

Recycled Cement for Low-Carbon Stabilized Compressed Earth Blocks

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Abstract. Earth is a vernacular construction material with low environmental impact. Nonetheless, stabilisation is often used to increase the durability of the earthen construction, susceptible to water, abrasion and erosion. The most common stabilisers of modern times, such as hydraulic lime and ordinary Portland cement (OPC), have a significant impact on the carbon footprint of earthen construction. Therefore, alternative solutions for stabilisation must be attempted, such as recycled cement (RC). Indeed, RC allows to avoid CO₂ emissions from clinker production, reduces the consumption of natural resources, and promotes the recycling of concrete and cement wastes. The study presents the savings in carbon emissions to produce compressed earth blocks (CEB) stabilised with RC rather than OPC. For comparison purposes, unstabilised blocks (UCEB) were also included. CEB stabilised with OPC or RC, have better mechanical behaviour and water resistance than UCEB. The modelling considered two scenarios: S₁ with CEB produced at the same cement plant of the stabilisers; S₂ with CEB produced at the construction site with soil retrieved from excavation and stabilisers produced in any Portuguese cement plant. In terms of carbon emissions, the substitution of OPC with RC allowed a reduction of about 2/3 of carbon emissions from CEB manufacture, consistent with the phase-out of clinker calcination. The carbon emissions for UCEB were estimated about 1/2 and 1/5 of the emissions from blocks stabilised with RC, ranging 0.027-0.113 kgCO₂/CEB for different scenarios. The lowest carbon emissions were found for UCEB under S₂, the closest to traditional construction practice.

Keywords: Earth Construction, Stabilisation, Recycled Cement, Carbon Emissions.

1 Introduction

The building sector is responsible for over 35% of the total waste generation and about 50% of all extracted material in the European Union (EU) [1]. The European Environment Agency (EEA) estimates that between 1990-2023 a 37% decrease in the total GHG emissions was achieved in EU. With the mitigation strategies already implemented, by 2030, a 43% reduction is expected, with the possibility of getting to 49% and approach to the 55% reduction target set by the European Commission [2]. A greater material efficiency is expected to save up to 80% of the 5-12% total GHG emissions that the construction (and renovation) sector is responsible for. The use of more eco-efficient construction materials could be part of the solution. Engineering traditional earth constructions, such as rammed earth, adobe or cob [3] can respond to the increasing need of lower environmentally impacting materials. Indeed, earthen construction had traditionally low embodied energy (no heating), proximity to the construction site (no transportation), and the possibility of being a byproduct of other construction works, namely foundations execution. Raw earth also happens to be completely reusable if not stabilised. The stabilisation can technically improve earth-based materials, commonly ensuring higher mechanical performance and water resistance. For this reason, the interest has grown over the last 10 years on researching new stabilisers for earth construction [4,5]. Researchers have tested various types of agro-industrial byproduct (such as fibers of natural and animal origin, biopolymers, fungi and blast furnace slag) as alternatives to the less environmentally friendly Portland cement and hydraulic lime [6-8].

Ordinary Portland Cement (OPC) has high production temperature and carbon content of raw material, released during the burning process, being far from a green building product. To reduce OPC environmental impact (considering not only the raw materials extraction and production stage but also the final disposal) one solution is to produce cement from recycled concrete and cement paste waste, through a low temperature thermoactivation process [9-10]. Recycled cement (RC) showed similar binding capacity than OPC and concrete produced with up to 40% replacement of OPC with RC showed similar mechanical strength and durability than concrete produced with OPC [11, 12]. Higher replacement was found to affect negatively the concrete properties due to the higher water demand of RC [11, 13]. Bogas et al. [14] developed a new technically and environmentally efficient separation method (magnetic separation) to obtain high-purity cement fraction (>75 wt%) from concrete waste. The recycled cement is obtained by a successive thermoactivation at lower temperature (650 °C) than for clinker production (1450 °C) [15]. A potential reduction of up to 80% in CO₂ emissions compared to OPC was found by Sousa et al., [16]. Also, the use of decarbonised raw material and lower temperature for thermoactivation, largely compensate the processing associated with the separation of the cement paste from the aggregates [17, 18].

