

Exploring alternative stabilization for compressed earth blocks: a systematic literature review

Ricardo Cruz ^{(1)*}, José Alexandre Bogas ⁽¹⁾, Alessandra Ranesi ⁽¹⁾ and Paulina Faria ⁽²⁾

(1) CERIS—Civil Engineering Research and Innovation for Sustainability, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal

(2) CERIS—Civil Engineering Research and Innovation for Sustainability, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica, Portugal

***Corresponding author for the paper:** Ricardo Cruz, ricardojtcruz@tecnico.ulisboa.pt

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Abstract

Compressed earth blocks (CEB) are gaining attention as a sustainable alternative to traditional masonry units due to their low embodied energy, reduced carbon emissions and use of locally sourced materials. However, their vulnerability to water, particularly in regions with heavy rainfall and flooding, remains a major challenge. To address this, Portland cement is often used as a stabilizer, but its significant environmental impact has driven researchers to seek more sustainable alternatives. In response, recent studies have explored partial replacement of Portland cement with industrial by-products and wastes such as fly ash and ground granulated blast furnace slag. While some of these substitutions showed promising results, they still raise concerns.

This systematic review evaluates the potential of stabilizing CEB solely with alternative reactive materials with low embodied energy. Using the PRISMA framework, relevant studies from the Web of Science database were analyzed. Findings indicate that both organic and inorganic alternative binders can substantially enhance the mechanical strength of unstabilized CEB. By highlighting eco-efficient stabilization strategies, this review contributes to advancing sustainable practices in earth-based construction.

Keywords:

Earth construction; alternative stabilization; mechanical strength; sustainability

1 Introduction

In response to the urgent need for sustainable and low-carbon alternatives in the construction industry, compressed earth blocks (CEB) have gained renewed interest as an environmentally friendly masonry unit [1]. Traditionally composed of locally sourced soil, CEB are compacted into blocks without the need for firing, which significantly reduces energy consumption and carbon emissions compared to conventional masonry units [2]. However, to improve structural integrity and durability, particularly in load-bearing applications or in areas with high moisture exposure, hydraulic binders are commonly added [3]. While cement and hydraulic lime have been widely used for stabilization, their high environmental impact has prompted a shift toward alternative binders derived from industrial by-products, agricultural residues, and bio-based materials with low embodied energy and CO₂ emissions.

The partial replacement of cement and hydraulic lime for CEB stabilization with greener products represents a pragmatic strategy to reduce environmental impacts. Numerous studies reviewed in the literature have explored this hybrid stabilization approach, where materials with low embodied energy are blended with cement or lime to achieve synergistic effects. While this strategy has been widely promoted [4–7], it still presents several limitations when assessed from an environmental performance perspective. Although it reduces the volume of high embodied energy and carbon intensive binders, it continues to rely on cement and lime undermining the full potential transition to low-impact construction. Additionally, for example fly ash (FA), a by-product of pulverized coal combustion in thermal power plants [8], faces uncertain long-term availability as global energy systems shift away from coal-based power generation.

This literature review systematically examines the existing research on the use of low embodied-energy binders for the stabilization of CEB. A meta-analysis was conducted using data from 29 studies selected based on defined inclusion and exclusion criteria. The analysis focuses on the testing methods employed for physical and mechanical characterization, as well as the reported results. Additionally, the review explores correlations between key properties – such as porosity and bulk density – and how these relationships may be influenced by different stabilization approaches..

2 Methodology

A systematic literature review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, recognized for its applicability across diverse research domains.

The literature search was performed using the Web of Science (WoS) database. Only peer-reviewed journal articles were considered, to ensure the inclusion of studies subjected to rigorous peer-review. Given the diversity in terminology across the literature, the search strategy employed a range of semantic variations, including

synonyms (e.g., "block" and "brick"), plural forms, and both American and British spellings (e.g., "stabilized" and "stabilised"). The review was restricted to studies published between January 2014 and December 2024.

An initial set of 441 records was retrieved. Literature reviews or studies that employed geopolymer stabilization were excluded at the outset. Although geopolymerization is a viable stabilization technique, it was excluded from this review due to its high energy demands – primarily from the calcination of aluminosilicate precursors and the need for elevated curing temperatures – as well as the substantial costs of alkaline activators like sodium silicate [9]. These factors pose significant barriers to the widespread adoption of geopolymer technology in CEB. Subsequently, the titles, keywords, and abstracts were screened, resulting in the exclusion of 190 of these studies. At this stage, studies that focused on stabilizing CEB solely with Portland cement or hydraulic lime or on the incorporation of fibers or aggregates that would solely modify the earth particle size distribution (physical stabilization) were removed. Physical stabilization would expand the volume of literature, making the review less focused and harder to manage within reasonable limits given the paper's length limitations. The remaining articles underwent full-text review. In this stage, articles that just partially replaced Portland cement or hydraulic lime, without fully addressing the scope of this review, were removed. Following this rigorous process, 29 scientific articles were deemed eligible. These were organized alphabetically by the first author's name, and relevant data were extracted manually or using image and graph digitization software (WebPlotDigitizer). The extracted data were compiled in Microsoft Excel (version 2502) and included the publication data and the results of various characterization tests for both control samples and those incorporating alternative binders. Control samples (unstabilized CEB, UCEB) served as performance benchmarks in each study. Any variations in performance relative to the control samples were identified for each measured property. In instances where data were unclear or not reported, the corresponding fields were not considered.

3 Publication data analysis

This chapter offers a critical overview of recent research trends related to the stabilization of CEB with low embodied-energy binders.

