Carbonation Potential of Recycled Aggregates from Construction and Demolition Waste

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Abstract

One of the biggest challenges currently faced by Society is climate change, leading to the need of mitigation of carbon dioxide (CO_2) emissions, among other consequences. The construction sector is responsible for a large part of these emissions. In addition, this sector is also responsible for a significant part of all waste globally produced, about one third in the European Union.

The use of construction and demolition wastes (CDW) as aggregates in mortars and concrete has been the objective of several studies. This incorporation reduces the volume of natural aggregates used in these construction products, decreasing the depletion of natural resources, while increasing the life cycle of the incorporated by-products. It thus contributes to the reduction of the environmental impacts of the construction sector. Nevertheless, recycled aggregates are not often incorporated in mortars and concrete due to their higher porosity and lower strength compared to natural aggregates.

Jointly with the Portuguese cement industry, this research intends to produce more sustainable mortars and concrete by using CDW aggregates as a carbon capture and storage source. This not only reduces the global greenhouse emissions of concrete but also potentially improves the CDW aggregates' properties. To this extent, different types of CDW aggregates will be subjected to forced and accelerated sequestration of CO_2, contributing to the capture of part of the CO_2 emissions of the Portuguese cement industry, providing it with more sustainable processes. As a result, this study intends to contribute to the reduction of non-renewable natural resources, in the form of natural aggregates, while reusing CDW and capturing part of the CO_2 released by the production of cement.

This article presents the characterization of three CDW from different origin and treatments, regarding the analysis of their carbonation potential.

Keywords: *C&DW, CO_2 sequestration, recycled aggregate, sustainable aggregates, carbon capture and storage*

1. Introduction

The increase in greenhouse gases in the atmosphere causes one of the today's greatest global environmental threats, known as global warming. Notwithstanding this problem, which requires a quick and effective response, the high quantity of waste generated by society also deserves attention. The construction sector is responsible for a great part of the carbon dioxide (CO_2) emissions, which contribute to global warming, as well as for a significant part of the waste generated - construction and demolition waste (CDW). This waste represents, in terms of volume, around one third of all waste produced in the European Union (European Commission, 2016).

Several researchers have studied the use of CDW as aggregates in construction products such as mortars and concrete. Nevertheless, these aggregates are not often incorporated due to their lower characteristics compared to natural aggregates'. This is mainly due to their higher porosity and lower mechanical strength.

However, when CDW are used as fine aggregates at ratios up to 15%, by volume, in cementitious mortars, some properties are little affected, such as compressive and flexural tensile strengths, water absorption by capillarity, adherence to the substrate and water retention (Braga et al. 2012).

The incorporation of recycled aggregates in mortars and concrete reduces the amounts of natural aggregates used in these construction products, reducing the CDW volume to manage and, at the same time, increasing its life cycle. It thus contributes to the reduction of the sector's environmental impact.

Various studies have been carried out regarding the incorporation of forced carbonated CDW aggregates in mortars and concrete. The aim is to improve the weaker characteristics of these aggregates compared to natural aggregates. Additionally, some of these studies show that concrete waste can act as a tool for CO_2 capture (Kou et al. 2014; Pade & Guimaraes 2007; Zhan et al. 2020).

Part of the carbon dioxide emitted during cement manufacturing is reabsorbed by cement mortars and concrete through carbonation (a reaction in which free lime reacts with carbon dioxide forming calcium carbonate). Furthermore, considering the entire Portuguese cement manufacturing production between 2005 and 2015, and the corresponding CO_2 emissions, Sanjuán et al. (2020) stated that this CO_2 capture due to reabsorption would be between 14.8% and 19.6%.

Hence, existing evidences show that carbonation can make up for the deficiencies of recycled aggregates from CDW at the same time that it can capture part of the CO_2 emitted by the cement industry.

The collaborative laboratory c^5Lab - Sustainable Construction Materials Association - intends to develop innovative technologies for a sustainable production of cement, mortars and concrete with low CO_2 emissions. Among the various projects that make up c^5Lab, the WP10B project - Forced and accelerated sequestration of CO_2 by CDW to incorporate as aggregates in mortars and concrete - intends to forcibly capture CO_2 through construction and demolition waste for subsequent incorporation as aggregates in mortars and concrete, thus eliminating part of the CO_2 emitted by the cement industry. The current article presents the objectives of this project and the first experimental results obtained so far, regarding the analysis of the carbonation potential of CDW aggregates from different origins.

