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Review

# A Comprehensive Review of the Improvement of the Thermal and Mechanical Properties of Unfired Clay Bricks by Incorporating Waste Materials

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**Abstract:** In recent years, the construction sector has significantly increased demand for new building materials that can reduce environmental impact and promote sustainable design strategies. In this context, the use of earth for construction purposes has received increasing attention in the last decade owing to its low environmental impact, local availability, and recyclability. The literature survey indicates that the incorporation of waste materials in the production of unfired earth bricks holds significant potential to partly substitute earth by satisfying specific requirements. Additionally, utilizing these waste materials for the development of unfired earth bricks provides a solution that conserves natural resources, reduces energy consumption, and contributes to efficient waste management. The aim of this paper is to present an overview of recent research focusing on the recycling of various types of waste into eco-friendly unfired earth bricks. Also, the effect of the incorporation of waste materials on the thermal and mechanical properties of unfired clay bricks is reviewed. The most common results, organized based on the type of additive (industrial or agricultural waste), are shown and discussed.

**Keywords:** unfired earth brick; waste materials; thermal properties; mechanical properties; environment impact

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## 1. Introduction

### 1.1. Background

The world's population has been growing rapidly and is expected to continue to grow in the coming decades. According to the United Nations, the world's population is projected to increase from 7.7 billion in 2019 to 9.7 billion in 2050 and it is estimated to exceed 10.9 billion by the end of this century [1]. The growing population will consequently increase the demand for energy, water, and natural resources.

According to the International Energy Agency (IEA), buildings were responsible for approximately one-third of global final energy consumption in 2017 [2].

In 2020, the building sector accounted for 36% of the world's final energy consumption and contributed to 37% of energy-related $CO_2$ emissions worldwide, as shown in Figure 1 [3]. The major areas of energy consumption in buildings are heating or cooling for indoor spaces, which account for approximately 35% of total building energy usage [4]. Building envelopes play a predominant role in controlling and regulating the thermal energy of the indoor environment. Moreover, it is a critical component for achieving energy-efficient buildings.

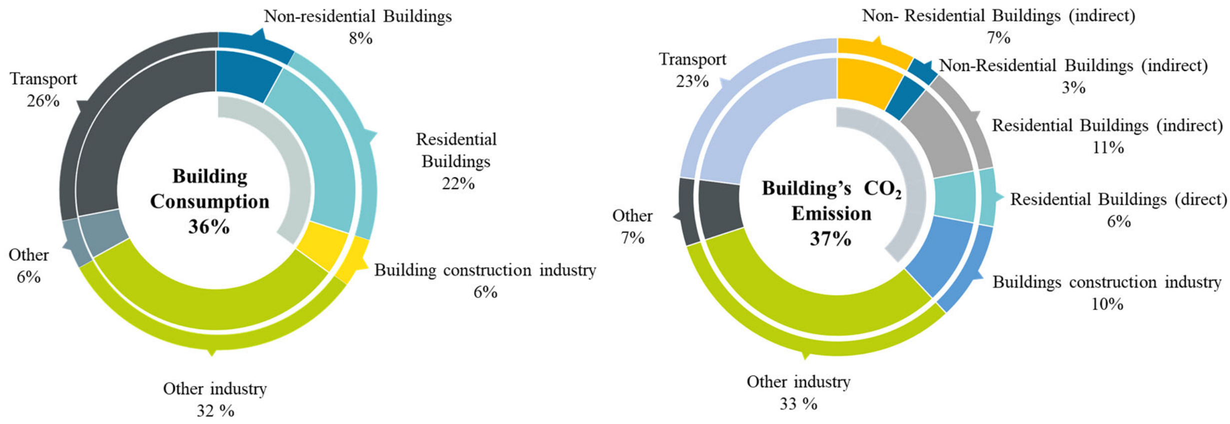


**Figure 1.** The contribution of the building sector to the world's final energy and energy-related $CO_2$ emissions in 2020.

Nowadays, the building construction sector is confronted with significant challenges in its quest to achieve sustainable development in both developed and developing countries. Employing locally available materials and techniques in construction projects is recognized as a promising approach to promote sustainable development [5]. The literature reveals that the development and potential use of more sustainable, environmentally friendly building materials, as well as waste management and recycling, are crucial measures for minimizing the environmental impact of construction activities [6].

Raw earth (unfired) constitutes a construction material that possesses numerous characteristics aligned with environmental considerations, making it an ideal choice for eco-friendly construction practices [7]. Raw earth is an abundant and recyclable natural resource that can be extracted and used locally, leading to cost-effective production and lower embodied energy when compared to fired clay bricks and concrete. Additionally, it contributes to a reduction in the energy needed for both construction and transportation [8]. In contrast to industrial construction materials like concrete, unfired earthen building materials require approximately 99% less energy during the manufacturing process [9]. Moreover, in term of thermal performance, earthen constructions exhibit a high level of thermal efficiency, particularly in warm and temperate climates [10,11]. Different cultures and societies worldwide have developed various techniques for utilizing earth in construction activities. Different forms of unfired earth materials including rammed earth, sun-dried earth bricks, and compressed earth blocks are employed in construction applications [12]. Despite the many advantages offered by the use of earthen material (earth block) in masonry construction, it is known to deteriorate rapidly under severe weather conditions [13]. In order to overcome this drawback, it is necessary to improve the physical and hydro-mechanical properties of the earth block. The improvement of these properties can be achieved through three potential methods: physical, mechanical, or chemical stabilization [14–16]. These techniques aim to enhance the durability and strength of earth materials while minimizing the damage associated with this drawback [13,17]. In recent years, there has been a growing number of investigations conducted on the incorporation of additives or stabilizers in earth materials. These investigations aim to improve the properties of earth materials, thereby expanding the potential application of this technique in a wider range of construction projects [18].

On the one hand, the boom of construction has led to the depletion of clay resources. This shortage has encouraged researchers to search for alternative materials or reuse the by-products generated from diverse anthropogenic activities in various industries [19,20].

On the other hand, the disposal and the management of waste generated by the industrial and agricultural sectors in developing countries poses an additional significant concern. Furthermore, the current global waste generation volume is estimated at around

1.3 billion tons per year, and it is anticipated to rise to approximately 2.2 billion tons by the year 2025 [21].

In their quest to encourage sustainability and adopt more eco-friendly practices, researchers have made considerable efforts to integrate various types of agricultural and industrial wastes into earth brick manufacturing. By incorporating waste materials in earth brick production, several benefits are achieved. It not only enhances the performance of bricks, but also overcomes the scarcity of natural resources, particularly clay, while effectively managing the environmental problems associated with traditional brick manufacturing [22].

Numerous research studies have been published focusing on the investigation of the mechanical and thermal properties of unfired earth bricks incorporating waste materials [23–27].

### *1.2. Focus and Research Questions*

Considering the above, this review paper addresses the state of the art of the recent research updates on utilizing various waste materials (agricultural and industrial) to produce unfired earth bricks and analyzes the impact of the inclusion of such additives on the performance of this kind of bricks. This analysis is conducted to make it easier for builders and researchers to select the best alternative with a better understanding of the consequences, including mechanical, thermal, and environmental aspects, that arise from the process of stabilization. To achieve this objective, this study is divided into six sections. Section 1 introduces the various types of earth bricks/blocks employed in construction masonry. Section 2 presents the main additives or stabilizers that have been commonly used in the manufacturing of unfired earth bricks. Section 3 highlights the main factors to consider in designing eco-friendly construction materials, including mechanical and thermal properties and environmental impact, and the Sections 4 and 5 focus on investigating the impact of the incorporation of waste materials on the mechanical and thermal performance of unfired earth bricks, specifically examining how each type of stabilizer is used to improve each parameter. Section 6 is dedicated to examining how the inclusion of waste materials affects the physical characteristics of unfired earth bricks.

## 2. Exploring the Use of Earth Bricks in Construction

### *2.1. Types of Earth Bricks/Blocks Used in Construction Masonry*

Bricks have been used for thousands of years as common building materials due to their durability and high compressive strength. These qualities make them well suited for being employed as a structural element, such as walls, and other elements in building construction. Various types of bricks are employed in masonry construction, and they can be classified based on raw material (clay, concrete, sand-lime, fly ash, . . .), as well as the manufacturing process employed, as depicted in Figure 2.

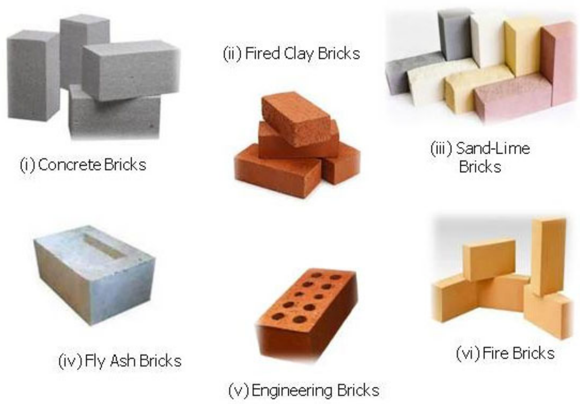


**Figure 2.** Different types of bricks based on raw materials [28,29].

Studies reveal that the majority of bricks used in building construction are made from clay, a material that has been utilized for centuries and possesses qualities that are highly significant [6,30]. Clay, the most abundant natural material on earth, is a multiphase mixture composed primarily of clay minerals along with other associated phases [31]. It is a cost-effective material that is easy to work with when compared to other building materials. Due to these qualities, clay has become a conventional and preferred raw material in brick manufacturing. Based on the manufacturing process, earth bricks are broadly classified into two types: fired clay bricks and unfired clay bricks. These types of bricks are commonly used in masonry construction and have been employed for thousands of years. Bricks made of air-dried clays are reported to have been utilized as early as the Neolithic period, while fired clay bricks date back to around 4500 BCE [32].

#### 2.1.1. Fired Earth Bricks

Fired earth bricks, also known as fired clay bricks, are produced by placing wet clay into a dry press or mold to give them their desired dimensions. After molding, the bricks undergo a drying process to reduce their moisture content. This is typically achieved through natural drying in sunlight or by using drying chambers (artificial drying). Finally, the bricks are fired in a kiln at high temperatures. The process of firing the bricks causes a chemical reaction that hardens the clay and makes it more durable and resistant to weathering. Fired earth bricks have been used for centuries and are still a popular building material today. Two well-known types of fired earth bricks that we can mention are clay solid and hollow clay bricks.