In terms of publication trends, the number of studies remained relatively the same between 2014 and 2019, accounting for only 14% of the total publications (5 occurrences in 6 years). A marked increase occurred in 2020 (+2 occurrences); however, this growth stabilized in subsequent years, with publications in 2021, 2022 and 2023 (4 occurrences each year). A second notable increase was observed in 2024, which comprised 34% of the total publications (10 occurrences). Fig. 1 presents the publication and citation distribution over the years. The number of citations were obtained using WoS database. By the end of 2024, the number of citations from 29 articles published between 2014 and 2024, was 445. The number of journals identified were 17, being mainly Q1 in Building and Construction, Civil and Structural

Engineering or Materials Science. In fact, of the 29 selected studies, approximately 28% were published by *Construction and Building Materials* (Elsevier) and 14% by *Journal of Building Engineering* (Elsevier). The remaining 58% was released by other journals such as *Buildings* (MDPI) and *Journal of Materials in Civil Engineering* (ASCE).

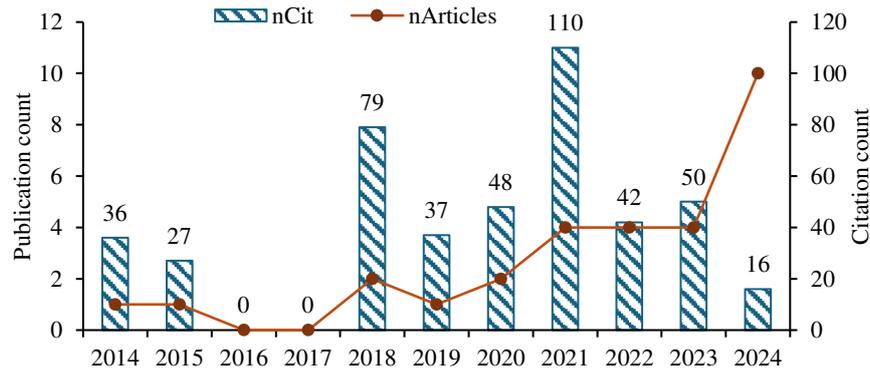


Fig. 1 – Number of citations (nCit) and publications (nArticles) per year.

A total of 24 different products for CEB for stabilization were found and classified into two macro-groups: organic and inorganic stabilizers.

Inorganic stabilizers were used in 69% of the studies included in the review. Wastes from different sectors were used as stabilizers, namely: mining and quarry waste (phosphate washing sludge, PWS; and phosphogypsum, PG); polymeric waste (glass powder, GP) and industrial waste and by-products such as ashes derived from coal; municipal solid waste, and other industrial combustion processes, including fly ashes (FA), municipal solid waste incinerator bottom ash (MSWIBA), medical waste incinerator bottom ash (MWIBA), sugarcane bagasse ash (SBA), cotton waste ash (CWA), rice husk ash (RHA), and wood biomass ash (WBA). Additional industrial wastes and by-products came from the metal industry (granulated ground blast furnace slag, GGBFS; and silica fume, SF), acetylene gas production (calcium carbide residue, CCR), construction and demolition waste industry (recycled cement, RC) and cement industry (cement kiln dust, CKD).

Organic binders were used in 31% of the studies analyzed and were mainly vegetal or animal based. Among vegetal bio-based stabilizers (24% of the studies) were found sugarcane molasses (SCM), cow dung (grass fibers processed in digestion), palm kernel oil residue (PKO residue), alginate, Xanthan gum, guar gum, carob gum. The remaining 7% (of the total) of the studies reported animal bio-based stabilizers such as animal glue and ovalbumin. The different categories and their percentages of occurrence can be seen in Fig. 2.

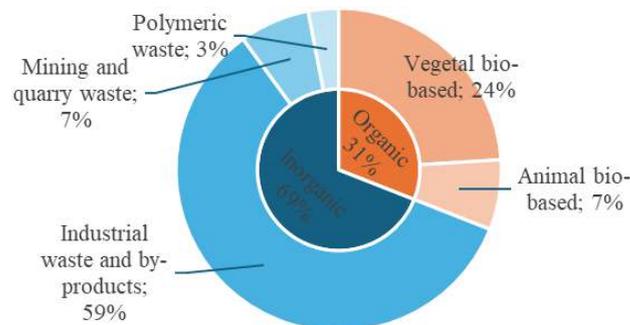


Fig. 2 – Distribution (%) of CEB stabilizers included in the review.

The tests were initially grouped into four main broad categories: i) physical properties; ii) mechanical properties; iii) durability properties; iv) microstructural analysis. Approximately 93% of the articles included in the review presented the mechanical characterization of the CEB, assessing compressive strength, bending strength, splitting strength and modulus of elasticity. The compressive strength was addressed in all the studies presenting the CEB mechanical characterization, as it is considered the most critical performance indicator. Physical characterization was run in about 76% of the studies, involving measurements of bulk density, porosity, shrinkage, water absorption by immersion and capillarity. Durability tests, such as wetting-drying cycles, drip test, accelerated erosion testing (spray test) and abrasion resistance were less observed (only 41% of the studies) although being an essential factor in earth-based construction. Nevertheless, water absorption can also be considered a key indicator of durability. Finally, about 41% of the studies presented results from microstructural analysis, such as SEM, MIP, XRD and N₂-adsorption.

