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Review

Effect of Fiber Addition on Mechanical and Thermal Properties of Compressed Earth Blocks

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Abstract

Compressed earth blocks (CEBs) represent a sustainable and low-carbon alternative to conventional construction materials. The performance of CEBs is strongly governed by the physical and chemical properties of the raw earth, including the chemical and mineralogical composition of the clay fraction, particle size distribution (PSD), and plasticity characteristics. This review examines how these fundamental soil properties influence the mechanical, thermal, and hydric behavior of CEBs. Particular attention is given to the incorporation of natural fibers as an eco-friendly reinforcement strategy. The addition of fibers such as wheat straw, sawdust, or other plant-based materials significantly modifies both mechanical and thermal properties by increasing porosity, reducing bulk density, and providing crack-bridging mechanisms. While optimal fiber contents improve compressive strength, flexural strength, and ductility, they also enhance thermal insulation by lowering thermal conductivity and diffusivity. This review presents the effect of adding fibers on the mechanical and thermal properties of compressed brick blocks.

1. Introduction

The growing demand for sustainable and environmentally friendly building materials has renewed interest in earthen construction techniques [1], [2]. Compressed earth blocks (CEBs) have emerged as a viable alternative to conventional fired bricks and concrete blocks due to their low embodied energy, recyclability, and excellent hygrothermal regulation capabilities. However, the performance of these blocks is highly dependent on the intrinsic properties of the source soil material[3], [4].

The physicochemical characteristics of earth play a decisive role in determining the final quality of CEBs. Key parameters such as the chemical and mineralogical composition of the clay fraction, particle size distribution, and plasticity significantly affect compaction behavior, porosity development, and the overall matrix cohesion. Clays with different structures (kaolinite versus smectite or illite) exhibit varying binding capacities, swelling potential, and interaction with additives, directly influencing the mechanical strength and durability of the final product[5], [6].

Understanding particle size distribution and plasticity limits is essential for optimizing the mix design of CEBs. Standards and guidelines recommend specific ranges of clay, silt, sand,

and gravel contents to achieve adequate strength while maintaining workability. Deviations from these optimal proportions can lead to excessive shrinkage, low compressive strength, or poor water resistance, limiting the structural application of earthen materials[7], [8].

To overcome the inherent brittleness and limited tensile strength of unstabilized earth, the incorporation of natural fibers has gained considerable attention in recent years. Fibers such as wheat straw, hemp, or sawdust act as internal reinforcement, bridging micro-cracks and improving the post-cracking behavior of CEBs. This approach not only enhances mechanical performance but also contributes to reducing the reliance on energy-intensive stabilizers such as cement or lime[9], [10].

This review paper aims to provide a comprehensive analysis of the effect of fiber addition on the mechanical and thermal properties of compressed earth blocks. It begins with a detailed examination of the physical and chemical properties of earth, followed by an in-depth discussion of how natural fiber reinforcement modifies the mechanical strength, ductility, and thermal insulation characteristics of CEBs.

2.Physical and chemical properties of earth

The physicochemical properties of soil are fundamental determinants of the overall performance of earthen construction materials. Key parameters, including particle size distribution, plasticity, and chemical/mineralogical composition, significantly dictate the material's compaction behavior, porosity, and density. Consequently, these structural variables govern the resulting mechanical, thermal, and hygro-thermal properties, as well as the long-term durability of the stabilized or unstabilized earthen matrix

2.1. Chemical and Mineralogical Composition of the Clay Fraction

The type of clay minerals present in the soil is a primary factor influencing the physical, hydric, and mechanical behavior of earthen construction materials[11], [12] . Due to their distinct structures and chemical properties, different clays respond uniquely to mechanical and environmental actions [13].

Clay minerals are broadly categorized by their structure. "Two-layer" clays, such as kaolinite, are characterized by a low specific surface area, low cation exchange capacity, and a low plasticity index. Consequently, they exhibit limited swelling and shrinkage during wetting and drying cycles. However, this also means they act as relatively weak binders for the coarser soil fractions. In contrast, "three-layer" clays possess a high specific surface area, high cation exchange capacity, and high plasticity index, making them effective binders. This category is further divided into swelling clays (like smectites, e.g., bentonite) and non-swelling clays [14].