#### 2.1.2. Unfired Earth Bricks

Unfired earth bricks, also called sun-dried bricks or raw earth bricks, are construction units made by mixing earth material (clay) and usually some additives that enhance their properties. After putting the mixture in specific molds, they are left to dry under sunlight to reduce shrinkage and enhance strength.

Utilizing unfired earth as a building material presents a sustainable alternative that contributes to the reduction of the environmental impact of dwellings. Raw earth offers the benefit of being locally sourced and can be implemented in construction projects with minimal alterations.

In the field of earth building construction, several techniques are used, with the most common ones being adobe and compressed earth bricks (CEB) [33].

- **Adobe:** Adobe, a natural construction material composed of sand, clay, and water, incorporates some kind of fibrous or organic elements such as straw, sticks or dung, which is formed into bricks using frames and dried naturally under the sun [34,35]. The mixture, which has the consistency of thick mud, is poured into parallelepiped molds with dimensions of conventional bricks and dried in the sun for several days. After this, the blocks are removed from the molds and used to build masonry structures like ordinary fired bricks [36]. It is important to note that adobe constructions offer significant thermal, economic, and environmental advantages. Nevertheless, they commonly face criticism due to their sensitivity to water and perceived limitations in terms of durability [25].
- **Compressed earth bricks/blocks (CEB):** Compressed earth bricks, a modern eco-friendly product and descendent of the traditional molded mud block known as adobe, are becoming increasingly popular as a construction material worldwide due to their numerous advantages. In comparison to earlier methods and techniques of earthen construction, they exhibit enhanced strength and are more dimensionally stable [37]. Additionally, they are unfired; no coal or burning materials are needed during production. Compressed earth blocks (CEB) are considered environmentally friendly building materials and represent one of the most commonly used materials in earthen building construction. They are often manufactured on-site by compacting moist soil to a relatively high density inside a parallelepiped mold with the dimensions

of a standard brick. Compaction is achieved using hydraulic or mechanical presses that apply loads between 2 MPa and 15 MPa [38]. The process of compacting earth not only enhances the quality and performance of the molded earth blocks [39], but also promotes numerous social, economic, and environmental advantages [10,40].

Each type of earth brick has its advantages and disadvantages, and it is essential to select the appropriate brick material for a specific construction project to ensure optimal results.

### *2.2. Unfired Earth Bricks in Construction: An Analysis of Benefits and Limitations*

Unfired earth bricks have served as building materials for thousands of years in many different cultures around the world and are still extensively used in many developing countries. In the context of increasing environmental awareness in the construction sector, earth construction has gained significant attention by a great number of researchers and builders that are looking for alternative, eco-friendly, and sustainable building methods [41].

The use of unfired earth bricks provides multiple benefits when compared to other building materials. The combination of the benefits of unfired clay bricks makes them a highly desirable material for building construction. While earthen materials have several benefits, it is important to consider the drawbacks or challenges associated with their use in construction. It is crucial to find effective solutions for these drawbacks to ensure the suitability, durability, and structural stability of unfired earth bricks before utilizing them in building construction.

A summary of the various benefits and the potential drawbacks of unfired earth bricks is presented in Table 1.

**Table 1.** Benefits and drawbacks of using unfired earth bricks in building construction.

| Advantages [42] | Drawbacks [43] |
|---|---|
| (i) Economically beneficial/cost-effective<br>(ii) Require basic tools and less skilled labor<br>(iii) Hygroscopic regulation<br>(iv) Environmentally sustainable<br>(v) Low energy consumption<br>(vi) Good acoustic properties<br>(vii) Good fire resistance<br>(viii) Availability and accessibility of raw materials<br>(ix) Easy to design and high aesthetical value | I. Longer construction time<br>II. Low durability<br>III. High water absorption capacity<br>IV. Longer construction time |

## 3. Stabilizers and Additives Used in the Manufacturing of Unfired Earth Bricks

Suitable materials in construction must be long-lasting. The buildings are designed to last at least 50 years.

Despite the numerous benefits of using raw earth bricks, such as sustainability and cost-effectiveness, there is one significant drawback when using earth alone as a building material: its limited durability, which is strongly correlated to its compressive strength [44,45]. In the past, they have been considered less superior to more durable materials like stones and fired clay bricks [46]. For instance, the reason why fired earth bricks are preferred instead of unfired ones is that the temperature used during the firing process makes them more durable and enhances the strength of bricks. This in turn results in buildings that are more suitable and favorable.

To fully harness the potential of raw earth bricks, it is necessary to stabilize them before their usage in building construction. There are various types of stabilization methods, including mechanical, physical, chemical stabilization, or combined methods [47,48]. Mechanical stabilization refers to compacting the soil, leading to alterations in its density, porosity, permeability, and mechanical strength. On the other hand, "physical stabilization" involves modifying the soil's texture. This includes the controlled mixing of different soil fractions or natural soils, as well as the inclusion of fibers. However, chemical stabilization is the process of introducing additional materials or chemical binders to the soil, either through a physical-chemical reaction between the material and the soil grains or by creating a matrix that binds or coats the soil, thereby adjusting its properties. This process aims to improve the physical and mechanical properties of earth bricks [49], such as density, porosity, strength, impermeability, and durability [50], while also enhancing their thermal and acoustic performance. The choice of the stabilization technique will depend on the specific properties and characteristics of the raw earth material and the desired final product.

### 3.1. Stabilizers

For unfired clay bricks, which are the principal subject of this paper, different materials, including fly ash, cement, lime, gypsum, and bitumen, have been used as chemical stabilizers to enhance both their durability and mechanical performance. In the majority of studies, lime or cement [14], or the combination of both materials [51], has been used as stabilizers for earthen construction. Extensive documentation about this type of stabilization method can be found in the published literature [52–54].

In the case of using cement as a stabilizer, it is generally agreed that the incorporation of cement can result in notable enhancement in both compressive strength and moisture resistance [55,56]. Nevertheless, according to several authors, the utilization of cement often carries environmental drawbacks attributed to the high energy requirements and significant $CO_2$ emissions associated with its production [43,57,58]. Although lime has been suggested as a potential substitute for cement based on its perceived lower environmental impact, an ongoing discussion persists regarding the actual validity of this claim [59].

On the other hand, P. Walker and the Australian standard [60] recommend the use of aerial lime for cohesive soils, while cement is advised for granular soils.

### 3.2. Additives: Incorporation of Waste Materials

Some other techniques can be used to stabilize unfired earth bricks, such as adding fibers or other reinforcing materials to the mixture. In recent years, there has been growing interest in the use of various types of wastes and low-cost materials as additives in the manufacturing and production of earth bricks. The utilization of waste materials serves a dual purpose: it enhances the thermal and the mechanical properties of bricks and simultaneously it mitigates the scarcity of natural resources and effectively controls the related environmental issues [61,62].

Waste materials as additives are commonly employed to address issues with earthen building materials. Generally, these materials are helpful in improving specific properties, including thermal insulation, mechanical strength, durability, abrasion resistance, and fire resistance, as well as reducing water absorption and minimizing environmental impact. The amount of additives varies based on the particular type of additives employed and the existing soil conditions.

The common additives can be categorized into two main groups: agricultural and industrial wastes.

#### 3.2.1. Incorporation of Inorganic Waste/Industrial Waste

One of the most efficient strategies for sustainable waste management is giving industrial waste a second life as construction material. The construction industry is one of the major consumers of natural resources and generates significant amounts of waste. The reuse of industrial waste in construction material manufacturing offers a solution to concerns regarding waste disposal and ecological impact and moves toward a more sustainable future.

The utilization of industrial waste as a substitute stabilizer in construction activities has been demonstrated to be a practical approach for reducing environmental impacts while simultaneously offering social and economic advantages [63,64]. Recycling industrial waste by integrating it into building materials offers numerous benefits, such as waste reduction, conservation of natural resources, reduction of greenhouse gas emissions, enhancement of building performance, and lowering of production costs.

Industrial waste consists of materials that become unusable during the production process in factories, mills, and mines. Among various types of industrial waste, fly and bottom ash generated by thermal power plant ashes are widely employed in the production of unfired earth bricks. In addition to bottom and fly ash, various other industrial wastes such as steel fibers, copper mining tailings, glass, sludge, red mud, and plastic fiber have been also recycled in unfired brick manufacturing.

Table 2 summarizes a literature review on different industrial wastes used in the manufacturing of unfired earth bricks.

**Table 2.** Literature review of types of industrial wastes used in the manufacturing of unfired earth bricks.

| Waste Material | Reference | Content (wt%) | Length (mm) | Type of Brick | Year |
|---|---|---|---|---|---|
| Coal fly ash | [12] | 10, 12, and 16% | —— | Unfired earth bricks | 2018 |
| Bottom ash | [65] | 52.5–75% | —— | Unfired compressed bricks | 2013 |
| Polypropylene | [37] | 0.2, 0.4, 0.6, 0.8, and 1.0 w% | 54 mm | Compressed earth blocks | 2015 |
| Polyurethane | [66] | 5–15% | —— | Adobe | 2016 |
| Plastic fiber/polystyrene fabric | [67] | ——— | —— | Mud bricks | 2005 |
| HDPE and PET waste plastics | [68] | 1%, 3%, 7%, 15%, and 20% | 1 mm < δ ≤ 6 mm | Unfired lightweight clay bricks | 2020 |
| Alumina filler (AF) and coal ash (CA) | [69] | AF: 16.1, 32.2, and 247.82% CA: 7%. | ——— | Unfired clay bricks | 2013 |
| Calcium carbide residue | [70] | 0–15% | ——— | Compressed earth bricks | 2018 |
| Magnesium oxide | [71] | 4–10% | ——— | Unfired clay bricks | 2017 |
| Ceramic waste | [72] | 50%, 75%, and 100%. | ——— | Compressed earth bricks | 2016 |
| Waste marble dust (WMD) and polypropylene fiber (PF) | [73] | (PF): 0.5, 1.0, 1.5, and 2.0% (WMD): 10 and 20%. | Length of (PF): 12 mm | Adobe | 2017 |
| Concrete waste | [74] | 20%, 25%, and 30% | 4 mm | Unfired bricks | 2018 |
| Brick dust waste | [75] | 5%, 10%, 15%, and 20% | | Unfired clay bricks | 2014 |
| Glass fiber-reinforced polymer (GFRP) waste | [76] | 0 to 10% | 8.5 mm | Adobe | 2019 |
| Steel fibers (salvaged from used tires) | [77] | 1.7%, 2%, and 2.7% | 20, 35, and 50 mm | Unfired earth blocks | 2012 |
| Rubber crumbs and polyurethane | [66] | 5%, 10%, and 15% | ——— | Adobe | 2016 |
| Granulated blast furnace slag | [64] | 0–45% | 0.1–3.5 mm | Compressed earth blocks | 2018 |
| Paper and pulp | [78] | 0–20% | 1.5 mm | Adobe | 2020 |
| Crushed brick waste | [11] | 6%, 12%, 18%, and 24% | 0.15–0.6 mm | Compressed earth block | 2021 |
| Wastewater treatment plant sludge | [79] | (0%, 1%, 3%, 7%, 15%, and 20%) | 5–15 mm | Unfired earth bricks | 2021 |

### 3.2.2. Incorporation of Agricultural Waste

This section focuses on promoting the development of eco-building materials and highlights the potential of agricultural waste to enhance the performance of unfired earth bricks.