The present review excluded (dashed pattern in Fig. 3) included all durability and microstructural properties and certain mechanical and physical properties (splitting tensile strength, modulus of elasticity, shrinkage, low pressure water absorption and capillary water absorption). This decision was based on two main factors: (i) limited representation of these properties in the reviewed literature (Fig. 3), which would hinder meaningful comparative analysis; and (ii) their inclusion would have made the review difficult to manage within reasonable limits given the paper's length limitations. Therefore, bulk density, porosity, compressive strength, and bending strength were prioritized. In addition, the microstructural mechanisms responsible for the variations in these properties will also be explored. Focusing exclusively on these parameters ensures consistency and strengthens the reliability of the conclusions drawn from the reviewed studies.

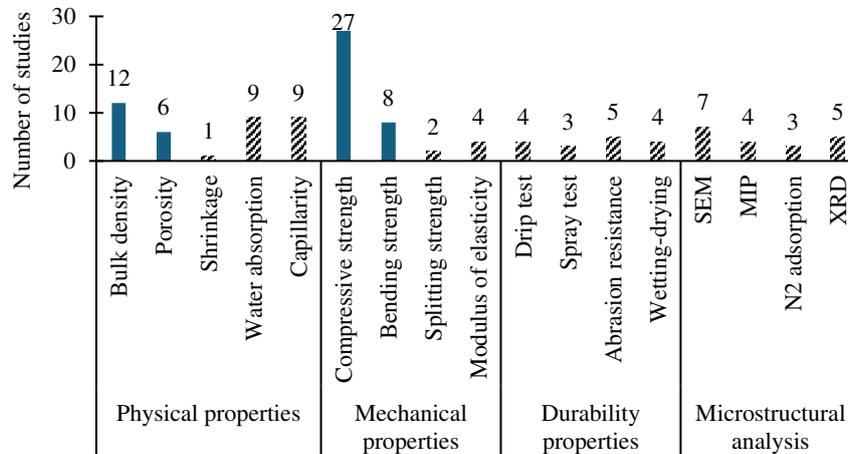


Fig. 3 – Most common tests conducted by the authors. In dashed pattern the properties excluded from the present literature review.

4 Testing methods

Accurate and consistent testing methods are essential for evaluating the performance and suitability of CEB in construction applications. To this end, a variety of standardized and non-standardized testing techniques have been developed to assess the key properties of CEB. This subchapter presents a comprehensive overview of the testing methods employed in the reviewed literature, to identify gaps or inconsistencies in current testing practices.

4.1 Bulk density

Bulk density is a key physical property of CEB, representing the mass per unit volume, including both solid material and pore spaces. It is critical for evaluating the quality, strength, and thermal performance of CEB and serves as an indirect indicator of compaction and structural integrity. Accurate measurement is therefore essential. However, although all studies define bulk density as the ratio of mass to volume, the procedures used to determine these parameters vary significantly, mainly in terms of preconditioning but, in some cases, also of testing methods. The preconditioning of the blocks influences their mass, which was found to be measured under different moisture conditions. Some studies [10–15] oven-dried the blocks until constant mass at 105 ± 5 °C, others [16, 17] at 60 ± 5 °C, while some others [3, 12, 13, 18, 19] refer values for air-dried blocks at ambient laboratory conditions (typically 23 ± 3 °C and 55–75% relative humidity). These differing drying protocols result in varying moisture contents, which directly affect the measured mass and, consequently, bulk density. Variation of the method itself was also found: most studies (11 out of 12 studies) determine volume using geometric measurements but one study [20] employed hydrostatic weighing for stabilized CEB, a more

precise method that accounts for surface irregularities but cannot be used on UCEB due to their susceptibility to water.

4.2 Total Porosity

Total porosity (Φ) represents the proportion of the material's volume that is occupied by voids or pore spaces. It plays a crucial role in CEB performance and serves as an indirect indicator of compaction and the internal structure of the material. Again, the methods used for the determination of total porosity vary significantly from study to study. Nshimiyimana *et al.* [20, 21] determined Φ as being the ratio between bulk density and skeletal density (ρ_s) obtained through helium pycnometer testing. Other researchers [3, 12–15] considered Φ (Eq. 1) as the sum of the volume of voids after compaction (V_v) with the volume of voids from free hydration water (V_{H_2O}), determined (Eq. 2) as the difference between the volume of mixing water (M_w) and the volume occupied by hydration products. The latter was calculated as the product of: i) α_H the long-term degree of hydration; ii) w_b the bound water (by weight of binder) at full hydration, and iii) M_b the mass of binder.

$$\Phi = V_v + V_{H_2O} \quad (1)$$

$$V_{H_2O} = \frac{M_w - \alpha_H * w_b * 0.746M_b}{\rho_w} \quad (2)$$

Other studies [3, 14, 15, 17] estimated the porosity through MIP and/or N_2 adsorption. However, these techniques are more suitable for analyzing pore size distribution and connectivity in the accessible pore network rather than determining the total porosity of CEB. For example, MIP only measures pores that are accessible to mercury. Closed pores cannot be intruded by mercury and therefore go undetected.

4.3 Compressive strength

Compressive strength is one of the most critical mechanical properties used to evaluate the structural performance and load-bearing capacity of CEB. The determination of compressive strength involves subjecting a block or a representative specimen to a compressive load until failure, using a compression testing machine. Standardized procedures or other national specifications, guide the preparation, curing, and testing of samples to ensure reliable and reproducible results.

