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Shrinkage Behavior of Stabilized Earth Bricks Reinforced with Wheat and Barley Straw

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Abstract: Due to its ecological and financial benefits, earth building has gained global attention, with earth bricks being extensively used. Shrinkage and crack development have a considerable impact on the performance and quality of earth bricks. This study employs laboratory experiments to examine the shrinkage behavior of earth bricks reinforced with wheat and barley straw. In addition to this, the impact of cement and gypsum additives is examined. The obtained results indicate that increased fiber content reduces crack formation effectively. However, higher levels of cohesive soil have been shown to have a negative influence on shrinkage behavior. In general, higher fiber contents contribute to the improvement of earth brick performance. These findings offer useful insights for improving the composition and characteristics of reinforced earth bricks, resulting in enhanced performance and quality in sustainable construction practices.

Keywords: unfired earth bricks; natural fibers; cement and gypsum stabilization; shrinkage property

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1. Introduction

Sustainability plays an ever-increasing role in contemporary building practices [1]. The global interest in utilizing earth materials for construction has been steadily growing, driven by the pressing environmental and resource concerns within the building sector [2]. Earth building techniques, such as rammed earth and earth bricks, have gained prominence as viable alternatives. However, earth as a building material is characterized by drawbacks such as low strength and susceptibility to shrinkage cracks.

To address these limitations, compressed earth blocks (CEBs) have been developed as masonry units. CEBs are combinations of soil, stabilizers, and water set under pressure in order to form robust earth blocks. The functioning of these units relies on the soil's characteristics and the formulation of the mixture [3]. Enhancing the earth's properties can be achieved through the addition of additives like cement, gypsum, and natural fibers such as hemp and straw [4]. The use of straw, which is abundantly available in many regions, represents a sustainable and ecologically sound approach to recycling [5]. Furthermore, incorporating natural fibers as strengthening components in composite materials provides notable benefits, including reduced density and biodegradability [6,7]. Notable examples of such fibers include wheat straw, barley straw, and rice straw.

In previous research, we have observed that the fiber content and type significantly influence the erosion resistance of earth plasters for straw bale buildings [4]. Hossain et al. [8] investigated the impact of additives, specifically volcanic ash and cement/lime, on drying shrinkage. They observed that soil mixtures stabilized with volcanic ash exhibited greater resistance to shrinkage in comparison to soils stabilized with cement/lime.

Bouhicha et al. [9] examined the effects of fiber length and content in earth reinforced with chopped barley straw with different soil compositions, revealing the positive impact of straw in reducing shrinkage-induced cracks [10]. Campbell et al. [11] explored the potential of wood fibers as reinforcement in structural composite materials, finding that pulp is suitable for slurry dewatering applications, whereas thermomechanical pulp is well suited to applications involving slurry dewatering. Bai et al. [12] examined the effects of replacing natural sand with furnace bottom ash on the drying shrinkage of concrete. Their study revealed that, when maintaining a constant water–cement ratio, the reduction in drying shrinkage corresponds to higher levels of sand content. In their study, Al-Amoudi and collaborators [13] explored the effects of four distinct superplasticizers combined with three varieties of silica fume. These were employed to create cement concrete slab samples, enabling the measurement of plastic shrinkage strain and the duration required to achieve maximum strain. Ashour and Wu [14] studied the shrinkage behavior of earth plaster for straw bale buildings, noting that reinforcement with wood shavings led to the highest shrinkage, while barley straw fibers resulted in the lowest shrinkage. The significance of fibers in reducing shrinkage cracking and improving the behavior of adobe masonry has also been recognized [15–18].

Furthermore, the swelling and shrinkage potentials of these materials have been found to be governed by relative humidity [19]. Despite the available literature on the subject, several major research gaps still exist. While many researchers attribute improved shrinkage behavior to fibers, some studies suggest that additives such as cement, lime, and gypsum also play pivotal roles. Moreover, most investigations have focused on earth plasters, with limited research conducted on the shrinkage of earth bricks. The small dimensions of earth bricks and their preparation methods necessitate special consideration. In Chan's work [20], it was noted that cement, acting as the binder in the composite material, significantly influences the strength and shrinkage of fiber bricks.

More recent research shows a significant advancement in the utilization of industrial and agricultural waste materials in the production of unfired earth bricks, leading to a remarkable improvement in both compressive and flexural strength, alongside a substantial reduction in thermal conductivity, positioning them as a promising and sustainable construction option [21]. Furthermore, the incorporation of various waste materials like eggshell powder (ESP), sawdust powder (SDP), and coconut husk powder (CHP) has demonstrated a profound impact on the physicomechanical and durability properties of unfired clay blocks, underscoring the potential for these materials in addressing environmental concerns and cost-effective building solutions. [22].

Other investigations have highlighted the potential of incorporating plant aggregates, particularly barley straw, hemp shiv, and corn cob, into earthen materials, significantly enhancing their thermal behavior by reducing thermal conductivity. Notably, the inclusion of straw at a 6% weight percentage led to a remarkable 75% decrease in thermal conductivity, emphasizing the potential for improved energy efficiency in construction materials [23].

