

Review

Advancing Earth-Based Construction: A Comprehensive Review of Stabilization and Reinforcement Techniques for Adobe and Compressed Earth Blocks

Gabo Cyprien Bailly ^{1,2}, Yassine El Mendili ^{1,*} , Athanas Konin ² and Eliane Khoury ¹ 

¹ Institut de Recherche de l'ESTP, ESTP Cachan, 28 Avenue du Président Wilson, 94230 Cachan, France; gbailly@estp.fr (G.C.B.); ekhoury@estp.fr (E.K.)

² Laboratoire de Génie Civil, Géoscience et Sciences Géographiques, Institut National Polytechnique Félix Houphouët Boigny (INP-HB), Yamoussoukro BP 1093, Côte d'Ivoire; athanas.konin@inphb.ci

* Correspondence: yelmendili@estp.fr

Abstract: This comprehensive literature review investigates the impact of stabilization and reinforcement techniques on the mechanical, hygrothermal properties, and durability of adobe and compressed earth blocks (CEBs). Recent advancements in understanding these properties have spurred a burgeoning body of research, prompting a meticulous analysis of 70 journal articles and conference proceedings. The selection criteria focused on key parameters including construction method (block type), incorporation of natural fibers or powders, partial or complete cement replacement, pressing techniques, and block preparation methods (adobe or CEB). The findings unearth several significant trends. Foremost, there is a prevailing interest in utilizing waste materials, such as plant matter, construction and demolition waste, and mining by-products, to fortify or stabilize earth blocks. Additionally, the incorporation of natural fibers manifests in a discernible reduction in crack size attributable to shrinkage, accompanied by enhancements in durability, mechanical strength, and thermal resistance. Moreover, this review underscores the imperative of methodological coherence among researchers to facilitate scalable and transposable results. Challenges emerge from the variability in base soil granulometry and disparate research standards, necessitating concerted efforts to harness findings effectively. Furthermore, this review illuminates a gap in complete lifecycle analyses of earthen structures, underscoring the critical necessity for further research to address this shortfall. It emphasizes the urgent need for deeper exploration of properties and sustainability indicators, recognizing the inherent potential and enduring relevance of earthen materials in fostering sustainable development. This synthesis significantly contributes to the advancement of knowledge in the field and underscores the continued importance of earth-based construction methodologies in contemporary sustainable practices.

Keywords: adobe; compressed earth block; stabilization; reinforcement; mechanical and hygrothermal properties; durability



Citation: Bailly, G.C.; El Mendili, Y.; Konin, A.; Khoury, E. Advancing Earth-Based Construction: A Comprehensive Review of Stabilization and Reinforcement Techniques for Adobe and Compressed Earth Blocks. *Eng* **2024**, *5*, 750–783. <https://doi.org/10.3390/eng5020041>

Academic Editor: F. Pacheco Torgal

Received: 12 April 2024

Revised: 23 April 2024

Accepted: 24 April 2024

Published: 30 April 2024



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1. Introduction

Faced with the phenomenon of global warming, building sustainably becomes a necessity if we aim to diminish the environmental impact of the construction sector [1–3]. To this end, construction techniques aimed at minimizing environmental impacts by minimizing industrial processes and utilizing locally available materials, such as earth, are gaining momentum [4]. Traditional materials such as cement generate a significant amount of CO₂ in their production chain. Cement production has substantial environmental consequences: it ranks as the third-largest industrial source of air pollution, and if the cement industry were a country, it would stand as the world's fourth-largest greenhouse gas emitter [5]. The scale of cement production contributes to over 7% of annual anthropogenic greenhouse gas (GHG) emissions [6]. Consequently, numerous measures are being considered during

construction, including the emergence of the circular economy concept, the selection of low-carbon materials, and the utilization of waste and materials generated by demolition, construction, and renovation projects [7–11].

The production of these new alternative materials has three objectives: to reduce energy consumption during production, provide solutions to avoid the consumption of resources such as aggregates, and decrease reliance on cement.

The most popular earth construction techniques (Figure 1) worldwide are adobe and compressed earth blocks (CEBs), which combine clay, sand, water, and plant fibers. Because they utilize locally available soil-fibers and require minimal water and energy, traditional earth construction is eco-friendly, cost-effective, and sustainable [12]. However, various environmental factors can impact the structural behavior of earth constructions. Increased moisture content, resulting from rising humidity or a damaged roof, can reduce material strength and lead to fiber decay. Additionally, the high fiber content in cob walls may attract insects and rodents, which can dig deep tunnels, posing a threat to structural integrity. Moreover, clayey soils commonly used in earth construction are prone to issues such as differential settlement, low shear strength, and excessive compressibility, necessitating stabilization measures to enhance mechanical performance.

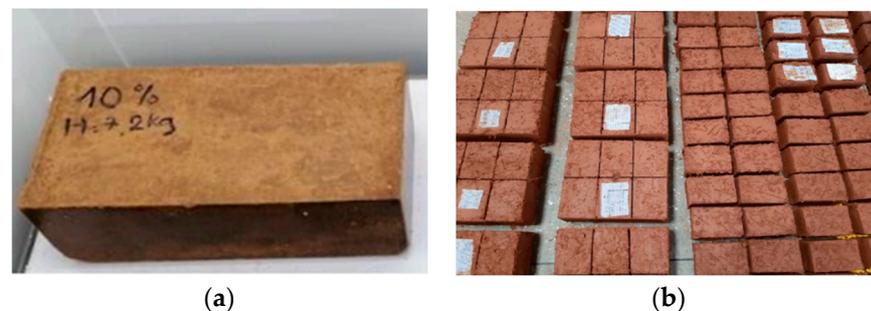


Figure 1. General figure of the earth blocks in focus: (a) CEB specimen; (b) adobe specimen.

The stabilization of earth construction encompasses various techniques and methods aimed at enhancing the strength, durability, and stability of structures primarily built with earth-based materials, including adobe, rammed earth, cob, and compressed earth blocks. The following is an overview of the common stabilization techniques employed:

- **Soil Stabilization Additives [13,14]:** Various binders such as cement, lime, fly ash, or bitumen are mixed with the soil to improve its mechanical properties. For example, cement stabilization increases compressive strength and reduces water susceptibility, making it suitable for load-bearing structures;
- **Compaction [15]:** Proper compaction techniques ensure dense packing of soil particles, thereby increasing strength and stability. Compaction also minimizes settling and enhances load-bearing capacity;
- **Fiber Reinforcement [16]:** Addition of natural or synthetic fibers to the soil mix enhances tensile strength and crack resistance. Materials like straw, sisal, or polypropylene fibers help mitigate shrinkage and cracking, especially in earth-based materials prone to these issues;
- **Moisture Control [17]:** Maintaining optimal moisture content is crucial for earth construction stability. Excessive moisture can lead to swelling and instability, while insufficient moisture results in poor compaction and weak structures. Techniques such as moisture conditioning and drainage systems help regulate moisture levels;
- **Geogrids and Geotextiles [18]:** Geosynthetic materials like geogrids and geotextiles reinforce earth structures, improving stability and preventing erosion. These materials provide additional tensile strength, particularly useful in slope stabilization and retaining wall construction;

- Surface Treatments [19]: Plastering, rendering, or applying protective coatings protect earth constructions from weathering, erosion, and moisture penetration. These treatments enhance durability and aesthetics;
- Innovative Techniques [20–22]: Technological advancements have led to innovative stabilization methods such as soil-cement blocks, stabilized earthbags, and rammed earth with reinforced concrete elements. These techniques offer improved structural integrity, faster construction, and enhanced sustainability.

Overall, the stabilization of earth construction is pivotal in creating durable and resilient structures that can withstand environmental forces while retaining the inherent benefits of using earth-based materials, such as sustainability, thermal performance, and aesthetic appeal. However, it is crucial to meticulously consider site-specific conditions, material properties, and construction techniques to ensure effective stabilization and long-term performance. Raw earth construction materials are typically stabilized for two primary reasons [23]. Firstly, to enhance the cohesion and strength of the soil group, which may not otherwise be suitable for construction purposes. Secondly, to bolster the material's resistance to water-induced erosion or improve its durability. Durability is of utmost importance for any construction material due to the anticipated lifespan of buildings, typically estimated at around 50 years, although many structures remain in use for much longer periods. Earth constructions have the potential to endure various climatic conditions, provided the appropriate soil is chosen, proper precautions are taken during construction, and regular maintenance is carried out.

To date, most industrial applications and scientific endeavors have relied on cement and lime to stabilize raw earth construction. However, the high carbon footprint associated with these mineral binders, coupled with their significant incorporation rates, raises concerns about the ecological sustainability of stabilized raw earth construction, particularly considering the limited performance gains. As a result, there is growing interest in the use of biopolymers, as evidenced by their historical use in ancient constructions and traditional practices across various regions of the world [24]. These organic binders derived from Agri-Resources hold promise as stabilizers for modern raw earth constructions.

In the realm of earth construction, there is a trend towards characterizing fibers [25] or waste materials [26] for their potential as new construction materials. The addition of fibers or industrial waste has been shown to effectively enhance the properties of earth blocks [27] and even geopolymer composites [2]. Thus, gaining a better understanding of the intrinsic properties of these natural reinforcements becomes imperative to meet criteria such as strength, comfort, and durability. This necessitates a thorough knowledge of the characteristics and various properties of the soil [28]. Some research efforts have focused on developing the thermal properties of lime-reinforced mud blocks [29], while others have evaluated the mechanical properties and durability of cement-stabilized earth blocks made from waste materials such as cassava wastewater [30]. Additionally, studies have explored organic binders of plant origin, such as research on sargassum muticum [31] or date palm fibers [32]. These studies focus on mechanical strength (compressive, tensile, flexural), hygrothermal parameters (thermal conductivity, heat capacity, dry density), and durability, as shown in Figure 2.

Earth blocks are increasingly utilized in the load-bearing system of buildings or as cladding. Regardless of their specific application, earth blocks are now commonly stabilized or reinforced to enhance their mechanical, thermal, and acoustic performance, as well as their durability [33].

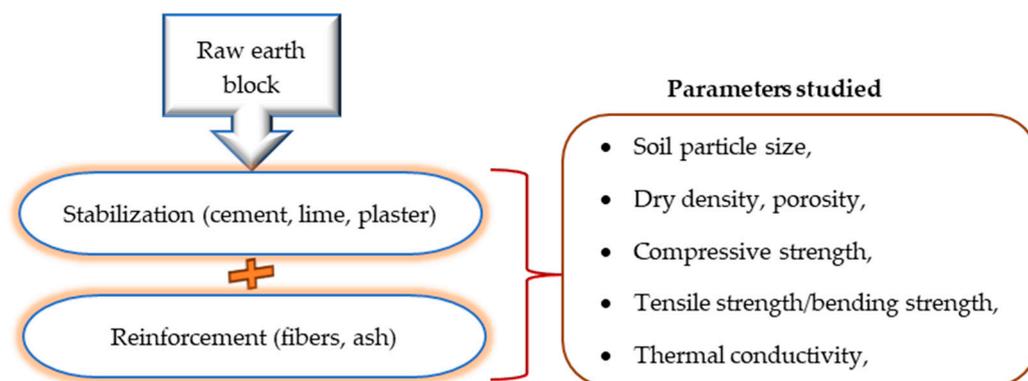


Figure 2. Parameters studied in raw earth blocks.

Stabilization and reinforcement methods vary and alter the soil matrix based on several factors:

- The intrinsic characteristics of soil [34]: including grain size, Atterberg limit, mineralogical composition, optimum water content, density, etc.;
- The type of binder employed: whether it is cement, lime, plaster, etc.;
- The nature and properties of the fibers utilized: encompassing factors such as absorption, tensile strength, morphology, etc.;
- The type of blocks being produced: whether they are adobe or compressed earth blocks (CEBs);
- The pressing force applied during block formation: this applies specifically to CEBs;
- The cure period and conditions post-production.

Numerous studies have investigated the mechanical strength of earth blocks, whether utilizing cement as a binder, as evidenced by Dao et al. [35] and Toure et al. [36], or through partial [37] or complete replacement [38] of cement.

Legal regulations regarding environmental protection, particularly concerning groundwater contamination, impose significant restrictions on the use of artificial materials in construction. These regulations aim to mitigate adverse environmental impacts and ensure the long-term sustainability of construction practices. For instance, a study by Johnson et al. [39] highlighted the potential risks posed by the infiltration of harmful chemicals into groundwater sources due to the leaching of artificial additives used in construction materials. Their research emphasized the need for stringent regulations to safeguard water quality and public health. Moreover, Smith et al. [40] conducted a comprehensive review of legal frameworks governing construction material usage in different regions. They revealed significant variations in regulatory approaches, ranging from strict prohibitions on certain additives to comprehensive monitoring and mitigation measures. This underscores the complex interplay between legal regulations, environmental protection, and construction practices, necessitating harmonized policies to ensure consistent and effective enforcement. Furthermore, Garcia et al. [41] investigated the economic and environmental impacts of transitioning to natural building materials in compliance with stringent regulatory requirements. Their research demonstrated the feasibility of adopting alternative construction practices that prioritize environmental sustainability while complying with legal regulations. By aligning legal obligations with sustainable development goals, stakeholders can promote responsible construction practices and foster the long-term health and resilience of the environment.

