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CO_2 sequestration by construction and demolition waste aggregates and effect on mortars and concrete performance - An overview

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ABSTRACT

Global warming is one of the greatest environmental threats worldwide. It is mainly caused by the growing amount of greenhouse gases in the atmosphere, such as argon and carbon dioxide (CO_2), among others. Hence, the need to reduce these gases' emissions, in particular CO_2, is imperative. This reduction may be achieved through strategies that allow capturing and storing emitted CO_2 (CCS - carbon capture and storage).

Construction and demolition waste (CDW) is found in great abundance with diverse potential in the building sector. However, its incorporation as recycled aggregates (RA) in construction materials, such as mortars and concrete, is still limited. This is mainly due to its higher heterogeneity, porosity and lower strength compared to natural aggregates (NA).

Several studies have been carried out focusing on the reduction of CO_2 emissions and of NA exploitation, as well as improving these RA's characteristics. This article intends to provide a review of the performance of mortars and concrete with RA from CDW after undergoing a CO_2 curing treatment, thus contributing to CCS.

Overall, CO_2 curing of RA has a positive effect on their physical and mechanical characteristics. By increasing the apparent density, their porosity and water absorption consequently decrease. Also, these treatments considerably reduce the crushing index of RA, increasing their strength.

Mortars and concrete produced with carbonated recycled aggregates (CRA) show increase in workability and decrease in shrinkage in comparison to those with uncarbonated RA. The mechanical performance of these construction materials is also positively influenced. Therefore, the levels of confidence in its use should increase.

1. Introduction

One of the biggest challenges currently faced by society is fighting climate change, namely by mitigation of CO_2 emissions. The construction sector is responsible for a significant part of these emissions. Furthermore, the sector is responsible for a significant part of the waste globally produced. This waste, referred to as construction and demolition waste (CDW) is, according to the European Waste List (EWL) [1], what results from the construction, reconstruction, expansion, alteration, conservation, and demolition of buildings. In terms of volume, this waste represents about one third of all waste produced in the European Union [2]. Thus, there has been a growing interest in the construction sector with a view to reducing its environmental impact.

Bearing in mind that any construction material used has an influence on the environmental impact of a building, it is important to consider these materials in terms of their manufacture and use [3,4]. Particularly, the cement industry is responsible for the production of one of the most used materials in the construction sector. It is known that this industry is responsible for the emission of about 600–700 kg of CO_2 for each tonne of cement produced [5], making it one of the most polluting in terms of CO_2 emissions. Nevertheless, these emissions occur throughout the manufacture of cement, either from the extraction of the raw material, namely natural, finite and scarce resources, to the expedition phase. There is an exponential growth of the consumption of these resources and of the corresponding impact on the environment, which has been

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List of abbreviations

CDW	Construction and demolition wastes
RA	Recycled aggregates
CRA	Carbonated recycled aggregates
NA	Natural aggregates
CO_2	Carbon dioxide
$CaCO_3$	Calcium carbonate
CCS	Carbon capture and storage
RCA	Recycled concrete aggregates
RMA	Recycled masonry aggregates
MRA	Mixed recycled aggregates
RFA	Recycled fine aggregates
CRFA	Carbonated recycled fine aggregates
CRCA	Carbonated recycled concrete aggregates
Rc	Concrete, concrete products, mortar and concrete masonry units
Ru	Unbound aggregates, natural stone and hydraulically bound aggregates
Rb	Clay masonry units, such as bricks and tiles and calcium silicate masonry units
Ra	Bituminous materials
Rg	Glass
X	Other materials, including cohesive, metals, plastic, rubber, non-floating wood and gypsum plaster

subjected to changes and measures taken by this sector. To this aim, the European Union has fostered action strategies and legal framework measures, such as the Strategy for the Sustainable Competitiveness of the Construction Sector and Enterprises [6], the Communication on Resource Efficient Opportunities in the Building Sector [7], the European Commission's Circular Economy Package [8] and the European Union's Construction and Demolition Waste Management Protocol [2, 9], establishing clear mitigation objectives of CO_2 emissions, as well as promoting a circular economy for CDW.

The use of construction and demolition waste as aggregates (i.e. RA) in mortars and concrete has been the subject of several studies. However, it is of fundamental importance to find environmentally efficient ways of offsetting the drawbacks of using RA, such as forced carbonation. It is thus possible to avoid compromising the quality and performance characteristics of these mortars, or even to improve them [10].

In a research focused on the characteristics of fresh concrete produced with the use of RA [11], it was possible to confirm that their use as coarse aggregates decreased the consistency and fluidity in the first hour after mixing, comparing with concrete fabricated with NA only. It was also found that the addition of fly ash decreased the rate and capacity of segregation of concrete, produced with NA and RA.

The incorporation of fine powder aggregates from ceramic brick debris, in proportions of 5% and 10% of the total volume of aggregates, in cementitious mortars, significantly improved their performance in terms of compressive and flexural strengths [12]. Braga et al. [13] conducted a research on the performance of cementitious mortars with incorporation of 5%, 10% and 15% by volume of very fine aggregates from crushed concrete. Good results were obtained, with improvements in all mortars with different incorporation ratios in terms of compressive and flexural strengths, water absorption by capillarity, adhesion to the substrate, and water retention. The mortar that presented better results was the one with the highest volume of RA (15%). Conversely, in terms of water vapour permeability, modulus of elasticity, dimensional stability and susceptibility to cracking, mortars produced with RA had worse performance than the reference mortar (with no RA). Using sanitary wastes as aggregates, it is possible to obtain coating mortars with less environmental impact [14], without compromising their performance [15]. The incorporation of sanitary waste RA presented a negligible effect in terms of dimensional stability and an improvement in water vapour permeability and adhesion to the substrate when subjected to artificial ageing.

Jesus et al. [16] studied the behaviour of cementitious rendering mortars in which two types of very fine aggregates from CDW were incorporated: crushed concrete aggregate and a mixture of aggregates from CDW such as mortar, concrete, plastic, glass, metals, plaster and wood. The results showed that the mortars produced with aggregates from CDW showed better performance in most of the tests compared with mortars with NA, with special emphasis on the hydraulic and mechanical behaviour. However, the authors also concluded that the incorporation of different types of RA influenced the performance of mortars in different ways, due to their characteristics [16].

