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Study of the Physico-Mechanical Performances and Durability of Adobe Bricks Reinforced with Kenaf Fibres

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Abstract

Plant fibres have been added to stabilize the adobes bricks in order to maximize the use of local resources and save construction costs as well as the energy needed for heating and air conditioning. The primary objective of this work is to produce earthen bricks with high mechanical resistance, great water durability and lower thermal conductivity, in order to improve the increase the housing quality and comfort. In order to do this, raw earth bricks were made from moderately plastic clay soil from Kofila (Burkina Faso) which is made up of quartz (61 wt.%), kaolinite (22 wt.%), illite (7 wt.%), and goethite (6 wt.%). 1.5 cm long kenaf fibres were used to reinforce the raw earth bricks at percentages of 0, 0.2, 0.4, 0.8, and 1.2 wt.%. Kenaf fibres physiochemical and mineralogical properties were assessed, along with the earthen bricks mechanical (flexural and compressive resistance), durability (capillary water absorption and spray test), and physical (apparent density, closed porosity, and thermal conductivity) qualities. The results indicated that the primary constituents of kenaf fibres are cellulose (71 wt.%), hemicelluloses (20 wt.%), lignin (4 wt.%), and ash (2 wt.%). The incorporation of kenaf fibres into adobe bricks effectively reduced crack propagation and enhanced fiber adhesion within the clay matrix. This improvement led to better physical, mechanical, and durability properties in the reinforced adobe bricks. In view of their good water resistance, low thermal conductivity and good mechanical strength, the raw earth bricks produced are suitable for housing construction, particularly in arid regions.

Keywords

Clay Soil, Kenaf Fibres, Adobe Bricks, Physico-Mechanical Performances and Durability, Thermal Conductivity

1. Introduction

The study of sustainable construction materials is rapidly gaining popularity in light of environmental, financial, and energy-related issues. Raw earth is one of these materials that is widely available, inexpensive, and has no effect on the environment. Used for centuries in many parts of the world, particularly in subtropical Africa and in Burkina Faso in general, rammed earth construction offers a solution tailored to people's housing needs, whilst helping to protect the environment. Although they have many advantages, the quality of the finished raw earth bricks leaves much to be desired due to their low mechanical strength and, above all, their poor water resistance; this reduces their durability. These problems may be due to a lack of rigorous scientific research into the clay soils used and the processes involved in making raw earth bricks.

To address these issues, research has been carried out into the stabilisation of raw earth bricks using mineral binders (cement and lime) [1] [2] and organic binders (decoctions of néré and cow dung) [3] [4]. However, the impact of the chemical and mineral composition of organic and mineral binders on the earthen material has hardly been taken into account in these studies, even though the chemical and mineral characteristics of these binders influence interactions within the matrix and are likely to improve the performance characteristics of raw earth bricks.

To the best of our knowledge, a number of studies on the application of natural plant fibres (kenaf fibres) as a reinforcing material to enhance the mechanical and physical characteristics of raw earth bricks have previously been conducted and published in the scientific literature [5]-[8]. The usage of kenaf fibres is crucial since they are cheap, plentiful, and, most importantly, have strong tensile strength, which could increase the flexural resistance of raw earth bricks in Burkina Faso. Kenaf fibres are natural plant fibres traditionally used by people in developing countries, particularly in Burkina Faaso, to reinforce mud bricks and improve their resistance to water erosion. This age-old practice has shown that kenaf fibres present great potential for improving the and physico-mechanical characteristics of adobes bricks whilst contributing to the thermal comfort of homes.

The adherence of kenaf fibres and their mineral and chemical compositions may be crucial in lowering thermal conductivity and shielding clay bricks from water erosion. To clarify the mechanisms of interaction between these fibres and the clay matrix, extensive scientific investigation is thus required.

The primary objective of this study is to produce earthen bricks with high mechanical resistance, great water durability and lower thermal conductivity, in order to improve the increase the housing quality and comfort. The investigation of the earth bricks mechanical, hydric and thermal performance as well as their stabilization mechanism using the composite of clay-kenaf fibres, will receive special attention. The expected results will provide a better understanding of the potential of kenaf fibres as a reinforcing material and contribute to the development of sustainable construction solutions adapted to local climatic conditions. The expected results will further knowledge of kenaf fibres potential as a reinforcing material and aid in the creation of environmentally friendly building solutions adapted to local climatic conditions.

