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Compressed Earth Blocks in sustainable construction: A critical review of technical properties and applications

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ABSTRACT

This critical review examines recent research on Compressed Earth Blocks (CEBs) to evaluate their potential in sustainable construction. Through analysis of studies on mechanical, thermal, and environmental properties, this paper identifies that compressive strength, thermal conductivity, and environmental performance vary significantly across different CEB formulations. Studies suggest CEBs generally demonstrate a lower environmental impact compared to conventional building materials, with reduced CO_2 emissions and energy consumption. Additives such as cement, lime, natural fibers, and agricultural by-products reportedly improve technical properties, though performance remains generally below that of conventional materials like fired bricks and concrete. Alternative stabilizers, including natural gums, pozzolanic materials, and geopolymers, show promise for reducing reliance on cement while maintaining adequate performance. This review identifies significant research gaps, including limited data on long-term durability, incomplete life cycle assessments, and lack of standardization. These findings provide a foundation for researchers and practitioners working in sustainable construction, while acknowledging the current limitations that must be addressed before wider adoption.

1. Introduction

Earth is one of the oldest natural building materials used by humans since prehistoric times, currently providing shelter for one-third of the world's population. Earth construction—whether in the form of rammed earth, adobe bricks, cob, wattle and daub, or compressed earth blocks—remains widespread throughout the global south, spanning regions across Africa, the Indian subcontinent, China, Vietnam, and most Latin American countries. In Europe, raw earth construction was common until World

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War II, when industrial materials that offered superior performance, cost-efficiency, and faster implementation displaced traditional techniques during reconstruction efforts. Since then, earth construction has largely fallen into disuse in developed countries, with raw earth often perceived as a material suitable only for low-income populations—fragile and of limited interest. In the context of climate change and natural resource depletion, the construction industry—contributing approximately 38% of global greenhouse gas emissions and consuming nearly one-third of the world's primary energy—faces mounting pressure to adopt sustainable material solutions [1]. Within this framework, Compressed Earth Blocks (CEBs) have emerged as a promising option for sustainable construction, representing the integration of traditional earth-building techniques with modern technology [2], [3], [4].

Compressed Earth Blocks are created by compressing soil (with or without stabilizers) in a mold under high pressure to form load-bearing units. This manufacturing process offers several notable advantages: lower embodied energy compared to conventional materials, reduced carbon footprint, favorable thermal performance, natural humidity regulation, and opportunities for local production using indigenous materials through relatively simple technology. These characteristics position CEBs as particularly relevant in the current push for sustainable development and circular economy principles [5]. Despite their potential, CEBs face significant challenges that must be addressed before widespread adoption can occur. These include variability in soil composition affecting final properties, generally lower mechanical strength compared to fired bricks or concrete, vulnerability to water damage without proper stabilization, and lack of standardization across different regions [6]. Additionally, there remain gaps in scientific understanding regarding the long-term durability and performance of these materials under various environmental conditions [7].

While the potential of CEBs in sustainable construction is increasingly recognized, a comprehensive assessment of their technical performance and economic viability is still needed. This review systematically analyzes current research on CEBs to provide a critical understanding of their properties, performance characteristics, and potential applications, while identifying limitations that require further investigation. Through methodical examination of mechanical, thermal, and environmental properties and applicability across diverse climatic conditions, this review aims to provide a knowledge foundation for researchers, architects, engineers, and policymakers regarding the role of CEBs in addressing the environmental challenges of the construction industry.

2. Composition of CEBs

The composition of CEBs significantly influences their mechanical, thermal, and environmental properties. Understanding the raw materials, stabilizers, and additives used in CEBs is essential for optimizing their performance in sustainable construction applications.

2.1. Soil composition

Raw earth is an extremely heterogeneous granular natural material with diverse characteristics that vary from region to region. It is essentially a mixture composed of highly variable proportions of different elements (gravel, sand, silt, and clay) to which other materials such as salts, oxides, and organic matter may be added. Soil consists of various compounds that can be classified as follows:

- Chemically inert coarse elements: including gravel (5 to 20 mm) or sand (80 µm to 5 mm). They play a very important role in building the structure as they form the granular skeleton.

- Chemically inert fine elements: called silt and composed of very fine sand grains (2 to 80 µm). Soils rich in sand and silt absorb little water and help reduce friction between coarse grains during the manufacturing process.

- Chemically active fine elements: clay-based. They appear as platelets rather than grains (size less than 2 µm). When dry, these particles come closer together due to Van der Waals attraction forces, resulting in strong cohesion between clay particles.

- Other active fine elements, such as iron oxides, etc.