The literature refers that several types of CDW can be incorporated as aggregates in mortars and concrete. This incorporation reduces the levels and quantities of NA used in these construction products, reducing the need of extraction from nature, while increasing their life cycle. In this way, it contributes to the reduction of the environmental impact of the construction sector and, in particular, of the construction products industry. However, these solutions must be improved, and others must be found considering this waste.

Concrete is one of the most used building materials globally [17]. Cement acts as a binder for all components of concrete, being obtained from clinker (transformed raw material containing silicates and aluminates). Clinker is obtained by calcination at high temperature of calcareous marl (based on calcium carbonate), producing quite considerable amounts of CO_2 that are emitted into the atmosphere. Any cement-based mortar and concrete undergoes carbonation, a reaction in which free lime reacts with CO_2 to form calcium carbonate. In this way, it is possible to state that part of the CO_2 emitted during the manufacture of cement is reabsorbed by these materials [18]. Considering the entire CO_2 emission process in the manufacture of Portuguese cement between 2005 and 2015, CO_2 capture would be between 14.8% and 19.6% [18]. This article presents a review on mortars and concrete produced with RA derived from CDW after being subjected to a forced and accelerated carbonation process. Additionally, a comparison between these construction products incorporating RA without any treatment and treated with a CO2 cure is made. Hence, this article intends to collect and discuss the main findings of the studies that are being performed on this subject.

Section two is dedicated to CDW and their main treatments at the recycling sites. It is well known that CDW are available in mixtures with a wide scope of materials. Proper knowledge on these materials and their properties is thus fundamental. Section three assesses several CO_2 curing methods of recycled aggregates. It also presents the properties of recycled aggregates before and after being subjected to the CO_2 curing, such as their bulk density, water absorption and crushing index.

The properties of mortars and concrete containing recycled aggregates either in their original form or after carbonation are presented in sections four and five, respectively. Also, a comparison of the fresh state, physical and mechanical performance of these materials containing recycled aggregates and carbonated recycled aggregates is outlined. Finally, section six is devoted to the durability properties of these materials, mainly water absorption, carbonation and steel corrosion.

2. Recycled aggregates

CDW are available in mixtures with a wide scope of materials, as a result of different sources [19]. These mixtures may contain materials such as concrete, bricks, tiles, ceramics, wood, glass, plastic, asphalt and metals, among others [19–21]. Owing to the heterogeneity of materials comprised in the RA mixtures, it is fundamental to know and quantify these materials. Therefore, the constituents of these mixtures can be classified according to the standard EN 933–11 [22] into six categories:

- Rc - concrete, concrete products, mortar and concrete masonry units;
- Ru - unbound aggregates, natural stone and hydraulically bound aggregates;
- Rb - clay masonry units, such as bricks and tiles and calcium silicate masonry units;
- Ra - bituminous materials;
- Rg - glass;
- X - other materials, including cohesive, metals, plastic, rubber, non-floating wood and gypsum plaster.

According to Silva et al. [23], CDW RA can be divided in Recycled Concrete Aggregates (RCA), Recycled Masonry Aggregates (RMA) and Mixed Recycled Aggregates (MRA). Firstly, RCA include Rc and Ru class materials, i.e. elements of concrete and natural stone, with a minimum of 90%, by mass [23]. On the other hand, RMA mixtures comprise a minimum of 90%, by mass, of ceramic bricks and tiles and calcium silicate masonry units (Rb) [23]. Similarly, MRA are composed of the two previously referred RA, i.e. have in their composition materials of Rc, Ru and Rb [22,23].

Barbudo et al. [25], state that the recovery of CDW does not start at the recycling plants, but instead at the time of the construction, reconstruction, expansion, alteration, conservation, and demolition of buildings. Thus, it is relevant to consider that its recovery starts at the origin, with the differentiation between the several types of CDW.

Generally, the processes of recovery and treatment of CDW are similar although with some differences, either in terms of equipment or the process itself. These differences can greatly influence the final characteristics of the RA. At the entrance to the recycling plant, wastes are visually inspected and characterized as clean or dirty [25]. Clean wastes are those that apparently only contain construction and demolition materials, directly entering the treatment process. Conversely, the so-called soiled wastes contain contaminants such as plastics, wood and cardboard in their mixtures [19,25,26]. These wastes are subjected to a mechanical sorting process, in which materials such as plastic, rubbers, wood, paperboard and glass, among others, are separated from the remaining; these can be recycled for other processing industries. From the initial screening, various waste materials are obtained with recovery purposes. To some extent, it should be noted that portions of this waste do not integrate the treatment process, namely through grinding, and are stored in specific and differentiate sites. Some recycling plants possess appropriate equipment to reduce the size of the waste, such as hydraulic clamps [27,28], consequently avoiding machinery obstructions in the treatment process.

Firstly, the waste is placed on a conveyor belt with the assistance of hydraulic excavators [29]. In this phase, a pre-screening is carried out, meaning the separation of materials under a defined size, which may vary according to the recycling plant. Hence, the first recovered RA are obtained and stored. The larger size material is subjected to a mechanical grinding by means, for instance, of a jaw crusher [19,30]. This size reduction occurs by impact. Afterwards, CDW is subjected to electromagnetic separation, usually achieved through magnetic mats [31–33]. As a result, a free metals mixture is obtained. Several recycling plants make use of air jigging equipment in order to separate lightweight materials, such as paper, plastic or cardboard, from the waste mixture [25,28,31,34–37]. Nevertheless, this separation is often carried out by means of water jets; water is not always available and can raise issues related to the aggregates wetting, making their treatment and subsequent application difficult [37,38]. Once this process is completed, the mixture is then submitted to manual screening in order to remove the remaining undesirable materials. Later on, the separation between fine and coarse RA is achieved; further crushing can be implemented in order to obtain the target particle size [17,33,34,39].

