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Life Cycle Carbon Assessment of Mortars with Carbonated and Non-Carbonated Recycled Aggregates

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Abstract: Global warming is one of the most important issues that the world is currently facing. The cement industry accounts for around 7% of total global CO_2 emissions. According to the 13th United Nations Sustainable Development Goals, cement plants must become carbon neutral by 2050. This neutrality may be achieved by a reduction in CO_2 emissions complemented with carbon capture, utilization and storage (CCUS) technologies. In accordance with these sustainable goals, several approaches have been studied. This paper investigates life cycle carbon of mortars produced with carbonated recycled aggregates. In previous works, the carbon dioxide capture capacity of construction and demolition waste (CDW) was analysed, and mortars with CDW recycled aggregates submitted to high levels of CO_2 were evaluated in terms of their mechanical performance. This paper focus on the life cycle carbon impact assessment (LCCA) of industrial mortar formulations in a cradle-to-gate boundary. This assessment is carried out through a global warming potential environment impact assessment, since it represents the amount of CO_2 equivalent that is sent to the atmosphere and contributes to the "greenhouse effect". This LCCA includes the impacts associated with the treatment and additional transportation routes of the recycled aggregates. With this work, it was found that mortars with carbonated recycled aggregates have a considerably lower global warming potential impact than mortars without recycled aggregates. The mortars with recycled aggregates presented lower CO_2 emissions of up to 6.31% for 100% incorporation of non-carbonated recycled aggregates. These values were incremented with the carbonation of the recycled aggregates, achieving a reduction of CO_2 emissions of up to 36.75% for 100% of incorporation.

Keywords: construction and demolition waste; recycled aggregates; cement; carbon capture and storage; life cycle carbon assessment; global warming potential

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1. Introduction

The cement industry is responsible for several environmental impacts, including the extraction of natural resources and burning of fossil fuels. Among several environmental impacts, carbon dioxide (CO_2) emissions are the major environmental impact associated with cement production [1,2]. CO_2 is part of a set of gases that contribute to global warming. The high concentration of CO_2 in the atmosphere, together with other greenhouse gases, is responsible for a greater reflection of the radiation emitted by the earth's surface, which results in an incremental increase in the planet's average temperature [3,4] and has significant consequences for various ecosystems, namely the increase in water levels due to the thawing of glaciers. Therefore, global warming is one of the important issues that the world is confronting today. For this reason, cement plants need to become carbon neutral by 2050, in accordance with the 13th United Nations Sustainable Development Goals. This neutrality can be achieved by a reduction in CO_2 emissions complemented with capture and utilization of the remaining CO_2.

In parallel, the generation of construction and demolition waste (CDW) has also emerged as a significant environmental challenge, particularly in the European Union. It is estimated that CDW accounts for 25–30% of all waste generated in the EU, making it one of the largest waste streams [5]. The disposal of this waste in landfills or through incineration can further contribute to greenhouse gas emissions and environmental concerns [6].

To address these two major concerns, studies have been made regarding the potential of using recycled aggregates from CDW as a substitute for natural aggregates in concrete and mortar production. Several studies have investigated the global warming potential (GWP) and life cycle assessment (LCA) of mortars and concrete containing recycled aggregates [7,8].

Comparing the environmental and economic impacts of concrete with natural and recycled coarse aggregates from a cradle-to-gate perspective, Braga et al. [7] conducted a LCA of 216 concrete mixes from 24 references. The results show that using coarse recycled concrete aggregates can significantly reduce environmental impacts and costs compared to natural aggregates, with cement identified as the main contributor to both impacts. Therefore, the referred study proved the viability of using recycled concrete aggregates as a more sustainable alternative to natural aggregates in concrete production, with the potential to reduce environmental impacts and costs for the construction industry.

Dias et al. [9] used LCA to compare the environmental and economic impacts of using recycled aggregates (RAs) to replace natural aggregates (NAs) in concrete production. It was concluded that transport distances significantly impact the environmental results, with shorter distances favouring the use of RAs. Also, environmental product declarations (EPD) show that recycled coarse aggregates have the lowest impacts, while natural coarse crushed aggregates have the highest.