According to Sánchez-Calvillo et al, [19], compressed earth blocks (CEB) are among the most studied earth-based construction methods, (about 400 research papers published from 1968 to 2023). In 1958, the CINVA-Ram machine (first manual press) was patented turning this building material widely used [20]. Through compression, the

earth is mechanically stabilised but can be also additionally stabilised in chemical way, for instance with OPC.

The effectiveness of using RC for CEB stabilisation has already been presented in previous studies, regarding the physical, mechanical [21], hygroscopic [22], thermal [23] and durability behaviour [24, 25]. It was found that this binder can be an alternative low-carbon substitute for OPC although recycle cement stabilised earth blocks (RC CEB) tend to achieve less density than ordinary Portland cement stabilised earth blocks (OPC CEB), due to the higher optimal moisture content of the RC stabilised formulations. The effect observed was a reduction of mechanical strength and an increase of water absorption properties. However, RC showed the same binding capacity of OPC, leading to similar mechanical strength if produced with the same porosity [21] that could be obtained with additives additions. Nevertheless, RC CEB showed resistance to water erosion, thermal and hygroscopic behaviour comparable to that of OPC CEB. Moreover, unlike unstabilised compressed earth blocks (UCEB), RC CEB maintained the integrity in water and improved the mechanical strength about 2-3 times, being viable for unprotected outdoor applications [24, 25].

To sum up, RC was found a viable option for substituting OPC in CEB stabilisation for durability purposes, but its environmental effect has never been analysed. Accordingly, the present research quantifies the possible saving in terms of carbon emissions of CEB stabilisation with RC over OPC. Two scenarios are presented, considering the possible production of CEB in the same cement plant where PC and RC are produced (S_1) and their production in the same construction site, with soil retrieved from excavation (S_2) in a more traditional scenario. The carbon emissions are also estimated for UCEB, along with stabilised CEB.

2 Materials, Methods and Scenarios

2.1 The Compressed Earth Blocks (CEB)

The compressed earth blocks (CEB) were produced with soil (FA) classified as silty-clayey sand [26] composed by 85.6% of sand (0.075-4.75 mm), 13% of particles below 0.075 mm (silt + clay) and 1.4% of gravel (>4.75 mm) as reported in [24]. To address FA low content of clay, a clayish earth, byproduct of tiles production (TV), was added in formulation, with 49.3% of particles below 0.075 mm in composition [24]. Additionally, 25% (by wt) of soil was replaced with construction and demolition waste (CDW) with particle size distribution similar to FA, <8 mm, and composed by 45% concrete and mortar waste. Ordinary Portland cement (OPC) CEM I 42.5 R and Portland-composite cement (PLC) CEM II B-L 32.5 N were selected as commercial products for stabilisation, produced with 93% and 67% clinker content, 3% gypsum and 4% and 30% of limestone filler, respectively. The recycled cement (RC) was produced from concrete (RCC) and cement paste (RCP) wastes. To have higher control of the procedure, concrete and cement blocks were produced in laboratory for the scope and after 120 curing days, were crushed and grinded to obtain particles between 0.15 and 0.5 mm (corresponding to 34% of the initial mass). Afterwards, the selected particles underwent

air cleaning (dust removal) and magnetic separation, additional grinding and thermal reactivation process (with a maximum temperature of 650 °C) as described in [15,16,18, 27].

In Table 1 the CEB composition is presented along with a synthesis of physical and mechanical properties such as fresh density (ρ_F); hardened bulk density ($\rho_{28,LC}$) and unconfined compressive strength ($f_{c,un,LC}$) under laboratory conditions; the thermal conductivity converted to the equivalent temperature of 10 °C ($\lambda_{10^\circ C}$, dry) in dry conditions; and the volumetric water absorption after 24 hours of immersion ($A_{i,v,24h}$).

Table 1. Synthesis of CEB composition and main properties.