As previously mentioned, the incorporation of RA, resulting from the recycling of CDW in construction products, in mortars and concrete decreases the exploitation of natural resources while increasing the life cycle of these wastes through their recycling. This incorporation is carried out in terms of fine RA or as filler, or else as fine and coarse RA, in mortars and concrete [39]. On the other hand, despite the evident contributions of this use to the decrease of the environmental impact of the construction sector and the several studies carried out, RA are not widely and often incorporated in mortars and concrete. This is mainly due to the perception of lower performance of these aggregates, compared to primary aggregates [25,40,41]. Hence, in order to improve their characteristics and their suitability to be incorporated in construction materials, several treatments can be applied to RA, either physical or chemical [42].

3. CO_2 curing and properties of carbonated recycled aggregates

3.1. Treatment of recycled aggregates by CO_2 curing

Cement matrix carbonation is an exothermic chemical reaction related to the diffusion of CO_2 through the matrix pores, reacting with the present alkaline elements. Once embedded in the cement matrix, in the presence of water, CO_2 reacts with calcium oxide in the form of calcium hydroxide ($Ca(OH)_2$), resulting from the reaction between calcium and water. Additionally, it also reacts with hydrated calcium silicate (CSH), forming calcium carbonate ($CaCO_3$). This formation within the cement matrix pores causes an increase in the RA's density and a decrease of their water absorption [43,44]. This natural reaction can be accelerated and be applied as chemical treatment to be performed on the CDW aggregates in order to improve their properties. Likewise, carbonation appears as an eco-friendly treatment method for RA [45] as it consumes CO_2 from the environment.

Generally, the carbonation reaction is influenced by various factors, thus facilitating it, or on the contrary, making it more difficult. According to some authors, this reaction is greatly influenced by the temperature, relative humidity and CO_2 concentration and pressure [46]. On top of that, carbonation of RA is not only influenced by those factors but also by its particle size, moisture content, CO_2 pressure and carbonation time [47,48].

Carbonation as a RA treatment presents numerous and distinct test conditions among the several studies conducted. For instance, there is a wide scope of pre-treatments prior to CO_2 curing. In a study conducted by Chinzorigt et al. [49], the coarse and fine aggregates from old concrete, from a RA commercial producer, were soaked in water for 10 min and then subjected to conditions of 21 °C and 40–45% RH up to 5 h. This pre-conditioning enables RA to undergo CO_2 curing with a moisture content around 60% and 70%, in order to boost their carbonation. Other authors, such as Gholizadeh-Vayghan et al. [50], also soaked RA in water prior to forced carbonation. Alternatively, in order to help the carbonation reaction, before being exposed to CO_2, RA could also be immersed in lime saturated water [51,52]. A previous drying can enforce the carbonation of non-carbonated RA. Thus, by controlling the moisture content of the aggregates prior to carbonation and unsealing the pores for a better CO_2 penetration, so that carbonation is not only superficial, Gholizadeh-Vayghan et al. [50] dried crushed concrete cubic specimens with 28-day compressive strength of 57.6 MPa at 80 °C for a day, while Shi et al. [53] dried RA derived concrete samples at 60 °C for 48 h. Additionally, in further research works, RA were placed in drying chambers at temperature around 25 °C and relative humidity around 50% [51,54–57].

Carbonation can be artificially promoted. Besides the differences in treatments previously described applied to RA, there is still a variation regarding the equipment in which the carbonation process takes place. While in some studies [45,50,53,55,58–63] carbonation chambers designed for this purpose are used, in others airtight steel cylindrical vessels are used, in which it is possible to carry out pressure variations inside [51,54,56,57,64–67]. Altogether, in these last cases, pre-treatments can be applied in which the equipment is vacuumed at negative pressures, immediately before the beginning of carbonation. It is assumed that the negative pressures increase the CO_2 diffusion within the pores of RA. Among others, Kou et al. [64] and Zhan et al. [67] placed the RA into an airtight steel vessel and then vacuumed it to −0.5 bar, whereas Li et al. [54] and Xuan et al. [56] vacuumed the carbonation equipment to −0.6 bar.

Not only the carbonation pre-treatments and the equipment used differ between studies, but so do carbonation conditions such as temperature, relative humidity and duration. Table 1 presents the carbonation conditions used in several studies. Regarding the duration of the carbonation treatment, a wide range of time that the RA are subjected to CO_2, from minutes to hours, is observed. For instance, Abate et al. [58] used a duration of 7 days whilst for the test conducted by Kazmi et al. [51] this duration was 24 h. Nevertheless, some authors defined a single period of duration while others used different intervals of time [64].

The characteristics of the RA from CDW before and after being subjected to carbonation are presented thereafter.

3.2. Bulk density

Generally, RA derived from CDW present lower densities compared to NA [69,70]. This is mainly due to the cementitious mortar adhered to the RA's surface, which has greater porosity than NA's [24,69,71]. The quality of the products with RA is defined by several properties such as their density. During the carbonation process within the RA pores, CO_2 reacts with calcium hydroxide forming calcium carbonate in the solid form, thus filling these pores and increasing density [71]. Therefore, it is possible to enhance the properties of RA by carbonation treatment, namely their density and their porosity, by improving the quality of the adhered mortar to the original NA's surface [60,64,65].

Zhan et al. [67] carried out a study in which the density of RA resulting from crushed concrete was measured before and after CO_2 curing. It was found that density slightly increased with the curing process, from 2620 kg/m^3 (RA) to 2670 kg/m^3 (CRA). This clear tendency was also observed in many other studies - see Fig. 1, mainly owing to the reduction of volume of the aggregates pores that are filled with $CaCO_3$ crystals resulting from the carbonation process.

Some authors present in their studies a distinction between the fine and coarse RA [45,54,56,57,64] - Fig. 2. This distinction is important in terms of the application of the aggregates [72].

Table 1
Carbonation conditions found in the literature for CO_2 curing of crushed concrete aggregates.

