RECYCLED CEMENT AS AN ALTERNATIVE TO ENHANCE THE ENVIRONMENTAL PERFORMANCE OF STABILIZED COMPRESSED EARTH BLOCKS

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ABSTRACT

The technical feasibility of recycled cement (RC) stabilized compressed earth blocks (CEB) has been demonstrated in terms of mechanical performance and durability, but its environmental implications have yet to be evaluated. This study addresses this gap by assessing their energy consumption and greenhouse gas (GHG) emissions, and benchmarking against CEB using CEMI and CEMII Portland cement (PC) has stabilizer. The results demonstrate that, despite the slight increase of the absolute energy demand (2%) in the most conservative scenario, stabilization with RC enables a reduction of approximately 50 % in GHG emissions compared to PC-stabilized CEB, even after normalizing by the compressive strength of the CEB. These findings demonstrate the potential of RC as a more eco-efficient alternative to PC in earth stabilization. Comparison with unstabilized CEB is also presented for reference in indoor applications, considering their limited durability in water exposed conditions.

Keywords

compressed earth blocks, chemical stabilization, recycled cement, energy consumption, greenhouse gases emissions

1 INTRODUCTION

Earth construction is one of the oldest building construction techniques used by humans, primarily due to the availability of material, the low technological requirements, and the flexibility and ease of application (Heathcote 1995; Doat et al. 1979; Burroughs 2001). The use of earth as a construction material is widespread across dry and temperate regions worldwide, with a predominance in the Southern Hemisphere. Additionally, earth buildings display a wide variety of cultural, regional, and temporal variations, making them an important part of humanity's heritage that needs to be preserved and rehabilitated (Balderrama 2001; Maini 2005).

Although earth construction is an ancient technique, it is still widely used today in underdeveloped or developing countries with dry or temperate climates, particularly in various parts of Africa, Asia, and Central and South America (Balderrama 2001; Minke 2006; Pacheco-Torgal and Jalali 2012). In developed countries, particularly in dry zones (desert climates) of Australia and the United States, there has been a resurgence of earth construction over the recent decades. In these and other regions of the globe, the advantages of earth construction, especially thermal inertia, can be fully utilized, while its drawbacks, particularly moisture-related behaviour, are naturally minimized. According to CSIRO (1987), in regions of Australia where conventional construction materials are scarce or transport costs are high, earth construction remains a viable and practiced alternative. In Europe, CRATerre and other partners have been promoting the revival of earthen architecture since the 1980s through the development of efficient technologies and criteria, rules, and specifications for design and construction. The relevance of earth construction nowadays is reflected in the more than 70 official dedicated standards/regulations published worldwide (Reddy et al. 2022).

Environmental concerns are also a significant driver of the revival of earth construction (Arrigoni et al. 2017; Christoforou et al. 2016; Melià et al. 2014; Reddy and Kumar 2010; Reddy and Jagadish 2003; Serrano et al. 2013; Shukla et al. 2009), along with socio-economic benefits (Morel et al. 2001; Ramesh 2012). However, in particular in the more developed countries, traditional earth construction methods (e.g., cob, adobe) are generally considered obsolete and rammed earth or compressed earth blocks (CEB) are more often used. Originally, CEB represent an evolution of traditional adobe blocks by resorting to mechanical stabilization (using a press) to increase strength and durability (Mansour et al. 2016). However, chemical stabilization is also required to reduce the water susceptibility of CEB (also referred to in the literature as stabilized compressed earth blocks). Various chemical stabilizers have been tested (Losini et al. 2021), but lime (Danso et al. 2015; Arrigoni et al. 2017) and Portland cement (PC) (Alam et al. 2015; Burroughs 2010; Zak et al. 2016) are the most common. Lime has already been used for stabilizing earthen constructions for centuries (Parracha et al. 2020), while the use of PC is more recent, providing a higher mechanical strength and water resistance.

Fernandes et al. (2019) found that most environmental impacts of CEB result from the addition of the chemical stabilizer. Considering that these authors used lime, these conclusions are even more pronounced when PC is used due to its higher environmental burden. Literature recommendations suggest 4–12% PC content for stabilizing CEB (Adam and Agib 2001; Rigassi 1985; Walker 1995; Egenti and Khatib 2016), hindering their environmental benefits. Nevertheless, the energy consumption of CEB stabilized with PC is about 50% of that of ceramic masonry blocks (Walker 2002), positioning it as a sustainable alternative.

So, in terms of environmental performance, the stabilizer is the bottleneck in CEB production. Therefore, more sustainable alternative chemical stabilizers are the cornerstone to enhance the environmental benefits of earth construction. In this context, recycled cement (RC) has been successfully explored for CEB stabilization, showing significant mechanical improvements over unstabilized CEB (Bogas et al. 2023) and comparable hygrothermal (Real et al. 2024a,b) and durability (Cruz et al. 2024) performance to PC-stabilized CEB. However, although the technical viability of RC-stabilized CEB has been demonstrated, its economic and environmental performance remains to be assessed. The objective of this study is to analyse the environmental performance of RC-stabilized CEB regarding energy consumption and greenhouse gas (GHG) emissions and to compare them with those of unstabilized and PC-stabilized CEB.

2 MATERIAL AND METHODS

2.1 PRESENTATION

The CEB were produced in an existing factory in Montemor-o-Novo, involving the following stages: i) materials preparation; ii) material mixing; iii) CEB molding and compression; and iv) CEB curing. The materials used were: i) earth; ii) chemical stabilizer; and iii) tap water. The earth composition was amended with clay powder waste (CPW) from a tile plant due to its poor suitability for CEB production. Additionally, construction and demolition waste (CDW) was used as partial earth replacement to further enhance CEB sustainability. RC and PC, namely CEM I 42.5R (OPC) and Cement CEM II/B-L 32.5N (LPC), were used as chemical stabilizers. The RC was produced at IST from concrete waste using a novel patented magnetic separation-based method. The components were dosed and mixed in a mechanical mixer and a hydraulic press was used to produce 295x140x90 mm blocks. Finally, the CEB were cured outdoors in a sheltered area protected from rain and direct sunlight.

The composition of the different types of CEB produced are detailed in Table 1, along with some of their main mechanical (unconfined compressive strength in laboratory conditions - $f_{c,un,LC}$) and physical (fresh - and dry bulk density) properties. RC CEB were produced with a higher stabiliser content (12%) than PC CEB (8%) to compensate for the aggregate contamination in RC. RC CEB also required more water (12%) than PC CEB (9%) due to its higher surface area and porous morphology (Carriço et al. 2020). Mixes combining both stabilizers were also produced (PC/RC – 80%/20% and 50%/50%), along with unstabilised blocks (UCEB). The latter are unsuitable for unprotected outdoor applications and were included for reference purposes with other studies. Earth was partially replaced by 25% CDW in all mixes, except for UCEB_CDW0 that aims at representing the traditional CEB.

Table 1 – CEB mix composition and main physical and mechanical properties

Designation	Soil (kg/m³)	CPW (kg/m³)	PC (kg/m³)	RCC (kg/m³)	CDW (kg/m³)	$Water_{Tot}$ (kg/m³)	ρ_f (kg/m³)	$\rho_{28,LC}$ (kg/m³)	$f_{c,un,LC}$ (MPa)
OPC	1244	153	144	-	400	211	2155	2064	7.9
LPC	1244	153	144	-	400	211	2157	2071	6.4
RC	1139	138	-	197	367	256	2114	2018	5.5
OPC80_RC20	1235	151	114	43	398	211	2122	2039	7.2
OPC50_RC50	1222	149	71	105	394	211	2118	2047	6.4
UCEB	1253	272	-	-	438	216	2188	2001	2.1
UCEB_CDW0	1623	351	-	-	-	205	2195	2075	1.8

The experimental work reported herein was developed in other research efforts, namely in Cruz and Bogas (2024), Cruz et al. (2024), Real et al. (2024a,b), and Bogas et al. (2023), among others, that demonstrate the technical viability of RC CEB as an alternative to PC CEB for the same applications.

2.2 DATA AND METHODOLOGY

A cradle-to-gate analysis is performed in this study, encompassing stages A1 (Raw material extraction and processing), A2 (Transportation to manufacturer) and A3 (Production), as defined on EN 15804+A2 and ISO 21930.

As referred, the CEB were produced at an existing traditional plant located in Montemor-o-Novo, Portugal. Accordingly, the environmental assessment was conducted by simulating the process using production data collected on site. Complementary sources, particularly data from CEB equipment manufacturers, were also used to contextualize and validate the observations, as production at the plant was not fully optimized.