Building upon previous research, the authors of this study aim to elucidate the influence of stabilization and reinforcement on the mechanical, hygrothermal performance, and durability [21] of blocks. The focus lies primarily on the type of stabilization/reinforcement, with less emphasis on other parameters such as processing conditions and intrinsic characteristics of the raw material. The objective of this review is to provide updated insights into the advancements made in recent years concerning the stabilization of earth blocks

utilizing fibers or powders derived from industrial waste [42] or invasive plants [43,44], which hold potential for construction purposes.

This paper follows the following structure: In Section 2, the methodology of the literature review is outlined, along with the research questions and filters applied to select relevant articles. Section 3 introduces the various types of block stabilization and discusses their impact on mechanical, thermal, hydric, and durability properties. The findings are subsequently analyzed and discussed in Section 4. Finally, Section 5 presents conclusions drawn from the study.

2. Methodology of the Literature Review

In this section, we present the methodology adopted for conducting this review. We support our arguments with tables and figures to provide clarity on our choices.

2.1. Research Questions

- What problems are the authors of the selected articles attempting to address (improving block properties, recycling waste, or both)?
- What are the main results obtained from these studies, and are they transferable (i.e., the geographical scope of applicability)?
- What are the limitations of the studies consulted, and how can knowledge on raw earth blocks be enhanced?

2.2. Article Search and Filtration Technique

The search technique used servers such as ScienceDirect, Researchgate, MDPI, and Google Scholar. The keywords used were: “earth block”, “compressed earth block”, “compressed and stabilized earth block”, “mechanical parameters of CSEB”, “hygrothermics and CEB”, “natural fibers or powders”, “waste recovery”, “lightened earth block”, “thermal comfort”, “cement and CEB or adobe”, “literature review”, “bio-based materials”, “characterisation of CEB”, and “durability of earth blocks”.

The initial filtration step involved limiting the publication years of the articles to the last decade (January 2014 to December 2023). To align with the objectives of the present research, articles focusing on cementitious matrices, synthetic binders, cob, terracotta bricks, and extruded earth were excluded from the list of works. However, adobe blocks were retained due to their potential for exhibiting interesting mechanical resistance.

Figure 3 illustrates the filtration process applied to obtain the literature reviews.

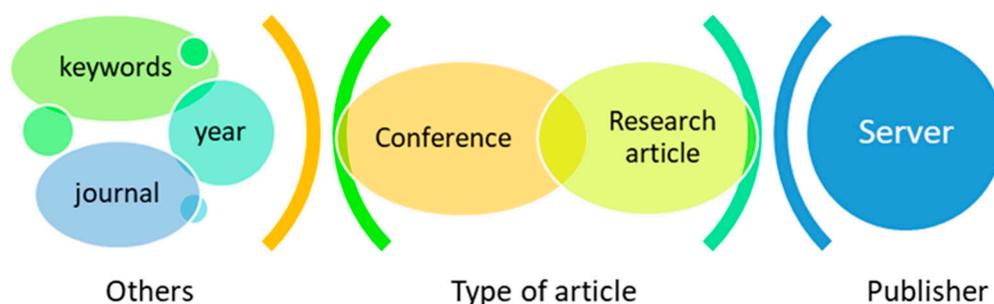


Figure 3. Filter for literature reviews.

The primary objective was to select verified and verifiable resources that had undergone rigorous peer review processes. Data pertaining to the years of publication were presented in both tabular and graphical formats, with Figure 4 depicting the percentage of annual representativeness. Table 1 lists the parameters studied during the review process.

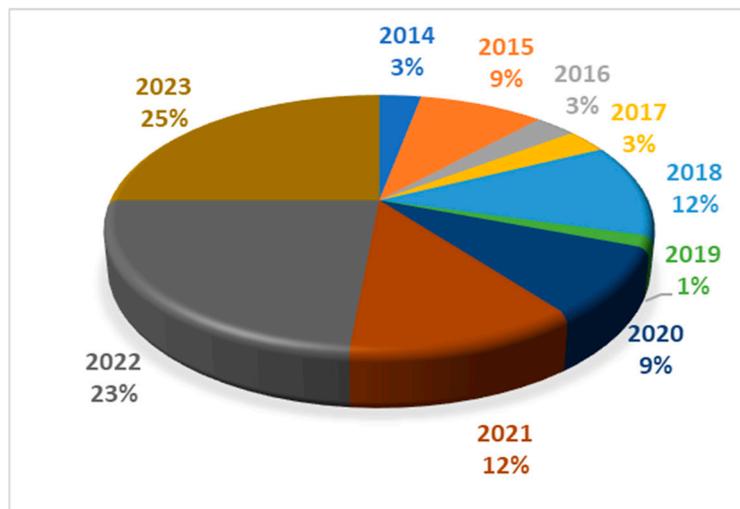


Figure 4. Percentage distribution of the articles’ year of publication.

Table 1. Classification of articles according to the parameters studied.

	Physical Properties	Mechanical Properties	Thermal Properties	Indicators and Sustainability Properties
Details	<ul style="list-style-type: none"> - Dry density - Porosity - Shrinkage - Swelling 	<ul style="list-style-type: none"> - Compression - Traction - Flexion - E Modulus 	<ul style="list-style-type: none"> - Thermal conductivity - Thermal diffusivity - Specific heat capacity 	<ul style="list-style-type: none"> - Abrasion coefficient - Erosion coefficient - Emission of CO₂ - Water absorption
Number of articles	70	59	17	31

A classification by year, cross-referenced with the themes covered in each article, enabled the extraction of the number of articles addressing specific themes over the chosen period (2014–2023). The topics covered were grouped into four broad categories of properties: physical, mechanical, thermal, and durability. It is worth noting that an article may address one or more properties simultaneously (Table 1).

In the period 2014–2023, eighteen research projects have focused on the valorization of plant-based waste and seashells (powder, fibers, and straw) through their incorporation into earth blocks. The following details allow for the classification of the nature of these wastes:

- Nine articles focused on powder: water hyacinth ash [44], sugarcane bagasse ash [7,35,45,46], and rice husk ash [47–50];
- Five articles focused on fibers: Pennisetum setaceum [51], plantain pseudo-stem fiber [52], coconut fiber [53], alfa fiber [54] and paper cellulose [55];
- Four items studied other types of waste: wheat and barley straw [27], sargassum muticum seaweed [31], crepidula fornicata seashells [56], and shea butter waste [57].

During the same period, ten items addressed excavated soil and other construction waste or industrial by-products utilized in earthen construction:

- Three items focused on excavated soils [58–60];
- The other seven dealt with gravel wash mud [59], phosphate waste rock [39], marble waste [9], waste concrete powder [26], coal fly ash [61] sawdust [62], and cassava wastewater [30].

These works were often supported financially by international institutions, demonstrating their relevance in the scientific field. As an example, the work of Hussain et al. [58] has been funded by the European Union project, Next Generation EU under the France

Relance program for the valorization of inert excavated soils (VALODEB) with the collaboration of Unilasalle Rennes and Gendrot TP. Similarly, the research of El Mendili et al. [56] was supported by the European Regional Development Fund in the frame of a BLUEPRINT to a Circular Economy project (Interreg V A France (Channel) England, Project n°206).

3. Influence of the Type of Stabilization and/or Reinforcement on Block Properties

The use of mineral or organic binders improves the properties of blocks. The reinforcement also improves the strength of the blocks. However, some improvements in one parameter may result in performance loss in other properties [45]. The optimization of raw earth blocks, therefore, requires a cross-analysis of the modification of its properties according to the binder used or the reinforcement materials.

3.1. Presentation of the Different Types of Stabilization or Reinforcement

Three types of stabilization or reinforcement have been studied.

3.1.1. Raw or Compressed Earth Blocks Stabilized with Cement Only

The articles focusing solely on cement stabilization were published between 2017 and 2023, spanning six out of the ten years covered by this review. The distribution of articles across these years is as follows: 2018 had the highest number of articles, with three out of ten (30%), followed by 2023, each with two articles (20%). Additionally, 2020, 2021, and 2022 each had one article (10%).

Regarding the optimal rate of cement used for stabilizing earth blocks, it varies from 6% [30] to 16% [46], with intermediate values of 8%, 9%, 10%, 12%, and 15%. These findings are summarized in Figure 5.

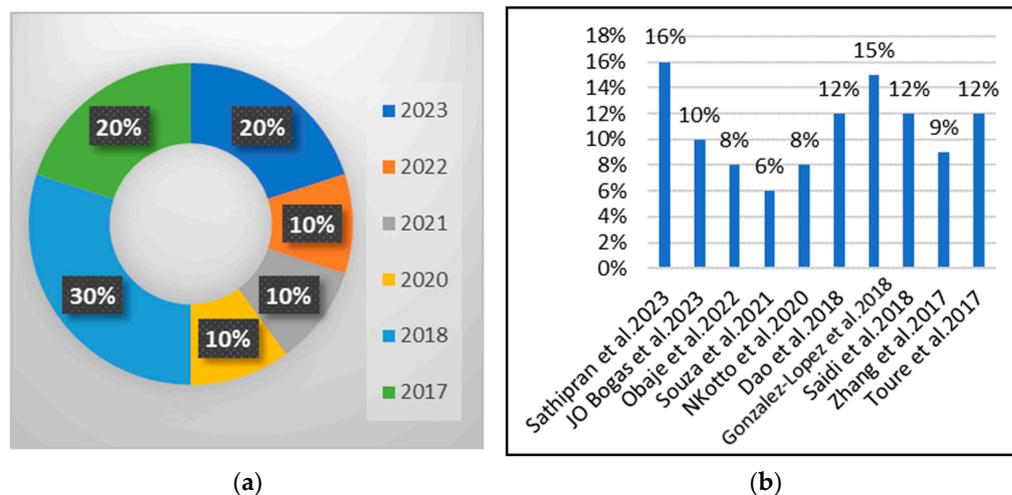


Figure 5. (a) Distribution by year of articles on cement-only stabilization; (b) optimal percentage of cement [3,30,35,36,45,46,63–66].

3.1.2. Earth Blocks Stabilized with Cement and Reinforced by Fibers

In some cases, the use of cement as a binder is supplemented with the addition of fibers to reinforce the raw or compressed earth block. With the exception of the years 2017 and 2020, at least one study each year has focused on “composite binders,” which entail the use of fiber reinforcement in conjunction with cement (Figure 6).

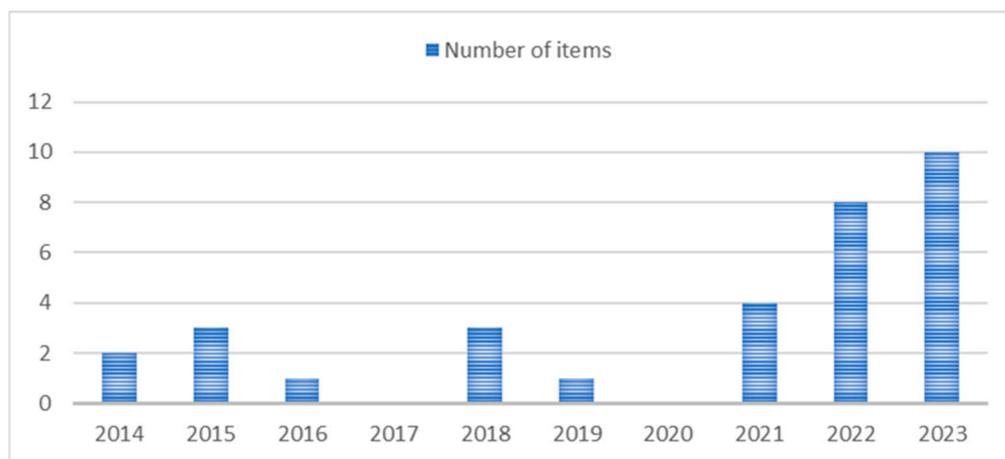


Figure 6. Distribution by year of articles on cement stabilization with fiber or powder reinforcement.

For instance, Taalah et al. [37] utilized an optimal mix of cement (8%) and date palm fibers (0.5%) as a binder in their study on the mechanical properties and hygroscopic behavior of compressed earth blocks.

This emerging trend, particularly evident over the last three years, suggests a sustained interest in exploring alternative means of stabilization beyond the traditional use of cement.