REF	TV (%)	OPC ^{a)} (%)	RC (%)	CDW (%)	H ₂ O _{T₀} _t (%)	ρ_F (kg/m ³)	$\rho_{28d,LC}$ (kg/m ³)	$f_{c,un,LC}$ (MPa)	$\lambda_{10^\circ C,LC}$ (W/(mK))	$A_{i,v,24h}$ (%)
OPC8	11	8	-	25	9	2155	2064	7.9	1.03	20.0
PLC8	11	8*	-	25	9	2157	2071	6.4	0.98	20.5
RCP8	11	-	8	25	12	2097	2008	5.7	0.83	23.2
RCC8	11	-	12	25	12	2114	2018	5.5	0.80	23.3
UCEB	18	-	-	25	9	2188	2001	2.1	0.80	-

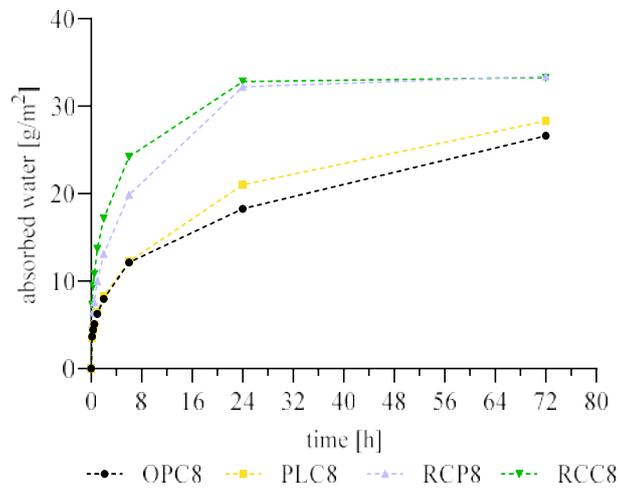
Notation: TV – clay; OPC – ordinary Portland cement; RC – recycled cement from paste (RCP) and concrete (RCC); CDW – construction and demolition waste; ρ_F – fresh density; $\rho_{28d,LC}$ – hardened density at laboratory conditions; $f_{c,un,LC}$ – unconfined compressive strength at laboratory conditions; $\lambda_{10^\circ C,LC}$ - thermal conductivity at the equivalent temperature of 10°C; $A_{i,v,24h}$ – 24 hour volumetric water absorption by immersion. ^{a)} CEM I 42.5R except for * CEM II/B-L 32.5N.

The formulation of RCC CEB was adjusted to the binder content of reference OPC CEB, and due to the higher (33 wt%) aggregate contamination than usually achieved with this method (<25%, Carriço et al., 2021b), it required a higher amount (50% more) of binder. Also, RC CEB needed higher mixing water (12% by weight of solids) and showed lower bulk density in hardened state ($\rho_{28d,LC}$) and, accordingly, lower unconfined compressive strength ($f_{c,un,LC}$) than PC CEB. Nevertheless, the stabilisers PC and RC offer the same binding capacity [21], and their compressive strength was found more affected by the amount of stabiliser rather than the type. Thus, similar $f_{c,un,LC}$ is expected for CEB stabilised with either binder (PC or RC) with the same amount of mixing water and similar dry density. The thermal conductivity in dry conditions ($\lambda_{10^\circ C, dry}$) showed slightly higher conductivity for CEB stabilised with PC over UCEB and RC CEB, consistent with their higher density. Results from volumetric water absorption by immersion showed a higher absorption for CEB stabilised with RC than PC, related with their higher total porosity (26% for PC and 28-30% for RC) [24]. Any tested stabilisation was found effective for increasing the water resistance of CEB, that stayed undamaged after immersion (up to 48 hours).

The capillary water absorption and successive drying **Error! Reference source not found.**(Fig. 1) showed faster absorption for CEB stabilised with RC, probably due to their higher volume of larger pores (>10 μ m). Also, the final water content of RC CEB

was higher after 72 hours (about 33 g/m², against the 26 g/m² and 28 g/m² of OPC and PLC, respectively) indicating a more hydrophilic behaviour. From the shape of the absorption curve, PC CEB were not saturated yet at the end of 72 hours and possibly going to absorb more water, after longer time. The drying behaviour (after complete saturation by immersion) was found similar in the first phase of drying, but OPC CEB were not able to desorb as much water as PLC and RCP in second phase (more driven by water vapour transport and less by liquid water one). This was explained by the lower SSA and lower mean diameter of fine pores (<150 nm, $d_m=14.8$ nm) of OPC8 over all other CEB, due to the lower water binder ratio and connectivity of pores, for denser C-S-H [24].