Agro-wastes encompass all undesirable materials that arise from agricultural activities which can be obtained from either plants or animals. These materials are cost-effective, sustainable, and abundantly available in many agricultural regions. The majority of research papers examined in this study included plant-derived wastes. Some of the most common agricultural waste materials used in the production of unfired earth bricks include rice husks, wheat straw, coconut shells, date palm fiber, sugarcane bagasse, sawdust, cassava peels, and typha plants.

A literature review on different agricultural wastes used in the manufacturing of unfired earth bricks is presented in Table 3.

**Table 3.** Literature review of types of agricultural wastes used in the production of unfired earth bricks.

| Reference | Additives | Content (wt%) | Fiber Length | Type of Brick | Year |
|---|---|---|---|---|---|
| [80] | Rice husks | 0%, 3%, 6%, and 9% | —— | Unfired bricks | 2021 |
| [81] | Sugarcane bagasse | 1, 3, 5, 7, 9, and 11% | 15-mm | Soil bricks | 2020 |
| [82] | Sugarcane bagasse | —— | 0.78 | Soil blocks | 2015 |
| [83] | Sugarcane bagasse | 5% | — | Unfired clay bricks | 2020 |
| [6] | Palm fronds and palm seeds | 10% to 60% | —— | Unfired clay bricks | 2022 |
| [49] | Coconut Coir | 0.25–1 wt.% | 38 and 50 mm | Soil building blocks | 2015 |
| [67] | Straw | | | Mud bricks | 2005 |
| [27] | Wheat and barley Straw | 0 1% to 3% | 4 cm | Unfired earth bricks | 2015 |
| [84] | | 25% and 33% | | Adobe | 2011 |
| [85] | Banana fiber | 0.35% | 25 and 50 mm | Compressed earth blocks | 2015 |
| [86] | Sawdust | 0%, 1%, 3%, 7%, 15%, and 20% | $0.5 \leq \delta \leq 3$ mm | Compressed earth bricks | 2016 |
| [87] | Straw and sawdust | 30% to 70% by volume | $0.5 \leq \delta \leq 8$ cm | Adobe | 2021 |
| [88] | Date palm fiber | 0.05%, 0.1%, 0.15%, and 0.2% | 2–3.5 cm | Compressed earth blocks | 2016 |
| [89] | Olive waste and date palm fiber | 0 to 30% | —— | Clay bricks | 2019 |
| [90] | Sawdust, tobacco, and grass | 0%, 2.5%, 5%, and 10% | —— | Clay bricks | 2008 |
| [91] | Pineapple leaf fiber | 0.25–0.75% | | Clay bricks | 2011 |
| [92] | Cassava peels | 0%, 2.5%, and 5% | | Compressed earth blocks | 2012 |
| [93] | Saw palmetto fibers | (0%; 1%; 5%; 7%; 10%, and 12%) | | Unfired clay bricks | 2023 |
| [94] | Almond husk | 0%, 2%, 5%, 10%, and 20% | | Unfired clay bricks | 2023 |
| [95] | Jute | 0.5 and 2.0 wt% | 7, 15, and 30 mm | Adobe | 2021 |
| [96] | Jute and banana | 0.25%, 0.5%, 0.75%, and 1.0% | 60–70 mm | Compressed earth blocks | 2018 |
| [97] | Sisal | 0.75% | 25 mm | Adobe | 2019 |
| [98] | Pennisetum setaceum | 0, 2, 4, 8, and 8% | 0.28–1.36 mm | Adobe | 2022 |
| [26] | Millet | 0, 1, 2, 3, and 4% | ——— | Adobe | 2020 |
| [99] | Doum fiber | From 2% | 3.5–4 cm | Compressed earth bricks | 2022 |
| [9] | Hemp and flax fibers | 1% and 3% | ——— | Unfired earth bricks | 2016 |

Furthermore, numerous research studies have demonstrated that for achieving thermal comfort in buildings, it is highly recommended to utilize unfired clay bricks mixed with vegetable fibers. These particular types of bricks offer remarkable energy-saving advantages in contrast to bricks fabricated with conventional materials such as cement agglomerates and concrete [25].

## 4. Essential Factors to Consider in Designing Eco-Friendly Construction Materials: Mechanical and Thermal Properties and Environmental Impact

The engineering properties of a material play a critical role in determining its suitability for use as a building material. These properties not only influence the quality and capacity of the material but also determine its potential applications in construction projects.

Building materials are typically classified into several categories based on their physical, mechanical, and thermal properties. Physical properties refer to the characteristics of a material that can be observed or determined without changing its identity, while mechanical properties refer to a material's ability to withstand applied forces or deformations. Thermal properties are another key category of building material properties and relate to a material's ability to transfer and conduct heat.

To develop sustainable buildings, it is essential to have knowledge about the thermal and mechanical properties of building materials to be employed. The durability of a building significantly depends on the mechanical properties of the construction material utilized. On the other hand, the energy efficiency of a building can be greatly affected by the thermal characteristics of its construction materials, which play a crucial role in terms of its thermal inertia or insulation.

The essential factors to consider carefully during the manufacturing of eco-friendly unfired earth bricks, in our case, are as follows:

### *4.1. Thermal Conductivity*

The thermal conductivity of bricks plays a crucial role as it directly impacts the heat losses from buildings, consequently leading to increased energy consumption. It measures the rate heat transfer through a material's unit area when a perpendicular temperature gradient is present in the area. Lower thermal conductivity in construction materials provides better insulation against heat transfer, reducing the reliance on heating, ventilation, and air conditioning systems and conserving energy and natural resources.

The thermal conductivity of unfired earth brick measures 0.961 W/m.K [27], and it can be further decreased to align with insulating materials by incorporating various types of waste.

Construction materials exhibit a wide range of thermal conductivity values, as shown in Figure 3.

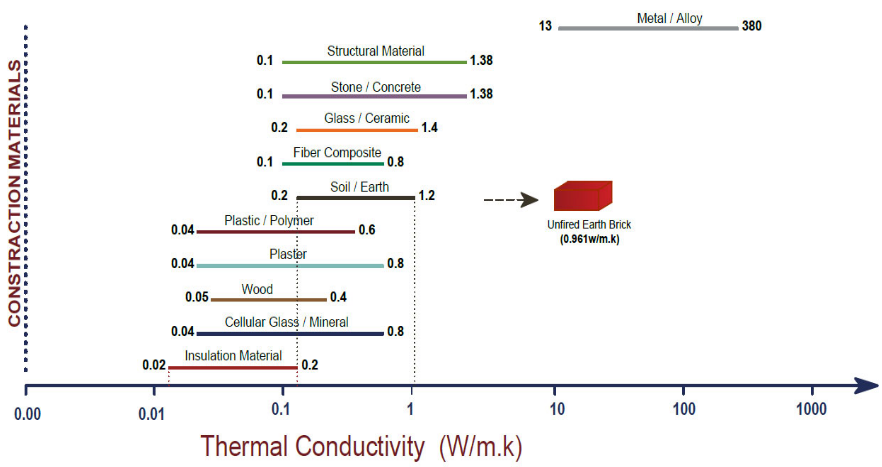


**Figure 3.** Thermal conductivity values of typical construction materials [27,100].

### 4.2. Compressive Strength

Compressive strength is the most critical mechanical characteristic of bricks, playing a fundamental role in designing and evaluating structures. It ensures the engineering quality of bricks and their suitability for load-bearing or non-load-bearing walls. It represents the ability of unfired earth bricks to withstand loads without deflection or cracks, and it can be measured using the device shown in Figure 4. Compressive strength testing is essential, especially in large-scale construction projects, to prevent accidents and building failures. The strength depends on mixture composition, compaction pressure, and curing time. It influences the design of structures, as some materials fracture at their limit, while others undergo irreversible deformations.

$$CS = \frac{F}{S}$$

where CS (Mpa) represents the compressive strength, F (kN) is the breaking force of the specimens, and S ($cm^2$) represents the surface area of the specimens.

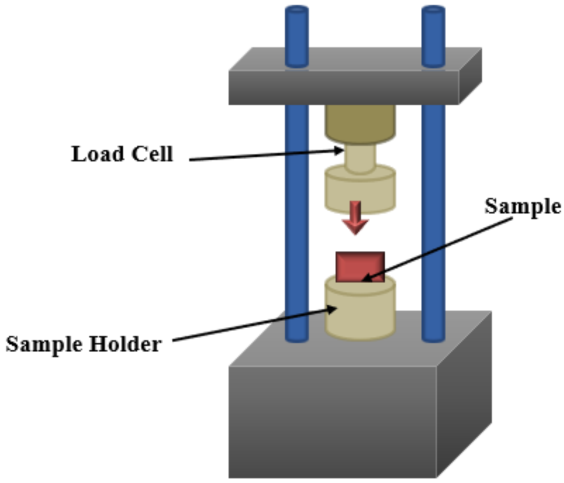


**Figure 4.** Compressive strength test.

Bricks commonly used in the construction of building walls are categorized with grades from M3.5 to M7.5, which correspond to the compressive strength values between 3.5 MPa and 7.5 MPa [80].

