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Review Article

Review: Influence of the Size of Plant Aggregates on the Microstructure, Physical and Mechanical Properties of Stabilised Adobe Blocks

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Abstract

The primary objective of this study is to conduct a comparative analysis of the influence of the length and type of plant aggregates on the enhancement of the microstructural and physico-mechanical properties of developed adobe bricks. To this end, a clay soil composed of kaolinite (28 wt%), quartz (49 wt%), goethite (7 wt%), and muscovite (9 wt%) with moderate plasticity was used to prepare adobes reinforced with fonio straws, rice husks, or kenaf fibres (*Hibiscus altissima*) measuring 1.5 or 3 cm in length at varying contents up to 1 wt%. The physical, mechanical, and microstructural characteristics of the adobes were evaluated. The incorporation of plant aggregates generally improved the microstructure, physical, and mechanical properties of the reinforced adobes. This improvement is primarily attributed to the homogeneous microstructure of the adobes with fewer pores, strong adhesion between the plant aggregates and the clay matrix, the prevention of crack propagation in the composites, and the cellulose content in the aggregates. The presence of aggregates in the clay matrix rendered the composite material ductile, exhibiting at least two failure peaks: one due to the breakdown of the clay matrix and the others attributed to the load-bearing capacity of the aggregates following matrix cracking. Adobes reinforced with kenaf fibres exhibited the best thermal conductivity and flexural strength, while those reinforced with rice husks demonstrated superior compressive strength and water erosion resistance due to the acceptable silica content in the husks. According to applicable standards, adobes containing plant aggregates at concentrations not exceeding 0.4 wt% are suitable for constructing thermally comfortable housing.

Keywords

Clay Soil, Plant Aggregates, Adobe, Microstructure, Physical and Mechanical Properties, Thermal Comfort

1. Introduction

The use of clay soil dates back thousands of years, with approximately 30% of the global population living in earthen homes (either raw or fired) [1]. In housing construction, clay soil is exploited through various techniques, including adobe, rammed earth, cob, wattle and daub, and compressed earth blocks (CEBs). Despite their traditional

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construction methods, these models face significant challenges such as durability issues, low mechanical strength, and poor water resistance.

Scientific research on adobe stabilisation has been carried out using mineral binders such as quicklime, cement, and metakaolin [2-4], as well as plant fibres like palm fibres and sugarcane bagasse [5-8]. In Africa, particularly in Burkina Faso, adobes are traditionally stabilised using natural plant aggregates. While this empirical practice improves the physical and mechanical properties of adobes, they still exhibit low durability against natural weather conditions. Nevertheless, the use of plant aggregates offers advantages, including their abundance as agricultural by-products, non-polluting nature, energy efficiency, and affordability.

In the scientific literature, studies have investigated the impact of sisal, coconut, and bamboo fibres on the physical and mechanical properties of adobe [9-12]. These studies have shown that fibres enhance the mechanical properties of the clay matrix but have not extensively examined the role of fibre length. Research by Ouedraogo *et al*. (2017) [13] demonstrated that the improvement in the microstructure, physical, and mechanical properties of adobe largely depends on the length of kenaf fibres. However, to the best of our knowledge, a comparative study that simultaneously considers the type and length of plant fibres has not been conducted.

The present work aims to perform a comparative analysis of the influence of the length and type of plant aggregates on the enhancement of the microstructural and physico-mechanical properties of developed adobe bricks.

2. Raw Materials, Methods, and Experimental Procedures

2.1. Raw Materials

2.1.1. Clayey Raw Material

The clayey raw material, designated as KORS (Korsimoro clay), used for adobe production was collected from the locality of Korsimoro (12°79′ N, -1°09′ W) in the north-central region of Burkina Faso. The clay soil from this area is traditionally exploited by local populations, primarily for the fabrication of raw earth bricks (adobes).

The geotechnical characteristics (Table 1) and mineralogical composition (Table 2) of the KORS material have been previously reported in scientific publications [13, 14]. These findings indicate that KORS is rich in quartz and clay minerals (kaolinite and muscovite), contains a significant amount of goethite, and can be classified as a silt-like clay with moderate plasticity. Based on the obtained geotechnical and mineralogical properties, the KORS sample is deemed suitable for the production of adobes.

Table 1. *Geotechnical characteristics of KORS [13, 14].*

Characteristics	Results
Particles size distribution (wt%)	
Clay (< 2 μm)	29.9
Silt (2-20 μm)	22.7
Fine sand (20-200 μm)	37.9
Coarse sand (> 200 μm)	4.7
Atterberg Limits	
Liquid limit, W_L (%)	31
Plasticity limit, W_P (%)	17
Plasticity Index, P_I (%)	14
Blue Methylene Value (g/100 g)	5.17

Table 2. *Mineralogical composition of KORS [13, 14].*

Minerals	Quartz	Kaolinite	Muscovite	Goethite
wt%	49	28	9	7

2.1.2. Plant Aggregates

The plant aggregates (kenaf fibres, rice husks and fonio straws) used in this research were previously studied by Ouedraogo *et al.* (2017, 2019 and 2023) [13, 15, 16].

(i). Kenaf Fibres

The kenaf fibres (*Hibiscus altissima*) (Figure 1a) used in this study were extracted from an experimental field managed by the Institute of Environment and Agricultural Research (INERA) located in Farakobâ (11°6′ N, 4°19′ W). These fibres are biodegradable and can last throughout the lifespan of a building when incorporated into an earthen matrix [17, 18]. Results from the physical, mineralogical, biochemical, mechanical, and microstructural characterisations of the kenaf fibres revealed that:

Diameter and Density: The diameter (0.14 mm) and absolute density (1.05) of these fibres are nearly identical to those of *Hibiscus cannabinus* kenaf fibres from Burkina Faso (diameter: 0.13 mm, density: 1.04). This indicates that the variety has minimal influence on the absolute density and diameter of the fibres. These parameters are also within the same range as sisal, coconut, and Lechuguilla fibres [9, 19, 20].

Moisture Content: The moisture content (4.56 wt%) of *Hibiscus altissima* fibres is lower than that of *Hibiscus cannabinus* fibres and other natural fibres such as sisal, coconut, and Lechuguilla [9, 19, 20]. This relatively low moisture content (indicating low hygroscopic water absorption) could enhance the tensile strength of the fibres and improve their durability within the clay matrix.

Water Absorption: The water absorption after 24 hours is approximately 230 wt%, attributed to the hydrophilic nature of kenaf fibres due to their cellulose and hemicellulose molecules. This saturation absorption value is similar to that of sisal fibres but higher than that of coconut and flax fibres [20, 21], and lower than that of straw [22]. Compared to *Hibiscus cannabinus* fibres, water absorption remains lower, which aligns well with the observed moisture content. High water absorption values could lead to aging issues in clay matrix composites.

Surface and Composition: Kenaf fibres have a rough surface and are primarily composed of cellulose (71 wt%), hemicellulose (20 wt%), lignin (4 wt%), and ash (2 wt%) [13]. This biochemical composition is similar to that of *Hibiscus cannabinus* fibres [23]. Variations in composition are more influenced by soil type, climate, and growing region than by plant variety.

Tensile Strength: Tensile strength was measured for three gauge lengths: 5, 10, and 20 mm. Results show a decrease in tensile strength with increasing gauge length. The average stress values for gauge lengths of 5, 10, and 20 mm are (965 ± 135) MPa, (880 ± 145) MPa, and (821 ± 202) MPa, respectively. A high dispersion of tensile strength values (large standard deviation) was observed, likely due to the heterogeneity of the fibres and the manual defibration process [13].