The impact of clay type is illustrated by Liuzzi et al. [15], who studied three soil mixtures with a consistent sand (58%), gravel (2%), and total clay (40%) content. The clay fraction itself varied: it was composed of either 40% or 33% clay quarry fines, supplemented with 0% or 7% kaolinite, and 0% or 7% bentonite. The mixture containing 33% quarry fines and 7% bentonite demonstrated superior water vapor permeability, higher sorption isotherm, and greater moisture buffer capacity. This enhanced performance was attributed to the high specific surface area and pore volume of bentonite, a swelling smectite clay[15] . This confirms that bentonite has a greater capacity to adsorb, release, and regulate moisture compared to the less reactive kaolinite. These findings are further supported by the work of Fionn et al. [16].

However, mineralogical composition alone is insufficient for predicting soil behavior; a complementary chemical analysis is crucial[17]. For instance, Mkaouar et al. [17] studied three soils, each composed of 70% sand and 30% clay, but with different clay mineralogies and chemical compositions. Soil A1 contained 13.58% kaolinite (K), 25.7% illite (I), 11.82% smectite (S), and 48.90% quartz (Q). Soil A2 was composed of 25.3% K, 45.83% I, 38.9% S, and 24.98% Q. Soil A3 consisted of 38.34% K, 24.89% I, 18.74% S, and 18.03% Q. The study found that soil A1 had the highest compressive strength, followed by A2, and then A3. This ranking was explained by the higher content of potassium oxide (K_2O), ferric oxide (Fe_2O_3), and sodium oxide (Na_2O) in soils A1 and A2, which act as densifiers for clays [17]**.**

These oxides contribute to improved soil properties through several mechanisms:

-Ferric oxide (Fe_2O_3) forms coatings on clay particles, masking their permanent surface charges [18]. This process reduces repulsion between particles, limits dispersion, promotes aggregation, and improves overall cohesion. It also decreases water uptake and swelling, enhancing aggregate stability [18].

-Sodium and potassium oxides (Na_2O, K_2O) react with water to form hydroxides (NaOH, KOH). These hydroxides then interact with silica (Si) and alumina (Al) from the clay to form silicate and aluminate gels (e.g., Na_2SiO_3, $KAlO_2$). These gels contribute to the development of a strong, three-dimensional structure that enhances mechanical strength and reduces shrinkage[19], [20] .

Furthermore, the mass ratio of silicon dioxide (SiO_2) to aluminum oxide (Al_2O_3) serves as a useful indicator [17]. For pure kaolinite, this ratio is approximately 1.18, while for montmorillonite, it ranges from 2.36 to 3.31 [17]. A high SiO_2/Al_2O_3 ratio often indicates a significant presence of quartz relative to clay minerals [21]. In such cases, the clay binder may be insufficient to achieve good cohesion between aggregates, leading to a weaker material with reduced adsorption/desorption capacity and lower hydric and mechanical performance [21].

2.2. Particle Size Distribution

Particle size distribution (PSD), or soil texture, refers to the distribution of different particle types and sizes such as clay, silt, sand, and gravel that constitute the soil[22] . PSD is a fundamental characteristic that significantly affects the final properties of earthen materials. For Compressed Earth Blocks (CEBs), various standards and guidelines specify acceptable PSD limits. The French standard XP NF P13-901 (AFNOR 2022) provides upper and lower limits that align with the Spanish MOPT guidelines and the recommendations of CRATerre-EAG .

A broad consensus in the literature suggests that the ideal soil for earthen construction is one with a high proportion of sand and gravel, a certain amount of silt, and sufficient clay to act as a binder and facilitate compaction [23]. According to Van Damme et al. [24], the most suitable soils are silty or clayey gravels and sands, followed by low-plasticity silts and clays.

For CEBs specifically, several studies recommend optimal ranges for each soil constituent[24] .

The influence of PSD on material properties has been investigated by varying constituent proportions[25], [26]. In a related study on cement-stabilized soils, Ngo et al. [27] investigated the effect of increasing clay content. They tested mixtures with clay soil proportions of 0%, 20%, 30%, and 40%. The results demonstrated a clear negative impact of high clay content. At 7 days, compressive strength dropped from 1.2 MPa (0% clay) to 0.6 MPa (40% clay). Similar reductions were observed at 28 days (from 2.4 to 1 MPa) and 180 days (from 5 to 2.5 MPa). Concurrently, drying shrinkage increased with clay content, becoming particularly significant at the 40% clay level, where it was approximately 600% higher than the clay-free reference mix.