Cuenca-Moyano et al. [10,11] studied the environmental assessment of masonry mortars with the incorporation of recycled fine aggregates from CDW. The results showed that the use of recycled fine aggregates reduced the environmental impacts in most categories, analysed by avoiding the impacts of disposing in landfills. However, some environmental impacts were slightly increased, namely ecotoxicity, due to a higher transport distance of the RAs when compared to the location of NAs used in the referred study. Additionally, Grabois et al. [12] studied the environmental performance of cement-based mortar considering the incorporation of recycled aggregates from a site demolition. The life cycle assessment was carried out based on a cradle-to-gate scope. The authors analysed different replacement ratios and concluded that the environmental impacts were reduced with the increase in RA incorporation.

In another study, Kurda et al. [13] analysed the mechanical behaviour and environmental impacts of concrete mixtures containing high amounts of fly ash (FA) and RAs. Life cycle assessment (LCA) methodology was used to determine the influential factors, non-renewable energy consumption (PE-NRe) and global warming potential (GWP) for different scenarios in central Portugal. The study concluded that the GWP and PE-NRe of RA concrete are not considerably affected, contrary to previous studies where transportation scenarios played a significant role. The LCA of concrete decreases substantially with the use of FA, regardless of transportation scenario.

Santos et al. [14] reviewed the LCA of several mortars produced with different aggregates assuming that the use of alternative materials in mortar production, such as recycled or earth-based, can provide environmental benefits quantified through LCA. These alternatives can promote the circular economy and enhance mortar performance, while reducing energy-intensive processing and transportation compared to conventional materials. Other authors [15–17] studied the LCA of mortars with recycled industrial waste aggregates, finding out that these performed better environmentally in several environmental impact categories compared to natural aggregate mortars, reaching benefits of up to 20% in some environmental impacts.

In sum, several studies have generally found that the use of RAs can lead to a reduction in the environmental impact of the final product, primarily due to the avoidance of the energy-intensive extraction and processing of natural aggregates. Nonetheless, the specific environmental benefits of using RAs from CDW that have undergone forced carbonation, a process that can further enhance their properties, have not been extensively explored. Forced carbonation is a technique that can improve the quality of recycled aggregates by reducing their water absorption and increasing their strength, potentially leading to improved performance and reduced environmental impacts in mortar and concrete applications [18]. In the work of Shi et al. [18], the RCA properties were improved by CO_2 treatment, as were the old and new interfacial transition zones (ITZ) of the new composites with treated RCAs.

In previous studies, the carbon dioxide capture capacity of construction and demolition waste (CDW) was determined. Bastos et al. [19] concluded that mixed recycled aggregates that came from recycling plants were still able to capture 0.66% of their weight of CO_2. Concrete aggregates from recycling plants and from selective demolition sites can capture between 0.88% and 0.97%. Concrete aggregates from industrial wastes are lowly carbonated and, in this sense, the results pointed out that they are able to capture 4.09%. Finally, a reference concrete produced in a laboratory was able to capture 4.9%. All the materials were submitted to forced carbonation at 23 °C, 60% relative humidity and 25% CO_2 at different exposure times. After subjecting CDW recycled aggregates to high levels of CO_2, they were incorporated in mortars. Infante Gomes et al. [20] evaluated these mortars in terms of their mechanical performance.

This paper aims to address the gap in assessing the environmental impacts of the use of RAs subjected to forced carbonation by conducting a focus on the life cycle carbon impact assessment (LCCA) of mortar formulations in a cradle-to-gate boundary. In order to quantify the benefits of the use of carbonated RAs in mortars, a life cycle carbon assessment focused on global warming potential (GWP), that corresponds to the emissions of a CO_2 equivalent to the atmosphere, is presented in this study. The paper's objective is to quantify the GWP of these mortars and compare them to those made with natural aggregates and with RAs from CDW not subjected to forced carbonation, providing valuable insights into the environmental benefits of using recycled aggregates in the construction industry.

2. Goal and Scope Definition

2.1. Functional Unit and System Boundary

The functional unit defined for this life cycle assessment (LCA) was 1 m^3 of industrially formulated powder-state mortars. In this LCA, a "cradle-to-gate" boundary was considered. This boundary corresponds to environmental impacts associated with the product stage (Table 1). It includes the environmental impacts associated with the extraction and processing of raw materials (A1), their transport (A2) and the product manufacturing process (A3). The manufacturing process comprises:

- A3.1—packaging materials that leave the factory with the final product (raw materials and transport of the packaging materials);
- A3.2—manufacturing process (energy used, internal transport and waste production during the manufacturing process);
- A3.3—production and disposal of wastes resulting from raw materials' packaging and from packaging materials' wastes.