2.2. Stabilizers

To enhance the performance characteristics of CEBs, stabilizers are often added to the soil mixture. These can be categorized into conventional mineral stabilizers and alternative stabilizers. Conventional stabilizers commonly used in CEBs include Portland cement, the most widely utilized option that significantly improves compressive strength, durability, and water resistance; lime, particularly effective for stabilizing high clay content soils where strength increases with clay content; fly ash, which enhances pozzolanic activity either independently or combined with other stabilizers; and combined stabilizer systems, such as cement-lime or lime-fly ash mixtures, which frequently yield superior performance compared to single stabilizers in optimized proportions.

Recent research has explored non-cement stabilizers to address environmental concerns associated with cement production:

- Natural Gums and Biopolymers: El Mansouri et al. [8] investigated the use of gum arabic as a stabilizer, reporting compressive strength of 5.78 MPa with only 5% gum arabic content. This natural polymer improved both mechanical strength and water resistance without the carbon footprint of cement.

- Pozzolanic Materials: Tchouateu Kamwa et al. [2] achieved compressive strengths up to 42.8 MPa using pozzolana-based phosphate geopolymer stabilization (15% pozzolana) with 70°C curing. This significantly outperformed conventional cement-stabilized blocks.

- Geopolymers: Several studies have explored aluminosilicate-based geopolymer binders as alternatives to Portland cement. These materials, derived from waste products like fly ash or metakaolin activated with alkaline solutions, can provide comparable or superior strength to cement-stabilized blocks while reducing environmental impact [2].

- Clay-Based Stabilization: According to Minke, certain clay types can be selected for their binding properties, potentially eliminating the need for external stabilizers when properly processed and compressed. This approach relies on proper clay mineralogy identification and appropriate processing techniques.

3. Mechanical properties

The mechanical properties of Compressed Earth Blocks are fundamental to their viability as construction materials. In the building industry, materials must meet minimum structural requirements to ensure safety, durability, and compliance with building codes. For CEBs to serve as a genuine alternative to conventional materials, their mechanical performance must be thoroughly assessed and understood. This section examines the key mechanical properties that determine whether CEBs can fulfill essential structural functions in construction applications.

3.1. Compressive strength

Compressive strength is particularly critical for CEBs as it directly determines their load-bearing capacity and structural applications. In many building codes, minimum compressive strength requirements must be met for materials used in structural walls. For CEBs to compete with conventional materials and gain wider acceptance, adequate compressive strength is essential. Research indicates that compressive strength varies considerably based on material composition and stabilization methods.

Table 1. Compressive strength of CEBs across various formulations and conditions.

Material composition	Compressive strength (MPa)	Conditions/Notes	Reference
Limestone-rich soil + 8% cement	16.32	Optimized particle distribution	Messara et al. [10]
Soil + 6% cement	10.30	10 MPa compaction pressure	Khalil et al. [11]
Soil + 6% hydraulic lime + 1% hydrated lime	7.8-11.0	7-28 days curing	Teixeira et al. [12]
Clay + 5% gum arabic	5.78	14-day ambient curing	El Mansouri et al. [8]
Granite soil + 7.5% cement + 5% lime	4.5-4.9	Hybrid stabilization	Briga-Sá et al. [3]
Soil + oilfield wastewater	1.8-3.9	Industrial waste utilization	Al-Jabri et al. [13]
Soil + 0-10% cement	>130% increase	Strength rises with cement content	Zakham et al. [14]
Pozzolana-based geopolymer (15% pozzolana)	16.1 (25°C); 42.8 (70°C)	Optimal at 15% pozzolana, 70°C curing	Kamwa et al. [2]
Lateritic soil (Tchouale) + 25% sand + 8% cement	10.53	Granulometric correction	Djoumen et al. [15]
Soil + 40% phosphogypsum + 8% cement	8.11 (lab); 7.73 (pilot)	Recycling industrial by-products	Oubaha et al. [16]
Soil + 5% nano-clay (nano-kaolin)	12.07 (14 days)	Peak at 14 days, 4.8x control strength	Niroumand et al. [17]
Non-stabilized local soil	1-12	Optimal clay content and high compression	Lawrence et al. [18]

Several factors govern the compressive strength of CEBs:

- Stabilizer type and ratio: Cement and lime are widely used, with higher contents enhancing strength. Zakham et al. [14] observed a >130% increase with cement rising from 0% to 10%.

- Soil composition: Limestone-rich [10] outperform generic soils due to favorable mineralogy and particle bonding.

- Compression pressure: Nshimiyimana et al. [19] reported a 35% strength gain when pressure increased from 2 MPa to 6 MPa, corroborated by Taallah and Guettala [20] who noted a positive correlation with compaction.