Four different approaches were detected (Fig. 4). Approximately 15% of the studies [19, 20, 22, 23] followed the RILEM TC 164 recommendations, cutting blocks in half and stacking them with earth mortar to increase the slenderness ratio and approximate to unconfined compressive strength. However, Olivier *et al.* [24] found that this method yielded lower compressive strength values compared to cylindrical samples with a slenderness ratio of 1.5. This underestimation occurs regardless of the earth mortar's composition, as its strength and stiffness are generally lower than those of CEB [25, 26]. Other researchers measured

compressive strength directly on whole [11–15, 27–33], half blocks [3, 10, 16, 17, 34, 35] or cylinders [18, 36–38] (46%, 23% and 15%, respectively). When using half blocks, the sawing process introduces local stresses that damage the sample, as reported by Aranda-Jiménez *et al.* [39], who observed a 21.7% reduction in compressive strength and higher variability compared to whole blocks. It is important to note that most researchers did not account for confinement effects in their tests on whole or halved blocks. The remaining studies [3, 12, 13] applied correction factors based on sample slenderness, referencing those found in HB-195 [40], which are derived from Krefeld's work [41] on fired bricks. However, Aubert *et al.* [25] argued that the correction factors proposed by Heathcote & Jankulovski [42] are more suited for CEB.

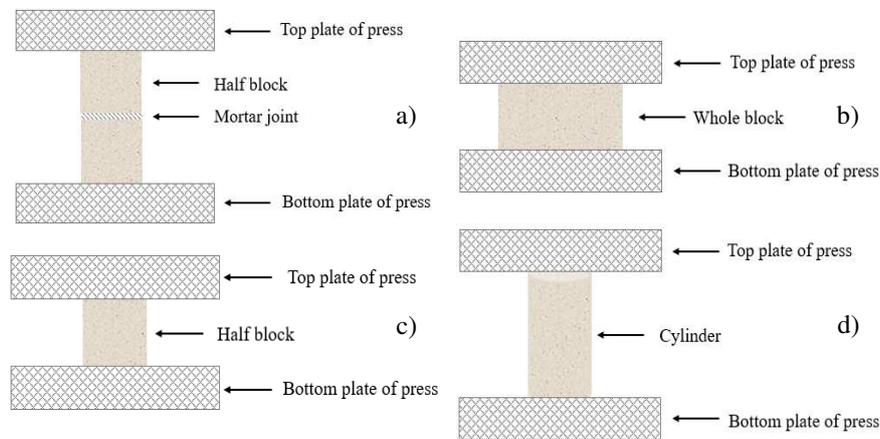


Fig. 4 – Compressive strength testing scheme: a) RILEM TC 164 recommendation; b) whole block; c) half block; d) cylinder.

Another important factor influencing the compressive strength of CEB is their moisture content. Testing blocks in wet or saturated conditions often results in significantly lower strength values compared to those measured in oven-dried or air-dried specimens. To determine the dry compressive strength, samples are typically oven-dried until their mass become stable. However, drying temperatures reported in the literature vary widely, ranging from $45 \pm 5^\circ\text{C}$ to $105 \pm 5^\circ\text{C}$. According to Fabbri *et al.* [43], drying at the higher end of this range ($105 \pm 5^\circ\text{C}$) can alter the material's properties, potentially producing misleading strength values. Conversely, lower temperatures, such as $45 \pm 5^\circ\text{C}$, may not fully eliminate moisture and can lead to inconsistent results due to fluctuations in the oven's relative humidity.

When assessing wet or saturated compressive strength, the duration of water immersion becomes a critical parameter. Studies have employed immersion times ranging from as little as 10 minutes to over 48 hours. Short durations are generally used to evaluate the sample's initial water sensitivity, whereas longer immersion periods are intended to simulate full saturation, reflecting a worst-case exposure scenario.

4.4 Flexural strength

Flexural strength, also known as bending strength, is a key mechanical property used to evaluate the tensile performance of CEB under bending loads. The most common method mentioned in the reviewed literature was the three-point bending test, in which a specimen (often a whole block) is supported at both ends and loaded at the center until failure. The flexural strength was then determined based on the maximum load applied, the span length, and the specimen's dimensions. Worth mentioning the application of a four-point bending test by one study.

5 Results overview

5.1 Bulk density and total porosity

Despite the differences in procedures, the general trend is that the incorporation of organic or inorganic binders decreased the bulk density of CEB compared to the control samples (Table 1, in brackets). On one hand, for instance, the use of animal glue (1 wt%) and xanthan gum (1 wt%) led to a reduction in ρ of approximately 4% compared to unstabilized blocks, dropping from 2199 kg/m³ to around 2113 and 2108 kg/m³, respectively (Table 1). Similarly, CEB stabilized with 10 wt% CWA showed a 4% decrease in ρ (from 1847 to 1769 kg/m³). The most pronounced reduction was observed for CEB stabilized with CCR, with reductions of bulk density by 5% to 18% across different replacement levels (5–25 wt%). The combination of CCR and RHA in different proportions also resulted in a decreasing trend in bulk density. This behavior is primarily attributed to the physical characteristics of the binders. Both CCR and RHA have significantly lower specific density compared to the lateritic soil [20, 21]. As the proportion of these binders increases, the block becomes lighter, leading to a consistent decrease in bulk density. On the other hand, some materials demonstrated the tendency to increase ρ of CEB. Notably, PG at higher contents (up to 80%) increased ρ by up to 25%, likely due to its higher packing capacity. Likewise, the use of cow dung at 15–30 wt% replacement increased ρ by 3% to 9%, indicating potential for enhancing the compactness when well-processed. For example, Kulshreshtha *et al.* [44] recommends the removal of fibers of fresh cow-dung, what is not practical.