Table 1. Detailed life cycle stages of building materials from EN 15804.

Life Cycle Assessment Boundaries		Life Cycle Stages	Life Cycle Stages Designation and Description	
Cradle-to-cradle	Cradle-to-gate	Product stage (A1–A3)	A1	Raw material extraction and processing, processing of secondary material input
			A2	Transport to the factory
			A3	Manufacturing
	Gate-to-grave	Construction process stage (A4–A5)	A4	Transport to the building site
			A5	Installation into the building
		Use stage—information modules related to the building process (B1–B5)	B1	Use or application of the installed product
			B2	Maintenance
			B3	Repair
			B4	Replacement
			B5	Refurbishment
		Use stage—information modules related to the operation of the building (B6–B7)	B6	Operational energy use
			B7	Operational water use
		End-of-life stage (C1–C4)	C1	De-construction, demolition
			C2	Transport to waste processing
			C3	Waste processing for reuse, recovery and/or recycling
			C4	Disposal
		Benefits and loads beyond the system boundary (D)	D	Reuse, recovery and/or recycling potentials

2.2. LCA Assumptions

The LCA approach considered the following assumptions:

- Global warming potential was selected as the environmental impact category to consider in the LCA, since it is the most affected by RA carbonation;
- The LCA of the powdered mortars was considered as cradle-to-gate. Construction, use and end-of-life stages were not taken into account;
- The mortar plant, cement plant and recycled aggregate recycling plant were considered in specific locations. Different locations would affect the transport distances and, consequently, the transport environmental impacts and the overall results;
- The data used to obtain the environmental impacts of the processing of recycled aggregates from CDW were collected from Portuguese companies that produce limestone aggregates. The energy used to crush these recycled aggregates can differ from that of limestone aggregates;
- The recycled aggregates are carbonated in a rotary equipment to promote carbonation. However, it was considered that the energy spent in this process is negligible by comparison with the other processes under analysis. Hence, the environmental impacts of the carbonation process were not considered;
- The data used to obtain the environmental impacts of the mortars production were collected from a specific Portuguese company. The energy used can differ if a different company is chosen;

- The environmental impacts of the mortar production were considered dependent only on the mortars' bulk density, and other aspects could change these impacts;
- In some cases, it was not possible to use an environmental product declaration (EPD), a site-specific data collection or scientific research to estimate the environmental impacts of a product or process, as discriminated in Section 3.1. In those cases, databases from SimaPro software (Ecoinvent 3 and ELCD) were used. The data from these databases present some uncertainty because they are generic.

3. Life Cycle Inventory

3.1. Raw Materials Production (A1)

The mortars analysed in this research are composed of sand, recycled aggregates, cement and admixtures. The global warming potential (GWP) environmental impact associated with these raw materials (A1) was quantified through site-specific data, scientific research data, EDPs and databases (Table 2).

Table 2. Source and location of the databases used.

Product Stage	Raw Materials	Technical Details	Location	Sources
A1	Cement	CEM II	EU	International EPD system (ECRA [21])
	Sand	River sand	EU/PT	European Life Cycle Database (ELCD [22])
	Air entrainer	Powder admixture	EU	International EPD system (EFCA [23])
	Superplasticiser	Powder admixture	EU	International EPD system (EFCA [24])
	Water proofing	Powder admixture	EU	International EPD system (EFCA [25])
	MRA-RP/MRA-RP Carbonated	Mixed recycled aggregate	EU/PT	Site-specific data (adapted from Braga et al. [7])
	RCA-IS/RCA-IS Carbonated	Concrete recycled aggregate	EU/PT	Site-specific data (adapted from Braga et al. [7])
	RCA-RP/RCA-RP Carbonated	Concrete recycled aggregate	EU/PT	Site-specific data (adapted from Braga et al. [7])
	RCA-IW/RCA-IW Carbonated	Concrete recycled aggregate	EU/PT	Site-specific data (adapted from Braga et al. [7])
	CA-L/CA-L Carbonated	Recycled aggregate	EU/PT	Site-specific data (adapted from Braga et al. [7])

The GWP associated with sand utilization was obtained from the European Life Cycle Database (with the designation of "Sand 0/2 mm, wet and dry quarry, production mix, at plant, undried RER S"). The environmental impact associated with CEM II/B-L 32.5 N was obtained from an EPD of the European Cement Research Academy [3]. Similarly, the GWP impact of the admixtures used came from three EPDs of the European Federation of concrete admixtures associations. The information about the environmental global warming potential impact of cement, sand, admixtures and recycled aggregates presented in this paper was calculated by the authors using Simapro software (using version 3.05 of CML 2 baseline 2000 released by CML in April 2013, and CED version 1.10).