Regarding the raw materials, the environmental assessment resorted to a multitude of sources available. Concerning clinker, official data from the cement plants operating the mainland Portugal was used has the primary sources. The environmental declaration of the Portuguese grey cement was used as a complement for the information missing on the official cement plants data and to convert from the clinker to OPC and LPC. RC data was obtained from a companion study (Romão 2025), that improves the accuracy of the estimates obtained in past efforts (e.g., Sousa and Bogas 2021; Sousa et al. 2023a,b; Real et al. 2022; Ranesi et al 2025). The official data reported by the local water utility to the Portuguese water, wastewater and waste regulator was used to determine the environmental impact of the water. Finally, since the additives are production wastes, only the transportation was accounted for by simulation.

The assessment focuses exclusively on energy consumption and GHG emissions associated with CEB production. In most of the cases, the approach adopted consists in estimating the former and determining the latter based on the emission factors of the type of energy used, namely electricity and fuel (diesel).

2.2.1 Energy consumption

Production

At the CEB plant, the 3 kWh mechanical mixer is capable of producing material for 21 CEB in 4 min. Assuming continuous operation, this corresponds to a productivity of 315 CEB/h and an electricity consumption of 9.5 Wh/CEB. The CEB were produced with a 7.5 kW Oskam V/F semiautomatic press (5–6 MPa). Based on effective production data, the equipment can produce 1 CEB in 10 s, which corresponds to a productivity of 360 CEB/hour an and energy consumption of 20.8 Wh/CEB. Overall, the production of a CEB at the Montemor-o-Novo plant requires 30.4 Wh, which corresponds to a specific energy consumption of 8.31 kWh/m^3 or 4.11 kWh/t, considering the dry weight of the CEB. This value is consistent with the 1 l/diesel required to produce 145 CEB reported by OSKAM (N.D.) for a solar power CEB plant in Denmark, which corresponds to 72.4 Wh/CEB, 19.8 kWh/m^3 or 9.7 kWh/t, including the soil preparation.

Lontto (https://www.block-machine.net/) and Oskam V/F (https://oskam-vf.com) CEB equipment manufacturers indicate production capabilities of 240 to 360 CEB per hour for mobile sets (mixer and press). Based on the specifications and assuming continuous production, the resulting total energy consumption ranges between 46.1 Wh/CEB and 63.8 Wh/CEB. Stationary automatic integrated machines performing all CEB production stages (mixing and compression) from the same manufacturers have production rates starting at 1000 CEB/h. The energy consumption is relatively constant, around 55 kWh, since the productivity change is a function of the number of blocks produced simultaneously with very slight power increase. For these machines the specific energy consumption is estimated to be 42.5 Wh/CEB. Considering that the CEB produced have a volume of 3654x10^{-6}-5800 x10^{-6} m^3 and weighs roughly 7.9-12.5 kg after dry, the specific energy consumption is 8.0-11.6 kWh/m^3 or 3.7-5.4 kWh/t.

Despite the differences between observed and estimated values, the energy consumption for producing CEB from the various sources ranges from 3.7 to 9.7 kWh/t. Consequently, the environmental burden of CEB arise mainly from the materials used in their production, namely: i) soil; ii) stabilizers; and iii) water and additives. Regarding the stabilizers, RC and PC were considered, and the additives include CWD and CPW.

Soil

When only local soils from excavation operations associated with other activities (e.g., excavation for foundations) are used, the corresponding environmental burden can be neglected. In this scenario, the fuel consumption for extracting and handling the soil is allocated to the earthworks and using it as a construction material may even reduce the need to find an adequate deposition site. In a CEB plant, however, the fuel consumption associated with obtaining the soil needs to be accounted for. Various aspects affect the environmental performance of earthworks, including (Roy et al. 2024): i) equipment factors (e.g., engine, controls, fuel); ii) operational factors (e.g., operator skill, equipment maintenance, scheduling, fleet configuration); iii) site factors (e.g., depth of excavation, soil type, site grade, weather conditions). Devi et al. (2017) report an average diesel consumption for excavation ranging from 0.28 l/m^3, for loose soil, to 6.48 l/m^3, for hard rock. Trani et al. (2016) reported values between 0.189-0.194 l/m^3 for excavating silty sand in a real construction site, while Li et al. (2010) report 0.883 l/m^3 for excavation and transportation to landfill. Considering a specific equipment, namely the CAT 330 excavator, the fuel consumption may be as low as 0.050 l/m^3 in optimal conditions (CAT 2018). In real conditions, a CAT 336 recorded a consumption of 20.94 l/h with 25.6% idling time over 656 hours of operation (CAT 2021). Assuming an average cycle time of 20s based on CAT (2022), this corresponds to a fuel consumption of 0.083 l/m^3.

In addition to the excavation and handling, earth undergoes mechanical pulverizing and sieving. At the CEB plants, the electrical energy consumption of these operations is estimated at 4.03 kWh/t. These values fall within the range reported by equipment manufacturers, with Lontto (https://www.block-machine.net/) and Oskam V/F (https://oskam-vf.com) citing 0.7–1.8 kWh/t for stationary installations and 12 kWh/t for mobile installations.

Portland cement

The environmental performance of OPC and PLC was estimated from the environmental reports of the two Portuguese cement producers (Secil and Cimpor). The official environmental declarations for each production unit located in mainland Portugal were retrieved, except for the Cibra-Pataias plant (Secil), which has produced only white cement in recent years. The latest data is from 2020 for Souselas plant (Cimpor) and 2023 for the remaining 4 plants. The data for each plant is presented in Table 2, along with the corresponding weighted average (Av) based on the amount of clinker produced in each plant.

Table 2 – Specific energy consumption and emissions for producing clinker at grey cement plants in mainland Portugal (SECIL 2023,a,b; CIMPOR 2020, 2023a,b)

Cement Plant	Units	Secil			Cimpor				PT Av
		A	B	Av	C	D	E	Av	
Energy Consumption									
Thermal Energy	MJ/t	3790.0	3892.4	3825.7	3621.3	3778.4	3528.6	3600.7	3689.7
Electrical Energy	KWh/t	145.4	169.9	153.9	139.2	153.0	123.0	134.0	141.9
Process Emissions									
Combustion + Calcination	kgCO2/t	799.5	786.4	794.9	817	810	819	817	808.3

The values are consistent with the environmental product declaration for Portuguese grey cement developed for the Portuguese Technical Cement Association (DAPHabitat 2023), which estimates a thermal energy consumption of 3722.7 MJ/t clinker. The total electricity consumption (147.5 KWh/t cement) is split between the clinker (60%) and cement (40%) phases. Assuming that the electrical energy consumption in the cement stage is associated exclusively with clinker grinding, this corresponds to a specific consumption of 189.3 MJ/t clinker. According to DAPHabitat (2023), the equipment used for extracting natural raw materials from quarries within the cement plant consumes an additional 12.0 MJ of fuel per ton of raw material. Assuming the same specific energy consumption for extraction from external quarries and neglecting the energy required for transportation since no information is provided regarding the transportation distance, clinker production requires 20.1 MJ of engine fuel per ton of clinker. In Portugal, heavy duty vehicles are, invariably, diesel powered.

The process emissions amount to 821.6 kg CO_2/t clinker, with 296.5 kg CO_2/t clinker resulting from fuel combustion and 525.1 kg CO_2/t clinker originating from the raw material calcination (DAPHabitat 2023). This implies that the carbon intensity of the fuel mix used in the kiln is 0.0797 kg CO_2/MJ, which is consistent with the 0.08 kg/MJ reported by GCCA (2020) for Europe.

The most relevant GHG emitted during clinker production is CO_2, but nitrogen oxides are also emitted. The official environmental declarations of the cement plants in Portugal reveal that nitrogen oxides emissions are less than 1 kg NO_x/t clinker. However, according to Mosca et al. (2014), only up to 2% of the nitrogen oxides emitted during clinker production reduce to nitrous oxide. Considering that the global warming potential of nitrous oxide is 273 times higher than that of CO_2, the actual greenhouse gas emissions from clinker production are approximately 5 kg CO_2eq/t higher than estimates based solely on CO_2 emissions.

The energy consumption for gypsum and limestone filler was considered the same for the extraction and preparation of the raw material for cement production. As indicated previously, in Portuguese cement plants, an average of 12 MJ per ton of raw material is consumed as fossil fuel by the vehicles and equipment used for extracting natural raw materials from the internal quarry (DAPHabitat 2023). According to the literature, the electricity consumption for the raw material processing corresponds to roughly 30% of the total needed for cement production (Madlool et al. 2011; Afkhami et al 2015; ECRA 2017), resulting in an average consumption of 24.9 kWh/t adopting a 1.7 raw material/clinker ratio based on the cement plants data.

