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Review

Analysis of the effect of incorporating construction and demolition waste on the environmental and mechanical performance of earth-based mixtures

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A B S T R A C T

In recent years, construction industry has been looking for ways to adopt technical solutions towards environmental preservation and conservation of natural resources. With the scarcity of building materials and the consequent increase in construction prices intensified after the Covid-19 pandemic, sustainable development based on the concepts of the circular economy has become increasingly essential. Meanwhile, the environmental impact associated with most conventional building systems has renewed interest in earth as a building material, combining traditional techniques with technological advancement. The main objective of this work is to understand the environmental and mechanical performance of earth-based mixtures incorporating construction and demolition waste (CDW), filling the gap represented by the absence of review articles that address this new material more comprehensively. The outcomes demonstrated the potential of CDW in improving environmental performance and increasing the compressive strength. Key findings include the need to consider the impact of the transport distance from the waste treatment plant to the construction site in environmental feasibility studies. Results describe the concrete prospect of a construction solution that adapts the environmental and functional advantages of earthen construction to the circular economy model. Further studies on the behaviour of CDW as a substitute for chemical binders are encouraged.

1. Introduction

The construction industry plays a fundamental role in socio-economic development, making it responsible for numerous activities that lead to significant environmental impacts [1,2]. The entire sector represents around 9% of the Gross Domestic Product (GDP) of the European Union (EU), contributing to the economy by offering direct and indirect employment opportunities (18 million direct jobs in the EU) [3] and meeting the needs of users in buildings and facilities [4]. On the other hand, it is one of the main consumers of resources: around 50% of the total use of raw materials and 36% of the final use of global energy [4]. Therefore, any effort related to global climate change and cleaner production must include this industry as a key player [5].

Demand for natural aggregates is increasingly becoming an issue due to the declining supply of natural deposits and related environmental impacts [6,7]. This situation was further intensified by the pandemic situation caused by Covid-19 [8,9]. According to Eurostat [10], in March 2021, the adjusted production in the construction sector increased by 14.9% in the EU compared with March 2020. In Portugal, the Construction Production Index, which is a business cycle indicator that measures monthly changes in construction price adjusted production, grew by 8.1% in May 2021, 4.6% higher than in April 2021[11]. Faced with this phenomenon, construction prices are rising globally, and much is due to the scarcity of materials, causing an inflationary effect on the construction market. According to the Associated General Contractors of America [12], the US government index that measures the selling price of materials and services used in new non-residential construction has jumped 1.9% from January 2021 to February 2021 and 12.8% since April 2020. At a national level, in March 2021, Portugal registered an average increase in the price of construction materials of 3.3% compared to the previous month [13]. Since January 2021, variations above 35% have already been registered due to the strong rise in the international raw material markets [13]. Therefore, the increase in the price of raw materials drives the construction industry to seek alternative solutions, for example through the reuse and recycling of resources [14].

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On the other hand, another major problem faced globally is the growth in construction and demolition waste (CDW) production and its subsequent disposal. In fact, they represent about a third of the total waste generated in the EU [15] and, since a significant portion is simply disposed in landfills (38.5%), CDW lead to serious environmental problems throughout the life cycle of buildings [16–18].

The construction industry needs to adopt more efficient strategies and a circular economy approach, ensuring that biosphere resources are harnessed to the same extent that the natural environment is able to produce them and assimilate the waste generated [19,20]. Among the mentioned strategies, CDW can be used as recycled aggregates to replace the natural ones in civil constructions such as: drainage works, paving, road construction and building products or elements (concrete blocks, mortars and subfloors) [7,21,22]. Moreover, CDW can be also used as backfilling material for binder partial replacement or for mine tailings in the underground mining industry [23–28]. Using this type of waste, its deposition in landfills will decrease, reducing both waste management costs and demand for natural resources [29,30].

However, the solution on the path to sustainability also involves the re-adoption of old building habits and techniques [31], improving them on the basis of current technical and scientific knowledge [32]. In this context, a renewed interest in the use of natural materials for building construction, such as earth [33–35], has emerged in recent decades. Earth materials and techniques have been re-established in contemporary buildings, combining tradition with technological advancement [31,36–39]. Earth-based building solutions are often recognised as sustainable [31]. This feature is mainly due to the fact that they require low-tech processing and are low energy intensive during their production process [40]. Additionally, earth is a material of natural origin, extracted and applied locally, resulting in low production costs and embodied energy [41–43]. Additionally, regarding thermal performance, earthen constructions have a good thermal performance, particularly in with warm and temperate climates [7,44,45].

Along with the inherent benefits of earthen construction, the possibility of optimising some of their properties by incorporating materials previously disposed in landfills has become a topic of great interest in the scientific community [46]. Over the past decade, in fact, many authors have addressed this issue. Some review articles have provided a general overview of industrial waste and by-products used for this purpose [47–51]. Others have focused specifically on materials of natural origin, such as vegetable fibres [46,52,53]. In this framework, the incorporation of CDW in earthen products represent an additional strategy to achieve more ecological and sustainable building materials [46,54]. However, the challenge is to reduce the use of natural resources by replacing raw materials with waste while maintaining product performance [54,55].

This work aims to understand the environmental and mechanical performance of earth-based mixtures incorporating construction and demolition waste. Such a study represents a novelty in the literature since, to the authors' knowledge, no similar ones have been found. In particular, it proposes a comparison of the results obtained in recent studies, filling a gap in the existing literature. Within this scope, the main objective is to compare the potential environmental impact of the different mixtures involved. These mixtures are usually used in the production of so-called 'earthen building materials', e.g., adobe, rammed earth, soil–cement bricks, and Compressed Earth Blocks (CEBs). Therefore, the mixtures considered in this study are composed of raw earth (when the soil is used for building purposes it is called earth [56]), water, and the aforementioned aggregates. The presence of additional chemical binders, such as cement or lime, is not an exclusion criterion.

The compressive strength values obtained from the studies adopted as reference were used as a parameter from the mechanical side, while the Life Cycle Assessment (LCA) method was adopted for environmental impact purposes. In fact, the LCA method represents one of the best approaches to develop this type of investigations [57,58]. It quantifies inputs (e.g. energy, water and materials) and outputs (e.g. CO_2 emissions, solid and liquid waste) and transforms them into potential environmental impacts using characterisation factors [59]. LCA allows to estimate the potential impact on humans and environment and identifies areas for improvement [60].

Based on what has been exposed so far, the present study is composed by three main parts. Section 2 provides an extensive literature summary of the current state-of-the-art about implementing various CDW in earth-based building products. Section 3 reports the methodology adopted defining the water absorption, mineralogical composition, mechanical resistance, and environmental evaluation criteria of the specimens developed by the selected studies. Section 4 contains the results obtained and a critical comparison between the environmental performance and the mechanical characteristics of the mixtures considered. Finally, in Section 5 some key conclusions are presented.

2. Earth-based products with CDW

The research landscape involving CDW in earth mixtures has changed in recent years. Several studies have focused on the incorporation of CDW as aggregates in earth-based products. Oti et al. [61] reported the potential of using brick dust waste as a partial substitute for clay in the production of unfired clay building materials at different levels of replacement. Incorporating these wastes up to 20% improved the compressive strength, while water absorption, linear expansion, and weight loss after thawing cycles increased along with the percentage of brick dust. In turn, Jayasinghe et al. [34] studied the mixture of crushed concrete waste with stabilised cement rammed earth. They verified that walls incorporating crushed concrete also provided satisfactory results, particularly for one- and two-storey buildings.

Seco et al. [62] carried out an experimental investigation where concrete and ceramic waste was used to partially replace clayey soil in the production of raw bricks. Bricks containing ceramic waste showed higher compressive strength than the control bricks and those with concrete wastes, regardless of the types and combinations of stabilisers adopted. Meanwhile, bricks with concrete waste exhibited higher resistance to freezing and thawing. It was established that concrete waste could replace up to 50% of clay, while ceramic waste would replace a maximum of 30% of the clay.

Arrigoni et al. [42] determined the effect of different levels of natural aggregates replacement by recycled concrete aggregates (RCA) on the mechanical strength, sustainability, and hygroscopic properties of the material. The study concluded that the particle size distribution strongly influenced the compressive strength, rather than the amount of RCA used. Although it did not affect the durability, the mechanical strength decreased with RCA replacement. The authors identified that this construction technique, which was already considered durable, proved to be resistant, with good moisture protection capacity and potentially sustainable (replacing part of the natural aggregates in the mixture with RCA slightly reduced the potential environmental impact, but the lowest greenhouse gas emissions results were achieved using alternative stabilisers, i.e., fly ash).

Rajurkar [63] prepared cement stabilised CEBs by adding various percentages of demolition waste consisting of crushed brick and mortar to replace natural sand and improve the block's strength properties. Best results were obtained by replacing 40–45% of the soil. According to the author, demolition waste can be effectively used in this construction as a substitute for natural sand to restrict the extraction of natural material. In addition, recycling and reusing this material is the ideal solution for waste management.

Similarly, Bogas et al. [64] characterised the physical, mechanical and water-resistant behaviour of unstabilised and stabilised CEBs produced with partial incorporation of fine recycled aggregates from construction debris. It was pointed out that CEBs with partial replacement of recycled aggregates presented results comparable to conventional CEBs. Stabilisation with cement was more effective than the combination of lime and cement, satisfying the minimum strength requirement under saturated conditions. However, the effect of recycled aggregates has not been studied separately. According to the authors' conclusions, CEBs solutions with partial incorporation of recycled aggregate can be produced with mechanical strength and water resistance similar to those reported in the literature for conventional CEBs.

Joshi et al. [65] investigated the use of crushed bricks (CB) in the preparation of stabilised adobe blocks. Replacing 60–80% of natural soil with CB waste, the test results indicated better mechanical strength and durability characteristics. Souza et al. [66] investigated the use of CDW for partial replacement (50%) of lateritic clayey soil in soil–cement mixtures. The results showed higher strength values for the blocks with waste concerning the soil–cement ones. This confirms that the use of CDW reduces the percentage of cement needed to stabilise a clayey soil and represents an environmentally more suitable alternative for this material than disposal.