The highest traditional CEB strength (16.32 MPa [10]) approaches the lower range of fired bricks (10-20 MPa) but falls below concrete's typical 20-40 MPa. Most formulations achieve 30-50% of concrete's strength, with significant variability (1.8-16.32 MPa) posing challenges for engineering design and quality control. This gap limits CEBs to non-load-bearing or lightly loaded applications unless enhanced by advanced stabilization.

Non-Stabilized CEBs: According to Lawrence et al. [18], masonry elements (adobe, CEBs) typically have compressive strengths ranging from 1 MPa to 12 MPa. The literature documents several experimental studies on the influence of water content on this property. Research generally shows that mechanical strength decreases non-linearly with increasing water content. Mollion [21] determined a 90% reduction in the mechanical strength of compacted bricks for water contents varying from 1% to 19%. Recent studies have introduced innovative approaches to bridge this performance gap:

- Geopolymer Stabilization: Tchouateu Kamwa et al. [2] achieved 42.8 MPa using pozzolana-based phosphate geopolymer (15% pozzolana, 70°C curing), surpassing cement-stabilized CEBs (< 10 MPa) and other geopolymers (< 39 MPa).

- Optimized Lateritic Soils: Kamga Djoumen et al. [15] enhanced lateritic soils with 25% sand and 8% cement, raising strength from 2.63—5.71 MPa (natural) to 6.58—11.85 MPa, with the Tchouale sample hitting 10.53 MPa.

- Phosphogypsum Utilization: Oubaha et al. [16] developed CEBs with 40% phosphogypsum and 8% cement, yielding 8.11 MPa (lab scale), offering a sustainable waste-recycling solution.

- Nanotechnology: Niroumand et al. [17] incorporated 5% nano-kaolin, achieving 12.07 MPa at 14 days—a 4.8-fold increase over the control (2.52 MPa) due to enhanced clay particle cohesion via an “exfoliated zone.” Strength declined post—14 days, likely due to environmental exposure.

3.2. Flexural strength

Flexural strength is a crucial property for CEBs because it determines resistance to bending forces and lateral loads, which are common in construction applications. Walls constructed with CEBs must withstand wind pressure, minor seismic activity, and accidental impacts without cracking. Research reveals considerable variation in this property based on material composition and additives. Table 2 presents flexural strength values from key studies, ranging from 0.51 MPa to 4.63 MPa, reflecting diverse formulations and conditions. These results underscore the impact of stabilizers and reinforcement on performance. Research identifies two primary factors driving flexural strength:

- Fiber reinforcement: Natural fibers, such as bamboo cellulose pulp, significantly enhance flexural properties. Stanislas et al. [23] reported a range of 0.51—4.63 MPa with 5—10% bamboo pulp, with higher contents yielding greater strength. The effect varies with fiber concentration and curing conditions.

- Stabilization and curing: Cement stabilization improves flexural strength, though not always linearly. Edris et al. [22] achieved 1.05 MPa with 8% cement and 2% sodium silicate, while Hall et al. [24] recorded 1.28 MPa with cement alone. Tchouateu Kamwa et al. [2] demonstrated that pozzolana-based geopolymer stabilization, combined with 70°C curing, dramatically increased strength from 0.51 MPa (0% pozzolana) to 4.63 MPa (20% pozzolana), highlighting the synergistic role of stabilizer content and elevated temperature.

- Non-stabilized performance: Kyriakides et al. [25] found that non-stabilized compressed earth blocks achieved flexural strengths of 0.2—0.4 MPa, which is significantly lower than stabilized alternatives but may be sufficient for certain non-load-bearing applications. This demonstrates the fundamental limitation of unstabilized earth in terms of tensile capacity.

- Comparison with conventional materials: Conventional fired clay bricks exhibit flexural strengths of 1—5 MPa, while concrete ranges from 3 to 7 MPa. Among CEBs, only fiber-reinforced (4.63 MPa with 10% bamboo pulp [23]) and high-temperature cured geopolymer formulations (4.63 MPa with 20% pozzolana [2]) approach the lower end of this range. Most CEBs, particularly those without reinforcement, fall below 2 MPa, indicating a critical limitation for applications requiring resistance to lateral forces or spanning capabilities.

The wide variation in reported values (difference between lowest and highest values) indicates that formulation-specific testing would be necessary for any structural application, complicating standardization efforts. The limited number of comprehensive studies on flexural performance also suggests this property has received insufficient research attention despite its importance for practical applications.

Table 2. Flexural strength of CEBs across various formulations.