References	Duration	CO_2 concentration (%)	Temperature (°C)	RH (%)	Pressure (bar)
[58]	7 days	5	20	50	–
[59]	72 h	5	20 ± 2	60 ± 5	1
[50]	1, 4 and 24 h	–	20	–	1
[51]	24 h	100	–	–	0.8
[64]	6, 12, 24, 48 and 72 h	–	–	–	0.1
[54]	7 days	100	–	–	1
[45]	10 days	20 ± 3	20 ± 2	70 ± 5	–
[60]	–	–	22	55	–
[65]	6, 12, 24, 48 and 72 h	–	–	–	4
[53]	3 days	20 ± 2	20	60	–
[61]	–	20	20 ± 2	70 ± 2	–
[66]	30 and 90 min	–	–	–	0.75 and 1.5
[55]	24 h	–	–	50	0.1
[71]	3 weeks	–	–	60	–
[56]	24 h	100	–	–	0.1 and 5
[57]	1, 2, 3, 6, 18 and 24 h	–	–	–	0.1 and 5
[67]	–	–	28–31	35–75	0.1
[62]	–	20 ± 2	20 ± 2	60 ± 5	–
[63]	4 h	–	–	–	2

3.3. Water absorption

Water absorption is one of the most important properties of the aggregates, because it affects the mortars' or concrete's workability [24,73], and it is considerably different in NA and RA [68]. More porous aggregates will absorb a higher volume of water. Therefore, workability decreases and more water is needed for the mortar to be workable. However, hydraulic reactions do not spend all the water used. The water absorbed by the wastes will be released later and evaporate, increasing the mortar's porosity. Water absorption depends on the volume and diameter of pores within RA. Therefore, water absorption can be an indicator of the RA's quality [74,75].

Briefly, the higher the material's porosity, the lower its density is and the higher its water absorption is. Abate et al. [58] noticed that CO_2 curing process had an impact on the water absorption of RA obtained from a local construction waste disposal facility, in the Republic of Korea, by reducing it by about 6% (Fig. 3).

Nevertheless, other authors claimed to obtain much higher decreases in the water absorption of RA, such as Kou et al. [64] with a decrease of about 38% for both recycled fine aggregates (RFA) and recycled coarse aggregates (RCA), as Figs. 4 and 5, respectively, show. Additionally, RFA present higher water absorptions than RCA, for both untreated RA and those treated by CO_2 curing.

3.4. Crushing index

The crushing value or crushing index is a measure of the strength and durability of the aggregates; the lower its value, the higher these two properties are [68]. Therefore, for the purpose of construction materials' production, such as mortars and concrete, it is better to have aggregates with lower crushing index.

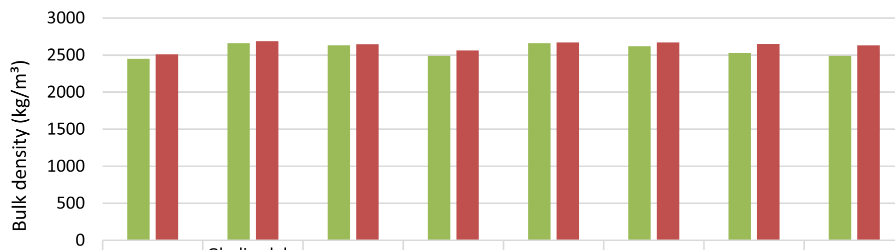
The carbonation curing treatment modifies the pore structure of RA, mainly due to the precipitation of $CaCO_3$ into crystals that are lodged in the aggregates pores leading to a reduction of the pore volume. It is thus expected to obtain lower values of the crushing index of RA subjected to CO_2 curing (Table 2). A reduction of this index for all the studies mentioned is observed. It must be noted that, in these works, different types of RA were used. Thus, CO_2 curing improves the durability and strength of RA, regardless of their type.

4. Properties of mortars containing CRA

4.1. Mix proportions and replacement ratios

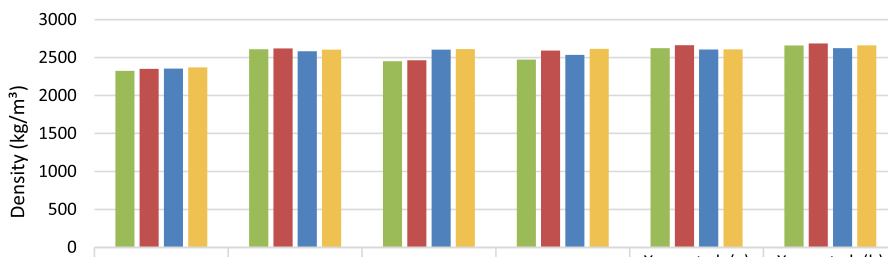
Mortars always have in their constitution at least a binder, an aggregate and water. As previously stated, the properties of RA are different from those of NA; thus optimal ratios of replacement of NA with RA must be used in order to improve the mortars' performance [13].

At present, several studies have been developed focused on the incorporation of carbonated RA in concrete by contrast with the few focused on this incorporation in mortars [53,58,62,77]. For instance, Abate et al. [58] studied volumetric replacements of 25% and 50% of NA with uncarbonated and carbonated RA at a fixed water/cement ratio (w/c) of 0.3. Additionally, in a study conducted by Muñoz et al. [76], the same replacement ratios were used to study the influence of carbonated RA on cement-based mortars, except for the w/c used: 0.65. Other authors, such as Shi et al. [53], fully replaced (i.e. 100%) NA with RA and carbonated RA and used a w/c of 0.5. Next, some properties of the



	Chinzorigt et al. [59]	Gholizadeh-Vayghan et al. [50]	Luo et al. [65]	Shi et al. [53]	Wu et al. [68]	Zhan et al. [67]	Zhang et al. (a) [62]	Zhang et al. (b) [63]
RA	2450	2663	2633	2490	2660	2620	2530	2490
CRA	2510	2687	2647	2562	2670	2670	2650	2630

Fig. 1. Bulk density of recycled aggregates before (RA) and after being exposed to CO_2 curing (CRA).



	Kou et al. [64]	Li et al. [54]	Liang et al. [45]	Lu et al. [60]	Xuan et al. (a) [56]	Xuan et al. (b) [57]
RFA	2326	2611	2452	2473	2624	2658
CRFA	2351	2621	2464	2592	2663	2685
RCA	2355	2583	2604	2535	2605	2624
CRCA	2371	2604	2612	2615	2609	2660

Fig. 2. Bulk density of recycled fine aggregates (RFA) and recycled coarse aggregates (RCA) before and after subjected to forced carbonation (CRFA and CRCA).