When reported, Φ generally exhibited the inverse trend than ρ (Fig. 5 and Table 1). The relationship shown in Fig. 5 holds consistently regardless of the type and amount of alternative binder used and is independent of the method employed to determine ρ and Φ , with the exception of one study [17]. Rivéra-Gómez *et al.* [17] incorporated 3 wt% alginate into three different clayey soils to produce CEB and estimated Φ using MIP. As discussed in Section 4.1, MIP is known to underestimate the total porosity of CEB and is therefore not considered a reliable method for this measurement. For example, Cruz & Bogas [3] found that MIP porosity accounted for only about 75–79% of Φ . Based on this correction, the adjusted Φ values for the samples studied by Rivéra-Gómez *et al.* [17] would be approximately 47.0, 46.6,

and 42.6 % for CEB produced with Soil I, Soil II and Soil III, respectively, instead of 36.2, 35.9, 32.8 % found by the authors. As with bulk density, Φ decreased in alternative stabilized CEB compared to UCEB (Table 1). However, stabilization can alter the pore size distribution and pore tortuosity. For example, a coarser pore structure was observed in UCEB compared to RC-stabilized CEB [3, 14], despite lower Φ .

Table 1 – Physical properties of CEB stabilized with alternative binders and unstabilized CEB (in brackets).

Ref	Binder (wt %)	ρ (kg/m ³)	Φ (%)
[3]	RC (4–8%)	1960–1980 (2000)	28.8–29.8 (26.2)
[10]	MWIFA (10–40%)	1649–1533 ^a (1653 ^a)	-
[11]	Cow-dung (15–30%)	1797–1910 ^a (1748 ^a)	-
[12–15]	RC (5–10%)	1718–1729 (1815)	39.3–39.0 (34.3)
	RC (10%)	1640 ^a (1745 ^a)	
[14, 15]	RC (8%)	1778 ^a (1835 ^a)	32.8 (30.4)
[16]	CWA (10%)	1769 ^a (1847 ^a)	-
[17]	Alginate (3%) – Soil I	1510 ^a	36.2
	Alginate (3%) – Soil II	1450 ^a	35.9
	Alginate (3%) – Soil III	1390 ^a	32.8
[18]	Animal glue (1%)	2113 (2199)	-
	Xantham gum (1%)	2108 (2199)	-
[19]	PG (20–80%)	1792–2166 (1739)	-
[20, 21]	CCR (5–25%)	1711–1477 ^a (1801 ^a)	38–45 (35)
	CCR:RHA (20:0–12:8)	1522–1578 ^a (1801 ^a)	44–39 (35)

Notation: RC – recycled cement; MWIFA – medical waste incinerator fly ash; CWA – cotton waste ash; PG – phosphogypsum; CCR – calcium carbide residue; RHA: rice husk ash; ρ – bulk density; Φ – porosity; ^a – oven dried

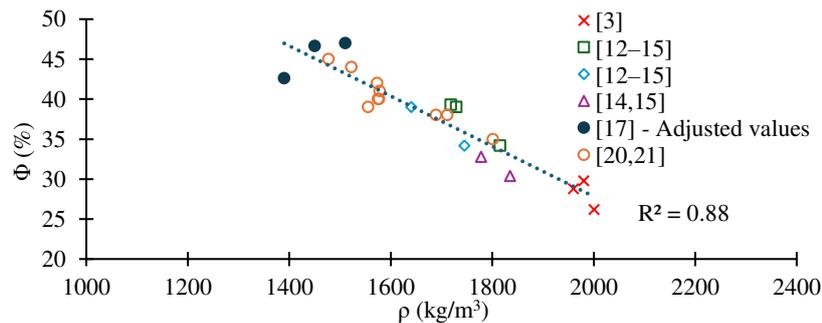


Fig. 5 – Total porosity (Φ) as a function of bulk density (ρ).

5.2 Compressive strength

Vegetal or animal bio-based binders showed improvement of compressive strength in some cases higher than others (Table 2). For instance, guar gum (2–4% wt.) offered just a slight improvement in strength relative to control sample, whereas SCM presented outstanding performance, with 2.3–3.4 times increase in dry strength for 5–10% wt dosage. Surprisingly, the XRD of CEB containing SCM revealed that no new phases were generated [28]. However, the SEM micrograph revealed a sticking behaviour of SCM that glued the earth particles, possibly responsible for the increased mechanical performance [28]. The same conclusions were obtained by Ouedraogo *et al.* [36] for CEB stabilized with 2–4% wt. of ovalbumin. The authors obtained 2.0–2.3 or 2.8–3.8 times increase in compressive strength depending on the earth used (Soil I and Soil II, respectively). The variation in strength development between formulations was attributed to the differing mineralogical compositions. In addition to quartz, feldspars, and illite, Soil I and Soil II contained montmorillonite and kaolinite, respectively [36]. The presence of expansive clays led to drying cracks, which negatively impacted strength. Interestingly, ovalbumin improved the water resistance of Soil I more than that of Soil II (Table 2), likely due to stronger molecular interactions with the clay particles [36]. In other study, Nouaouria & Nouaouria [38] reported a 2–time increase in compressive strength for CEB stabilized with 1 wt% carob gum, which further increased to 2.8 times at a 2 wt% dosage. The researchers attributed this strength improvement with the same type of gelling and entanglement mechanisms found for SCM by Chantit *et al.* [28], mentioned above. For the same reason, Ma *et al.* [18] reported an approximate 2–time increase in compressive strength after incorporating 1% wt of animal glue or xanthan gum. In addition, the researchers also observed the formation of hydrogen, covalent, and ionic bonds between the biomolecules and clay. The slight difference in compressive strength between the stabilization of CEB with animal glue and Xanthan gum (Table 2) was attributed to their bonding mechanisms: animal glue formed a more cohesive and durable matrix through multiple types of bonds, whereas Xanthan gum primarily interacted through hydrogen bonding and physical entanglement, which led to a slightly weaker structure [18]. Yalley and Manu [11] developed CEB stabilized with 15–30 wt% cow dung and observed that even the lowest dosage effectively prevented disintegration during a 10-minute water immersion (Table 2). They also reported a maximum wet compressive strength of 2.8 MPa for CEB containing 20 wt% cow dung. Kulshreshtha *et al.* [44] attributed the enhanced water resistance of cow dung-stabilized CEB to the presence of naturally occurring hydrophobic, small-sized microbial aggregates in cow dung. Their study demonstrated a marked improvement in water durability, with the first visible crack in the stabilized CEB appearing only after 6 hours of water exposure, in contrast to the complete disintegration of UCEB within a few minutes. Finally, Rivéra-Gomez *et al.* [17] reported air-dry compressive strengths of 3.9, 3.8, and 1.7 MPa for CEB produced with three different clayey soils—Soil I, Soil II, and Soil III, respectively—and stabilized with 3% alginate (Table 2). Based on the Φ values of the CEB made with these soils (Table 1), a higher compressive strength was expected for the block