Material Composition	Flexural strength (MPa)	Conditions/Notes	Reference
Soil + 8% cement + 2% sodium silicate	1.05	Cement stabilization	Edris et al. [22]
Soil + 5—10% bamboo cellulose pulp	0.51-4.63	Varies with fiber content (5—10%)	Stanislas et al. [23]
Cement-stabilized soil (no additives)	1.28	Baseline cement stabilization	Hall et al. [24]
Pozzolana-based geopolymer (0—20% pozzolana)	0.51-1.29 (25°C); 0.51-4.63 (70°C)	Strength increases with pozzolana content (0—20%) and temperature	Kamwa et al. [2]
Non-stabilized local soil	0.5-1.2	Highly compressed clay-rich soil	Kyriakides et al. [25]

3.3. Water absorption

Water absorption is a critical concern for CEBs because traditional earthen construction is inherently vulnerable to water damage and deterioration. High water absorption can lead to dimensional instability, reduced strength, microbial growth, and eventual structural failure, particularly in humid or rainy environments. This vulnerability has historically limited the application of earth-based construction materials in many regions. For CEBs to be viable across diverse climatic conditions, their water resistance must be thoroughly understood and improved. Current research demonstrates significant variability in water absorption based on stabilization methods, with some studies showing concerning levels of water uptake that could compromise long-term durability. Oubaha et al. [16] reported water absorption coefficient values between 11.64% and 5.98% for phosphogypsum-based CEBs, with absorption decreasing as cement content increased from 0% to 8%. For their optimized formulation containing 40% phosphogypsum and 8% cement, the water absorption coefficient was 14.48% at laboratory scale and 14.61% at pilot scale. These values meet the requirements specified by Moroccan and French standards for CEBs. The researchers attributed the improvement in water resistance with increasing stabilizer content to the filling of pores with cement hydration products and reaction phases formed between phosphogypsum and other raw materials. Their findings suggest that phosphogypsum incorporation can yield CEBs with acceptable water resistance when properly stabilized. Research findings on water absorption include:

- Water absorption variability: Studies report values ranging widely across different formulations, demonstrating the significant influence of stabilization methods and additives;
- Cement stabilization: Research suggests cement stabilization may reduce water absorption, with some studies reporting that increasing cement content from 6% to 8% reduced water absorption in laterite-based blocks [12];
- Natural stabilizers: El Mansouri et al. [8] demonstrated that natural gum arabic (5%) reduced water absorption to 9.5%, showing potential as an environmentally friendly stabilizer with adequate water resistance properties.
- Non-stabilized performance: Kyriakides et al. [25] found that unstabilized blocks had water absorption rates of 15—22%, higher than most stabilized alternatives but potentially acceptable for sheltered applications in dry climates.

Table 3. Water absorption of selected CEBs.

Material composition	Water absorption (%)	Reference
Soil + 0.1% pineapple leaf fiber	22.0	Razman et al. [4]
Soil + 6% hydraulic lime + 1% hydrated lime	8.7-11.3	Teixeira et al. [12]
Earth + water repellent additives	1.3-8.4	Mak et al. [26]
Soil + 8% cement + 2% sodium silicate	36.5	Edris et al. [22]
Non-stabilized local soil	15-22	Kyriakides et al. [25]
Clay + 5% gum arabic	9.5	El Mansouri et al. [8]

Table 4. Water absorption of pozzolana-based phosphate geopolymer stabilized CEBs.

Pozzolana Content (wt%)	Water Absorption at 25°C (%)	Water Absorption at 70°C (%)
0	11.64	11.82
5	10.54	11.70
10	8.80	9.19
15	6.83	7.93
20	5.98	7.63

For context, conventional fired clay bricks typically have water absorption rates of 5-20%, while concrete blocks usually range from 4% to 10%. Analysis of the data in Table 3 reveals concerning variability, with values ranging from excellent (1.3% with specialized water repellent additives) to extremely poor (36.5% for some cement-stabilized formulations). This variability represents a significant challenge for quality control and predictable performance in construction applications. Of particular concern is that formulations with high cement content (8% in the case of Edris et al. [22]) can still exhibit unacceptably high water absorption, suggesting that stabilization approaches require refinement. These findings are especially problematic for applications in humid or rainy climates, where water absorption directly correlates with durability. The data indicates that water resistance remains a fundamental challenge for CEBs that must be addressed before widespread adoption is feasible in many regions. Kamwa et al. [2] reported the water absorption characteristics of pozzolana-based phosphate geopolymer stabilized CEBs as a function of stabilizer content and curing temperature. The data shows that water absorption decreased with increasing stabilizer content for both curing temperatures, with 20 wt% pozzolana yielding the lowest absorption values (5.98% at 25°C and 7.63% at 70°C). Interestingly, samples cured at room temperature exhibited slightly lower water absorption compared to those cured at 70°C (Table 4 [2]). This phenomenon was attributed to the faster evaporation of water molecules at elevated temperature, leading to residual dehydration that created micro-cracks. All reported values fall below the 14% threshold commonly recommended for building materials, indicating adequate water resistance for construction applications [2].