2. Materials and methods

2.1. Materials

In this research, three types of CDW were studied, two of which were chosen from a recycling plant, located near Lisbon, Portugal. The first one, designated W1 corresponds to a mixture of particles with particle size lower than 4 mm, whilst the second (W2) has a particle size below 40mm. The third CDW (W3) was selected from a recycling plant located near Figueira da Foz, Portugal, and has also a maximum particle size of 40 mm.

The W1 waste undergoes no treatment whatsoever besides metals removal, corresponding to about 40% of the total volume of CDW recovered at this recycling plant. Next, the larger material is subjected to pre-grinding by means of an impact grinding mill. After this size reduction, the waste is manually sorted, to remove unwanted materials, such as plastic and wood. Finally, the waste is grinded until the desired particle size is achieved and W2 is obtained. The third waste studied (W3) is obtained through grinding by a hammer crusher until the target particle size of less than 40 mm is reached. This crushing process takes place after ballistic and magnetic separation, aiming to remove materials such as paper, plastics and metals.

2.2. Methods

The carbonation potential was assessed through a thermogravimetric analysis, jointly with the information given by the classification of the CDW's constituents. Additionally, in order to obtain the characteristics of the CDW and compare with the ones declared by the suppliers, the particle size distribution, bulk density and classification of constituents were performed.

Thermogravimetric analysis was conducted to obtain the portlandite and calcium carbonate contents in the materials used (Scrivener et al., 2017). The corresponding test was performed using a SETARAM TGA92 apparatus, with an argon atmosphere (3 L/h), at a heating rate of 10 °C/min from 25 to 1000 °C. One sample of each fraction of the three CDW was tested.

The material samples obtained by the two recycling facilities, about 15 kg of each CDW, were dried in a ventilated-oven at 60 ºC for 24 h and afterwards placed in a mechanical sieve shaker equipment, with a series of ASTM sieves (13.2 mm to 0.063 mm), to obtain the particle size distribution and the correspondent sizing curves.
The loose bulk density test quantifies the dry mass of aggregate necessary to fill a container of known capacity, without compaction. The test procedure was carried out according to the French standard documentation Cahier 2669-4 (CSTB, 1993).. The material was placed in a conical trunk container of know capacity from a well-defined distance and weighed on a scale with an accuracy of 0.1g. To obtain the bulk density, three measures of each particle size fraction of the CDW's were carried out.

Given the heterogeneity and different composition of the recycled waste mixtures, their constituents were classified as per European standards EN 933-11 (2009) and EN 13242 (2007). The procedure involves an initial separation of the floating parcels from the non-floating ones. Once the non-floating portion is obtained, the remaining portion is then separated and classified into the various constituents as stated in Table 1.

Table 1. Categories for the coarse constituents of concrete (EN 933-11, 2009; EN 13242, 2007)