(a)



(b)

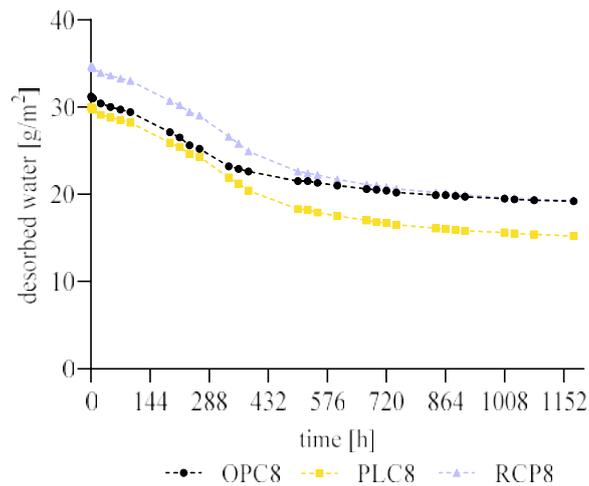


Fig. 1. Capillary water absorption and drying (adapted from [24]).

Summing up, the stabilisation with RC was found to increase the mechanical strength of UCEB and their water resistance. The higher amount of water required by CEB stabilised with RCC and RCP led to higher porosity of these blocks and consequently lower values (by 28-30%) of compressive strength compared to OPC CEB. However, the RC stabilisation increased by 160-170% the compressive strength of UCEB. The RC stabilisation was found as effective as PC for water resistance, with faster water transport. The carbon emissions of stabilised CEB and UCEB were evaluated and compared, considering the enhancement of these properties related to CEB durability aspects. For the above-mentioned reasons, the functional unit selected for the study was 1 CEB.

2.2 Methods and Scenarios

The study considers the production phase in a cradle-to-gate analysis (A_1 - A_3) [28] accounting for carbon emissions of the CEB produced with and without stabilisation. The calculations were all made by mass and later converted to the functional unit of 1 CEB. The simulation model is hybrid, including external information, analogies and direct simulations (Fig. 2a). The differences in the mechanical and hygrothermal behaviour of the final product were also considered when discussing the carbon footprint of the different CEB formulations.

The scenarios considered were two (Fig. 2b), namely:

- 1) S1 – The CEB are produced at any cement plant in Portugal, most of them located within an area covered with a maximum distance of 200 km and the soil is extracted for the purpose of CEB production. The stabilisers (OPC, PLC and RC) are produced in the same cement plant. TV and CDW are retrieved from two different recycling companies located at 100 km of distance from the production site.
- 2) S2 – The extraction, production and construction site are the same, so no additional energy for extraction or transport of the soil is accounted for. TV and CDW are retrieved from two different recycling companies located at 100 km of distance from the production site. The stabilisers (OPC, PLC and RC) are produced at any Portuguese cement plant, 200 km away from the manufacture facility.

The stages (A_1 - A_3) included in the cradle-to-gate analysis are described in the following sub-sections.