Narayanaswamy et al. [6] also assessed the potential for incorporating solid inorganic waste as aggregates into stabilised earth materials. In their study, it was identified that the use of CDW had no significant deleterious effects on mechanical and thermal performance. However, rammed earth specimens using CDW recorded the highest thermal conductivities compared to the addition of manufactured sand and processed granulated blast furnace slag.

Konrád et al. [67] produced CEBs using waste materials including RCA. In terms of compressive strength, CEBs made from these materials demonstrate potential to be used as simple structural elements. Nevertheless, the authors identified that the water dosage needs to be optimised when dealing with porous recycled concrete aggregate, likely by saturating the aggregate with water before mixing.

In the study by Kongkajun et al. [54], soil–cement bricks were produced by replacing from 10% to 50% (by weight) of the laterite with waste of local clay bricks, among other industrial by-products. The results showed that the compressive strength of all by-product bricks exceeded industry standards (maximum compressive strength was achieved with 10% replacement by clay brick waste) and they had lower thermal conductivity in comparison with the control formula. However, the percentage of incorporated water absorption was higher. The authors further concluded that using earth mixtures containing this type of CDW can save natural resources, lowering fuel consumption and CO_2 emissions during transportation, due to the weight reduction compared to the reference samples.

Raavi and Tripura [33] in their work also investigated the effect of including CB on the properties of rammed earth blocks in terms of strength and durability, replacing from 10% to 30% of the dry soil mass. Results showed that compressive and tensile strength increased by up to 20% when recycled aggregates are incorporated. All blocks produced met the durability criteria specified by the study's reference standards. The authors further reiterate that the optimal aggregate content varies according to the soil type, aggregate and stabiliser adopted and must be determined specifically for each soil type, based on strength and durability performance.

Finally, Kasinikota and Tripura [7] studied the engineering properties of stabilised CEBs incorporating CB waste in the soil-sand mixture. Results showed that the presence of this type of waste represented a significant improvement in the block's performance, mainly in the wetting–drying and sulphate attack cycles. It was concluded that the particle size of the CB waste and the replacement ratio directly influenced the mechanical strength and water absorption of CEBs. In this context, the authors identified that the block strength is negatively affected by the removal of powder content and the water absorption increases with the replacement rate. Furthermore, an increase in compressive and flexural strengths was identified when up to 20% of CB with particle size less than 4.75 mm is added. For higher contents, the resistance decreases.

3. Methodology

3.1. Studied earth mixtures

In an effort to establish a comparison between different earth mixes with CDW incorporation, ten recent works were selected as references. They can be identified in Table 1, where each mixture considered in this study and its main characteristics are also listed. The CDW-based mixtures that showed the best compressive strength, along with the respective control mixtures, were subjected to an analysis of the mechanical and environmental performance, to understand the effect of partial replacement of their constituents by CDW. Only works that presented proportions of material per cubic meter of the mixture and that provided the percentage of replacement of raw material with waste were considered. The proportions of the studied mixes are described in Table 2. In this table, each mixture is identified according to the pattern: Author-Incorporation%Cement%Lime%.

3.2. Water absorption

Water absorption characteristics are significant for earthen building materials as they influence the strength and durability of the products, and are necessary to ensure proper mortar adhesion between masonry elements [65]. Therefore, the results of the water absorption tests carried out in the considered studies were analysed in order to identify the influence of CDW on this property. All the tests performed were conducted with the complete immersion of the specimens in water for 24 h, similar to ASTM C67 [68] recommendations.

Table 1
Reference studies involving earth mixtures with CDW incorporation and their characteristics.

Reference	Country	Construction technique	Incorporation	Particle dimension	Optimal CDW content	Stabiliser
Kasinikota and Tripura [7]	India	Compressed earth blocks (CEBs)	Crushed brick (CB)	0/4.75 mm	24%	Cement
Raavi and Tripura [33]	India	Rammed earth blocks	CB	4.75/10 mm	20%	Cement
Kongkajun et al. [54]	Thailand	Soil-cement bricks	CB	0/4 mm	10%	Cement
Narayanaswamy et al. [6]	India/UK	Rammed earth and CEBs	Concrete, ceramic brick and mortar (CDW)	0/5 mm	50%	Cement and lime
Konrád et al. [67]	Czechia	CEBs	Recycled concrete aggregate (RCA)	0/8 mm	40%	Cement
Joshi et al. [65]	India	Adobe blocks	CB	0/4.75 mm	70%	Cement
Souza et al. [66]	Brazil	Soil-cement mixtures	Concrete and mortar (CM)	0/2 mm	50%	Cement
Bogas et al. [64]	Portugal	CEBs	Concrete, brick and mortar (CBM)	0/2 mm	15%	Cement and lime
Rajurkar [63]	India	Rammed soil–cement blocks	Brick and mortar (BM)	0.075/10 mm	60%	Cement
Arrigoni et al. [42]	Italy/UK/Australia/France	Rammed earth	RCA	0.6/19 mm and 6/19 mm*	50%	Cement

* 0.6/19 mm was used when RCA was the only constituent; 6/19 mm was used when RCA was paired with soil.

Table 2
Proportion of studied earth mixtures.

Reference	Mixture	Soil (kg/m^3)	CDW (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Lime (kg/m^3)	Water (kg/m^3)
Kasinikota and Tripura [7]	Ka-CB0C10	526.91	0.00	1229.45	175.64	0.00	201.89
	Ka-CB24C10	388.64	409.09	906.82	170.45	0.00	238.13
Raavi and Tripura [33]	Ra-CB0C10	1609.09	0.00	0.00	160.91	0.00	307.98
	Ra-CB20C10	1343.51	335.88	0.00	167.94	0.00	340.65
Kongkajun et al. [54]	Kg-CB0C15	1281.00	0.00	274.50	274.50	0.00	274.50
	Kg-CB10C15	1101.73	126.43	270.92	270.92	0.00	265.50
Narayanaswamy et al. [6]	Na-CDW0C7L2	894.50	0.00	894.50*	125.23	35.78	195.00
	Na-CDW50C7L2	889.91	889.91	0.00	124.59	35.60	194.00
Konrád et al. [67]	Kr-RCA0C10	1809.09	0.00	0.00	180.91	0.00	279.84
	Kr-RCA40C10	1085.45	723.64	0.00	180.91	0.00	279.84
Joshi et al. [65]	Jo-CB0C9	1532.11	0.00	0.00	137.89	0.00	467.60
	Jo-CB70C9	498.17	1162.39	0.00	149.45	0.00	416.30
Souza et al. [66]	So-CM0C8	1380.00	0.00	0.00	120.00	0.00	444.30
	So-CM50C8	763.60	763.60	0.00	132.80	0.00	345.78
	So-CM50C6	775.50	775.50	0.00	99.00	0.00	354.75
Bogas et al. [64]	Bo-CBM15C0L0	1639.65	289.35	0.00	0.00	0.00	185.18
	Bo-CBM15C8L4	1510.32	266.53	0.00	142.15	0.00	182.31
	Bo-CBM15C4L4	1576.44	278.19	0.00	74.19	74.19	200.30
Rajurkar [63]	Rj-BM40C8	991.11	660.74	0.00	132.15	0.00	307.56
	Rj-BM60C8	688.15	1032.22	0.00	137.63	0.00	306.57
Arrigoni et al. [42]	Ar-RCA0C7	1841.12	0.00	0.00	128.88	0.00	161.54
	Ar-RCA50C7	901.87	901.87	0.00	126.26	0.00	239.32
	Ar-RCA100C7	0.00	1672.90	0.00	117.10	0.00	286.40

* Manufactured Sand.

3.3. Mechanical evaluation

For the evaluation of the mechanical resistance, compressive strength was adopted as the reference characteristic since it was the only one investigated in all the reference studies. As already mentioned, in addition to the reference mixtures, those with the highest compressive strength were evaluated to indicate the optimal incorporation percentage of CDW into the earth mixtures.

The results were obtained from three different test methods, i.e., dry compressive strength, unconfined compressive strength (UCS) and wet compressive strength. Compressive strength tests (dry and wet) were carried out on standard presses or Universal Testing Machines (UTMs), capable of uniformly applying load until the specimen failure. The difference between the two involves the saturation of the specimens for the wet compressive strength test after water immersion periods of 24 h or 48 h before testing [6,7,33]. UCS, on the other hand, represents the maximum axial compression stress that a specimen can withstand under zero confinement stress, also using an UTM. This test is commonly used for testing rammed earth-like materials [42].

3.4. Microstructural and mineralogical analysis

To understand the mechanical behaviour of the earth mixtures developed, some of the studies found in the state of art analysis determined the mineralogical composition of the materials used and carried out microstructural investigations on the morphology of the specimens produced by scanning electron microscopy (SEM). The analysis of the internal morphology and the reaction products of the mixtures was performed on the same fractured specimens after the compressive strength tests, identifying the reasons why that one represented its most fragile section.

In some studies [7,42,66], the chemical compositions were identified from the analysis of X-ray diffraction (XRD). Narayanaswamy et al. [6] and Joshi et al. [65], on the other hand, used energy-dispersive X-ray spectroscopy (EDS). Finally, the work by Kongkajun et al. [54] was the only one who used X-ray fluorescence spectrometry (XRF) to monitor the constituents of the elaborate mixtures.

3.5. Environmental assessment

3.5.1. Goal and scope

The main goal in this sub-section is to estimate the environmental performance of different earth mixes that contain CDW. The method used in this study followed the Life Cycle Assessment's (LCA) phases: objective and scope definition, inventory analysis and impact assessment. Comparative analysis and aggregation of indicators were developed using the multicriteria decision support Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC) [69,70].

The MARS-SC methodology is based on three groups of sustainability dimensions: environmental, functional and economic [70,71]. However, as this study is aimed at evaluating the environmental performance of different earth mixtures, only the environmental dimension of MARS-SC was considered.