Recycled cement

The energy consumption for the RC was estimated considering a novel technology developed under the scope of the EcoHydb project (Carriço et al 2021). This patented technology (Bogas et al. 2021) resorts to magnetic separation to extract the cement paste from actual concrete waste, entailing a prior stage of crushing and milling the cement waste to separate the cement paste from the aggregates and a subsequent stage of thermoactivation of the cement paste. In the separation stage, the cement waste is split into 4 fractions based on the particle sizes, and only the particles between 0.15 and 0.5 mm undergo the magnetic separation. The technology also enables the obtention of fine recycled concrete aggregates (HQRA – Hight Quality Recycled Aggregates) with less than 5 wt% of hydrated cement paste, recycled concrete waste filler (NRF – Normal Recycled Filler) and fine recycled concrete aggregates (NRA – Normal Recycled Aggregates).

Past studies on the topic addressed this issue (Sousa and Bogas 2021; Sousa et al. 2023a,b), but the results presented herein entail two fundamental differences. The first was resorting to the theoretical enthalpies of the cement paste dehydration reactions and the lime production process as an analogy as the references to estimate the energy consumption. This was motivated by two major issues associated with making the analogy with clinker production, namely: i) the temperature required for the sintering reactions (1450ºC) in clinker production is much higher than the temperature required for the thermoactivation of RC (650ºC); and ii) some of the chemical reactions during clinker production are exothermic, while the dehydration taking place during the RC thermoactivation is endothermic. These differences affect the efficiency of the production process (e.g., energy losses) and the energy balance of the reactions (theoretical energy required), respectively. If the former leads to a conservative estimate when assuming identical production efficiency, the latter does not. The second is that attributing all energy consumption to RC is highly penalizing when other technically and commercially viable products are obtained in the production process (HQRA, NRF and NRA). In particular, the HQRA are similar to natural crushed fine aggregates, making them a suitable alternative to boost the use of recycled aggregates with the downsides attributed to the presence of cement paste in normal recycled aggregates (e.g., see Nedeljovic et al. 2021 for a review).

Concerning the allocation of the energy on the various products obtained in the RC production, the following scenarios were considered: i) S1 – all impact are allocated to the RC; ii) S2 – the impacts are distributed over the RC and HQRA depending on the amount produced and the stages involved in their production; and iii) S3 – the impacts are distributed by all products depending on the amounts produced and stages involved in their production. RC is the only product that requires the reactivation stage, HQRA requires both the release and separation stages, while NRA and NRF require only the release stage. The base RC production process is only focused in obtained the cement paste (ALT1), but there is an optional alternative that increases the amount of HQRA produced by passing the coarser fraction (0.5-1.0 mm) obtained in the separation stage through the magnetic separator to extract clean aggregate particles from aggregate particles with adhered cement paste (ALT2). Table 3 resumes the energy consumption estimates for RC for the various scenarios and alternatives considered.

Table 3 – Total energy consumption per unit of RC produced (Romão 2025)

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
Thermal					
Reactivation	MJ/t	1422.8			
Electricity					
Release	kWh/t	25.0	6.2	3.3	1.6
Separation	kWh/t	28.9	7.2	7.2	7.2
Reactivation	kWh/t	8.9	8.9	8.9	8.9
Fuel					
Release	MJ/t	1098.3	274.0	147.1	70.2
Transportation	MJ/t	158.2			

Water and additives

In Portugal, the public water supply has a mixed model and, in many regions, there is a separation between bulk and retail water suppliers. Bulk water suppliers are responsible for water abstraction, treatment, and conveyance to retail water suppliers, which in turn handle the distribution to the final consumers. At the CEB plant, water is supplied by the Municipality of Montemor-o-Novo, which obtains its bulk water from the company Águas Públicas do Alentejo. The two companies have a declared specific energy consumption of 0.346 kWh/m^3 and 0.801 kWh/m^3, respectively, resulting in a total of 1.147 kWh/m^3. The corresponding emissions are 52.3 gCO_2eq/m^3 and 121.0 gCO_2eq/m^3, respectively, totalling 173.3 gCO_2eq/m^3 (ERSAR 2024).

Regarding the additives considered (CPW and CDW), only the transportation was accounted for because they are wastes and it is assumed that no additional processing is required. A distance of 100 km between the source of additives and the CEB plant was assumed, which corresponds to a 200 km journey (both ways).

Transportation

The transportation of the stabilizers to the CEB plant was also accounted for. Five of the cement plants located in mainland Portugal are located along a stretch of approximately 200 km on the western coast between Setúbal and Souselas. The sixth is in the south (Algarve), roughly 250 km from the closest one, which is located in Setúbal. Without accounting for possible suppliers in Spain, the maximum distance between the closest cement plants and any point in mainland Portugal would be around 250 km (from Souselas to the northeast corner of Portugal). However, considering that CEBs are more adequate for the dry and hot climate in the southern part of Portugal, the Outão (Secil) and Loulé (Cimpor) plants are the closest, and the maximum distance in a straight line to any location in this region of Portugal is, at most, 200 km. It was assumed that RC would also be produced in the south, so, a journey of 400 km (one way full and return empty) was assumed for all stabilizers (RC, OPC and LPC).

2.2.2 Greenhouse gases emissions

The energy consumptions were converted into GHG emissions, in particular CO_2 when other GHG emissions were unavailable, using the emission factors of the corresponding source of energy. Exceptions apply for the thermal energy used in PC production, which include emissions from both energy consumption and raw materials reactions, and water, since water utilities have variable renewable energy production in their facilities. For these, the emissions reported in the official documents used to extract the energy consumption data were already reported in the previous section.

Between 2005 and 2023, the electricity GHG emission factor in mainland Portugal declined from 0.526 to 0.092 kg CO_2eq/kWh, averaging 0.156 kg CO_2eq/kWh between 2019 and 2023 (APA 2025). It should be noticed that the values change slightly depending on the source, with the EEA (2025) reporting a value of 0.115 kgC0_2eq/kWh for Portugal in 2023. In addition to the decreasing time trend, electricity emission factor is also highly seasonal in Portugal. According to the Electricity Maps (2025) reports, between January 2024 and December 2024, the minimum and maximum carbon intensities of electricity in Portugal were 0.011 kgCO_2eq/kWh (25/02/2024) and 0.181 kgCO_2eq/kWh (13/12/2024), respectively. Figure 1 displays the electricity origins for Portugal in 2025 and 2024, based on data from the national electrical grid operator data hub (REN 2025).

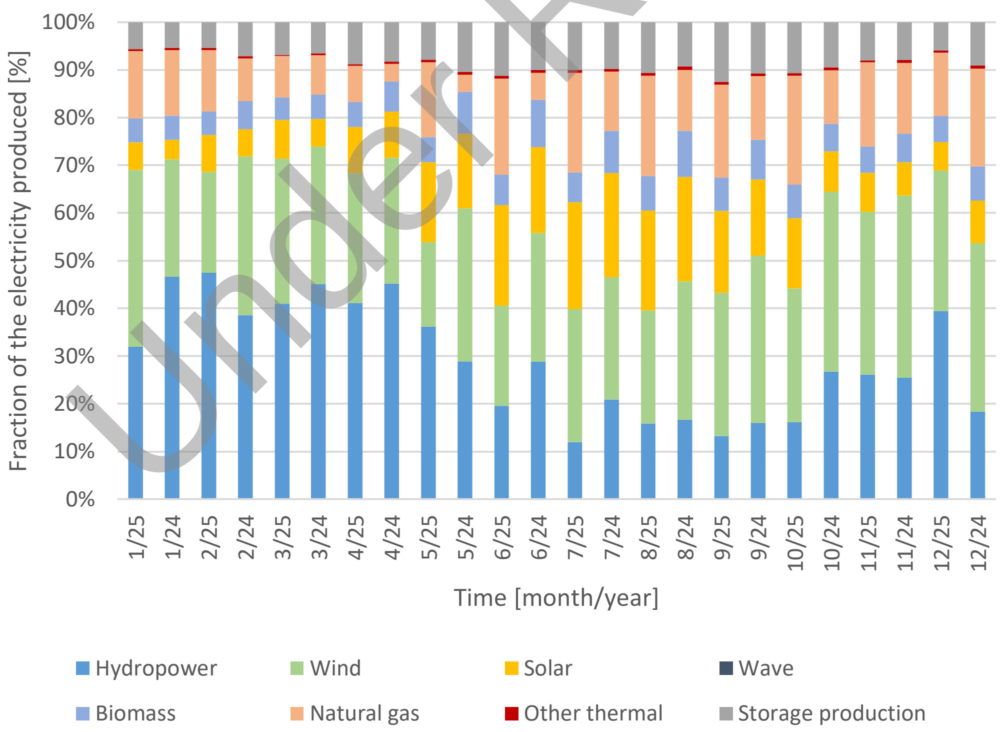

Figure 1 – Monthly electricity origins for Portugal in 2024 (REN 2025)

Considering that most of the storage production is from pumping at hydropower stations using excess of wind energy, over the last 2 years, more than 70% of the electricity has been consistently from renewable energy sources. The highest fraction of green energy production has been between February and April and the lowest tends to be concentrated in the summer months and December.