Studies comparing the effects of different straw additives on earth bricks have revealed intriguing insights, with barley straw enhancing thermal conductivity and lavender straw demonstrating superior results in compressive strength, dry abrasion resistance, erosion resistance, and mold growth resistance. The incorporation of lavender straw has also shown potential for improved thermal insulation properties within the bricks, providing a promising solution for sustainable construction practices [24].

Furthermore, the evaluation of wheat straw as an insulation material in fired clay hollow bricks has confirmed its effectiveness in enhancing thermal performance and contributing to energy savings in building applications. The varying degrees of compaction of wheat straw have demonstrated significant potential in achieving energy efficiency, highlighting its relevance in sustainable building practices [25].

Additionally, the stability of compressed earth blocks has been significantly enhanced by incorporating sugarcane bagasse ash and wheat straw, leading to reduced water absorption and increased dry compressive strength. The interplay between these additives has been observed to improve the overall water resistance properties and structural integrity of the blocks [26].

In line with the presented advancements, this current study aims to further investigate the drying shrinkage of earth bricks reinforced with varying amounts of wheat and barley straw fibers, while also examining the effects of cement and gypsum on the shrinkage behavior of earth bricks.

2. Materials and Methods

2.1. Materials

The present work focuses on the utilization of four distinct materials, namely, cohesive soil, cement, gypsum, and agrofibers, in the production of earth bricks. The grain distribution analysis of the cohesive soil was performed in our laboratory. The cohesive soil composition consisted of 63.3% silt, 28.7% clay, 5% sand, and 3% gravel. Geotechnical laboratory tests were conducted to determine the Atterberg limits, yielding a liquid limit (WL) of 32%, a plastic limit (WP) of 17.3%, and a plasticity index (IP) of 14.7%. In accordance with the unified soil classification system, the soil falls under the category of low-plastic clay.

X-ray diffraction was employed for the analysis of clay mineral composition. The analysis indicated the presence of clay minerals in the following distribution: 30% illite (with high binding force), 10% kaolinite (with high binding force), 10% vermiculite (with medium binding force), and 50% smectite (with low binding force). Figure 1, reproduced from Ashour et al. [4], illustrates the grain size distribution of the tested soil.

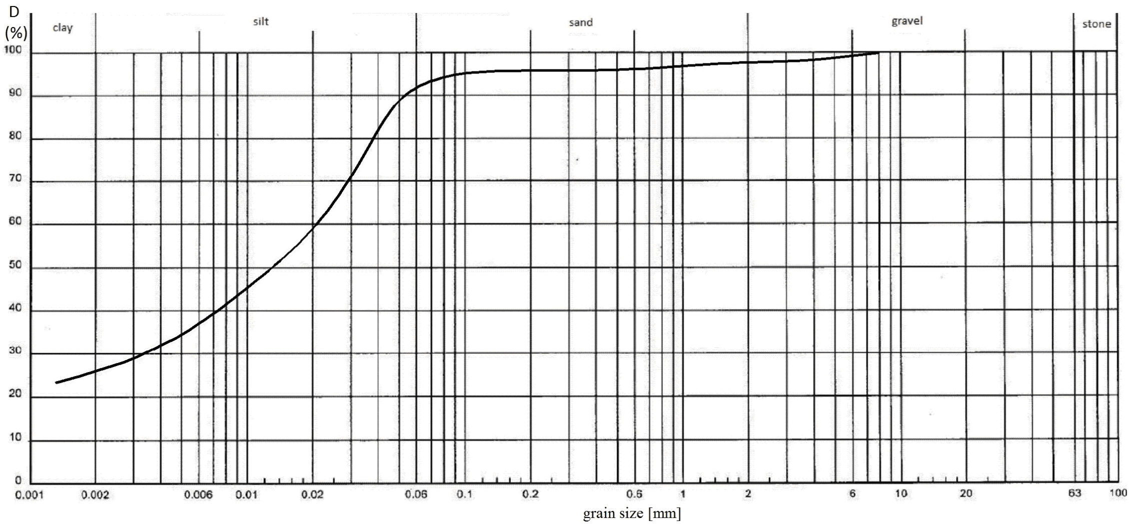


Figure 1. Grain size distribution of soil (Ashour et al. 2015 [4]).

For reinforcement purposes, two types of fibers, specifically, wheat and barley straw, were employed. The length of the straw particles utilized for reinforcement was approximately 4 cm.

2.2. Sample Preparation

In the initial stage, the natural cohesive soil underwent a meticulous removal process, eliminating oversized gravel and organic matter, including grass roots. Subsequently, the samples were subjected to oven drying at a constant temperature of 105 °C until they attained a dry, stabilized weight. Similarly, the fibers were also dried in the oven at 105 °C to achieve a constant mass.

A comprehensive set of experiments involved the fabrication of numerous earth bricks, each featuring different compositions of cohesive soil, cement, gypsum, and fibers. The dosage of the various materials was precisely controlled based on their dry weight proportions. A mechanical mixer was employed to blend the predetermined quantities of soil, cement, gypsum, and fiber, ensuring a uniform mixture through approximately 30 min of dry blending. Following this, water was incrementally sprayed onto the mixture until it reached a desired moisture content of 24%. The materials were then subjected to additional blending using an electric mixer, shown in Figure 2, for approximately 30 min, ensuring the achievement of a homogeneous mixture.