(ii). Rice Husks

The rice bales (Figure 1b) used in this study are of the variety FKR 45N, grown in INERA's experimental rice field. They were collected in the village of Bama (11°20' N and 04°21' W), located 30 kilometres from the town of Bobo Dioulasso, in western Burkina Faso. Studies carried out by Ouedraogo *et al.* 2023 [16] on the microstructure and physical and mechanical properties of adobes stabilised with rice husks showed that rice husks are low in cellulose and high in lignin compared with kenaf fibres. Both plant materials have hemicelluloses contents in the same order of magnitude [23]. Unlike plant fibres in general, and kenaf fibres in particular, rice husks contain a significant amount of silica. This high silica content is responsible for the hardness of rice husks. Rice husks also have a rough, hooked surface that helps them adhere well to clay particles [16].

(iii). Fonio Straws

The dried fonio straws (Figure 1c) were collected from the locality of Peni (10°57′ N, 4°28′ W) in the "Hauts Bassins" region of Burkina Faso. This site was chosen due to the availability of fonio straws in the area. Mineralogical and microstructural characterisations of the fonio straws reveal the presence of free hydrogen and lone pairs of oxygen atoms in the molecular structure of the straws. A comparison between the XRD (X-ray diffraction) spectrum of fonio straws and that of kenaf fibres [23] confirms that the crystalline substance in the fonio straws primarily consists of cellulose. Each microfibril is a bundle formed by the association of 30–60 individual cellulose chains, arranged in stacked layers. The potential for hydrogen bonding within and between the cellulose chains stabilises the overall structure [15], thereby improving tensile strength. These microfibrils are the main components of the plant's primary cell wall. Crystalline cellulose exhibits a relatively high elastic modulus (90–137 GPa), compared to that of fibreglass, which is 75 GPa. Thus, a high cellulose crystallinity in a fibre correlates with enhanced mechanical properties [15, 23]. Additionally, fonio straws exhibit parallel striations oriented in the same direction. This grooved fibre structure can enhance adhesion to the clay matrix, significantly influencing mechanical properties [13, 24].

Figure 1. *Pictures of plant aggregates: (a) Kenaf fibres, (b) Rice husks, (c) Dried fonio straws [13, 15, 16].*

2.2. Experimental Methods and Procedures

2.2.1. Elaboration of Adobes

The elaboration of adobes was carried out inspired by the protocol described by Ouedraogo *et al.* 2017 [13]. The clay raw material used to make the adobes was first dried at 105 ℃ for 24 hours and ground to obtain particle sizes < 5 mm. The clay powder obtained was mixed with various quantities of kenaf fibres (1.5 and 3 cm long) or fonio straws or dried rice husks (up to 1 wt%) and an optimum water content equal to 24 wt% of dry clay soil in order to obtain a paste suitable for making adobes. The pastes obtained were homogenised for 15 minutes, manually pressed in two layers with 30 shocks for each layer in prismatic moulds (4 x 4 x 16 cm^3) and kept in the shade (30±5 ℃) and in the open air for 24 hours in the test room. The specimens were removed from the moulds and re-dried in the shade for 21 days to prevent cracking [23]. Specimens that had dried for at least 21 days were subjected to mechanical, physical and microstructural characterisation.

2.2.2. Microstructural, Physical and Mechanical Characterisation of the Adobes Produced

The morphology of the adobe samples was analysed using a Keyence VH-5911 optical video microscope [20].

The apparent density (d_a) of the adobes was measured on the prismatic samples (4 x 4 x 16 cm^3) by the hydrostatic weighing method using a 0.001 g precision digital balance [24]. The apparent density of the specimens was calculated according to Equation 1:

$$d_a(g/cm^3) = \frac{m}{V} \quad (1)$$

The closed porosity of the adobes (η) was deduced from the apparent density d_a using Equation 2 below by determining the absolute density (d_{ab}) of the adobe specimen using the pycnometer method [13].

$$\eta\ (\%) = (1 - \frac{d_a}{d_{ab}}) \times 100 \quad (2)$$

The thermal conductivity (λ) of the adobes was measured using a TR-1 probe (2.4 mm in diameter, 10 cm in length, operating within a range of 0.1 to 4 W m^{-1} K^{-1}) connected to a KD2 Pro thermal properties analyser. The probe was inserted into a hole made at the center of one square face of the adobe, which had been previously dried, ensuring no contact with air [14].

The water absorption by capillarity tests on adobe samples were conducted on prismatic specimens (4 × 4 × 16 cm^3) after drying at 105 ℃ for 24 hours, following the AFNOR standard NF EN 1015–18 [25].

Erodibility refers to the ability of a material to undergo erosion. The erosion process caused by rainfall was simulated using a spray test device. This setup involved continuously spraying water at a pressure of 2 bars and a constant flow rate of 5 L/min for 10 minutes [14]. The sprinkler, positioned 50 cm above, directed water vertically onto an inclined plane set at approximately 60° relative to the horizontal, where the prismatic specimens (4 × 4 × 16 cm^3) were placed.

The percentage of mass loss of the material (P_M) after the test determines the degree of erosion, which is estimated using an erosion coefficient calculated through Equation 3.

$$P_M\ (\%) = \frac{m_0 - m_s}{m_0} \times 100 \quad (3)$$

Where m_0 is the initial mass of adobes and m_s the mass of adobes in the ground after erosion.

The mechanical strengths (3-point bending and simple compression) were tested using a CONTROLAB multiform press at a speed of 0.5 mm/min with a maximum load of 200 kN [16]. The bending and compression tests were carried out in accordance with AFNOR standard NF P 15-451 [27] and AFNOR standard NF P18-406 [28] respectively.

3. Results and Discussion

3.1. Microstructural Characterisation of Adobes Amended with Plant Aggregates

To better understand the effect of plant-based aggregates on the microstructure of adobe samples, video microscope observations were performed on the fracture surfaces of the specimens. Video microscopy images of adobes reinforced with plant-based aggregates (kenaf fibres, fonio straws, and rice husks) are presented in Figure 2.

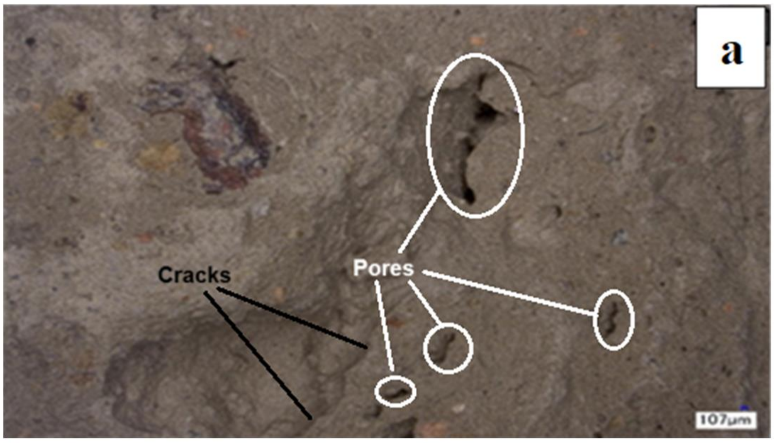
Microscopic observations of the different fracture facies of the adobe formulations revealed cracks and numerous pores in the adobe without plant aggregates (Figure 2a). However, the addition of kenaf fibres to the clay matrix, at a content of up to 0.4 wt% for 1.5 cm fibres and 0.2 wt% for 3 cm fibres, resulted in a homogeneous microstructure free of cracks and reduced porosity. Beyond these fibre contents, the number and size of pores and cracks progressively increased, with fragments of adobe often visible, due to fibre accumulation in certain zones of the clay matrix (Figure 2c and 2e).

At low fibre contents, the fibres were evenly distributed and adhered well to the clay matrix, an adhesion attributed to the rough surface of the fibres [29]. This adhesion may also result from hydrogen bonding formed during the mixing of the adobe components (clay soil, kenaf fibres, and water). These bonds arise from interactions among the molecular components of kenaf (cellulose, hemicellulose, and lignin), clay minerals (kaolinite and muscovite), and goethite [13]. These interactions involve the free electron pairs of oxygen molecules and hydrogen atoms from the same molecules [8, 24], increasing the compactness of the composites and potentially enhancing the mechanical properties of the adobes.