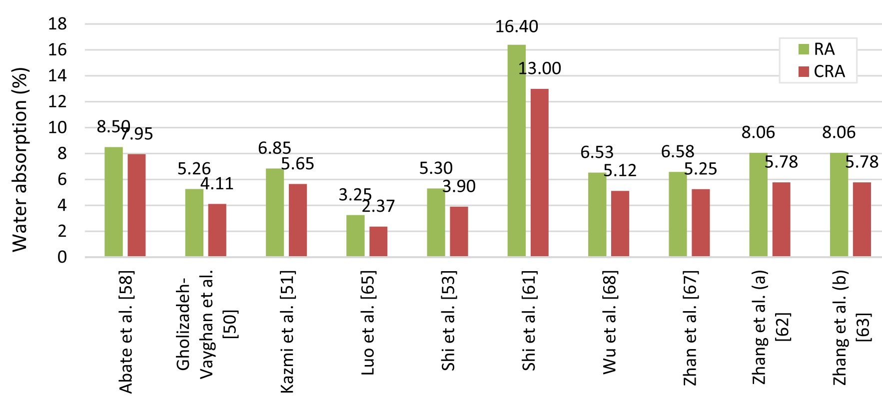


Fig. 3. Water absorption of recycled aggregates before (RA) and after (CRA) being subjected to forced carbonation.

mortars affected by CDW incorporation are presented.

4.2. Fresh state performance

Relative to NA, RA from CDW are more absorbent. The higher volume of absorbed water has a great influence on the mortars' workability and their further application [25,73]. This high absorption reduces the mortars' workability as some of the water added to the mix is absorbed by RA [75]. Overall, as the carbonation treatment process decreases the water absorption of RA, an inverse trend is expected regarding the workability of mortars with carbonated aggregates. Shi et al. [53] and Zhang et al. [62] confirmed this phenomenon; by treating RA with a CO_2 curing process, an increase of the workability of the mortars (from 205 to 210 mm and 140–180 mm, respectively) was obtained.

4.3. Physical performance

4.3.1. Water absorption

As stated by Muñoz et al. [76], the reduction in water absorption of carbonated RA influences the mortars' water/binder ratio and consequently the mortars' water absorption. The CRA mixes with 25% and 50% replacement ratios showed higher values of water absorption by capillarity, at 30 and 90 days, relative to the reference mortar produced with NA only. However, at 180 days, the CRA mixes presented water absorption in the same range or lower than that of the reference mortar.

Conversely, Zhang et al. [62] obtained values of water absorption

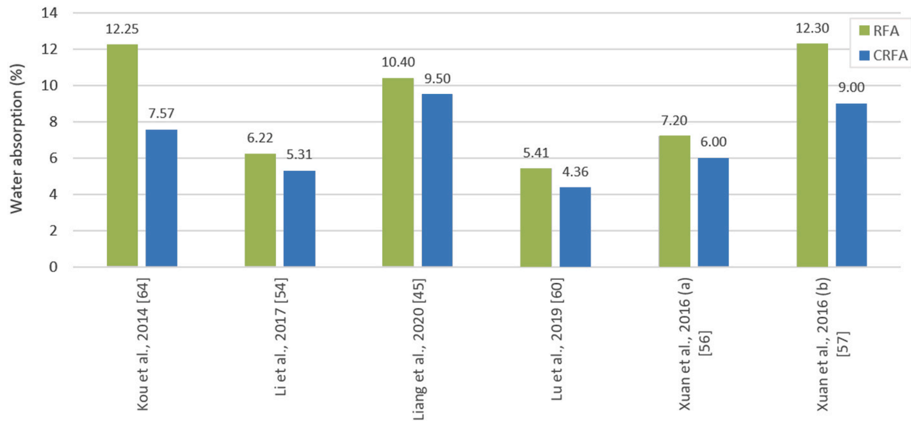


Fig. 4. Water absorption of recycled fine aggregates before (RFA) and after (CRFA) being exposed to CO_2 curing.

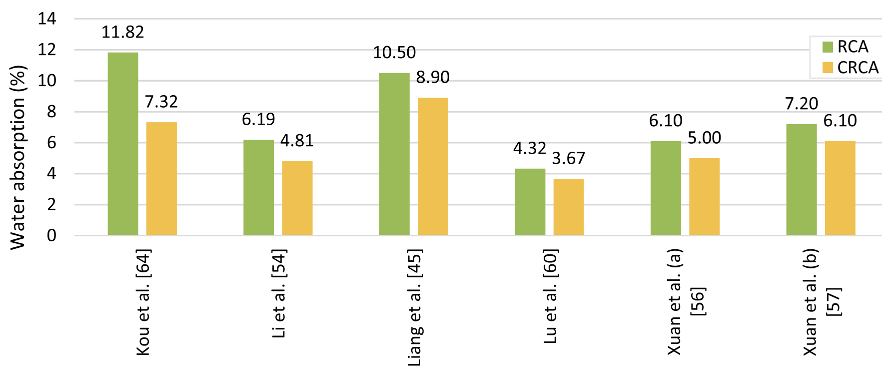


Fig. 5. Water absorption of recycled coarse aggregates before (RCA) and after (CRCA) being exposed to CO_2 curing.

Table 2
Crushing values of RA before and after the carbonation treatment process.

Reference	Crushing index (%)	
	Before CO_2 curing	After CO_2 curing
[51]	31.00	30.46
[54]	27.80	21.90
[60]	14.30	9.80
[65]	13.42	12.78
[56]	27.80	20.60
[62]	18.60	16.90
[63]	17.10	15.80

around 10% for mortars made exclusively with NA, 13% for mortars with RA and 12.5% for those with CRA. Therefore, a slight decrease of the water absorption of mortars with CRA relative to those with RA can be observed, indicating that aggregate's CO_2 curing had influence on mortars' porosity.

4.3.2. Autogenous and drying shrinkage

Shrinkage is a relevant subject when dealing with cementitious materials as it can lead to several problems affecting their performance, mainly leading to cracks on their surface [77,78]. It can be easily understood as a phenomenon in which the material suffers volume changes and can be divided into autogenous shrinkage, resulting from the hydration reactions of cement, and drying shrinkage, a result of the evaporation of the water present in the materials' surface [79,80]. This phenomenon is influenced not only by the composition of the material itself but also by the environmental conditions to which the material is exposed [79,81,82].

