The main sources of concrete generating waste in a concrete batching plant (CBP) are the returned concrete waste (RCW). The RCW corresponds to the concrete that returned to the plant without being discharged. In contrast, the CBP is the ballast that comes back adhered to the wall of the concrete mixer trucks after the mixture has been completely unloaded. According to Vieira et al. [12], the mixing volume can be returned to the plant for an excess order, a transport time that was exceeded, a load that was rejected, or equipment failure. According to the authors, 5% of the trucks return from the works with residual concrete, but they all return with adhered concrete, which can only be removed by washing. For this reason, internal and periodic cleaning of the concrete mixer drum is necessary to avoid the hardening of the concrete inside the equipment and its deterioration.

Some alternatives can be adopted within concrete companies to reduce generated waste. Recycling centers have equipment that separate the cement paste from the recovered aggregates, which can be utilized in subsequent mixes [13]. Another alternative is the use of a hydration stabilizer admixture, which, when incorporated into the washing water of concrete mixer trucks, stabilizes the cement hydration until the next mix ratio is produced. This new mixture can be made the day after or after a weekend or a long weekend. The hydration stabilizer contents will vary according to the desired stabilization time [14].

In addition, RMC have already been studied in concrete and concrete block incorporation, replacing aggregates [8,9,15,16] and in mortars replacing limestone filler [17]. Ferrari et al. [18] found satisfactory results when producing recycled aggregates using non-toxic additives in returned concrete. Aggregate incorporation recovered through recycling plants was carried out in the study by Vieira et al. [13] and the residual cement paste was also studied in different ways [9,19–21]. However, despite the alternatives that help reduce RMC generation and different works that have sought ways to use it, the waste is being generated on a large scale. Martins et al. [22] evaluated the possibility of using waste generated in the sedimentation basins of concrete plants as a partial replacement (20%) of Portland cement. The results showed mechanical behavior and durability similar to mineral additions such as limestone filler. Furthermore, the development of alternatives for the use of concrete waste to promote the reduction of the amount of cement produced is extremely important, reducing environmental impacts associated with the CO_2 emissions and the consumption of non-renewable resources.

The aforementioned papers [6,8–22] present different information and/or evaluate a specific type of concrete waste (granular or fine). Furthermore, correlations between management and use of concrete wastes are not usually described in the literature. In this context, it is important to know which methodologies are being adopted in the world, aiming at reducing the disposal of these wastes in the environment. The concrete batching plants use different techniques of destination of the concrete waste generated. However, most of those processes are not efficient and generate high financial costs. The use of this type of waste in a concrete batching plant or in another sector is still not common. The characterization of a waste is the initial step to propose its reinsertion in the productive sector, different ways of reusing it and avoiding its disposal in the environment. In this condition, this present study innovated in proposing a management process in the company coupled to use of waste.

Given this scenario, this study aims to evaluate ways of generating and managing concrete batching plant (CBP) waste in the metropolitan region of Belo Horizonte, Brazil, to verify the measures are being adopted to reduce the disposal of this material and characterize them with a focus in its reinsertion in the productive sector.

2. Materials and methods

The first step of this research consisted of visiting nine Concrete Batching Plant centers (CBP) to collect information related to the production process and waste management. A questionnaire was given to each CBP for the purpose of verifying the generation of different types of concrete waste and to verify how wastes are treaded within the CBP (use and disposal of waste). The second stage of this research was the characterization of the wastes collected in the sedimentation tanks at concrete plants (concrete sludge waste) and to propose sustainable solutions for this specific waste. The focus was on concrete sludge wastes since this is the most generated wastes at CBPs visited.

2.1. *Waste production and management waste within the concrete batching plant*

Visits were carried out in nine CBP located in the metropolitan region of Belo Horizonte. During the visits, concrete production process and the forms of waste generation and management information were collected. Collected characteristics from plants were the monthly volume of cementitious compound produced, demand for concrete mixer trucks, concrete production process and materials used. Subsequently, the main sources of waste generation and the management process adopted by concrete companies were also determined.

Items evaluated during visits are summarized in Table 1. With the information collected it is possible to identify the scenario of concrete companies in the region, with a view to identifying possible alternatives to be implemented in the management of waste generated, from generation to the most appropriate destination. It should be noted that the questionnaire focused on fresh concrete waste and concrete sludge waste. The first waste comes from the returned concrete. On the other hand, concrete sludge waste is obtained from the solids in the settling tanks.

2.2. *Characterization of the concrete sludge waste*

During the visits, it was observed that most of the waste generated in the CBP is the concrete sludge waste, where it remains stored until the dispatch to final destination. For this reason, samples of these materials were collected for characterization. In this study, fresh concrete sludge was collected from the batching of the dosing plants in their fresh state and stored in closed containers for 2–3 days. Then, the samples were dried at 100 ± 5 °C, for 48 h, disaggregated and sieved. The samples were stored in containers hermetically closed until the test date. Concrete sludge waste (CSW) characterization collected in the nine concrete batching plants was carried out to determine the physical and chemical properties. Thus, it is possible to characterize this material and identify probable recycling forms and/or disposal.

Particle size distribution was performed on 500 g of the sample. Initially, the analysis was performed by sieving up to sieve #100 (0.15 mm) [23]. Subsequently, the fraction smaller than 0.15 mm (fine fraction) was analyzed in water dispersion in a granulometer by laser diffraction, Sympatec brand, model Helos 12LA, computerized in a 50 mm lens, with the sodium hexametaphosphate dispersant (0.05%).

The chemical composition was determined by using a Malvern Panalytical X-ray fluorescence (XRF) spectrometer, model MagixFast from Geosol. Samples were prepared by lithium tetraborate fusion. The Loss on Ignition was carried out by sample decomposition through calcination in a muffle furnace at 1000 °C. Thermogravimetric analysis was performed in a nitrogen atmosphere, with a flow of 50 mL/min, temperature ranging from 25 to 1000 °C and heating rate of 10 °C/min. A Thermal Analyzer (Shimadzu, model TGA-51) was used. To determine the amount of calcium hydroxide and calcium carbonate, the stoichiometric calculation of mass loss for each of these compounds was used. Details about this methodology can be found in the literature [24–26]. The amount of hydrated calcium silicate cannot be calculated by this method, as this hydrated compound has a variable chemical composition. The crystalline phases of the residue were determined using an X-ray diffractometer (XRD) for powder samples, Philips's brand, X'Pert-APD system, PW 1830/40 generator, PW 3020/00 goniometer, computerized PW 3710/31 controller.

The specific surface area (SSA) and the porosity were evaluated in the fine fractions of the residues with the Quantachrome Nova 1200e equipment, the software Quantachrome NovaWin version 11.02, being used as an adsorbate with nitrogen (N_2). The analysis time for each sample was 24 h. The specific surface area was calculated by the multipoint method using the Brunauer–Emmett–Teller (BET) adsorption isotherm and non-local density functional theory method (NLDFT) using the desorption isotherm to calculate the porosity. The specific gravity of the fine fraction was analyzed in a Quantachrome brand, model SPY-3, helium gas pycnometer.

The fine fraction of the nine samples was analyzed in the focused ion beam (FIB) scanning electron microscope (SEM - Quanta FEG 3D FEI), and the images were obtained with a secondary electron detector with 5 kV. This SEM was coupled to an energy dispersive X-ray spectrometer (EDS): 15 kV, working distance of 10 mm. A 15 nm thick carbon overlay was used.

Table 1 – Items evaluated in visits to the plants.