3.5.2. Declared unit and system boundaries

The declared unit is 1 m^3 of earth mixture, which represents the basis for comparison throughout the study. This research considers the boundaries of the cradle-to-gate assessment, comprising the embodied environmental impacts of: (i) the extraction of raw materials (soil, CDW, sand, cement, lime, and water) and preparation processes, (ii) the transportation to the production facilities, and (iii) the mixing process. Fig. 1 adapts the simplified steps usually included in the LCA analysis to this study, also indicating the research boundary mentioned above. Despite the different compositions of the mixtures, limiting the study to the cradle-to-gate stage is justified because, considering the production of the same earthen products, their use and disposal at the end of the life cycle will result in similar environmental impacts.

3.5.3. Inventory analysis

The inventory analysis was used to quantify the inputs (e.g. energy and materials amount) and outputs (e.g. emissions and waste production) of the production system [57,72]. As previously mentioned, this study considers: (i) the extraction of raw materials, (ii) the transportation to the production facilities, and (iii) the mixing process. These three main steps were included in the inventory.

The inventory of raw materials refers to the proportions of the mixtures shown in Table 2. In the process of transporting materials to the production site, it was considered the distance from the suppliers to

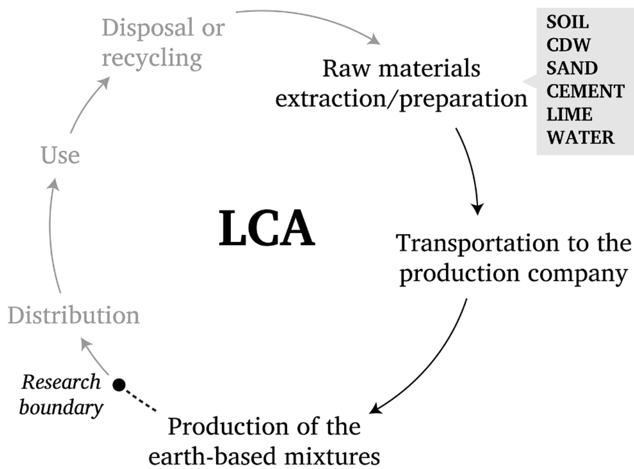


Fig. 1. Simplified steps and boundary of the LCA study.

the production unit of a Portuguese earth construction company (Table 3). The suppliers closest to the company's facilities were selected and a map application (e.g., Google Maps) was used to calculate the transportation distance. This approach is the same as the one used in the study performed by Fernandes et al. [31]. The inventory of transportation correlates the amount of each raw material and the transport distance per m^3 of mixture and is shown in Table 4. The impact categories were calculated using different Life Cycle Impact Assessment (LCIA) methods. To facilitate the quantification process, the life cycle analysis software SimaPro, version 8.4, was used to modelling the life cycle of the different mixtures.

The study adapted all the analysed compositions, fitting them into the Portuguese context. As can be seen from Table 2, the soil is mostly extracted from the construction site and, therefore, has no impacts associated with transportation (except for the mixtures based on the study by Arrigoni et al. [42], who use crushed limestone in their earth mixtures). Regarding the transportation of CDW, two scenarios were analysed. Scenario 1, reference, considers the transport from a waste treatment plant located 139 km away from the Portuguese company. Scenario 2 considers that the CDWs, like soil, can be obtained directly on the construction site and, therefore, no impacts are related to their transport. It should be noted that in Portugal, CDWs are classified as waste products, and they offer no economic value. It follows that, according to the allocation rules established by ISO 14040 [73], no environmental impact is assigned to their production.

Finally, in the modulation of the other materials used in the mixtures (sand, cement, and lime), their transportation and production process, generic data from the life cycle inventory database Ecoinvent report v3 [74] were used. This database covers the average inventory data of the primary building materials and processes in different regional contexts [71]. Therefore, all the processes used from the Ecoinvent database were adapted and contextualisation of the electricity input flows was made

Table 3
Transport distances established for each raw material, considering two different scenarios.

Raw Material	Transport Distance (km)	
	Scenario 1	Scenario 2
Soil	0	0
Crushed Limestone	296	296
CDW	139	0
Manufactured Aggregate	107	107
Natural Aggregate	214	214
Cement	177	177
Lime	283	283
Water	0	0

considering the Portuguese energy production mix.

3.5.4. *Impact assessment*

At this stage, the classification, characterisation and normalisation of the impact categories are carried out [60]. Life cycle inventory data were converted into potential environmental impacts using two LCIA methods: the CML-IA baseline method (version 3.04) was used to assess the environmental indicators expressed in impact categories; and from the Cumulative Energy Demand (CED) method (version 1.09) the life cycle energy inputs were assessed. In MARS-SC, the environmental performance assessment is based on the following environmental impact indicators (Table 5): global warming, ozone depletion, soil and water acidification, eutrophication, photochemical ozone creation, and depletion of abiotic resources of fossils fuels. Compared to the list of impact categories found in EN 15804 standard [75], MARS-SC does not consider the depletion of abiotic resources elements in its analysis.

3.5.5. *Normalisation and aggregation*

To avoid scale effects when aggregating parameters belonging to different indicators, and since some of them are of the "higher is better" type and others, "lower is better", the indicators were normalised using the same methodology recommended by Mateus et al. [71]. The normalisation was done using the Diaz-Balteiro [76] equation (Eq. (1)).

$$\overline{P_i} = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \quad \forall i \tag{1}$$

where:

P_i is the value of the ith parameter;
P_i^* and P_{*i} are the best and worst value of the ith environmental parameter among the analysed mixtures.

Afterwards, the environmental indicators were aggregated into a single score (ND_A) that describes the overall environmental performance of each mixture. According to the MARS-SC methodology, the quantification of the ND_A follows Eq. (2). A similar application of the MARS-SC was carried out in the study developed by Teixeira et al. [70].

$$ND_A = \sum_{i=1}^{n} w_i \bullet \overline{P_i} \tag{2}$$

where:

ND_A is the environmental performance, resulting from the weighted average of each normalised indicator $\overline{P_i}$;
w_i is the weight of the ith environmental indicator.

For aggregation, this study considered the default weights of the MARS-SC: $w_{GWP}= 38\%; w_{ODP} = 12\%; w_{AP} = 12\%; w_{EP} = 12\%; w_{POCP} = 14\%; w_{ADP\_FF} = 12\%$ [71].

The results were presented in a "radar" or Amoeba diagram, also known as sustainability profile. In the diagram, the number of rays is equal to the number of indicators that are analysed. In each sustainability profile, the overall performance of the CDW-based and the control earth mixtures is monitored and compared to each other.

4. Results and discussion

In this section, the influence of CDW incorporation on water absorption, compressive strength, microstructural, mineralogical composition, and environmental performance of earth mixtures is presented and discussed. Following, some relationships between mechanical and environmental properties are established.

Table 4
Results of the transportation inventory for each earth mixture (figures per m^3 of produced mixture).

Mixture	Soil	CDW		Sand	Cement	Lime	Water	Unity
		Scenario 1	Scenario 2					
Ka-CB0C10	0	0	0	263	31	0	0	tkm*
Ka-CB24C10	0	57	0	194	30	0	0	tkm
Ra-CB0C10	0	0	0	0	28	0	0	tkm
Ra-CB20C10	0	47	0	0	30	0	0	tkm
Kg-CB0C15	0	0	0	59	49	0	0	tkm
Kg-CB10C15	0	18	0	58	48	0	0	tkm
Na-CDW0C7L2	0	0	0	96	22	10	0	tkm
Na-CDW50C7L2	0	124	0	0	22	10	0	tkm
Kr-RCA0C10	0	0	0	0	32	0	0	tkm
Kr-RCA40C10	0	101	0	0	32	0	0	tkm
So-CM0C8	0	0	0	0	21	0	0	tkm
So-CM50C8	0	106	0	0	24	0	0	tkm
So-CM50C6	0	108	0	0	18	0	0	tkm
Jo-CB0C9	0	0	0	0	24	0	0	tkm
Jo-CB70C9	0	162	0	0	26	0	0	tkm
Bo-CBM15C0L0	0	40	0	0	0	0	0	tkm
Bo-CBM15C8L0	0	37	0	0	25	0	0	tkm
Bo-CBM15C4L4	0	39	0	0	13	21	0	tkm
Rj-BM40C8	0	92	0	0	23	0	0	tkm
Rj-BM60C8	0	143	0	0	24	0	0	tkm
Ar-RCA0C7	545	0	0	0	23	0	0	tkm
Ar-RCA50C7	267	125	0	0	22	0	0	tkm
Ar-RCA100C7	0	233	0	0	21	0	0	tkm

* Transport of 1 ton x km.

Table 5
Indicators, units, and life cycle impact assessment (LCIA) methods.

Environmental indicators	Units	LCIA Methods
Global warming (GWP 100)	[kg CO_2 eq]	CML-IA baseline V3.04
Ozone layer depletion (ODP)	[kg CFC-11 eq]	CML-IA baseline V3.04
Acidification potential (AP)	[kg SO_2 eq]	CML-IA baseline V3.04
Eutrophication potential (EP)	[kg PO_4 eq]	CML-IA baseline V3.04
Formation potential of tropospheric ozone (POCP)	[kg C_2H_4 eq]	CML-IA baseline V3.04
Abiotic depletion potential of fossil resources (ADP_FF)	[MJ eq]	Cumulative energy demand V1.09

4.1. Water absorption

The results of the available water absorption tests are presented in Table 6. The missing references did not present this evaluation in their studies. As a general rule, despite the tendency to increase water absorption with the increasing percentage of CDW in the mixture, all the results obtained were below the limit acceptable by most of the standard prescriptions for earthen building elements (20%) [46]. This behaviour corresponds to those found in similar previous works [44,61,77] and can be justified by the higher water absorption normally exhibited by recycled aggregates [6,7,78]. According to Katkhuda and Shatarat [79], recycled aggregate from construction waste may contain surface cracks that can affect its porosity and its degree of water absorption. Furthermore, compared to soil particles, particle deformation and sliding caused by CDW compaction are less likely to occur during the phenomenon of particle packing [79].