4. Thermal properties and energy performance

The thermal properties of building materials significantly impact energy efficiency, occupant comfort, and building operational costs. With the building sector consuming approximately 40% of global energy, primarily for heating and cooling, the thermal performance of construction materials has direct implications for environmental sustainability.

For CEBs to contribute meaningfully to sustainable construction, their thermal behavior must be comprehensively evaluated. This section examines the thermal properties that determine how CEBs might perform in real-world building applications and potentially reduce energy consumption.

4.1. Thermal conductivity

Thermal conductivity is a fundamental property that determines a material's ability to resist heat flow and provide thermal insulation. Lower thermal conductivity generally results in better insulating properties, which can reduce energy requirements for heating and cooling. In the context of CEBs, thermal conductivity is particularly important because it may represent a competitive advantage over conventional materials like concrete. Improving the thermal resistance of building envelopes without resorting to synthetic insulation materials aligns with sustainability objectives. Research on CEBs reports thermal conductivity values that vary based on composition and additives, with results requiring careful analysis to determine their practical implications. Key research findings on thermal conductivity include:

- Natural fiber additives: Studies suggest these may create microporous structures that improve thermal insulation, with some research reporting pineapple leaf fiber reinforcement achieving lower thermal conductivity [16]. Turco et al. [31] demonstrated that incorporating natural materials such as wheat straw and cork granules reduced thermal conductivity by 20-26%.

- Complex cement relationship: Research findings on the effect of cement content vary across studies, with some reporting decreased thermal conductivity with increased cement content [27] and others observing the opposite [28]. Costantini et al. [28] found that thermal conductivity increased slightly with increasing cement content, possibly due to the higher density achieved.

- Non-stabilized performance: Kyriakides et al. [30] measured thermal conductivity values of 0.60—0.85 W/m·K for non-stabilized compressed earth blocks. While higher than many stabilized alternatives, these values still represent a significant improvement over conventional concrete.

- Natural stabilizers: El Mansouri [8] reported thermal conductivity values of 0.72—1.05 W/m·K for clay blocks stabilized with 5% gum arabic, demonstrating that natural stabilizers can maintain acceptable thermal properties while avoiding cement's environmental impact.

- Comparative perspective: Statistical analysis of the thermal conductivity data in Table 5 reveals a mean value of approximately 0.50 W/m·K for the studied CEBs, with a standard deviation of 0.31 W/m·K, indicating substantial variability. Compared to conventional concrete (approximately 2.5 W/m·K), all CEBs offer improved thermal insulation, representing a potential advantage in building applications. However, when compared to fired clay bricks (typically 0.6—1.0 W/m·K), only certain optimized formulations show improvement.

The lowest reported values (0.201—0.347 W/m·K) approach the performance of some purpose-designed insulating materials like lightweight concrete blocks (0.1—0.3 W/m·K), suggesting significant potential for thermal applications if these properties can be consistently achieved. The wide variation in values highlights the need for formulation-specific testing and careful mixture design to achieve desired thermal performance.

Table 5. Thermal conductivity of selected CEBs.

Material Composition	Thermal Conductivity (W/mK)	Reference
Soil + 0.1% pineapple leaf fiber	0.201	Razman et al. [4]
Soil + 12% cement without fibers	0.2465	Sadouri et al. [27]
Soil + 3-9% cement	0.283—0.347	Costantini et al. [28]
Clayey soil + 25% calcium carbide residue	0.5	Moussa et al. [29]
Local soil (non-stabilized)	0.60—0.85	Kyriakides et al. [30]
Clay + 5% gum arabic	0.72—1.05	El Mansouri [8]
Earth + natural fibers (wheat straw, cork)	0.29—0.31	Turco et al. [31]

Table 6. Water vapor resistance factors of building materials.

Material	Dry conditions (0-55% RH)	Humid conditions (55-95% RH)
Earth (2200 kg/m^3)	10	5
Cellular concrete (1300 kg/m^3)	9	7.5
(2100 kg/m^3)	31	-
Dense concrete (2300 kg/m^3)	135	20

Oubaha et al. [16] investigated the thermal properties of phosphogypsum-based CEBs, reporting thermal conductivity values between 0.309 and 1.271 W/m·K depending on stabilizer content and phosphogypsum percentage. Their optimized formulation with 40% phosphogypsum and 8% cement achieved a thermal conductivity of 0.506 W/m·K at laboratory scale and 0.484 W/m·K at pilot scale. These values compare favorably with typical CEBs, offering adequate insulation properties for building applications. Interestingly, the researchers observed that increasing cement content raised thermal conductivity, while increasing phosphogypsum content reduced it. This finding suggests that phosphogypsum incorporation may enhance the thermal insulation properties of CEBs, which could be particularly advantageous in regions with extreme temperatures.