This implies that the concentration of the production of CEB out of the summer months would benefit their environmental performance.

The fuel used was considered to be diesel, since it is the most commonly used in commercial vehicles and machinery in Portugal. The energy content of diesel engine fuel varies slightly depending on the reference, from 38.3 MJ/l, reported by the Bureau of Transportation Statistics (2025), to 39.3 MJ/l, reported by the Department for Energy Security and Net Zero (2025). Schmied and Knörr (2012) stipulates a value of 35.9 MJ/l based on the ISO 16258 approach. Herein, an average value of 37.6 MJ/l was adopted. Schmied and Knörr (2012) indicate a GHG emission factor of 2.67 kg CO_2eq/L for diesel, consistent with ISO 16258, whereas a retail fuel supplier in Portugal reports a lower value of 2.30 kg CO_2eq/L (BP 2024). The difference is due to the incorporation of biodiesel in the latter, since 7% biodiesel decreases the GHG emissions factor to 2.48 kgCO2eq/l, which also affects the energy content, since biodiesel has a lower specific energy (32.8 MJ/l). The diesel energy and emissions intensity used herein only accounts for the direct use in the combustion engine. According to Schmied and Knörr (2012), accounting for the energy consumed during the fuel production cycle increases the energy intensity to 51.3 MJ/L and the greenhouse gas emission intensity to 3.24 kg CO_2eq/L.

Fuel consumption and GHG emissions for transportation were estimated using the data from Mulholland et al. (2023). The vehicle considered for transportation was a VECTO 5-RD, with axle configuration of 4x2, a gross vehicle weight rating above 16 t and a load capacity of about 10 t. The truck is assumed to run about 90% under regional delivery, resulting in average consumption of 31.7 l/100 km and GHG emissions of 853.7 gCO_2eq/km. The same truck category, but operating on long haul regime (only 10% in regional delivery), decreases the fuel consumption to 28.3 l/100 km and the GHG emissions to 773.5 gCO_2eq/km. These values are consistent with the range from 23 l/100 km (empty) to 36 l/100 km (loaded) and an average of 33.1 l/100 km reported in ICCT (2018). The reference truck used in ICCT (2018) was developed in ICCT (2017) and represents a 40-tonne truck with a load capacity of 25.6 t. So, despite the similar fuel consumption on a distance base only, the fuel consumption per unit weight and distance is distinct. The specific fuel consumption of the VECTO 5RD is 0.0317 l/t.km, while the reference truck of ICCT (2017) is 0.01715 l/t.km. These values are slightly lower than reported by Schmied and Knörr (2012) for the corresponding load category. Schmied and Knörr T (2012) applied the EN 16258 methodology. However, this standard has recently been replaced by ISO 14083. Additionally, other frameworks for estimating GHG emissions in transportation exist, which can influence the results obtained (Wild 2021).

3 RESULTS AND DISCUSSION

3.1 ENERGY CONSUMPTION

CEB production requires very little energy, estimated at 30.4 Wh/CEB or 4.11 kWh/t (considering that a dry CEB weights roughly 7.5 kg), so the majority of the energy is associated with extracting/producing and transporting its components, namely the: i) soil and additives; ii) water; and iii) stabilizers. This agrees with Fernandes et al. (2019), who reported 36.2 kWh of electricity and 0.327 MJ of fuel for a 6.1 kg CEB.

The soil was assumed to be available at the CEB plant, so only extraction, handling and preparation was accounted for. Typical soil density is within the range between 1.0-1.5 t/m^3 (Turco et al. 2021), so an average value of 1.25 t/m^3 was adopted for the density of the soil in the natural deposit. The soil excavation and handling was estimated considering a fuel consumption of 0.35 l/m^3, which is a very conservative value based on the literature, resulting in an energy consumption of 10.6 MJ/t.

The specific energy consumption adopted for the water was 1.147 kWh/m^3, estimated based on the total energy demand and authorized water used reported by the water utilities. The estimate based on the metered water would be slightly higher (1.152 kWh/m^3). These values depend not only on energy required for water abstraction, treatment, conveyance and distribution, but also on the water losses, which for the bulk and retail water suppliers was roughly 5% and 25%, respectively.

Regarding RC production, the estimates from the previous section were adopted. For OPC and LPC, the typical clinker content is 93% and 67%, respectively. According to DAPHabitat (2023), the average gypsum content in Portuguese grey cement is roughly 5%, so limestone filler is 2% and 28% of the OPC and LCP cements, respectively. Specific energy consumption for the CEB components and production is listed in Table 4.

Table 4 – Specific energy consumption of the components and production of CEB

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
Thermal					
OPC	MJ/t	3431.4			
LPC	MJ/t	2472.1			
RC	MJ/t	1422.8			
Electricity					
OPC	kWh/t	133.7			
LPC	kWh/t	103.5			
RC	kWh/t	62.8	22.3	19.4	17.7
Soil	kWh/t	4.03			
Water	kWh/m3	1.15			
CEB Production	kWh/t	4.11			
Fuel					
OPC	MJ/t	19.5			
LPC	MJ/t	17.1			
RC	MJ/t	1098.3	274.0	147.1	70.2
Soil	MJ/t	10.6			
Transportation					
OPC	MJ/t	337.4			
LPC	MJ/t				
RC	MJ/t	495.6			
CPW	MJ/t	168.7			
CDW	MJ/t				

Considering the compositions of the CEB, the corresponding energy consumptions are detailed in Table 5. The unstabilised CEB have, by far, the lowest energy consumption. The CEB produced with RC have the highest energy consumption if all energy demand is allocated to RC. Distributing the energy consumption in the release and separation stages by the various products obtained in the process places the RC stabilized CEB energy consumption bellow OPC and LPC CEB stabilized blocks.

Table 5 – Specific energy consumption of the different CEB

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
Thermal					
OPC	MJ/m3	494.1			
LPC	MJ/m3	356.0			
RC	MJ/m3	280.3			
OPC80_RC20	MJ/m3	452.4			
OPC50_RC50	MJ/m3	393.0			
UCEB	MJ/m3	-			
UCEB_CDW0	MJ/m3	-			
Electricity					
OPC	kWh/m3	28.6			
LPC	kWh/m3	24.3			

RC	kWh/m3	21.4	13.4	12.8	12.5
OPC80_RC20	kWh/m3	27.3	25.5	25.4	25.3
OPC50_RC50	kWh/m3	25.4	21.1	20.8	20.6
UCEB	kWh/m3	9.4			
UCEB_CDW0	kWh/m3	10.9			
Fuel					
OPC	MJ/m3	16.0			
LPC	MJ/m3	15.6			
RC	MJ/m3	228.4	66.0	41.0	25.9
OPC80_RC20	MJ/m3	62.5	27.1	21.6	18.3
OPC50_RC50	MJ/m3	129.6	43.1	29.8	21.7
UCEB	MJ/m3	13.3			
UCEB_CDW0	MJ/m3	17.2			
Transportation					
OPC	MJ/m3	141.9			
LPC	MJ/m3	141.9			
RC	MJ/m3	182.8			
OPC80_RC20	MJ/m3	152.4			
OPC50_RC50	MJ/m3	167.6			
UCEB	MJ/m3	119.8			
UCEB_CDW0	MJ/m3	59.2			
Total					
OPC	MJ/m3	755.0			
LPC	MJ/m3	600.9			
RC	MJ/m3	768.4	577.3	550.3	533.9
OPC80_RC20	MJ/m3	765.5	723.7	717.8	714.3
OPC50_RC50	MJ/m3	781.6	679.7	665.3	656.6
UCEB	MJ/m3	166.9			
UCEB_CDW0	MJ/m3	115.6			

However, the CEB have different performances, so a direct comparison is not adequate. The inclusion of stabilizers impacts negatively on the environmental performance of CEB when compared with the UCEB, but also increases both the mechanical properties and durability. Table 6 presents the energy consumption normalized by the 28-day compressive strength of the CEB.