Table 6
Results of water absorption tests obtained by the main references.

Ref.	Mixture	Water Absorption (%)
Kasinikota and Tripura [7]	Ka-CB0C10	8.41
	Ka-CB24C10	10.52
Raavi and Tripura [33]	Ra-CB0C10	11.98
	Ra-CB20C10	11.64
Kongkajun et al. [54]	Kg-CB0C15	10.00
	Kg-CB10C15	10.50
Narayanaswamy et al. [6]	Na-CDW0C7L2	12.10
	Na-CDW50C7L2	13.90
Joshi et al. [65]	Jo-CB0C9	10.49
	Jo-CB70C9	6.51
Bogas et al. [64]	Bo-CBM15C0L0	–
	Bo-CBM15C8L0	13.60
	Bo-CBM15C4L4	16.50

However, in two other cases evaluated, the situation is reversed, i.e., the water absorption of the specimens decreases with the increase of the recycled aggregate content. According to Raavi and Tripura [33], this occurrence can be attributed to the low content of aggregates in the control samples, resulting in the formation of voids and increased water absorption. Joshi et al. [65], in turn, reported a decrease in water absorption with the CB replacement rate until the optimal percentage of 70%, then increasing again with additional incorporation. The authors attributed these differences to the gradual reduction of the fines portion until the Jo-CB70C9 mixture and the increase of sand factions in it.

The remaining study is the one of Bogas et al. [64], in which only the type of binder is varied. In their research, water absorption was measured only for the stabilised mixtures, since unstabilised earth products tend to progressively lose their cohesion properties in contact with water, making the material unsuitable in places and situations of prolonged exposure to water. Regarding the stabilised mixtures, the samples produced with lime and cement had a higher absorption than the samples with only cement. This is due to the higher void rate presented by cement-lime mixtures (32.9% vs. 29.9%). It can be concluded that the porosity of cement-stabilised mixtures is less interconnected than that of cement-lime ones.

4.2. Compressive strength

The compressive strength values obtained from all studied earth mixtures and the information relating to the tests are summarised in Table 7. All specimens are tested after 28 days of curing, but three different tests were performed, as aforementioned in section 3.3. Therefore, the results reported in Fig. 2 were grouped according to this difference.

To establish a criterion in which all the different mixtures can be directly compared, the Compressive Strength Ratio, i.e., the ratio

Table 7
Results and characteristics of compressive strength tests.

Ref.	Mixture	Test Performed	Reference Standard	Specimen Dimension	Compaction Process	Compressive Strength (MPa)	Compressive Strength Ratio
Kasinikota and Tripura [7]	Ka-CB0C10	Dry compressive strength	Not reported	290x140x100 mm	Manual press (compaction ratio of 1.85)	8.20	
	Ka-CB24C10					9.57	1.17
Raavi and Tripura [33]	Ra-CB0C10	Unconfined compressive strength (UCS)	IS 4332-Part 5:1970	100x100x100 mm	Dynamic compaction rammer	5.57	
	Ra-CB20C10					6.47	1.16
Kongkajun et al. [54]	Kg-CB0C15	Dry compressive strength	ASTM C90-16a	100x125x250 mm	Manual brick making machine	12.00	
	Kg-CB10C15					18.00	1.50
Narayanaswamy et al. [6]	Na-CDW0C7L2	Wet compressive strength	Not reported	230x110x70 mm	Constant volume manual block press	7.80	
	Na-CDW50C7L2					6.70	0.86
Konrád et al. [67]	Kr-RCA0C10	Dry compressive strength	Not reported	80x80x200 mm	Hydraulic press	3.50	
	Kr-RCA40C10					4.50	1.29
Joshi et al. [65]	Jo-CB0C9	Wet compressive strength	ASTM C67-21	230x145x100 mm	Manual moulding	3.04	
	Jo-CB70C9					5.37	1.77
Souza et al. [66]	So-CM0C8	UCS		50x100 mm (cylinder, diameter x height)	Five-layer moulding in a metal cylinder	1.55	
	So-CM50C8		ASTM D2166-16			3.11	2.00
	So-CM50C6					1.96	1.26
Bogas et al. [64]	Bo-CBM15C0L0	Dry compressive strength	NBR 8492:1986 and NTC 5324:2004	145x140x90 mm	Manual press	2.40	
	Bo-CBM15C8L0					5.40	2.25
	Bo-CBM15C4L4					3.10	1.29
Rajurkar [63]	Rj-BM40C8	Wet compressive strength	Not reported	100x100x100 mm	Dynamic compaction method	2.06	
	Rj-BM60C8					3.70	1.80
Arrigoni et al. [42]	Ar-RCA0C7	UCS	Not reported	100x200 mm (cylinder, diameter x height)	Five-layer moulding in a metal cylinder	15.00	
	Ar-RCA50C7					8.00	0.53
	Ar-RCA100C7					4.00	0.27

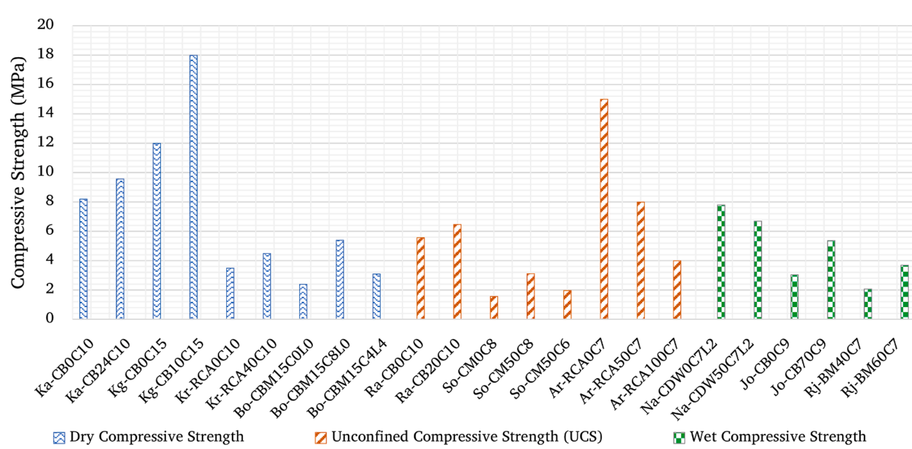


Fig. 2. Compressive strength results grouped by the test method.

between the compressive strengths of the mixtures with CDW and the reference ones, was used. It is worth noting that all the mixtures proposed by Bogas et al. [64] have the same CDW content and what is analysed is the amount of binder in their composition. Rajurkar [63] also does not provide a control mixture without CDW and the mixture with the lowest CDW content, i.e. 40%, was adopted as control.

As Fig. 2 shows, only the mixtures proposed by Narayanaswamy et al. [6] and Arrigoni et al. [42] did not experience an improvement in compressive strength after the incorporation of CDW. The reduction noted in the first study can be justified by the presence of manufactured sand produced by crushing granite rock in the composition of the reference mixture. Arrigoni et al. [42], on the other hand, identified that this decrease was not related to the amount of RCA substitution but more to the particle size distributions and quality of the recycled aggregates used. However, the values obtained by these CDW-based mixtures surpass those reached by the control samples from other studies: [1.55–3.50 MPa] [63,65–67].

In general, the discrepancy between results is due to the different sizes of the specimens, the different production processes and compaction techniques, the test method performed as well as the different geographic location and nature of the materials. Given this, it is not recommended to identify the best proportions of earth mixture in terms of mechanical strength among different studies. Nevertheless, as demonstrated by [64,66], comparing mixtures that vary only the percentage of binder, higher compressive strength values are associated with higher cement contents, which, in turn, is directly related to increased environmental impact. This correlation will be demonstrated later in subsection 4.4. In general, the studied mixtures show the potential for improving the mechanical strength that the incorporation of CDW provides to the earth as a building material. The following subsection (4.3) discusses more comprehensively the influence of CDW on the mechanical behaviour of the mixtures studied.

4.3. Microstructural and mineralogical analysis

The tests to determine the chemical composition of the materials identified a pattern in the evaluated soil samples. In all the studies that carried out a mineralogical evaluation of the soil [7,54,66], the most predominant mineral was quartz, which according to Souza et al. [66] comes from basaltic rocks. Kongkajun et al. [54] and Souza et al. [66] also observed the presence of hematite due to the occurrence of iron oxides and hydroxides, minerals characteristic of lateritic soils. Moreover, Souza et al. [66] identified the existence of kaolinite, as well as Kasinikota and Tripura [7]. Other minerals identified in soils: illite [7] and alumina [54].

Regarding the mineralogical composition of the CDWs, Souza et al. [66] identified the predominance of the mineral calcite, found in sedimentary rocks, which characterises it for the manufacture of cement and mortars. This is because its composition is mainly composed of concrete structures, rich in mortar. On the other hand, the CB waste from [7] have quartz as its main constituent. According to [66], the presence of quartz in waste material is due to its sandy fraction. The most abundant mineral in the CB waste used by [54] is alumina. In turn, the XRD analyses by Arrigoni et al. [42] on RCA samples revealed the presence of quartz, calcite, anorthite, and traces of the larnite phase. The authors elucidate that the latter indicates the presence of residual unhydrated cement in the RCA, while the appearance of anorthite can be attributed to the presence of bricks or other ceramic contaminants.

In terms of SEM analysis of the microstructure of the fractured samples, the binding matrix of the mixture with 100% RCA by [42] resulted in cementitious products of rich hydration, identifiable in dendrites and needle-shaped phases that can be attributed to Calcium Hydrate Silicate (CSH) gel and ettringite. Similarly, SEM micrographs presented by [54] showed that specimens composed of CB waste had the dense microstructure of the cured cementitious matrix. The authors point out that this result is consistent with the water absorption data obtained for the material.