Abate et al. [58] conducted a study in which they assessed the autogenous and drying shrinkage of mortars with RA either uncarbonated and carbonated. It was observed that the mixes with RA and CRA presented good results in terms of autogenous and drying shrinkage, with focus on those containing CRA, which exhibited about 21% and 40% less autogenous and drying shrinkage, respectively, than mortars containing NA only. Similarly, Zhang et al. [62] obtained a reduction of 8% and 13% of the drying shrinkage of mortars incorporating RA and CRA, respectively, at 56 days. In spite of this, the results at 3 days for the autogenous shrinkage were not satisfactory as it increased 126% and 526% for mortars containing CRA.

4.4. Mechanical performance

Aggregates have a fundamental role on the characteristics of the final products. This influence concerns both physical properties and mechanical performance. Hence, mechanical strength depends on the aggregates' grain size distribution, shape, crushing index and overall strength. As the aggregates subjected to forced carbonation present lower crushing indexes than those without any treatment, it is expected to obtain mortars with greater compressive strength when formulated with these treated aggregates, in comparison with mortars containing untreated RA.

Generally, RA present lower strengths than NA, resulting in compressive strength losses for materials containing RA [24]. This can be seen in the study of Muñoz et al. [76], in which mortars made with RA showed a loss of compressive strength. However, mortars with CRA showed a different behaviour, similar or slightly lower compared to the mortar with NA only. At 180 days, the compressive strength of the RA mortars was around 25% less than that of the NA mortar and that of the

CRA mortars only 1% and 5% less, for replacement ratios of 25% and 50%, respectively. Zhang et al. [62] obtained similar results; the compressive strength at 7, 28 and 90 days was higher than that of the RA mortar, by 11%, 6% and 8%, respectively. Mortars with CRA showed higher compressive strength than those with RA at 7 and 28 days, in the work of Shi et al. [53]. However, at 3 days, there is no evidence that the carbonation treatment had an influence in the compressive strength of CRA mortars.

5. Properties of concrete containing CRA

Treatments through forced carbonation of concrete containing RA has been the subject of numerous studies in recent years. For instance, among others, studies such as those conducted by Sáez del Bosque et al. [82], Zhan et al. [83] and Monkman and MacDonald [84] evaluate the properties of concrete formulated with RA, with different incorporation ratios, subjected to forced carbonation. Despite the promising results in these studies, the present review focuses on the incorporation of carbonated recycled aggregates (CRA) in concrete and not on carbonation posterior to the incorporation. Hence, the analysis spectrum is reduced, and only the studies currently working on concrete containing prior CRA are presented.

5.1. Mix proportions and replacement ratios

The mix proportions of the production of concrete and the replacement ratios of NA with RA widely differ in the literature. Some authors define a target strength for the control concrete [59], with NA only, whereas others fix the water cement ratio and proceed with replacing the aggregates [45,54,56]. There is also a variability in the replacement ratios between studies. In some, NA are replaced with 100% RA and CRA [45], while in others the 100% replacement is performed only for the coarse aggregates, maintaining the fine NA [51,54,64]. In addition, Lu et al. [60], Luo et al. [65], Tam et al. [66] and Xuan et al. [56] studied several replacement ratios, varying between 0% for the control concrete and 100%.

5.2. Fresh state performance

Concrete slump is a measurement of its consistency and workability, in the fresh state. The higher this value, the more workable the concrete is; however, too high slump values carry risks, namely in terms of segregation, precluding its use.

Kazmi et al. [51] found out that the replacement of NA with RA and CRA did not influence the concrete samples' slump, with values for all the mixes in the range of 100–150 mm. Similarly, in the study of Chinzorigt et al. [59], the difference between the slump of the control concrete and that of concrete with CRA is only of 1 cm, with a lower value for the latter.

Tam et al. [66] found a slump of 150 mm for the control concrete and, for the mixes with incorporation of CRA of 30% and 100%, 140 and 210 mm, respectively. Therefore, a replacement of 100% drastically increases slump, whereas for a replacement of 30% a decrease is found. On the other hand, the slump of concrete with either RA or CRA is often higher than that of the control mix, mainly due to higher contents of free water in the concrete mix with RA [64].

5.3. Shrinkage

Compared with NAC, RAC displays lower autogenous shrinkage; however, RAC has higher autogenous shrinkage when compared to carbonated RAC (CRAC) [60]. In this study, NA was replaced with RA and CRA at 50% and 100%. An autogenous shrinkage decrease of about 12.8 and 26.4% occurred for 50% and 100% RA, respectively. Additionally, CRAC formulated with the same replacement ratio resulted in 31.6% and 61.2% higher autogenous shrinkage relative to the control concrete. Concerning drying shrinkage, there were higher results for both RAC and CRAC. Conversely, it was noticed that, for concrete specimens with CRA, the drying shrinkage was 16.6% and 25.1% lower than for the specimens with uncarbonated RA, for 50% and 100% replacement ratios, respectively. As stated by Lu et al. [60], as the content of coarse RA and CRA increases, the drying shrinkage of RAC and CRAC increases.

In another study, a larger shrinkage of RAC compared to the control concrete was also noted, with a shrinkage about 26% higher [59]. In addition, this larger shrinkage is also found for CRA, relative to NAC, with an increase of approximately 29% and 12% for CRAC with 30% and 100% incorporation ratios, respectively. There was no difference between the concrete specimens with replacements only of fine RA or coarse RA.

Finally, the drying shrinkage of RAC and CRAC was, once again, higher than that of the concrete with NA only in the study conducted by Kou et al. [64]. Despite this, the drying shrinkage of CRAC was 10% and 15% lower than that of RAC, for both types of carbonated RA used.

5.4. Mechanical performance

5.4.1. Compressive strength

The effect of incorporating RA subjected to CO_2 curing treatment on the mechanical performance of concrete was studied by Kazmi et al. [51]. A great reduction (32%) of the compressive strength of RAC, made with RA from a concrete recycling plant, relative to NAC, was obtained. Nevertheless, concrete with CRA showed an increase of the compressive strength of 14% relative to RAC.