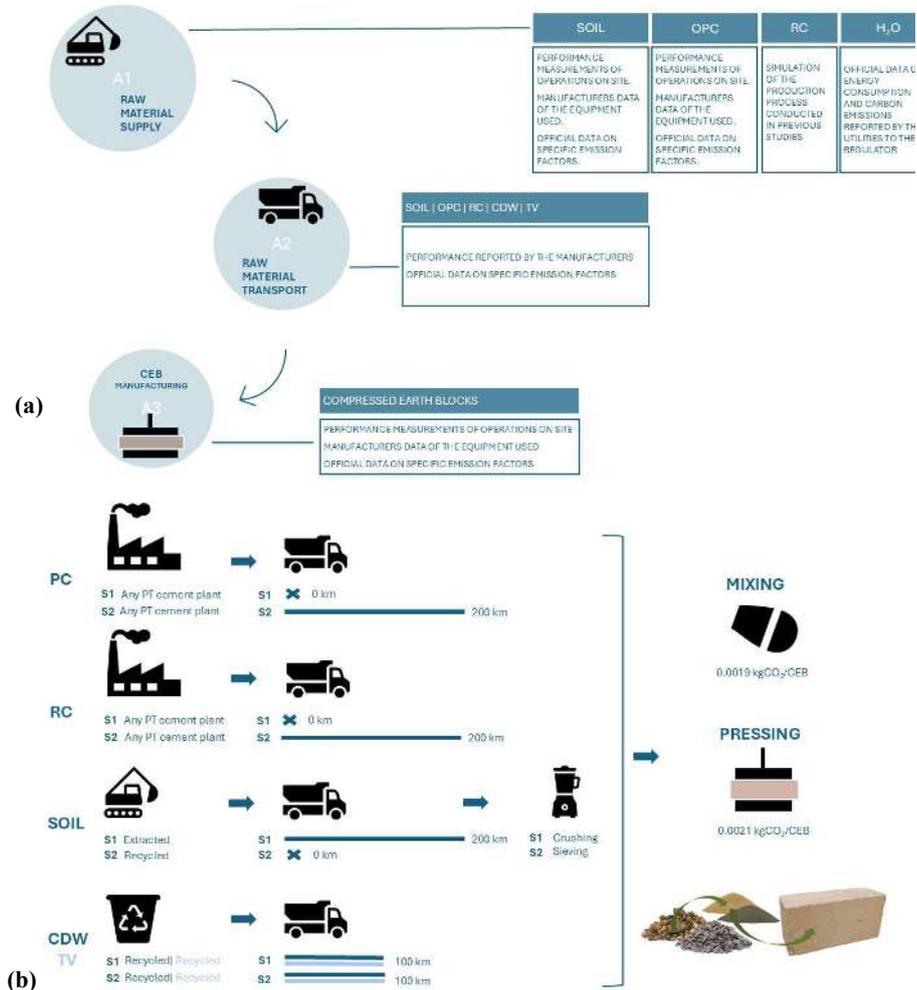


Fig. 2. Methodological approach (b) and modelled scenarios (a).

Stage A₁ – RAW MATERIALS SUPPLY

The soil FA extraction was modelled with a VOLVO EC209C excavator (18.5 l/h fuel consumption, 2.67 kgCO₂/l vehicle emission, 26 t/h productivity). The carbon emissions for soil extraction were estimated 1.89 kgCO₂/t. CDW and TV were assumed to be available at the recycling company without need of extraction or processing. Only transport was considered for these two byproducts.

The carbon emissions to produce OPC and PLC were estimated according to the most recent environmental declarations for clinker production of the five active cement plants in Portugal from Sival and Cimpor companies [29-33]. The weighted average on energy consumptions for clinker production used the conversion factor for Portugal

0.198 kgCO_{2eq}/kWh [34] and resulted in 836.4 kgCO₂/t_{clinker}, consistent with the estimations of the Portuguese Technical Cement Association of 821.6 kgCO₂/t_{clinker} [35]. The clinker content was assumed to be 93% and 67% for OPC and PLC, with 3% gypsum, and 4% and 30% limestone filler content, respectively. The carbon emissions to produce gypsum and limestone filler were calculated in analogy with clinker production considering only approx. 30% of the total electrical energy used [36] and the average value of 12 MJ/t spent with fossil fuels for raw materials extraction [35]. Accordingly, the carbon emissions for gypsum and limestone fillers were estimated 8.9 kgCO_{2eq}/t, consistent with value of 8 kgCO_{2eq}/t reported by Bolte et al. [37].

The method for RC production was published in previous research efforts [15, 16] and includes four main steps with associate energy consumptions: i) crushing and milling; ii) air cleaning for dust removal; iii) magnetic separation; and iv) additional grinding and thermal reactivation. The assumptions made to model the carbon emissions associated to RC production were that: a) the cement and concrete waste are already pre-demolished at the recycling plant, and the additional treatments requires only 1/3 of the energy applied for crushing and milling the raw material for clinker production; b) the thermal reactivation consumes about 1/2 of the energy for clinker production, based on the ratio between 650°C (for recycling) and 1450°C (clinker production); c) the air cleaning is used for dust removal as it was found the most environmentally friendly method [18]; d) the particle size after the magnetic separation is below 250 mm, and after thermal treatment below 85 mm [38, 39]. The model built for the recycled cement from concrete waste was assumed also to produce RCP, in a more conservative assessment. Finally, the transport distance of the concrete and cement waste (for RC production) was fixed at 100 km, and carbon emissions for RC production were found 185.9 kgCO₂/t.