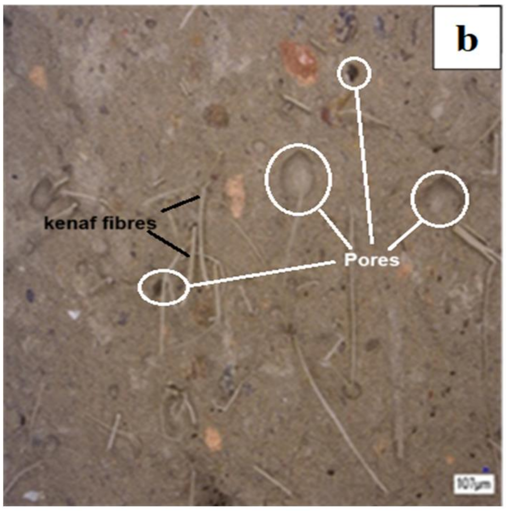
At low fibre contents, fibre size did not influence the microstructure (Figure 2b and 2d). However, at higher fibre contents, fibre size significantly impacted the microstructure (Figure 2c and 2e). As fibre size increased, the microstructure became more porous and heterogeneous, with fibre agglomerations in many areas.

Video microscopy of adobes containing 0.2 wt% fonio straws showed a low porosity despite a slightly heterogeneous microstructure (Figure 2f), with no cracks, small pores, and areas devoid of fonio straws. This fibre content contributed to improved flexural strength, though the distribution of fonio straws could be optimised [15]. Adobes with more than 0.2 wt% fonio straws (Figure 2g and 2h) exhibited increasing structural heterogeneity, indicating the accumulation of fonio straws within the matrix (Figure 2h). This led to larger pores and significantly reduced flexural strength.

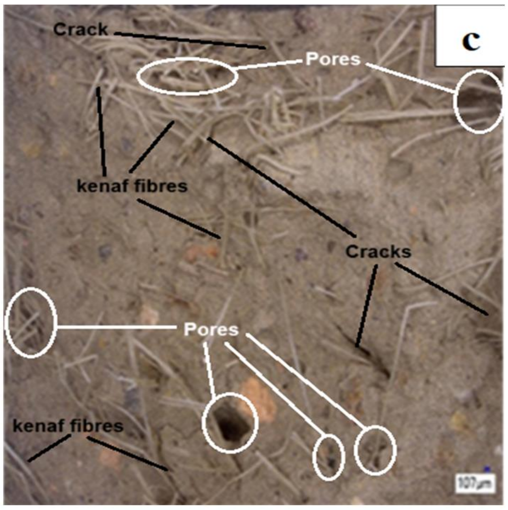
Observations of fracture surfaces of adobes reinforced with 0.2 wt% rice husks showed a homogeneous microstructure, free of cracks but with some small pores (Figure 2i). This homogeneous structure with low porosity favored improved physical and mechanical properties. However, adobes containing more than 0.2 wt% rice husks (Figure 2j and 2k) displayed a highly heterogeneous microstructure, with reappearance of cracks, large pores, and rice husk agglomerations in certain areas, particularly at a rice husk content of 1 wt% (Figure 2k). Such a microstructure could predict a decline in physical and mechanical properties [16].



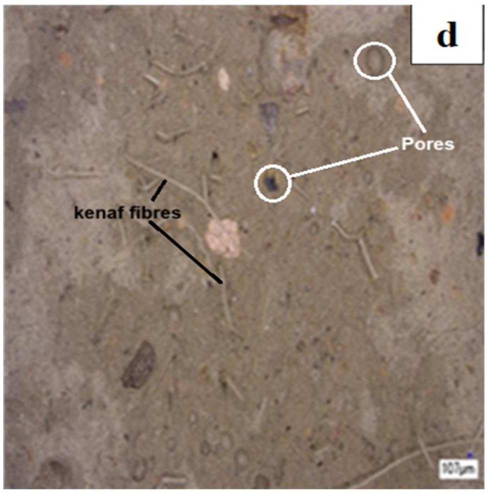
(a) Raw adobe



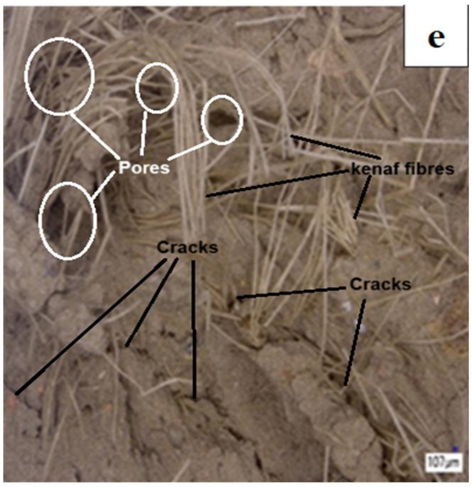
(b) Adobe content 0.2 wt% kenaf fibres (1.5 cm)



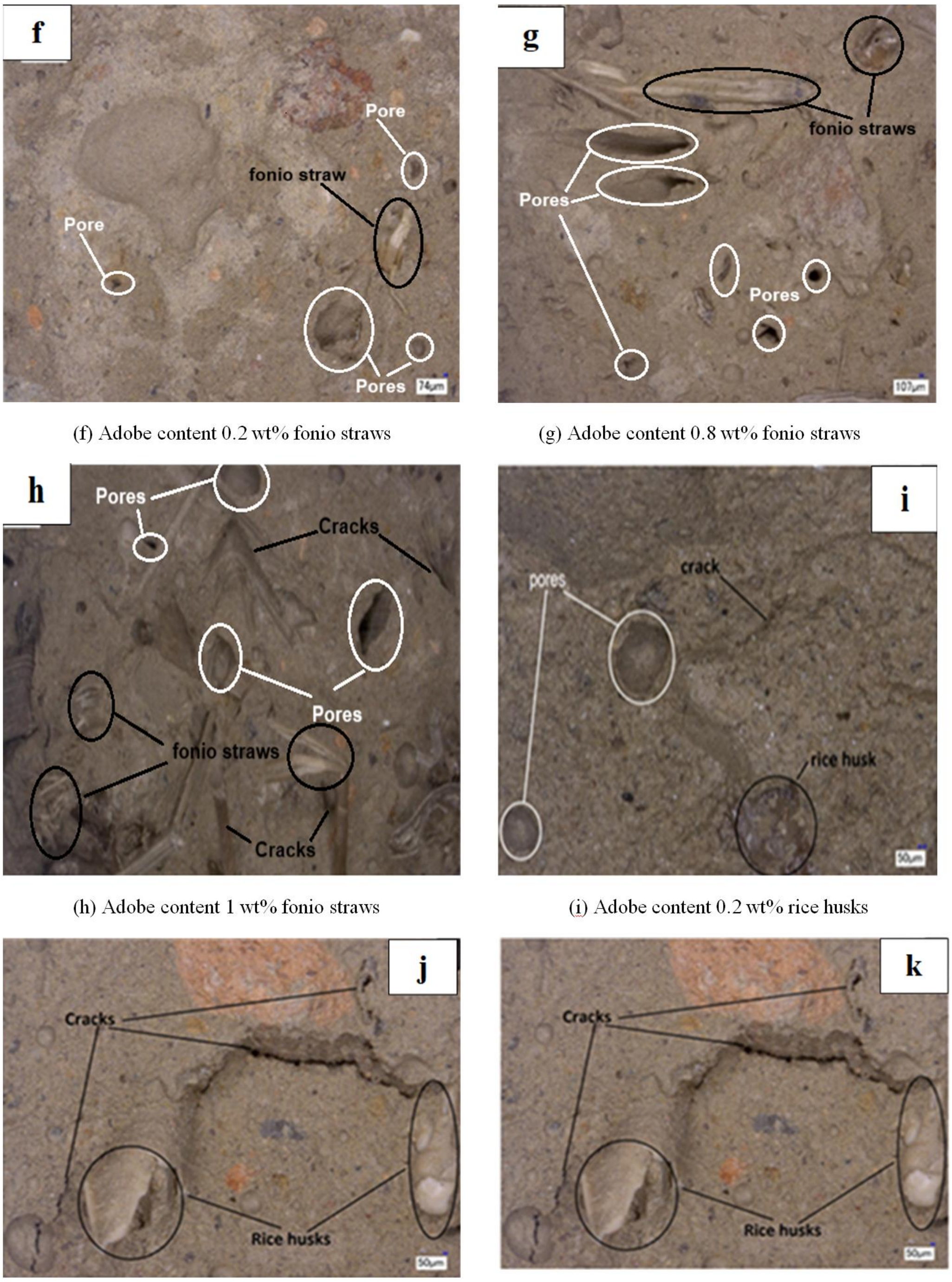
(c) Adobe content 1 wt% kenaf fibres (1.5 cm)