2. Materials and Experimental Methods

2.1. Raw Materials

2.1.1. Clay Soil Sample

The clay sample referenced KOF was collected in the village of Kofila, located about fifty kilometres from Bobo Dioulasso, in the Guiriko region in the west of Burkina Faso (11˚20'N and 03˚55'W). The brown-coloured clay collected from the village of Kofila comes from a termite mound. Figure 1 shows the KOF sample clay.

Figure 1. Image of KOF sample clay.

2.1.2. Kenaf Fibres

The kenaf plants (**Figure 2(a)**) and the fibres extracted (**Figure 2(b)**) from them (**Figure 2(b)**) were collected from the village of Farakoba near Bobo Dioulasso, in the Guiriko region (Burkina Faso). Although biodegradable, these fibres can offer a durability equivalent to the service life of a building if they are added to a soil mixture [9]. Kenaf fibres used in the manufacture of adobe bricks has already been the object of previous research carried out from Ouédraogo *et al.* [10] and by Sanou *et al.* [11]. The kenaf fibres were used without any chemical treatment. In order to minimize the impact of their high absorbency on the workability of the mixture, the mechanical properties and the porosity of the adobe bricks, they were drying in a kiln at 105˚C for a full day prior to being mixed into the clay matrix. The physical characteristics of Kenaf fibres, including their diameter, bulk density, moisture content and water absorption capacity are shown in **Table 1**.

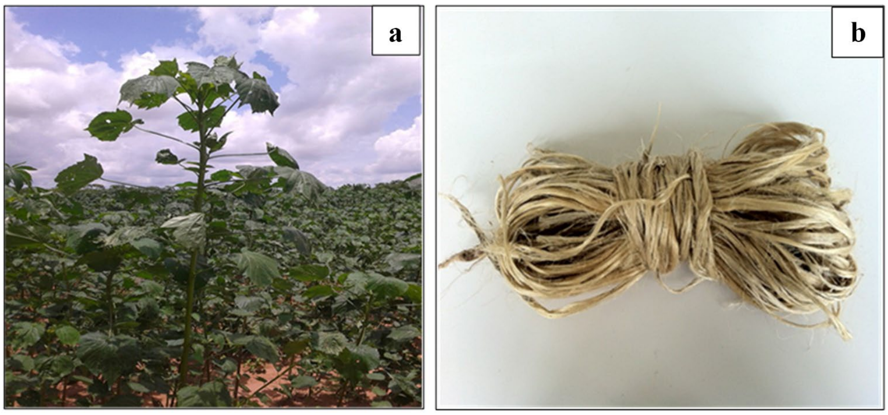

Figure 2. Photos of kenaf plants (a) and the extracted fibres (b).

Table 1. The physical characteristics of the examined kenaf fibres.

Characteristics	Results
Diameter (mm)	0.14
Bulk density	1.05
Natural moisture content (wt.%)	4.56
Water absorption: W (%)	230

These fibres diameter (0.14 mm) and bulk density (1.05) are comparable to those of *Hibiscus cannabinus* variety kenaf fibres cultivated in Burkina Faso (diameter (0.13 mm), bulk density (1.04)). This indicates that the diameter and absolute density of these fibres are not significantly affected by the type of plant. Furthermore, their values compare well with those of lechuguilla [12]. However, they are still below the levels found in palm straw and palm fibres [13] [14]. Flax fibres, on the other hand, are denser but less thick than those of *Hibiscus altissima* (kenaf fibres) [15]. The differences in density observed between the fibres are likely to be linked to their biochemical composition.

Kenaf fibres lower natural moisture content (4.56 wt.%) indicates little absorption of hygroscopic water. This characteristic could enhance tensile strength and enhance durability inside the clay matrix. Natural moisture content obtained in this study is lower than that observed for other natural plant fibres, notably sisal, coconut and Lechuguilla fibres [5] [12].

The results for water absorption by kenaf fibres show that it increases over time up to 24 hours, then stabilises, indicating that the fibres have reached water saturation. After 24 hours, the water absorption rate reaches approximately 230%. The hydrophilic nature of fibres, which is associated with the existence of cellulose, hemicelluloses, and lignin, is the cause of this high water absorption [11]. Compared with fibres from the *Hibiscus cannabinus* variety, fibres from *Hibiscus altissima* (kenaf fibres) absorb less water, which confirms their low moisture content. However, this high absorption capacity may accelerate the ageing of composite materials based on clay.