Table 6 –Normalized specific energy consumption of the different CEB to the 28 days compressive strength

Energy	Units	S1	S2 - ALT1	S2 - ALT2	S3
OPC	MJ/m3.MPa	95.6			
LPC	MJ/m3.MPa	93.9			
RC	MJ/m3.MPa	139.7	105.0	100.1	97.1
OPC80_RC20	MJ/m3.MPa	106.3	100.5	99.7	99.2
OPC50_RC50	MJ/m3.MPa	122.1	106.2	104.0	102.6
UCEB	MJ/m3.MPa	79.5			
UCEB_CDW0	MJ/m3.MPa	64.2			

UCEB and UCEB_CDW0 still outperform all the stabilized CEB, but it is important to refer that the former are sensible to water, so their use is restricted to indoor dry areas.

3.2 GREENHOUSE GASES EMISSION

The average of the yearly mean GHG emissions of the Portuguese electricity between 2019 to 2023 is used to determine the emissions from electricity consumption. The exception is for the energy consumption associated with the public water supply, for which the GHG emissions reported by the water utilities is used. It is somewhat surprising that the GHG emission factor of the energy consumed to supply the water (0.173 $kgCO_2eq/kWh$) is slightly higher than the GHG emission factor of electricity from the grid (0.156 $kgCO_2eq/kWh$), considering that the water utilities produce some energy also. This may be attributed to seasonal variations in water consumption, especially when higher distribution coincides with periods of lower renewable energy availability.

A GHG emission factor of 2.485 kg CO_2eq/L was adopted for diesel fuel, corresponding to 0.0657 kg CO_2eq/MJ. This value entails that most diesel for road transportation incorporates some additives (e.g., biodiesel) lowering both the energy and emissions. Table 7 details the GHG emission factors of CEB components and production by energy type. Fuel-related emissions from material production and transportation are separated for clarity and reproducibility.

Table 7 – Specific GHG emission factor of the components and production of CEB

Emissions	Units	S1	S2 - ALT1	S2 - ALT2	S3
Thermal					
OPC	kgCO2eq/t	751.72			
LPC	kgCO2eq/t	541.56			
RC	kgCO2eq/t	80.13			
Electricity					
OPC	kgCO2eq/t	20.86			
LPC	kgCO2eq/t	16.15			
RC	kgCO2eq/t	9.80	3.48	3.03	2.76
Soil	kgCO2eq/t	0.63			
Water	kgCO2eq/m3	0.20			
CEB Production	kgCO2eq/t	0.64			
Fuel					
OPC	kgCO2eq/t	1.28			
LPC	kgCO2eq/t	1.12			
RC	kgCO2eq/t	72.20	18.01	9.67	4.62
Soil	kgCO2eq/t	0.70			
Transportation					
OPC	kgCO2eq/t	22.18			
LPC	kgCO2eq/t				
RC	kgCO2eq/t	32.58			
CPW	kgCO2eq/t	11.1			
CDW	kgCO2eq/t				

The GHG emission factor of the different CEB is presented in Table 8, based on the respective compositions. Like with the energy, the unstabilized CEB present the lowest values but the major differences occur when comparing CEB stabilize only with PC-based or RC stabilizers. The fact that the RC eliminates the calcination emissions associated with clinker production decreases substantially the overall GHG emissions of the CEB.

Table 8 – Specific GHG emission factor of the different CEB

Emissions	Units	S1	S2 - ALT1	S2 - ALT2	S3
Thermal					
OPC	kgCO2eq/t	108.9			
LPC	kgCO2eq/t	78.5			
RC	kgCO2eq/t	15.8			

OPC80_RC20	kgCO2eq/t	89.7			
OPC50_RC50	kgCO2eq/t	62.1			
UCEB	kgCO2eq/t	-			
UCEB_CDW0	kgCO2eq/t	-			
Electricity					
OPC	kgCO2eq/t	4.5			
LPC	kgCO2eq/t	3.8			
RC	kgCO2eq/t	3.3	2.1	2.0	2.0
OPC80_RC20	kgCO2eq/t	4.3	4.0	4.0	4.0
OPC50_RC50	kgCO2eq/t	4.0	3.3	3.2	3.2
UCEB	kgCO2eq/t	1.47			
UCEB_CDW0	kgCO2eq/t	1.70			
Fuel					
OPC	kgCO2eq/t	1.1			
LPC	kgCO2eq/t	1.0			
RC	kgCO2eq/t	15.0	4.3	2.7	1.7
OPC80_RC20	kgCO2eq/t	4.1	1.8	1.4	1.2
OPC50_RC50	kgCO2eq/t	1.0	1.0	1.0	1.0
UCEB	kgCO2eq/t	0.9			
UCEB_CDW0	kgCO2eq/t	1.1			
Transportation					
OPC	kgCO2eq/t	9.3			
LPC	kgCO2eq/t	9.3			
RC	kgCO2eq/t	12.0			
OPC80_RC20	kgCO2eq/t	10.0			
OPC50_RC50	kgCO2eq/t	11.0			
UCEB	kgCO2eq/t	7.9			
UCEB_CDW0	kgCO2eq/t	3.9			
TOTAL					
OPC	kgCO2eq/t	123.8			
LPC	kgCO2eq/t	92.6			
RC	kgCO2eq/t	46.2	39.7	37.7	36.5
OPC80_RC20	kgCO2eq/t	108.1	105.5	105.1	104.8
OPC50_RC50	kgCO2eq/t	78.1	77.4	77.4	77.4
UCEB	kgCO2eq/t	10.2			
UCEB_CDW0	kgCO2eq/t	6.7			

Al-Sakkaf et al. (2025) report carbon emissions of 50 kg CO_2/m^3 of CEB, which, considering the density of the CEB produced, is between the stabilized and unstabilized CEB estimates. The authors simulated the process without using real data, and no information is provided on the CEB composition, productivity, or energy emission factors for comparison.

As with energy consumption, the GHG emission factors of the different CEB were normalized to their respective 28-day compressive strength (Table 9). The results show that, although RC requires higher energy input, it offers significant GHG emission benefits. When normalized, RC-stabilized CEB exhibit GHG emissions closer to unstabilized CEB than to PC-stabilized CEB.

Table 9 –Normalized specific GHG emission factor of the different CEB to the 28 days compressive strength

Emissions	Units	S1	S2 - ALT1	S2 - ALT2	S3
OPC	kgCO2eq/t.MPa	15.67			
LPC	kgCO2eq/t.MPa	14.47			
RC	kgCO2eq/t.MPa	8.39	7,21	6,86	6,64
OPC80_RC20	kgCO2eq/t.MPa	15.01	14,65	14,59	14,56
OPC50_RC50	kgCO2eq/t.MPa	12.21	12,10	12,09	12,09
UCEB	kgCO2eq/t.MPa	4.87			
UCEB_CDW0	kgCO2eq/t.MPa	3.74			

3.3 DISCUSSION

The results reveal that RC-stabilized CEB present a substantial environmental benefit over RC-stabilized CEB, reducing the absolute and normalized GHG emissions by 60% and 50%, respectively. Still, the emissions and 50% than the unstabilized CEB. Considering that the energy consumption of RC CEB and both OPC and LPC CEB is of the same order of magnitude, the major saving results from avoiding the calcination emissions. This highlights the advantages of promoting a circular economy in the RC production process, in particular the possibility of avoiding the major GHG emission source associated with PC production.

As expected, the energy consumption of the stabilizers is, by far, the largest contributor to the overall energy consumption of the CEB. Concerning the RC, the scenario of allocation to the various products obtained from the RC production plays a pivotal role. Other aspect that stands out is the inversion between fuel and electricity consumption between RC and OPC and LPC. However, there is a significant potential to improve RC production and the increased commercial value that it represents for the concrete waste will certainly boost innovation and optimization of the processes. In the scenario assessed, transportation of the CEB components not available on site also has significant contribution to their environmental burden. However, contrarily to alternative materials for the same applications (e.g., masonry blocks), CEB may be produced at the construction sites. This would require mobilizing the CEB production equipment, but it would also save the transportation of CEB from the plant to the construction site (outside of the scope defined for the assessment - cradle to gate).