3.1.3. Raw or Compressed Earth Blocks Stabilized Only by Fibers

Out of seventy articles reviewed, sixteen (approximately 23%) focus on methods to reinforce raw or compressed earth blocks without the use of hydraulic binders, such as cement or lime. This represents a 1.6-times higher number compared to articles dealing solely with stabilization using cement or lime. Moreover, similar to cement stabilization, these articles span six out of ten years, with the last three years (2021 to 2023) accounting for nine of the sixteen articles, representing 56.25% of the publications. This indicates a continued interest among researchers in exploring alternative methods to effectively replace hydraulic binders in the earth matrix. The primary objective is to manufacture more resilient adobe or compressed earth blocks.

Among the articles focusing on fiber reinforcement, the lowest mass percentage of fibers is reported by Millogo et al. [47], who used 0.4% of kenaf fibers to stabilize earth blocks. Olumodeji et al. [48] utilized 2.5% of fibers in their study, while higher values include 4% of shea butter waste [49], 7% of alpha fibers [50], and 8% of pennisetum setaceum [48].

In total, twenty-six studies explore the use of fibers as binders.

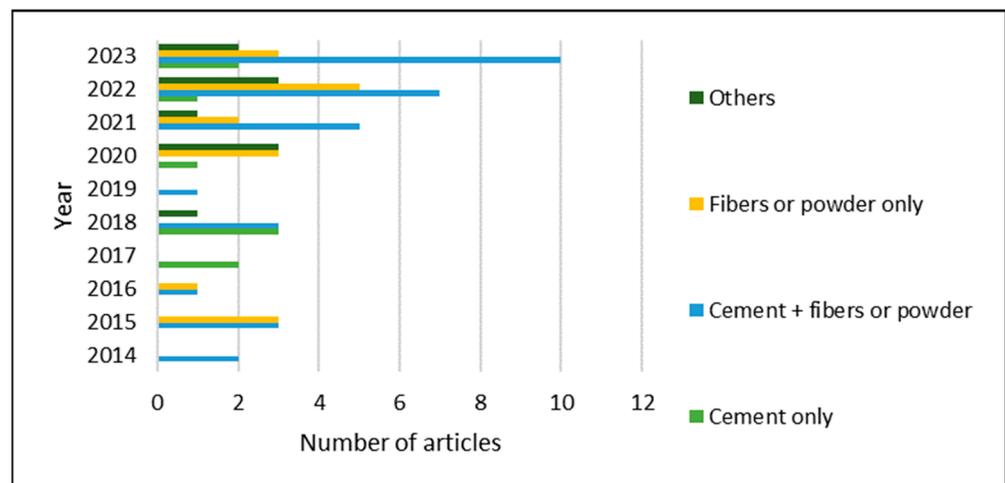
3.1.4. Other Types of Stabilization or Reinforcement

Table 2 presents various methods of stabilizing or reinforcing earth blocks as studied in the selected articles. These include the use of lime with or without reinforcement methods [52], as well as the utilization of excavated soil or calcined laterite [53].

Figure 7 shows a summary of the types of stabilization by means of an annual distribution of the articles selected. The four types of stabilization or reinforcement of CEBs and adobes discussed above are represented. It was clearly observed that alternative methods of stabilization and reinforcement have been studied more in the last four years (2020 to 2023) than in the first six years (2014 to 2019).

Table 2. Other types of stabilization and reinforcement of earth blocks.

Reference	Stabilization	Reinforcement	Other
[54]	Compaction	-	Use of excavated soil
[55]	Lime + dairy	Polypropylene fiber	-
[56]	Lime	Sawdust	-
[57]	Lime + coal aggregates 2/20	-	-
[52]	Lime + gravel	-	-
[29]	Compaction + (limestone, sandstone, porphyry) aggregates	-	-
[58]	Compaction + calcium carbide residue	-	-
[50]	Phosphoric acid + burnt laterite	-	-
[56]	Lime	Wood + coal	-
[47]	Lime	Alfa fiber	-

**Figure 7.** Annual distribution of items by methods of stabilization.

3.2. Influence of Stabilization and/or Reinforcement on Block Properties

Stabilization involves altering the characteristics of the soil–water–air mixture to impart improved properties. The overarching goal is to enhance mechanical strength, reduce porosity, and minimize water sensitivity. Reinforcement, on the other hand, may entail the addition of secondary elements, such as fibers, alongside chemical stabilization. These secondary elements serve to further bolster the stability of the soil structure.

Unstabilized and unreinforced earth blocks typically exhibit weaknesses in terms of mechanical and thermal resistance, as well as susceptibility to water. Generally, hydraulic binders (such as cement and lime) and fibers or biological binders (such as powders) are utilized to reinforce the blocks, leading to improvements in mechanical and hygrothermal performance [22]. However, it is important to note that some properties may evolve in opposite directions, necessitating a closer examination of how stabilization and/or reinforcement influence them in a cross-cutting manner. Therefore, this study distinguishes between modifications that act physically or chemically and their direct impacts on the block's behavior under stress.

To understand the effects of stabilization and reinforcement techniques on the performance of adobe and compressed earth blocks (CEBs), several studies have provided valuable insights. For instance, a comprehensive review by Smith et al. [67] examined the impact of various stabilization methods, such as cement and lime additives, on the mechanical properties and durability of adobe and CEBs. Their findings indicated that while

stabilization techniques can enhance compressive strength and resistance to environmental degradation, careful consideration must be given to factors such as material compatibility and long-term performance.

Furthermore, a study by Johnson et al. [68] investigated the effects of fiber reinforcement on the structural integrity of adobe and CEBs. Their research demonstrated that the incorporation of natural fibers, such as straw or hemp, can significantly improve tensile strength and crack resistance, thereby enhancing the overall performance of earth-based materials. However, they also noted the importance of optimizing fiber content and distribution to achieve desired mechanical properties without compromising material workability.

Moreover, a study by Brown et al. [69] explored the combined effects of stabilization and reinforcement techniques on the hygrothermal properties of adobe and CEBs. Their findings suggested that while certain stabilization methods may improve moisture resistance, the addition of fibers can influence thermal conductivity and moisture absorption characteristics. These insights underscore the complex interplay between different stabilization and reinforcement strategies and their impact on the overall performance of adobe and CEBs.

3.2.1. Physical Properties

In this section, physical properties including density, porosity, shrinkage, and void volume are examined. Table 3 provides a sample of sixteen articles discussing physical properties, with four articles categorized per type of stabilization (cement only, cement + additive, fibers or powders only, other types of stabilization and/or reinforcement). The density of an adobe or compressed earth block significantly influences its thermal inertia and mechanical strength. It varies based on the soil composition (proportion of sand, clay, and silt). During block manufacturing, factors such as compression, stabilization, and the percentage of binder can cause fluctuations in density.

Table 3. Influence of stabilization methods on physical properties.

Reference	Stabilization and/or Reinforcement	Dry Density (kg/m ³)	Porosity (%)	Shrinkage (%)	Void Volume
[60]	Bamboo fibers	1430–1560	25.0–35.0	-	-
[61]	Hemp fibers	1429–1673	-	3.60–10.50	-
[70]	Plantain banana stalk fiber	1560–1594	-	-	-
[71]	Jute fiber	1844–1879	-	-	-
[72]	Cement + sugarcane bagasse	1485–1628	-	2.04–4.76	-
[73]	Cement + sisal fiber	1520–1770	-	1.22–10.14	-
[27]	Cement + wheat/barley straw	1099–1445	-	0.9–1.5	-
[21]	Cement + coir, flax, areca fiber	-	-	0.10–0.21	-
[63]	Recycled cement	1640–1750	34.2–39.0	-	8.9–14.6
[35]	Cement	1620–1780	28.0–33.0	-	-
[64]	Cement	1500–2100	17.5–40.0	-	-
[3]	Cement	1600–1800	-	-	-
[50]	Lime + alfa fibers	1010–1030	45.0–68.0	-	-
[52]	Lime	1675–1940	-	-	-
[55]	Lime + polypropylene	1638–1854	-	-	-
[57]	Lime + coal aggregates	1600–2000	-	-	-

Figure 8 illustrates the distribution of references according to the physical properties studied.

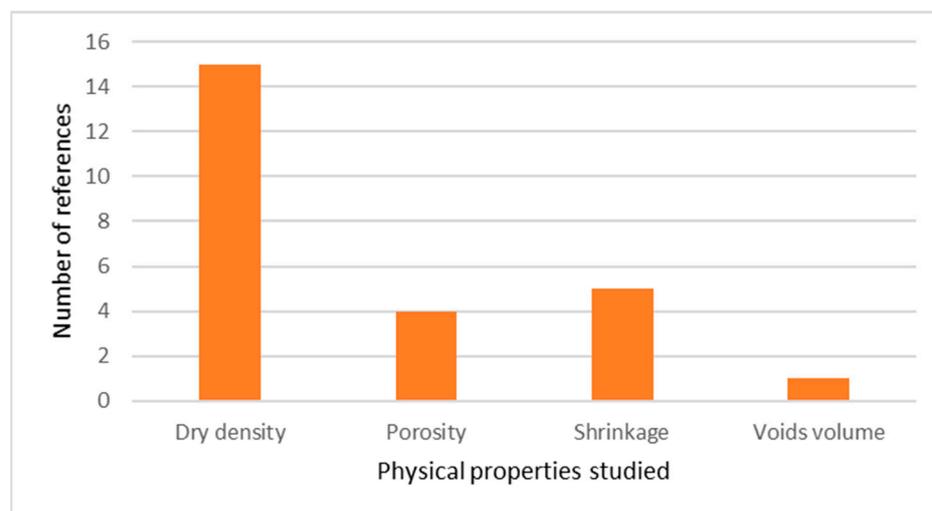


Figure 8. Number of references according to the physical properties studied.

Dry Density

In most of the selected articles, both the dry density of the earth and the blocks is studied (as presented in Table 3). Concerning the blocks, the dry density values range from 1020 kg/m^3 for lime-stabilized earth blocks reinforced with alpha fibers [50] to 2100 kg/m^3 for cement-stabilized earth blocks without additional reinforcement [3]. A notable observation is that cement-only stabilized earth blocks tend to have the highest density. This can be attributed to the effect of cement hydration, which agglomerates the earth particles, reduces voids, and results in a denser block [35]. The addition of cement to clayey soil can also lead to the formation of calcite and calcium silicate hydrates (CSHs) and ettringite. These CSH formations contribute to a more homogeneous microstructure with smaller pores that connect the soil particles.

For earth blocks stabilized with cement or lime and reinforced with fibers, the dry density values are relatively lower compared to earth blocks stabilized solely with cement [60,64]. This can be attributed to the fact that the fibers used typically have a lower density than the earth itself. Combining chemical and mechanical stabilization has additional positive effects. It helps cement the soil particles together and fill the soil pores, thereby preventing the reorientation and flocculation of soil particles, which in turn prevents the formation of dilated pores and cracks.

Furthermore, blocks stabilized with fibers are even lighter than those stabilized solely with cement or lime. The density of the mixture decreases as the fiber content increases due to the lower density of the fibers compared to the compressed mix [74].

The compaction process is also a parameter that influences the density of the blocks. Indeed, to achieve the best compaction, the water content within the matrix (soil and binder) must be controlled and kept as close as possible to the optimum moisture content (OMC) or the optimum water content (OWC). This allows for achieving maximum dry density when the right compaction force is applied.

Gonzalez-Lopez et al. [65] conducted a study on the impact of compaction force on the compressive strength and durability of stabilized earth blocks. It is mentioned in this work that the arrangement of the sand grains and the compaction forces impact the density of the block. This is measured by a higher compressive strength.

Porosity

Porosity is a measure of the void spaces in a material, representing the portion of its volume that is not occupied by solid matter.

The lowest porosity value (17.5%) is reported by Zhang et al. [64] in their study on the thermal conductivity of cement-stabilized earth blocks. This value is achieved with a 3% cement content and an equivalent bulk density of 2.1 g/cm^3 . Interestingly, for the same cement content (3%), the porosity increases to 40% when the density decreases to 1.5 g/cm^3 . Surprisingly, despite increasing the cement content from 5 to 9%, the highest value of porosity in this study remains unchanged. According to the authors, “[...] the cement content shows no obvious effect on the density-porosity relationship, which is probably due to the similar density of cement and earth material used in this study.”

There exists a linear correlation between density and porosity in stabilized earth blocks, wherein the block porosity decreases as the density increases. Stabilized earth blocks can be considered as a two-phase composite, comprising solid (soil and cement) and air. Increasing the solid content enhances the density while reducing the porosity simultaneously. Generally, porosity decreases by a factor of 2 to 3, while density increases by 1.5 to 2.1 g/cm^3 for cement-stabilized blocks [64].