The mineralogical, biochemical, and microstructural characteristics reveal that the rough-surfaced kenaf fibres are mostly made of 71 wt.% cellulose, 20 wt.% hemicelluloses, 4 wt.% lignin and 2 wt.% ash [5]. The biochemical component of the kenaf fibres studied is similar to the composition of the *Hibiscus cannabinus* variety [8], which shows little influence of the different varieties on this biochemical composition. As shown in the research carried out by Sanou *et al.* [11], the fibres used in this study have a different biochemical composition to that of other varieties of kenaf fibre [16]-[18]. These observed differences in biochemical composition could be explained by soil type, climatic conditions and the area where the plants were grown.

2.2. Experimental Methods

2.2.1. Geotechnical, Chemical and Mineralogical Characterization of the Clay Raw Material

Granulometric distribution, methylene blue value, and Atterberg limits are the geotechnical characteristics assessed on the clay raw material. According to standards NF P94-056 [19] and NF P 94-057 [20], KOF clay size of the particle distribution was ascertained by sedimentation for particles with a diameter < 80 µm and dry sieving for particles having a diameter ≥ 80 µm. The NF P94-051 [21] and NF P94-068 [22] standards were used to determine the Atterberg limits and methylene blue value of KOF clay, respectively.

Inductively coupled plasma atomic emission spectrometry (ICP-AES) was used to analyze the chemical composition of the clay raw material on a sample that had been processed to a particle size of less than 80 µm. The sample was calcined to 1000˚C in order to calculate the loss on ignition.

A Siemens D5000 diffractometer equipped with a monochromator employing a cobalt anti-cathode ($K\alpha$ = 1.789 Å) was used to acquire the powder diffractograms of the KOF clay. Powders that had been pulverized to 80 µm and put in a revolving sample holder were used for all assays. Relation 1 was used to assess the semi-quantitative composition of the mineral phases in KOF clay by comparing the results of the X-ray diffraction and the chemical analysis [23]:

$$T(a) = \sum M_i P_i(a) \tag{1}$$

where: $T(a)$ is the proportion of oxide composing element a, M_i is the proportion of mineral i and $P_i(a)$ is the proportion of oxide a in i.

A Nicolet 510FT-IR spectrometer operating in the 4000-500 cm^{-1} range was used to acquire the infrared spectra of KOF clay. A Netzsch SATA 449 F3 Jupiter instrument was used to record the clay's ATG-DTG thermograms. For the analyzes, a constant heating rate of 10˚C/min was employed.

2.2.2. Manufacture of Adobe Bricks

The methods described by Ouédraogo *et al.* [10] and Sanou *et al.* [11] were used to create the adobe bricks. After being cured at 105˚C for a full day, the raw clay used to make the adobe blocks was ground into particles smaller than 5 mm using an agate mortar. The obtained clay powder was combined with various weight percentages of 15 mm-long kenaf fibres (0; 0.2; 0.4; 0.8 and 1.2 wt.%). The relation 2 was used to determine how much water was needed for this investigation [24]:

$$W(\%) = (W_L + W_P)/2 \quad (2)$$

where: W_L and W_P represents the values for the clayey soil liquidity limit and plasticity limit, respectively.

This calculated amount of water produced a paste suitable for making raw earth bricks, consisting of clay and kenaf fibres. The contents were homogenized for 15 minutes before being put ($4 \times 4 \times 16$ cm^3) prismatic molds. Moulding is carried out in two stages. The mould is first filled halfway, then compacted manually 15 times. The remainder of the mixture is then added and the same process is repeated. In order to minimize cracking, the adobe bricks were demolded after 24 hours (**Figure 3**) and then dried in the lab for around 21 days at an ambient temperature of 30˚C ± 7˚C and an average humidity of 32% ± 10% [8]. The ratios for each of the mixtures used to create the adobe bricks are shown in **Table 2**.

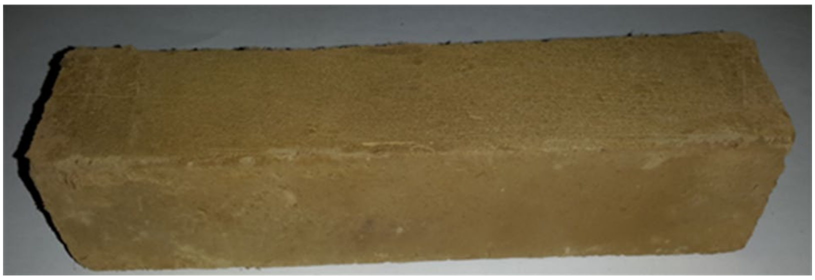

Figure 3. Image of one of the formulated test specimens.