(d) Adobe content 0.2 wt% kenaf fibres (3 cm)



(e) Adobe content 1 wt% kenaf fibres (3 cm)



(f) Adobe content 0.2 wt% fonio straws

(g) Adobe content 0.8 wt% fonio straws

(h) Adobe content 1 wt% fonio straws

(i) Adobe content 0.2 wt% rice husks

(j) Adobe content 0.8 wt% rice husks

(k) Adobe content 1 wt% rice husks

Figure 2. *Video microscope images of adobes reinforced with plant fibres [13, 15, 16].*

3.2. Physical Properties of Adobes Amended with Plant Aggregates

Tests of the apparent density, closed porosity, thermal conductivity, water absorption by capillarity and spray test of the adobes produced were carried out to study the physical properties.

The apparent density of adobes added to plant aggregates (kenaf fibre, fonio straws and rice husks) is shown in Figure 3. The apparent density of adobes decreased with the addition of plant aggregates (kenaf fibre, fonio straws and rice husks). This decrease is due to the replacement of certain soil particles by the plant aggregates, which are less dense than those of the clay soil. This same result has been reported by certain authors in their studies on the stabilisation of clayey soils by agricultural residues [7, 26, 30-32]. For these authors, the densification of the material depends on the size distribution of the grains of raw material and agricultural residues. Initially, the agricultural residues cover the clayey raw material to form large aggregates which consequently occupy large spaces. As a result, the apparent density decreases.

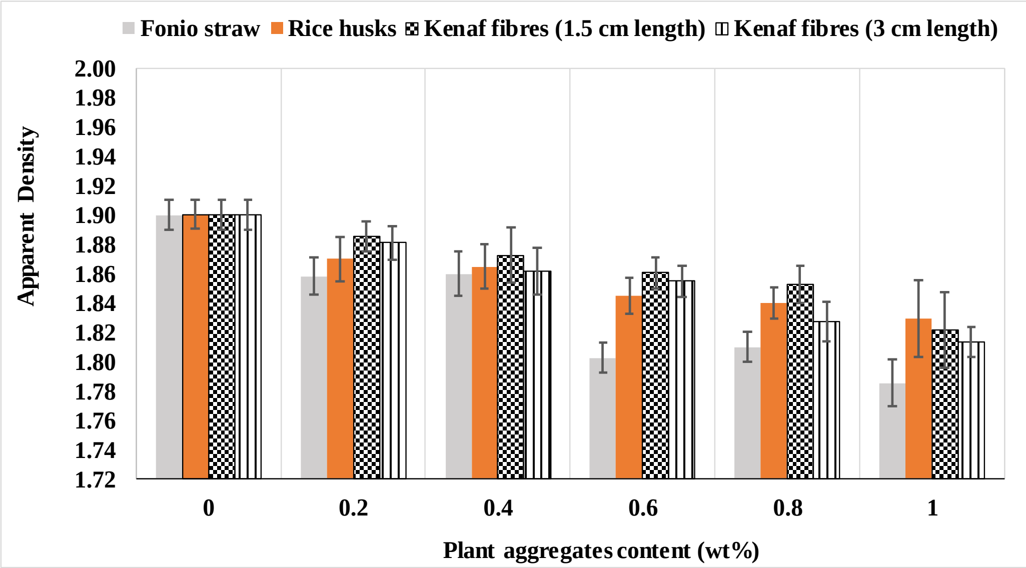


Figure 3. Apparent density of adobes admixed with plant aggregates.

Figure 4 shows the results for the closed porosity of adobes reinforced with plant aggregates (kenaf fibres, fonio straws and rice husks). The closed porosity of adobes reinforced with plant aggregates increases with the addition of the latter. This increase is due to the fact that with the addition of large quantities of plant aggregates to the clay matrix, the aggregates pile up, creating pores in different parts of the adobes [15, 24]. These internal (closed) pores are filled with air. These results generally evolve in the opposite direction to the apparent density, which is mainly linked to the open porosity. This is confirmed by video-microscopic observations of fibre-rich formulations. Generally speaking, the closed porosity of adobes with fonio straws is more noticeable than those with kenaf fibres and rice husks.

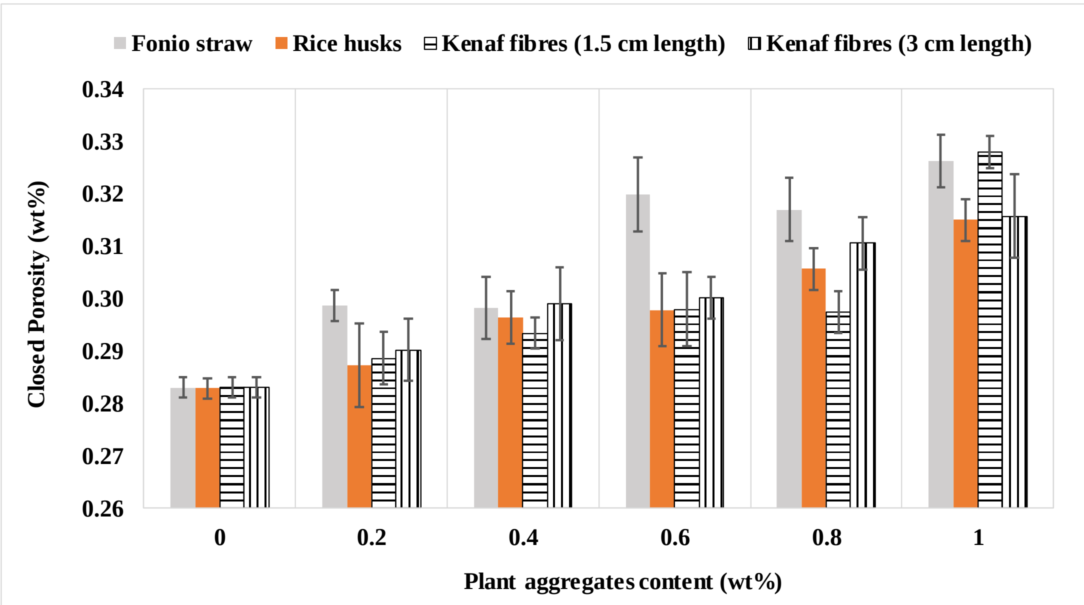


Figure 4. Closed porosity of adobes reinforced with plant aggregates.

The three modes of thermal conductivity (convection, conduction, and radiation) occur simultaneously in adobes with varying amounts of plant-based aggregates. The most significant are conduction (due to particle contacts) and radiation (due to spaces between particles). In adobes, particles are generally in contact with one another; however, differences in thermal conductivity among the various adobe formulations are strongly influenced by pore proportions (via radiative conductivity).