In line with the other references, the images by Joshi et al. [65] reveal typical characteristics of the microstructure of concrete in all mixtures: crystals of CSH and ettringite, as well as pores and cracks distributed over the entire surface. The microstructure of the control samples is quite simple, only the sparse distribution of dense CSH crystals can be seen on the surface of the aggregate. Few pores and cracks can also be seen. The CDW-based mixture, however, presents a dense distribution of CSH crystals that manifest in two forms: massive crystals without a defined shape and thin fibrous crystals branched between the former.

On the other hand, Souza et al. [66] identified that, in the case of the control mixture, when the structure is observed superficially, there is no evidence of products related to cement hydration. At higher magnification, the formation of ettringite crystals is visible in the form of short needles and thin bundles, characterising the early stages of cement hydration. As the compressive strength tests confirmed, hydration reactions are inhibited in the soil–cement mixture due to the large amount of water, preventing the material from developing strength, even in more advanced stages of curing.

In contrast, in the CDW-based mixtures, the cement hydration products can be seen on the surface of the sample in the form of an agglomerate adhered to the particle and occupying the free spaces. At higher magnification, it is possible to observe the formation of agglomerations that fill the spaces between the grains. These clusters represent the formation of CSH, which in the cement hydration process has the function of covering the particle and in advanced stages of curing it continues to form and fill the space between the hydration layer and the non-hydrated particle. The presence of these structures, related to advanced stages of cement hydration, corroborates the fact that the mixtures with CDW present superior mechanical resistance to the control samples, even in the mixture with lower cement content. This indicates that the use of CDW can reduce the percentage of cement content needed to stabilise earth mixtures and to reach the required strength levels [66].

SEM micrographs of Kasinikota and Tripura [7] revealed that the control sample showed a homogeneous structure with the formation of CSH and calcium aluminate hydrate (CAH) with a very small amount of ettringite. On the other hand, the incorporation of CB waste increased the concentration of hydrated products. SEM analysis of the CDW-based sample showed a more compact structure with well-established CSH and CAH compounds, so there is no ettringite and portlandite intensity was reduced due to the pozzolanicity of the CDW.

This indicates that the superior strength of the Ka-CB24C10 mixture is due to the pozzolanic reaction between the CB waste and portlandite, as well as the better particle size distribution, as reported by [61,62]. Particularly, the CB particles, with rough and irregular surfaces, are evenly distributed over the matrix and induce a strong bond with the soil–cement matrix.

However, Narayanaswamy et al. [6] showed that even with the CDW having a pozzolanicity of 0.25 MPa while the sand used in the control samples does not present pozzolanic reactivity, the CDW-based mixture obtained lower compressive strength than the control. The authors justified this fact by the variability of the CDW, which depends on the nominal strength of the source materials.

4.4. Environmental performance assessment

The values obtained from the quantification of the environmental impact categories for 1 m^3 of the different earth mixtures for scenarios 1 and 2 are presented in Table 8 and Table 9, respectively.

For the environmental aspect, it is possible to establish comparisons between the different studies as only materials belonging to the Portuguese context were considered. Analysing the results obtained in both scenarios, the worst values for all impact categories are represented by control mixtures: Kg-CB0C15 (GWP 100), Ar-RCA0C7 (ODP, EP, and ADP_FF), and Ka-CB0C10 (AP and POCP). The greatest environmental impact of these mixtures may be associated with the proportion of materials other than soil: Kongkajun et al. [54] present the mixtures with the highest amount of cement. The mixtures of Kasinikota and Tripura [7] have sand in their composition. Finally, the mixtures by Arrigoni et al. [42] are composed of crushed limestone. In general, it is possible to verify that the earth mixtures with a larger amount of cement have higher values in terms of environmental impacts. In this context, the values of ADP_FF and GWP stand out as they are directly related to the presence of clinker, the main constituent of cement, which is characterised by high CO_2 emission and energy consumption during its production process [80].

Moreover, the environmental impact is also negatively affected by the transportation phase as in the case of the mixtures proposed by Bogas et al. [64]. In this case, the mixture stabilised with lime has a higher environmental impact than that one with cement, possibly due to

Table 8
Values obtained for the different environmental impact categories for each earth mixture in scenario 1.

Mixture	GWP	ODP	AP	EP	POCP	ADP_FF
Ka-CB0C10	2.45E + 02	1.77E-05	7.95E-01	1.73E-01	3.34E-02	1.89E + 03
Ka-CB24C10	2.28E + 02	1.62E-05	7.12E-01	1.57E-01	2.94E-02	1.71E + 03
Ra-CB0C10	1.70E + 02	5.34E-06	3.99E-01	8.05E-02	1.91E-02	9.32E + 02
Ra-CB20C10	1.81E + 02	7.02E-06	4.35E-01	9.10E-02	1.98E-02	1.04E + 03
Kg-CB0C15	2.86E + 02	1.15E-05	6.78E-01	1.47E-01	2.93E-02	1.56E + 03
Kg-CB10C15	2.83E + 02	1.19E-05	6.75E-01	1.47E-01	2.88E-02	1.55E + 03
Na-CDW0C7L2	1.82E + 02	9.07E-06	4.74E-01	1.07E-01	2.08E-02	1.17E + 03
Na-CDW50C7L2	1.82E + 02	9.55E-06	4.72E-01	1.05E-01	2.01E-02	1.19E + 03
Kr-RCA0C10	1.91E + 02	5.97E-06	4.45E-01	9.00E-02	2.14E-02	1.04E + 03
Kr-RCA40C10	1.98E + 02	9.10E-06	4.89E-01	1.05E-01	2.11E-02	1.18E + 03
Jo-CB0C9	1.48E + 02	4.63E-06	3.54E-01	7.06E-02	1.72E-02	8.31E + 02
Jo-CB70C9	1.72E + 02	1.00E-05	4.51E-01	1.01E-01	1.82E-02	1.12E + 03
So-CM0C8	1.30E + 02	4.07E-06	3.13E-01	6.22E-02	1.53E-02	7.37E + 02
So-CM50C8	1.51E + 02	7.77E-06	3.90E-01	8.45E-02	1.66E-02	9.60E + 02
So-CM50C6	1.21E + 02	6.77E-06	3.32E-01	7.07E-02	1.44E-02	8.36E + 02
Bo-CBM15C0L0	3.13E + 01	1.57E-06	1.48E-01	2.10E-02	9.58E-03	4.24E + 02
Bo-CBM15C8L0	1.58E + 02	5.91E-06	3.90E-01	7.91E-02	1.85E-02	9.40E + 02
Bo-CBM15C4L4	1.69E + 02	6.95E-06	4.31E-01	9.26E-02	2.05E-02	1.10E + 03
Rj-BM40C8	1.51E + 02	7.30E-06	3.89E-01	8.27E-02	1.71E-02	9.58E + 02
Rj-BM60C8	1.60E + 02	9.08E-06	4.25E-01	9.33E-02	1.77E-02	1.06E + 03
Ar-RCA0C7	2.14E + 02	2.20E-05	7.79E-01	1.82E-01	2.82E-02	2.04E + 03
Ar-RCA50C7	1.84E + 02	1.68E-05	6.10E-01	1.42E-01	2.23E-02	1.59E + 03
Ar-RCA100C7	1.47E + 02	1.12E-05	4.24E-01	9.80E-02	1.58E-02	1.10E + 03

Table 9
Values obtained for the different environmental impact categories for each earth mixture in scenario 2.

Mixture	GWP	ODP	AP	EP	POCP	ADP_FF
Ka-CB0C10	2.45E + 02	1.77E-05	7.95E-01	1.73E-01	3.34E-02	1.89E + 03
Ka-CB24C10	2.18E + 02	1.44E-05	6.65E-01	1.46E-01	2.76E-02	1.56E + 03
Ra-CB0C10	1.70E + 02	5.34E-06	3.99E-01	8.05E-02	1.91E-02	9.32E + 02
Ra-CB20C10	1.73E + 02	5.57E-06	3.96E-01	8.19E-02	1.84E-02	9.14E + 02
Kg-CB0C15	2.86E + 02	1.15E-05	6.78E-01	1.47E-01	2.93E-02	1.56E + 03
Kg-CB10C15	2.80E + 02	1.14E-05	6.60E-01	1.44E-01	2.82E-02	1.51E + 03
Na-CDW0C7L2	1.82E + 02	9.07E-06	4.74E-01	1.07E-01	2.08E-02	1.17E + 03
Na-CDW50C7L2	1.62E + 02	5.70E-06	3.68E-01	8.08E-02	1.63E-02	8.64E + 02
Kr-RCA0C10	1.91E + 02	5.97E-06	4.45E-01	9.00E-02	2.14E-02	1.04E + 03
Kr-RCA40C10	1.81E + 02	5.97E-06	4.04E-01	8.58E-02	1.81E-02	9.20E + 02
Jo-CB0C9	1.48E + 02	4.63E-06	3.54E-01	7.06E-02	1.72E-02	8.31E + 02
Jo-CB70C9	1.45E + 02	4.99E-06	3.16E-01	6.93E-02	1.33E-02	7.00E + 02
So-CM0C8	1.30E + 02	4.07E-06	3.13E-01	6.22E-02	1.53E-02	7.37E + 02
So-CM50C8	1.34E + 02	4.47E-06	3.01E-01	6.39E-02	1.34E-02	6.81E + 02
So-CM50C6	1.03E + 02	3.42E-06	2.42E-01	4.98E-02	1.11E-02	5.53E + 02
Bo-CBM15C0L0	2.47E + 01	3.21E-07	1.14E-01	1.32E-02	8.37E-03	3.18E + 02
Bo-CBM15C8L0	1.52E + 02	4.75E-06	3.59E-01	7.19E-02	1.74E-02	8.43E + 02
Bo-CBM15C4L4	1.63E + 02	5.74E-06	3.99E-01	8.51E-02	1.93E-02	9.96E + 02
Rj-BM40C8	1.36E + 02	4.45E-06	3.13E-01	6.49E-02	1.43E-02	7.17E + 02
Rj-BM60C8	1.37E + 02	4.62E-06	3.05E-01	6.54E-02	1.33E-02	6.86E + 02
Ar-RCA0C7	2.14E + 02	2.20E-05	7.79E-01	1.82E-01	2.82E-02	2.04E + 03
Ar-RCA50C7	1.64E + 02	1.29E-05	5.05E-01	1.17E-01	1.85E-02	1.26E + 03
Ar-RCA100C7	1.09E + 02	3.98E-06	2.30E-01	5.28E-02	8.82E-03	4.91E + 02

the longer distance travelled by the lime from the Portuguese company compared to the cement (283 km vs 177 km).