produced with Soil III due to the lower porosity. However, the CEB made with Soil III exhibited a poorer pore distribution, with an average diameter of 129.9 nm – approximately 2.2 times larger than that of the CEB produced using Soil I.

Table 2 – Compressive strength of organic binder-stabilized CEB and unstabilized CEB (in brackets).

Ref	Binder (wt %)	Compressive strength (MPa)		
		Dry	Air-dry	Wet
[11]	Cow-dung (15–30%)	4.6–5.8 (4.6)	-	0.9–2.8
	Alginate (3%) – Soil I	-	3.9	-
[17]	Alginate (3%) – Soil II	-	3.8	-
	Alginate (3%) – Soil III	-	1.7	-
[18]	Xanthan gum (1%)	-	6.8 (3.6)	-
	Animal glue (1%)	-	7.2 (3.6)	-
[27]	Guar gum (2–4%)	-	2.8–2.9 (2.6)	-
[28]	SCM (5–10%)	7.5–11.1 (3.3)	-	6.7–9.9
[33]	PKO residue (2–8%)	4.0–4.3 (4.0)	-	-
[36]	Ovalbumin (2–4%) – Soil I	10.9–12.9 (5.5)	-	2.9–5.7
	Ovalbumin (2–4%) – Soil II	8.6–11.8 (3.1)	-	4% – 2.6
[38]	Carob gum (1–2%)	-	1.6–2.2 (0.8)	-

Notation: SCM – sugarcane bagasse molasse; PKO – palm kern oil.

For the inorganic stabilization the highest improvements were observed for CEB stabilized with 10 wt% CWA (1.6 times), 10 wt% SCA (1.7 times), 20 wt% WBA (Type B – 2 times), 30 wt% MWIFA (2.4 times), 8 wt% RC (2.7 times), 25 wt% CKD (Soil I – 3.1 times; Soil II – 3.3 times), 15 wt% CCR (4.2 times) and 16:4 wt% CCR:RHA (6.4 times). According to Mebarkia *et al.* [35], the chemical analysis of CKD revealed a high tricalcium silicate (C_3S) content, which is associated with enhancing the durability of clayey soils and a reduction in their swelling behavior. Accordingly, XRD analysis of CEB produced with either Soil I or Soil II and containing 25% CKD revealed the presence of C-S-H despite its low crystallinity. For CEB stabilized with WBA (Type A and Type B), the researchers observed the formation of C-S-H and C-A-H [22]. However, the type B WBA presented a higher content of MgO, characterized by its hydrophobicity [22]. In addition, the reaction between SiO_2 , Al_2O_3 and MgO produced magnesium silicate hydrate (M-S-H) leading to a more compact microstructure [22] and, consequently, higher strength values. For CEB stabilized with CCR or CCR:RHA blends, the XRD patterns revealed the presence of C-S-H and C-A-H in both types of CEB [45]. However, the SEM micrographs of CCR CEB revealed uncemented pores visible in the inter-particle regions, while CCR:RHA CEB exhibited a more cohesive microstructure, with inter-particle zones well cemented. This difference in the microstructure helps explain the greater improvement in compressive strength observed in the CCR:RHA samples. For RC, the improvement in strength can be mainly attributed to the C-S-H covering the earth particles surface and filling the inter-particle regions [3]. In

addition, as mentioned in section 5.1, RC stabilization altered the pore size distribution and pore tortuosity of UCEB, promoting the formation of a less coarse pore structure. In the case of MWIFA, its high CaO content (63.9%) promoted the occurrence of pozzolanic reactions with the aluminosilicates of the earth [10]. Salim *et al.* [32] also suggested the occurrence of pozzolanic reactions when SCA was added. However, the researchers reported a low content of CaO in SCA (2.8%), which makes the strength improvement more likely to be due to a filling effect. Similar conclusions can be drawn from the findings of Salem *et al.* [37] and Elahi *et al.* [30], who reported modest strength improvements – 1.1 to 1.3 times for 4–10 wt% SF and 1.3 to 1.5 times for 10–30 wt% FA, respectively (Table 3) – suggesting limited pozzolanic activity, corroborating the chemical compositions of the materials. In fact, CEB stabilized with FA crumbled upon water immersion regardless of the dosage (Table 3). The remaining studies are those of Latha *et al.* [29], Sekhar *et al.* [31], Benaicha *et al.* [34] and Oubaha *et al.* [19], who stabilized CEB with 5–25 wt% MSWIBA, 25 wt% GGFBS, 1.5–4.5 wt% GP and 20–80 wt% PG, respectively (Table 3). Again, the slight improvements in compressive strength were attributed to the occurrence of pozzolanic reactions. However, in the works of Latha *et al.* [29] and Oubaha *et al.* [19] there was a strength reduction above a certain binder content, suggesting the presence of unreacted particles.