Analysis	Analyzed Items
Concrete production	Monthly production of concrete and mortar Main mix ratio produced Materials used for the mix ratio production
Waste generation and management	Water volume for washing trucks Number of trucks Truck washing frequency Waste generation in settling tanks Use of hydration stabilizing admixture Waste treatment and disposal Amount of mud generated monthly

3. Results

3.1. *Concrete batching plant characteristics*

The monthly volume production of cementitious compound produced by the visited CBPs ranged from 2500 to more than 10,000 cubic meters. Thus, The CBPs have from 7 to 45 concrete mixer trucks to transport the cementitious compounds. The first step to concrete and mortar production is the storage of aggregates in bays. Note that, there is constant monitoring of aggregate moisture to correct the water/cement ratio of concrete and mortars. According to the plant's production schedule, the aggregates are sent to the stock lines and are subsequently weighed for mixing. Cement is stored in silos and chemical admixtures in tanks, ready to be used. Posteriorly, the materials are weighed and released at the loading point along with water. Note that the water is added in a smaller amount than stipulated in the mix and then it is manually re-dosed in the concrete mixer truck. It is important to keep in mind that, from one plant to another, there may be variation in automation level, in types of materials used, in the mix ratio produced, etc. The basic concrete production process is shown schematically in Fig. 1.

The materials used in each CBP are shown in Table 2. The coarse aggregates used were limestone or gneiss rocks with sizes ranging from 4.8 to 19.0 mm. Moreover, the fine aggregates were natural river sand (rich in quartz), gneiss, limestone, or a combination of these types. It should be note that, the kind of fine aggregate used varies according to the

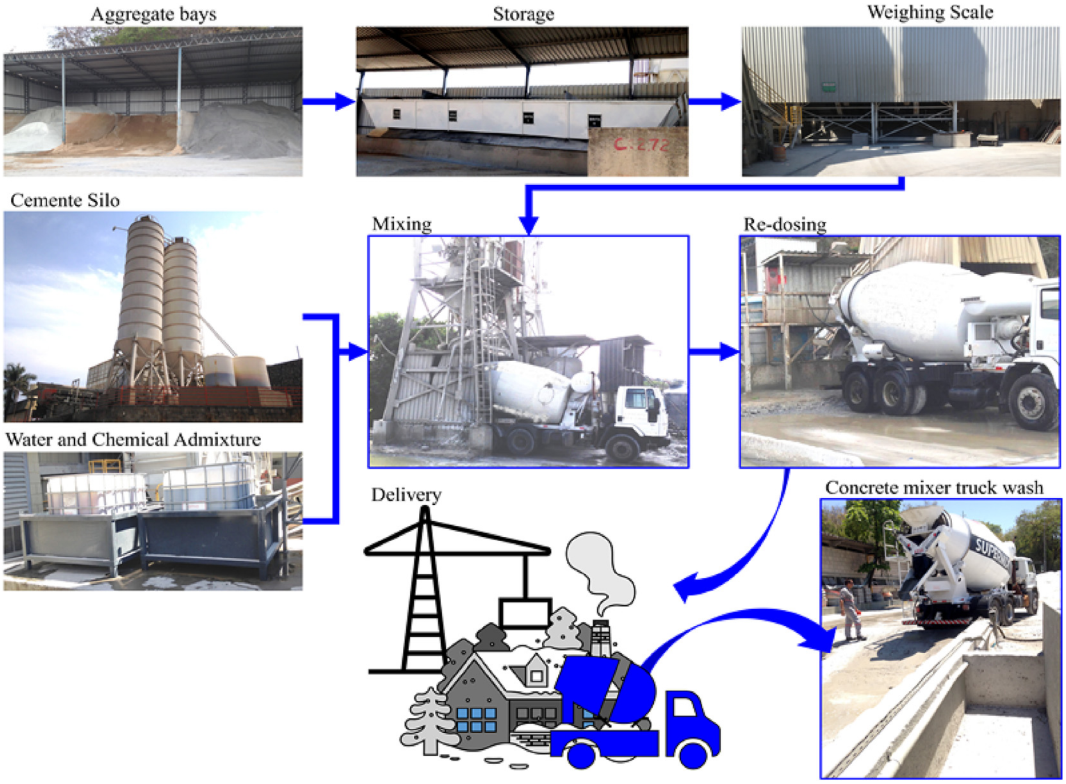


Fig. 1 – CBP Concrete production general flowchart.

Table 2 – Materials used for the mix ratio production in the visited CBP's.

CBP	Production	Coarse	Fine	Cement	Addition	Chemical admixture
1	Concrete 20 MPa	Gravel 0 e 1 Gneiss	Natural	CP II E 40	Varied	Polyfunctional
2	Concrete 20–30 MPa assorted mortars	Gravel 1 Gneiss	Artif. Gneiss	CPV Ari RS	Non	Plasticizer
3	Concrete 20 and 25 MPa	Gravel 0 e 1 Limestone	Natural	CPV Ari CPIII 40 RS	Non	Plasticizer
4	Concrete 20 MPa	Gravel 0 e 1 Limestone	Natural Artif. Limestone	CPV Ari RS	Polypropylene fiber	Plasticizer Mid-Range Waterproofing
5	Concrete 20–30 MPa	Gravel 0 e 1 Limestone	Natural Artif. Limestone	CPV Ari	Non	Polyfunctional Superplasticizer
6	Concrete 20–30 MPa Subfloor mortar	Gravel 0 e 1 Limestone	Natural Artif. Limestone	CPV Ari RS CPIII 32	Limestone powder Others according to the customer	Polyfunctional
7	Concrete above 25 MPa assorted mortars[a]	Gravel 0 e 1 Gneiss e Limestone	Natural Artif. Gneiss	CPV Ari RS Others	Limestone powder Others according to the customer	Varied
8	Concrete 15–30 MPa Subfloor mortar	Gravel 0 e 1 Gneiss	Natural Artif. Gneiss	CPV Ari RS	Limestone powder	Polyfunctional Superplasticizer
9	Concrete 20–30 MPa Subfloor mortar	Gravel 0 e 1 e pebble Gneiss	Artif. Gneiss	CPV Ari RS	Limestone filler	Polyfunctional Superplasticizer

Portland cement: CPII E 40 – $\leq$ 24% blast furnace slag addition and compressive strength of 40 MPa; CPV Ari RS - $\leq$5% limestone powder and with sulfate resistance; CPIII 40 RS - $\leq$ 50% addition of blast furnace slag, with sulphate resistance and compressive strength of 40 MPa; CPIII 32 - $\leq$70% addition of blast furnace slag and compressive strength of 32 MPa.

[a] The mortar waste generated in plant 7 has a separate destination and is not included in the composition of the LRCU.

localization of the concrete plant, and the type of composites produced. In addition, some plants used mineral additions such as limestone filler to produce self-compacting concretes; formulated mainly for concreting cast-in-place concrete walls. In some specific cases, other mineral additions are also used in some plants. Plasticizers and polyfunctional admixture are used for the structural concrete production, while superplasticizers are used in self-compacting concrete. Note that, other chemical admixture can also be added for mortar production.

3.2. *Waste generation and reuse*

Two main sources of waste generation from the concrete production process were identified. One of these sources is concrete leftover due to the loss of excess production or when the casting concrete exceed the maximum time specified by standards. In this case, the concrete mixer trucks return to the CPBs without being unloaded with a waste known as fresh concrete waste (FCW). The other source of waste generation comes from the concrete that remains adhered to the internal mixer truck walls after the concrete has been completely unloaded. In this case, cleaning is carried out daily and after the last concrete mixer truck journey. However, on days with less production, washing is done whenever the truck is stopped for more than 2 h. Therefore, concrete sludge waste (CSW) is generated, and it is known as a waste containing sedimentable solids of the cementitious compounds. Table 3 shows the forms of concrete waste generation into each plant, and the frequency of waste collection for shipment to storage bays.