Table 10 presents the normalised values obtained for each environmental impact category in scenarios 1 and 2. The normalisation procedure converts them in a dimensionless scale, adjusting the values in the range between 0 (worst) and 1 (best). This allows for a better understanding of the environmental performance of each earth-based mixture.

In scenario 1, where the influence of all raw materials transportation was considered, including CDW, half of the mixtures with waste experienced a worse environmental performance than the control ones, while another two had similar results. In scenario 2, the situation is reversed: 60% of the CDW-based mixtures showed better results than the control mixtures, while another three showed similar performances (the mixtures by Bogas et al. [64] were not considered in these criteria as the percentage of CDW in their composition did not vary). This scenario reflects the relevant contribution of transport to the overall environmental impact of building materials. This statement can be corroborated by analysing the CDW-based compositions that showed the greatest improvements in environmental performance.

Based on the method developed by Zulcão et al. [81] and adapted by Paula Junior et al. [21], Fig. 3 draws the relationship between the transport distances and the GWP of the mixtures proposed by Joshi et al. [65] and Konrád et al. [67]. They were selected to apply this method because their CDW-based mixtures had higher GWP values in scenario 1 and started to show a lower impact than the control ones in scenario 2. In the graph, the GWP of the two control mixtures remains constant while those corresponding to the CDW-based mixtures vary according to the waste transport distance in scenarios 1 and 2 (139 km vs 0 km). It emerges that the incorporation of CDW becomes environmentally

Table 10
Normalised values of the studied environmental impact categories.

Mixture	Scenario 1						Scenario 2					
	GWP	ODP	AP	EP	POCP	ADP_FF	GWP	ODP	AP	EP	POCP	ADP_FF
Ka-CB0C10	0.16	0.21	0.00	0.05	0.00	0.09	0.16	0.20	0.00	0.05	0.00	0.08
Ka-CB24C10	0.23	0.29	0.13	0.15	0.17	0.20	0.26	0.35	0.19	0.21	0.23	0.28
Ra-CB0C10	0.45	0.82	0.61	0.63	0.60	0.69	0.44	0.77	0.58	0.60	0.57	0.64
Ra-CB20C10	0.41	0.73	0.56	0.56	0.57	0.62	0.43	0.76	0.59	0.59	0.60	0.65
Kg-CB0C15	0.00	0.51	0.18	0.22	0.17	0.30	0.00	0.48	0.17	0.21	0.16	0.28
Kg-CB10C15	0.01	0.49	0.19	0.21	0.20	0.30	0.02	0.49	0.20	0.22	0.21	0.31
Na-CDW0C7L2	0.41	0.63	0.50	0.46	0.53	0.54	0.40	0.60	0.47	0.44	0.50	0.51
Na-CDW50C7L2	0.41	0.61	0.50	0.48	0.56	0.53	0.47	0.75	0.63	0.60	0.68	0.68
Kr-RCA0C10	0.37	0.79	0.54	0.57	0.51	0.62	0.36	0.74	0.51	0.54	0.48	0.58
Kr-RCA40C10	0.35	0.63	0.47	0.48	0.52	0.53	0.40	0.74	0.57	0.57	0.61	0.65
Jo-CB0C9	0.54	0.85	0.68	0.69	0.68	0.75	0.53	0.80	0.65	0.66	0.65	0.70
Jo-CB70C9	0.45	0.59	0.53	0.50	0.64	0.57	0.54	0.79	0.70	0.67	0.80	0.78
So-CM0C8	0.61	0.88	0.74	0.74	0.76	0.81	0.60	0.83	0.71	0.71	0.72	0.76
So-CM50C8	0.53	0.70	0.63	0.61	0.71	0.67	0.58	0.81	0.73	0.70	0.80	0.79
So-CM50C6	0.65	0.75	0.72	0.69	0.80	0.74	0.70	0.86	0.81	0.78	0.89	0.86
Bo-CBM15C0L0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bo-CBM15C8L0	0.50	0.79	0.63	0.64	0.63	0.68	0.51	0.80	0.64	0.65	0.64	0.70
Bo-CBM15C4L4	0.46	0.74	0.56	0.56	0.54	0.58	0.47	0.75	0.58	0.57	0.56	0.61
Rj-BM40C8	0.53	0.72	0.63	0.62	0.68	0.67	0.57	0.81	0.71	0.69	0.76	0.77
Rj-BM60C8	0.49	0.63	0.57	0.55	0.66	0.60	0.57	0.80	0.72	0.69	0.80	0.79
Ar-RCA0C7	0.28	0.00	0.02	0.00	0.22	0.00	0.27	0.00	0.02	0.00	0.21	0.00
Ar-RCA50C7	0.40	0.25	0.29	0.25	0.47	0.28	0.47	0.42	0.43	0.38	0.59	0.45
Ar-RCA100C7	0.54	0.53	0.57	0.52	0.74	0.58	0.68	0.83	0.83	0.77	0.98	0.90

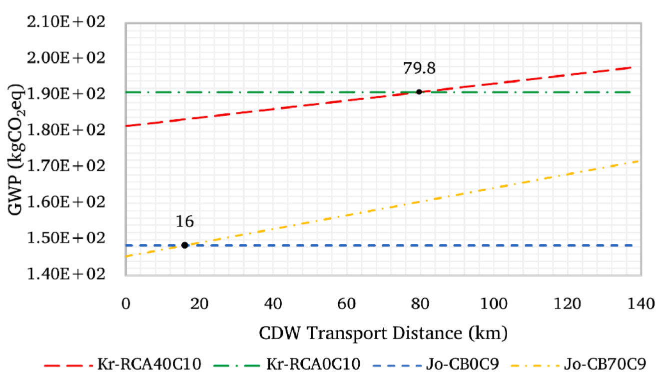


Fig. 3. Correlation between global warming emissions (GWP) and CDW transport distance.

advantageous for transport distances less than 16 km (Jo-CB70C9) and 79.8 km (Kr-RCA40C10).

Finally, it is important to mention that the proposed method uses the GWP impact category as this is the one with the highest weight in the quantification of the aggregated environmental performance using the MARS-SC. In this context, this discrepancy between the maximum distances can be attributed to the different proportions of the mixtures and the respective amounts of incorporated CDW (70% vs 40%).

As above mentioned, this study focused on the unprecedented development of an environmental assessment of different earth mixtures obtained from the literature analysis to demonstrate the sustainable potential of CDW incorporation in earth construction products. However, this potential depends on the transport distance between the waste treatment plant and the production site. This statement can be justified by the variation between Table 11 and Table 12, which show the sustainability profiles and the environmental performance of each earth mixture respectively in scenarios 1 and 2. Within the profiles, the shaded area represents the overall environmental performance that results from the values achieved in each impact category. The best mixtures at the environmental performance level are the ones that have a ND_A closer to one.

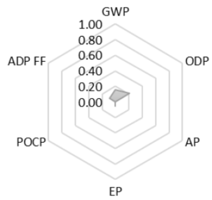
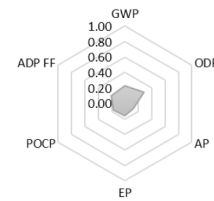
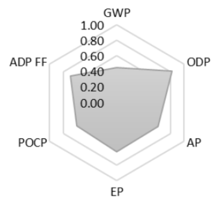
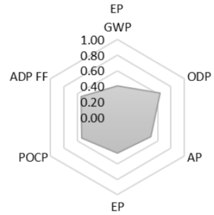
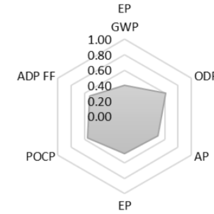
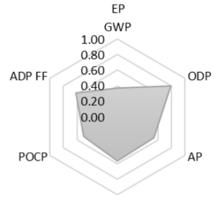
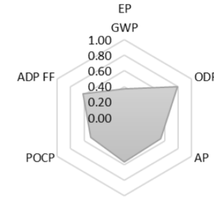
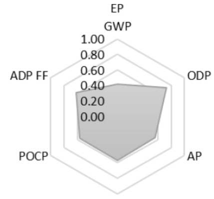
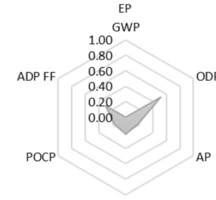
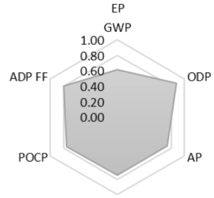
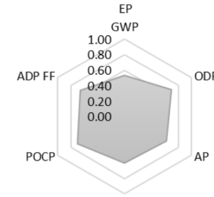
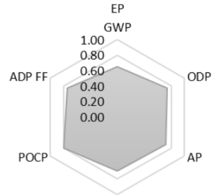
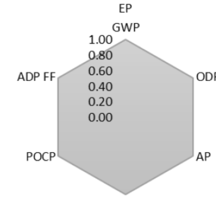
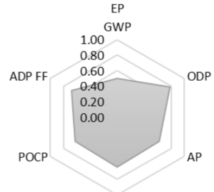
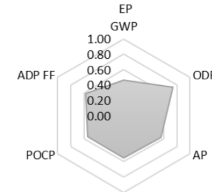
As expected, in both scenarios the mixtures with the worst environmental performances are those identified previously (Ka-CB0C10, Ar-RCA0C7, and Kg-CB0C15), and the best performing mixture is that one without conventional binders (e.g., lime or cement) in its composition, i.e., Bo-CBM15C0L0. Considering that the compressive strength obtained by this mixture was higher than the minimum recommended by the literature and by the reference standards in the topic [33,42,44,64,67,82–85], the potential of CDW to replace the binders in earth mixes should be emphasised. However, in these cases, special attention should be paid to the material's water absorption, as explained in subsection 4.1. Regarding the stabilised ones, the CDW-based mixtures by Souza et al. [65] presented the best environmental performances in scenario 1. On the other hand, considering scenario 2, the Ar-RCA100C7 mixture emerged as one of the best performances. This fact helps to clarify that the incorporation of CDW can improve the environmental performance of earth-based materials.