Figure 2. Electrical mixer for different materials.

2.2.1. Preparation of Bricks without Fibres

After the mixing process, the contents of the mixer were tipped into the framework and distributed. A trowel was used to flatten the surface and ensure that the corners of the framework were filled with the earth. The industrial framework dimensions were 2400 × 1200 × 600 mm. The industry process moisture content was 24%. The experiments for full bricks are as follows in Table 1. The bricks are shown in Figure 3.

Table 1. Treatments of bricks stabilized with cement and gypsum for moisture desorption.

Recipes	Cement			Gypsum		
Mixing ratio	1%	2.5%	5%	1%	2.5%	5%

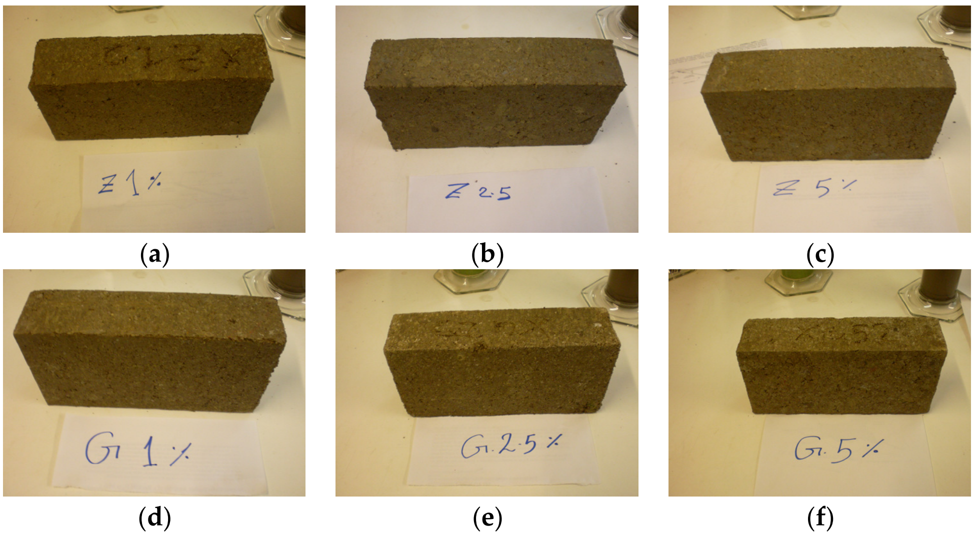


Figure 3. Brick samples stabilized with cement and gypsum: (**a**) cement 1%, (**b**) cement 2.5%, (**c**) cement 5%, (**d**) gypsum 1%, (**e**) gypsum 2.5%, and (**f**) gypsum 5%.

2.2.2. Sample Preparation with Fibres

The earth bricks used in the shrinkage test were prepared by combining various mixtures with different natural fibers, as outlined in Table 1 (reproduced from Ashour 2014 [27] and Ashour et al. 2015 [4]).

The composition of materials in Table 2 is presented as the dry weight percentage of the earth components. Subsequently, the mixture was poured into a steel mold with an internal size of 15 × 4 × 4 cm.

Table 2. Recipes for earth bricks (source: Ashour 2014 [27] and Ashour et al. 2015 [5]).

Earth Brick Recipes	Wheat (%)	Gypsum (%)	Barley (%)	Cement (%)	Clay (%)
Clay	-	-	-	-	100
B_1	-	-	1	-	99
W_1	1	-	-	-	99
B_3	-	-	3	-	97
W_3	3	-	-	-	97
B_1C_5	-	-	1	5	94
W_1C_5	1	-	-	5	94
B_1C_{10}	-	-	1	10	89
W_1C_{10}	1	-	-	10	89
B_3C_5	-	-	3	5	92
W_3C_5	3	-	-	5	92
B_3C_{10}	-	-	3	10	87
W_3C_{10}	3	-	-	10	87
B_1G_5	-	5	1	-	94
W_1G_5	1	5	-	-	94
B_1G_{10}	-	10	1	-	89
W_1G_{10}	1	10	-	-	89
B_3G_5	-	5	3	-	92
W_3G_5	3	5	-	-	92
B_3G_{10}	-	10	3	-	87
W_3G_{10}	3	10	-	-	87

The component was compressed using a loading plate with an applied force of approximately 50 kg. The samples were dried at 105 °C in an oven to obtain a constant mass and monitored by weighing once every 24 h. A total of thirty samples, comprising diverse brick materials, were utilized for the shrinkage test.