In the study of Chinzorigt et al. [59], concrete specimens were prepared with RA from a concrete recycling plant with and without CO_2 treatment. The compressive strength of these specimens was measured at 28 days; all specimens complied with the compressive strength target of 30 MPa. However, the compressive strength was lower than the one for the control concrete with NA only. This reduction is approximately 19% and 11% for RAC and CRAC, respectively. Therefore, the treatment of RA by CO_2 curing revealed to be positive in terms of compressive strength.

Moreover, higher compressive strength of CRAC relative to RAC was found by Li et al. [54], with an improvement of 8.2%, 17.5% and 12.2% at 7, 28 and 90 days, respectively. Also, despite obtaining lower compressive strength than the control concrete for all mixes, Kou et al. [64] obtained a rise of the compressive strength in concrete made with CRA compared to RAC.

The CRAC formulations with 50% and 100% incorporation ratios of coarse crushed concrete aggregates studied by Lu et al. [60] showed significant improvements regarding compressive strength relative to RAC. For instance, CRAC with 50% replacement increased its compressive strength by 24.1% (28 days) and 26.8% (90 days). Despite this improvement, NAC still presented a greater compressive strength than RAC and CRAC; for RAC at 50% and 100% incorporation ratios, the compressive strength was respectively 23.7% and 36.2% lower than that of NAC.

The compressive strength of NAC, RAC and CRAC was the subject of other studies, in which more replacement ratios were used [56,65,66]. Xuan et al. [56] studied replacement of NA with RA and CRA, from demolished old concrete structures and from crushing a concrete batch, at 20%, 40%, 60%, 80% and 100%. The compressive strength of concrete with 100% incorporation of RA suffered a decrease of 26.3% compared to the control concrete. Incorporation of 30% of RA and up to 60% of CRA showed insignificant drops of compressive strength. However, when the content of CRA was 100%, there was a rise of compressive strength of approximately 22.6%, relative to RAC also with 100% replacement. Furthermore, the compressive strength of RAC with crushed concrete waste derived from an old pavement, with replacement ratios of 30–100%, showed a decrease of 7.9–18.3% relative to NAC [65]. Once again, when concrete is produced with CO_2 treated

CRA, there is an increase in the compressive strength comparative to the concrete produced with uncarbonated RA. This increase was about 2.3%, 12.4%, 13.6% and 14.5% for CRAC, respectively for replacement ratios of 30%, 50%, 70% and 100%. Lastly, Tam et al. [66] noticed a 30% loss of compressive strength of concrete with 100% CRAC and an increase of 4% for concrete produced with 30% incorporation ratio of CRA.

Fig. 6 presents the 28-day compressive strength of RAC of several studies [50,58,65,84,85] and CRAC [50,58,65] for several replacement ratios.

5.4.2. Tensile strength

The tensile strength of concrete with RA subjected to forced carbonation was described in the studies of Chinzorigt et al. [59] and Kou et al. [64]. In the first one, the tensile strength of concrete specimens was tested after 28 days and a reduction of 37% was noticed for RAC relative to NAC, and it was stated by the authors that the use of CRA in concrete may not have a significant impact on the tensile strength's improvement [59]. In the second study, it was noticed that, before 28 days, the tensile strength of RAC and CRAC is lower than that of the control concrete. Nevertheless, at 90 days, an increase of 5% and 10% was found in the tensile strength of RAC and CRAC relative to the control concrete [64].

5.4.3. Modulus of elasticity

In general, the modulus of elasticity of NAC is higher than that of RAC [25,56]. Chinzorigt et al. [59], based on the results of their experimental campaign, stated that the use of RA treated by CO_2 curing has an insignificant impact on concrete's modulus of elasticity. Conversely, an increase of approximately 6% and 13.2% of the modulus of elasticity of CRAC relative to RAC was noted by Luo et al. [65] and Xuan et al. [56], respectively. Also, an improvement of the modulus of elasticity of concrete with RA was obtained by Kazmi et al. [51] by means of their carbonation. However, these improvements were not sufficient to increase the modulus of elasticity up to that of the control concrete; RAC exhibited a modulus of elasticity 15% lower than that of the control concrete, whereas for CRAC this reduction is 6%. The modulus of elasticity is greatly influenced by the porosity of the concrete aggregates; thus, this can be explained by the higher porosity shown by RA in comparison with NA [86,87].

6. Durability

6.1. Water absorption

As previously mentioned, recycled aggregates concrete (RAC) has higher water absorption than natural aggregates concrete's (NAC) [68] and that may have direct influence on durability. For instance, an increase of water absorption of RAC compared to NAC was obtained, possibly owing to the porosity of RA [51]. Nevertheless, in parallel with mortars formulated with CRA, CRAC also exhibited a reduction of the water absorption in comparison to RAC's. This can be confirmed by Kou et al. [64], which noted water absorption values for CRAC 38.1%–47.9% lower than those of RAC. However, the carbonation treatment of the aggregates can induce lower decreases of water absorption between RAC and CRAC. To this extent, Kazmi et al. [51] confirmed this lower drop; a decrease of 7% only was found for CRAC relative to RAC.

6.2. Carbonation and steel corrosion

The treatment of RA by forced carbonation improves their characteristics; however, it can raise concerns in terms of durability of the materials in which they are incorporated. For instance, concrete exposed to environmental conditions interacts with CO_2 present in the atmosphere, which enters concrete's porous medium, by diffusion, and promotes its carbonation [39,87,88]. This has an effect on the pH reduction of concrete, thus promoting depassivation of the steel reinforcement and progress of corrosion. This phenomenon is relevant as it allows steel reinforcement's corrosion [39,88,89]. For this reason, the carbonation of CRAC must be studied in order to assure the service life of concrete structures. Liang et al. [45] found out that, by enhancing the quality of RA by forced carbonation, a decrease in carbonation depth of CRAC is observed. Thus, by replacing RA with CRA an improvement in carbonation depth of CRAC is obtained. Additionally, in the same study, tests were conducted in which an initial crack is induced in concrete specimens and their carbonation depth is measured. It was found that this initial crack increases the carbonation depth of CRAC. Nevertheless, comparing the carbonation depth of RAC and CRAC, it was noticeable that CRAC's was lower.