Table 2. Ratios for each of the mixtures used to create the adobe bricks.

Raw Earth Bricks	Clay mass (g)	Kenaf fibres mass (g)	Water volume (mL)
Raw earth bricks	1400	0	301
Raw earth bricks + 0.2 wt.% kenaf fibres	1397.2	2.8	300.4
Raw earth bricks + 0.4 wt.% kenaf fibres	1394.4	5.6	299.8
Raw earth bricks + 0.8 wt.% kenaf fibres	1388.8	11.2	298.6
Raw earth bricks + 1.2 wt.% kenaf fibres	1383.2	16.8	297.4

2.2.3. Physico-Mechanical Characterization and Durability of Adobe Bricks Reinforced with Kenaf Fibres

Apparent density and closed porosity are key parameters for assessing the quality of manufactured adobe bricks. In accordance with standard NF EN 1015-10 [25], the hydrostatic weighing method was used to measure the test specimens' apparent density using a digital balance having a precision of 0.001 g. Closed porosity of test specimens was calculated from the apparent density, assuming an absolute grain density

d_g of 2.65. A value of 2.65 g/cm^3 was adopted as the absolute density of the particles, in line with standard values for silicate and clay soils, as the addition of a low content of plant fibres (≤1.2 wt.%) does not significantly affect the density of the mixture. This technique is commonly used in the study of plant-fibre-stabilised earth bricks and ensures a consistent comparison of porosity values between different formulations. Relation 3 was then used to determine the closed porosity [26]:

$$P(\%) = \left(1 - \frac{d_a}{d_g}\right) \times 100 \quad (3)$$

where: P: closed porosity; d_a: apparent density of the fired adobe bricks; and d_g: absolute grain density equal to 2.65.

A Neotim hot-wire probe that was attached to a power source and a Neotim FP2C data gathering device was used to assess the specimens thermal conductivity. The probe was positioned in close proximity to the surfaces of two adobe bricks.

To determine their mechanical strengths in the dry condition, four test specimens from each formulation were dried and then put through simple compression and three-point bending tests. An R.M.U-Testing Equipment Bergamo machine was used to perform the three-point bending tests on prismatic test objects that measured 4 × 4 × 16 cm^3. The test was conducted with a load cell of 50 N/s at a speed of 0.5 mm/min, applying a load on the specimen's center until it failed. Relation 4 is used to compute the flexural strength (MPa) [27]:

$$\sigma(\text{MPa}) = \frac{3FE}{2le^2} \quad (4)$$

where; F is the applied force's intensity; E the separation between the test specimens two supports; l stands for test specimen width, e for thickness and σ for stress at break.

A CONTROLS Multitester hydraulic press was used to assess the test specimens' compressive strength on the eight half-prisms that were acquired after the three-point flexural test. A load cell rated at 2400 N/s until failure was used for the test. Relation 5 is used to compute the compression strength [27]:

$$R_c(\text{MPa}) = \frac{P}{S} \quad (5)$$

where: R_c: compressive strength of the test specimen; P: crushed load in kN; S: average cross-sectional area in cm^2.

The NF EN 1015-11 [28] standard was followed in conducting the three-point flexural and compression tests.

The manufactured adobe bricks were tested for durability using capillary water absorption and rain erosion (spray test). The water absorption test measures how much water the adobe bricks absorb. In compliance with standard EN 15801 CEN 2009 [29], it was performed on prismatic test specimens of 4 × 4 × 16 cm^3 that had been dried at 105˚C for 24 hours. The mass of water absorbed by the adobe bricks over time and their base area were used to calculate the water absorption coefficient (A). Relation 6 is used to calculate its value [30]:

$$A\left(\mathrm{kg}\cdot\mathrm{m}^{-2}\cdot\mathrm{s}^{-1/2}\right)=\frac{m_h-m_s}{S_h\sqrt{t}} \tag{6}$$

where: m_h is the mass of the moist testing sample after water absorption (g), m_s is the mass of the test sample drying of 105˚C (g) and S_h is the test specimens area of surface when in touch to the water (m^2).