2.3. Dry Density

Dry density was determined by drying the bricks in the oven at temperature of 105 °C and then weighing them on a scale with an accuracy of 0.01 g. Also, the bricks' dimensions were measured, and then their density was calculated using the following equation:

$$P_d = m/V$$

where:
P_d: dry density (kg/m^3)
m: mass of brick (kg)
V: volume of the sample (m^3)

2.4. Microscopy of Earth Bricks

To assess the adhesion between the fibers and the matrix, as well as to examine the composite morphology, optical microscopy was employed. The fracture surface was meticulously prepared by sectioning drying bricks, enabling investigation of the interior surface and visualization of the fiber distribution within the bricks. A total of five replicates were examined for each recipe, ensuring statistical validity and reliability. The microscopy of the bricks is further discussed and explained in the results, specifically in Section 3.2.2.

2.5. Moisture Content Desorption Procedure

The samples were weighed on a scale with an accuracy of 0.01 g and dried in the oven, and the associated water contents were determined by drying the samples at 105 °C. The moisture content was determined using the following equation:

$$m_c = (m_w - m_d/m_d) \times 100$$

where

m_c is moisture content (%), m_w is initial mass (g), and m_d is dry mass (g).

2.6. Shrinkage Test Procedure

Shrinkage tests were conducted in accordance with ASTM D4943 [28] standards. The mixture was carefully tipped into a steel frame and compressed. Subsequently, the samples were exposed to controlled drying in the oven until they achieved a constant weight, as per the guidelines specified in DIN EN ISO 12570 [29].

3. Results and Discussion

3.1. Shrinkage for Bricks Stabilized with Cement and Gypsum without Reinforcement Fibers

3.1.1. Moisture Desorption Behavior of Bricks without Fibres and Stabilized with Cement and Gypsum

Figure 4 shows the moisture desorption and weight behavior of bricks stabilized with cement and gypsum with different mixing ratios. The maximum moisture desorption percentages for bricks stabilized with cement were 13.38, 13.87, 14.41 and 17.1% for a cement content of 1%, 2.5%, and 5%, and clay, respectively, while the moisture desorption percentages for bricks stabilized with gypsum were 13.58, 13.8, 13.44, and 17.1% for a gypsum content of 1%, 2.5%, and 5%, and clay, respectively.

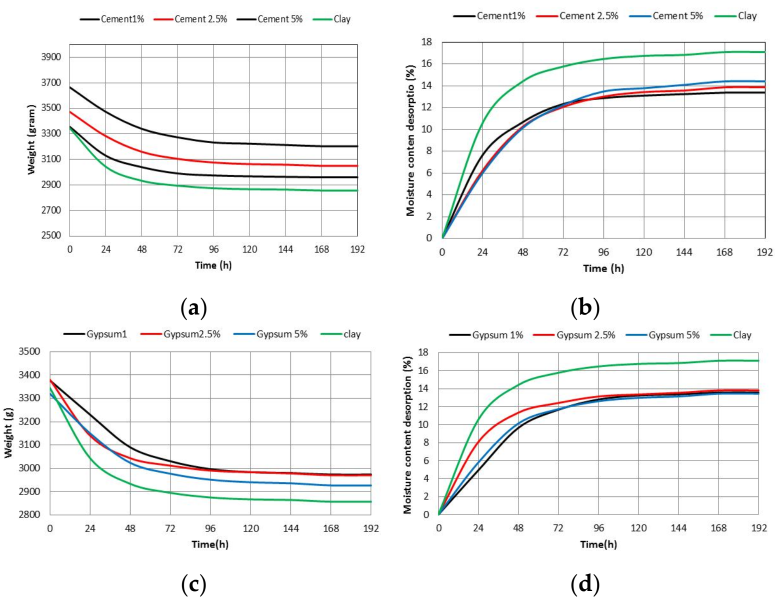


Figure 4. Brick weights and moisture desorption behavior for bricks stabilized with cement and gypsum: (**a**) weight decreasing behavior of bricks (cement), (**b**) moisture desorption (cement), (**c**) weight (gypsum), and (**d**) moisture desorption (gypsum).

Figure 4 also shows that the weight decreased gradually with increasing drying time until a constant weight was achieved, while moisture desorption increased with increased drying time.

3.1.2. Brick Length Shrinkage

Figure 5 depicts the behavior of length shrinkage in the bricks. The minimum lengths were 3329 mm, 2334.67 mm, 2338 mm, and 2341.3 mm for bricks stabilized with 1% gypsum, 2.5% gypsum, 5% gypsum, and clay, respectively. Correspondingly, the lengths were 2333.67 mm, 2337.67 mm, 2331.6 mm, and 2341 mm for bricks stabilized with 1% cement, 2.5% cement, 5% cement, and clay, respectively.