Stage A₂ – RAW MATERIAL TRANSPORT

A VECTO 5-RD (gross vehicle weight rating above 16 tons, a load capacity of about 10 tons and axle configuration of 4x2 [40]) was selected for modelling the transport of all the raw materials. The fuel conversion factor adopted was 2.67 kgCO₂/l for diesel [41,42]. The average consumption of this truck group for the year 2020 was 31.7 l/100km, with associated carbon emissions equal to 83.2 gCO₂/(t·km), according to Mulholland et al. [40].

Stage A₃ – CEB MANUFACTURING

The A₃ stage includes soil FA crushing and sieving, in the facility for CEB production, using two different equipment with electricity consumption of 1.1 and 4.1 kWh, respectively. The amount of 0.1 ton of earth is crushed for 7 minutes and sieved for 4 minutes, with associated carbon emissions of 0.018 kgCO_{2eq}/t and 0.122 kgCO_{2eq}/t. The water supply environmental cost is calculated from data published by ERSAR for the year 2022 [43] and required the selection of a specific municipality for CEB production. The Outão (Secil) cement plant in the region of Setúbal, was selected for S₁ and the Municipality of Alcochete for S₂, with a specific energy consumption for water supply of 0.79 (kWh)/m³ and 0.544 (kWh)/m³, respectively. The 5-years (2018-2022) moving average

of 198 gCO_{2eq}/kWh published by APA, the Portuguese Agency for the Environment [34], was used to convert the water supply energy consumption into 0.156 and 0.108 kgCO_{2eq}/t, respectively. Nevertheless, it is important to notice that data on carbon intensity for electricity production in Portugal, show a significant decreasing trend over the last decades, i.e. from 519 gCO_{2eq}/kWh in 1990 to 119 gCO_{2eq}/kWh in 2023 [44]. Lastly, the CEB production includes the use of mixing and pressing devices. The first consumes 3 kWh to produce 21 CEB, for a calculated efficiency of 315 CEB/h, for a carbon emission of 0.0019 kgCO_{2eq}/t. The Oskam V/F semiautomatic press (5-6 MPa) with an energy consumption of 7.5 kWh was used for compression. According to recorded data, 1 CEB was produced in 5 seconds, for a calculated efficiency of 720 CEB/hour. The semiautomatic hydraulic press accounted for 0.0021 kgCO_{2eq}/CEB.

3 Results and Discussion

Results from Table 2 confirm that UCEB have the lowest carbon emissions with 0.113 (S₁) and 0.027 (S₂) kgCO₂/CEB.

Table 2. Carbon emissions of CEB for scenario 1 and 2.

S ₁ - Carbon Emissions [kgCO ₂ /CEB]					
Designation	OPC8	PLC8	RCP8	RCC8	UCEB
FA	0.086	0.086	0.082	0.079	0.087
TV	0.005	0.005	0.004	0.004	0.008
OPC	0.417	0.302	-	-	-
RC	-	-	0.094	0.136	0.000
CDW	0.012	0.012	0.012	0.011	0.014
H ₂ O _{TOT}	0.00012	0.00012	0.00015	0.00015	0.00013
Mix			0.0019		
Press			0.0021		
<i>Total</i>	<i>0.525</i>	<i>0.410</i>	<i>0.197</i>	<i>0.235</i>	<i>0.113</i>
S ₂ - Carbon Emissions [kgCO ₂ /CEB]					
Designation	OPC8	PLC8	RCP8	RCC8	UCEB
FA	0.001	0.001	0.001	0.001	0.001
TV	0.005	0.005	0.004	0.004	0.008
OPC	0.426	0.311	-	-	-
RC	-	-	0.103	0.148	-
CDW	0.012	0.012	0.012	0.011	0.014
H ₂ O _{TOT}	0.00008	0.00008	0.00010	0.00010	0.00009
Mix			0.0019		
Press					
<i>Total</i>	<i>0.448</i>	<i>0.333</i>	<i>0.124</i>	<i>0.169</i>	<i>0.027</i>

It is followed by RCP stabilisation, with 0.197 and 0.124 kgCO₂/CEB, respectively under Scenario 1 and 2 reducing carbon emissions, up to 63% (S₁) and 72% (S₂) as

displayed in Fig. 3. RCC was found a little less effective than RCP due to the higher content of aggregate contamination and resulting higher binder content. PLC stabilisation was found to be slightly more environmentally friendly than OPC stabilisation, with about 22-26% of avoided emissions.