Table 3 summarises the GWP of sand, cement and admixtures.

The GWP impact associated with recycled aggregates in the raw materials component (A1) includes the CDW treatment. This treatment includes metal separation, plastics separation, paper separation (in some recycling plants), crushing processes and sieving processes [26]. The energy used to crush CDW depends on the type of aggregates used in mortars as well as their volume of incorporation. Concrete aggregates (CAs) and recycled concrete aggregates (RCAs) spend more energy to be treated (crushed and sieved) than mixed recycled aggregates (MRAs). Part of the energy used in Portugal consumes fossil fuels, and so in this sense the recycling process that aggregates pass through contributes to the GWP. This difference was considered in this LCA. The total GWP associated with recycled aggregates, carbonated and non-carbonated, is presented in Table 4.

Table 3. Environmental GWP impact of cement, sand and admixtures.

Raw Materials (Except Recycled Aggregates)	GWP (kg CO_2 eq./kg)
Cement (CEM II/B-L 32.5 N)	6.83×10^{-1}
Sand	2.46×10^{-3}
Air entrainer	5.27×10^{-1}
Superplasticiser	1.88
Water proofing	2.67

Table 4. Environmental GWP impact of recycled aggregates.

Recycled Aggregates (RAs)	GWP (kg CO_2 eq./kg)		
	Associated with RA Treatment	Associated with CO_2 Capture	Total
MRA-RP	4.39×10^{-4}		4.39×10^{-4}
RCA-RP	1.45×10^{-3}		1.45×10^{-3}
RCA-IS	1.45×10^{-3}		1.45×10^{-3}
RCA-IW	1.45×10^{-3}		1.45×10^{-3}
CA-L	1.45×10^{-3}		1.45×10^{-3}
MRA-RP Carbonated	4.39×10^{-4}	-6.60×10^{-3}	-6.16×10^{-3}
RCA-RP Carbonated	1.45×10^{-3}	-8.80×10^{-3}	-7.35×10^{-3}
RCA-IS Carbonated	1.45×10^{-3}	-9.70×10^{-3}	-8.25×10^{-3}
RCA-IW Carbonated	1.45×10^{-3}	-4.09×10^{-2}	-3.95×10^{-2}
CA-L Carbonated	1.45×10^{-3}	-4.90×10^{-2}	-4.76×10^{-2}

On the other side, the environmental impacts associated with sand, namely natural extraction, are eliminated when sand is replaced with recycled aggregates. On the other hand, besides the GWP impacts associated with their treatment, carbonated aggregates are able to absorb CO_2 through carbonation. The CO_2 uptake associated with carbonated aggregates counts as a benefit in their GWP impact. This uptake depends on the recycled aggregates used. In Table 5 the CO_2 uptake of each recycled aggregate is summed up, based on a previous study by Bastos et al. [19].

Table 5. CO_2 uptake of aggregates [19].

Recycled Aggregates	Carbonation Conditions	CO_2 Captured (kg of CO_2 per Tonne of Aggregate)
MRA-RP Carbonated	23 °C, 60% RH, 25% [CO_2] for 5 h	6.6
RCA-RP Carbonated	23 °C, 60% RH, 25% [CO_2] for 12 h	9.7
RCA-IS Carbonated	23 °C, 60% RH, 25% [CO_2] for 12 h	8.8
RCA-IW Carbonated	23 °C, 60% RH, 25% [CO_2] for 12 h	40.9
CA-L Carbonated	23 °C, 60% RH, 25% [CO_2] for 5 h	49.0

3.2. Transport (A2)

The raw materials were transported from their origin to the mortar plant. The mortar plant considered in this analysis was SecilTek, located in Montijo. Thus, the distance between each raw material origin and Seciltek was evaluated. Due to the close distance to the mortar plant, it was defined a cement plant from the Secil group, located in Outão. A medium distance from several suppliers was chosen to define the distance travelled by the natural aggregates (sand). It was assumed that admixtures came from the centre of Portugal. CDWs were the raw materials that had a greater transport distance. Figure 1 shows a scheme of the transport of CDWs from their origin to the mortar plants.