The minimum value of compressive strength that makes unfired clay bricks acceptable for constructing buildings is 3.50 MPa [101].

### 4.3. Flexural Strength

Flexural strength is a mechanical property that measures a material's ability to withstand deformation or fracture under bending forces. It is determined by applying a bending force to a specimen and measuring the maximum stress or load before fracturing. The most common method to assess flexural properties is through a transverse bending test using a three-point technique, as illustrated in Figure 5. Flexural strength is also known as bending strength, modulus of rupture, or transverse rupture strength, and it involves a combination of tensile and compressive stresses.

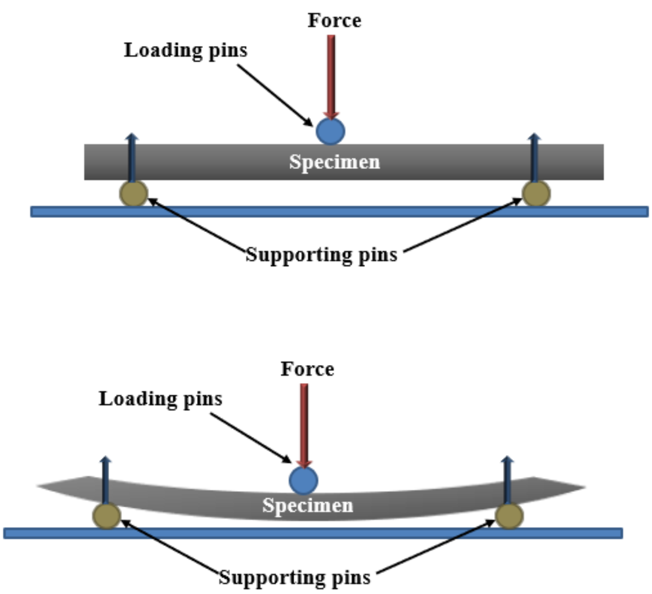


**Figure 5.** Three-point flexural test.

The minimum flexural strength required for building materials intended for structural applications is 0.65 MPa [101].

### *4.4. The Environmental Impact of Using Unfired Earth Bricks in Building Construction*

Another aspect that is extremely important to take into consideration during the production of building materials is the environmental impact. The construction industry is increasingly alarmed by the significant amount of carbon emissions that are released into the Earth's atmosphere during the production of construction materials, particularly for those materials that require the use of extreme temperatures during refinement or extraction. This concern has been further intensified by the growing awareness of the impacts of climate change around the world.

Unfired bricks can be more environmentally beneficial than fired bricks because they do not require the high temperatures and energy consumption involved in firing, which can result in significant greenhouse gas emissions and air pollution. Additionally, unfired bricks can use locally available and low-cost materials, such as clay, sand, and straw, which can reduce the environmental impacts associated with transportation and resource extraction.

There are several approaches available for measuring the environmental impact of construction materials. One notable approach is the life cycle analysis (LCA), which serves as a valuable approach for assessing the environmental consequences of a product through its life cycle. This encompasses activities ranging from the raw material extraction and processing to manufacturing, distribution, utilization, recycling, and final disposal [102].

The life cycle assessment of bricks is becoming an essential methodology for understanding its environmental impact during different stages of production. It was found that the production of bricks through burning is responsible for most of the emissions, which are notably intensive. The combustion of fuels during the burning of bricks leads to considerable $CO_2$ emissions, which have a significant impact on triggering environmental hazards. In this context, only a few studies have been caried out to assess the environmental impact of unfired earth brick production using life cycle analyses, specifically focusing on evaluating and comparing the $CO_2$ emissions associated with unfired earth bricks and fired earth bricks [74,103–105]. We can cite the investigation of Youssef et al. [106], which revealed that unfired earth bricks can effectively reduce $CO_2$ emissions by up to 55% in comparison to traditional fired bricks.

## 5. Effectiveness of Waste Material on Improving Thermal Performance of Unfired Earth Bricks

Enhancing energy efficiency has been identified as a crucial factor for the success of sustainable building design, according to multiple research studies. Improving a building's thermal performance leads to a decrease in energy consumption and a reduction in energy production costs.

The objective of this section mainly focuses on evaluating the effect of incorporating various types of waste on the thermal performance of unfired earth bricks.

### *5.1. The Impact of Agricultural Wastes on the Thermal Conductivity of Unfired Earth Bricks*

Ashour et al. [27] investigated the thermal conductivity of unfired earth bricks composed of earth, gypsum, cement, and straw. Two types of fiber, namely wheat and barley straw, were employed with various mixing ratios.

The results revealed a reduction in thermal conductivity for all tested variants as fiber content increased; conversely, a higher level of cement and gypsum content resulted in an increase in thermal conductivity.

The results indicate that the increase of the wheat straw fiber content in earth brick from 0% to 3% led to a remarkable decrease in thermal conductivity by 54.4% when compared to unfired earth bricks without any reinforcement fibers. Additionally, the increase of barley straw fiber content from 0% to 3% led to a reduction in thermal conductivity by 53% compared to bricks without any reinforcement fibers, with extremely satisfying results.

Finally, increasing the gypsum percentage from 0% to 10% resulted in an increase in the thermal conductivity, ranging from 0% to 48.7%, when compared to bricks without gypsum and containing 3% wheat reinforcement fibers. Barley straw fibers exhibited an increase in thermal conductivity ranging from 0% to 51.6% when gypsum percentages were raised from 0% to 10%, while maintaining the same fiber content.

The integration of plant aggregates in unfired clay bricks was explored in a study carried out by Laborel-Préneron et al. [107]. The hygrothermal characteristics of seven formulations consisting of earth with different weight percentages of corn cob, barley straw, and hemp shiv, ranging from 0 to 6%, were evaluated. The study revealed a considerable decrease in thermal conductivity with the incorporation of a large amount of plant aggregates, whereas the incorporation of plant aggregates had the opposite effect on the thermal inertia parameters.

The earth specimens prepared without the inclusion of any plant aggregate had a thermal conductivity of 0.57 $W.m^{-1}.K^{-1}$. However, in the case of specimens that incorporate plant aggregates, the thermal conductivity values varied from 0.14 $W.m^{-1}.K^{-1}$ for the specimen that contained six percent of barely straw (S6) to 0.35 $W.m^{-1}.K^{-1}$ for the specimens that contained three percent of corn cob (CC3). These results demonstrate that the incorporation of plant aggregates in an earth matrix results in a decrease in the material's thermal conductivity. Among the plant aggregates considered, straw appears to be the most effective in enhancing the thermal insulation of the material. When six percent of straw was added, the thermal conductivity decreased by 75% compared to an earth specimen, while the decrease was only 55% when six percent of corn cob was added.

In their research, Khoudja et al. [25] investigated a composite material that consists of stabilized unfired earth bricks using lime which are mixed with date palm waste (DPW) aggregates. The study aimed to explore the impact of different weight percentages (ranging from 0 to 10%) of waste materials on the thermal characteristics of the obtained bricks. The thermal conductivity assessment confirmed the material's thermal insulation performance.

The obtained results revealed a quasi-linear reduction in the thermal conductivity of the composites as the date palm waste (DPW) content increased. This reduction led to an improvement of the thermal insulation properties, estimated at 49% for an adobe sample containing 10% DPW. The thermal conductivity of this sample was 0.342 W/m.K, which is lower than that of adobe without date palm waste (control sample), which measured 0.677 W/m.K.

The performance of earth bricks incorporating two types of straw were evaluated by Giroudon et al. [108]. The straw additions were made at mass ratios of three percent and six percent. One type of straw examined was barley straw, which belongs to the group of cereal straws and has been widely investigated for similar applications. The other type was lavender straw, a non-recovered by-product that had not been previously studied for its potential in earth brick production. Tests were conducted on three specimens for each mixture to investigate their effect on thermal conductivity.

The results demonstrate that the integration of straw leads to a decrease in thermal conductivity; this implies that as the amount of straw increases, the material becomes more effective at insulating heat. At a constant mass dosage, it has been observed that barley straw provides better thermal insulation compared to lavender straw. This distinction can be attributed to the microstructures of the two types of straw. Lavender straw demonstrates a denser structure, in contrast to the greater porosity found in barely straw.

In study conducted by Laborel-Préneron et al. [109], the correlation between thermal conductivity and bulk density of raw earth matrix materials that incorporate plant aggregates have been highlighted. As the material's density increases, its insulation properties also improve.

Olacia et al. [110] are investigating the potential of utilizing Mediterranean seagrass Posidonia oceanica as a reinforcing material in adobe bricks. In this study, they conducted a comparative analysis between earthen specimens containing these sea-plant fibers with adobes incorporating the conventional additives, i.e., straw. Both types of biomass fibers were used in varying quantities and lengths. The thermal properties of this new sustainable material were examined.

The analysis of the thermal performance of the earthen specimens revealed that an increase in the quantity of biomass fiber, particularly with higher lengths, leads to a reduction in the density. Consequently, this generally leads to a decrease in the thermal conductivity, thereby improving the thermal performance of the examined materials. Due to the lighter nature of straw fibers compared to seagrass, the density of the adobe specimen tends to be lower, resulting in improved thermal insulated properties. The results demonstrate an enhancement in thermal conductivity ranging from 2% to 24% when a higher ratio of straw fibers is incorporated into adobe bricks compared to unreinforced specimens. In the case of adobe bricks reinforced with seagrass, an improvement from 3% to 19% is reached. When comparing the ratio and the lengths of the reinforcing fibers, it is generally found that thermal conductivity enhances as longer fiber lengths and higher percentages of fibers are incorporated in adobe samples.

The review of several research papers leads to the clear conclusion that the thermal efficiency of unfired earth bricks is improved through the incorporation of agricultural waste materials.

The analysis of all studies reviewed in the literature consistently demonstrates a decrease in the thermal conductivity value with the addition of agricultural wastes [5].

The unfired earth bricks reinforced with barley straw fibers showed the lowest thermal conductivity value (0.14 W/m.K), while samples reinforced with date palm fiber recorded higher conductivity values (0.342 W/m.K).