Constituents	**Content (wt. %)**	**Categories**
Rc: concrete, concrete products, mortar and concrete masonry units	Rc ≥ 90	Rc90
	Rc ≥ 80	Rc_{80}
	Rc ≥ 70	Rc_{70}
	Rc ≥ 50	Rc_{50}
	Rc < 50	$Rc_{declared}$
	Not required	Rc_{NR}
Ru: unbound aggregates, natural stone and hydraulically bound aggregates	-	-
Rg: glass	Rg ≤ 2	Rg_{2-}
	Rg ≤ 5	Rg_{5-}
	Rg ≤ 25	Rg_{25-}
	Not required	Rg_{NR}
Rc + Ru +Rg	Rcug ≥ 90	$Rcug_{90}$
	Rcug ≥ 70	$Rcug_{70}$
	Rcug ≥ 50	$Rcug_{50}$
	Rcug < 50	$Rcug_{declared}$
	Not required	$Rcug_{NR}$
Rb: clay masonry units, such as bricks and tiles and calcium silicate masonry units	Rb ≤ 10	Rb_{10-}
	Rb ≤ 30	Rb_{30-}
	Rb ≤ 50	Rb_{50-}
	Rb > 50	$Rb_{declered}$
	Not required	Rb_{NR}
Ra: bituminous materials	Ra ≥ 95	Ra_{95}
	Ra ≥ 80	Ra_{80}
	Ra ≥ 50	Ra_{50}
	Ra ≥ 40	Ra_{40}
	Ra > 30	Ra_{30}
	Ra ≤ 30	Ra_{30-}
	Ra ≤ 20	Ra_{20-}
	Ra ≤ 10	Ra_{10-}
	Ra ≤ 5	Ra_{5-}
	Ra ≤ 1	Ra_{1-}
	Not required	Ra_{NR}
X: other materials, including cohesive (clay and soil), metals, plastic, rubber, non-floating wood and gypsum plaster	X ≤ 1	X_{1-}
Fl: floating material	Fl ≤ 5 cm^3/kg	Fl_{5-}
	Fl ≤ 10 cm^3/kg	Fl_{10-}

3. Results of the wastes characterization

3.1. *Thermogravimetric analysis*

Figure 1 presents an example of the thermogravimetric curves (TGA) of the tested wastes. The derivative thermogravimetry (DTG) enables a better resolution of the weight losses obtained (Figure 2). From DTG curves, three zones can be identified (R1, R2 and R3). These zones correspond to:

- R1 [$Troom$ - 380 ºC]: weight loss associated to release of moisture and dehydration of hydrated calcium silicates (C-S-H) and calcium sulphoaluminates (AFt and AFm phases);
- R2 [380-530 ºC]: weight loss mainly associated to dihydroxylation of portlandite;
- R3 [530-900 ºC]: weight loss due to carbonate decarbonation.

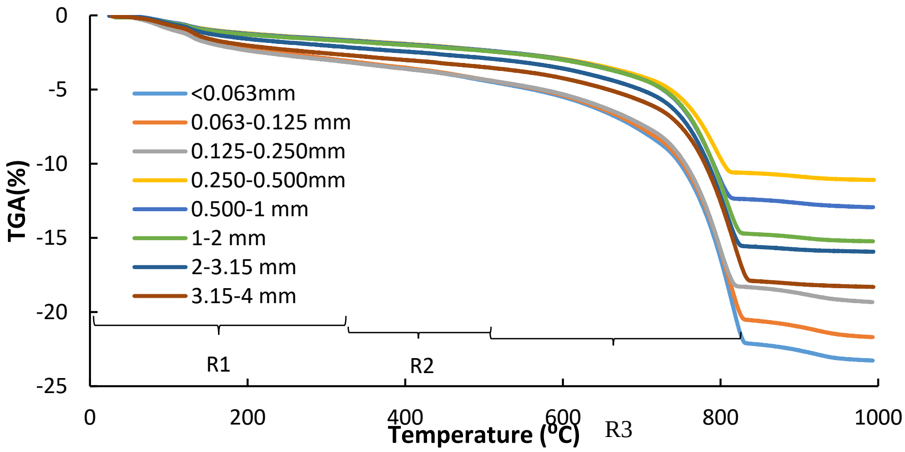

Figure 1. TGA charts of the fractions < 4 mm for W3

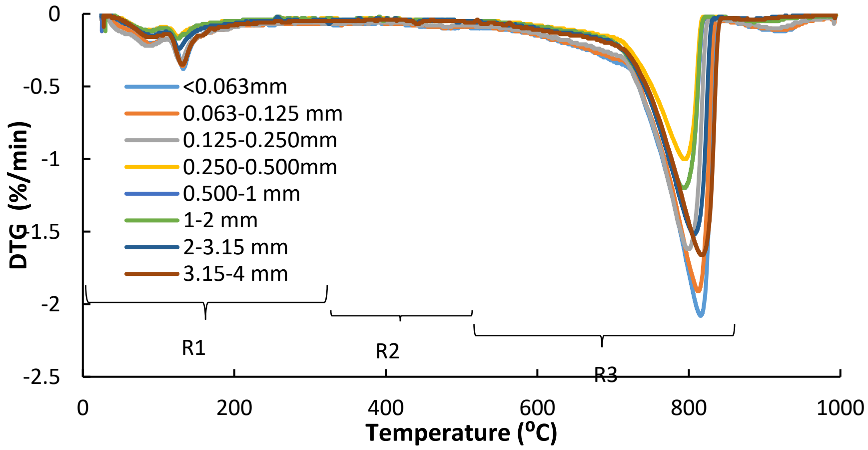

Figure 2. DTG charts of fractions < 4 mm for W3

The portlandite content was obtained by using equation (2):