In the case of fiber-reinforced earth blocks, Abessolo et al. [60] demonstrate that porosity increases with the quantity and length of bamboo fibers. Hence, the least porous blocks (25%) are those without fibers, whereas the most porous ones (35% porosity) contain the longest fibers (1%) with a length of 6 cm. This outcome can be attributed to the fact that increasing the quantity and length of fibers introduces voids in the compressed earth blocks (CEBs).

The highest reported porosity value among the selected studies (68%) is documented by Garrouri et al. [50]. In this study, the blocks were stabilized using a mix of hydraulic lime binder (NHL5) and alpha fibers. The porosity ranged from 45% to 68% as the alpha fibers content increased from 0% (control specimen) to 68%. It is evident that porosity increased with the fibers content.

Voids Volume

The voids volume is discussed only once in the study conducted by Bogas et al. [63]. They obtained values ranging between 8.9% and 14.6%. These values are associated with the water content of the mixture and the compaction method employed to produce the block. Consequently, a high proportion of binder will lead to a higher quantity of water and an increased risk of compaction errors, resulting in a larger voids volume.

Shrinkage

Shrinkage is a phenomenon resulting from variations in internal hygrometry and the humidity of the surrounding environment. It also depends on the evaporation of excess water within the block. Shrinkage typically initiates on the faces exposed to evaporation, with the drying front gradually spreading from the surface towards the core of the block. Consequently, the skin of the block undergoes drying shrinkage faster than the core of the earth block. Shrinkage values range from 0.19% [21] to 10.50% [61] and are reported by five studies (as shown in Figure 7) out of the sample of sixteen articles presented in Table 3.

Sujatha et al. [21] investigated the potential of reinforced and cement-stabilized soil blocks using three types of fibers (cor, flax, and areca). The soil was stabilized with 2.5% cement and reinforced with 1% fiber. The lowest linear shrinkage (0.1%) was observed with a composition of 2.5% cement + 1% areca fiber as a binder. When only fibers were used, the linear shrinkage ranged from 0.88% to 0.34% as the areca fiber content varied from 0% to 1%.

According to the conclusions of Latha et al. [74], there exists a close relationship between the level of linear shrinkage and density. Thus, the linear shrinkage of compressed earth blocks (CEBs) will increase proportionally with density. The lowest value of linear shrinkage in this study is obtained with 8% cement content and 1.5% sisal fiber content. For this composition, the shrinkage is approximately 1.6%.

Ashour et al. [27] demonstrate that earth blocks without reinforcement are highly susceptible to crack formation, leading to specimen disintegration. However, the incorporation

of fibers, cement, and gypsum has a positive impact on reducing shrinkage. Additionally, it is noteworthy that shrinkage decreases with the curing time of the blocks. Longitudinal shrinkage exceeds transverse shrinkage, suggesting that shrinkage increases with the block's size. Moreover, fibers exhibit greater resistance to shrinkage compared to cement or gypsum [75]. A higher fiber content helps reduce crack formation and improve shrinkage behavior. For instance, in the study conducted by Singh et al. [76], the authors obtained the following shrinkage values:

- 6.5% for a mixture of 5% cement + 4% sugarcane bagasse ash + 4% wheat straw + 87% soil;
- 9.4% for a mixture of 5% cement + 95% soil.

These results suggest that shrinkage decreases with increasing mass percentage of binder.

3.2.2. Mechanical Properties

In this sub-section, the mechanical properties studied include compressive strength, tensile strength, flexural strength, and ductility. All structural studies typically incorporate at least one of these parameters. Ensuring the mechanical strength of the structure is a major concern in construction, and the selected articles largely address these properties.

Compressive Strength

Compressive strength defines the ability of a material to resist vertically applied pressure without excessive longitudinal and transverse deformation. Researchers have studied four types of stabilization and/or reinforcement in this regard. These include cement stabilization alone, cement stabilization with fiber reinforcement, as well as lime-stabilized blocks with or without fibers.

- Cement stabilization only

Many researchers have investigated the effect of cement stabilization on the compressive strength of raw earth blocks. Table 4 illustrates the influence of cement stabilization on compressive strength (R_c).

Table 4. Influence of cement stabilization on compressive and tensile strengths.

Reference	Cement (%)	Main Elements of the Soil	Bloc Type	R_c (MPa)	R_t^1 (MPa)	Curing Time (Days)
[59]	10%	Soil (clay 40%, silt 8%, sand 52%)	CSEB	7.00	-	28
[73]	15%	Highly plastic clay ($W_L = 64.5\%$, $W_P = 22.65\%$)	Adobe	5.48	-	28
[30]	6%	Soil (clay 19.91%, silt 11.44%, sand 63.61%, gravel 5.04%)	CSEB	4.90	-	49
	12%		CSEB	2.42	-	49
[66]	8%	Soil (clay 25.70%, silt 35.14%, sand 37.55%, gravel 1.61%)	CSEB	4.78	0.33	28
[36]	12%	Soil (clay 18.4%, silt 19.5%, sand 40.3% gravel 21.8%)	CSEB	3.30	-	28
[35]	12%	Soil (4.8% gravel, 42.6% sand, 22.7% silt, 29.9% clay)	Adobe	3.15	-	28
[77]	8%	Soil (67% sand, 25% silt, 8% gravel)	Adobe	5.42	-	90
[78]	8%	Soil (6.30% sand, 93.70% silt-clay) + 20% waste concrete powder	CSEB	10.68	-	28
[42]	10%	10% red clay + 80% PhWR ²	CSEB	11.18	-	28
[46]	16%	Soil (gravel 4.3%, sand 95.2%, silt 0.4%, clay 2.51%)	CSEB	5.00	-	28
[79]	9%	40% soil + 52% coarse sand	CSEB	6.53	-	28

Table 4. Cont.

Reference	Cement (%)	Main Elements of the Soil	Bloc Type	R _c (MPa)	R _t ¹ (MPa)	Curing Time (Days)
[3]	8%	Clayey soil (W _L = 43%, W _P = 28%)	CSEB	5.60	-	28
[65]	10%	Sand–clay (W _L = 33.46%, W _P = 21.82%)	CSEB	11.84	-	28
[63]	10%	Soil (20.1% gravel, 48.4% sand, 31.5% silt+clay)	CSEB	5.90	-	28
[64]	9%	Soil (17% clay, 51% silt, 32% sand)	CSEB	9.00	-	28

¹ Tensile strength, ² Phosphate waste rocks.

Seventy-five percent of the compressive strength results fall within the range of 2.42 MPa [30] reported by Souza et al. to 7.00 MPa reported by Masuka et al. [59]. The cement dosage varies from 6% to 16%. The remaining 25% of results range between 9.00 MPa [64] and 11.84 MPa [65], with cement amounts ranging from 8% to 10%.

There are specificities in the composition of the base material or in the compaction force for the highest compressive strength values. For instance, Zhang et al. [64] manufactured several compressed stabilized earth blocks (CSEBs) using a 60 kN press at a rate of 3 N/mm²/min. The density ranged from 1.5 g/cm³ to 2.1 g/cm³ (the highest value among all the selected studies) for the same cement content. With a 9% cement content, the resistance varied from 1 MPa to 9 MPa. Thus, it can be inferred that the value of 9 MPa is attributed to a high compaction force.

In the study conducted by Aninda et al. [26], the utilization of 20% waste concrete powder (WCP) could account for the achieved compressive strength of 10.68 MPa. Specifically, in the same soil mixture containing 8% cement but without the inclusion of waste concrete powder, the compressive strength of the blocks was limited to 6.67 MPa. This value closely aligns with the 7 MPa obtained by Souza et al. [30], which represents the upper limit of the first group constituting 75% of the results.

In the research by Mouih et al. [42], a formulation comprising 80% phosphate residual rock, 10% soil, and 10% cement was studied. The enhancement in compressive strength may be attributed to the optimization of the quantity of clay (10%) and phosphate residual rock (80%). This leads to a reduction in water absorption rate by generating Calcium Silicate Hydrate (C-S-H) and Calcium Aluminum Silicate Hydrate (C-A-S-H) gels upon contact with cement. Subsequently, the formation of insoluble C-A-S-H reacts with the clay minerals and fills the pores, facilitating the binding of fine particles with sand and gravel.

Regarding the compressive strength of 11.84 MPa obtained by Gonzalez-Lopez et al. [65], two major factors could explain this result. Firstly, the authors utilized a high addition of cement (15%). Secondly, they applied a high compressive force (1.96 kN). This idea is reflected in the conclusion of their article, where they state, “[...] CSEB will develop a minimum strength of 6 MPa, either with a high compressive force and a low addition of cement, or with a low compressive force and an increase in the cement stabilizer content.” This suggests that a combination of high compressive force and increased cement stabilizer content can significantly enhance the compressive strength of compressed stabilized earth blocks (CSEBs).

Figure 9 provides an overview of the impact of cement dosage on compressive strength. In the study conducted by Mouih et al. [42], the cement dosage exceeds the compressive strength of the manufactured blocks. In certain instances, the percentage of cement is double or even triple the strength of the blocks. This suggests that compressive strength is not necessarily significantly enhanced by cement stabilization alone [78].

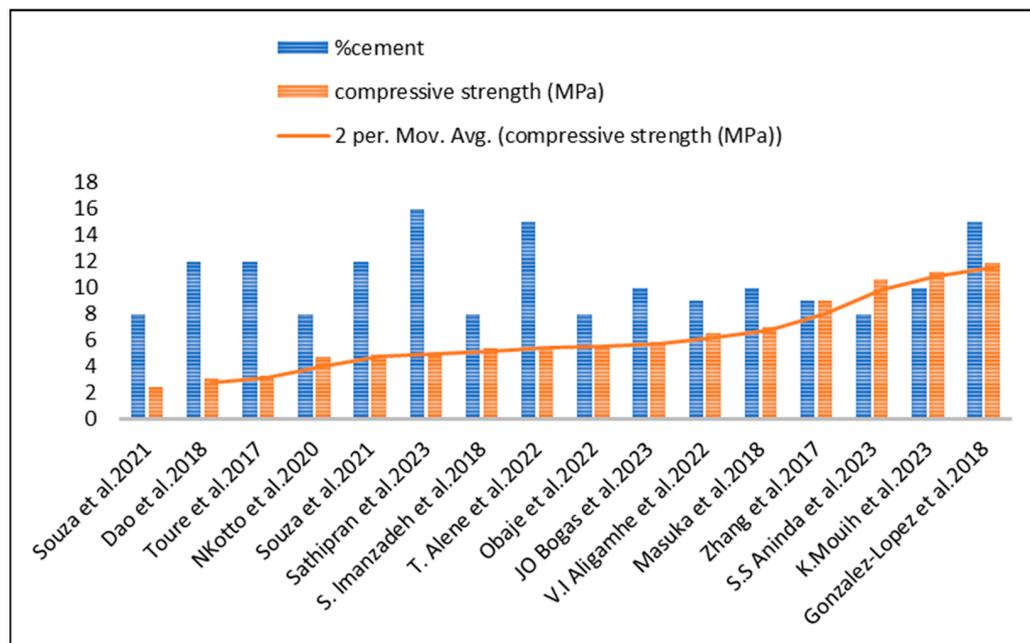


Figure 9. Impact of cement dosage on compressive strength [3,26,30,35,36,42,46,59,63–66,73,77,79].

- Cement stabilization reinforced with fibers or powders.

Cement-stabilized earth blocks reinforced with fibers (natural or synthetic) or with powders addition have been widely studied. Table 5 shows the influence of cement stabilization combining to fiber reinforcement or powder addition on compressive and tensile strengths.

Table 5. Influence of cement stabilization with fiber reinforcement or powder addition on compressive and tensile strengths.

Reference	Cement %	Main Elements of the Soil	Fibers or Additive (%)	Type	Rc (MPa)	Rt (MPa)	Cure (d)
[37]	8%	Soil (67% sand, 20% silt, 13% clay)	Date palm fiber (0.5%)	CSEB	12.50	1.6	28
[73]	10%	Highly plastic clay (W _L = 64.5%, W _P = 22.65%)	Sisal fibers (1%)	Adobe	10.33	-	28
[80]	7%	Soil (23% sand, 52% silt, 22% clay)	Alfa fibers (0.5%)	CSEB	8.26	-	28
[81]	4%	Soil (10% sand, 80% silt, 10% clay)	Rice husk ash (5%)	CSEB	6.95	-	28
[76]	12%	Soil (11% sand, 58% silt, 31% clay)	Sugarcane bagasse (0.5%)	CSEB	4.48	-	28
[82]	10%	Soil (38.5% gravel, 48.8% sand, 9.4% silt, 3.3% clay)	Oil palm fibers (0.5%)	Adobe	4.11	-	28
[83]	12%	70% soil (5% sand, 30% silt, 65% clay) + 30% dune sand	Cork aggregate (2%)	CSEB	2.87	0.57	28
[21]	2.5%	Soil (98,4% sand, 1,6% silt)	Coconut fibers (1%)	CSEB	9.65	6.25	28
[84]	10%	Soil (3% gravel, 5% sand, 66% silt, clay 26%)	Flax fibers (3%)	CSEB	0.65	-	28

Table 5. Cont.