### *5.2. Examining the Impact of Industrial Wastes on the Thermal Conductivity of Unfired Earth Bricks*

There has been limited research conducted on the effects of incorporating industrial waste materials on the thermal characteristics of unfired clay bricks. The results obtained from some selected articles will be discussed in this section.

Limami et al. [68] examined the impact of the incorporation of plastic wastes on the thermal performance of unfired earth bricks. Two types of plastic wastes, namely high-density polyethylene and polyethylene terephthalate, were incorporated into the earth clay with different proportions, including 0%, 1%, 3%, 7%, 15%, and 20%, and using three different grain sizes. The study evaluated the thermal conductivity of the various prepared samples. The results demonstrated that as the proportion and grain size of the additives increase, the thermal conductivity of the prepared samples decreases. In the case of unfired earth bricks incorporating HDPE, the sample with the lowest additive proportion (1%) and smallest grain size ($\delta \leq 1$ mm) recorded the highest thermal conductivity value (0.46 W/m.K), resulting in a gain of 4%, while the specimen with the highest additive percentage (20%) and biggest grain size (3 mm < $\delta$ < 6 mm) exhibited the smallest thermal conductivity value (0.20 W/m.K), with a gain of 10%. Similarly, in the case of unfired earth bricks incorporating polyethylene terephthalate (PET), the highest thermal conductivity value (0.43 W/m.K) was achieved with a significant gain of 58% when using the lowest additive percentage and grain size, specifically 1% and $\delta \leq 1$ mm, respectively. Conversely, the smallest thermal conductivity value (0.18 W/m.K) with a gain percentage of 63% was observed when using the highest polyethylene terephthalate additive content with the largest grain size, specifically 20% and 3 mm < $\delta \leq 6$ mm, respectively. This implies that incorporating a bigger grain size and higher content of plastic wastes, HDPE and PET, leads to specimens with lower thermal conductivity. Consequently, this improves the thermal properties of the samples and results in a substantial gain in the thermal conductivity percentage.

Gandia et al. [76] studied the utilization of glass fiber-reinforced polymer (GFRP) waste in adobe manufacturing and evaluated the impact of the incorporation of GFRP waste on the thermal, mechanical, and physical properties of adobe. The mass fraction of GFRP waste incorporated into adobe varies from 0 to 10%. The results demonstrated that the incorporation of the GFRP waste led to a reduction in the thermal conductivity of the adobe. The incorporation of 10% GFRP waste showed the best results, leading to a significant reduction of 1.1 C and consequently improving its thermal comfort in a house.

Muñoz et al. [79] assessed the technological feasibility of using paper and pulp industry residues (PPR) for adobe reinforcement. Multiple series have been produced by varying the PPR waste percentage, reaching up to 20%. Furthermore, the technological properties of samples were evaluated, revealing that the inclusion of PPR resulted in the production of lighter adobes with reduced thermal conductivity and enhanced compressive strength.

The thermal conductivity measurement was conducted using the transient plane source (TPS) method. The results demonstrate a linear reduction in the thermal conductivity of adobes when PPR fibers are incorporated, in comparison with that of the control sample (without fibers), which has a thermal conductivity value of 0.861 $W.m^{-1}.K^{1}$. The decrease of thermal conductivity has been evaluated in various samples of adobes. In this study, the incorporation of 15% PPR fibers leads to a significant reduction of 30% in the thermal conductivity. The main factor contributing to this reduction is the additional thermal resistance provided by the addition of PPR fibers. The presence of gases within the interface between soil and PPR fibers creates a convective phase that contributes to the reduction in the overall thermal conductivity of the brick. Furthermore, the lower thermal conductivity of PPR also contributes to this decrease.

In all instances examined in the studies, the incorporation of waste materials into unfired earth bricks resulted in improved thermal performance by lowering thermal conductivity values.

According to Schroeder [111], the thermal conductivity values for earth-building materials varied between 0.10 W/m.K and 1.40 W/m.K, corresponding to material densities ranging from 300 $kg/m^3$ to 2.200 $kg/m^3$. Based on the reviewed studies, it was observed that the addition of agro-wastes in unfired earth bricks resulted in a decrease in the thermal conductivity value, which ranged from 0.14 to 1 W/m.K. These findings align with the results reported by Schroeder [111].

Table 4 provides a comparative analysis, based on the existing literature, of the thermal conductivity of unfired earth bricks without additives and the thermal conductivity of unfired earth bricks incorporating waste materials at their optimal fiber content. Table 4 provides a summary of these values for easy reference and analysis.

**Table 4.** Thermal conductivity of unfired earth bricks incorporating waste materials.

| Waste Used | Thermal Conductivity ($W.m^{-1}.K^{-1}$) | | Decrease in Thermal Conductivity (%) |
|---|---|---|---|
| | Without Additives | At Optimum Fiber Content (%) | |
| Straw fiber [112] | 0.3825 | 0.320 | 15.79 |
| Hemp fiber [112] | 0.3825 | 0.329 | 13.76 |
| Glass fiber [76] | 0.86 | 0.68 | 20.93 |
| Straw [27] | 0.961 | 0.31 | 67.74 |
| Date palm [25] | 0.677 | 0.342 | 49.48 |
| Barley straw [103] | 0.57 | 0.14 | 75 |
| Corn cob [103] | 0.57 | 0.256 | 55 |
| Barely straw [108] | 0.471 | 0.155 | 67.09 |
| Lavender straw [108] | 0.471 | 0.289 | 38.64 |
| HDPE and PET waste plastics [68] | 0.48 | 0.2 | 58.33 |
| Sawdust [87] | 0.44 | 0.23 | 47.73 |
| Straw [87] | 0.44 | 0.20 | 54.55 |

## 6. Assessing the Potential of Waste Material in Improving the Mechanical Properties of Unfired Earth Bricks

In the literature, several research studies are dedicated to evaluating the performance of earthen bricks that integrate waste materials, including agricultural and industrial wastes. These studies primarily focus on evaluating various mechanical properties, including compressive and flexural strength.

This section aims to evaluate the impact of incorporating two types of waste on the mechanical properties of unfired earth bricks.

### *6.1. The Impact of Agricultural Wastes on the Compressive and Flexural Strength of Unfired Earth Bricks*

Several studies have investigated the utilization of sugarcane bagasse ash as a reinforcing material incorporated into earthen brick composition, primarily due to its $SiO_2$ content, which serves as a binding agent when subjected to firing processes. However, despite the high cellulose content of the material that enhances its strength, the investigation of sugarcane bagasse fibers is not commonly conducted. Moreover, SBF is a relatively cost-effective and abundant resource in Indonesia in the form of waste [112]. The incorporation of SBFs (sugarcane bagasse fibers) into unfired earth bricks resulted in enhanced compressive strength, particularly when the SBFs were cut to an optimum length measuring 15 mm and made up five percent of the overall clay mixture. The compressive strength values typically varied between 1.82 MPa and 3.98 MPa [82].

Niyomukiza et al. [6] investigated the effectiveness of palm seeds and palm fronds in improving the properties of unfired earth bricks. Additionally, there is potential for the utilization of blended binders in the production of unfired earth bricks. The inclusion of both palm seeds and palm fronds led to an enhancement of the strength characteristics of the unfired earth bricks, effectively binding the soil particles together. In this context, a total of seven samples containing different proportions of palm fronds and palm seeds were prepared. The compressive strength of brick samples varied between 2.03 $N/mm^2$ to 4.23 $N/mm^2$, depending on the percentage of palm seeds and palm fronds used. After 14 days of a curing period, sample 6 of unfired earth brick contained a concentration of 25% palm fronds and 10% palm seeds, exhibiting an average compressive strength of 4.23 $N/mm^2$, the highest among all samples. This could be attributed to the optimal conditions reached during the curing process. However, beyond this concentration, compressive strength is compromised. For instance, sample 7, which included a concentration of 40% palm fronds and 25% palm seeds, exhibited a lower compressive strength of 3.47 $N/mm^2$ compared to sample 6. This indicates that a significant increase in the concentration of palm seeds and palm fronds led to a decrease in the compressive strength of the unfired earth bricks. In the case of the unfired earth bricks incorporating only palm seed concentrations, sample 2, with a concentration of 50%, showed a notably higher compressive strength, measuring 3.21 $N/mm^2$, when compared to sample 3, with a concentration of 40% and a recorded compressive strength of 2.03 $N/mm^2$. This indicated that the reduction of the concentration of palm seeds decreases the compressive strength of unfired earth bricks.

Limami et al. [23] evaluated the physicochemical and mechanical properties of unfired earth bricks incorporating Typha fibers as additives. These additives were included at different weight proportions (0%, 1%, 3%, 7%, 15%, and 20%), and the bricks were prepared with an optimal moisture content of 17%. The compressive strength analysis was conducted to evaluate the mechanical performance of the produced brick samples. Specimens with a higher content of Typha fibers exhibited a reduction in compressive strength properties. The highest recorded compressive strength value was 5.95 MPa, which was achieved by incorporating a 1% Typha additive. In contrast, the lowest compressive strength value of 3.67 MPa was observed at the 20% additive percentage, indicating a significant reduction of 36% in compressive strength compared to the control samples. The reduction in compressive strength can be attributed to the formation of multiple pores resulting from the higher additive content incorporated. Furthermore, the decrease in strength can be attributed to the lower silica content in the brick matrix caused by the inclusion of Typha fiber additives. This leads to the weakening of the crystalline mineral structure and a consequent reduction in the mechanical threshold of the sample. Based on these results, it can be concluded that the inclusion of higher amounts of Typha fiber additives led to the production of high-performing brick samples. These samples successfully meet the standards specified by both the Moroccan and international testing protocols. Moreover, they exhibited more porous and lightweight structure, reduced compressive strength, and a higher water absorption ratio.