$$Ca(OH)_2(\%wt) = WL_{R_2} \times \frac{MM_{Ca(OH)_2}}{MM_{H_2O}} \quad (2)$$

Where WL_{R_2} is the weight loss in the R2 zone, while $MM_{Ca(OH)_2}$ and MM_{H_2O} are the molecular masses of portlandite and water.

Table 2 presents the portlandite contents of the CDW materials under evaluation, which gives a measure of their probable carbonation potentials.

From these results, it is possible to conclude that the highest Portlandite content occurred in the smallest fractions (< 0.250) of all wastes, meaning that those fractions should have a higher carbonation potential.

However, two of the three CDW's (W2 and W3) show significant portlandite content in their higher fractions, in contrast to W1, in which fractions > 3.15 mm have no indication of portlandite content, and thus, low carbonation potential.

Table 2. Portlandite content (wt. %) for the various size fractions

Samples	Size fractions													
	< 0.063	0.063-0.125	0.125-0.25	0.25-0.50	0.50-1	1-2	2-3.15	3.15-4	4-5	5-7.1	4-8	8-16	16-25	25-40
W1	0	6.1	4	3.9	3.2	3.5	4	0	0	0				
W2	5.1	5.1	4.4	0	0	0	0	0	-	-	0	2.1	2.1	2.3
W3	4.6	5.5	3.7	4.9	0	0	0	3.4	-	-	2.3	2.2	1.6	2.9

3.2. Physical tests

3.2.1. Particle size distribution

Figure 3 illustrates the average particle size distribution of the three different CDW. It was found that W1 waste has the highest percentage of fines, while W3 has the highest amount of coarse material. The sizing curves obtained in the laboratory were compared with those declared in the technical products files. It was found that, for all CDW, there are non-significant differences between the curves obtained in the laboratory and those declared.

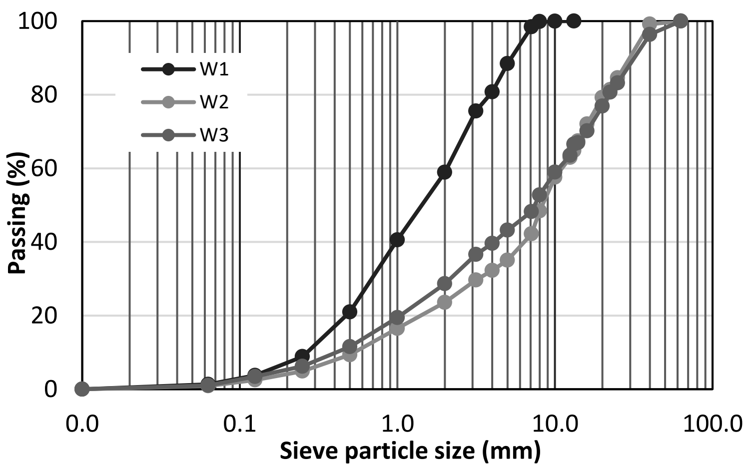

Figure 3. Particle size distribution of the three CDW's studied

3.2.1. Loose bulk density

The test was carried out for the particle size fractions below 4 mm. The average results of loose bulk density of three measures for each size fraction are presented in Figure 4. It should be noted that, due to constraints related to the amount of material available, the loose bulk density test was not performed for all size fractions, except for the W3 sample.