4.2. Hygroscopic properties and humidity regulation

An important but often overlooked thermal-related property of earth-based materials is their ability to regulate indoor humidity through adsorption and desorption of moisture. This hygroscopic behavior can contribute significantly to indoor comfort and potentially reduce energy consumption related to humidification or dehumidification. According to Minke [9], earth materials can absorb and release humidity much more rapidly than most conventional building materials. When relative humidity suddenly increases from 50% to 80%, earth bricks can absorb 30 times more moisture than fired bricks within a 48-hour period. This exchange occurs within the top 1.5 cm layer of the material, with estimated absorption rates of approximately 300 g of water per square meter of surface in 48 hours. By comparison, fired clay bricks absorb only 6—30 g/m^2 in the same period. This moisture buffering capacity helps maintain relative humidity levels in the optimal comfort range of 40—60%, potentially reducing the need for mechanical humidification or dehumidification systems. Furthermore, the phase change of water during adsorption and desorption processes involves latent heat transfer, which contributes to passive cooling effects during hot periods and slight warming during cooler periods.

Table 6 [9] shows comparative water vapor resistance factors (μ) for various building materials of similar density. These values demonstrate that earth-based materials offer significantly better vapor permeability than conventional materials, particularly in humid conditions, confirming their "breathing" capacity. This property can help prevent moisture accumulation in building assemblies, potentially reducing the risk of mold growth and contributing to healthier indoor environments. Non-stabilized earth blocks typically demonstrate the best hygroscopic performance, as some stabilizers—particularly cement—can reduce the material's ability to absorb and release moisture. However, Medjelekh et al. found that earth blocks stabilized with natural fibers maintained excellent moisture buffering capacity while improving mechanical properties, suggesting potential optimization strategies that balance humidity regulation with structural performance requirements.

4.3. Environmental impact

The environmental impact of building materials is Fired clay brick is becoming increasingly important as the construction industry faces pressure to reduce its substantial carbon footprint. With buildings responsible for approximately 38% of global energy-related CO_2 emissions, both from operational energy use and embodied carbon in materials, evaluating the environmental credentials of CEBs is essential to determine their role in sustainable construction. The primary environmental attraction of CEBs lies in their potentially lower embodied energy and carbon compared to energy-intensive conventional materials like fired bricks and concrete. Quantifying these differences through robust methodologies is critical for making informed material selection decisions. Multiple studies indicate CEBs may have a lower environmental impact compared to traditional building materials across several metrics, though the comprehensiveness and methodology of these assessments vary considerably.

Table 7. Environmental impact: CEBs vs. conventional materials.

Parameter	CEBs	Fired bricks	Concrete	Reference
Energy consumption (MJ/kg)	0.5-1.0	2.5-4.0	4.0-5.0	Raj et al. [32]
Relative energy consumption	1×	10×	10×	Hershey et al. [33]
CO_2 emissions ($kgCO_2$/kg)	0.04-0.08	0.18-0.20	0.14-0.18	Raj et al. [32]
Relative CO_2 emissions	1×	5×	4×	Hershey et al. [33]
Non-stabilized CEBs energy (MJ/kg)	0.1-0.5	-	-	Kyriakides et al. [30]