3.3. *Fresh concrete waste*

Fresh concrete waste is treated differently in concrete plants. According to Table 3, plants 1, 2, 4, 5 and 8 do not have waste from returned concrete. This is explained because those plants used this waste to produce blocks with non-structural purposes (Fig. 2). These blocks are used by the concrete plants themselves, for example, to build bays for storing materials. In contrast, plants 3 and 9 deposit fresh concrete waste in the settling tanks, while plants 6 and 7 deposit the FCW directly in the storage bays specific for this purpose.

Fresh concrete waste can also be sent to a recycling plant for aggregate reuse. However, the recycling plant was used only in one of the visited plants; on the day of the visit, it was damaged. It was observed that recycling plant has not been adopted by most concrete companies due to expensive high maintenance frequency, excessive use of energy, high investment cost, and necessary yard space, which is often unavailable. Numerous attempts were made to visit another CBP in the region that uses recycling machine, but it was undergoing maintenance.

3.4. *Truck wash waste*

Concrete mixer truck internal walls are washed daily to remove adhered concrete. This process is necessary to avoid internal truck ballast deterioration. It is important to note that the wash-water contains aggregates and cement solids from the cementitious compounds. Consequently, this water must be properly treated [27]. Therefore, the wash-water is received by the inlet chamber (known as ballast pumping) and conducted to the decantation tanks. Thus, the suspended particles are allowed to settle, and the water is sent to the outlet chamber and then it is pumped and stored according to its final destination. According to Paula and Ilha [28] in addition to passing the wash-water through the settling tanks, it is also necessary to correct the pH, apparent color, turbidity, alkalinity and hardness of the water, before considering ways to reuse it. Generally, the wash-water is sent to an exclusive water tank and used in activities at the concrete plant such as production of a new concrete or for washing the CBP or the concrete mixer trucks.

Note that, the settling tanks also receive different types of wastes. As an example, there are wastes that come from the draining part of the dosing water at the loading point, from the re-dosage water runoff and wash-water from operation yard. Furthermore, as previously described, plants 3 and 9 also deposit fresh concrete waste in the settling tanks. However, the internal washing water from the concrete mixer trucks is the main waste deposited in the settling tanks in all the concrete plants visited. In the case of the plants visited, the number of settling tanks varied from 3 to 11. One must keep in mind that the quantity of these devices varies from one plant to another, as it depends on the concrete demand of each plant.

Solid material that settled forming the concrete sludge waste is periodically removed from the ballast and other sedimentation chambers and sent to the storage bays (Fig. 3). In the storage bays, the solid material loses moisture and then the waste is transported to final destination. Note that, this destination can be a recycling of waste for backfilling ditches, such as crusher run gravel, but its main destination is still the landfills. As with fresh concrete waste, concrete sludge waste can be sent to a recycling plant to obtain recovered aggregate. These results agree with Sérifou et al. [6] since the use of recovered aggregates on roads or in landfills is a current practice in concrete waste management in France. Reuse as a crusher run gravel in sub-base for paving is carried out by outsourced companies that collect waste from the plants at no cost, in CBP 7. It is a beneficial alternative for CBPs, as it eliminates the expense of transporting and disposing of waste.

Finally, an alternative to reduce the generation of fresh concrete waste and avoid concrete sludge waste is the use of Hydration Controlling Admixtures (also known as Hydration Stabilizers). This chemical admixture maintains the concrete fresh for up to 72 h, allowing the returned concrete to be reused [29,30]. Some of CBP's visited commonly used to use Hydration Stabilizers in the past, however, they discontinued its use. This can be explained because a very strict content control of incorporated chemical admixture is required to avoid delaying in concrete setting time. Furthermore, CBP's that use hydration stabilizers also generate waste. The reason for this is that in some applications, quick setting time is required such as concreting concrete walls. Consequently, this type of chemical admixture cannot be used in this case. This reality is not consistent with the bibliography [22,24], which states that the use of the hydration stabilizer admixture is a growing practice among concrete producers and that its use provides financial benefits to concrete production plants.

Table 3 – Type of waste generation in the concrete plants visited.

FCW	Form of generation	Waste removal
1	A-B	Daily
2	A-B-C	Daily
3	A-B-C-D (little)	2 times per week
4	A-B	Daily
5	AB-C	Daily
6	A-B-C-D (mostly)	2 times per week
7	A-B-C-D (mostly)	Daily
8	A-B-C	Daily
9	A-B-C-D	Daily

A - Internal washing of the drums; B - Concrete dosage; C - Operating yard washing; D - Returned concrete.

3.5. *Material characterization*

Hydrated cement clusters were formed during the concrete sludge waste collection. This happens because the concrete slurry is stored in the CBP. Furthermore, cement paste adhered to the surface of the aggregates was also observed. As a result, this material was disaggregated before the waste characterization (Fig. 4).

The particle size distribution of the CSW with particles larger than 150 μm is shown in Fig. 5 (a). There is a wide variation in the particle size distributions of the collected CSWs. The particle size distribution of the material passing through the 150 μm sieve is shown in Fig. 5 (b). The results show that there were few variations among the nine residues since the median diameters (D50) of the materials are close (Table 4).

Due to the possibility of differentiated use between the fractions, the chemical composition of the CSW and the fine fraction (>150 μm) of the CSW was determined. The chemical composition of the CSW is shown in Table 5. Silicon dioxide (SiO_2) is the predominant compound in all wastes, followed by calcium oxide (CaO). The chemical composition of the fine fraction (<150 μm) is shown in Table 6. The results show that calcium oxide and silica are also predominant in all wastes.

Diffractograms of the coarse fraction are shown in Fig. 6 (a). It is possible to observe the presence of characteristic peaks of quartz and calcite in all samples. However, there is a tendency for quartz peaks to be higher than calcite peaks. Furthermore, it is possible to observe calcium hydroxide (portlandite) in almost all samples, except for residues 1 and 8. In the waste from CBPs that use gneiss aggregates, the presence of micaceous and feldspathic minerals is also observed.

Fig. 2 – Concrete blocks produced.

Fig. 3 – Concrete waste bay in batching plants.

Figure 7 is a representative result of TGA and DTG of three concrete sludge wastes (CSW1, CSW5 and CSW7). The CSW1 is composed of natural gneiss aggregates, CSW5 by limestone aggregates and CSW7 by gneiss and limestone aggregates. These wastes were chosen to illustrate the behavior of all the CSWs. According to TGA and DTG results the decomposition of concrete sludges wastes can be divided into three major regions. The first mass loss (between ~ 25 and 400 °C) corresponds to evaporable water and cement hydrates decomposition. At the same time, the dehydration of portlandite occurs at about 400 °C or higher. The last mass loss represents the decarbonation of $CaCO_3$ recorded between from 600 to 835 °C. According to the results, CSW1 does not present calcium hydroxide due to the absence of a negative CTG peak at around 400 °C. In addition, CSW 5 presents highest calcite content, since this sample exhibited the greatest mass loss between 600 and 800 °C. As a result, from thermal analysis, it was possible to estimate the amount of hydrated calcium silicate (C–S–H), calcium hydroxide and calcite present in the fine fraction (Fig. 8). It must be noted that calcium carbonate and calcium hydroxide are shown as a percentage amount, whereas C–S–H is shown only as the mass loss of the TG curve. The results show that wastes 1 and 8 had no calcium hydroxide and it agrees with the XRD results.