2.3. Plasticity

Soil plasticity is a critical property that significantly influences the behavior of earthen materials. It is governed not only by the water content but also by the amount and type of clay present in the soil[26] . The plasticity index (PI) serves as a key indicator: a higher PI generally signifies a higher clay content and/or the presence of an active clay mineral, which in turn leads to greater potential for swelling and shrinkage during moisture variations [26].

The importance of plasticity in determining the performance of earthen materials, particularly Compressed Earth Blocks (CEBs), is well-documented [28]. Consequently, standard guidelines recommend specific consistency limits to ensure optimal material behavior . According to these references, the liquid limit (LL) for suitable soils should fall between 25% and 50%, with an ideal range of 30% to 35%. The plastic limit (PL) should be between 10% and 25%, ideally ranging from 12% to 22%. These recommended values align with those proposed by CRATerre-EAG. A graphical representation of the acceptable ranges for the plasticity index and liquid limit, based on these references, is provided in Figure 1.

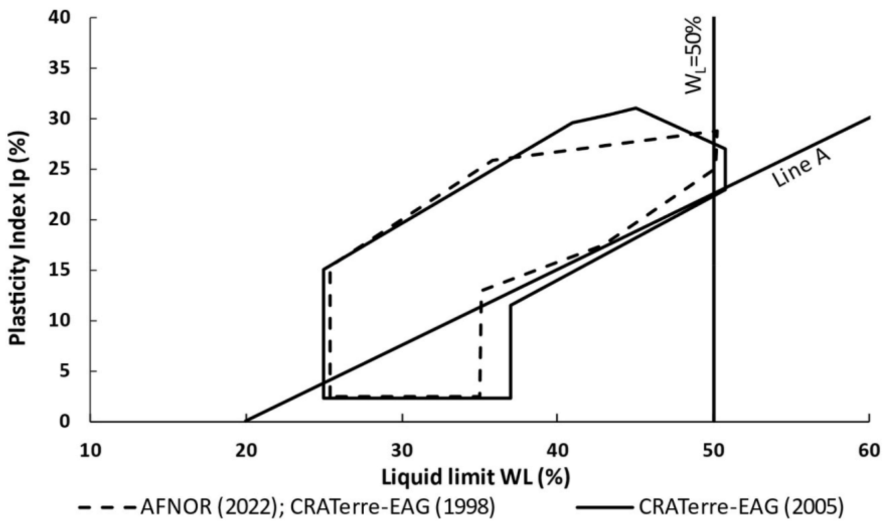

Fig. 1 Plasticity diagram showing the recommended upper and lower limits for Compressed Earth Blocks (CEBs) according to standard XP NF P13-901 (AFNOR 2022) [29], CRATerre [30], and CRATerre-EAG (Reproduced with permission from Delgado et al. [31]).

3. Effect of Fiber Addition on Mechanical Properties

The integration of natural fibers into compressed earth blocks (CEBs) significantly influences their mechanical properties by serving as internal reinforcement within the earthen matrix. Fibers like wheat straw and sawdust residues help bridge micro-cracks, promote more uniform stress distribution, and contribute to improved structural integrity all while minimizing the reliance on cement[32], [33]. This approach effectively mitigates the inherent brittleness of unstabilized earth, resulting in enhanced load-bearing capacity suitable for low- to mid-rise construction. Research consistently indicates that adding fibers at low proportions (approximately 3–5% by volume) yields optimal performance, striking a balance between strength improvement and minimal reduction in material density.

Compressive strength, a key performance metric for CEBs, shows significant improvement with the inclusion of natural fibers at optimal levels. For instance, in a study by Turco et al.[34], wheat straw fibers cut to lengths of 30–50 mm were incorporated at a 5% volumetric ratio into blocks stabilized with 5% hydraulic lime. This resulted in a 16.7% increase in dry compressive strength compared to control blocks, achieving values of up to 2.4 MPa. This enhancement is attributed to the fibers' capacity to absorb tensile stresses during loading and to inhibit crack propagation, as illustrated in Figure 2.