The relative of the transportation is also the major source of uncertainty on the assessment, since the energy consumption and GHG emissions can vary substantially, not only depending on the relative locations of the CEB production site and its components suppliers, but also on the characteristics of the transportation itself. In addition to the vehicle characteristics (e.g., engine size and type; vehicle weight; maintenance) other factors that may significantly impact the environmental performance of road transportation include (Zarkadoula et al. 2007; Barth and Boriboonsomsin 2009; Fontaras and Samaras 2010; Demir et al. 2011, 2014; Kamal et al. 2011; Carrese et al. 2013; Zhou et al. 2016; Fontaras et al. 2017; Yang et al. 2022): i) environment (e.g., road gradient, type and roughness; altitude; weather); ii) traffic (e.g., congestion; signalling); iii) operation (e.g., distance; payload; empty kilometres); and iv) driver (e.g., speed; gear shifting; acceleration and deceleration; idling time). Zhang et al. (2023) observed real fuel consumptions between 30 to 40 l/100 km in 83 different heavy vehicles for average speeds between above 40 km/h. Bellow this speed threshold down to 20 km/h, the fuel consumption was found to increase up to 60 l/100 km.

4 CONCLUSIONS

This study assessed the environmental performance of compressed earth blocks (CEB) stabilized with recycled cement (RC) and compared it with reference solutions that were either unstabilized (UCEB) or stabilized with Portland cement (OPC) or blended cement (LPC). The assessment considered the separate production stages of RC and CEB, as well as different scenarios involving the parallel production of HQRA, NRA, and NRF. Environmental impacts were evaluated in terms of energy consumption and GHG emissions, using a hybrid approach combining simulation and analogy with established clinker and lime production processes. The results were found to be highly sensitive to location and transport conditions.

When evaluating the products from the separation process individually, CEB stabilized with RC showed a 30% lower energy consumption than OPC-stabilized CEB in absolute terms. However, when normalized by compressive strength, the energy consumption was 2% higher. The most balanced solutions were achieved with CEB stabilized using a blend OPC and RC, with the mix of 80% OPC and 20% RC presenting the lowest energy consumption. In addition, stabilized CEB consumed roughly four times more energy than UCEB, emphasizing the effect of stabilization on the embodied energy of earth construction. However, unstabilized solutions exhibit poor water durability, limiting their use to indoor applications.

However, the greatest benefit of RC-stabilized CEB lies in the reduction of GHG emissions. Even when normalized by compressive strength, RC CEB achieve reductions of 56% and 52% compared to OPC- and LPC-stabilized CEB, respectively. Blended mixes present emissions close to LPC CEB, so limited to no benefit in this parameter. Nonetheless, their emissions were still about 43% higher than those of non-water-resistant UCEB.

In conclusion, although RC stabilization requires slightly more energy, it substantially reduces GHG emissions while maintaining comparable mechanical and durability performance in CEB. Furthermore, RC production could benefit from the potential use of electric kilns. These results highlight the potential of RC as an eco-efficient alternative to PC for earth stabilization.

5 ACKNOWLEDGMENTS

The authors acknowledge the Portuguese Foundation for Science and Technology (FCT, https://ror.org/00snfqn58) for funding this research through project PTDC/ECI-CON/0704/2021, and through the project UIDB/06438/2025 (https://doi.org/10.54499/UID/06438/2025) of the research unit CERIS. The authors also acknowledge the support of SECIL, Vimajas, Portuguese Air Force, and Cobert for supplying the materials used during the experimental campaign, and Oficinas do Convento, Montemor-o-Novo, for supporting the production of the CEB.

REFERENCES

Adam, E. A. Agib, A. R. A. (2001). Compressed stabilized earth block manufacturing in Sudan. Technical Note No. 12, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France.

Afkhami, B., Akbarian, B., Beheshti, N., Kakaee, A. H., Shabani, B. (2015). Energy consumption assessment in a cement production plant. Sustainable Energy Technologies and Assessments, 10, 84–89. https://doi.org/10.1016/j.seta.2015.03.003

Alam, I., Naseer, A., Shah, A. A. (2015). Economical stabilization of clay for earth buildings construction in rainy and flood prone areas. Construction and Building Materials, 77, 154–159. https://doi.org/10.1016/j.conbuildmat.2014.12.046

Al-Sakkaf, Y. K., Bashir, F. M., Mohamed, M. A. S., Falude, E., Gammoudi, T., Dodo, Y. A., Nazoktabar, M. (2025). Advancing Sustainable Compressed Earth Blocks Practices: A Critical Application of

Simulation and Optimization in Reducing Energy Consumption and Greenhouse Emissions in Green Building. Energy Science & Engineering, 13: 926-943. https://doi.org/10.1002/ese3.2053

APA (2025). Fator de emissão da eletricidade – 2025. Agência Portuguesa do Ambiente (APA), Portugal. (in Portuguese) https://apambiente.pt/sites/default/files/_Clima/Inventarios/20250808/fe_gee_eletricidade_2025_final_apc.pdf (accessed 22/11/2025)

Arrigoni, A., Beckett, C., Ciancio, D., Dotelli, G. (2017). Life cycle assessment of natural and recycled aggregates for road pavements. Construction and Building Materials, 142, 124–135. https://doi.org/10.1016/j.conbuildmat.2017.03.066

Balderraman, A. A. (2001). The conservation of earthen architecture, The Getty Conservation Institute Newsletter, 16(1), 31 pp.

Barth, M., Boriboonsomsin, K. (2009). Energy and emissions impacts of a freeway-based dynamic eco-driving system. Transportation Research Part D: Transport and Environment, 14(6), 400–410. https://doi.org/10.1016/j.trd.2009.01.004

Bogas, J. A., Pereira, M. C., Guedes, A. M., Carriço, A., Hu, S., Sousa, R. (2021). https://worldwide.espacenet.com/patent/search?q=ap%3DPT2021050005W Process for separating the components of hardened concrete waste for producing recycled cement. Portuguese Patent Office. PT116130A, 2021-08-24. https://worldwide.espacenet.com/patent/search/family/075539885/publication/WO2021173022A1?q=WO%202021%2F173022

Bogas, J. A., Real, S., Cruz, R., Azevedo, B. (2023). Mechanical performance and shrinkage of compressed earth blocks stabilised with thermoactivated recycled cement. Journal of Building Engineering, 79, 107892. https://doi: 10.1016/J.JOBE.2023.107892

BP (2024). Informações sobre produtos comercializados. BP p.l.c., Portugal. https://www.bp.com/content/dam/bp/country-sites/pt_pt/portugal/home/products-and-services/informa%C3%A7%C3%A3o-sobre-produtos-comercializados/Dever%20de%20Informa%C3%A7%C3%A3o%20Madeira%20-%2018%20mar%C3%A7o%202024.pdf (accessed 18/10/2025)

Bureau of Transportation Statistics (2025). Energy consumption by mode of transportation (metric). U.S. Department of Transportation. https://www.bts.gov/content/energy-consumption-mode-transportation-0 (accessed 18/10/2025)

Burroughs, V. (2001). Quantitative criteria for the selection and stabilization of soils for rammed earth wall construction. PhD Thesis, University of New South Wales.

Carrese, S., Gemma, A., La Spada, S. (2013). Impacts of driving behaviours, slope and vehicle load factor on bus fuel consumption and emissions: A real case study in the city of Rome. Procedia - Social and Behavioral Sciences, 87, 211–221. https://doi.org/10.1016/j.sbspro.2013.10.605

Carriço, A., Bogas, J. A., Hu, S., Real, S., Pereira, M. F. C. (2021). Novel separation process for obtaining recycled cement and high-quality recycled sand from waste hardened concrete. Journal of Cleaner Production, 309, 127375. https://doi.org/10.1016/j.jclepro.2021.127375

CAT (2018). 330 Hydraulic excavator. Caterpillar. https://www.teknoxgroup.com/fileadmin/user_upload/330_HRC.pdf (accessed 13/09/2025)

Christoforou, A., Kylili, A., Fokaides, P. A., Ioannou, I. (2016). Cradle to site Life Cycle Assessment (LCA) of adobe bricks. Journal of Cleaner Production, 112(1), 443–452. https://doi.org/10.1016/j.jclepro.2015.09.016

Cimpor. (2020). Declaração ambiental atualizada 2020: Centro de produção de Souselas. Cimpor – Indústria de Cimentos, S.A. https://www.cimpor.com/documents/20124/343251/DA_Atualizada_2020_CPS_Final_site.pdf/baa89b15-1842-3e38-e2d4-1f3a34a1b822?t=1634228932616 (accessed 24/10/2025)

Cimpor. (2023a). Declaração ambiental atualizada 2023: Centro de produção de Alhandra. Cimpor – Indústria de Cimentos, S.A. https://www.cimpor.com/documents/20124/1130338/Declara%C3%A7%C3%A3o_Atualizada_Alhandra_2023.pdf/63b40724-9c4d-a6bb-988a-29020f57dad9?t=1726475575898 (accessed 24/10/2025)

Cimpor. (2023b). Declaração ambiental atualizada 2023: Centro de produção de Loulé. Cimpor – Indústria de Cimentos, S.A. https://www.cimpor.com/documents/20124/1130341/Declara%C3%A7%C3%A3o_Atualizada_Loul%C3%A9_2023.pdf/3fedc123-5530-169b-2616-dce0610f2a12?t=1726475607718 (accessed 24/10/2025)

Cruz, R., Bogas, J. A. (2024). Durability of compressed earth blocks stabilised with recycled cement from concrete waste and incorporating construction and demolition waste. Construction and Building Materials, 450, 138673. https://doi.org/10.1016/j.conbuildmat.2024.138673

Cruz, R., Bogas, J. A., Balboa, A., Faria, P. (2024). Water resistance of compressed earth blocks stabilised with thermoactivated recycled cement. Materials, 17(22), 5617. https://doi.org/10.3390/ma17225617

CSIRO. (1987). Earth wall construction (Bulletin 5). Commonwealth Scientific and Industrial Research Organization, Division of Building, Construction and Engineering.