According to the classification of the International Union of Pure and Applied Chemistry [31] both materials have pores that fall within the range of mesopores. Table 7 shows the specific surface area (SSA), the pore volume, average pore diameter and the density of the residues. The highest SSA value was observed for residue 2, while residue 7 had the lowest SSA value. In this case, there was a variation of 55% in relation to the largest specific surface.

4. Analysis

The volume of FCW generated ranged from 0.2 to 7.5%. This variation is because some plants reuse part of the waste, before sending it to the bays, by considering: (i) using HCA; (ii) recycling machines; or (iii) taking advantage of the returned concrete. These percentages exceed the loss limits, from 1 to 4%, estimated for Europe and agree with the estimate for Brazil of up to 9% [32]. It must be highlight that, when recycling facilities are used, this value is estimated at 0.8% [20].

(a) (b) (c)

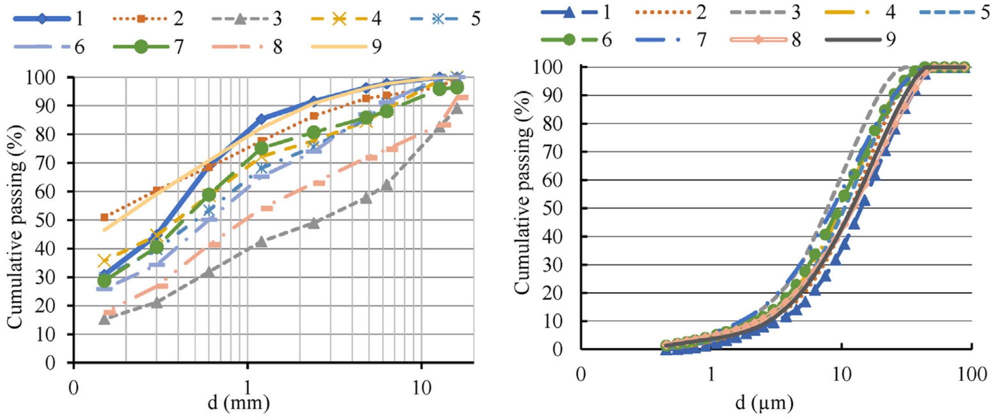
Fig. 4 – Concrete sludge waste (a) Moist collected at the plant. (b) After drying in an oven. (c) Post crumbling.

Concrete sludge waste collected at Belo Horizonte plants had a mineralogical composition rich in quartz and calcite, and particles smaller than 16 mm in size. As the concrete batching plants visited do not employ recycling plants, the presence of natural aggregates in this waste is common. Taking this into consideration, the coarse fraction of concrete sludge waste is basically composed of aggregate fractions and this waste has a potential to be used as a replacement of sand or limestone filler in concrete or mortars [13]. As observing Fig. 9, the recycled aggregate from all wastes presents particle size ranges within the limits established by standards.

The percentage of material passing through the 150 μm sieve ranged from 15.4% in sample 3–51% in sample 2 (Fig. 10), with a greater amount of fine material than in the studies carried out by Audo et al. [17] and Correia et al. [8], where a variation of up to 40% was found. As previously described, plants 3 and 9 also deposit fresh concrete waste in the settling tanks, however, from the granulometry graph, it is not possible show that the variation in the coarse aggregate content would be greater because of this. This happens due to the great variation that occurs daily in each concrete plant. Thus, the collected residue represents only the sample of a short period in that concrete plant. Some concrete companies collect material every two weeks or, in some cases, up to 3 times a week, depending on the company's concrete demand.

The characterization of the material smaller than 150 μm was necessary, since fine materials can be used as an addition to cement or concrete. It is important to note that, although the sieving to obtain the fine fraction was carried out in a 150 μm sieve, in both sludges, all particles are smaller than 50 μm. However, the same was not observed in the SEM images (Fig. 11), since particles larger than 50 μm are visible. A possible explanation for this difference between the results is that particle agglomerations were disaggregated during the laser particle size test. The use of concrete sludge waste can be also performed in the fresh state. Concrete sludge waste in the fresh state, after passing through a pressure filter, was used in the study by Xuan et al. [20]. In this case, the fresh sludge is mixed vigorously in a mechanical mixer and used as cement paste in concrete blocks. Positive results were observed in relation to compressive strength and porosity when ground waste sludge was used as a substitute for cement, up to a content of 10%. The authors also found that the residue accelerates the binder hydration [34].

The presence of silica in all samples is explained by natural sand or gneissic aggregates used. However, the amount of SiO_2 tends to be higher in the waste from concrete plants that use gneissic coarse aggregate. Furthermore, the CaO compound may come from calcite, calcium hydroxide and other cement hydrated compounds. However, CaO appears in greater



(a) (b)

Fig. 5 – Particle size distribution of the CSW: (a) > 150 μm and (b) ≤ 150 μm.

Table 4 – Granulometry results.

Fraction		1	2	3	4	5	6	7	8	9
Coarse	$D_{máx}$ (mm)	4.8	12.7	16	9.5	9.5	9.5	6.3	16	4.8
	Percentage of Particles <150 μm	30.8	51.0	15.4	35.8	30.0	25.9	28.8	17.5	46.5
Fine (<150 μm)	D_{50} (μm)	14.13	11.79	7.81	10.02	10.52	9.46	8.57	12.23	12.01
	$D_{máx}$ (μm)	36.5	30.50	21.5	25.5	25.5	25.5	30.5	36.5	30.5

proportion in wastes with limestone as a coarse aggregate (waste 3, 4, 5, 6 and 7). Note that, among those residues that use limestone as a coarse aggregate, residue 7 had the smallest amount of CaO and the largest amount of SiO_2. This is due to the use of gneiss as a fine aggregate and the mixture of gneiss and limestone as a fine aggregate. On the other hand, in the CBP that used coarse and fine artificial gneiss aggregate (waste 1, 2, 8 and 9), SiO_2 was the most abundant compound.

The difference in chemical composition between the CSW and fine fraction may be explained due to types of minerals present in each size. As an example, quartz has high resistance to chemical weathering and is a very hard mineral [35]. This explains the greater amount of silica in the coarse fraction and the increase in CaO in the fine fraction. Note that quartz is common in gneiss aggregates and natural sand [17]. Comparing the diffractograms of the coarse fraction with the fine fraction (Fig. 6 (b)), the characteristic peak of calcite (29.5°) is higher in waste from concrete plants that used limestone aggregates. On the other hand, wastes with gneiss aggregates present characteristic quartz peak intensity (26°) close to the calcite peak (29.5°), in addition to micaceous and feldspathic minerals. In the case of residues 3 and 4, the presence of micaceous minerals corresponds to impurities present in the aggregates. The waste 2 presented the largest portion of hydrated products (CH and C–S–H), followed by samples 4, 5 and 9, in that order. Finally, the amount of calcite was higher in waste from plants that used limestone aggregates. Thus, the TG and illustrative EDS (Fig. 12) results agree with the chemical composition and the XRD results. It is possible to notice the presence of some particles composed predominantly of calcium and silicon, which may also have aluminum and/or iron. These particles correspond to compounds from Portland cement. On the other hand, regions composed practically of calcium are also noticeable, which can be attributed to calcite or calcium hydroxide. As it is a sample with gneiss aggregates, they are also notable compounds with potassium, magnesium, calcium, and aluminum, corresponding to feldspathic and micaceous minerals.