Accelerated carbonation of RAC and CRAC was performed by Kazmi et al. [51] and afterwards the carbonation depth of the specimens

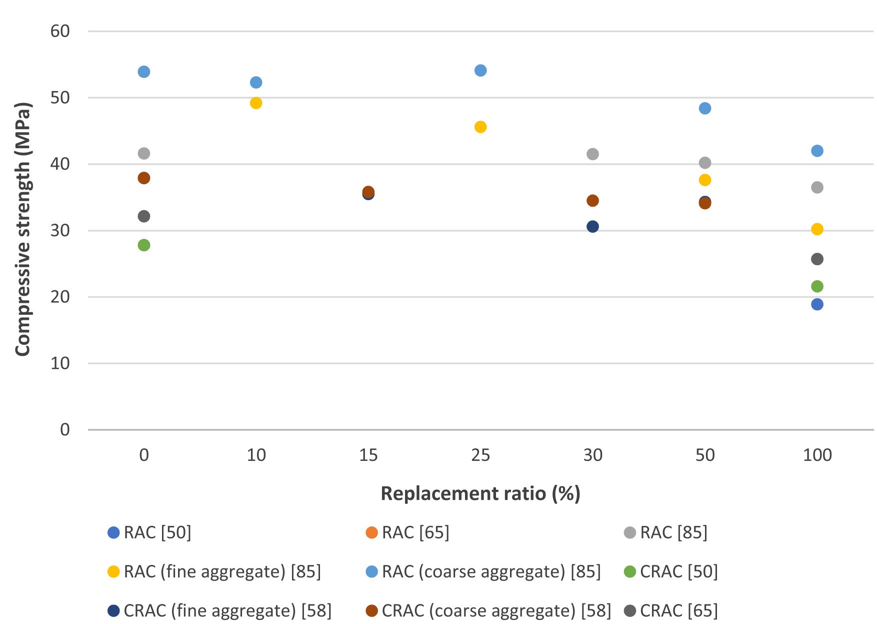


Fig. 6. 28-day compressive strength of concrete containing recycled aggregates (RAC) and carbonated recycled aggregates (CRAC).

measured. Concrete with NA exhibited a carbonation depth of 6 mm whereas concrete with RA increased it to 13 mm. This may be explained by the influence of the high porosity of RA on carbonation resistance. Therefore, by treating RA with CO_2, a reduction of 2% in carbonation depth was obtained for CRAC. Similarly, Chinzorigt et al. [59] obtained a decrease of the carbonation depth of CRAC relative to RAC's.

As the steel reinforcement corrosion is greatly affected by the carbonation of concrete, a reduction in carbonation depth of concrete with CRA can decrease the risk of steel corrosion. Liang et al. [45] measured the corrosion potential of concrete formulated with NA, RA and CRA. Both RAC and CRAC presented higher values of corrosion potential than NAC's However, CRAC had significantly lower values of this potential than RAC's. Concrete specimens with RAC presented corrosion potential of 84%, for replacement of the fine aggregates, and 81%, for coarse aggregate's replacement. Conversely, CRAC showed a corrosion potential of 67% and 62%.

7. Conclusions

CDW are widely available with low costs of acquisition. The incorporation of these wastes as recycled aggregates in construction products such as mortars and concrete has a significant impact on the reduction of the volume of natural aggregates used in these products, as on decreasing the depletion of natural resources, thus increasing their life cycle. However, CDW are not often used as recycled aggregates in mortars and concrete due to their higher porosity and lower strength compared to the natural ones. Therefore, the need to find eco-friendly treatments capable of enhancing the properties of these aggregates emerges. CO_2 curing can be considered a good treatment with satisfactory results in the improvement of recycled aggregates' characteristics, in a short period of time. Additionally, there is the possibility to use CO_2 from industrial CO_2 emission sources and sequestrate it in these materials, thus requiring low energy inputs.

There seems to be a considerable variability in the literature concerning the conditions to be adopted in the treatment of recycled aggregates by forced carbonation. Nevertheless, CO_2 curing, even applied under different conditions, seems to produce promising results in the utilization of CDW as recycled aggregates for the production of mortars and concrete.

CO_2 curing of recycled aggregates produces a positive effect on their physical characteristics, such as increasing the apparent density, and consequently decreasing their porosity and water absorption. In addition, in terms of mechanical properties, this treatment considerably reduces the crushing index, i.e. it increases their capacity in terms of mechanical strength.

Subjecting the recycled aggregates to forced carbonation induces an increase on the consistency of mortars and the slump of concrete, compared with uncarbonated CDW. Additionally, it produces a decrease of shrinkage, although this is more noticeable in mortars than in concrete.

In terms of mechanical performance, the incorporation of carbonated recycled aggregates instead of recycled aggregates has a significant impact on the compressive strength of mortars and concrete, despite the fact that it is still lower than that pf the mortars and concrete produced with natural aggregates only. Conversely, this impact is little on the tensile strength of carbonated recycled aggregates concrete. On the other hand, the use of carbonated recycled aggregates has a positive impact in terms of increase of the modulus of elasticity of carbonated recycled aggregates concrete relative to recycled aggregates concrete.

It should be noted that, in several studies, almost all the characteristics of mortars and concrete produced with carbonated recycled aggregates improved comparatively to those of mixes with (uncarbonated) recycled aggregates. Nevertheless, these characteristics normally remain below those of the mixes with natural aggregates only. Still, it is possible to use recycled aggregates in construction products such as mortars and concrete when subjected to carbonation treatments. These treatments produce significant effects by improving the characteristics of these aggregates, increasing the levels of confidence in their use. Thus, CO_2 curing may be used, both as a method of capture and storage of CO_2 emitted in the production of cement and other construction materials, and also as a treatment methodology to reduce the drawbacks of RA.

However, it is necessary to evaluate these construction products with regard to their field of application. Namely, concerning the adherence of mortars to the substrate and their consequent cracking tendency due to restrained shrinkage, or even their ageing and durability problems, or their behaviour when in contact with water. As regards concrete, several aspects concerning the corrosion of reinforcement bars and its application should also be taken into account and studied in future studies. A proper industrial feasibility assessment of the production of mortars and concretes incorporating these recycled aggregates is needed.

Declaration of competing interest

The authors have no conflict of interest whatsoever.

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