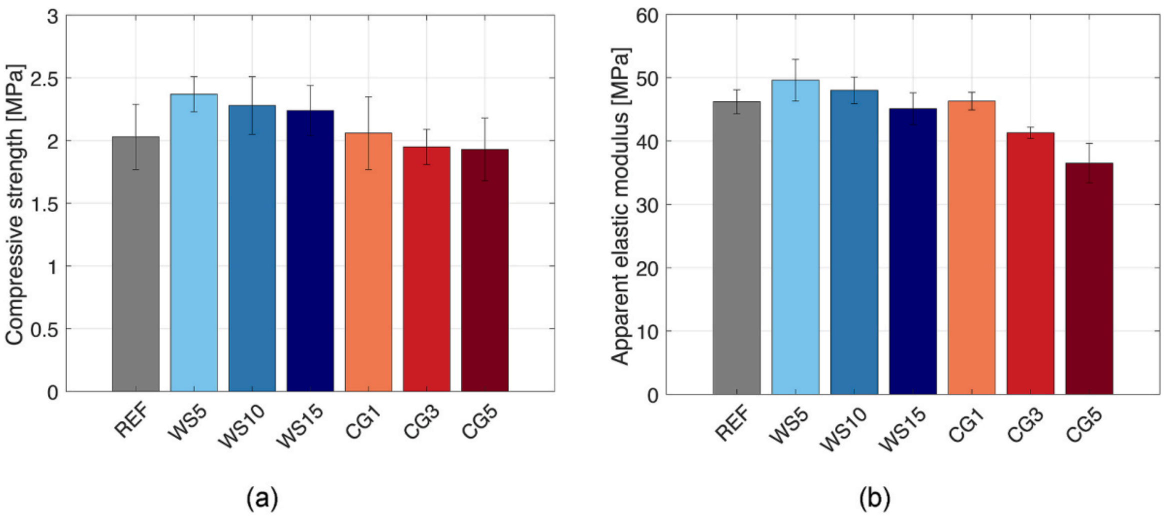

Fig. 2 Compression test results: (a) peak compressive strength, and (b) tangent modulus (Reproduced with permission from Turco et al. [34]).

However, exceeding the optimal fiber content negatively affects compressive performance. At wheat straw ratios of 10–15% or higher sawdust proportions, compressive strength declines due to increased porosity, inadequate fiber-matrix bonding, and the formation of excessive voids that weaken the interlocking of soil particles. Similarly, research on cork granules as a lightweight filler showed that adding more than 5% by volume led to a notable decrease in strength[5], [34].

Flexural and split tensile strengths also show improvement with fiber reinforcement, especially when combined with supplementary materials. For instance, incorporating fly ash alongside cement (20–30% fly ash with 5–7% cement) enhanced flexural strength and split tensile strength by up to 30–40%, attributed to pozzolanic reactions and better particle packing. The addition of wheat straw further contributed to these gains by providing tensile bridging across bending planes, as illustrated in Figure 3 [35] **.**

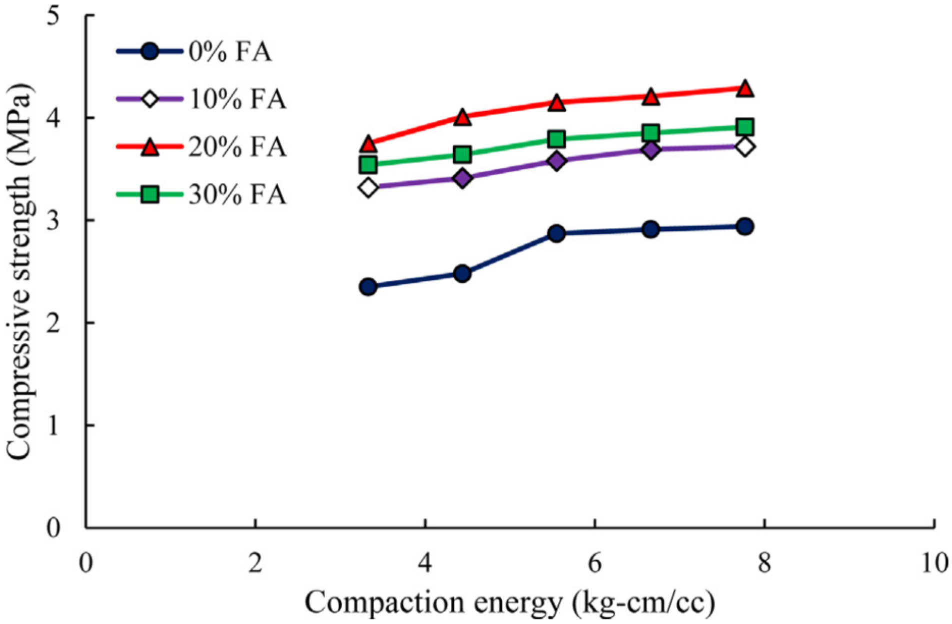

Fig. 3 Relationship between compressive strength and compaction energy for specimens containing 5% cement(Reproduced with permission from Elahi et al**.**[35]).