Masuka et al. [12] investigated the improvement of the mechanical strength and water resistance properties of low-cost unfired earth bricks (UEBs). These UEBs were stabilized using different ratios of lime (L), coal fly ash (F), and wood aggregates (W), specifically L4%-F16%-W1.5%, L4%-F16%-W3%, L8%-F12%-W3%, and L10%-F10%-W1.5%. The engineering properties of the unfired earth bricks produced were compared to those of unstabilized (sample control) and unfired earth bricks stabilized with 10% cement. The variation of the lime–fly ash ratio had a significant impact on the dry compressive strength, resulting in a substantial enhancement according to a curvilinear power function. At a mix ratio of 1:1, the maximum strength reached was 8.3 MPa. However, UEBs showed low wet strength. Nevertheless, the addition of four percent cement resulted in a significant increase ($p < 0.001$) in the wet compressive strength of UEBs, reaching 0.94 MPa. UEBs that were stabilized with 10% coal ash, 10% lime, 1.5% wood aggregates, and 4% cement (F10%-L10%-W1.5%-C4%) displayed a water absorption rate of 15.8%, which was similar to that of UEBs stabilized with 10% cement. Moreover, unfired earth bricks reinforced a composition of L10%-F10%-W1.5%-C4% complied with the technical specifications set by British Standards for low-density clay masonry units [113]. Notably, these bricks were 50% more cost-effective compared to cement-stabilized bricks, highlighting the low cost of the UEBs. Two of the four unfired earth bricks (UEBs) investigated met the requirement of British Standards for unfired clay masonry units in terms of their dry compressive strength. The dry compressive strength of unfired earth bricks stabilized with F10%-L10%-W1.5% (8.3 MPa) exhibited a significant increase ($p < 0.001$) compared to that of 10% cement-stabilized unfired bricks (7 MPa).

Costi de Castrillo et al. [87] carried out a study to examine the impacts of fiber type (straw or sawdust), fiber quantity, and the manufacturing methodology on the mechanical properties of conventional adobe bricks. Various adobes were manufactured in the laboratory with sawdust or straw volume ranging from 30% to 70%. The physico-mechanical properties of the adobe bricks were evaluated by comparing them with values documented in the international literature and standard documents.

The experimental findings clearly indicate that, in general, the adobe produced in the laboratory exhibit enhanced physico-mechanical properties when compared to the reference adobes obtained from a contemporary Cypriot producer or reproduced in the laboratory using pre-mixed raw materials provided by the same producer.

Specifically, the incorporation of different quantities of sawdust into adobe bricks has resulted in the notable enhancement of the compressive and flexural strength. Based on the results presented, it can be concluded that utilizing smaller fibers (i.e., sawdust) results in a higher value of flexural strength compared to using longer fibers (i.e., straw). The above-mentioned results can be attributed to the improved flexibility of smaller-sized fibers, which offer particular advantages in low-fiber compositions. In such cases, the fibers are distributed more uniformly inside the material's core and enhance cohesion with the soil, thus effectively minimizing shrinkage cracks and gaps in the final product. It is important to highlight that the adobes manufactured in the laboratory with the same soil and fiber type/content (i.e., 30–40% $v/v$ straw) as the reference adobes displayed a notable enhancement of their physico-mechanical properties. This statement implies that it is crucial to handle the process of mixing, casting, and drying with great care. It also suggests that even soils with inferior properties have the potential to be utilized in the production of adobe bricks that have a good quality.

The majority of the adobe bricks manufactured in this study meet the minimum requirement for compressive and flexural strength set by international standards, confirming their suitability for structural applications. Specifically, the utilization of sawdust has resulted in adobe bricks exhibiting a normalized compressive strength surpassing 4 MPa, along with flexural strength that exceeds 2 MPa. This fine nature of sawdust fiber enables it to mix homogenously with the soil matrix, leading to a strong interaction between the fiber and the silty clay loam soil utilized in the production of the adobes under investigation. Increasing the fiber content of all adobe bricks produced in the laboratory resulted in a reduction in their thermal conductivity, bulk density, and flexural and compressive strength. When sawdust fibers were incorporated into adobe bricks, a noticeable enhancement in capillary absorption was observed with the increase in fiber content. This observation contrasted with the behavior observed in adobe bricks incorporating straw fibers.

The study conducted by Jannat et al. [114] explored the potential use of different agricultural wastes, including sawdust powder (SDP), eggshell powder (ESP), and coconut husk powder (CHP), in the manufacturing of unfired earth blocks. Samples were prepared using different proportions of agricultural wastes ranging from 10 to 50% of the dry weight of clay for ESP and from 2.5 to 10% for SDP and CHP. The study examined a range of physico-mechanical properties, including linear shrinkage, density, capillary water absorption, and compressive and flexural strength. The testing process consisted of two phases. The initial phase involved incorporating the waste materials individually into the mixture, while the second phase combined ESP (10–30%) with the optimal proportions of SDP (2.5%) and CHP (2.5%). Based on the test results, it was observed that the sample with 40% ESP performed the best when used as an individual additive, while the SDP and CHP 2.5% content also showed improved performance. However, when ESP, SDP, and CHP were used together, the overall characteristics of the sample deteriorated.

Regarding the mechanical properties, all the samples integrating waste materials met the minimum requirements of compressive strength (ranging from 1 MPa to 2.80 MPa) and flexural strength (ranging from 0.25 MPa to 0.50 MPa) specified by the standards after 28 days. Samples incorporating eggshell powder exhibited higher values of compressive and flexural strength (FS: 2.24 MPa, CS: 5.68 MPa) when compared to SDP (FS: 2 MPa, CS: 4.74 MPa) and CHP (FS: 2.14 MPa, CS: 4.78 MPa) samples. Nevertheless, the combination of ESP with SDP and CHP led to a reduction in strength.

The results of this study revealed that ESP, SDP, and CHP show promise in evaluating their suitability for the production of unfired clay blocks. These additives improved the overall properties of the sample, and all the samples met the strength requirement set by the standards and successfully passed the durability tests.

Muntohar et al. [115] conducted a study investigating the incorporation of lime and rice husk into compressed stabilized earth. This study consists of various tests, including compressive and three-point flexural strength tests, as well as assessing compressive strength after water submersion. The obtained results indicate the potential for utilizing blended binders for the making of unfired earth bricks. The investigation results show that the inclusion of sand in the mixture enhance the compressive and flexural strength of clay bricks, while the inclusion of lime and RHA further improves their strength performance. In this study, the highest strength was achieved with the optimum ratio of lime and RHA at 1:1. By incorporating the lime and RHA mixture ratio, the compressed stabilized earth demonstrated reduced water absorption and met the requirement of the Indonesian Standard SNI 15-2094-2000 for brick production [116]. Overall, the compressive strength of the specimens remained at 62–95% of the normal (dry) compressive strength even after being submerged in water.

### 6.2. Effect of Industrial Wastes on the Compressive and Flexural Strength of Unfired Earth Bricks

Donkor et al. [37] conducted an assessment to determine the feasibility of enhancing the strength and deformability of compressed earth blocks (CEBs) by incorporating polypropylene fibers while meeting or exceeding the minimum requirement specified in relevant codes. CEBs were manufactured using varying weight fractions of fibers (0.2, 0.4, 0.6, 0.8, and 1.0) and their compression and bending were evaluated. The inclusion of fibers resulted in enhanced performance in terms of bending and ductility. The amount of fibers present in the blocks was observed to impact their strength, post-crack response, and their deformability. The average compressive strength of the control sample (unreinforced control samples) was measured to be 4.19 MPa. On the other hand, the reinforced blocks with 0.2%, 0.4%, and 0.6% polypropylene fibers exhibited average compressive strengths that were respectively 10%, 22.5%, and 3.0% higher compared to the unreinforced blocks. The additional 0.8% and 1.0% polypropylene fibers led to a reduction in compressive strength of the blocks by 1.6% and 11.5%, respectively, when compared to the unreinforced blocks. As the fiber fraction increased up to a weight proportion of 0.6%, there was a noticeable enhancement in strength when compared to the unreinforced earth bricks (CEBs). The addition of the fiber content of 0.4% led to a significant improvement in both compressive strength, which increased by 22.5%, and three-point bending strength, which improved by 22.0%. However, when the weight fraction of fibers surpassed 0.6%, the mixing process became more difficult, and the strength started to decrease. Consequently, it is advised not to surpass a polypropylene fiber weight content of 0.6% when producing compressed earth blocks. The optimal range for adding polypropylene fibers to compressed earth block matrices lies near 0.4%.

According to the results obtained from this study, the use of polypropylene fibers is considered a viable choice for CEB production. These fibers, when used at an appropriate dosage, have the potential to improve the ductility, strength, and deformability of soil–cement matrices used for compressed earth block manufacturing.

Lahdili et al. [33] conducted a study to examine the impact of coal aggregates (CAs) in compressed earth bricks (CEBs) with the aim of reducing the footprint of the coal industry. For this purpose, CEBs were prepared by incorporating different percentages of CAs (10%, 15%, and 20% by weight). Initially, an analysis was conducted on three different soils in the region of Marrakesh, Morocco, to examine their chemical composition and thermo-mechanical behavior. Subsequently, the selected soil was reinforced with CAs and lime, and the resulting mixture was compressed in a Brava machine to produce unfired earth bricks (CEBs).

The incorporation of coal aggregates into the chosen soil has led to a notable reduction in the specific weight of the CEBs. Specifically, CEBs produced with an optimal value of 15 wt% of coal aggregates are 11% lighter compared to the referenced bricks. However, it was observed that the compressive strength of CEBs decreased with the inclusion of coal aggregates. Consequently, to ensure compliance with international standards regarding the compressive strength of CEBs, it is recommended to limit the addition of CAs to not more than 15%, even when lime is included.

In their study, Sufian et al. [61] examine the utilization of waste marble powder as an additive in brick manufacturing, aiming to enhance the natural environment through the recycling of this waste material.

Various proportions of marble powder ranging from 5% to 30% were examined as a partial substitute for clay. A total of 105 samples were produced to evaluate the performance of the prepared marble clay bricks. Key aspects assessed included bulk density, water absorption, apparent porosity, and compressive strength. The obtained bricks exhibited a weight reduction of 1.3% to 19.9% compared to conventional bricks. Additionally, the bricks incorporating 5% to 20% of marble powder as an additive demonstrated satisfactory compressive strength values in accordance with international standards. As the content of marble powder increased, the compressive strength and bulk density of the bricks was reduced, whereas their porosity and water absorption capacity were improved. The empirical equations derived from the study exhibited good agreement with the experimental results. Incorporating waste marble powder in construction masonry not only leads to cost reduction but also reduces the risks of soil erosion and water contamination.