It is interesting to note that the pore volume presented a correlation with the specific surface. This can be explained because of the surface characteristics of the residue grains. Through the results of the chemical and mineralogical composition, described above, it was possible to verify that in the residues there is a predominance of fine fractions of aggregates and hydrated cement compounds. The fine fraction of the waste has cement paste adhered to the surface, as shown in Fig. 13. In addition, the SSA of LRCBP without sieving and with particles predominance above 100 μm, studied by Silva [16] was of approximately 27 m^2/g, which proves the morphology influence of the particles on the specific surface area [36]. Interestingly, the SSA followed the same number of hydrated products noted in the previous section. Finally, regarding the specific mass, there was a small variation between values, being greater in waste 7 (2.66 g/cm^3) and smaller in waste 2 (2.36 g/cm^3).

5. Implications for future practice

From the visits to nine concrete batching plants in the metropolitan region of Belo Horizonte, capital state of Minas Gerais, southeast Brazil, it was noticed that there are two main sources of waste generation from the Concrete Production Process at the CBP: the concrete waste from the washing water of the concrete mixer trucks, and the fresh concrete waste from concrete loss of excess production or when the casting concrete exceed the maximum time specified by standards, named here as a returned concrete.

Although the plants already have some form of reuse the concrete wastes, the largest volume of those wastes is still sent

Table 5 – Chemical composition of the CSW (Coarse + fine fraction).

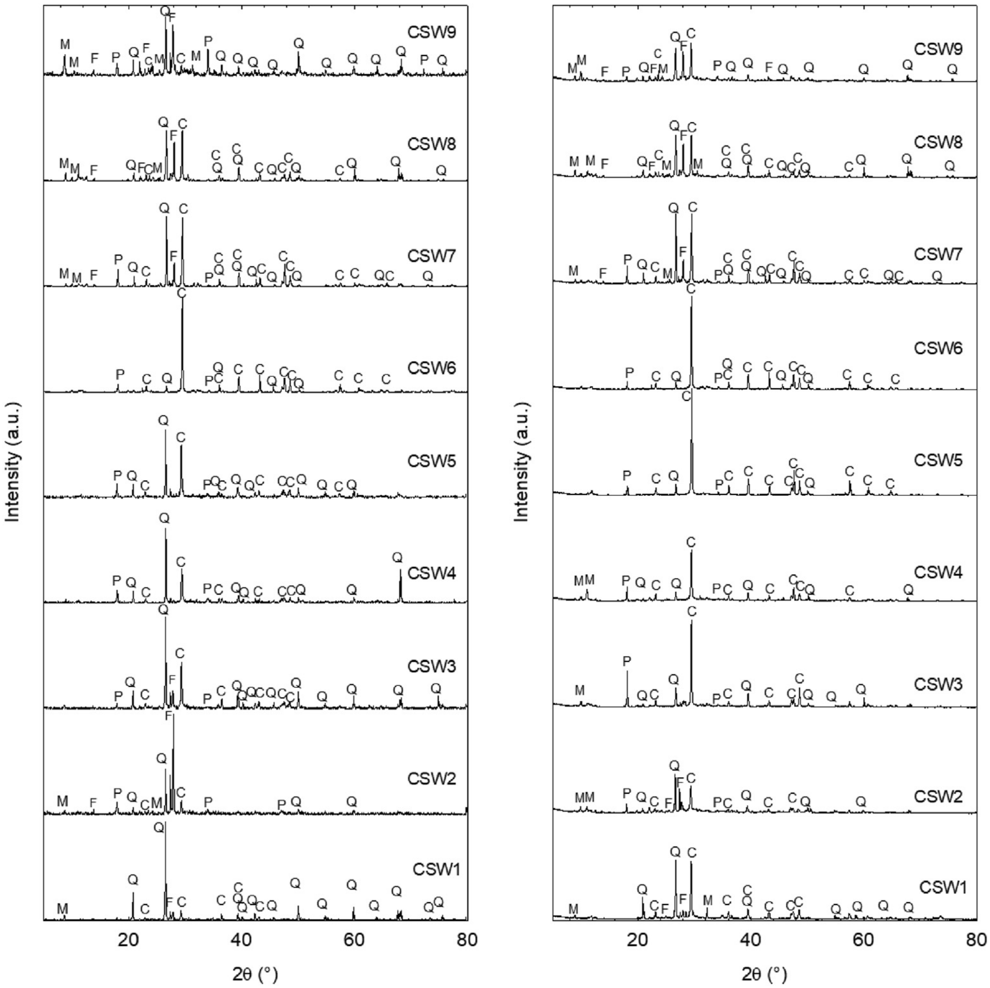
Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
	%	%	%	%	%	%	%	%	%	%	%	
1	68.00	0.29	6.33	2.76	0.11	0.78	11.70	1.04	1.62	0.05	7.61	100.29
2	42.10	0.26	9.18	2.40	0.13	1.39	27.60	1.66	1.71	0.13	12.74	99.30
3	49.20	0.15	5.34	1.42	0.05	0.91	24.20	1.04	1.38	0.07	15.45	99.21
4	40.80	0.22	4.31	1.77	0.11	1.24	31.40	<0.1	1.00	0.10	17.45	98.40
5	37.50	0.20	3.04	2.77	0.10	0.63	32.40	<0.1	0.57	0.13	20.80	98.14
6	43.30	0.14	2.55	1.32	0.09	0.79	30.30	<0.1	0.76	0.08	19.89	99.22
7	52.30	0.17	5.98	1.67	0.10	0.52	22.40	1.32	1.46	0.08	13.87	99.87
8	68.30	0.20	10.80	3.11	0.06	0.54	7.83	2.88	2.31	0.06	4.91	101.00
9	55.00	0.27	11.70	2.58	0.11	1.06	16.50	2.95	1.85	0.12	6.69	98.83

Table 6 – Chemical composition of the fine fraction.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
	%	%	%	%	%	%	%	%	%	%	%	
1	34.90	0.41	7.99	3.81	0.17	1.67	27.80	0.88	1.44	0.10	19.17	98.34
2	37.10	0.27	8.41	2.48	0.15	1.43	29.40	1.30	1.53	0.15	15.85	98.07
3	23.50	0.24	4.94	2.20	0.11	1.64	40.90	0.51	0.96	0.11	23.53	98.64
4	21.60	0.28	5.25	2.28	0.17	1.66	42.30	<0.1	0.71	0.16	23.50	97.91
5	15.60	0.23	3.42	3.11	0.13	0.87	44.60	<0.1	0.36	0.17	29.33	97.82
6	17.30	0.24	3.46	2.28	0.17	1.43	45.30	<0.1	0.49	0.11	27.41	98.19
7	28.20	0.24	5.63	2.34	0.17	0.82	36.50	0.84	1.23	0.14	21.86	97.97
8	47.30	0.30	10.00	3.12	0.12	0.88	20.80	2.01	1.82	0.14	13.08	99.57
9	41.50	0.33	9.42	2.87	0.18	1.35	27.60	1.71	1.38	0.18	12.28	98.80

to landfills. It is known that concrete residues have a high pH, due to the cement's hydration process. Because of this, this type of waste is considered dangerous and its disposal in landfills causes harmful effects on the soil and the environment [20]. Thus, it is worth noting the importance of developing appropriate methods for recycling and using these materials.

In view of this scenario, a waste management process is proposed, expressed in the flowchart in Fig. 14, which aims to reinsert concrete waste in the productive sector of civil construction. Next, each part of the proposed flowchart is detailed, describing: the circumstances of generation and thus ways to reduce or eliminate the generation of waste; or ways



(a) (b)

Legend: C: calcite; F: felspar; M: mica; P; portlandite; Q: quartz.