Based on the context involving environmental performance and mechanical strength, it is important to emphasise that the worst mixtures environmentally obtained the best results of compressive strength among the control samples. In this sense, the graphs of Fig. 4 proposes a correlation between the GWP and compressive strength values in both scenarios. The graphs on the left (Fig. 4.a and Fig. 4.c) integrally represent the dataset, while the graphs on the right (Fig. 4.b and Fig. 4.d) only represent data relating to mixtures including conventional binders, thus excluding the mixture Bo-CBM15C0L0 (which is highlighted in Fig. 4.a and Fig. 4.c). It can be observed that in the first case the linear relationship is slightly weaker than in the second, where the coefficient of correlation (represented by R^2) increases by 17.7% and 11.1%, considering scenarios 1 and 2, respectively.

Additionally, it should be noted that the compressive strength of the mixture without a binder (Bo-RA15C0L0) even surpasses some mixtures that have cement in their composition. This is evidence that helps support the potential of CDW to improve the mechanical strength to earth mixtures. But of course, it all depends on several factors that must be studied separately.

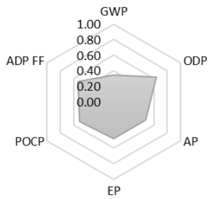
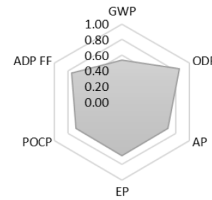
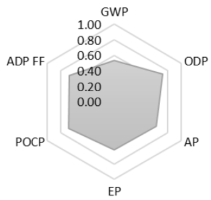
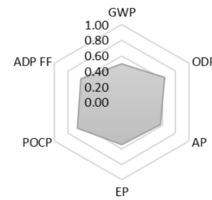
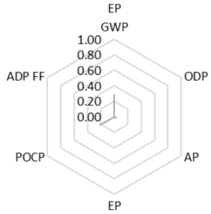
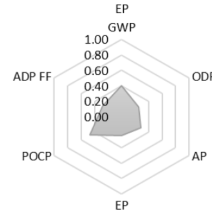
Fig. 5 shows the relationship between GWP and other mechanical properties i.e., flexural and tensile strength, provided by some of the studies included in this research [7,33,64–66], in the two scenarios. Analogously to the previous situation, the correlation tends to be directly proportional for both properties and is stronger when only mixtures including conventional stabiliser are considered (Fig. 5.b and Fig. 5.d).

Table 11
Environmental performance and sustainability profile in scenario 1.

Mixture	Sustainability Profile	Environmental Performance ND_A	Mixture	Sustainability Profile	Environmental Performance ND_A
Ka-CB0C10		0.10	Na-CDW0C7L2		0.48
Ka-CB24C10		0.20	Na-CDW50C7L2		0.49
Ra-CB0C10		0.59	Kr-RCA0C10		0.51
Ra-CB20C10		0.53	Kr-RCA40C10		0.46
Kg-CB0C15		0.17	Jo-CB0C9		0.66
Kg-CB10C15		0.17	Jo-CB70C9		0.52
So-CM0C8		0.72	Rj-BM40C8		0.61
So-CM50C8		0.61	Rj-BM60C8		0.56
So-CM50C6		0.71	Ar-RCA0C7		0.14

(continued on next page)

Table 11 (*continued*)

Mixture	Sustainability Profile	Environmental Performance ND_A	Mixture	Sustainability Profile	Environmental Performance ND_A
					
Bo-CBM15C0L0*		1.00	Ar-RCA50C7		0.34
Bo-CBM15C8L0		0.61	Ar-RCA100C7		0.57
Bo-CBM15C4L4		0.54			

* Best performing mixture.

Table 12
Environmental performance and sustainability profile in scenario 2.

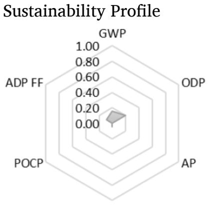
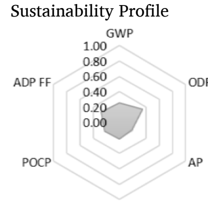
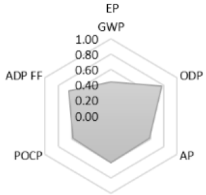
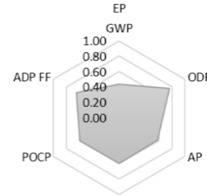
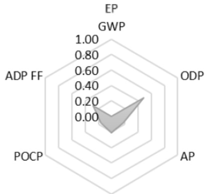
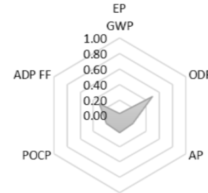
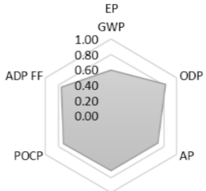
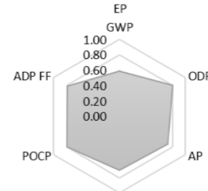
Mixture	Sustainability Profile	Environmental Performance ND_A	Mixture	Sustainability Profile	Environmental Performance ND_A
Ka-CB0C10		0.10	Na-CDW0C7L2		0.46
Ka-CB24C10		0.25	Na-CDW50C7L2		0.59
Ra-CB0C10		0.56	Kr-RCA0C10		0.49
Ra-CB20C10		0.56	Kr-RCA40C10		0.54

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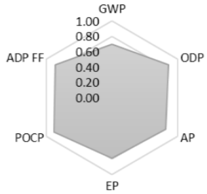
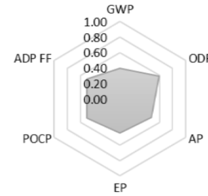
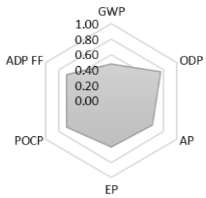
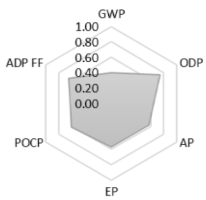
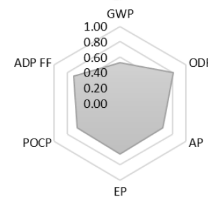
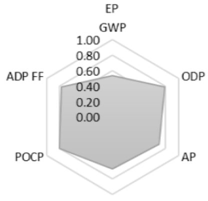
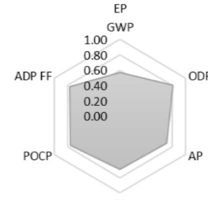
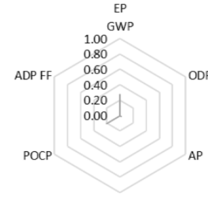
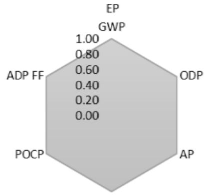
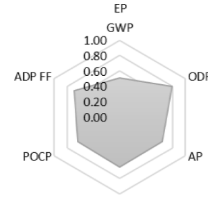
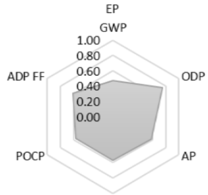
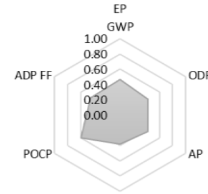
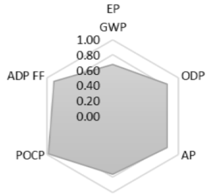
Table 12 (*continued*)

Kg-CB0C15		0.16	Jo-CB0C9		0.63
Kg-CB10C15		0.18	Jo-CB70C9		0.67
So-CM0C8		0.69	Rj-BM40C8		0.68
So-CM50C8		0.70	Rj-BM60C8		0.69
So-CM50C6		0.79	Ar-RCA0C7		0.14
Bo-CBM15C0L0*		1.00	Ar-RCA50C7		0.46
Bo-CBM15C8L0		0.62	Ar-RCA100C7		0.79
Bo-CBM15C4L4		0.56			

* Best performing mixture.