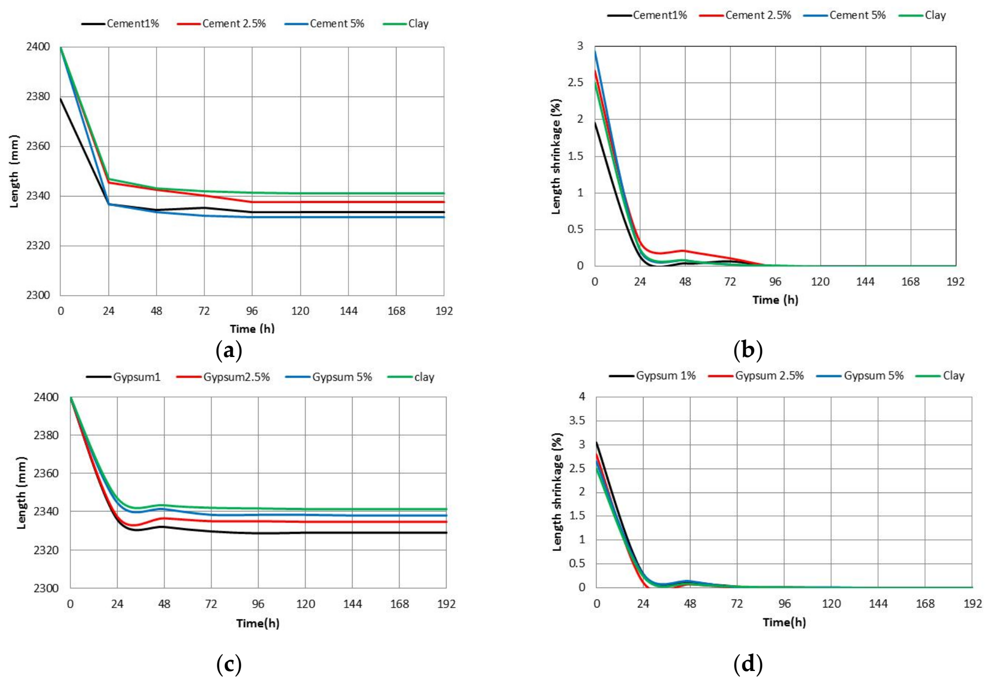


Figure 5. Length shrinkage behavior for bricks stabilized with cement and gypsum: (**a**) length decreasing behavior of bricks (cement), (**b**) percentage of length shrinkage (%) (cement), (**c**) length decreasing behavior of bricks (gypsum), and (**d**) percentage of length shrinkage (%) (gypsum).

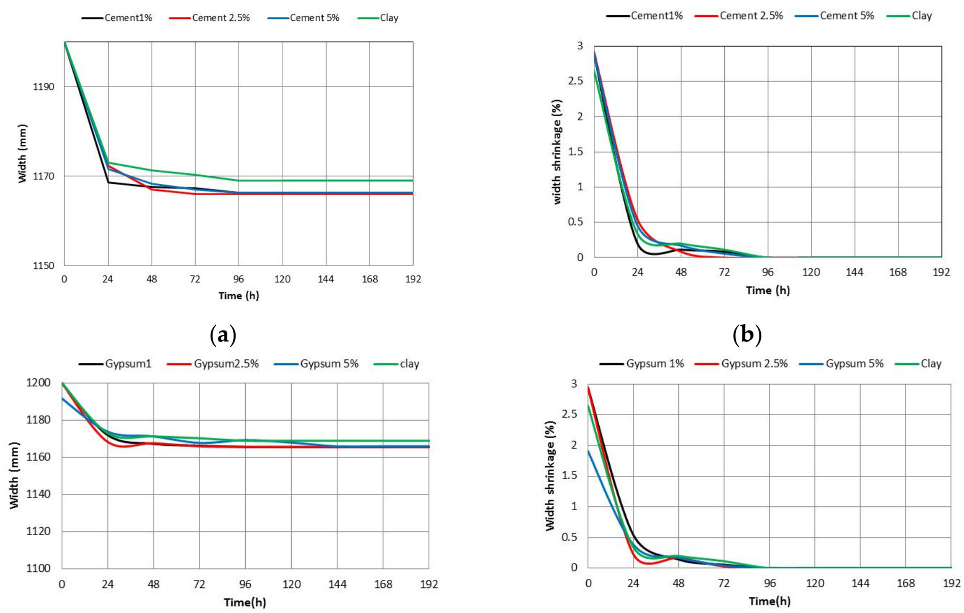
It was observed that the bricks reached a constant length after 96 h for all cement brick compositions, whereas for gypsum samples, the times were 120 h, 120 h, 96 h, and 96 h for 1%, 2.5%, 5%, and clay ratios, respectively.

The results indicated that the maximum length shrinkage for gypsum was 3.05%, 2.8%, 2.65%, and 2.5% for 1%, 2.5%, 5%, and clay ratios, respectively. For cement, the maximum length shrinkage was 1.96%, 2.67%, 2.93%, and 2.5% for 1%, 2.5%, 5%, and clay ratios, respectively.

Additionally, Figure 5 demonstrates that the length shrinkage diminished as the drying time increases until the bricks reached a constant weight.

3.1.3. Brick Width Shrinkage

Figure 6 demonstrates the behavior of width shrinkage in the bricks. The maximum width was 1200 mm across all compositions for bricks stabilized with 1% cement, 2.5% cement, 5% cement, and clay, respectively. Meanwhile, the widths were 1200 mm, 1200 mm, 1191 mm, and 1200 mm for bricks stabilized with 1% gypsum, 2.5% gypsum, 5% gypsum, and clay, respectively.