The thermal conductivities of adobes reinforced with plant aggregates (kenaf fibres, fonio straws, and rice husks) are shown in Figure 5. Overall, thermal conductivity decreases with the addition of plant aggregates. This phenomenon aligns with the intrinsic property of cellulose in plant-based aggregates, which acts as a thermal insulator [13].

For adobes reinforced with kenaf fibres, thermal conductivity decreases by up to 69% for formulations with 1.5 cm fibres and 34% for those with 3 cm fibres. This greater reduction for shorter fibres is due to their higher number within the clay matrix. Additionally, this reduction correlates well with the increase in closed porosity within the adobes. The presence of air-filled voids slows heat conduction, thereby reducing thermal conductivity. This outcome has also been observed in compressed adobe blocks (CABs) reinforced with Hibiscus cannabinus kenaf fibres [29].

The thermal conductivity results are better than those reported by Laibi *et al.* (2017) [33] for compressed earth blocks (CEBs) stabilised with kenaf fibres from Benin. This difference is attributed to the fabrication process, as CEBs are less porous than adobes, leading to higher thermal conductivity.

Adding fonio straws to adobes decreases thermal conductivity by up to 67%. This reduction can be attributed to the combined effects of increased closed porosity and the low thermal conductivity of fonio straws, which contain cellulose, a good thermal insulator [15, 29]. This significant reduction makes adobes amended with high levels of fonio straws suitable as construction materials for heat-exposed buildings, provided their mechanical strength is sufficient.

The thermal conductivity of adobes decreases with increasing rice husk content. This finding aligns with the observed increase in closed porosity. A greater number of internal pores reduces heat conduction due to the presence of air, which has a low thermal conductivity of 0.02 W/(m*K) [16]. Additionally, the reduction in thermal conductivity is linked to the presence of rice husks, which contain cellulose, also a good thermal insulator.

Compared to kenaf fibre-stabilised adobes [13], the thermal conductivity of rice husk-reinforced adobes is higher, reflecting the higher cellulose content in kenaf fibres relative to rice husks. However, the thermal conductivity of rice husk-reinforced adobes is lower than that of lateritic blocks from Toussiana (0.96 W/(m*K)) and adobes made from KORS and other clayey soils stabilised with cement [14, 34, 35]. The higher thermal conductivity of cement-stabilised adobes results from their homogeneous microstructure with few pores, particularly closed pores, which facilitates heat conduction.

The presence of rice husks in the clay matrix promotes the formation of internal pores, contributing to reduced thermal conductivity due to the combined effect of internal pores and the insulating property of the cellulose in rice husks.

Overall, the thermal conductivity values of the adobes developed in this study are comparable to those reported in the literature for raw or plant aggregate-reinforced bricks [7, 35, 36]. Lower thermal conductivity is beneficial for buildings, as it reduces heat transfer from the exterior to the interior and helps regulate indoor temperatures. This enhances thermal comfort and reduces energy consumption.

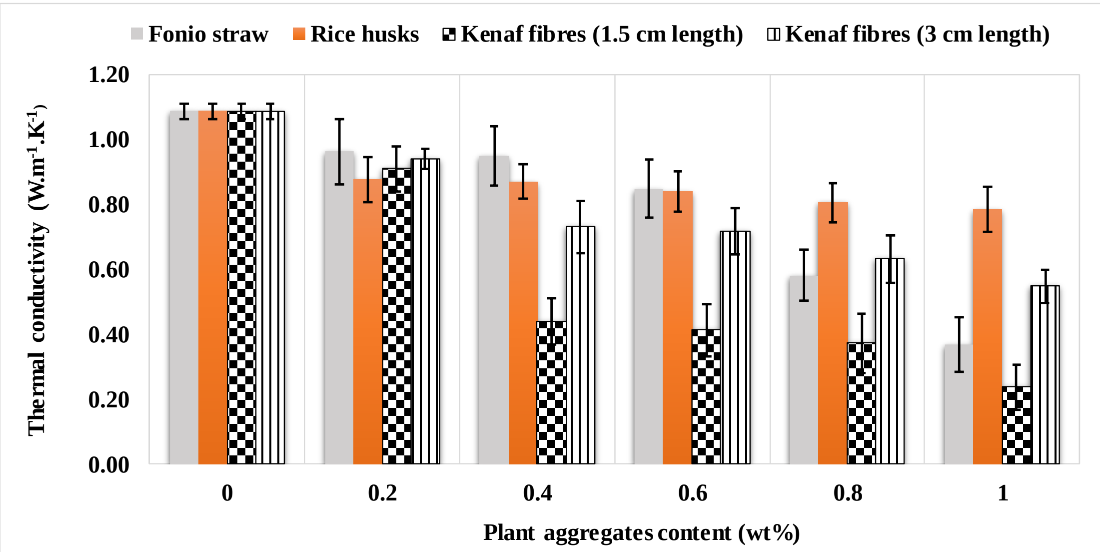


Figure 5. *Thermal conductivity of adobes reinforced with plant aggregates.*

The water behavior of adobes is a critical aspect for their acceptance in building construction. Figure 6 illustrates the variation of the water absorption coefficient by capillarity in adobes as a function of plant aggregate content (kenaf fibres, fonio straws, and rice husks).

The capillary water absorption of adobes reinforced with 1.5 cm-long kenaf fibres increases up to 0.8 wt% fibre content by mass, while adobes reinforced with 3 cm-long kenaf fibres exhibit a rising capillary water absorption up to 0.2 wt% fibre content, followed by a decrease. The increase in capillary water absorption with kenaf fibre addition is primarily due to the high cellulose content in the fibres, which is hydrophilic in nature [13, 23]. The decrease in this parameter, especially with increased fibre content and/or fibre length, is attributed to the packing of kenaf fibres in the clay matrix, which slows the capillary rise of water. The absorbent nature of the fibres (due to cellulose) creates pathways within the adobe's clay matrix that facilitate water capillarity [13, 36]. Beyond 0.4 wt% of 3 cm-long kenaf fibres, the reduction in the absorption coefficient is due to fibre clustering, which prevents some fibres in the clay matrix from being fully exposed to water. As a result, water rises very slowly by capillarity in these adobes, which display heterogeneity in fibre distribution within their structure.

The water capillary absorption coefficient of adobes increases with the percentage of fonio straws up to 0.4 wt%. This behavior is due to the high water absorption capacity of the dry fonio straws in the adobes. A similar phenomenon was noted by Ismail *et al.* (2011) [10], who linked the increased water absorption in lateritic bricks to higher palm oil fibre content. This high water absorption is mainly attributed to the presence of hemicelluloses [15, 37] in fonio straws. Beyond 0.4 wt%, the formation of bundles and the increase in open porosity (Figure 2h) slow down the water absorption kinetics, indicating a strong dependence on the microstructure of the composites. Furthermore, at higher fonio straw content, fibres are arranged in clusters (Figure 2h) within the material, which slows the capillary rise of water.

The water capillary absorption coefficient of adobes amended with rice husks decreases up to 0.8 wt% plant material content. This decrease is due to the absence of capillary fibres in rice husks and the homogeneous microstructure with few pores in rice husk-amended adobes. Beyond 0.8 wt% rice husk content, the absorption coefficient increases due to the clustering of rice husks in the clay matrix. This increase is also attributed to the morphology of the rice husks, which feature cavities that create a large number of interconnected pores, imparting a porous and absorbent nature to adobes with rice husk content exceeding 0.8 wt%.

The decrease in the capillary absorption coefficient is also linked to the lower hydrophilicity of rice husks, which is due to their high silica content [16]. This result contrasts with adobes stabilised with kenaf fibres [13], as kenaf fibres are more hydrophilic due to their higher cellulose content compared to rice husks.