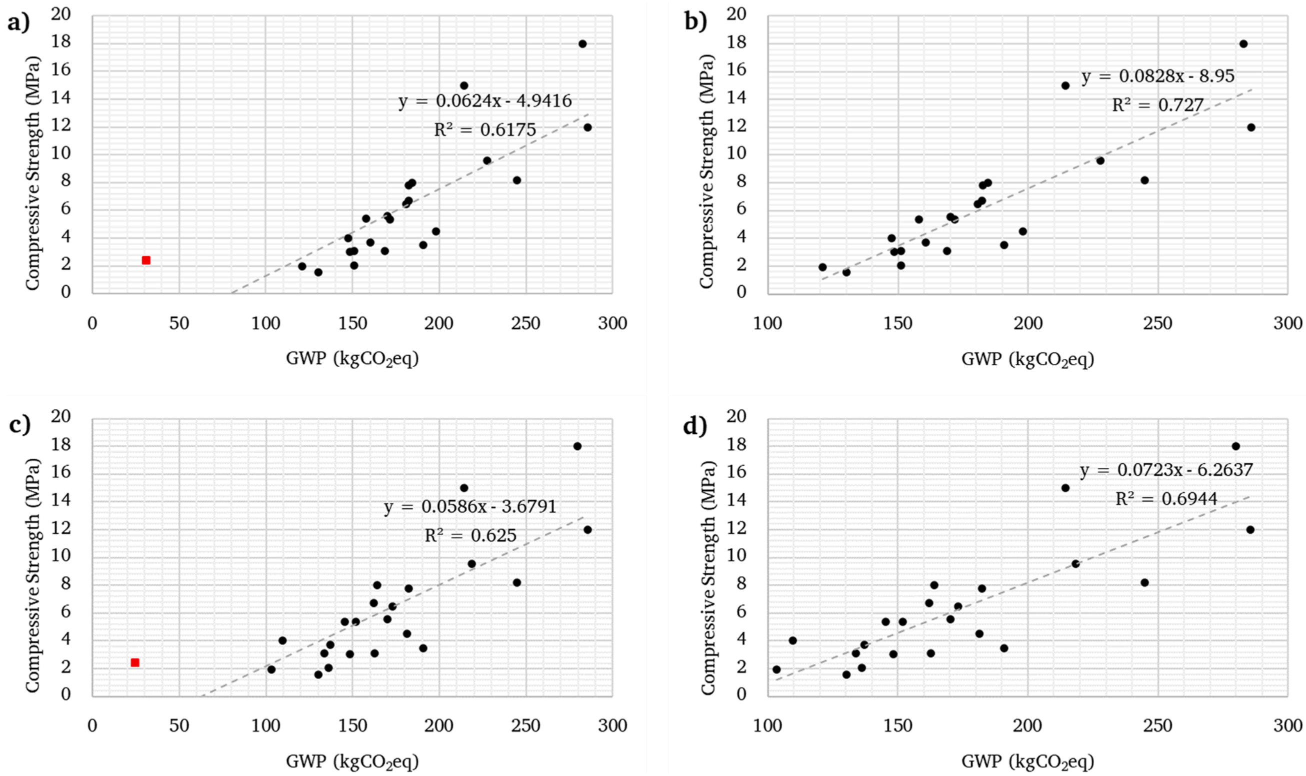


Fig. 4. Correlation between GWP and compressive strength: a) Scenario 1; b) Scenario 1, excluding Bo-CBM15C0L0; c) Scenario 2; d) Scenario 2, excluding Bo-CBM15C0L0.

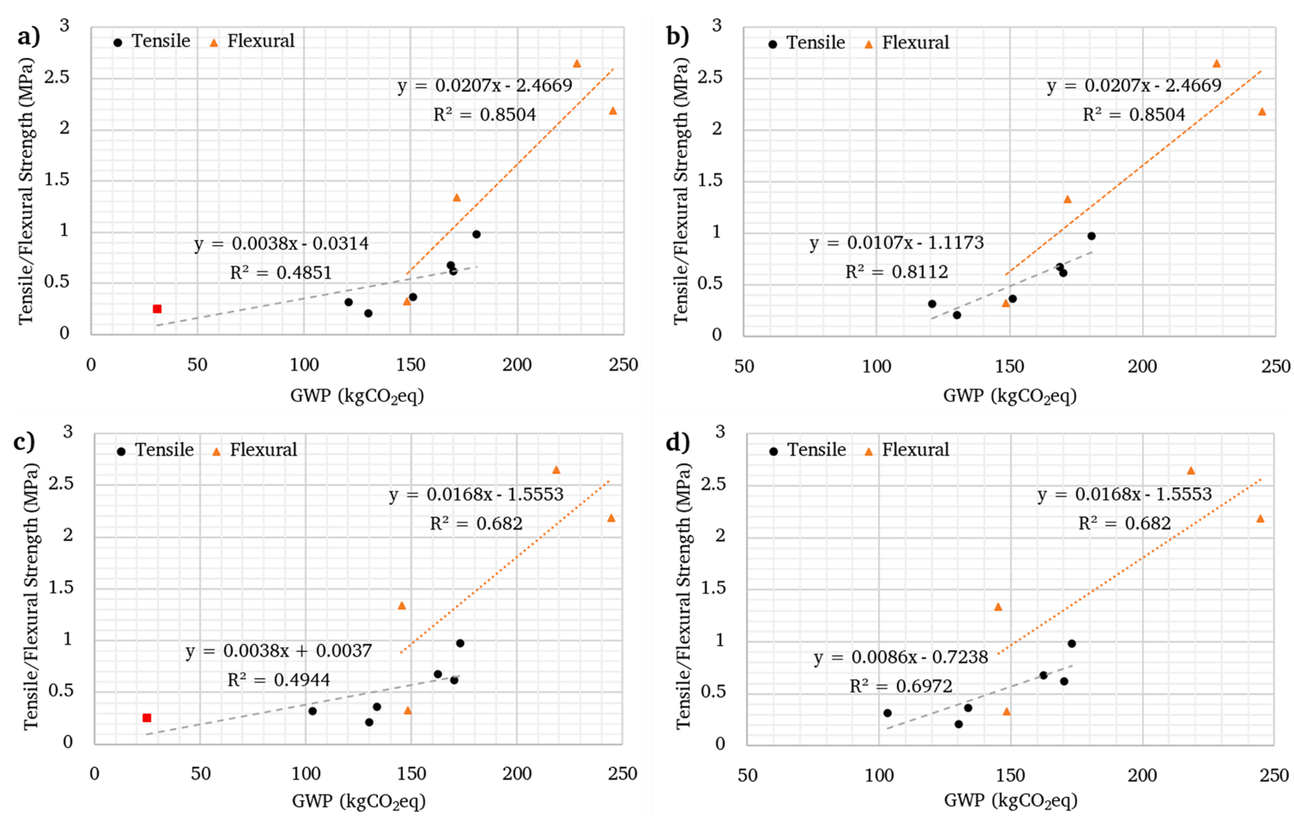


Fig. 5. Correlation between GWP and tensile/flexural strength: a) Scenario 1; b) Scenario 1, excluding Bo-CBM15C0L0; c) Scenario 2; d) Scenario 2, excluding Bo-CBM15C0L0.

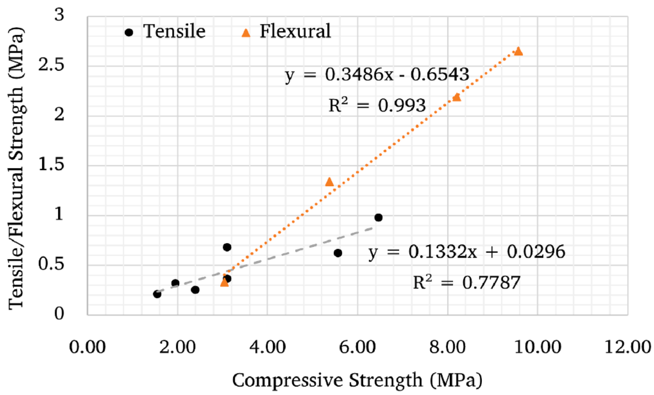


Fig. 6. Correlation between compressive strength and tensile/flexural strength.

This second finding corroborates the overall analysis, showing how the trend of the mechanical characteristics related to the GWP emissions tends to increase proportionally. Fig. 6 depicts the strong relationship between the compressive and tensile/flexural strengths, confirming the trend observed above. Overall, identifying the factors that influence environmental performance and the possibility of producing a functionally and environmentally optimised material represents a solution on the path to sustainability in the construction industry.

5. Conclusions

Sustainable construction has increasingly moved towards adapting traditional construction techniques to functional requirements and using recycled materials to reduce both raw materials consumption and landfill disposal. Within this scope, the present study investigated the effect on the environmental performance of the incorporation of CDW in different earth-based mixtures offering a comparative analysis of their mechanical and water absorption characteristics. To this end, the results obtained from ten recent studies published in international peer-reviewed journals that have experimented with different mixtures in terms of materials and proportions were analysed.

Based on the information collected and the results discussed, some relevant conclusions can be drawn:

- The water absorption of earth mixtures is directly proportional to the amount of CDW in its composition, due to the intrinsic absorption properties of recycled aggregate from construction waste. The exceptions are associated with the quantity and granulometry of the aggregates. Despite this, all the values obtained by the mixtures studied were within the limits by the reference standards.
- While it is possible to establish a linear relationship between mechanical strength and the presence of conventional binders, the environmental impacts of earth-based mixtures, including or not CDW, is directly associated with the amount of binder used. Therefore, the correlation between mechanical strength and environmental impact becomes evident.
- CDW has shown potential to increase the compressive strength of earth-based building materials. This is supported by the presence of cement hydration products in the specimens evaluated by SEM. This phenomenon reveals the pozzolanic reactivity of CDW, which allows reducing the percentage of binder needed to stabilise and provide the required levels of mechanical strength. However, it depends on factors such as particle size distribution and the properties of the CDW source materials.
- It was identified that CDW can replace binder in earth mixtures. This finding is corroborated by the unstabilised mixture analysed in this study, which only by incorporating CDW without any binder reached the minimum required mechanical performance. Even so, attention should be paid to the water absorption of the unstabilised material, which tends to progressively lose its cohesion properties in contact with water.
- The incorporation of CDW can represent a positive contribution to the environmental performance of earth mixtures. Nevertheless, aspects related to the transport of CDW from the waste treatment plant, where it will be benefited, to the production site of the earth building material need to be carefully considered in the environmental feasibility study.

Although earth as a building material has a reduced environmental impact, the incorporation of CDW into earth-based mixtures showed the potential to maintain, and in some cases exceed, its sustainable potential. The concrete perspective of a valid construction solution is therefore outlined in which the benefits of earth building and the possibility of reducing the consumption of raw materials are combined, adapting to the circular economy model to be adopted in the construction sector.

Given the scarcity of studies found, it is still necessary to develop and investigate the topic of earth-based materials incorporating CDW, especially regarding the replacement of chemical binder. Additionally, the evaluation of the influence of this type of waste on other properties of earth mixtures and any correlation between them is also encouraged. For example, the thermal performance: among the main reference documents, in fact, only three studies provided an estimate of the thermal conductivity. Although the authors indicate benefits linked to the presence of CDW, the available data are still not sufficient to draw conclusions. Finally, future developments should be oriented to address the study of the other dimensions of sustainability (social and economic) to complete the knowledge framework necessary to assess the overall sustainable potential of this new building material.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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