(**a**) (**b**)

(**c**) (**d**)

Figure 6. Width shrinkage behavior for bricks stabilized with cement and gypsum: (**a**) width decreasing behavior of bricks (cement), (**b**) percentage of width shrinkage (%) (cement), (**c**) width decreasing behavior of bricks (gypsum), and (**d**) percentage of width shrinkage (%) (gypsum).

It was observed that the bricks reached a constant width after 72 h, 72 h, 72 h, and 96 h for cement brick compositions, while for gypsum samples, the times were 96 h, 96 h, 144 h, and 96 h for 1%, 2.5%, 5%, and clay ratios, respectively.

The results indicated that the maximum width shrinkage for cement was 2.89%, 2.92%, 2.89%, and 2.7% for 1%, 2.5%, 5%, and clay ratios, respectively. For gypsum, the maximum width shrinkage was 2.95%, 2.95%, 1.91%, and 2.7% for the corresponding ratios.

Moreover, Figure 6 highlights that the width shrinkage diminished with an increase in drying time until the weight of the bricks became constant. Shrinkage occurred due to water evaporation from the soil, primarily from its small pores. The shrinkage of a soil particle was attributed to the surface tension of water (Zak, 2012) [30].

3.1.4. Brick Height Shrinkage

Figure 7 illustrates the behavior of height shrinkage in the bricks. The maximum heights were 581.67 mm, 603 mm, 637.67 mm, and 588.3 mm for bricks stabilized with 1% cement, 2.5% cement, 5% cement, and clay, respectively. Conversely, the heights were 590 mm, 591.5 mm, 585.67 mm, and 588.3 mm for bricks stabilized with 1% gypsum, 2.5% gypsum, 5% gypsum, and clay, respectively.

It was observed that the bricks reached a constant height after 96 h, 96 h, 72 h, and 72 h for cement brick compositions, whereas for gypsum samples, the time was 96 h for all ratios, including 1%, 2.5%, 5%, and clay.

The results indicated that the maximum height shrinkage for cement was 1.16%, 0.95%, 0.90%, and 1.5% for 1%, 2.5%, 5%, and clay ratios, respectively. For gypsum, the maximum height shrinkage was 1.66%, 1.46%, 0.98%, and 1.5% for the respective ratios.

Additionally, Figure 7 demonstrates that the height shrinkage decreased as the drying time increased until the weight of the bricks remained constant.

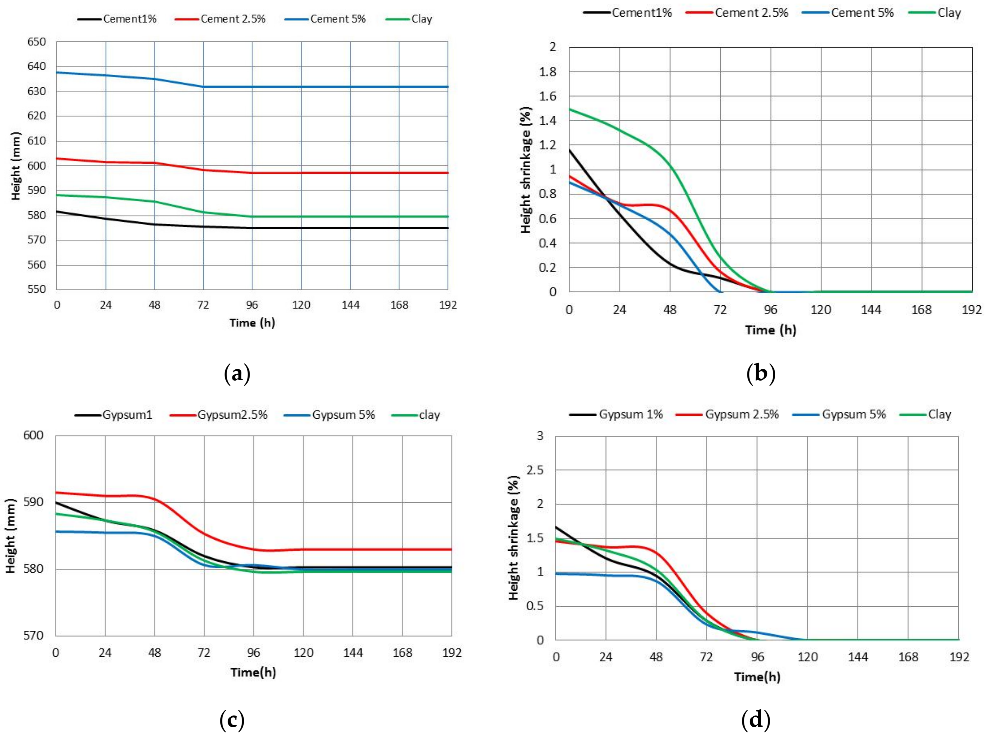


Figure 7. Height shrinkage behavior for bricks stabilized with cement and gypsum: (**a**) height decreasing behavior of bricks (cement), (**b**) percentage of height shrinkage (%) (cement), (**c**) height decreasing behavior of bricks (gypsum), and (**d**) percentage of height shrinkage (%) (gypsum).