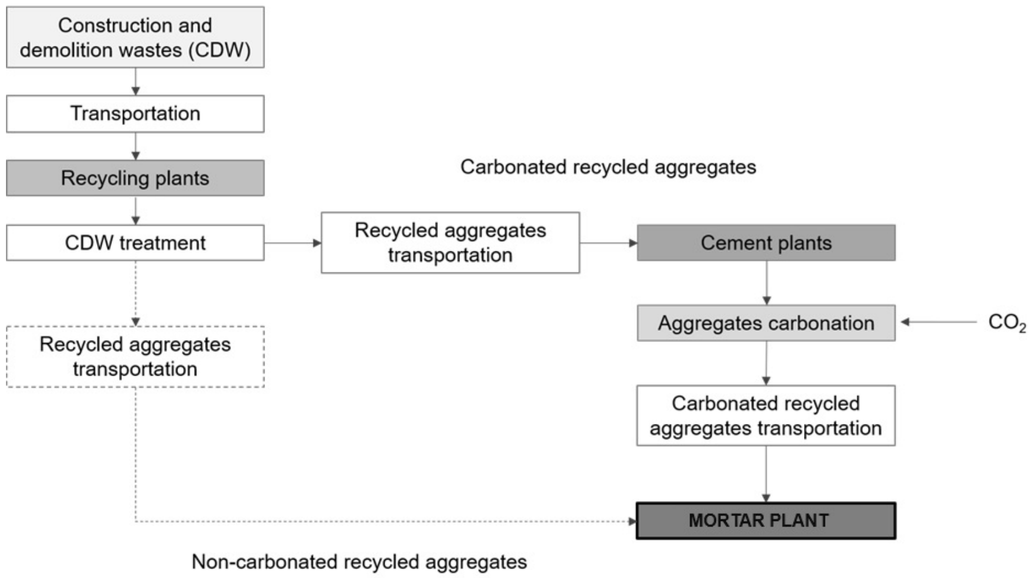

Figure 1. Transport route between the origin of the CDWs and their final destination at the mortar plant.

CDWs originate in specific locals during construction and demolition actions and then are transported to recycling plants. From recycling plants, the recycled aggregates can be sent to the mortar plant where they are used as aggregates (1st scenario) or can be transported to cement plants to be carbonated (2nd scenario). Therefore, carbonated aggregates have additional transport distances. In Table 6, the route of each recycled aggregates is detailed.

Table 6. Raw materials transport distances.

Raw Material	Origin	Recycling Plant	Cement Plant	Mortar Plant	Total Distance Travelled (km)
MRA-RP	Unknown [1]	Vimajas, Pêro Pinheiro		SecilTek	98.1
RCA-IS	Setúbal	SGR, Seixal			49
RCA-RP	Unknown [1]	Vimajas, Pêro Pinheiro			98.1
RCA-IW	Sintra	SGR, Seixal			72
CA-L	Sintra	SGR, Seixal			72
MRA-RP Carbonated	Unknown [1]	Vimajas, Pêro Pinheiro	Secil Outão		163.6
RCA-IS Carbonated	Setúbal	SGR, Seixal			81.5
RCA-RP Carbonated	Unknown [1]	Vimajas, Pêro Pinheiro			163.6
RCA-IW Carbonated	Sintra	SGR, Seixal			104.5
CA-L Carbonated	Sintra	SGR, Seixal			104.5

[1] For the recycled aggregates for which the origin was unknown, a distance of 50 km between the origin and the recycling plant was defined.

The raw materials are transported by lorries with a maximum capability of 27 tonnes. A GWP impact of 4.99×10^{-5} per kg·km travelled (value obtained from the European Life Cycle Database (ELCD) using SimaPro software for an "Articulated lorry transport") was considered. It was considered that the lorry in the return trip (empty lorry) produces less environmental impacts than when it is full [3]. In this sense, in the lorry return trip the environmental impacts were reduced by 30% [4].