Reference	Cement %	Main Elements of the Soil	Fibers or Additive (%)	Type	R _c (MPa)	R _t (MPa)	Cure (d)
[85]	2.5%	Sand–clay (W _L = 23.29%, W _P = 17.78%)	Grewia optivia fibers	Adobe	3.5	-	28
			Pinus R. fibers		3.2	-	28
[86]	4%	Soil (W _L = 40%, W _P = 19% fraction argileuse: 8%)	Paper (0.78%)	CSEB	7.76	-	30
[87]	10%	Soil (14% sand, 64% silt, 22% clay)	Rice pellets 0.3% Polypropylene 0.3%	CSEB	7.90	1.25	28
[88]	10%	Soil (40% gravel, 37% sand, 10% silt, 11% clay)	Doum palm fibers (1%)	CSEB	11.22	-	28
[49]	5%	Soil (5% gravel, 43% sand, 36% silt, 16% clay)	Shea butter waste (6%)	CSEB	6.2	-	28
[48]	2.5%	Soil (2.3% gravel, 51.5% sand, 41% silt, 5.2% clay)	Rice husk ash (2.5%)	CSEB	2.5	-	28
					7.90	-	108

The compressive strengths of the blocks range from 0.6 MPa [84] and 12.50 MPa [37], with cement dosages varying between 2.5% and 12%.

The lower value of 0.60 MPa was reported by Zak et al. [84]. Their study focused on the influence of natural reinforcement fibers, gypsum, and cement on the compressive strength of compressed stabilized earth blocks (CSEB). Two types of fibers, flax and hemp, were utilized, with their effects evaluated at two different percentages (1% and 3% mass of fibers) in addition to 5% or 10% mass of gypsum or cement. The highest compressive strength (0.60 MPa) was achieved with CSEBs composed of soil with 3% mass of flax fibers and 5% mass of cement.

Conversely, the higher value of 12.50 MPa was mentioned in the study by Taallah et al. [37]. In this research, the authors investigated the mechanical properties of CSEBs filled with date palm fibers. To achieve their objective, earth blocks stabilized with cement were compacted under static loading with three different compacting stresses (1.5 MPa, 5 MPa, and 10 MPa). The highest compressive strength was attained with the mix of CSEBs containing 8% cement, 0.05% fiber content, and compacted under 10 MPa pressure.

The general observation is that the addition of fibers or powders improves the compressive strength value more than cement stabilization only. The following comments help to demonstrate this:

- i. Twelve studies out of seventeen (70.6%) give results where the compressive strength is greater than the percentage of cement used. The strength values in these cases are between 2.5 MPa and 12.5 MPa for a cement mass percentage of 2.5% and 8%, respectively;
- ii. Five studies out of seventeen (29.4%) give results where the compressive strength is lower than the cement stabilization percentage. In this case, the strength values vary between 0.60 MPa and 7.90 MPa for stabilization rates of 10 to 12%.

Indeed, it appears that there may be a need to reconsider the limitation on the proportion of cement, particularly in cases where cement stabilization is accompanied by fiber reinforcement or the addition of biological binders (powders). Figure 10 illustrates the impact of cement dosage and fiber reinforcement or biological binder addition (powder) on compressive strength. This suggests that there may be potential for optimizing the cement dosage in conjunction with other reinforcing elements to achieve higher compressive strengths in compressed stabilized earth blocks (CSEBs).

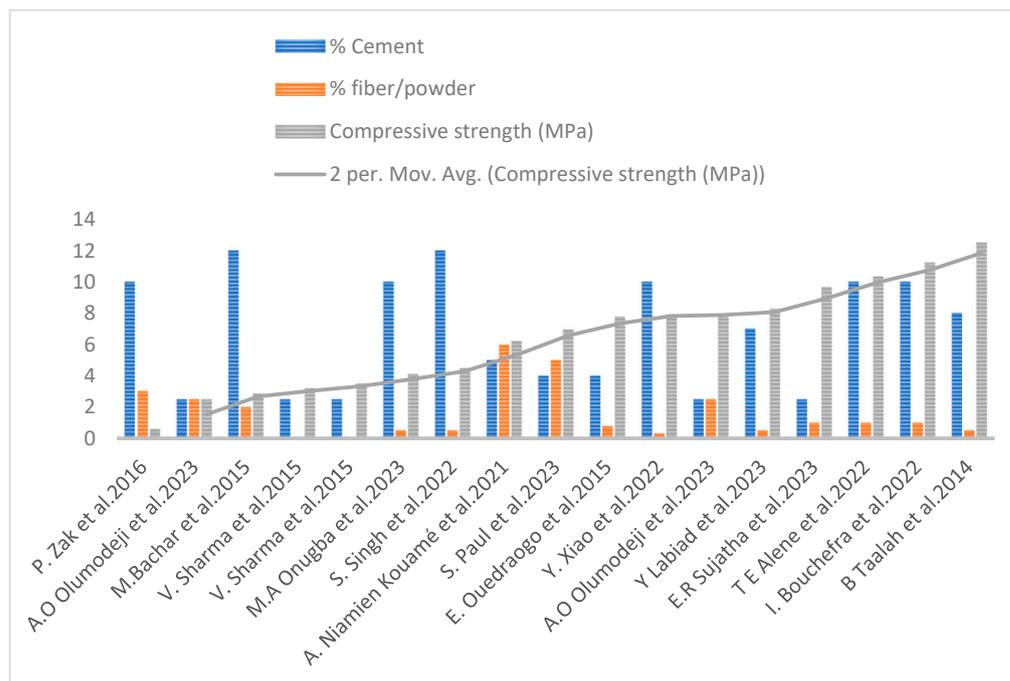


Figure 10. Impact of cement and fiber or powder dosages on compressive strength [1,21,37,48,49,73,76,80,82–88].

- Stabilization using fibers or biological binder (powder) only.

Natural or synthetic fibers are commonly used to stabilize or reinforce raw earth blocks, offering notable advantages in terms of compressive strength. For instance, in a study by Cottrell et al. [71], compressed stabilized earth blocks (CSEBs) incorporating jute fibers exhibited a compressive strength of 9.68 MPa. The study investigated the impact of jute moisture on compressive strength, revealing the potential degradation caused by soaked jute fibers. It was recommended to incorporate jute fibers in CSEBs at their natural moisture content to mitigate such degradation.

Similarly, Abessolo et al. [60] explored the effects of bamboo fiber length and percentage on the physical, mechanical, and hygroscopic properties of compressed earth blocks (CEBs). Blocks stabilized with 0.5% bamboo fibers measuring 4 cm in length demonstrated enhanced compressive strength, with the highest value reaching approximately 11.70 MPa.

Biological binders in the form of powders also contribute to significant improvements in compressive strength. In a study by Venkatesh et al. [89], blocks composed of soil, marble dust particles (MDP), and rice husk (RH) exhibited enhanced resistance. A composition comprising 70% soil, 30% MDP, and 1% RH resulted in compressed earth blocks capable of withstanding a compressive stress of 9.27 MPa.

Even in cases where the emphasis is not primarily on compressive strength, such as in the study by Charai et al. [51], compressed earth blocks (CEBs) can still exhibit satisfactory structural properties. In their investigation aimed at proposing eco-friendly thermal mass elements for construction, Charai et al. achieved a compressive strength of 1.05 MPa using 2% *Pennisetum setaceum* fibers in adobe production.

This demonstrates the feasibility of manufacturing compressed earth blocks suitable for use as structural elements, meeting various regulatory requirements. Indeed, the compressive strengths reported in several studies exceed the typical strength of a concrete block rated at 80 bars, equivalent to 8 MPa. Such concrete blocks are commonly utilized in foundations, base walls, and basements. Table 6 presents a summary of compressive and tensile strengths in cases involving fiber reinforcement or the addition of powder alone.

Table 6. Influence of reinforcement by fibers or addition of powder alone on compressive and tensile strengths.

Reference	Binder (%)	Main Elements of the Soil	Type of Block	R _c (MPa)	R _t (MPa)
[32]	Date palm fibers (0.5%)	Soil (36% gravel, 58% sand, 2% silt, 4% clay)	CEB	3.50	-
[60]	Bamboo fibers (0.75%)	Laterite soil (59% sand, 21% silt, 20% clay)	CEB	11.70	-
[90]	Fonio straw (0.4%)	Clayey raw (W _L = 31%, W _P = 17%)	Adobe	2.90	-
[66]	Coconut fibers (0.5%)	Soil (1.61% gravel, 37.55% sand, 35.14% silt, 25.70% clay)	CEB	6.88	1.17
[73]	Sisal fibers (1%)	Highly plastic clayey soil (W _L = 64.5%, W _P = 22.65%)	CEB	6.14	-
[47]	Kenaf fibers (0.4%)	Soil (44.5% sand, 30% silt, 25.5% clay)	CEB	2.80	1.80
[91]	Coconut fibers (1%)	Soil (12% gravel, 46% sand, 28% silt, 14% clay)	Adobe	1.35	0.29
[1]	Vetiver fibers (3%)	Soil (72.36% silt, 27.64% clay)	CEB	1.36	-
[80]	Alfa fibers (0.5%)	Soil (15% sand, 30% silt, 55% clay)	CEB	5.30	-
[89]	Rice husk ash (1%)	Soil (20% sand, 12% silt, 67.5% clay)	CEB	9.27	-
[92]	Polypropylene fibers (1%)	Low-plasticity clayey soil (W _L = 27%, W _P = 15.70%)	CEB	2.07	-
[51]	Pennisetum setaceum fibers (2%)	Soil (6.5% sand, 45% silt, 48.5% clay)	Adobe	1.05	0.25
[93]	Betel nut fibers (1%)	Soil (8.41% gravel, 77.89% sand, 13.70% clay–silt)	Adobe	1.87	-
[70]	Plantain banana fibers (0.75%)	Soil (19% gravel, 46% sand, 20% silt, 15% clay)	Adobe	1.76	0.3 ¹
[94]	Straw fibers (0.5%)	40% fine clay + 60% sand–gravel	Adobe	2.82	-
[71]	Jute fibers (0.5%)	80% Soil (22% sand, 56% silt, 22% clay) + 20% marine sand	CEB	5.22 9.68	0.13 ² 0.39 ³

¹ Tensile strength for 0.5% plantain stem fiber. ² Value corresponding to normal humidity conditions. ³ Value corresponding to jute fibers soaked to 205%.

- Lime stabilization with or without the addition of secondary elements.

Table 7 displays the compressive strength of lime-stabilized earth blocks with or without the inclusion of fibers or natural powder. The articles chosen in this section do not address tensile strength. The additives, which include powders (such as coal ash and sawdust) or fibers (like alfa fibers or polypropylene), were incorporated at proportions ranging from 0.2% to 10%.

Table 7. Compressive strength of lime-stabilized earth blocks with addition (fibers or biological binder).

Reference	Lime %	Main Elements of the Soil	Fibers or Biological Binder (% by Weight)	Type	R _c (MPa)	Cure (d)
[59]	10%	Soil (52% sand, 8% silt, 40% clay)	Wood aggregate (1.5%) Coal aggregate (10%)	CSEB	8.30	28
[55]	5%	Soil (4% gravel, 62% sand, 18% silt, 16% clay)	Polypropylene fiber (0.2%)	CSEB	7.14	28
[62]	40%	60% of clayey soil (10% sand, 54% silt, 36% clay)	Sawdust (4%)	CSEB	1.80	28
[50]	44%	-	Alfa fibers (2.85%)	Adobe	1.07	28
[57]	4%	Soil (10% gravel, 28% sand, 42% silt, 20% clay)	Coal aggregate (10%)	CSEB	0.99	28

The values of compressive strengths can be grouped into two intervals:

- The lowest values are between 0.99 and 1.80 MPa. For these values, the soil as raw material was not fully characterized. It is therefore impossible to analyze the effect of plasticity on these values. The mass percentage of lime is also highly variable (4 to 44%), which makes it impossible to discuss its effect on compressive strength. In terms of reinforcements, both powders (coal aggregates) and fibers (alfa fibers) are used;
- The highest values of compressive strength are 7.14 MPa [55] and 8.14 MPa [59]. These values were obtained with soils that contain more than 50% sand.

In the study of Ganesh et al. [55], the compaction parameters such as maximum dry density and optimum moisture content were determined. The authors used various mix proportion of soil with lime, geo-fibers, and ground granulated blast furnace slag (GGBS). The highest dry compressive strength of 7.14 MPa was recorded at 28 days for a CSEB with 5% lime + 30% GGBS + 0.2% geo-fibers + 64.8% soil.