Inspired by the procedure outlined from Dao *et al.* [26], the rain erosion test (spray test) was conducted on adobe bricks. For a period of 10 minutes at a pressure of 2 bars, the samples were sprayed with water in the form of tiny droplets while inclined at a 30˚ angle to the vertical. The proportion of the material's mass that was lost after the test was used to determine the extent of erosion. The erosion coefficient (C_E), which is provided by relation 7 is used to illustrate it [31]:

$$C_E\left(\%\right)=\frac{M_0-M_s}{M_0}\times 100 \tag{7}$$

where: M_0 is the first mass of adobe bricks and M_s is the mass of adobe bricks post erosion.

3. Results and Discussion

3.1. Geotechnical, Chemical and Mineralogical Characteristics of the Clay Soil

The granulometric analysis curve for the total specimen (**Figure 4**) reveals that sand constitutes 47 wt.%, forming the granular skeleton of the material, compared with 53 wt.% of fine particles (d < 80 µm). The clay fraction (d < 2 µm) represents 23 wt.% of the total mass on its own. This fine phase plays an essential role as a natural binder by ensuring cohesion between the larger particles [27]. The clay content obtained complies with the requirements of standard XP P13-901 [32] for the manufacture of unfired adobe bricks, as it falls within the range of 5 to 30 wt.% considered suitable for this purpose.

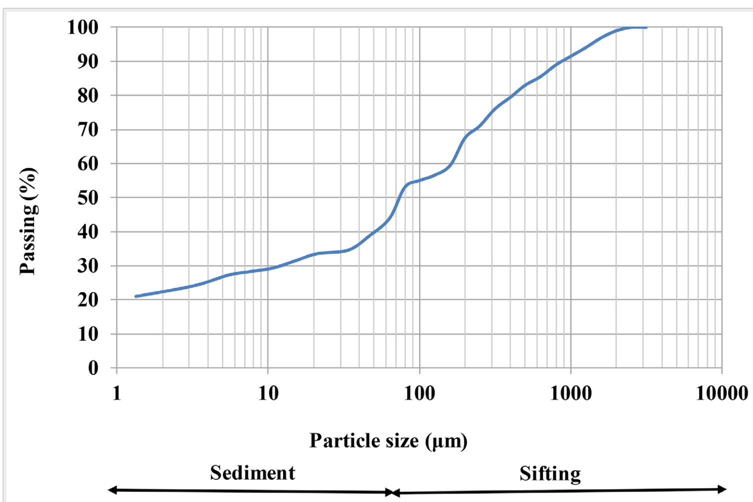

Figure 4. The granulometric analysis curve for the total specimen.

Table 3 s shows results from the Atterberg limits and the methylene blue test of KOF clay. Plasticity index obtained is 15%, which classifies this sample as a moderately plastic material according to standard NF P94-051 [21]. This relatively low value indicates a low content of clay minerals, which is consistent with the results of the granulometric analysis. Furthermore, the methylene blue value (VBS) is 2.14 g/100 g. According to standard NF P94-068 [22], the KOF sample can be categorized as a sandy-clay soil because this falls between 1.5 and 2.5 g/100 g. Results of the two tests are therefore consistent and lead to the same classification of the material.

Table 3. KOF sample Atterberg limits and the methylene blue value.

Liquid limit W_L (%)	Plasticity limit W_P (%)	Plasticity index I_P (%)	Methylene blue value V_{BS} (g/100g)
29	14	15	2.14

The KOF sample chemical analysis results (**Table 4**) show that silica (73.98 wt.%) and alumina (11.51 wt.%) are the predominant oxides. This composition indicates that the KOF sample consists mainly of clay minerals and quartz. Furthermore, Kofila clay distinctive brown color is explained by its comparatively high iron oxide content (5.19 wt.%).

Table 4. Chemical analysis of the KOF clay.

Oxydes	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	PF	Total
% en masse	73.98	11.51	5.19	0.30	0.20	0.06	0.84	0.81	6.35	99.32

The X-ray diffraction pattern of KOF sample is shown in **Figure 5**. Analysis of the diffraction peaks, based on ASTM (American Society for Testing and Materials) data sheets, enabled us to identify the main mineralogical phases present in our sample. These are mainly quartz (SiO_2), kaolinite ($Al_2Si_2O_5(OH)_4$), illite [$KAl_2(AlSi_3)O_{10}(OH)_2$] and goethite ($FeO(OH)$). This result is consistent with the data obtained from the chemical analysis.