The recycled aggregates, when in transportation, benefit from their lower bulk density when compared with natural aggregates. With this material, a lorry can transport a higher volume of material per trip, without exceeding maximal weight, which reduces the fuel consumed and, consequently, the GWP. Concerning transport distances, MRA-RP, RCA-RP and CA-L were the recycled aggregates that had to travel a longer distance from the origin to the mortar factory.

3.3. Production Process (A3)

Mortar production also contributes to the GWP environmental impact. The impact associated with this production process was adapted from site-specific data from a research study by Silvestre [3] in a Portuguese company and is summarized in Table 7.

Table 7. GWP environmental impact of the production process of 1 m^3 of powder mortar [3].

Product Stage		GWP (kg CO_2 eq.)
A3	Powder mortars packaging (A3.1)	2.78×10^{1}
	Mortars manufacturing (A3.2)	2.16×10^{-3}
	Production and disposal of packaging waste (A3.3)	7.57×10^{-5}

In mortar processing, the main difference between recycled versus natural aggregates is their bulk density. Recycled aggregates are lighter than natural aggregates, which causes a reduction in the energy used in mortar processing and packaging.

4. Life Cycle Impact Assessment

The life cycle impact assessment of this research is focused on the global warming potential (GWP) environmental impact of powder mortars. The mortars present a mixing ratio of 1:4 cement–sand by volume. The LCA of the powdered mortars was based on cradle-to-gate analysis, meaning it includes the environmental impacts associated with raw and recycled materials, transport distances and mortar manufacturing process All the rendering of mortars with the incorporation of recycled aggregates from CDW presented a lower GWP than the usual rendering of mortars with natural aggregates (Table 8 and Figure 2). The reduction is between 3.3% and 7.5%. This means that these mortars emit less CO_2 equivalent to the atmosphere, reducing the environmental impact associated with GWP. RCA-RP 50% and MRA-RP 50% presented a reduction in GWP of about 3.3–3.8%. Higher benefits were noticed for the mortars with 100% of incorporation of recycled aggregates. RCA-IS 100%, RCA-IW 100% and CA-L 100% are mortars with a reduction in GWP of more than 6%; respectively, 7.5%, 6.5% and 6.3%.

Table 8. Global warming potential impact (1 m^3 of powder mortar).

Mortars	GWP (kg CO_2 eq.)	GWP Reduction (In Comparison with REF)
REF	1.56×10^{2}	0.00%
MRA-RP_50%	1.50×10^{2}	3.86%
MRA-RP_100%	1.47×10^{2}	5.64%
RCA-IS_50%	1.49×10^{2}	4.80%
RCA-IS_100%	1.44×10^{2}	7.52%
RCA-RP_50%	1.51×10^{2}	3.34%

Table 8. *Cont.*

Mortars	GWP (kg CO_2 eq.)	GWP Reduction (In Comparison with REF)
RCA-RP_100%	1.49×10^2	4.60%
RCA-IW_50%	1.50×10^2	4.26%
RCA-IW_100%	1.46×10^2	6.45%
CA-L_50%	1.50×10^2	4.20%
CA-L_100%	1.46×10^2	6.32%
MRA-RP_50%—5 h	1.50×10^2	4.20%
MRA-RP_100%—5 h	1.46×10^2	6.31%
RCA-IS_50%—12 h	1.46×10^2	6.83%
RCA-IS_100%—12 h	1.38×10^2	11.59%
RCA-RP_50%—12 h	1.49×10^2	4.76%
RCA-RP_100%—12 h	1.45×10^2	7.44%
RCA-IW_50%—12 h	1.30×10^2	16.50%
RCA-IW_100%—12 h	1.08×10^2	30.92%
CA-L_50%—12 h	1.26×10^2	19.41%
CA-L_100%—12 h	9.88×10^1	36.75%