Shear strength parameters, which are essential for rammed earth and masonry applications, are significantly enhanced through the use of stabilized mixtures. Triaxial tests conducted by Elahi et al. [35] demonstrated that a combination of 20% fly ash and 5% cement increased cohesion from 159 kPa to 315 kPa and raised the angle of internal friction to 57.1°, reflecting improved resistance to lateral forces. Stiffness, represented by the tangent modulus, and fracture energy also show considerable improvement at low fiber inclusion levels. In blocks containing 5% wheat straw, both the apparent elastic modulus and fracture energy increased, indicating a greater capacity to absorb energy prior to failure. This behavior introduces a degree of ductility, contrasting with the brittle failure typically observed in unreinforced compressed earth blocks[5], [34] .

4.Effect of Fiber Addition on Thermal Properties

The incorporation of fibers whether plant-based or granular enhances the thermal performance of compressed earth blocks (CEBs) by increasing the overall porosity of the earthen matrix[33]. This results in the entrapment of more air (which has a very low thermal conductivity of approximately 0.03 W/m·K), thereby reducing thermal conductivity (λ), thermal diffusivity (a), and thermal penetration depth (δp). As a result, the blocks become more thermally efficient, offering improved insulation suitable for hot climates without requiring additional materials.

In addition, the inclusion of fibers lowers the bulk density (ρb) of the blocks while preserving compressive strength. This contributes to a higher coefficient of structural efficiency (CSE) and improved heat storage capacity, namely specific heat capacity[36]. These changes enhance the overall hygrothermal behavior of the blocks, including greater moisture absorption and a reduced thermal penetration depth over a 24-hour cycle. Consequently, this leads to better thermal comfort in multi-story buildings and reduced energy demand for air conditioning.

According to Nshimiyimana et al. [5], increasing porosity from 35% to 45% within the soil matrix significantly improves thermal insulation performance. Their study reports a decrease in thermal conductivity (λ) from 1.02 to 0.64 W/m·K and a reduction in thermal diffusivity (a) to 4.1×10^{-7} m²/s. The linear relationship between thermal conductivity and bulk density, illustrated in Figure 4 of their work, confirms that the use of plant fibers by lowering density and increasing air-filled pores acts as an effective mechanism for producing compressed earth blocks with superior thermal insulation characteristics.

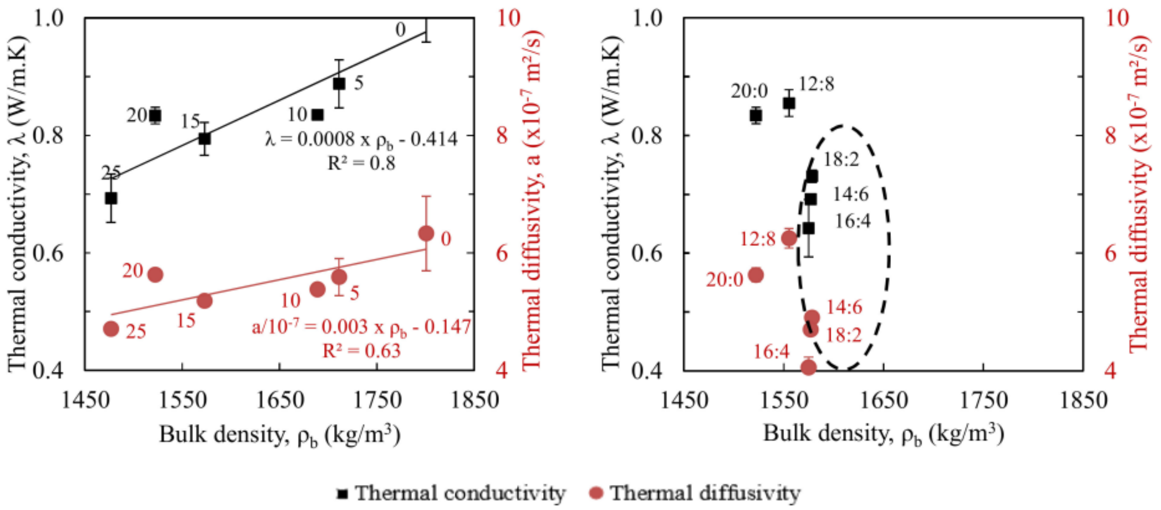

Fig. 4 Linear relationship between bulk density and thermal properties (thermal conductivity λ and thermal diffusivity a) of CEBs, demonstrating the decrease in these values as porosity increases **(** Reproduced with permission from Nshimiyimana et al.[5]).