Figure 4 shows that the different types of waste exhibit the same trend regarding the relationship between the loose bulk density with the respective size fraction, i.e. the loose bulk density increases progressively until the 0.50 mm particle size fraction and then decreases, as found by Silva (2006) for red clay waste. Additionally, for all CDW, the highest value obtained was recorded in the 0.50 mm particle size fraction, and the lowest one in the smallest fraction, either 0.125 or 0.250 mm.

According to the data in the literature, it would be expected to obtain an increasing trend of the loose bulk density with the increase of the particle size fraction, as found both for aggregates from crushed concrete (Neno et al., 2014) and fine glass waste (Penacho et al., 2014). Nevertheless, in several studies, such as those performed by Lucas et al. (2016) and (Silva et al., 2009), this trend was not confirmed.

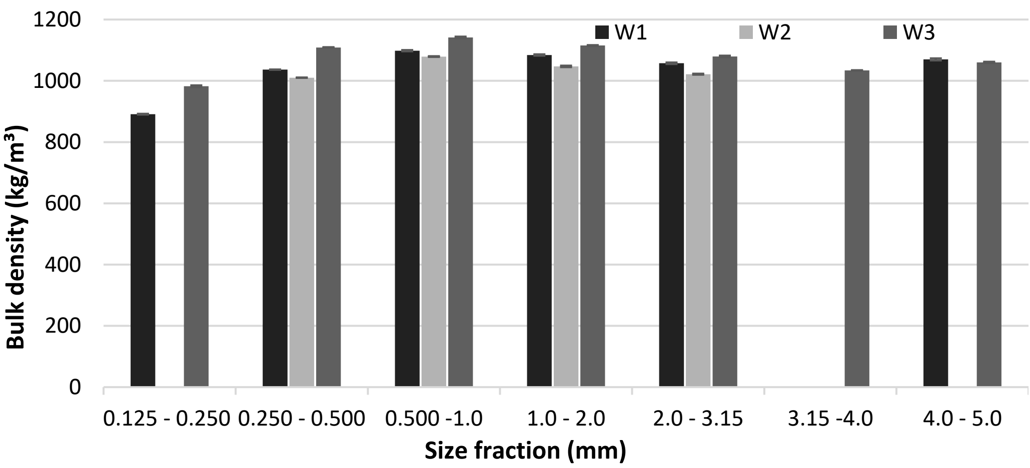

Figure 4. Bulk density of the recycled aggregates

However, when compared to natural aggregates, the results obtained for the loose bulk density of the recycled waste mixtures W1, W2 and W3 (only for particles < 5 mm) - respectively 1040, 1039 and 1075 kg/m³ - are lower than those obtained for sand, 1432.5 (Neno et al., 2014) and 1143 kg/m³ (Silva et al., 2009), and are in agreement with those described by Hansen (1986) and in other studies (Jiménez et al. 2013), i.e. the bulk density of recycled aggregates is lower. This is mainly due to the fact that recycled aggregates have adhered cement paste, with higher porosity, thus decreasing their density (Hansen 1986).

3.2.2. Wastes composition

As previously described, once the non-floating is obtained, the sample is separated into its several constituents - Figure 5. The mass of the non-floating particles was quantified for each of the samples analysed. It was found that sample W2 has a much higher amount of these non-floating particles, about 27.6 g, compared to W3 with less than 1 g.

Figure 5. Constituents separation of the three CDW's studied: a) W1; b) W2 and c) W3.

The results of samples W1, W2 and W3 are presented in Tables 6, 7 and 8, respectively. The analysis of these results shows that the Rc constituent, which includes cementitious materials, is the major component in the three recycled mixtures, with emphasis on W2 and W3 (between 50% and 53%). This component will be largely responsible for the accelerated and forced carbonation of the recycled aggregates from CDW. Therefore, it is suggested that the greater the amount of Rc constituents, the higher the carbonation potential of the mixture, although these results are affected by other factors, such as age, exposure and type of binder. The second major constituent is Ru, with a relatively higher proportion in W2. Afterwards, the waste mixture compositions were classified according to EN 933-11 (CEN 2009), and compared to the values provided by the suppliers - see Tables 6, 7 and 8.

By comparing the classifications declared by the Technical Product Files of the recycled mixtures, it is possible to conclude that only sampleW2 does not comply with the amount of bituminous materials (Ra) reported by the supplier. However, this non-conformity is not significant, since it is possible to request the recycling facility to extract this type of material before the recycling process is carried out.