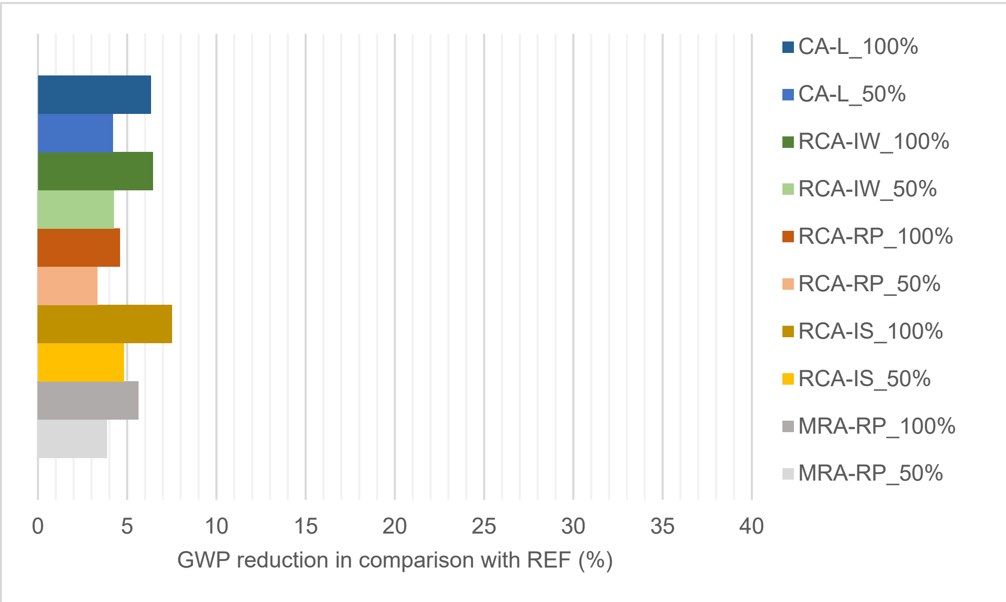

Figure 2. Global warming potential of mortars with non-carbonated recycled aggregates in comparison with REF mortar.

In Figure 3, the same recycled aggregates are presented but submitted to forced and accelerated carbonation. As can be noted, carbonated recycled aggregates improved the mortars' GWP performance, compared with the mortars with non-carbonated recycled aggregates. The improvements vary from 4.2% to 36.8%, depending on the mortar. The benefits are greater with the increase in CO_2 absorption capacity. CA-L and RCA-IW are the recycled aggregates with higher CO_2 absorption capacities, resulting in mortars with 36.8% and 30.9% lower emissions of CO_2 equivalent when compared with a REF mortar, respectively, considering a 100% replacement of the sand.

Comparing the reduction in GWP through the carbonation of recycled aggregates, it is noted that carbonation further reduces the carbon footprint, thereby enhancing the environmental performance of the mortars. Even though the use of non-carbonated RAs also reduces the environmental impacts of the mortars (Figure 2) when compared to mortars with natural aggregates, those with carbonation get a more significant reduction. Mortars with carbonated recycled aggregates can reduce the GWP impact by up to 37%.

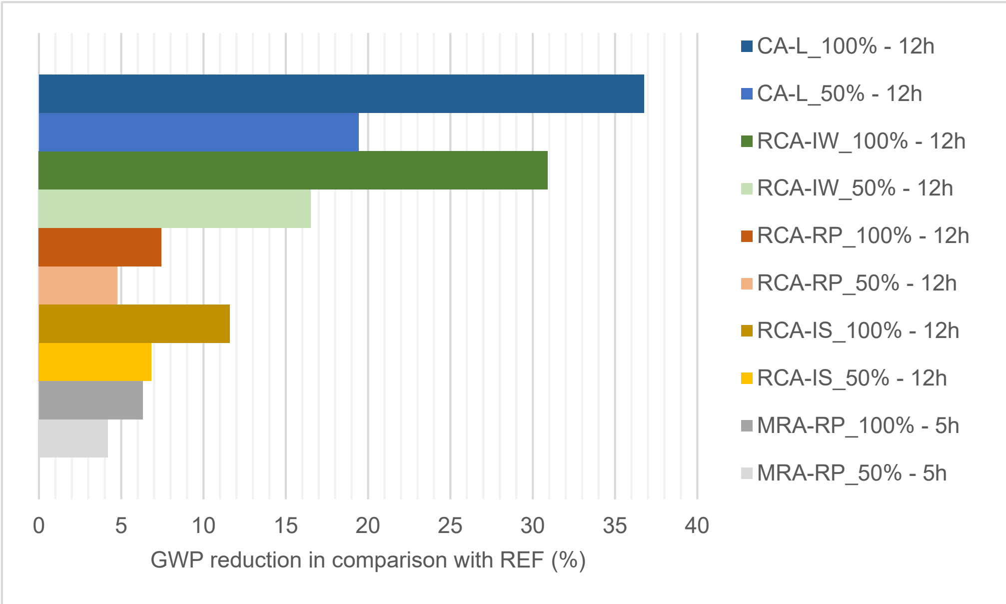

Figure 3. Global warming potential of mortars with carbonated recycled aggregates in comparison with a REF mortar.