Danso, H., Martinson, B., Ali, M., Mant, C. (2015). Performance characteristics of enhanced soil blocks: a quantitative review. Building Research & Information, 43(2), 253–262. https://doi.org/10.1080/09613218.2014.933293

DAPHabitat. (2023). Environmental product declaration: Portuguese "Grey" cement [Declaração de produto ambiental]. ATIC – Associação Técnica da Indústria de Cimento. https://www.atic.pt/wp-content/uploads/2024/01/Environmental-Product-Declaration-Portugue-Grey-Cement-ATIC-2023-EN.pdf (accessed 28/10/2025)

Demir, E., Bektaş, T., Laporte, G. (2011). A comparative analysis of several vehicle emission models for road freight transportation. Transportation Research Part D: Transport and Environment, 16(5), 347–357. https://doi.org/10.1016/j.trd.2011.01.011

Department for Energy Security and Net Zero (2025). Greenhouse gas reporting: conversion factors 2025. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2025 (accessed 17/01/2026)

Devi, P. S., Palaniappan, S. (2017). A study on energy use for excavation and transport of soil during building construction. Journal of Cleaner Production, 164, 543-556. https://doi.org/10.1016/j.jclepro.2017.06.208

Doat, P., Hays, A., Houben, H., Matuk, S., Vitoux, F. (1979). Construire en terre. Editions Alternative et Parallèles.

ECRA (2017). Evaluation of the energy performance of cement kilns in the context of co-processing. Technical Report A-2016/1039, European Cement Research Academy (ECRA), Germany. https://cembureau.eu/media/oyahklgk/12042-ecra-energy-performance-cement-kilns-2017-10-15.pdf (accessed 13/04/2025)

EEA (2025). Greenhouse gas emission intensity of electricity generation in Europe. European Environment Agency (EEA). https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1 (accessed 22/10/2025)

Egenti, C., Khatib, J. M. (2016). Sustainability of compressed earth as a construction material. In Sustainability of construction materials (2nd Edition), 309–341. https://doi.org/10.1016/B978-0-08-100370-1.00013-5

Electricity Maps (2025). Portugal 2024 Daily Carbon Intensity Data (Version January 27, 2025). Electricity Maps. https://www.electricitymaps.com (accessed 22/10/2025)

EN 15804:2012+A2:2019. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardization (CEN), Brussels, Belgium.

EN 16258:2012. Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers). European Committee for Standardization (CEN), Brussels, Belgium.

ERSAR (2024). RASARP 2024: Volume 1 - Caraterização do setor de águas e resíduos. Entidade Reguladora dos Serviços de Águas e Resíduos (ERSAR), Portugal. (in Portuguese) https://www.ersar.pt/pt/site-publicacoes/Paginas/edicoes-anuais-do-RASARP.aspx (accessed 17/09/2025)

Fernandes, J., Peixoto, M., Mateus, R., Gervásio, H. (2019). Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks. Journal of Cleaner Production, 241, 118286. https://doi.org/10.1016/j.jclepro.2019.118286

Fontaras, G., Samaras, Z. (2010). On the way to 130 g CO2/km—estimating the future characteristics of the average European passenger car. Energy Policy, 38(4), 1826–1833. https://doi.org/10.1016/j.enpol.2009.11.059

Fontaras, G., Zacharof, N. G., Ciuffo, B. (2017). Fuel consumption and CO2 emissions from passenger cars in Europe—Laboratory versus real-world emissions. Progress in Energy and Combustion Science, 60, 97–131. https://doi.org/10.1016/j.pecs.2016.12.004

Heathcote, A. (1995). Durability of earth wall buildings. Construction and Building Materials, 9(3), 185–189. https://doi.org/10.1016/0950-0618(95)00007-E

ICCT (2017). Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020–2030 time frame. International Council on Clean Transportation (ICCT). https://theicct.org/wp-content/uploads/2021/06/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf (accessed 08/10/2025)

ICCT (2018). CO2 emissions and fuel consumption standards for heavy-duty vehicles in the European Union. International Council on Clean Transportation (ICCT). https://theicct.org/publications/co2-emissions-and-fuel-consumption-standards-heavy-duty-vehicles-european-union (accessed 08/10/2025)

ISO 14083:2023. Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from transport chain operations. International Organization for Standardization (ISO), Geneva, Switzerland.

ISO 21930:2017. Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services. International Organization for Standardization (ISO), Geneva, Switzerland.

Kamal, M. A. S., Mukai, M., Murata, J., Kawabe, T. (2011). Ecological vehicle control on roads with up-down slopes. IEEE Transactions on Intelligent Transportation Systems, 12(3), 783–794. https://doi.org/10.1109/TITS.2011.2112648

Li, X., Zhu, Y., Zhang, Z. (2010). An LCA-based environmental impact assessment model for construction processes. Building and Environment, 45(3), 766-775. https://doi.org/10.1016/j.buildenv.2009.08.010

Losini, A. E., Grillet, A. C., Bellotto, M., Woloszyn, M., Dotelli, G. (2021). Natural additives and biopolymers for raw earth construction stabilization – a review. Construction and Building Materials, 304, 124507. https://doi.org/10.1016/j.conbuildmat.2021.124507

Madlool, N. A., Saidur, R., Hossain, M. S., Rahim, N. A. (2011). A critical review on energy use and savings in the cement industries. Renewable and Sustainable Energy Reviews, 15(4), 2042-2060. https://doi.org/10.1016/j.rser.2011.01.005

Maini, S. (2005). Earthen architecture for sustainable habitat and compressed stabilized earth block technology. Auroville Earth Institute, Auroville Building Centre.

Mansour, M. B., Jelid, A., Cherif, A. S., Jabrallah, S. B. (2016). Optimizing thermal and mechanical performance of compressed earth blocks (CEB). Construction and Building Materials, 104, 44–51. https://doi.org/10.1016/j.conbuildmat.2015.12.024

Melià, P., Ruggieri, G., Sabbadini, S., Dotelli, G. (2014). Environmental impacts of natural and conventional building materials: a case study on earth plasters. Journal of Cleaner Production, 80, 179-186. https://doi.org/10.1016/j.jclepro.2014.05.073

Minke, G. (2006). Building with earth: Design and technology of a sustainable architecture. Birkhäuser.