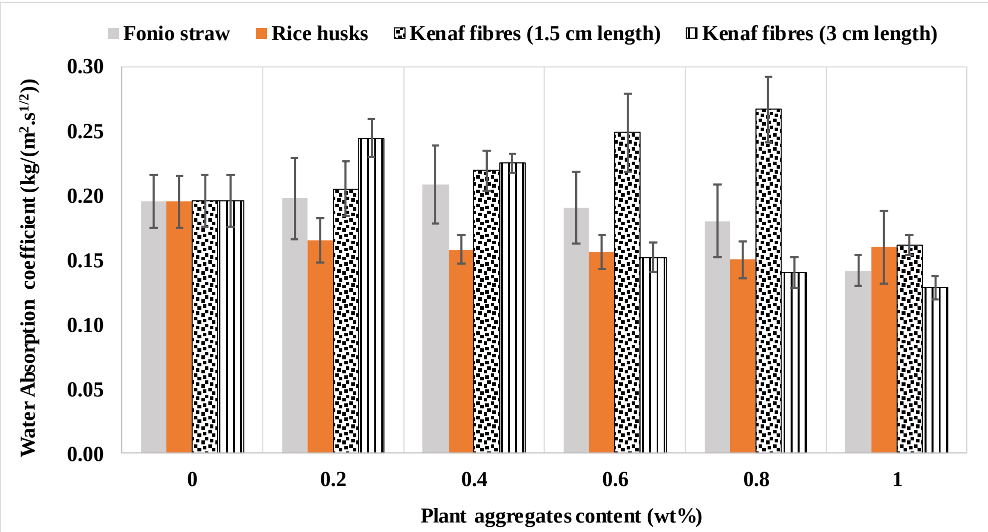


Figure 6. *Evolution of the water absorption coefficient by capillarity of adobes as a function of the plant aggregate content.*

To better evaluate the behavior of adobes in a humid environment, a spray test was performed on the developed samples. Figure 7 shows the evolution of mass loss in adobes as a function of plant aggregate content (kenaf fibres, fonio straws, and rice husks) after the spray test.

Analysis of this figure reveals that fibre-free adobes are more eroded than those containing fibres. This result is attributed, on the one hand, to the microstructure of the adobes and, on the other hand, to the strong cohesion between clay particles and kenaf fibres. This cohesion arises from the rough surface of the fibres and the potential formation of hydrogen bonds between the two raw materials. These bonds form between the hydrogen atoms of heteroatoms and the lone pairs of oxygen atoms in the clay minerals (kaolinite, muscovite, and goethite) and the fibres (cellulose, hemicellulose, and lignin) [13]. The behavior of kenaf fibres in the adobe matrix is comparable to that of plant roots, which combat erosion by stabilising the soil [13, 36, 38], thereby enhancing the water resistance of fibre-reinforced adobes.

Erosion generally occurs at the surface but can also result from water infiltration through cracks and external pores. Adobes containing 0.2 to 0.6 wt% kenaf fibres exhibit fewer cracks and pores, experience minimal erosion, and thus show a significantly reduced mass loss during the spray test.

The results clearly demonstrate that mass loss in adobes decreases with the addition of fonio straws. When comparing the various adobe formulations, the fibre-free adobe (adobe-0TF) is highly eroded, whereas adobes containing fonio straws are much less susceptible to water erosion. The primary mechanism behind this protective effect of fonio straws against erosion is likely the formation of hydrogen bonds between the fonio straw molecules and the clay minerals, which stabilise the composite material. Additionally, this behavior of fonio straws in adobes is akin to the function of plant roots in preventing erosion [15]. This observation is particularly significant as it validates an ancient technique of using straw in construction materials and suggests new, low-cost methods for protecting raw clay structures.

Comparing natural adobes to those reinforced with rice husks, a significant loss of clay particles is observed in the fibre-free adobes. The reduced particle loss in rice husk-reinforced adobes is due to the presence of rice husks, which enhance cohesion between particles in the clay matrix and contribute to pore closure, especially external pores [16]. This cohesion is further improved by the formation of hydrogen bonds between the lone pairs of oxygen atoms and hydrogen atoms in the clay minerals (kaolinite and muscovite) and those in the rice husks (cellulose, lignin, and hemicellulose).

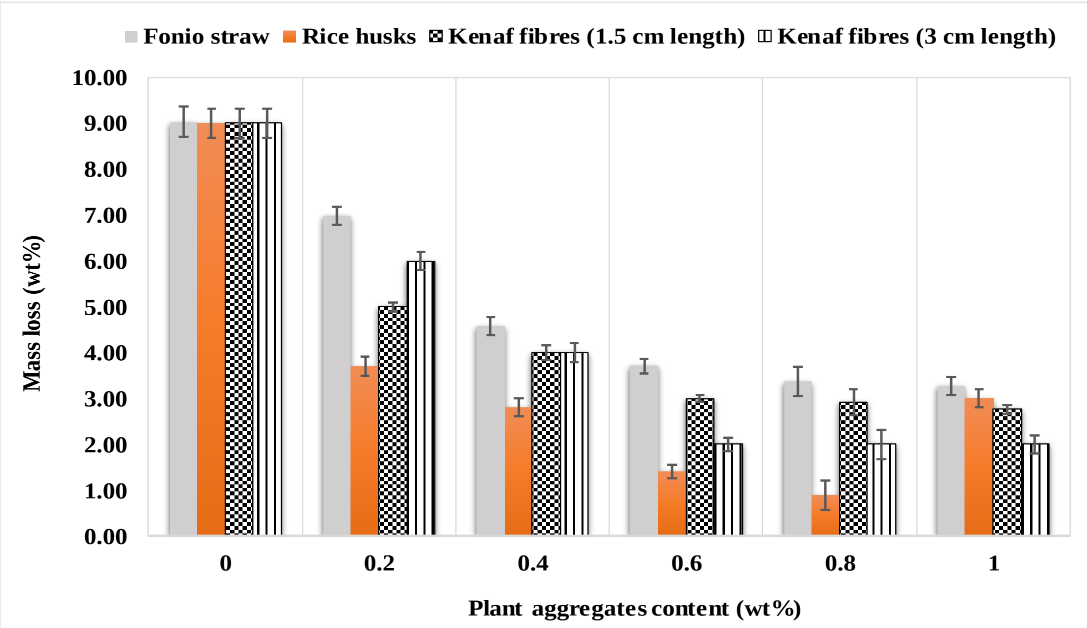


Figure 7. *Evolution of the loss of mass of adobes as a function of the plant aggregate content during the spray test.*

3.3. Mechanical Properties of Adobes Amended with Plant Aggregates

Mechanical strength (three-point bending, simple compression, and stress-strain curves) represents a key parameter for selecting construction materials.

The three-point flexural strength of adobes incorporating plant aggregates (kenaf fibres, fonio straws, and rice husks) is presented in Figure 8.

The results reveal that the inclusion of fibres enhances the flexural strength of reinforced adobes, with an improvement of up to 40% for 0.2 wt% by weight of 3 cm-long fibres. This improvement peaks at 0.2 wt% for 3 cm-long fibres and 0.4 wt% for 1.5 cm-long fibres before declining. Generally, for the same percentage of kenaf fibres, the highest flexural strength is achieved with fibres 3 cm in length. Longer fibres, within a certain limit, improve flexural strength by forming bridge-like connections in the clay matrix. This improvement is primarily due to the high tensile strength of kenaf fibres, attributed to their significant cellulose content (70 wt%), which provides considerable tensile resistance.

The flexural strength value is relatively high compared to adobes reinforced with 2 or 5 cm sisal fibres, which exhibit strengths of 0.23 MPa and 0.25 MPa, respectively [39]. This disparity is linked to the biochemical composition of the two fibres, as kenaf fibres contain more cellulose than sisal fibres, resulting in higher tensile strength and, consequently, better enhancement of adobe flexural strength. Flexural strength is further improved when kenaf fibres are oriented parallel to one another [40].