Other studies have also investigated the environmental performance of cementitious materials with the use of RAs. The work of Kurda et al. [13] indicated that the GWP of concrete is not significantly influenced by the incorporation of recycled aggregates. The authors tested 50% and 100% of replacement, and the results showed that the use of RAs did not affect this environmental impact, probably due to the transportation scenario. In addition to this, Grabois et al. [12,27] investigated the environmental performance of mortars with RAs. The authors verified that the environmental impacts of using RAs are strongly related to their transport distance. The transportation plays a crucial role in this context and can significantly limit the use of recycled aggregates, especially in countries with extensive territories. Fraj and Idir [27] also found that the transport distance and the amount of RAs incorporated are the main aspects regarding the environmental performance of cementitious products with RAs. The authors stated that the use of RAs can present better results in GWP if the transportation distance is up to 22 km.

Another matter to consider is the cement used; Braga et al. [7] highlighted that the GWP of cementitious materials is more affected by the type of cement used than by the type of aggregates (natural or recycled). Nevertheless, the authors analysed the environmental impacts of concrete with natural and recycled coarse aggregates from cradle-to-gate and the results showed that the use of coarse recycled concrete aggregates reduced the GWP up to 18% when compared to the natural ones.

In this study, it was possible to conclude that the aggregate treatment and the additional transportation distances travelled by these aggregates were more than compensated by carbonation benefits. The mortars' carbon footprints were considerably lower than the products that are currently being commercialized. This research has found that using carbonated recycled aggregates instead of non-carbonated recycled aggregates results in a lower environmental impact. This finding can be seen as a solution to mitigate the environmental impact associated with long transportation distances.

5. Conclusions

Previous works aimed to investigate the CO_2 capture capacity of CDW so that it can advantageously be applied in mortars and concretes as an aggregate. It was concluded that mixed recycled aggregates are able to capture 0.66% of CO_2 per weight of aggregate used. Recycled concrete aggregates, on the other hand, are able to capture between 0.88% and 4.09%. These percentages are interesting considering that mortars and concretes are composed of a higher volume of aggregates than binders. Thus, these percentages shall be incremented if a mortar or a concrete element is considered.

This paper presents a life cycle impact assessment of mortars with carbonated recycled aggregates in comparison with mortars with non-carbonated recycled aggregates and mortars with natural aggregates only. This LCA considers a cradle-to-gate boundary, meaning that it evaluates the environmental impacts associated with the extraction and processing of raw materials, as well as their transport and the product manufacturing process. This LCA was focused on the global warming potential (GWP) environmental impact, meaning that it quantifies the amount of CO_2 equivalent sent to the atmosphere for the m^3 of powder mortars produced.

On the one hand, the recycled aggregates in raw materials eliminate the impacts associated with sand extraction, and on the other, they add necessary treatments, namely through crushing and sieving processes which also produce environmental impacts. Considering transportation impact, recycled aggregates have more transportation routes than natural aggregates, since they have to be sent to recycling plants before being sent to mortar factories. Carbonated aggregates, in addition, must come from their recycling plant to a cement plant where they are submitted to flue gases to carbonate. Only after that, these aggregates are sent to mortar plants to be incorporated as aggregates. In mortar production, recycled aggregates are favourable since they have lower bulk densities which reduce the energy used in the process. In this research, it was concluded that even though the recycled aggregates are submitted to treatment processes and to additional trips, the mortars with them present a considerable reduction in GWP in comparison with mortars without recycled aggregates.

Recycled aggregates, when incorporated in mortars, reduce their CO_2 equivalent in amounts of 3.3% and 7.5%, depending on the type and origin of recycled aggregate and proportion of incorporation designed. With carbonation, the CO_2 emissions are even lower and between 4.2% and 36.8%, by comparison with the corresponding natural sand mortars. These results indicate that the carbonation of recycled aggregates, followed by their incorporation in mortars, significantly reduces the mortars' CO_2 footprint, contributing to the targeted carbon neutrality of the United Nations Sustainable Development Goals.

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