Kasinikota et al. [11] investigated the mechanical properties of compressed earth bricks that integrate crushed brick waste as a substitute for both soil–sand mixtures and sand. The addition of up to 24% crushed brick waste enhances the compressive and flexural strengths (wet–dry). Furthermore, the strengths exhibited further improvement after undergoing wetting–drying cycles and sulfate exposure, which can be attributed to the formation of additional compounds. Although the mass loss after wetting–drying cycles remained with acceptable limits, it demonstrated an increase with the rising percentage of crushed brick waste. While a mass gain was observed when exposed to a sulfate medium, the control sample exhibited the highest mass gain. The block incorporating 24% of crushed brick waste demonstrated the highest mechanical strength.

Jaramillo-Pérez et al. [117] investigated the use of gypsum mining wastes and lime as stabilization materials to enhance the engineering properties of compressed earth blocks. The research focused on evaluating the hardened properties, including water absorption and compressive and flexural strength. The results revealed that the addition of mining waste led to increased strength. Twenty-five percent of mining waste resulted in the highest resistance against softening in water. Moreover, the drying shrinkage decreased as the mining waste content increased. However, the dry unit weight did not meet the recommended standards. The results of this study demonstrate that gypsum mining wastes can be employed as alternative materials for stabilizing compressed earth blocks.

Gandia et al. [76] explored the application of fiber-reinforced polymer (GFRP) waste in adobe brick manufacturing. They produced different compositions with mass residues ranging from 0% to 10% and subjected them to comprehensive physical, thermal, and mechanical tests.

The utilization of the GFRP waste led to a reduction in both the bulk density and the linear shrinkage of adobe bricks. Moreover, when adobe was exposed to water through capillarity action or submersion, the addition of the GFRP waste significantly reduced the mass loss. Furthermore, an increase in the residue concentration resulted in a notable improvement in the compressive strength. Notably, the addition of 10% GFRP waste yielded the most favorable results compared to adobe brick without any additives, demonstrating a compressive strength increase of 45%. This increase can be attributed to the presence of reinforcement, structuring, and strong cohesion observed between the residue and the clay particles, as identified in the microstructural analysis. This correlation is confirmed by the results of water absorption and linear shrinkage tests. The incorporation of GFRP residue in adobe bricks leads to an enhanced structuring due to the fiber reinforcement, resulting in an increased resistance to compression.

In their study, Huy et al. [80] explored the use of bottom ash and raw rice husk as fine aggregates in the manufacturing of eco-friendly unfired bricks. Specifically, rice husk was employed to substitute 0%, 3%, 6%, and 9% of bottom ash weight content. Two group mixtures were formulated, each with a water-to-binder (W/B) ratio of 0.30 and 0.35.

An experimental program was conducted on brick samples at various periods from 3 days to 28 days to examine the impact of bottom ash and rice husk content as well as water-to-binder (W/B) ratios on the mechanical and physical properties of bricks. These properties including compressive strength, water absorption, and unit weight. The brick samples with a water-to-binder (W/B) ratio of 0.3 exhibited a higher compressive strength compared to those with a W/B ratio of 0.35. This difference can be attributed to the impact of the W/B ratio on the development of strength in cement hydration products. The range of compressive strength values of M30 bricks was 4.22 to 9.62 MPa, while that of M35 bricks ranged from 3.42 to 5.75 MPa. As the rice husk content increases, there is a reduction in the compressive strength of bricks.

Nevertheless, the compressive strength value of unfired bricks remains above 5.0 MPa (referred to as Grade M5.0) when three percent bottom ash is replaced by rice husk. Even with an increase in the rice husk proportion to six percent and nine percent, the compressive strength of bricks still exceeds 3.42 MPa, which could be categorized as Grade M3.5. This finding demonstrated that rice husk can be effectively used as a fine aggregate in the manufacturing of unfired earth bricks, particularly when lightweight characteristics are required.

In their research, Villamizar et al. [92] explored the effect of incorporating coal ash and cassava peels on the engineering properties of compressed earth bricks (CEBs). The study examines the hardened properties of the material, which include water absorption and compressive and flexural strengths.

Different tests were conducted to evaluate the flexural strength, compressive strength, and absorption performance of the samples. The results indicate that the best performance in terms of compressive and bending tests was achieved by the compressed earth bricks incorporating coal ash at a dosage of less than or equal to five percent. However, doses exceeding five percent result in compressed earth bricks that are more flexible and fragile. Furthermore, the addition of cassava peels to the clayed soil raises the necessary water content for extrusion, leading to an increase in the apparent plasticity.

At the University of Yaoundé I in Cameroon, a research study led by Medjo Eko et al. [77] was conducted to investigate the mechanical properties of unfired earth bricks incorporating salvaged steel fibers from used tires. Initially, tests were conducted to determine tensile strength using a six percent cement-to-soil ratio. This step aimed to assess the critical fiber length and the optimal fiber content. Subsequently, mechanical properties including unconfined flexural, compressive, and tensile strength were assessed afterward using different cement soil ratios with optimal fiber length and content. The obtained results indicated a satisfactory bond between the recycled steel fibers and soil–cement mixture.

Based on the recorded data of tensile strength, it was determined that the critical fiber length measured 35 mm, while the optimum fiber content was determined to be two percent by volume. Furthermore, it was noted that mechanical properties assessed over time remained unchanged in the presence of optimal fiber content, even with its random distribution. Based on the analysis of experimental results, it can be concluded that the addition of steel fibers functions as a spring, aiding the masonry unit in absorbing substantial plastic energy and withstanding substantial deformation without complete disintegration.

Table 5 provides a literature-based summary of the mechanical properties of unfired earth bricks incorporating waste materials.

**Table 5.** Mechanical proprieties of unfired earth bricks incorporating waste materials.

| Waste Used | Optimum Fiber Content | Compressive Strength (MPa) | | Flexural Strength (MPa) | |
|---|---|---|---|---|---|
| | | Without Additives | At the Optimum Fiber Content | Without Additives | At the Optimum Fiber Content |
| Palm seeds and palm fronds [6] | 10%PS 25%PF | 3.3 | 4.23 | —— | —— |
| Glass fiber-reinforced polymer waste [76] | 10% | 1.41 | 2.05 | —— | —— |
| Millet [26] | 2% | 4.69 | 6.5 | 0.125 | 0.17 |
| Calcium carbide residue and rice Husk ash [70] | 8% CCR | 1.9 | 3.4 | —— | —— |
| Ceramic waste [72] | 75% | 15.4 | 33.6 | — | — |
| Waste marble dust (WMD) and Polypropylene fiber (PF) [73] | 10% M + 0.5% PF | 1.09 | 3.47 | 0.84 | 1.34 |
| Bagasse, coconut, and oil palm [49] | 0.5 C% | 1.7 | 3 | —— | —— |
| Banana fibers [85] | 0.35% | 3.33 | 5.92 | 0.49 | 0.95 |
| Sawdust [86] | 3% | 8.75 | 7.69 | — | —— |
| Sawdust [87] | 11.9% | 2.44 | 7.32 | 0.44 | 2.99 3.6% |
| Straw [87] | 7.8% | 2.44 | 4.64 | 0.44 | 2.03 |
| Coal ash and cassava peels [92] | 5% CA | 1.93 | 3.37 | 0.68 | 1.09 |

## 7. Effects of Waste Materials on the Physical Properties of Unfired Earth Blocks

Bulk density, porosity, water absorption, and linear and drying shrinkage are the most frequently studied physical properties that significantly impact the quality of unfired earth bricks.

### *7.1. Effects of Waste Addition on the Density and Porosity of Unfired Earth Bricks*

The density of the unfired earth bricks varied depending on the type of earth material and waste materials used in their manufacturing processes. In general, integrating fibers into the soil during the production of unfired earth bricks resulted in a reduction in the bulk density of the reinforced soil specimens. This is because fibers possess a lower density than soil, aiding in the decrease of the overall density of the reinforced soil.

Ashour et al. [27] examined the density of unfired earth bricks made from a mixture of earth, cement, and gypsum, which were reinforced with varying ratios of natural fibers from wheat and barley straw. The results reveal a relationship between the fiber content and the density of unfired earth bricks, indicating that the dry density decreases with an increase in the quantity of fibers. It was observed that the densities of bricks reinforced with wheat straw were higher than those reinforced with barley straw. This distinction could be attributed to wheat straw containing more solid material and lignin compared to barley straw. Generally, the increase in fiber content in the mixtures led to a decrease in specimen weights. The replacement of dense materials like soil cement or soil gypsum with light materials such as wheat or barley straw fibers resulted in an overall volume increase even after compaction. Consequently, this led to a decrease in specimen weights and densities.

In the study conducted by Sujatha et al. [118], the inclusion of polypropylene fiber resulted in a significant reduction in the bulk density of soil blocks. This reduction can be attributed to the lightweight nature of the polypropylene fiber.

According to Danso et al. [49], the incorporation of coconut husk, sugarcane bagasse, and oil palm fruit fibers in unfired earth bricks resulted in a reduction in density due to the waste materials possessing a lower density (ranging from 810 kg/m$^3$ to 500 kg/m$^3$) compared to the soil density (1780 kg/m$^3$). Consequently, as the fiber content increased, it led to a decrease in the density of the samples, replacing the heavier soil components.

According to the study conducted by Limami et al. [23], which aimed to evaluate the physical properties of unfired clay bricks incorporating Typha fiber, there was a decrease in bulk density with higher Typha content in the brick samples' matrix. This decrease can be attributed to the higher recorded porosity observed in specimens with higher Typha content, which leads to the formation of multiple voids within the brick samples' structure, ultimately reducing the measured bulk density.

Porosity is considered an important parameter for assessing the durability and thermal performance of unfired earth brick specimens. Consequently, the porosity significantly impacts the performance and application of these brick specimens. The number of studies in the bibliography that explore the influence of waste incorporation on the porosity of unfired earth bricks is limited.

We can cite the study conducted by Limami et al. [23], which evaluated the physical properties of unfired clay bricks with Typha fiber-based additives at various proportions (0%, 1%, 3%, 7%, 15%, and 20%) by weight. The main results of the experimental procedures indicated that the inclusion of higher proportions of Typha fiber additives resulted in an increase in the porosity percentage of the specimens and led to the production of more porous brick samples. This phenomenon can be attributed to the formation of Typha fiber-clay flocculants during the preparation process, which created interlayer spacing within the bricks' matrix.