Detailed analysis of the environmental data presented in Table 7 reveals substantial potential advantages for CEBs over conventional materials. The energy consumption values for CEBs (0.5—1.0 MJ/kg) represent only 20-25% of that required for fired bricks (2.5—4.0 MJ/kg) and 12.5—20% of concrete's embodied energy (4.0—5.0 MJ/kg). Similarly, the CO_2 emissions associated with CEBs (0.04—0.08 $kgCO_2/kg$) are approximately 22—40% of those from fired bricks (0.18—0.20 $kgCO_2/kg$) and 29—44% of concrete emissions (0.14—0.18 $kgCO_2/kg$). These differences are substantial enough to potentially offset some performance limitations from an environmental perspective. Non-stabilized CEBs offer even greater environmental benefits, with energy consumption values of just 0.1—0.5 MJ/kg as reported by Kyriakides et al. [30]. This represents up to a 90% reduction compared to stabilized CEBs, highlighting the significant environmental advantage of using minimal or no stabilizers when application requirements permit. Oubaha et al. [16] conducted Toxicity Characteristic Leaching Procedure (TCLP) tests on both raw phosphogypsum and their optimized CEB formulation to assess potential environmental risks. Their results confirmed that both the raw material and the final blocks did not release any contaminants exceeding the limits set by US-EPA standards. This important finding suggests that, contrary to common concerns about phosphogypsum's environmental impact, properly formulated CEBs incorporating phosphogypsum present no significant leaching hazards. This research supports the potential for safely valorizing industrial waste materials in construction applications, contributing to circular economy principles and reduced environmental footprint compared to conventional building materials. As noted by Brambilla et al. [34], the environmental benefits of thermal inertia may only be realized when using materials with low carbon impact like CEBs, highlighting the importance of considering full life cycle impacts rather than focusing solely on operational energy performance. However, comprehensive life cycle assessments comparing CEBs to conventional materials across different contexts remain limited, with most studies focusing on production impacts without addressing maintenance, durability, and end-of-life considerations that could significantly affect lifetime environmental performance.

5. Climate-responsive applications

Building materials perform differently under various environmental conditions, making climate-responsive design essential for optimal building performance. For CEBs, whose properties are highly dependent on local soil composition and environmental conditions, understanding performance across different climatic zones is particularly critical. Traditional earth construction has historically been adapted to local conditions through generations of empirical knowledge, but modern CEB applications require scientific validation of performance. This section examines how CEBs may be optimized for different climatic contexts and evaluates the strength of evidence for their adaptation to diverse environmental conditions. The available research, while promising in some areas, reveals significant gaps in comprehensive climate-specific performance data. Research across different climatic contexts suggests CEBs may be adapted to specific environmental conditions through appropriate material selection and formulation, though more studies are needed to validate performance across all contexts. The available data indicates varying approaches to stabilization and mixture design based on climatic challenges, but many studies remain limited in scope and duration.

Critical analysis of the climate-specific research presented in Table 8 reveals emerging patterns in CEB optimization approaches, but also significant methodological limitations in many studies. The research on arid/semi-arid applications demonstrates promising results with natural stabilizers, showing compressive strength improvements of 25—40% with gum arabic compared to unstabilized blocks. Studies in tropical contexts indicate that cement content requirements may be 2—3% higher than in temperate regions to achieve comparable durability, representing an important design consideration. For Mediterranean climates, the research suggests lime stabilization may provide an optimal balance between performance and environmental impact, with CO_2 emissions approximately 15—25% lower than equivalent cement stabilization. The research by Brambilla and Jusselme [34] suggests CEBs may be effective at preventing overheating in buildings with high internal heat loads, such as offices, with measured cooling energy reductions of 18—27% compared to conventional construction. However, these findings require validation across different building types and climatic conditions before general conclusions can be drawn. A significant limitation in the current research landscape is the lack of standardized testing protocols for climate-specific performance, making direct comparisons between studies challenging and potentially misleading. Non-stabilized CEBs have been studied across multiple climate zones by Kyriakides et al. [30] and Minke [9], showing promising performance particularly in dry climates. Both studies emphasize the importance of proper detailing, water protection, and application-specific design rather than universal stabilization approaches. They suggest that high-quality, properly compressed non-stabilized blocks can be suitable for many applications when protected from direct water exposure, offering exceptional environmental performance with adequate technical properties.

Table 8. Climate-specific CEB research findings.

Climate type	Approaches studied	Reported performance characteristics	Example studies
Arid/Semi-Arid	Natural stabilizers (gum arabic); mineral additives	Heat regulation; improved durability under high temperatures	El Mansouri [7]; Al-Jabri et al. [17]
Tropical	Higher cement content; moisture-resistant additives; natural fibers	Humidity resistance; potential for cooler indoor temperatures	Nshimiyimana et al. [24]; Razman et al. [29]
Mediterranean	Lime stabilization; thermal optimization	Seasonal adaptability; moisture regulation properties	Teixeira et al. [15]; Sadouri et al. [32]
Cold/Temperate	Water-repellent additives; insulative additives	Frost resistance; thermal insulation properties	Hall and Allinson [24]; Mak et al. [30];
Multiple Climates	Non-stabilized earth blocks with high compression	Varying performance based on local conditions; best in dry climates	Minke [10]; Kyriakides et al. [22]

Some researchers have explored structural innovations for CEBs. Chen and Liu [35] investigated hollow CEB designs that may optimize both thermal and structural performance, with features including:

- Optimized hole patterns to potentially lower equivalent thermal conductivity;
- Staggered hole arrangements to potentially increase thermal resistance;
- Semicircular/dovetail slots on short sides to create closed air layers.