The ratio between wet and dry compressive strengths (wet/dry) is a critical indicator of durability. This ratio was the highest for CEB stabilized with 5–10 wt% SCM (0.89), indicating excellent water resistance (Fig. 6). However, the blocks were only immersed for 2h, evaluating solely the sample's initial water sensitivity. As mentioned in section 4.3, the immersion times and oven-drying temperatures are not standardized across the reviewed literature, which makes the comparison of the wet/dry ratio between studies impossible to perform. Nevertheless, for all reviewed studies the optimal composition presented a wet/dry ratio higher than 0.33 (Fig. 6), considered to be the minimum for CEB to have good durability in outdoor environments [3].

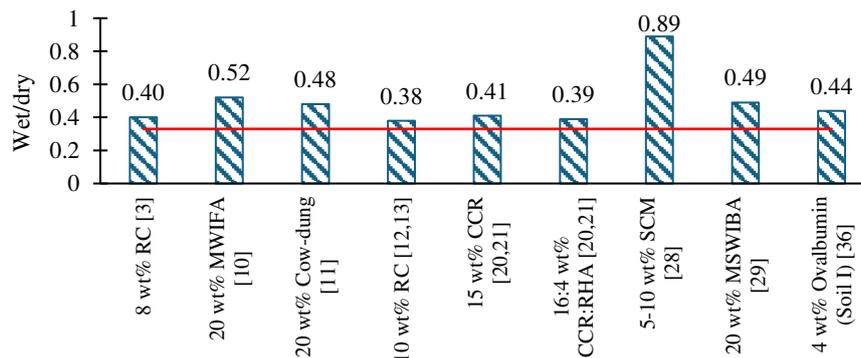


Fig. 6 – Optimal ratio between wet and dry compressive strengths (wet/dry) reported by the authors [3, 10–13, 20, 21, 28, 29, 36] and (in red) the value proposed by [3].

Table 3 – Compressive strength of inorganic binder-stabilized CEB and unstabilized CEB (in brackets).

Ref	Binder (wt %)	Compressive strength (MPa)		
		Dry	Air-dry	Wet
[3]	RC (4–8%)	8% – 12.0 (7.4)	6.0–9.8 (3.6)	8% – 4.8
[10]	MWIFA (10–40%)	2.1–2.9 (1.2)	-	0.7–1.5
[12–15]	RC (5–10%)	10% – 6.5 (2.3)	2.5–4.4 (2.3)	10% – 2.5
[14, 15]	RC (8%)	-	5.5 (2.1)	-
[16]	CWA (10%)	-	3.0 (1.9)	-
[19]	PG (20–80%)	-	1.5–1.0 (1.3)	-
[20, 21]	CCR (5–25%)	3.0–4.6 (1.1)	-	1.6–2.7
	CCR:RHA (20:0– 12:8)	4.4–7.0 (1.1)	-	1.8–2.7
[22]	WBA Type A (5– 20%)	-	13.0–14.3 (12.5)	-
	WBA Type B (5– 20%)	-	13.1–25.9 (12.5)	-
[23]	PWS (60%)	-	4.5	-
[29]	MSWIBA (5–25%)	3.6–4.0 (3.5)	-	1.7–2.0
[30]	FA (10–30%)	0.8–0.9 (0.6)	-	X
[31]	GGBFS (25%)	2.1 (1.5)	-	X
[32]	SCA (3–10%)	2.5–3.8 (2.3)	-	-
[34]	GP (1.5–4.5%)	-	5.8–7.1 (5.0)	-
[35]	CKD (5–25%) – Soil I	-	20.3–26.5 (8.6)	-
	CKD (5–25%) – Soil II	-	15.1–24.7 (7.4)	-
[37]	SF (4–10%)	-	1.8–2.0 (1.6)	-

Notation: RC – recycled cement; MWIFA – medical waste incinerator fly ash; CWA – cotton waste ash; PG – phosphogypsum; CCR – calcium carbide residue; RHA – rice husk ash; WBA – wood biomass ash; PWS – phosphate washing sludge; MSWIBA – municipal solid waste incinerator bottom ash; FA – fly ash; GGBFS – ground granulated blast-furnace slag; SCA – sugarcane bagasse ash; GP – glass powder; CKD – cement kiln dust; SF – silica fume.

5.3 Flexural strength

As observed with compressive strength, incorporating inorganic alternative stabilizers also enhanced CEB flexural strength. Compared to the control samples, the flexural strength increased by maximum of 1.2 times with CKD (Soil I) [35], 1.3 times with 20 wt% MSWIBA [29] and 20 wt% FA [30], 2.3 times with 10 wt% RC

[12], 2.4 times with 10 wt% CWA [16], 2.5 times with 20% WBA type A [22], 2.8 times with 25 wt% CKD (Soil II) [35], 3.3 times with 20 wt% WBA type B [22], and 3.6 times with 30 wt% MWIFA [10] (Table 4). Once again, these improvements can be attributed to hydration and pozzolanic reactions, whose resulting products densify the earth matrix and enhance the flexural strength of the CEB. Meanwhile, Benaicha *et al.* [34] observed a decrease in flexural strength with the addition of 1.5–4.5 wt% GP, despite the previously discussed improvement in compressive strength. The researchers, however, did not provide any explanation for this reduction. Within the studies included in the review, only Rivera-Gómez *et al.* [17] studied the flexural strength of CEB stabilized with organic binders. The authors reported a flexural strength of 0.91, 0.86 and 0.39 MPa for CEB produced with Soil I, II and III, respectively and stabilized with 3 wt% alginate. However, no UCEB was reported as reference. Nevertheless, it is anticipated that the gelling and entanglement mechanisms previously discussed would significantly enhance flexural strength.