Additionally, there was a proportional relationship between the porosity level of the brick samples and the capillary water absorption coefficient. Bricks with higher Typha fiber content displayed increased porosity and higher water absorption properties.

### *7.2. Effects of Waste Addition on the Water Absorption of Unfired Earth Bricks*

The water absorption coefficient is an important property of unfired earth bricks, as it affects the durability of brick samples. It measures the open porosity and the quality of bricks, as well as their resistance to weathering [119]. A notable correlation exists between water absorption and the strength of bricks: as water absorption decreases, the strength of the bricks tends to increase. Therefore, the capillary water absorption coefficient should be as low as possible.

Türkmen et al. [8] investigated the effect of gypsum and Elazığ Ferrochrome slag (EFS) additives on the physical properties of unfired earth brick. Four different samples were produced by using varying compositions of earth, gypsum, EFS, and straw fibers. The water absorption coefficient of the prepared unfired earth brick samples was investigated. The experimental findings showed a noticeable decrease in the capillary water absorption with increasing time. Furthermore, it was found that there exists an inverse correlation between the compressive strength and the capillary water absorption coefficient.

The study of Limami et al. [86] investigated the physicochemical properties of compressed earth bricks with recycled wood sawdust waste additives. Multiple waste additive proportions were utilized (0%, 1%, 3%, 7%, 15%, and 20%), by weight, at different sizes. The results of the capillary water absorption coefficient measurement demonstrated that brick samples with higher additive contents and larger sizes exhibited higher water absorption rates. Specifically, the bricks containing 20% additives displayed a capillary coefficient of 63.25 $g/(cm^2.min^{0.5})$, whereas the control samples had a coefficient of 25.75 $g/(cm^2.min^{0.5})$. Additionally, among the 20% brick samples, smaller sizes showed a water absorption of 45.17 $g/(cm^2.min^{0.5})$, while larger sizes displayed a higher value of 63.25 $g/(cm^2.min^{0.5})$. The inclusion of higher additive percentages in larger-sized bricks led to the formation of flocculants, which resulted in the creation of interlayer spacing and porous structures within the brick matrix. These pore structures contribute to capillarity as they act as void formations that function as capillary windows, facilitating the flow of fluid/water.

Niyomukiza et al. [6] conducted experiments to evaluate the water absorption of seven samples of unfired clay bricks, each incorporating different percentages of palm fronds and palm seeds. The measured water absorption values ranged from 16.1% to 100%, depending on the proportion of palm seeds and palm fronds in each sample.

Out of the seven samples tested, only two, namely sample 5 (comprising 80% clay and 20% palm fronds) and sample 6 (consisting of 65% clay, 25% palm seeds, and 10% palm fronds), showed promise for construction purposes, especially for internal non-load-bearing walls due to their low capillarity. Sample 5 and sample 6 recorded water absorption values of 18.1% and 16.1%, respectively. This can be attributed to the relatively lower concentration of palm seeds and palm fronds in these unfired clay bricks, which provided a higher amount of bonding soil particles. On the other hand, samples 1, 2, 3, 4, and 7 exhibited high capillarity, rendering them unsuitable for use in construction, particularly for external walls, as they are highly susceptible to water damage.

Danso et al. [49] reported that as the fiber content increased, the water absorption of the reinforced soil blocks also increased, but it showed a tendency to stabilize at higher fiber content levels. This finding aligns with the results of Ismail and Yaacob's study [120], which also observed a rise in the water absorption of laterite bricks with an increase in oil-palm empty fruit-bunch fiber content.

The rise in water absorption can be explained by the amount of water absorbed by the cellulose present in the fibers, which in turn is influenced by the void volume and the amount of cellulose material within the blocks.

### *7.3. Effects of Wastes on the Linear and Dry Shrinkage of Unfired Earth Bricks*

Shrinkage control is crucial for preventing the deformation and cracking of the unfired earth bricks. It is a physical phenomenon that is caused by the evaporation of moisture content in the samples during the drying process. It is highly affected by the nature and quantity of additives.

Linear shrinkage, an important parameter for earthen structures, can be determined by comparing the initial length of a soil specimen with its length after drying. This shrinkage is quantified as the ratio between the change in length after drying and the specimen's original length before drying. The inclusion of fiber results in a decrease in linear shrinkage for fiber-reinforced unfired earth brick. The reduction in shrinkage is higher at higher fiber contents. The results of the linear shrinkage test conducted by Gandia et al. [76] indicated that the addition of fiber (GFRP residue) resulted in a reduction in linear shrinkage for fiber-reinforced adobe. The reduction in linear shrinkage is attributed to the frame of the GFRP (glass fiber reinforced polymer) residue fibers, which stabilizes the adobe and prevent its contraction as humidity decreases.

The reduction in shrinkage is higher at higher fiber contents [76]. Due to the porous structure, the addition of fibers to the soil resists deformation and accelerates the movement of water through the fibers [76,118]. The reduction of linear shrinkage becomes more significant at high lengths of fibers, as an increased fiber length ensures the formation of adequate bond stress at the interface of soil and fiber, which prevents shrinkage.

Jannat et al. [114] conducted a test to investigate the influence of different agricultural wastes, such as eggshell powder (ESP), sawdust powder (SDP), and coconut husk powder (CHP), on the linear shrinkage of unfired clay blocks. The samples were produced with varying percentages of these wastes, ranging from 10% to 50% of the dry weight of clay for ESP and 2.5% to 10% for SDP and CHP. The results revealed that increasing the SDP concentration from 2.5% to 10% led to a reduction in the linear shrinkage of the samples, decreasing from 6.05% to 5.53%, which amounted to around a 31% reduction compared to the reference sample (8.07%). The bonding capabilities of SDP can be attributed to the presence of fibers in earthen materials, like straw, as they contain similar components. The incorporation of straw in the earthen matrix plays a vital role in mitigating shrinkage and subsequent fissuring during the drying process, especially when the earth is formed into blocks with a high clay content.

Another significant parameter to consider is the "drying shrinkage of unfired earth brick," which describes the reduction in dimensions or volume that occurs when an earth brick is allowed to dry naturally. In this regard, Turkman et al. [8] investigated the drying shrinkage behavior of unfired earth brick (UEB) samples manufactured with diverse additives. Four different UEB samples were prepared by using different compositions of earth, gypsum, (Elazığ Ferrochrome slag) EFS, and straw fibers. Due to the early setting time of gypsum, 1–2% lime was added to mitigate the risk of deformation and cracking during the drying period. The shrinkage measurements were conducted for all UEB samples during a period of 30 days. At the end of the 30th day, the minimum drying shrinkage value of 4.12% was observed in the G10 sample, which contained 10% gypsum and 1% straw fibers. In contrast, the reference sample exhibited the maximum drying shrinkage value of 7.57%. Notably, the drying shrinkage values of G10 samples were approximately half of the reference sample, and this significant decrease can be attributed to the addition of gypsum and lime. Additionally, the inclusion of EFS contributed to a decrease in the shrinkage values of UEB samples. Furthermore, combining both gypsum and EFS led to an even further reduction in the drying shrinkage of UEB samples.

The study emphasizes that drying shrinkage is dependent on the clay's characteristics, such as its mineralogical nature and particle size. When the material experiences more than 8% shrinkage, it may lead to problems in bricks, such as cracking and internal fractures. However, based on the findings of this experimental study, the overall drying shrinkage values fall within acceptable limits, which is promising for the application of these UEB samples in construction.

## 8. Conclusions

The environmental concerns associated with waste management in the developing world highlight the potential benefits of employing these wastes in the construction industry as an alternative approach to effectively tackle global environmental pollution.

Consequently, numerous studies have been conducted to investigate the incorporation of waste materials in the manufacturing of unfired earth bricks.

Based on the review of recent research studies on the manufacturing of unfired earth bricks that integrate various types of waste materials, as a partial or total replacement of the raw materials, as well as investigating the impact of these additives on the mechanical and thermal properties of unfired earth, the following conclusion can be deduced:

- A variety of industrial and agricultural wastes were investigated in the production of unfired earth bricks, such as adobe or compressed earth bricks. This research significantly contributes to the development of sustainable construction materials and eco-friendly building products.
- Waste material can be used to enhance the physical, mechanical, and thermal properties of unfired earth bricks.
- Considering mechanical properties, the use of fiber at its optimal content resulted in a substantial increase in compressive strength, ranging from 29.18% to 218.35%. And the compressive strength varied between 2.05 MPa to 33.6 MPa.

Also, the incorporation of fibers at their optimal content resulted in a significant enhancement of the flexural strength, ranging from 36% to 579.55%. The flexural value varied between 0.17 MPa and 2.99 MPa.

- Specimens that have a higher content of additives demonstrated a reduction in compressive strength properties. The reduction in compressive strength can be attributed to the multiple pores' formation with the inclusion of higher additive content.
- The addition of agricultural and industrial wastes also promoted a reduction in the thermal conductivity of the unfired earth bricks, consequently enhancing their thermal comfort in a house. Compared to the unstabilized samples, the straw-reinforced sample demonstrated the greatest reduction in thermal conductivity, resulting in a substantial reduction of 67.74%.
- The obtained eco-friendly bricks, with their lower thermal conductivity and higher compressive strength, offer an economical option for designing a green building.

To summarize, the literature has authenticated the suitability of agricultural and industrial additives for unfired earth bricks, demonstrating significant potential and contributing to the improvement of their mechanical and thermal properties. The collected findings align with testing standards in the building sector.

While the available literature contains numerous key findings regarding the incorporation of waste materials into unfired earth bricks, there are still certain potential gaps in the reviewed studies. These gaps including a lack of analysis regarding microstructures and the impact of density on thermal conductivities of unfired earth bricks when using a combination of stabilizers.

Furthermore, the environmental impact of unfired earth bricks remains an open research question for researchers. The production of alternative brick material presents several key challenges, such as the preservation of the soil, the minimizing of greenhouse gas emissions during production and transportation, enhancing energy efficiency by manufacturing materials with lower embodied energy, and offering potential low-cost options for the construction sector.

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