Sadouri et al. [37] investigated the effect of Juncus fibers on the thermal conductivity of cement-stabilized CEBs ,as illustrated in Figure 5, the thermal conductivity of the CEBs decreases progressively with an increase in fiber content, irrespective of the cement percentage used. For instance, in blocks stabilized with 12% cement, the addition of 0.20% Juncus fibers resulted in a substantial reduction in thermal conductivity of up to 34.7% compared to the unreinforced control sample. The lowest thermal conductivity value recorded was 0.2465 W/m·K for the composite containing 4% cement and 0.2% fibers, representing a significant improvement over the highest value of 0.4350 W/m·K observed in samples without fibers. This improvement is primarily attributed to two factors: the inherently low thermal conductivity of the Juncus fibers themselves (0.0756 W/m·K), and the increased porosity within the composite matrix due to the fibrous network, which collectively hinder heat transfer and make the material more insulating.

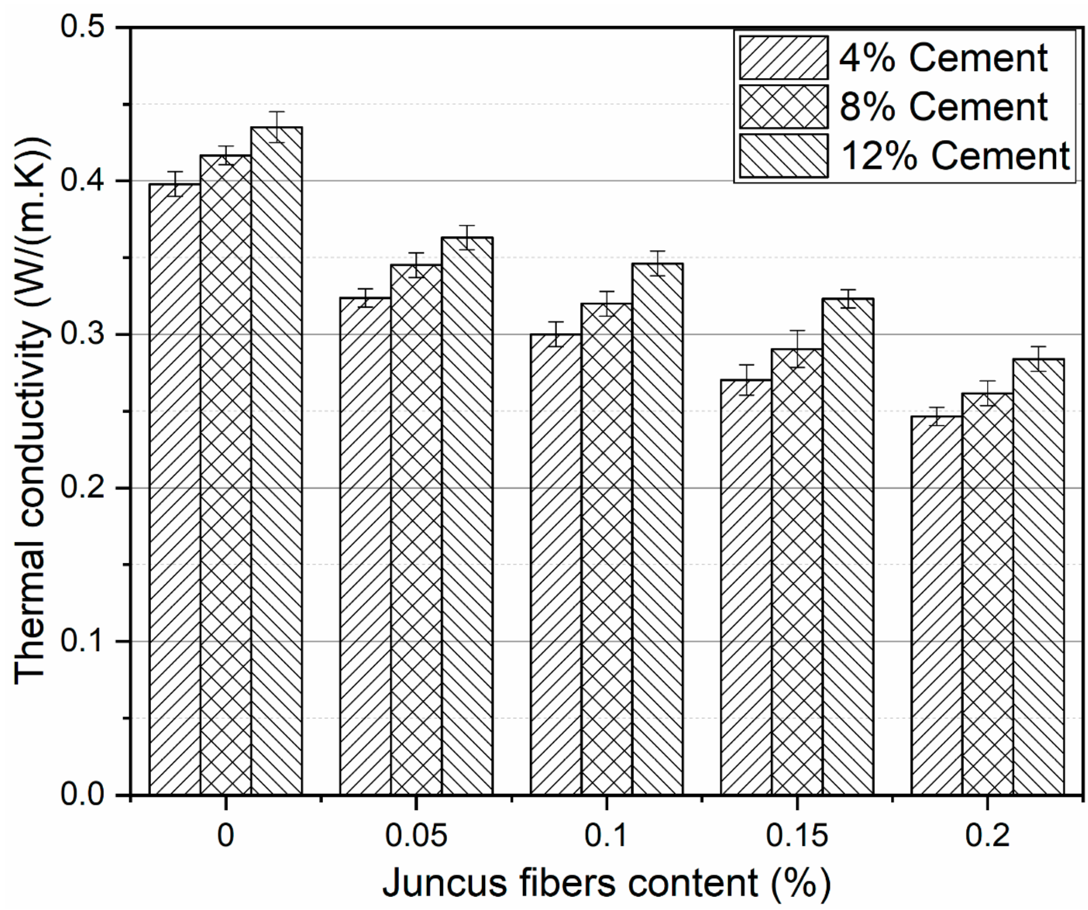

Fig. 5 Thermal conductivity of compacted soil blocks versus fiber content (Reproduced with permission from Sadouri et al. [37]).