Fig. 6 – Diffractogram (a) coarse and (b) fine fraction residue.

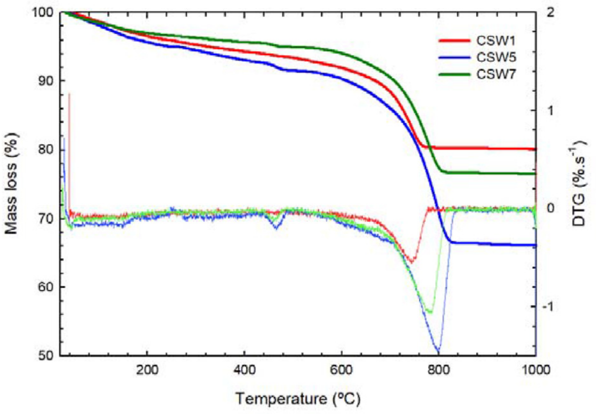


Fig. 7 – TGA and DTG results of concrete sludge wastes.

to reuse the generated waste, either in the concrete plant itself or in third-party companies.

5.1. *Returned concrete waste*

It was found that fresh concrete waste is reused differently in concrete plants in Belo Horizonte. Most of the plants already reuse the waste to make concrete blocks with no-structural function. This is believed to be the most efficient solution and incurs less interference in the company's production process. This type of waste is generated from an error: when the dosage is higher than demanded; or due to logistical problems, causing the truck to be delayed in arriving at the construction site. Thus, it is necessary to improve the management and control processes of the company to reduce and even eliminate the generation of this type of waste. Tools such as lean thinking and the PDCA (Plan, Do, Check, Act) cycle are good for optimizing spaces and services developed by the concrete company.

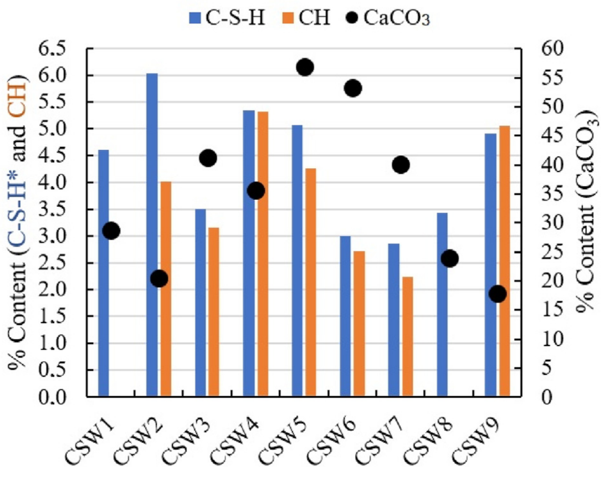


Fig. 8 – C–S–H, Calcium hydroxide and calcium carbonate amount. * Weight loss.

5.2. *Truck wash waste*

It is possible to use CSW is as a recycled aggregate, since the fine fraction of concrete sludge waste is composed of cement solids, silica, and calcite. However, to obtain this material a different processing from the one adopted is necessary. Concrete recycling center is an alternative that can be adopted by concrete companies to reduce the volume of waste generated. It is estimated that, with the adoption of such equipment, the amount of waste generated is about 0.8% in relation to the total concrete produced [20]. There are several advantages of using recycling plants, since these centers can process the concrete returned to the plant, the washing water from the concrete mixer trucks and the residual concrete present in the concrete pumps [13]. In those places, the aggregates – from unused fresh concrete – are recovered by washing and are reincorporated into the production process. The washing water with fine solids (cement paste and fine aggregate fractions) is destined for settling tanks to separate the recovered water from solid particles. The recovered water can be used in the concrete company's activities, such as in the process of recycling aggregates or cleaning the concrete company, as in washing the interior of the drums of concrete mixer truck [13,37]. Some waste management strategies for the CSW generated from the CBP industry is discussed in the following sections.

5.2.1. *Reclaimed aggregates*

Some studies [13,22] (and representatives of concrete companies) report that the recycling machine presents many problems and that the aggregate has adhered mortar, which may impair the properties of the new cementitious products. Therefore, training of the employees who take the concrete mixer truck to the works is recommended. As soon as they unload the truck, they must pour water to remove all the adhered material. They must drive the truck keeping the mixer turning. The movement will help remove adhered mortar and increase the efficiency of the recycling process. Upon arrival at the concrete plant, the truck will pour the material into the recycling machine, which will separate the coarse and fine aggregates and the fine material (which will go to the sedimentation basin). The reclaimed aggregates (washed and sieved aggregate) can be used together with conventional aggregates to produce new concrete. The passing material will represent aggregate powders, mineral additions, and hydrated cement.

5.2.2. *Filler and cement replacement in mixtures*

For the material passing through the 0.15 mm sieve, a comminution process is indicated to reduce the high porosity found in powders and cement hydrates (Fig. 13 and Table 7). This process tends to be inexpensive (low energy consumption) due to high porosity and specific surface area and low density (Fig. 13 and Table 7). After this process, the materials presented smaller granulometry than the cement, higher specific surface area and density (due to the removal of the previous pores) and lower porosity. It is expected that the water demand will be similar, and this material can be used as a filler (inert) addition in concrete and mortar with structural or non-structural purposes.

Table 7 – Fine fraction characterization of collected CSW.

Parameter	1	2	3	4	5	6	7	8	9
SSA (m^2/g)	26.84	29.02	14.85	27.72	21	14.41	13.15	16.32	23.58
Pore Vol. (m^3/g)	0.164	0.175	0.089	0.177	0.140	0.083	0.074	0.094	0.142
Pore diam. (nm)	603.4	508.8	429.9	750.8	482.0	557.3	611.9	558.6	800.9
Density (g/cm^3)	2.64	2.36	2.45	2.54	2.43	2.51	2.66	2.53	2.58

The fine fraction of the concrete sludge waste can be used as a replacement for the limestone filler in concrete since the fine fraction of the collected wastes presented considerable calcium carbonate and silica content. Audo et al. [17] used the waste as a simultaneous substitution of limestone filler and natural sand for making mortars. The workability was corrected by incorporating a superplasticizer additive. The results showed that the compressive strength at 28 days varied from 17% higher to 31% lower than the mortar with incorporation of lime filler, being found the highest strength when there was the lowest rate of substitution of sand and lime filler.

Martins et al. [22] evaluated the CSW fine fraction (<150 μm) influence as a mineral admixture in cements. The CSWs presented high values of specific surface area, associated with cement hydration that increased surface roughness. These features reduce the workability of the mortars and impaired their densification. Moreover, the compressive strength decreased with the replacement of cement by 25% of CSWs, however this effect was similar when the cement was also replaced by 25% of limestone powder. Furthermore, the carbonation range increases, and this can decrease the durability of concrete structures. However, Reis et al. [38] highlights that the use of mineral additions in cement tends to increase sequestered CO_2, representing a more sustainable solution.