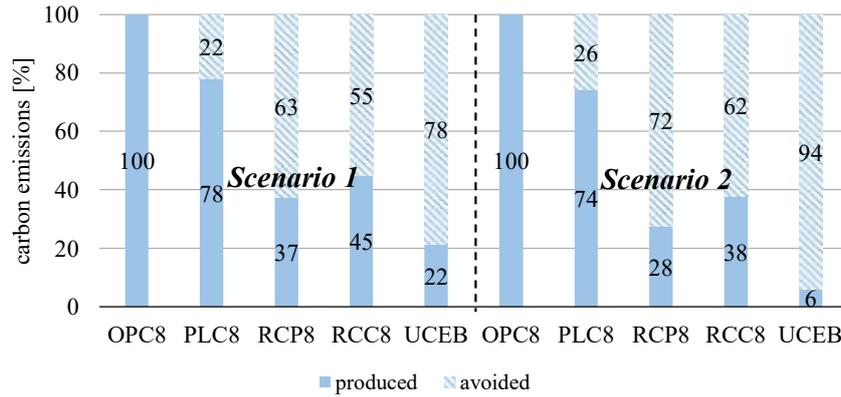


Fig. 3. Carbon emissions avoided (in dash) replacing OPC with alternative stabilisers or without stabilisation.

Moreover, the carbon emissions for RC production could suffer and additional reduction up to 20%, if the high-quality recycled sand (HQRS) produced as a byproduct of the separation process (about 18% of the concrete waste mass) was deducted. Additionally, due to the lower temperature required to thermally activate the hydrated cement waste compared with clinker production, the use of green energy sources for the scope is more feasible, potentially meeting the zero-carbon emissions target. Finally, the raw material of the RC is virtually decarbonated except for the hydrated cement paste. Considering the impact of each production stage (A_1 - raw materials supply, A_2 - transportation, A_3 - manufacturing) showed in Fig. 4, the stabilisation increased the carbon emissions from raw material supply (A_1), accounting for 92-98% of A_1 for scenario S_1 and 100% of A_1 for S_2 . The substitution of OPC and PLC with either RC solutions, introduced a decrease in the impact of stage A_1 on CEB production. The UCEB had the highest impact on carbon emissions from transportation (A_2) covered for the 78% by FA soil in S_1 and only by TV and CDW in S_2 . Although the similar water behaviour introduced by both stabilisations (PC and RC), the mechanical strength of RC CEB was found lower as discussed in section 2.1 due to the higher optimum moisture content of the mixing design. Thus, an additional environmental analysis including differences in mechanical performance was done, calculating the normalised carbon emissions (NCE) for compressive strength (Fig. 5).

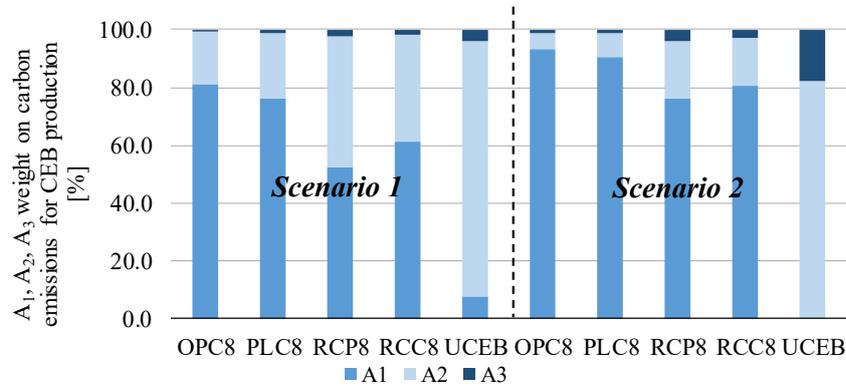


Fig. 4. Impact of each stage (A1 - raw materials supply, A2 - transportation, A3 - manufacturing) on carbon emissions for CEB production under scenario S₁ and S₂.