Masuka et al. [59] conducted a study to assess the impact of lime–coal fly ash–wood aggregate mixtures on the mechanical strength of CSEBs. Their ultimate aim was to compare the cost-effectiveness of the enhanced CSEB to that of the control (10% cement). The primary finding was that the dry compressive strength (8.14 MPa) of blocks stabilized by 10% lime + 10% fly ash + 1.5% wood aggregate was higher than that of blocks stabilized with 10% cement.

Using lime for stabilizing earth blocks typically results in lower compressive strength values, with two notable differences possibly stemming from a controlled stabilization rate (maximum of 10% lime).

Tensile Strength

Tensile strength is the maximum mechanical tensile stress with which a specimen can be loaded. When this resistance is exceeded, the absorption of forces decreases until the material sample breaks.

According to Avila et al. [4] tensile strength is one of the most relevant parameters in the analyses of earth-based construction failure, particularly in seismic conditions. To reinforce the blocks against the seismic phenomenon, rock materials can be used. These

materials such as granite, used in physical stabilization, also enable the block to better withstand vibrations. Indeed, when the combination of fine particles and gravel (often granite) is managed properly, it results in an improvement in the cohesion of the block structure. Therefore, it is essential to respect the recommended granular range when adding rock materials to fine clays.

- Cement stabilization only.

In the selected articles, only one out of the fifteen studies (Table 4) address tensile strength.

Nkotto et al. [66] focused their research on the influence of coco fiber content on the physical and mechanical properties of CEBs. They also compared these characteristics to those of CEBs stabilized with 8% cement. The study revealed that using cement does not increase flexural strength. Consequently, for stabilization with 8% cement, the tensile strength decreases by 57%, from 0.7 MPa for 0% cement to 0.33 MPa for 8% binder.

- Cement stabilization reinforced with fibers or biological binders (powders).

Four studies have highlighted the impact of cement stabilization with fiber or powder reinforcement on the tensile strength of earth blocks. The values range from 0.57 MPa [83] to 6.25 MPa [21] as shown in Table 5.

In the study by Sujatha et al. [21], it was mentioned that the use of fibers to reinforce the block gave it a more ductile character with progressive failure. This is explained by the ability of the fibers to sew the cracks, holding the earth block together for as long as possible.

Bachar et al. [83] investigated the mechanical and thermal properties of a composite (soil–sand dune–cement) with the aggregate of cork. The optimal mixture proposed was 58% of soil + 30% of dune sand + 12% of cement. The tensile strength of cement-stabilized compressed earth blocks increases with the percentage of dune sand, from 0.3 MPa to 0.57 MPa as the dune sand content increases from 0% to 30%.

- Reinforcement using fibers or biological binder (powder) only.

Tensile strength values range from 0.13 MPa in the study of Cottrell et al. [71] to 1.80 MPa in the study of Millogo et al. [47]. The advantage noted by these authors remains the same: the fibers confer greater ductility on the earth block. As a result, the tensile strength improves significantly until a certain percentage of fibers is reached.

Nkotto et al. [66] demonstrated that the tensile strength increases with fiber addition until a threshold of 0.8% of coco fibers, before dropping. In fact, the stabilization by fibers plays the role of reinforcement with good adhesion in the composite matrix, absorbing the bending forces applied to the material. Above 0.8% of fibers, this resistance drops, signifying the decrease in fiber–CEB matrix bond, as the fibers become more numerous and overlapped. The best percentage of fibers according to their study was 0.8%, which permitted the production of CEBs with a tensile strength of 1.17 MPa.

Flexural Strength

Bending strength is the maximum load that a long component can support without breaking when subjected to forces applied perpendicular to its longitudinal axis. Table 8 and Figure 11 show the values of this characteristic in several studies.

The study by Aninda et al. [26] explored the potential of using waste concrete powder (WCP) in CSEB fabrication. Durability, thermal assessment, and strength were studied using three cement contents (4%, 6%, and 8%) and four WCP contents. The optimal WCP replacement (20%) resulted in a peak strength of 1.92 MPa compared to the value of 1.12 MPa without WCP. The value of 1.92 MPa is close to that of a reinforced concrete block with a compressive strength of 20 MPa. These blocks can therefore be used to build a lightly loaded floor.

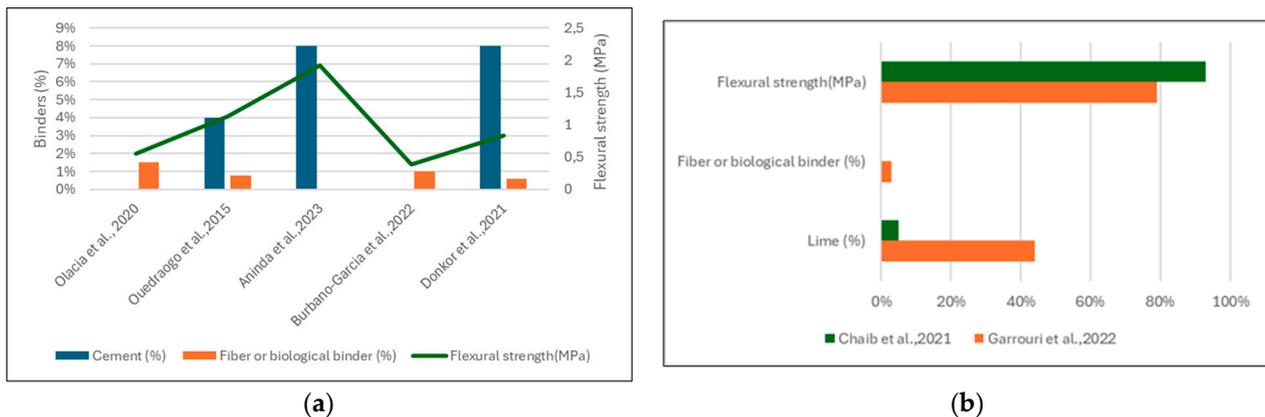


Figure 11. Variation in flexural strength based on the percentages of binders: (a) cement, fiber, or biological binder [26,86,92,94,95]; (b) lime, fiber, or biological binder [50,52].

The lower value in this category was obtained by Burbano-Garcia et al. [92] in their study on adobe mixture reinforced with fibrillated polypropylene fibers (FPFs). It should be noted that the incorporation of 1% FPFs decreased the flexural strength by 43%, from 0.68 MPa to 0.39 MPa. According to the authors, this significant reduction in flexural strength could be attributed to the formation of fiber clusters due to the manual mixing process.

3.2.3. Thermal Properties

The concern to ensure optimal hygrothermal comfort in earth construction has prompted several researchers to characterize the thermal and hydric response of earthen blocks [4]. The common parameters studied are thermal conductivity, heat capacity, and dry density (see physical properties for density, Table 3). Table 9 provides the thermal conductivity and heat capacity values for the selected articles.

Thermal Conductivity

Thermal conductivity is a measure of a substance's ability to transfer heat through a material by conduction. The higher the thermal conductivity, the better the material conducts heat. The thermal conductivity values reported by researchers range from $0.31 \text{ W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ [50] to $1.10 \text{ W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ [45].

For example, Garrouri et al. [50] focused on the potential of alfa fibers as reinforcement material in sustainable construction. They used a mix of hydraulic lime binder (NHL5) and varied amounts of alfa fibers to investigate the mechanical and thermal properties of the adobes fabricated. The thermal conductivity ranged from 0.28 to 0.31 W/m.k as the control temperature varied from 10 to 40 °C.

Saidi et al. [45] conducted an experimental investigation on the effects of stabilizers on the hygrothermal properties of compressed earth blocks. Their results indicated that thermal conductivity increases with the addition of stabilizers. Specifically, the thermal conductivity of lime-stabilized blocks ranged from 0.79 to 0.99 $\text{W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ as the lime content varied from 5% to 12%. Similarly, for cement-stabilized blocks, thermal conductivity varied from 0.8 to 1.10 $\text{W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ with increasing cement content from 5% to 12%.

It is important to note that the lowest, and thus optimal, thermal conductivity is achieved with a combination of lime and alfa fibers in adobe manufacturing. On the other hand, the highest thermal conductivity, indicating the least optimal performance, is observed with cement stabilization alone, particularly at a mass percentage of 12%.

Median thermal conductivity values ranging between 0.33 and 0.55 $\text{W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ were obtained without the addition of cement. Lime, along with fibers or biological binders (powder), was used to stabilize and reinforce the blocks. Conversely, when cement was

used alone or with additives such as fibers or powders, the thermal conductivity values obtained were higher.

In the study conducted by Aninda et al. [26], a thermal conductivity value of $1.09 \text{ W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ was reported for compressed earth blocks stabilized with 8% cement and the addition of waste concrete powder (WCP). Conversely, Ouedraogo et al. [86] achieved a thermal conductivity value of $0.59 \text{ W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ in their study, which is close to the median values. This lower conductivity value can be attributed to the incorporation of paper (0.78%) in addition to cement. The lightweight nature of paper contributed to reducing the density of the block as well as its thermal conductivity.

These findings suggest a decrease in thermal conductivity when fibers are incorporated into the soil matrix to reinforce it. For studies that did not mention thermal conductivity, it is reasonable to assume that the relatively low-density values obtained would have led to similar conductivity results if measurements had been made. This inference is supported by the literature review by Turco et al. [22], who demonstrated a linear relationship between apparent density and thermal conductivity based on a graph (Figure 12).

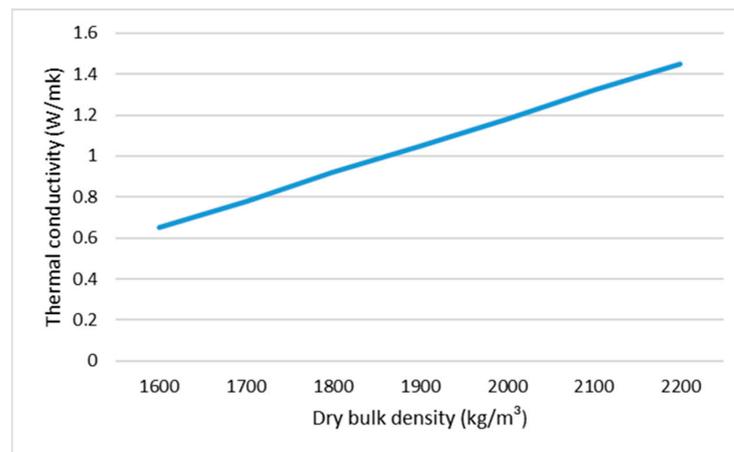


Figure 12. Linear relation between dry bulk density and thermal conductivity (adapted from [22]).

The linear correlation proposed by Turco et al. [22] between thermal conductivity and density of compressed earth blocks (CEBs) has been challenged by Nshimiyimana et al. [96]. According to them, Turco et al. oversimplified the relationship between thermal conductivity and density. Instead, they advocated for a parabolic curve described by an exponential function, as depicted in Figure 13 of their study.

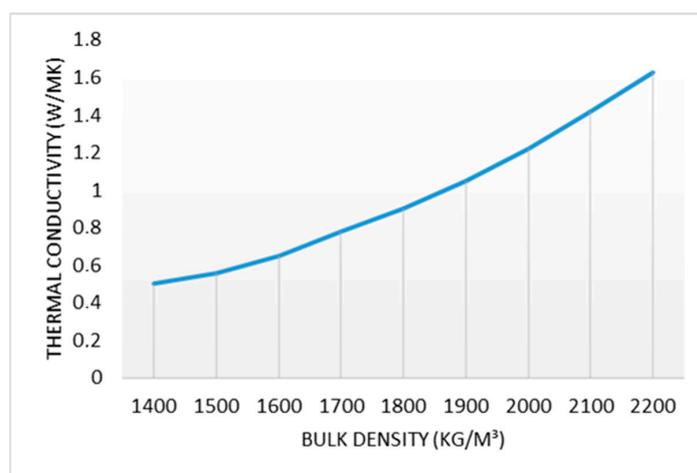


Figure 13. Parabolic relationship between dry bulk density and thermal conductivity (adapted from [96]).

In response to this discussion, Turco et al. [97] argue that there is a high risk of biased analysis, as the data presented by Nshimiyimana et al. [96] are drawn from nine studies selected without any apparent criterion or rationale defined. Turco et al. also mention that their review involved studies focusing on blocks optimized with natural origin materials, and the results presented in the mentioned graphs are only related to that specific situation.