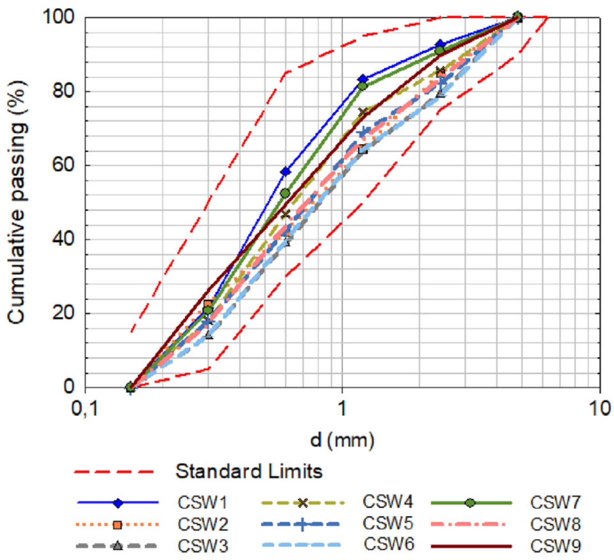


Fig. 9 – Particle sizes of fine aggregate that can be reclaimed and limits established by Standard [33].

Another (more expensive) alternative would be to use heat treatment to dehydrate the hydrated cement compounds. Shui et al. [39] and Bogas et al. [40] highlight that around 700 °C it is possible to dehydrate due to the loss of water combined in the cementitious pastes. The cement dehydration process begins with the decomposition of ettringite at approximately 80 °C [41]. Capillary water (free water - which is not influenced by Van der Waals attractive forces) evaporates, followed by evaporation of lamellar water and adsorbed water due to physical processes. Water chemically combined with C–S–H (hydrated calcium silicate) is lost [41,42]. The dehydration of C–S–H starts at 100 °C, resulting in the loss of cement paste and goes up to 700 °C where there is decomposition of C–S–H into belite (ß-C_2S), wollastonite (βCS) and water. According to Hager (2013), portlandite crystals ($Ca(OH)_2$) dehydrate at temperatures above 420 °C and decompose into calcium oxide and water. Another significant change is the decarbonation of calcium carbonate ($CaCO_3$), which starts at 650 °C. In view of this, the comminution process (before and after treatment) associated with heat treatment makes it possible to obtain new cement (not hydrated) and quicklime that can be used as original materials. Due to the complexity, this process would need to be developed outside the concrete plant, obtaining recycled cement and lime. In this condition, it is known that absorption of CO_2 by free lime in cementitious composites can be up to half of the total generated in the manufacture of limes [43]. In a conventional process, this would be achieved with temperatures above 900 °C [44]. From the results, it appears that current materials can be achieved from 650 °C. This reduces energy consumption and CO_2 emissions.

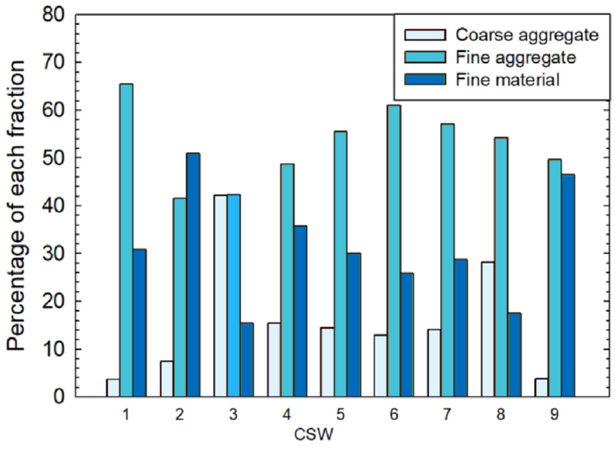


Fig. 10 – Fraction of coarse and fine aggregates that can be recovered from each residue and the amount of fine material.