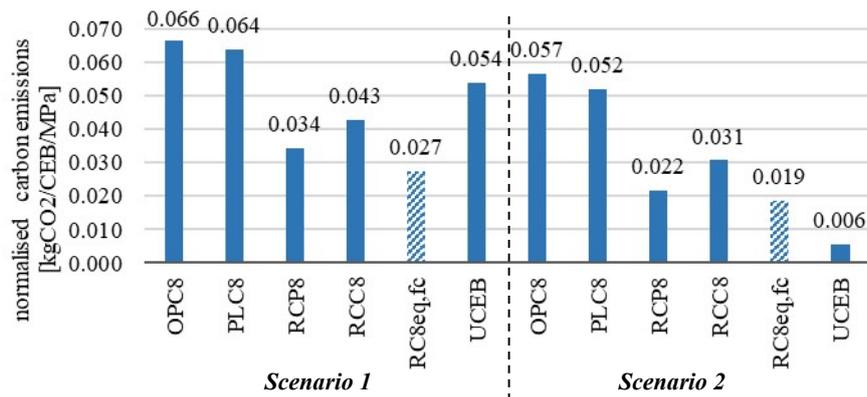


Fig. 5. Carbon emissions of CEB normalised for compressive strength. RC8_{eq.fc} (dashed) shows the potential of RC CEB produced with the same compressive strength of OPC8.

An additional composition, RC8_{eq.fc}, was modelled as the average carbon emissions for RC CEB divided by the unconfined compressive strength of OPC8 for each scenario. It was found that the NCE are about 35-61% lower for RC CEB than for PC CEB, that UCEB represent an effective more environmentally friendly solution for Scenario 2 (that corresponds to the more traditional layout of extracting soil and producing CEB in the same construction site), and that the production of RC CEB with same compressive strength of OPC CEB could further decrease by 13-17% the average NCE reduction introduced by RC stabilisation.

4 Conclusions

The carbon emissions of unstabilised compressed earth blocks (UCEB) or stabilised with ordinary Portland cement (OPC CEB), Portland-composite cement (PLC CEB) or recycled cement from concrete (RCC CEB) and cement paste (RCP CEB), were analysed in the present study. A cradle-to-gate environmental analysis on carbon emissions was carried out, considering the three (A₁-A₃) stages of production, applying a hybrid model built on external information and on direct simulation. Two scenarios were simulated: i) S₁ with CEB produced at any Portuguese cement plant (within the distance of 200 km); ii) S₂ with soil retrieved from foundation excavation, PC and RC manufactured at any Portuguese cement plant and then transported to CEB production at the construction site.

It was found that the production of UCEB under Scenario 2 had the lowest carbon emissions: 0.027 kgCO₂/CEB. The OPC stabilisation increased the carbon emissions of UCEB, up to 464% (S₁) and 1680% (S₂), consistent with the high thermal energy required for clinker production. PLC had a lower effect on carbon emissions, due to the lower amount of clinker in formulation, but still resulted into a significant increase (362% for S₁ and 1248% for S₂) of carbon emissions compared to UCEB. The use of RC instead of OPC allowed to reduce the carbon emissions for stabilisation up to 55-70%.

The carbon emissions were normalised for compressive strength considering that a different mechanical performance between compositions led to different durability and applicability. Normalised carbon emissions (NCE) were calculated as the ratio of carbon emissions per mechanical strength. Due to their lower compaction and consequent lower mechanical strength, the NCE of RC CEB were only 35-61% lower than for PC CEB. Nevertheless, RC CEB produced with similar porosity (and mechanical performance) of PC CEB, would lead to the lowest NCE (except for UCEB in S₂) as simulated by RC_{8eq.fc.}. The production of RC CEB with the same compressive strength of OPC CEB could further decrease by 13-17% the average NCE reduction introduced by RC stabilisation, reaching the 0.027 - 0.019 kgCO₂/CEB/MPa. Further studies will analyse the possibility of improving the performance of RC CEB, attempting for RC with higher separation efficiency (<25% aggregate contamination) and lower water demand, and the effect that RC stabilisation would have on long-term mechanical and hygrothermal performance, under real climate conditions.

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