Morel, J. C., Mesbah, A., Oggero, M., Walker, P. (2001). Building houses with local materials: means to drastically reduce the environmental impact of construction. Building and Environment, 36(10), 1119-1126. https://doi.org/10.1016/S0360-1323(00)00054-8

Mosca, S., Benedetti, P., Guerriero, E., Rotatori, M. (2014). Assessment of nitrous oxide emission from cement plants: Real data measured with both Fourier transform infrared and nondispersive infrared techniques. Journal of the Air & Waste Management Association, 64(11), 1270-1278. https://doi.org/10.1080/10962247.2014.936986

Mulholland, E., Ragon, P.-L., Rodríguez, F. (2023). CO2 emissions from trucks in the European Union: An analysis of the 2020 reporting period. International Council on Clean Transportation. https://theicct.org/publication/hdv-co2-emissions-eu-2020-reporting-jul23/ (accessed 09/10/2025)

Nedeljković, M., Visser, J., Šavija, B., Valcke, S., Schlangen, E. (2021). Use of fine recycled concrete aggregates in concrete: A critical review. Journal of Building Engineering, 38, 102196. https://doi.org/10.1016/j.jobe.2021.102196

OSKAM (N.D.). Clay blocks brown/ocher. https://oskam-vf.com/en/clay-products/compressed-earth-blocks/clay-blocks-brown-ocher (accessed 10/11/2025)

Pacheco-Torgal, F., Jalali, S. (2012). Earth construction: Lessons from the past for future eco-efficient construction. Construction and Building Materials, 29, 512-519. https://doi.org/10.1016/j.conbuildmat.2011.10.054

Parracha, J. L., Silva, A. S., Cotrim, M., Faria, P. (2020). Mineralogical and microstructural characterisation of rammed earth and earthen mortars from 12th century Paderne Castle. Journal of Cultural Heritage, 42, 226–239. https://doi.org/10.1016/j.culher.2019.07.021

Ramesh, S. (2012). Appraisal of Vernacular Building Materials and Alternative Technologies for Roofing and Terracing Options of Embodied Energy in Buildings. Energy Procedia, 14, 1843–1848. https://doi.org/10.1016/j.egypro.2011.12.1177

Ranesi, A., Cruz, R., Sousa, V., Bogas, J. A. (2025). Energy consumption and carbon emissions of compressed earth blocks stabilized with recycled cement. Materials, 18(17), 4194. https://doi.org/10.3390/ma18174194

Real, S., Bogas, J. A., Cruz, R., Gomes, M.G. (2024a). Eco-recycled cement's effect on the microstructure and hygroscopic behaviour of compressed stabilised earth blocks. Journal of Building Engineering, 95, 110227. https://doi.org/10.1016/j.jobe.2024.110227.

Real, S., Bogas, J. A., Cruz, R., Gomes, M.G., Nabais, M. (2024b). Thermal performance of compressed earth blocks stabilised with thermoactivated recycled cement. Energy and Buildings, 314, 114288. https://doi.org/10.1016/j.enbuild.2024.114288.

Real, S., Sousa, V., Meireles, I., Bogas, J. A., Carriço, A. (2022). Life cycle assessment of thermoactivated recycled cement production. Materials, 15(19), 6766. https://doi.org/10.3390/ma15196766

Reddy, B. V. V., Fabbri, A., Morel, J. C., Faria, P., Fontana, P., Oliveira, D. V., Serclerat, I., Walker, P., Maillard, P. (2022). Codes and standards on earth construction. In A. Fabbri, J. C. Morel, J. E. Aubert, Q. B. Bui, D. Gallipoli, & B. V. V. Reddy (Eds.), Testing and characterisation of earth-based building materials and elements, RILEM State-of-the-Art Reports, 35, 159–190. https://doi.org/10.1007/978-3-030-83297-1_7

Reddy, B. V. V., Jagadish, K. S. (2003). Embodied energy of common and alternative building materials and technologies. Energy and Buildings, 35(2), 129–137. https://doi.org/10.1016/S0378-7788(01)00141-4

Reddy, B. V. V., Kumar, P. P. (2010). Embodied energy in cement stabilised rammed earth walls. Energy and Buildings, 42(3), 380-385. https://doi.org/10.1016/j.enbuild.2009.10.005

REN (2025). Data hub. Redes Energéticas Nacionais (REN). https://datahub.ren.pt/pt/ (accessed 17/01/2026)

Rigassi, V. (1985). Compressed Earth Blocks: Manual of Production. CRAterre-EAG, Deutsches Zentrum fur Entwicklungstechnologien - GATE (Vol. I), Germany. ISBN 3-528-02079-2

Romão, F. L. N. (2025). Desempenho ambiental e económico de blocos de terra compactada estabilizados com cimento reciclado. Master Dissertation, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal. (in Portuguese)

Roy, A., McCabe, B. Y., Saxe, S., Posen, I. D. (2024). Review of factors affecting earthworks greenhouse gas emissions and fuel use. Renewable and Sustainable Energy Reviews, 194, 114290. https://doi.org/10.1016/j.rser.2024.114290

Schmied, M., Knörr, W. (2012). Calculating GHG emissions for freight forwarding and logistics services in accordance with EN 16258 – Terms, methods, examples. European Association for Forwarding, Transport, Logistics and Customs Services (CLECAT). https://www.clecat.org/media/CLECAT_Guide_on_Calculating_GHG_emissions_for_freight_forwarding_and_logistics_services.pdf (accessed 08/10/2025)

Secil. (2023a). Declaração ambiental 2023: Secil - Outão. Secil – Companhia Geral de Cal e Cimento, S.A. https://emas.apambiente.pt/sites/default/files/files/emas/declaracoes/DA%20EMAS%20Outao%202023%20vs01_signed.pdf (accessed 24/10/2025)

Secil. (2023b). Declaração ambiental 2023: Maceira - Liz. Secil – Companhia Geral de Cal e Cimento, S.A. https://emas.apambiente.pt/sites/default/files/files/emas/declaracoes/DA%20EMAS%20Maceira%20Liz%202023%20vs01_signed.pdf (accessed 24/10/2025)

Serrano, S., Barreneche, C., Rincón, L., Boer, D., Cabeza, L. F. (2013). Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA. Construction and Building Materials, 47, 872–879. https://doi.org/10.1016/j.conbuildmat.2013.05.018

Shukla, A., Tiwari, G. N., Sodha, M. S. (2009). Embodied energy analysis of adobe house. Renewable Energy, 34(3), 755-761. https://doi.org/10.1016/j.renene.2008.04.002

Sousa, V., Bogas, J. A. (2021). Comparison of energy consumption and carbon emissions from clinker and recycled cement production. Journal of Cleaner Production, 306, 127277. https://doi.org/10.1016/j.jclepro.2021.127277

Sousa, V., Bogas, J. A., Real, S., Meireles, I. (2023a). Industrial production of recycled cement: Energy consumption and carbon dioxide emission estimation. Environmental Science and Pollution Research, 30(4), 8778–8789. https://doi.org/10.1007/s11356-022-20887-7

Sousa, V., Bogas, J. A., Real, S., Meireles, I. (2023b). Recycled cement production energy consumption optimization. Sustainable Chemistry and Pharmacy, 32, 101010. https://doi.org/10.1016/j.scp.2023.101010

Trani, M. S., Bossi, B., Gangolells, M., Casals, M. (2016). Predicting fuel energy consumption during earthworks. Journal of Cleaner Production, 112(5), 3798-3809. http://dx.doi.org/10.1016/j.jclepro.2015.08.027

Turco, C., Junior, A. C. P., Teixeira, E. R., Mateus, R. (2021). Optimisation of Compressed Earth Blocks (CEBs) using natural origin materials: A systematic literature review. Construction and Building Materials, 309, 125140. https://doi.org/10.1016/j.conbuildmat.2021.125140

Walker, P. (1995). Strength, durability and shrinkage characteristics of cement stabilised soil blocks. Cement and Concrete Composites, 17(4), 301–310. https://doi.org/10.1016/0958-9465(95)00019-9

Walker, P. (2002). The Australian earth building handbook (HB195). Standards Australia International. ISBN 0733740006; 9780733740008

Wild, P. (2021). Recommendations for a future global CO_2-calculation standard for transport and logistics. Transportation Research Part D: Transport and Environment, 100, 103024. https://doi.org/10.1016/j.trd.2021.103024

Yang, Y., Gong, N., Xie, K., Liu, Q. (2022). Predicting gasoline vehicle fuel consumption in energy and environmental impact based on machine learning and multidimensional big data. Energies, 15(5), 1602. https://doi.org/10.3390/en15051602

Zak, P., Ashour, T., Korjenic, A., Korjenic, S., Wu, W. (2016). The influence of natural reinforcement fibers, gypsum and cement on compressive strength of earth bricks materials. Construction and Building Materials, 106, 179-188. https://doi.org/10.1016/j.conbuildmat.2015.12.031

Zarkadoula, M., Zoidis, G., Tritopoulou, E. (2007). Training urban bus drivers to promote smart driving: A note on a Greek eco-driving pilot program. Transportation Research Part D: Transport and Environment, 12(6), 449–451. https://doi.org/10.1016/j.trd.2007.05.002

Zhang, Z., Demir, E., Mason, R., di Cairano-Gilfedder, C. (2023). Understanding freight drivers' behavior and the impact on vehicles' fuel consumption and CO2e emissions. Operational Research an International Journal, 23, 59 (2023). https://doi.org/10.1007/s12351-023-00798-2

Zhou, M., Jin, H., Wang, W. (2016). A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing. Transportation Research Part D: Transport and Environment, 49, 203–218. https://doi.org/10.1016/j.trd.2016.09.008