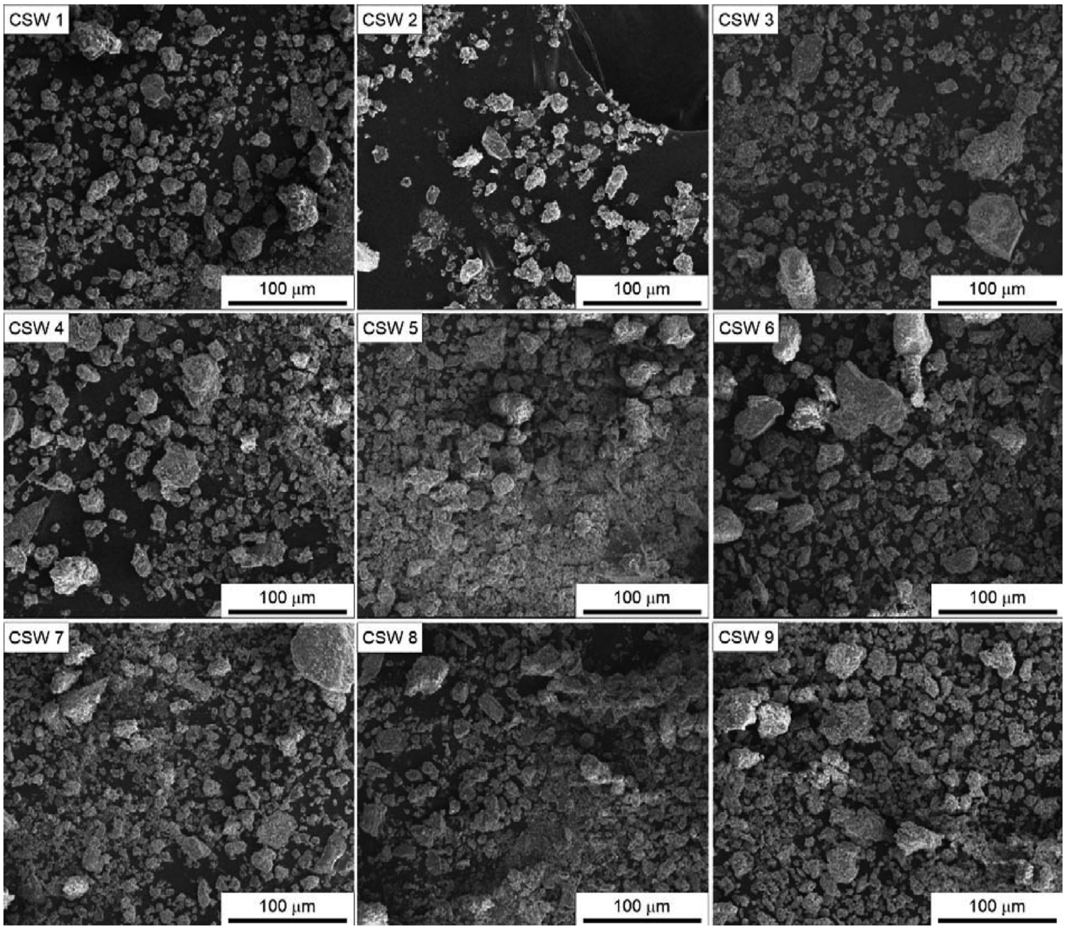


Fig. 11 – **SEM - SE image of particles <150 μm.**

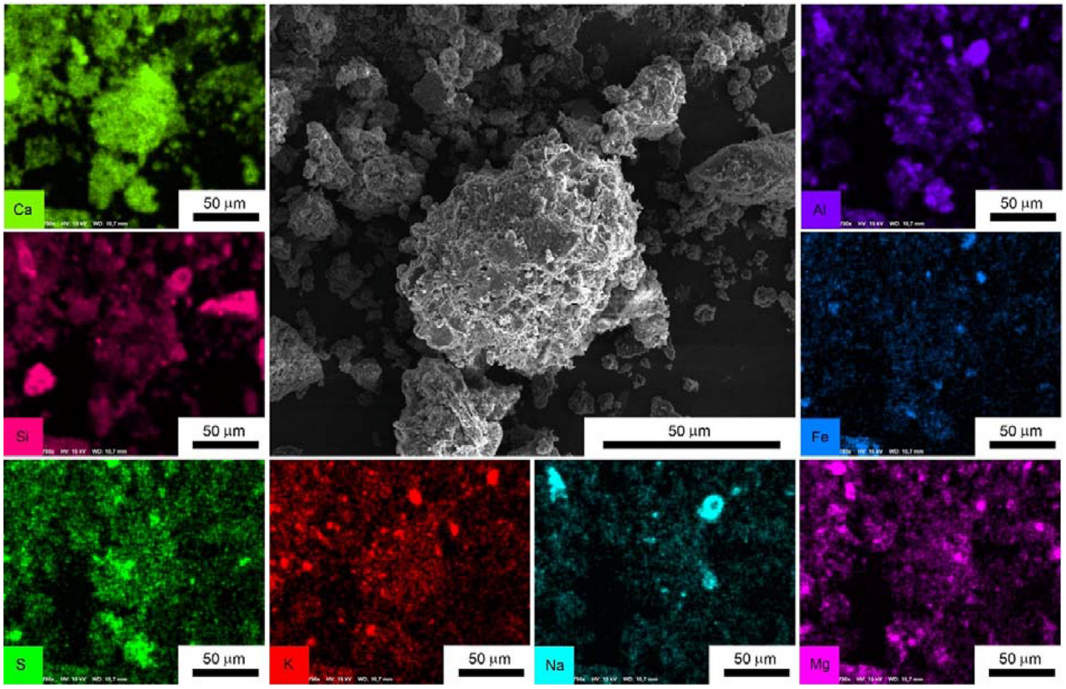


Fig. 12 – **EDS maps of CSW 2.**

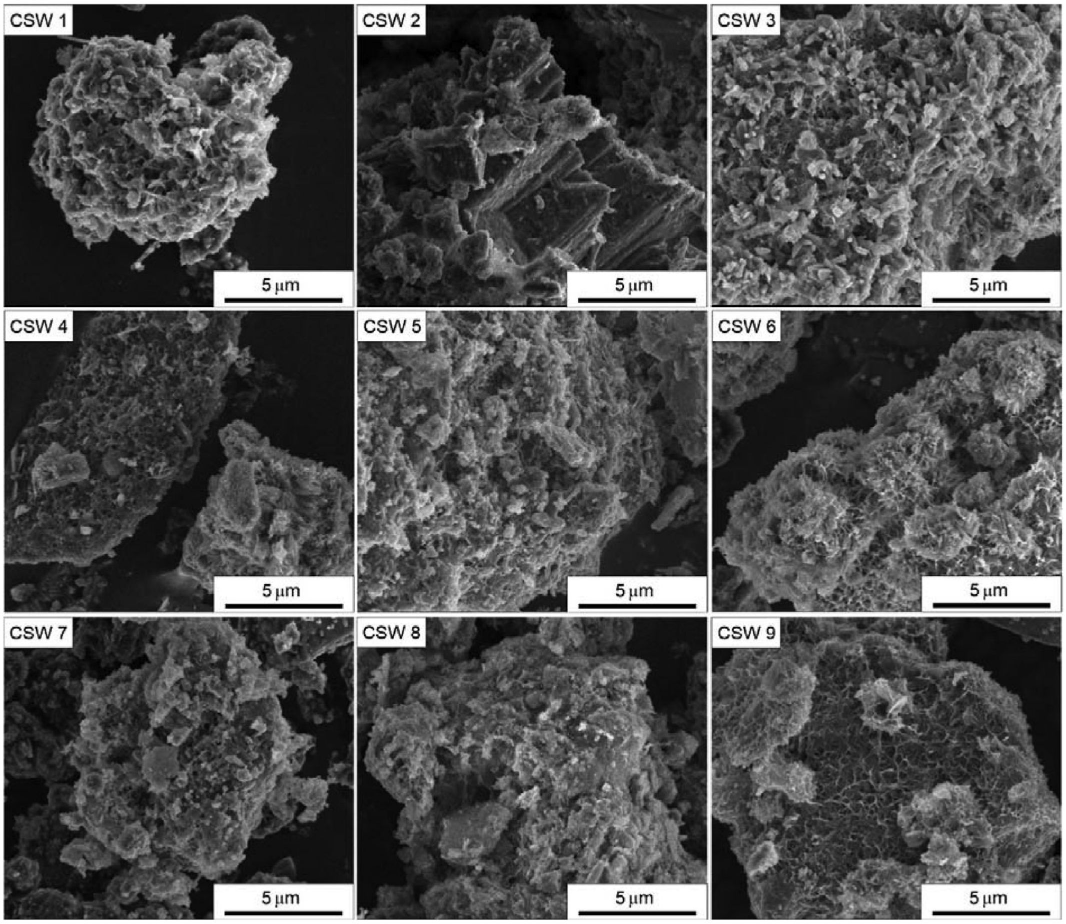


Fig. 13 – SEM images showing the roughness and porosity of the samples.

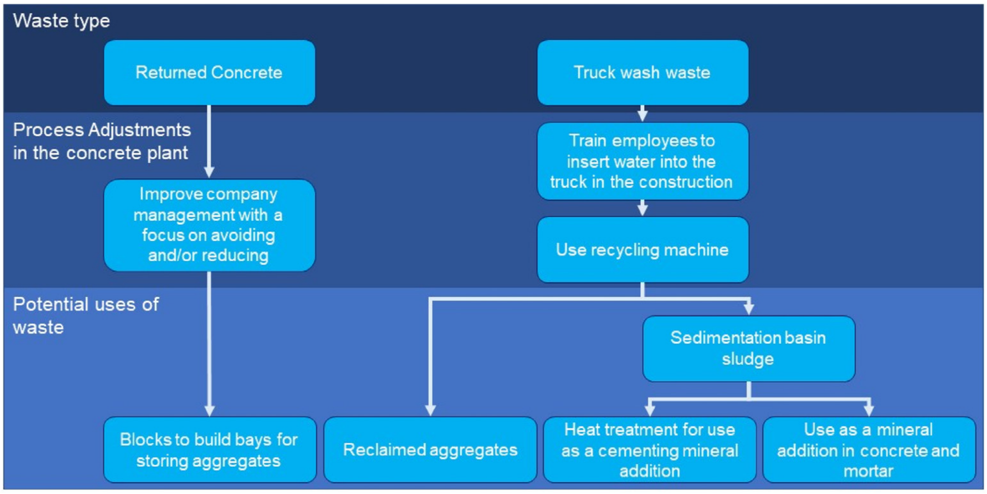


Fig. 14 – Process of management and recovery of waste from concrete producers.

6. Conclusions

It is possible to conclude that companies use different techniques/ways of management and destination of the waste generated at the concreting units. Most of the processes are inefficient and generate high financial costs and do not add value to the waste, either to allow its reuse in the company itself (reducing costs with acquisition of new materials), or in the reuse in another industrial sector.

Evaluated residues presented different crystalline phase constitutions, which influenced the chemical composition and granulometry. The coarse fraction granulometry showed the presence of fine and graded natural aggregates. It highlights the presence of mortar and hydrated cement paste adhered to the grains increasing porosity and water absorption. In this condition, they need to be treated with recycled aggregate and their use is limited to non-structural concretes. To avoid this adhered paste/mortar, it is suggested to wash the truck since on construction site, increasing the friction with the water removing it. Aggregates suitable for use in concrete and structural mortars are obtained.

The finer particles behave similarly to limestone powder. However, high values of specific surface area, associated with hydrated cement composites, which increased the surface roughness, stand out. This tends to increase water consumption and reduce the composites durability. For these, comminution processes are identified to reduce roughness and cement dehydration processes to extend the use of this waste.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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