The three-point flexural strength of adobes increases with the addition of fonio straws, reaching a maximum of 1.3 MPa for 0.2 wt% by weight of fonio straws. This improvement is mainly due to the high tensile strength of fonio straws, attributed to their crystalline cellulose content [15]. Natural fibres influence the "plastic" behavior of the material and affect the manner in which adobe samples fracture [41]. Beyond 0.2 wt% of fonio straws, the flexural strength decreases, correlating with increased porosity, as fibres tend to cluster with increasing quantity.

The three-point flexural strength of adobes stabilised with rice husks increases with the addition of rice husks, reaching a maximum of 1.25 MPa for 0.2 wt% of husks. This value is higher than the flexural strength of air-dried lateritic stone blocks from Burkina Faso, which is 1.08 MPa [34]. However, it is lower than the strength of adobes reinforced with 3 cm-long kenaf fibres [13]. This difference is due to the longer fibre length and higher cellulose content in kenaf fibres compared to rice husks. The positive impact of rice husks on adobe flexural strength is linked to their appreciable cellulose content, a crystalline molecule with significant tensile resistance [16, 42]. This result is also attributed to the homogeneous microstructure, with minimal porosity (Figure 2i), observed in rice husk-stabilised adobes at low rice husk content.

The significant drop in flexural strength observed in rice husk-rich formulations (beyond 0.4 wt%) is due to the heterogeneous distribution of husks within the clay matrix. This leads to a more heterogeneous microstructure, with increased porosity and even cracks, compared to fibre-free adobes (Figure 2j and 2k). The behavior of cellulose is similarly reported in the literature [29] and can be explained by its resistance to deformation and the small size of rice husks. Consequently, rice husks occupy pores in the adobe matrix, reducing crack propagation. The effectiveness of this reinforcement mechanism depends heavily on microstructural parameters, such as rice husk size, shear stress levels at the husk/clay matrix interface, and the average fracture strength of rice husk-stabilised adobes [16].

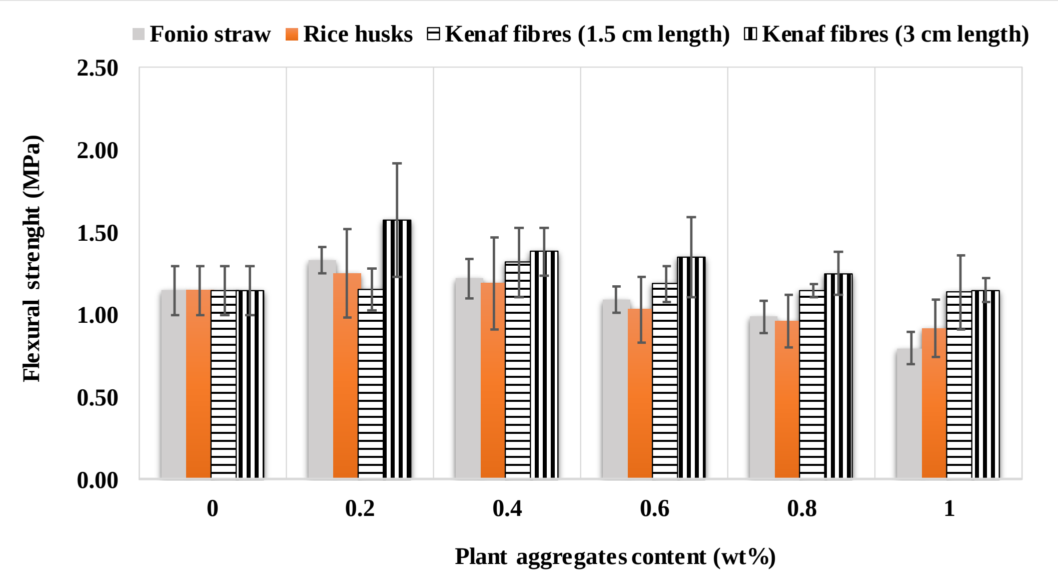


Figure 8. *3-point bending strength of adobes with the addition of plant aggregates.*

The results of the simple compressive strength tests for adobes reinforced with plant aggregates (kenaf fibres, fonio straws, and rice husks) are presented in Figure 9.

The simple compressive strength of the adobes increases with the addition of kenaf fibres, reaching optimal levels at 0.2 wt% for 3 cm-long fibres and 0.4 wt% for 1.5 cm-long fibres, before declining at higher fibre contents. The improvement in compressive strength is attributed to the fibres' presence in the clay matrix, which prevents crack propagation due to their rough surfaces and good adhesion to the matrix [13, 24]. At low fibre content, the adobes exhibit minimal porosity, as observed through video microscopy, further supporting the enhanced mechanical strength from fibre incorporation. Fibre length also influences mechanical strength; longer fibres enhance compressive strength by forming bridge-like connections within the clay matrix. The optimal compressive strength is achieved with 0.2 wt% of 3 cm kenaf fibres. However, at higher fibre contents, the adobe microstructure becomes highly heterogeneous, with fibre clustering creating closed porosity, reducing compressive strength compared to natural adobes.

The compressive strength of adobes reinforced with fonio straws increases up to an optimal level at 0.4 wt%. This improvement is due to the excellent adhesion between the fonio straws and the clay matrix, facilitated by their rough surface, and the inhibition of crack propagation by the incorporated straws [15]. Similar findings were reported by Danso *et al.* (2015) [36], who observed reinforcement effects in soil elements using bagasse, coconut, and oil palm fibres. Beyond 0.4 wt%, the compressive strength decreases, likely due to fibre aggregation at higher fonio straw content, as shown in video microscopy images. This study's results were compared to Pressed Adobe Blocks (PABs) reinforced with 30 mm-long *Hibiscus cannabinus* fibres [29], demonstrating that fonio straws offer better reinforcement than kenaf fibres for simple compressive strength. The superior performance of fonio-straw-reinforced adobes compared to PABs is attributed to the better distribution of fonio straws within the clay matrix.

Adding rice husks also improves the compressive strength of adobes, reaching an optimum at 0.4 wt%. This enhancement results from a more homogeneous microstructure in rice-husk-reinforced adobes (Figure 2i). The presence of rice husks prevents crack propagation observed in natural adobes and ensures good adhesion to the clay matrix due to their rough surfaces. Beyond 0.4 wt%, compressive strength declines due to the heterogeneous distribution of rice husks in the clay matrix (Figure 2j and 2k), leading to increased porosity and cracking. The compressive strength of rice-husk-reinforced adobes exceeds that of kenaf-fibre-reinforced adobes made with the same KORS material [13]. This is due to the superior microstructural organisation in rice-husk-reinforced adobes and the strengthening effect of rice husks, which contain high silica content.

In summary, incorporating fonio straws, rice husks, and kenaf fibres significantly improves the mechanical properties of adobes up to a certain content level. However, excessive fibre content results in property degradation due to heterogeneous microstructures. Kenaf fibres stand out for their superior efficacy in enhancing strength, thanks to their cellulose-rich composition. Given the compressive strengths exceeding 2 MPa, the developed adobes are suitable for construction purposes [43, 44].