Ajougum et al. [32] studied the effect of Moroccan Alfa fibers on the thermal performance of earth-based composites. Figure 6 shows that the thermal conductivity of the earth matrix decreased with the addition of both untreated and treated Alfa fibers. For instance, the sample made from earth alone (Ar) exhibited a thermal conductivity of approximately 1.51 W/m·K. This value dropped further with the addition of 1% treated fibers, particularly those modified by an alkali solution (ArSaFTa 1%), reaching 1.17 W/m·K. This improvement is attributed to the increased porosity and the modification of the granular structure due to fiber inclusion, which disrupts the solid conduction paths within the material . However, the study also notes that increasing the fiber content to 1.5% led to a slight increase in thermal conductivity, likely due to fiber segregation and a reduction in open porosity, highlighting that an optimal fiber content is crucial for maximizing thermal insulation [32].

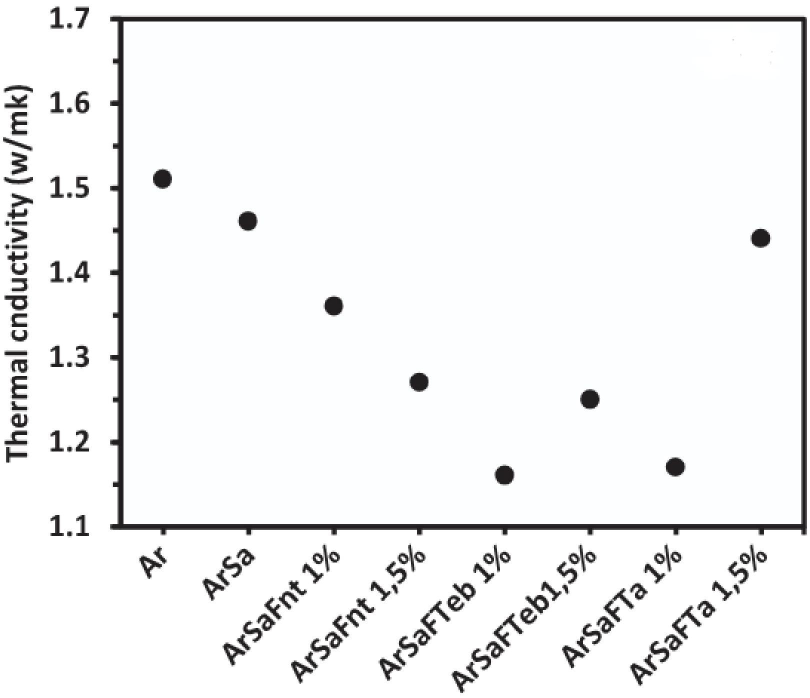

Fig. 6 Thermal conductivity of untreated and treated alpha fiber-reinforced biocomposites. (Reproduced with permission from Ajougum et al. [32]).

5.Conclusion

This review has demonstrated that the mechanical and thermal performance of compressed earth blocks can be significantly enhanced through careful soil characterization and strategic fiber reinforcement. The chemical and mineralogical composition of clay minerals, along with appropriate particle size distribution and plasticity, form the foundation for producing high-quality CEBs. The addition of natural fibers at optimal dosages (typically 3–5% by volume) effectively addresses the brittleness of earthen materials by improving compressive and flexural strengths, increasing ductility, and reducing crack propagation. From a thermal perspective, fiber incorporation increases porosity and reduces bulk density, leading to lower thermal conductivity and diffusivity, which enhances the insulating properties and energy efficiency of buildings. These improvements make fiber-reinforced CEBs particularly suitable for hot climates and multi-storey sustainable construction.

While promising results have been achieved, further research is needed to optimize fiber type, length, and treatment methods, as well as to evaluate long-term durability under various environmental conditions. Ultimately, the integration of natural fibers in CEBs offers a sustainable pathway toward reducing the environmental footprint of the construction industry while maintaining structural integrity and thermal comfort.

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Ethical Statement

This research does not contain any studies with human or animal subjects performed by any of the authors

Data Availability Statement

Not Applicable

Conflicts of Interest

The authors declare no conflicts of interest

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