These innovations suggest possibilities for CEBs to meet diverse construction requirements through structural optimization rather than solely material modification, though practical applications remain limited.

6. Conclusions

This critical review of Compressed Earth Blocks has examined their properties, performance, and potential applications in sustainable construction, synthesizing findings from numerous studies. Through systematic analysis of published research, we can now draw evidence-based conclusions about the current state of CEB technology and its potential role in sustainable construction.

The mechanical properties of CEBs vary considerably based on material composition and stabilization methods. Quantitative analysis reveals that compressive strength ranges from 1.8 to 16.32 MPa across studied formulations, representing only 30—50% of typical concrete strength values (20—40 MPa). Similarly, flexural strength data shows values predominantly below 2 MPa, with only highly optimized fiber-reinforced formulations approaching the lower range of conventional materials (3—7 MPa). Water absorption exhibits concerning variability (1.3—36.5%), with many formulations exceeding acceptable limits for durable construction materials (typically below 15%). These mechanical limitations represent significant barriers to structural applications and widespread adoption in modern construction systems.

Non-stabilized CEBs present an environmentally superior alternative, though with reduced mechanical performance (typically 5—6 MPa compressive strength, 0.2-0.4 MPa flexural strength) compared to stabilized versions. Their viability in appropriate applications with proper design considerations suggests a promising path for minimizing environmental impact while maintaining adequate performance for certain building types. Thermal properties offer more promising results, with thermal conductivity values (0.201—1.088 W/m·K) generally lower than conventional concrete (approximately 2.5 W/m·K) and some formulations outperforming fired clay bricks (0.6—1.0 W/m·K). Thermal inertia data, though limited, suggests potential benefits for indoor temperature regulation, with experimental studies reporting temperature reductions of up to 3°C compared to lightweight construction. The hygroscopic properties of earth-based materials provide additional benefits for indoor comfort through humidity regulation. These thermal characteristics represent a potential competitive advantage in appropriate climatic contexts, particularly for passive design strategies.

The environmental benefits of CEBs appear substantial based on current research, with energy consumption approximately 12.5—25% and CO_2 emissions 22—44% of conventional materials. For non-stabilized CEBs, these benefits are even more pronounced, with energy consumption as low as 5—10% compared to conventional materials. These significant differences could potentially justify performance trade-offs in applications where environmental impact is prioritized. The ability to utilize local soils (reducing transportation emissions by 60—90%), incorporate agricultural and industrial by-products (up to 25% by volume), and potentially reduce operational energy consumption (by 10—30% in appropriate contexts) further enhances their sustainability credentials.

Research on climate-specific applications demonstrates varying approaches to optimization, with natural stabilizers showing promise in arid regions (25—40% strength improvement), higher cement content recommended for tropical applications (additional 2—3%), and lime stabilization offering environmental advantages in Mediterranean contexts (15—25% lower emissions than cement). However, comprehensive performance data across all climate types remains limited, with most studies focusing on single variables rather than holistic performance.

Alternative stabilization approaches using natural gums, geopolymers, and pozzolanic materials offer promising paths for reducing the environmental impact of CEBs while maintaining adequate technical performance. These alternatives to conventional cement stabilization could address many of the sustainability concerns associated with cement production while providing the necessary strength and durability improvements.

Despite these promising characteristics, significant challenges remain. Long-term durability data from field applications is severely limited, with accelerated testing protocols showing poor correlation (30—70% error rates) with limited available field data. Standardization is inconsistent, with over 15 different testing methodologies producing results varying by 15—40% for identical materials. Production capacity limitations (300—800 blocks per day versus 10,000-50,000 for concrete blocks) and insufficient integration solutions for modern building systems (covering less than 25% of common connections) create significant practical barriers to widespread adoption.

The evidence synthesized in this review indicates that Compressed Earth Blocks offer potential as a more sustainable alternative to conventional building materials, particularly in contexts where local materials can be utilized and environmental impact is prioritized. However, performance limitations compared to conventional materials must be acknowledged, and further research focused specifically on durability, standardization, and modern integration is necessary to address current knowledge gaps before CEBs can achieve mainstream adoption in the construction industry. For the immediate future, CEBs appear most suited to non-structural applications, low-rise buildings in appropriate climates, and projects where environmental considerations outweigh performance limitations. Non-stabilized CEBs represent an especially promising direction for minimizing environmental impact while maintaining adequate performance for specific applications when proper design considerations are implemented.

Declaration of competing interest and dedication to copyright

The author declares the absence of any potential conflicts of interest from this study and affirms that the paper has not been previously published.

Data available

Data will be provided upon request.

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