3.2. Shrinkage Behavior for Bricks Reinforced with Wheat and Barley Straw and Stabilized with Cement and Gypsum

3.2.1. Brick Density

An increase in the quantity of fibers led to a reduction in density. The blocks initially demonstrated relatively high densities, ranging from 1476 kg/m^3 to 1277 kg/m^3 at fiber contents of 1% and 3%. This accounted for a decrease of 8.8% to 21% in comparison to soil bricks without fibers. Bricks reinforced with barley straw fibers exhibited densities ranging from 1445 kg/m^3 to 1099 kg/m^3. Notably, the densities of bricks strengthened with wheat straw fibers exceeded those enhanced with barley straw. This difference can be attributed to the higher concentration of solid materials and lignin content in wheat straw, in contrast to barley straw.

At a fiber content of 3%, the average densities of bricks stabilized with 5% and 10% cement were 1004 kg/m^3 and 1040 kg/m^3, respectively. In comparison, using the same fiber content, bricks reinforced with barley straw exhibited densities of 1146 kg/m^3 and 1025 kg/m^3 at 5% and 10% cement content, respectively.

Overall, the augmentation of fiber content in the mixtures resulted in decreased sample masses. Furthermore, the use of wheat and barley straw fibers as substitutes for cement or gypsum, acknowledged as lightweight materials, increased the bricks' volume after compression. This expansion in volume contributed to the reduction in the weights and densities of the samples [31–33].

3.2.2. Microscopy of Earth Bricks

The microstructures were visualized using optical microscopy, which allows the examination and observation of internal characteristics and features at a microscopic scale. Figure 8 depicts the fiber distribution of the brick surfaces.

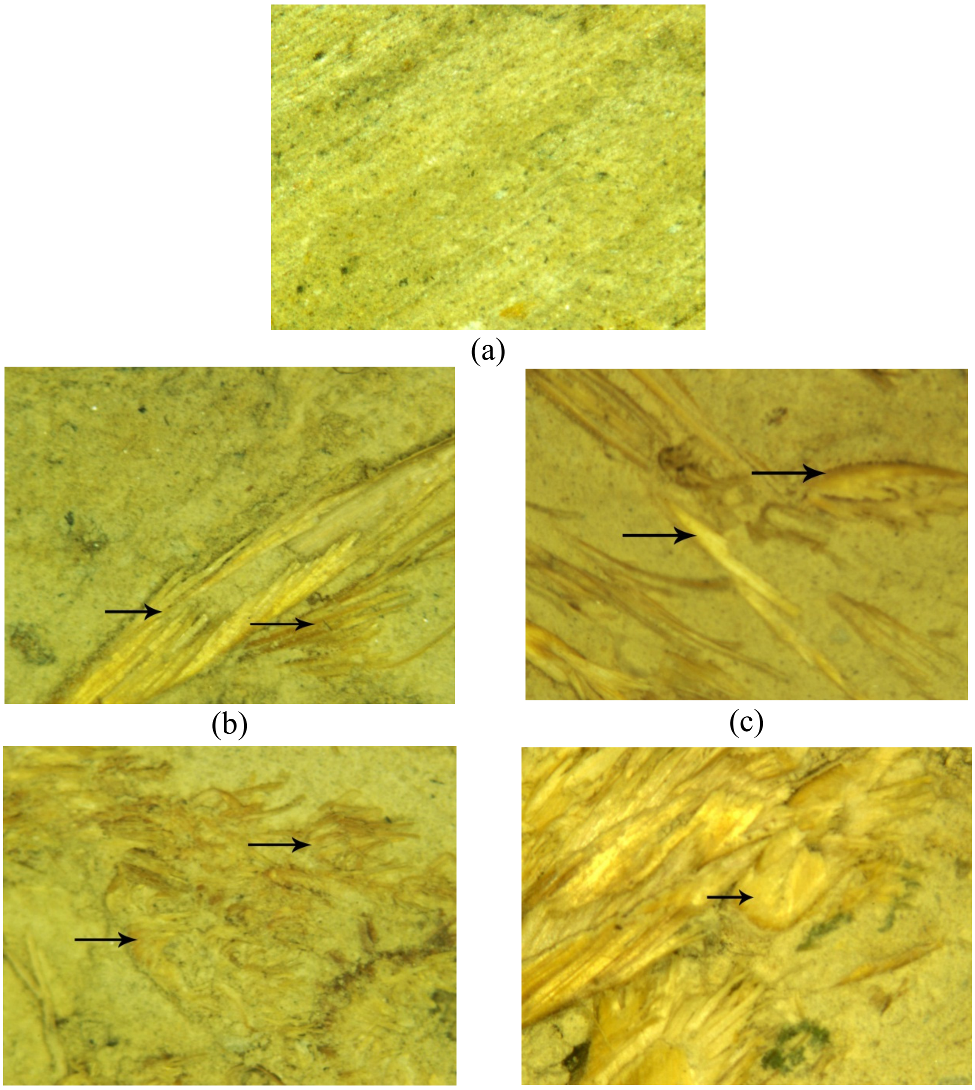


Figure 8. Microscope photos for bricks reinforced with different fibers: (**a**) without fibers, (**b**) 1% wheat straw, (**c**) 1% barley straw, (**d**) 3% wheat straw, and (**e**) 3% barley straw. Arrow refers to the distribution of straw particles within the bricks (magnification power ×12) (Ashour 2014 [27] and Ashour et al. 2015 [4]).