Mass Heat Capacity

The heat capacity of a body quantifies its ability to absorb or release energy through heat exchange as its temperature changes. Greater heat capacity means the body can exchange more energy during temperature variations. Regarding heat capacity, the values can be classified into two groups:

- Studies on adobes [51,52] give two values, 907 and 925 $\text{J}\cdot\text{kg}^{-1}\cdot\text{k}^{-1}$. These values are close and are obtained by using lime and fibers as a means of stabilization and reinforcement;
- In the case of CEBs or CSEBs, the values follow a linear progression as a function of thermal conductivity. For example, the mass heat capacity varies from 1704 to 1040 $\text{J}\cdot\text{kg}^{-1}\cdot\text{k}^{-1}$ while the thermal conductivity varies from 0.48 to 0.75 $\text{W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ [32,36,80,86].

These results suggest that incorporating natural fibers or biological binders (powder) improves the thermal performance of adobe or compressed earth blocks (Figure 14).

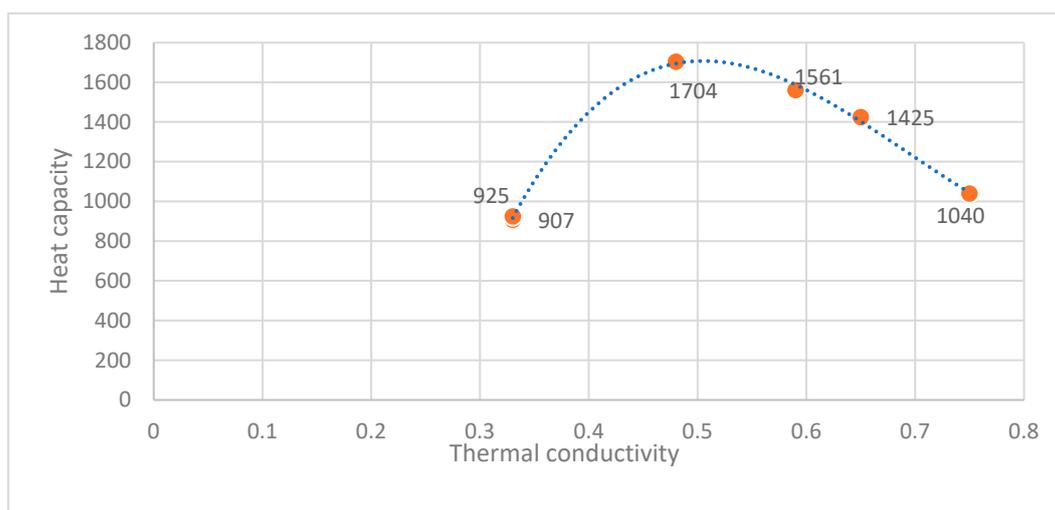


Figure 14. Variation in mass heat capacity related to thermal conductivity.

The mass heat capacity increases with thermal conductivity up to a conductivity limit value of around $0.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$. Above this value, specific heat decreases while conductivity increases. One can observe that the decrease is almost linear.

3.2.4. Properties and Sustainability Indicators

The durability of earth construction solutions has been primarily assessed in terms of mass loss, abrasion resistance, and erosion resistance, often evaluated through absorption tests. Some studies have also focused on economic aspects, such as cost analyses or environmental impact comparisons with concrete constructions [59,81]. Results on properties and sustainability indicators are summarized in Table 10.

Table 8. Flexural strength of stabilized raw earth blocks.

Reference	Main Elements of the Soil	Cement (%)	Lime (%)	Fibers or Biologicals Binders (Powder)	σ_f (MPa)	Cure (d)
[50]	-	-	44%	Alfa fibers (2.85%)	0.79	28
[94]	Soil (40% fine clay, 60% sand-gravel)	-	-	Seagrass (1.5%)	0.55	28
[86]	Soil ($W_L = 40\%$, $W_P = 19\%$; clay fraction: 8%)	4%	-	Paper (0.78%)	1.13	28
[52]	Soil (38% sand, 27% silt, 35% clay)	-	5%	Gravel (50%)	0.93	28
[26]	Soil (6.3% sand, 93.7% silt-clay)	8%	-	WCP (20%)	1.92	28
[92]	Low-plasticity clayey soil ($W_L = 27\%$, $W_P = 15.70\%$)	-	-	FPFs (1%)	0.39	28
[95]	Soil (87% sand, 2% silt, 12% clay)	8%	-	Geo-fibers (0.6%)	0.84	28

Table 9. Influence of stabilization type on thermal properties.

Reference	Binder (Stabilization and/or Reinforcement)	Main Elements of the Soil	Type	C_p ($J \cdot kg^{-1} \cdot K^{-1}$)	Conductivity λ ($w \cdot m^{-1} \cdot K^{-1}$)
[35]	Cement (4%)	Soil (5% soil, 42.5% sand, 20% silt, 32.5% clay)	Adobe	-	0.86
[36]	Cement (12%)	Soil (22% gravel, 40% sand, 20% silt, 18% clay)	CSEB	1040	0.75
[45]	Cement (12%)	Soil (1% gravel, 42% sand, 57% clay + silt)	Adobe	-	1.10
[83]	Cement (12%) Cork aggregate	Soil (65% clay, 30% silt, 5% sand)	CSEB	-	1.06
[26]	Cement (8%) + WCP	Soil (6.3% sand, 93.7% silt-clay)	CSEB	-	1.09
[86]	Cement (4%) + paper (0.78%)	Soil ($W_L = 40\%$, $W_P = 19\%$ clay fraction: 8%)	CSEB	1561	0.59
[80]	Cement (7%) Alfa fiber (0.5%)	Soil (15% sand, 30% silt, 55% clay)	CSEB	1425	0.65
[32]	Date palm (0.5%)	Soil (36% gravel, 58% sand, 2% silt, 4% clay)	R-CEB	1704	0.48
[61]	Reed fibers (7%) Hemp (1%)	Soil (45% sand, 42% silt, 8% clay)	Adobe	-	0.55
[50]	Lime (44%) Alfa fibers (15%)	-	Adobe	-	0.31
[52]	Lime (5%)	50% Soil (38% sand, 28% silt, 34% clay) + 50% gravel	Adobe	925	0.33
[88]	Lime (9%) Palm fibers (2%)	Soil (40% gravel, 37% sand, 10% silt, 11% clay)	CSEB	-	0.57
[94]	Seagrass (0.5%)	Soil (40% gravel-sand, 60% clay)	Adobe	-	0.55
[57]	Lime (10%) Coal aggregates (20%)	Soil (10% gravel, 28% sand, 42% silt, 20% clay)	CSEB	-	0.43
[51]	Pennisetum setaceum fibers (8%)	Soil (6.5% sand, 45% silt, 48.5% clay)	Adobe	907	0.33

Table 10. Durability properties of raw earth blocks.

Reference	Stabilization or Reinforcement	Water Absorption (%)	Abrasion (%)	Shrinkage (%)	Mass Loss (%)	Type of Block
[73]	Cement (10%) + sisal (1%)	-	-	-	10.14	Adobe
[80]	Alfa fibers (0.5%)	5.58–7.80	-	-	-	R-CEB
[59]	Cement + lime + wood	16.00–11.00	-	0.9	-	Adobe
[30]	Cement (12%) + Cassava wastewater	12.91	-	0.3	-	CSEB
[37]	Cement (8%) Date palm fibers (0.05%)	09.20	-	-	-	CSEB
[60]	Bamboo fibers (0.75%)	18.20	-	-	-	R-CEB
[53]	Calcined laterite Phosphoric acid solution	09.36–14.18	-	-	9.19	CEB
[81]	Cement (8%) Rice husk ash (10%)	18.78–05.18	-	-	-	CSEB
[21]	Cement (2.5%) Coconut fibers (0.25%)	18.37	0.69	0.19	7.90	CSEB
[70]	Plantain fibers (1%)	-	-	-	11.67	Adobe
[65]	Cement (5–10%)	10.00–05.00	5 to 150 ¹	-	-	CSEB
[45]	Cement (0–12%)	05.69–03.70	-	-	-	CSEB
[98]	Cement (5–15%)	12.40–07.00	-	-	-	CSEB
[26]	Cement (8%) + Waste concrete powder (20%)	13.00–07.00	-	-	-	CSEB
[42]	Cement (8%) + phosphate waste rock (PhWR)	7.00	-	-	-	CSEB
[55]	Lime + polypropylene fibers	11.80	-	-	-	CSEB
[51]	Pennisetum setaceum fibers (8%)	-	3	-	-	Adobe
[88]	Cement	12.48–11.60	-	-	-	CSEB
[27]	Cement	17.10–13.38	-	0.9 to 1.5	-	CSEB
[79]	Cement (9%)	11.43–05.71	-	-	-	CSEB

¹ The unit used in this study is g/cm².

For instance, Saidi et al. [45] reported the lowest percentage of absorption at 3.70%, followed by Gonzalez-Lopez et al. [65], with blocks exhibiting 5% absorption. These studies specifically pertain to cement-stabilized earth blocks, indicating that cement significantly reduces water absorption. In contrast, earth blocks produced by Abessolo et al. [60] exhibited the highest water absorption rate at 18.20%. However, this value still falls below the minimum requirement stipulated by various standards, typically set at 20% [30].

In terms of cost studies, Shantanu et al. [81] demonstrated an 8.65% cost reduction when using compressed earth blocks (CEBs) instead of fired clay bricks (FCBs). They compared the construction cost of a full-floor building measuring 6.9 m × 5.8 m × 3.05 m using both types of blocks of the same size. The CEBs option amounted to USD 1208, while the FCBs option cost USD 1303. Additionally, they highlighted that CEBs have a lower environmental impact across six environmental categories selected for their study.

Furthermore, Masuka et al. [59] compared the cost implications of different stabilization methods for producing 1000 units of unfired earth blocks (UEBs). They found that blocks stabilized with cement only (10%) cost twice as much as UEBs incorporating 10% lime + 10% coal ash + 1.5% biomass aggregates + 4% cement. However, these UEBs complied with the technical specifications of the British standard BS EN 772-1 [99], which served as a reference for their technical study.

4. Results Discussion

Promoting earth construction is a global concern because it contributes to fulfilling the demand for environmentally friendly building practices [12]. However, mastery of this construction method requires thorough understanding and characterization of the materials involved [100], as well as exploring avenues for optimization. In recent years, numerous researchers have focused on enhancing the performance of earth blocks to ensure they meet the technical specifications outlined in the applicable standards of their respective geographical regions. The percentage distribution of articles according to the parameters studied is as follows:

- 98.57% (69/70) of the articles selected studied the wet or dry density of the blocks, some often relating it to mechanical and thermal properties;
- 84.43% (59/70) characterized the mechanical properties of the blocks in terms of compressive, tensile, and flexural strength;
- 24.29% (17/70) assessed thermal properties such as thermal conductivity, thermal diffusivity, and heat capacity;
- 44.29% (31/70) of the articles studied the durability of the blocks.

These different trends are shown in Figure 15.

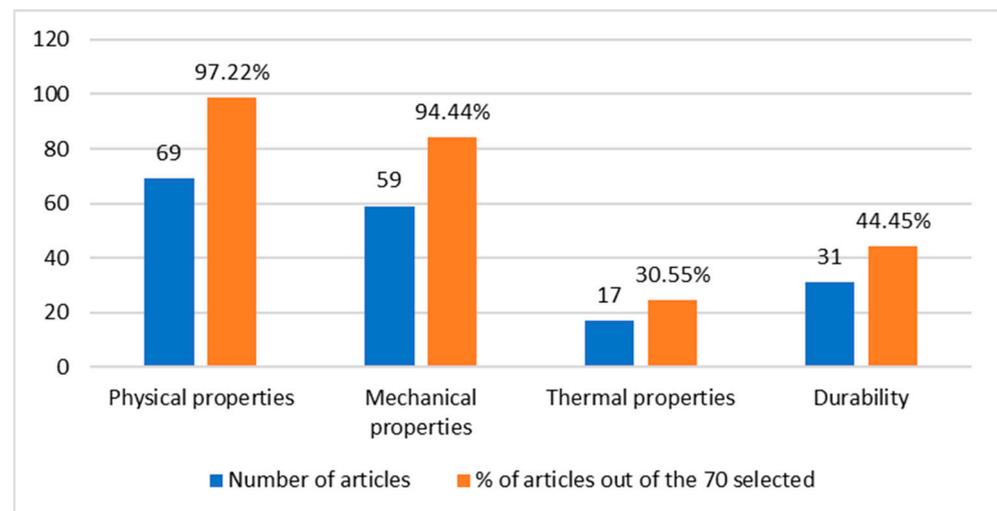


Figure 15. Percentage distribution of articles by theme.

The selected articles adequately cover each topic, although they are spread out across different geographical areas. The variation in soil properties used in these studies makes it challenging to compare results directly. However, the role of fibers, powders, or ashes is evident: they are introduced into the mix to enhance compressive strength, improve thermal conductivity, and optimize flexural or tensile strength.