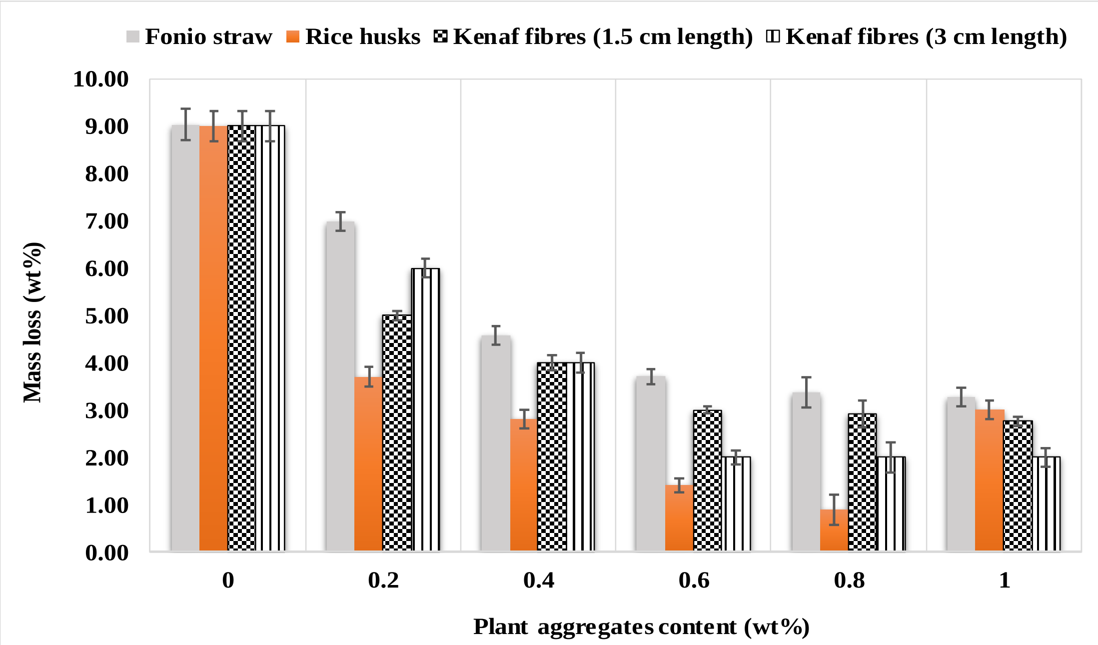


Figure 9*. Simple compressive strength of adobes admixed with plant aggregates.*

To understand the flexural failure behavior of the adobes, stress-strain curves (Figure 10) of the developed adobes were recorded. Unlike unreinforced adobes, which exhibit abrupt failure, adobes reinforced with kenaf fibres behave like elasto-plastic materials, displaying at least two failure points. This elasto-plastic behavior is more pronounced when longer fibres are used (e.g., 3 cm fibres) [13]. After the clay matrix fractures, the load is transferred to the fibres within the adobe. The first failure point corresponds to the fracture of the clay matrix, while the second point or post-peak corresponds to the rupture of the fibres.

Regarding adobes containing fonio straws and rice husks, they exhibit linear elastic behavior up to a failure threshold, where the clay matrix fractures due to microstructural defects. Although these reinforced adobes experience a similar fracture mechanism as unreinforced ones, total failure does not occur. The presence of fibres rich in crystalline cellulose, with high tensile strength, prevents crack propagation in the reinforced adobes [15]. The rough texture of the fibres ensures good adhesion between them and the clay particles, thereby enhancing the three-point flexural strength of the adobes.

This ductile property of the adobes makes them suitable for constructing habitats using such materials.

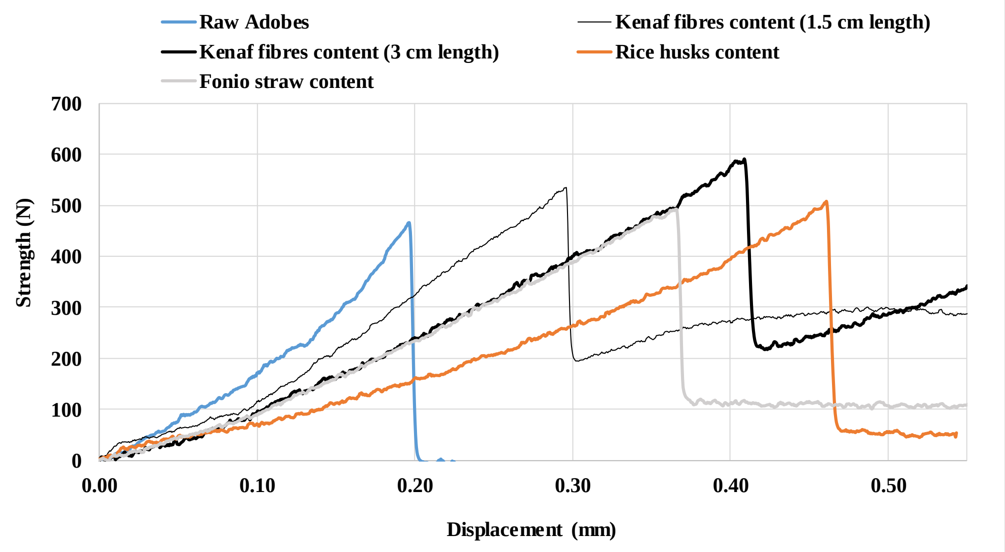


Figure 10. *Stress-strain curves for natural adobes and those reinforced with plant aggregates.*

4. Conclusion

A general review of the influence of the length and type of plant aggregates (kenaf fibres, fonio straws, and rice husks) on reinforcing the microstructural and physico-mechanical properties of the developed adobes was conducted. The study reveals that incorporating natural plant aggregates into adobes results in a homogeneous microstructure with few pores at low aggregate content (up to 0.4 wt%). This leads to improved physical and mechanical properties, notably reduced thermal conductivity and enhanced resistance to water erosion.

The improvement in compressive strength with the addition of plant aggregates is attributed to crack prevention in these composites through the bridging of the clay matrix by the fibres. This effect may also be linked to the formation of hydrogen bonds between the fibre molecules and the clay molecules. Regarding flexural strength, its increase is associated with the presence of plant aggregates with high tensile strength due to their significant cellulose content.

The inclusion of fibres in the clay matrix makes the composite material ductile, with at least two failure peaks: one due to the destruction of the clay matrix and the other(s) due to the presence of fibres, which take up the load after the matrix fractures. However, the use of plant aggregates also results in increased closed porosity and capillary water absorption, attributed respectively to the presence of fibres often forming clusters within the adobes and the hydrophilic nature of cellulose and hemicelluloses in the fibres.

Among the three studied fibres, kenaf fibres provide the best flexural strength to the adobes due to their high cellulose content, a crystalline molecule with excellent tensile strength. Rice husks offer the best compressive strength, thanks to their significant silica content, which reinforces the clay matrix. For thermal conductivity, kenaf fibres incorporated into adobes help reduce thermal conductivity due to the presence of cellulose, which is an excellent thermal insulator.

Adobes developed from KORS and enhanced with plant aggregates up to 0.4 wt%, with compressive strength exceeding 2 MPa, are most suitable for constructing durable habitats offering good thermal comfort and resistance to rainwater.

Based on these comparative results, rice husks and kenaf fibres are the most suitable for stabilising adobes at content levels not exceeding 0.4 wt% in the clay matrix. Considering the cost of these plant materials, rice husks are a more accessible choice, as they are agricultural residues widely available to the majority of Burkina Faso's population due to the increasing cultivation of rainfed rice in many regions of the country.

Abbreviations

CABs	Compressed Adobe Blocks
CEBs	Compressed Earth Blocks
INERA	Institute of Environment and Agricultural Research
KORS	Korsimoro clay
PABs	Pressed Adobe Blocks
PI	Plasticity Index
WL	Liquid limit
WP	Plasticity limit
XRD	X-ray Diffraction

Author Contributions

Moussa Ouedraogo: Conceptualization, Investigation, Methodology, Validation

Halidou Bamogo: Investigation, Methodology, Validation

Richard Ouedraogo: Investigation, Methodology, Validation

Issiaka Sanou: Validation
Jean-Emmanuel Aubert: Validation
Younoussa Millogo: Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

Moussa Ouedraogo: Building materials, Road construction, Water treatment, Tile formulation, Adobe stabilisation, Reinforcement of compressed earth bricks, Study of cut laterite bricks, Improvement of coatings

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