The images provided are representative micrographs captured from the surface of the blocks. Specifically, Figure 8a portrays the microstructure of the bricks lacking any reinforcement fiber. Conversely, Figure 8b,c showcase the bricks fortified with 1% wheat and barley straw, respectively. In addition, Figure 8d,e correspondingly depict the bricks strengthened with 3% wheat and barley straw. The analysis suggests that the distribution of fiber length is less affected than fiber diameter by processing-induced damage. This is evident in the broader distribution of fiber bundle diameters in comparison to lengths, as highlighted in previous research [27].

The observation can be made that during the processing, the natural fibers experience damage both diagonally and longitudinally. However, the damage primarily affects the diameter, while the change in length remains relatively constrained. Furthermore, it is evident that the straw particles within the bricks are randomly distributed. The visual evidence highlights that barley straw fibers consist of finer straw particles compared to wheat straw. It is noteworthy that the inclusion of straw introduces not only cellulose but also pectin, as substantiated by references [32–34].

Additionally, it is observed that wheat straw fibers have a stronger structure compared to barley straw fibers, due to the higher content of lignocelluloses and pectin in wheat straw. As a result, the quantity of barley straw fibers used in the bricks was greater than that of wheat straw fibers, due to the lower density of barley straw. As a result, the bricks reinforced with barley straw exhibited a superior performance when compared to those reinforced with wheat straw.

3.2.3. Shrinkage Behavior

Earth bricks formed exclusively from soil devoid of reinforcement fibers, cement, and gypsum display the highest degree of shrinkage and exhibit notable crack development.

Increasing the wheat straw content of bricks from 0% to 1% decreases shrinkage by 37.15% in comparison to bricks without reinforcement. The shrinkage can be even further reduced to 86.23% in bricks containing 3% wheat straw fibre in comparison to bricks without any fibre. Moreover, increasing the barley straw content of bricks from 0% to 1% reduces shrinkage to about 16.89% in comparison to bricks without reinforcement fibers, while increasing the percentage of barley straw from 0% to 3% reduces shrinkage to 82.27%.

The use of barley straw as a reinforcement in bricks leads to an increase in shrinkage of 1.5% when 5% cement is added, compared to bricks without any cement.

The bricks reinforced with wheat straw fibers exhibit average shrinkage values of 0.573%, 0.601%, and 0.653% for cement contents of 0%, 5%, and 10%, respectively.

On the other hand, the shrinkage of barley straw-reinforced bricks shows a significant increase of 15.82% when 5% cement is added, compared to bricks without cement. Interestingly, the inclusion of cement from 0% to 10% results in a decrease in the shrinkage percentage, amounting to around 33.77%.

The properties of fibers, including their structure, surface roughness, and surface polarity, play a significant role in fibre wettability and adhesion in composites. The variation in wheat and barley straw content exerts a greater influence on the shrinkage behavior than the presence of cement and gypsum. Higher fiber content reduces the shrinkage ratio due to the reinforcing influence of the fibers [9,10,33,35]. This correlation is also supported by the work of Yetgin et al. (2006) [10]. Nonetheless, the shrinkage identified in our investigation is slightly less than the shrinkage reported in the studies by Yetgin et al. (2006) [10] and Ashour (2014) [33]. This variance can be attributed to the varying fiber contents used in the respective studies.

Conversely, the outcomes align with those derived from the research conducted by Cai et al. (2006) [35], wherein they noted a rise in the rate of shrinkage corresponding to higher fiber content. This variation might stem from comparable fiber contents having identical water content (16%) (Ashour 2014 [33]).

4. Conclusions

The conclusions drawn from our experimental findings shed light on the factors influencing the shrinkage behavior of earth bricks, including cohesive soil characteristics, cement and gypsum as stabilized materials, and fiber content and type, as well as the presence of cement and gypsum. It is evident that earth bricks lacking fiber reinforcement exhibit a high susceptibility to crack formation, leading to eventual specimen disintegration. However, the incorporation of reinforcement fibers, cement, and gypsum has a positive impact on shrinkage mitigation.

The shrinkage percentage behavior is decreased with increasing drying time. The shrinkage percentages for brick length range from 2.5% to 3.05% for cement and gypsum percentages of 1% to 5%, while for brick width, the shrinkage percentages for cement and gypsum range from 1.91% to 2.95%. For brick height, the shrinkage percentages range from 0.98% to 1.66%.

Furthermore, it is noteworthy that the influence of reinforcement fibers on shrinkage surpasses that of cement and gypsum. A higher fiber content contributes to reduced crack formation and improved shrinkage behavior. Conversely, increasing cohesive soil content exhibits a negative impact on shrinkage characteristics. In general, the utilization of higher fiber contents is recommended to enhance the overall performance of earth bricks.

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