Although flexural strength and compressive strength reflect distinct mechanical behaviors, studies [12, 46] have demonstrated a clear correlation between the two. Analysis of the data from the reviewed literature – specifically the reported values of compressive and three-point flexural strengths – reveals a consistent linear relationship, irrespective of the type and content of alternative binders used (Fig. 7). However, the nature of this relationship is influenced by the method employed to determine compressive strength. Notably, differences arise depending on whether the RILEM TC 164 recommendation is followed or if the test is conducted directly on full-sized or halved blocks.

Table 4 – Flexural strength of alternative binder-stabilized CEB and unstabilized CEB (in brackets).

Ref	Binder (wt %)	Flexural strength (MPa)
[10]	MWIFA (10–40%)	0.30–0.49 (0.10)
[12]	RC (5–10%)	0.52–0.93 (0.41)
[16]	CWA (10%)	0.74 (0.31)
[17]	Alginate (3%) – Soil I	0.91
	Alginate (3%) – Soil II	0.86
	Alginate (3%) – Soil III	0.39
[22]	WBA Type A (5–20%)	0.90–1.43 (0.77)
	WBA Type B (5–20%)	1.32–2.50 (0.77)
[29]	MSWIBA (5–25%)	0.40–0.49 (0.38)
[30]	FA (10–30%)	0.21–0.24 (0.18)
[35]	CKD (5–25%) – Soil I	6.33–7.39 (6.08)
	CKD (5–25%) – Soil II	3.20–6.39 (2.32)

Notation: MWIFA – medical waste incinerator fly ash; RC – recycled cement; CWA – cotton waste ash; WBA – wood biomass ash; MSWIBA – municipal solid waste incinerator bottom ash; FA – fly ash; CKD – cement kiln dust.

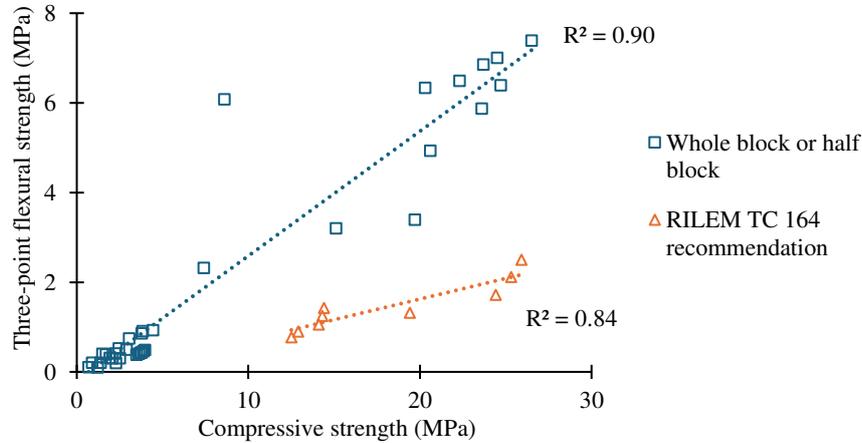


Fig. 7 – Compressive strength as a function of the three-point flexural strength.

6 Conclusions

This systematic literature review explored the potential of low-embodied energy alternative binders to stabilize CEB. From 29 peer-reviewed studies published between 2014 and 2024, this review highlights a growing interest in the use of organic and inorganic waste-derived materials to improve the properties of UCEB while keeping their environmental footprint low.

Both organic and inorganic binders contributed to improved performance, despite it being through different mechanisms. Organic materials such as sugarcane molasses, ovalbumin, alginate, and carob gum enhanced mechanical strength by forming adhesive matrices through gelling and binding effects. These improvements were often achieved without the formation of new mineralogical phases, indicating that physical and chemical interactions between the binders and soil particles played a critical role. In contrast, inorganic binders such as recycled cement, calcium carbide residue, wood biomass ash and cement kiln dust typically improved mechanical performance through pozzolanic and hydration reactions. These reactions led to the development of strengthening phases such as calcium silicate hydrate, calcium aluminate hydrate, and magnesium silicate hydrate, which helped densify the earth matrix and enhance overall block integrity.

In terms of physical properties, the inclusion of alternative binders generally resulted in a reduction in bulk density and a corresponding increase in porosity. However, the extent of this effect varied according to the binder's characteristics and dosage. In addition, compared to UCEB, the compressive strength showed marked improvements, increasing by as much as 6.4 times for CEB stabilized with 16:4 wt% blends of calcium carbide residue and rice husk ash.

Despite these promising outcomes, the review identified the application of different testing procedures for the same property in different studies. This lack of standardization complicates direct comparisons between studies and highlights the

need for harmonized testing protocols. Nevertheless, several organic stabilizers, such as sugarcane molasses and cow dung, introduced encouraging enhancements in CEB durability, with wet/dry strength ratios exceeding the minimum threshold considered suitable for exterior use.

In summary, the findings of this review support the technical viability and environmental benefits of using alternative, low-carbon binders for stabilizing CEB. However, further advancements in this field will require durability testing and the establishment of standardized testing frameworks. These steps are essential for scaling up the adoption of sustainable earth-based construction practices.

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