Table 3. Constituents classification of W1

Constituent	Rc	Ru	Rb	Ra	Rg	X	Rcug
Content (%)	42.5	27.5	19.3	9.6	0.2	0.8	70.25
Classification determined (according to EN 933-11 and EN 13242)	$Rc_{declared}$	-	Rb_{30-}	Ra_{10-}	Rg_{2-}	X_{1-}	$Rcug_{70}$
Classification declared (according to EN 933-11 and EN 13242)	Rc_{50}	-	Rb_{10-}	Ra_{10-}	Rg_{2-}	X_{1-}	$Rcug_{70}$

Table 4. Constituents classification of W2

Constituent	Rc	Ru	Rb	Ra	Rg	X	Rcug
Content (%)	50.7	34.3	9.1	0.8	0.9	0.3	85.85
Classification determined (according to EN 933-11 and EN 13242)	Rc_{50}	-	Rb_{10-}	Ra_{1-}	Rg_{2-}	X_{1-}	$Rcug_{70}$
Classification declared (according to EN 933-11 and EN 13242)	ND	-	Rb_{10-}	Ra_{20-}	Rg_{2-}	X_{1-}	$Rcug_{70}$

Table 5. Constituents classification of W3

Constituent	Rc	Ru	Rb	Ra	Rg	X	Rcug
Content (%)	53.2	21.0	17.7	0.2	0.1	0.6	74.29
Classification determined (according to EN 933-11 and EN 13242)	Rc_{50}	-	Rb_{30-}	Ra_{1-}	Rg_{2-}	X_{1-}	$Rcug_{70}$
Classification declared (according to EN 933-11 and EN 13242)	Rc_{50}	-	Rb_{30-}	Ra_{1-}	Rg_{2-}	X_{1-}	$Rcug_{70}$

4. Conclusions

In the three CDW samples evaluated, it was found that the greatest potential for carbonation is associated with the finest particle fractions of these materials, mostly below 0.250 mm. However, two of the CDW's also present some potential in the coarser fractions. According to the results of the constituents of the aggregates, it is found for the coarse particles that the higher the content of cementitious material the higher its carbonation potential is. Consistently, it was observed that the highest Rc values of the coarser fractions of samples W2 and W3 correspond to the highest portlandite contents obtained by TGA. Although a logical tendency is perceived for the Portlandite content to increase with the value of Rc, the same cannot be guaranteed, due to the fact that the cement-aggregate composition can vary with the grain size fraction and with the carbonated material.

In terms of grain size analysis, it can be seen that W1 has the highest percentage of fines, while W3 has the highest amount of coarse material. The different types of waste show the same tendency regarding the loose bulk density with the respective size fraction, i.e., the loose bulk density increases progressively up to the 0.500 mm particle size fraction and decreases thereafter. Accordingly, for all types of CDW, the highest value obtained for loose bulk density was recorded in the 0.500 mm particle size fraction, while the lowest was recorded in the finest fraction.

Regarding the classification of the constituents, it was found that the constituents of Rc classification, where the materials with cementitious matrices are included, assume a significant predominance in mixtures W2 and W3 (between 50% and 53%). These constituents will be largely responsible for the results of the accelerated and forced carbonation of the recycled aggregates from CDW. Regarding the floating particles, it is observed that W2 has a much higher amount of these materials. This may be due to the difference between the waste treatment processes of the two recycling facilities, in which the one that produces W3 includes separation operations through a ballistic technique, thus reducing the amount of unwanted materials. Comparing the classifications declared by the technical product files of the recycled waste mixtures, only W2 does not confirm the classification concerning bituminous materials, Ra.

From this first set of tests, it can be concluded that the wastes collected from the CDW management plants have characteristics that indicate they are suitable to be used as aggregates and as source for CO_2 fixation: their characteristics are generally according to those declared by the suppliers, which indicate possible reliability of characteristics; they have significant contents of cementitious constituents (about 50%) and they demonstrate carbonation potential, especially in the finer fractions, with values of 5-6% in some cases.

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