Regarding mechanical properties, Turco et al. [22] conclude in their review that natural fibers are not introduced to increase the compressive strength of blocks. Similarly, Taallah et al. [37] take a similar stance, suggesting that the addition of fibers may reduce compressive strength. However, this notion needs to be qualified in light of the work by Alene et al. [73] and Labiad et al. [80]. These studies present graphs illustrating that compressive strength increases with the percentage of fibers used (Figures 16 and 17). It is noteworthy that one study utilizes a composition of 5% cement + 1% sisal fibers, while the other employs 0.5% Alfa fibers, both showing similar trends up to a certain threshold. Natural fibers not only improve mechanical behavior (compressive strength, tensile strength, and flexural strength) but also enhance thermal behavior [101].

- Alfa fibers

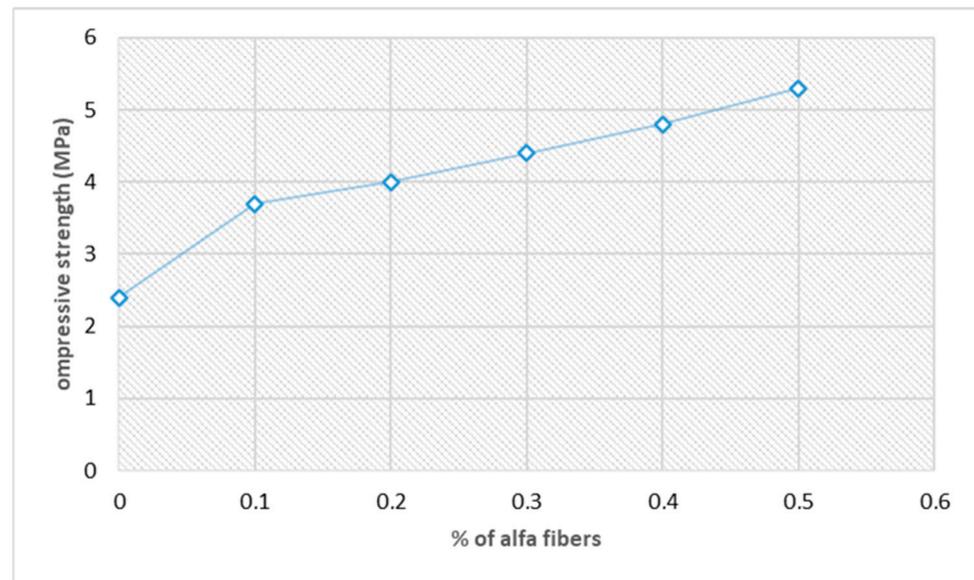


Figure 16. Effect of Alfa fibers on compressive strength (adapted from [80]).

- Sisal fibers

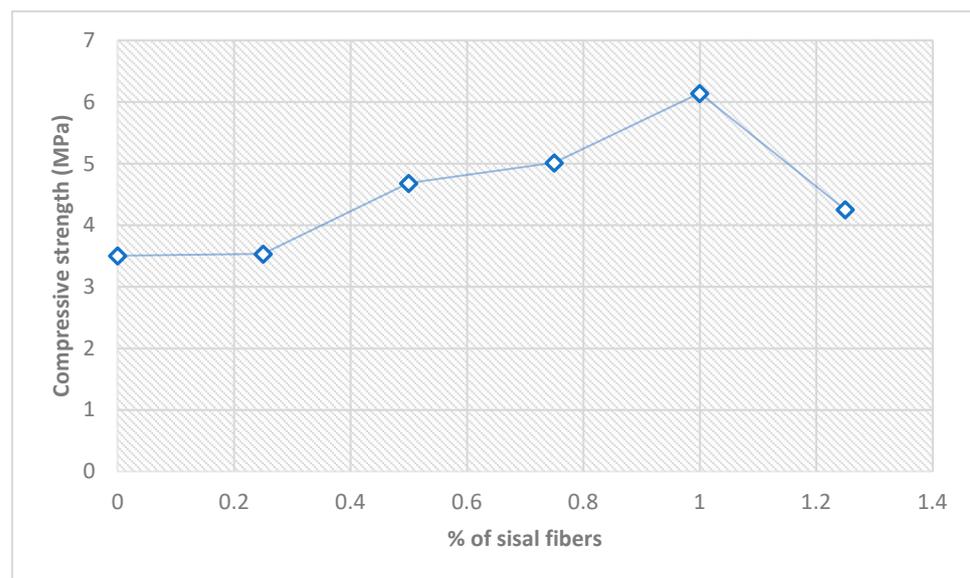


Figure 17. Effect of sisal fibers on compressive strength (adapted from [73]).

In the study by El Mendili et al. [102] on the contribution of crepidula shells to optimizing cob properties, a similar trend was observed. Gravel wash mud was utilized as a construction material, supplemented with 2% straw, 5% crepidula fornicata powder, and 25% fly ash. This resulted in a cob that was 2.65 times stronger than the reference cob.

Furthermore, a combination of cement and natural powder (8% cement + 10% RHA in the study by P. Shantanu et al. [81]) can lead to a 400% improvement in compressive strength. Regarding fiber-based cementitious composites, Zongo and Konin [103] demonstrate that mechanical strengths vary (increase or decrease) according to the type of fibers used (rice husk or rhun aggregates).

Indeed, in the case of mixtures of cement and rice husk aggregates, mechanical strengths decrease with increasing particle size. However, in the case of composites based on rhun fibers (*Borassus aethiopicum* mat.), strength increases with fiber size.

Further studies may confirm that the use of natural fibers and powders can improve the compressive strength of earth blocks. In terms of thermal conductivity, the addition of natural fibers or powders reduces dry density, increases porosity, and thus improves thermal conductivity (Figure 18).

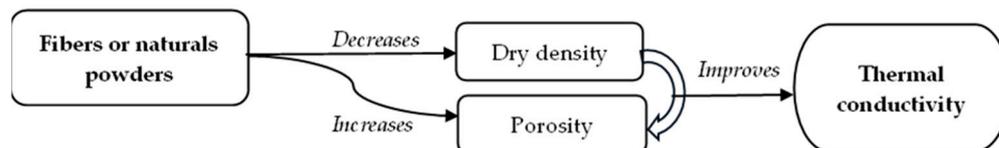


Figure 18. Impact of natural fibers or biological binders (powder) on thermal conductivity.

The relationship between the reduction in density and the improvement in thermal conductivity was observed by all the researchers. They all concluded that there is a maximum fiber content above which the block is no longer durable, as immersion in water for 24 h causes the block to disintegrate.

There are limited data on economic studies of earth blocks compared to other materials such as ordinary bricks or concrete. In the model of Shantanu et al. [81], the cost of the CEB solution is 92.25% of the cost of the sand–cement brick solution, representing a saving of 7.25%.

In addition to delivering excellent results in terms of thermal insulation and mechanical strength, building with raw earth can lead to direct cost savings in construction projects.

In the realm of sustainable construction, the incorporation of cement and fibers into cement-earth based materials has garnered considerable attention due to its potential to enhance mechanical properties. Several studies have investigated the effects of these additives on various aspects of material performance, shedding light on both their benefits and challenges.

A notable study by Zhang et al. [104] explored the impact of adding polypropylene fibers on the mechanical properties of cement-earth based materials. Their research demonstrated that the inclusion of fibers significantly improved tensile and flexural strength, as well as crack resistance. These findings underscore the potential of fiber reinforcement in enhancing the structural integrity of cement-earth based materials.

Similarly, a study by Wang et al. [105] investigated the effects of cement content on the mechanical properties of cement-earth based materials. Their findings revealed that increasing the cement content led to improvements in compressive strength and durability. However, they also noted that higher cement content could result in increased material costs, highlighting the importance of balancing mechanical performance with economic considerations.

Despite these advancements, challenges remain in optimizing the mechanical properties of cement-earth based materials while maintaining cost-effectiveness. As highlighted by Li et al. [106], the selection of appropriate fibers and cement proportions is crucial in achieving desired mechanical properties without significantly inflating production costs. Additionally, further research is needed to explore alternative additives and manufacturing techniques that can improve mechanical performance while minimizing economic burden.

One other topic concerned the substantial waste generated by municipal waste incineration plants that poses a significant challenge, particularly in terms of waste management. However, this waste material, known as municipal solid waste incineration (MSWI) bottom ash, offers potential for repurposing in construction applications. Studies have shown that MSWI bottom ash can serve as a supplementary cementitious material in concrete and mortar mixes (Hossain et al. [107]; Poon et al. [108]). Furthermore, research has explored its effectiveness as a stabilizing agent for soft marine clay in road construction (Tam et al. [109]). By incorporating MSWI bottom ash into construction practices, stakeholders can address waste management challenges while advancing sustainable construction objectives, thereby fostering a more circular and resilient built environment.

5. Conclusions

The advancement of raw earth construction necessitates a comprehensive understanding of the inherent properties of this versatile material. Raw earth, when stabilized and reinforced with fibers and biological binders (powders), offers myriad advantages. The extensive research conducted in recent years warrants a concerted effort to synthesize findings more effectively, thus establishing a cohesive framework for future investigations.

Key insights derived from the research underscore several pertinent observations.

Out of the 70 articles scrutinized in this study, a breakdown reveals:

- (i) 62.86% focused on waste recovery and the utilization of invasive plants;
- (ii) 22.86% addressed the enhancement of block properties through cement stabilization alone;
- (iii) 45.71% examined the partial replacement of cement with fibers, lime, or biological binders (powders);
- (iv) 27.14% explored the total replacement of cement, often employing waste or invasive plants.

The incorporation of natural fibers and biological binders (powders) significantly enhances the properties of soil blocks, contingent upon adherence to specific mass percentage thresholds. However, the variability of these parameters necessitates the establishment of a definitive relationship between the soil matrix and the binder, potentially through computational modeling, to facilitate result transposition.

The stabilization of earth blocks with cement and their reinforcement with fibers or plant powders offer several advantages but also present disadvantages. Adding cement to the earth increases the mechanical strength and durability of the blocks, which extends the lifespan of the structures and reduces the risks of cracking or collapse. Meanwhile, reinforcement with natural or synthetic fibers improves tensile strength, ductility, and the blocks' ability to absorb vibrations from impacts or earthquakes.

However, these techniques also have some drawbacks. Adding cement can reduce the permeability of the blocks, thus affecting their ability to manage internal moisture and causing condensation issues. Additionally, the use of cement increases the construction's carbon footprint, as cement production is energy-intensive and emits greenhouse gases. Regarding fibers, their aging behavior remains uncontrolled, and they must be well distributed in the mix to ensure optimal effectiveness.

While the addition of cement and fibers holds promise for enhancing the mechanical properties of cement-earth based materials, it is essential to consider the economic implications of these additives. By leveraging insights from research studies such as those by Zhang et al. [104], Wang et al. [105], and Li et al. [106], future endeavors can strive to strike a balance between mechanical robustness and economic feasibility, ultimately advancing sustainable construction practices.

To address the lack of comprehensive life cycle analysis (LCA) of adobe structures, several recommendations emerge from scientific literature. Firstly, a study conducted by Martinez et al. [110] emphasizes the importance of conducting holistic life cycle assessments that consider all phases of the adobe structures' life cycle, including construction, use, and end-of-life. They also highlighted the importance of including an environmental assessment component to quantify the environmental impacts associated with each life cycle phase. Additionally, another study by Garcia et al. [111] suggested the integration of life-cycle thinking into building design and construction processes to optimize material selection, construction techniques, and end-of-life strategies. By incorporating life-cycle analysis methodologies into decision-making processes, stakeholders can make more informed choices to minimize environmental impacts and improve the overall sustainability of adobe structures.

Life-cycle analyses, applicable to both tropical and temperate regions, are imperative to gauge the holistic sustainability of earth-based construction methodologies.

Optimizing earth block composition is a burgeoning field warranting the establishment of a standardized methodology. Moreover, the standardization of test procedures with equivalence in results, regardless of the standards employed, is paramount. For instance, defining compaction pressures and establishing correlations to ensure consistent resistance

levels in the face of pressure variations are crucial steps towards enhancing the reliability and applicability of earth-based construction practices.

It is anticipated that in the coming years, there will be a noticeable trend towards reducing the reliance on cement in building structures. This shift aligns with the global imperative to adopt more sustainable construction practices, driven by environmental concerns and the need to mitigate the carbon footprint of the construction industry. As researchers and practitioners increasingly recognize the environmental impact of cement production, there is growing interest in exploring alternative materials and construction techniques that minimize or eliminate the use of cement. This trend is evident in the significant portion of studies focused on partial or total replacement of cement with alternative binders, such as natural fibers, lime, or biological powders. By diversifying the range of materials used in construction and embracing innovative approaches, the industry can move towards more environmentally friendly and sustainable building practices, contributing to a greener future for generations to come.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The experimental and computational data presented in this present paper are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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