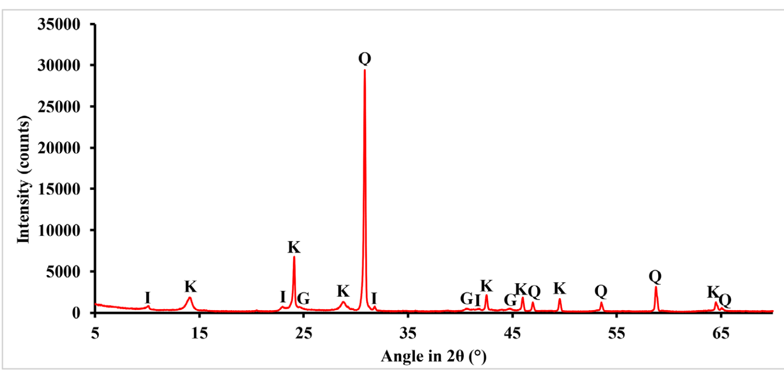

Figure 5. X-ray diffraction pattern of the KOF sample (**Q:** Quartz, **K:** Kaolinite, **I:** Illite et **G:** Goéthite).

The IR spectrum of clay soil (**Figure 6**) was analysed by attributing each band frequency to the chemical bond responsible for the vibration, stretching and deformation, with reference to the literature [3] [24] [26] [27] [33] [34]. The analysis highlights the characteristic bands of kaolinite at 3618 and 3689 cm^{-1} (O-H bond vibrations), at 1028 cm^{-1} (symmetric Si-O-Si stretching vibrations) and at 913 cm^{-1} (Al-OH bond vibrations). Bands attributed to quartz also appear at 800 cm^{-1} (Si-O-Si bond vibrations), whilst the band observed at 1008 cm^{-1} is characteristic of illite (Al-OH deformation vibrations). The presence of hygroscopic water in the sample is linked to the band at 1634 cm^{-1}. Furthermore, a low crystallinity of this mineral within the KOF clay is indicated by the lack of the characteristic kaolinite band at 3672 cm^{-1} [24] [26]. These results confirm those obtained by X-ray diffraction.

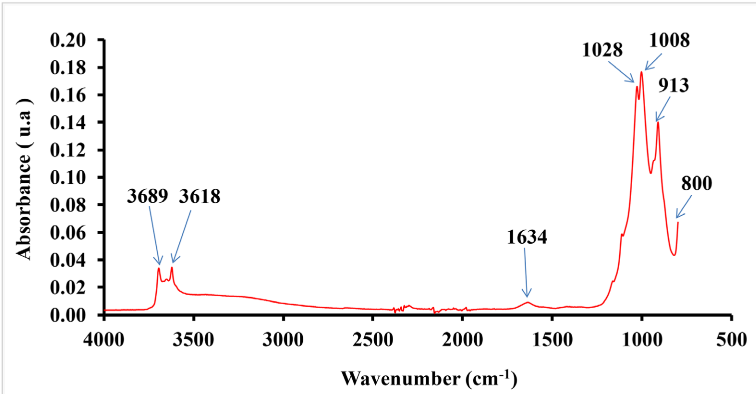

Figure 6. IR spectrum of KOF clay.

Figure 7 shows the KOF clay DTG-TGA curves. Analysis of these curves reveals three main thermal phenomena. The removal of hygroscopic water is represented by a first endothermic peak, which is seen at about 120˚C and is linked to a mass loss of 0.6 wt.%. The presence of several soil minerals, particularly illite, may also be connected to this loss. At about 304˚C, a second endothermic peak with a 1.7 wt.% mass loss emerges. It is explained by goethite's dehydroxylation and ensuing transformation to hematite. At about 525˚C, the third, more powerful peak is seen. It is equivalent to the removal of structural water from kaolinite and illite through dehydroxylation.

There is a 4.2 wt.% mass loss associated with this transformation. Equation 1 illustrates that in the case of kaolinite, this reaction results in the creation of an amorphous phase named metakaolinite [35] [36].

$$Si_2Al_2O_5(OH)_4(\text{kaolinite}) \rightarrow Si_2Al_2O_7(\text{metakaolinite}) + 2H_2O \quad \text{(Equation 1)}$$

The dehydroxylation of well-crystallised kaolinite generally occurs at around 600˚C, whereas it takes place at lower temperatures for disordered kaolinite [26]. The temperature observed in the KOF sample (525˚C) thus suggests that the kaolinite has low crystallinity. The sample total mass loss between room temperature and 1000˚C is 6.5 wt.%. This value is significantly lower than that of pure kaolinite, estimated at around 14 wt.%. It confirms that KOF clay consists of a mixture of several natural clay minerals, in line with the results of the mineralogical characterisation.

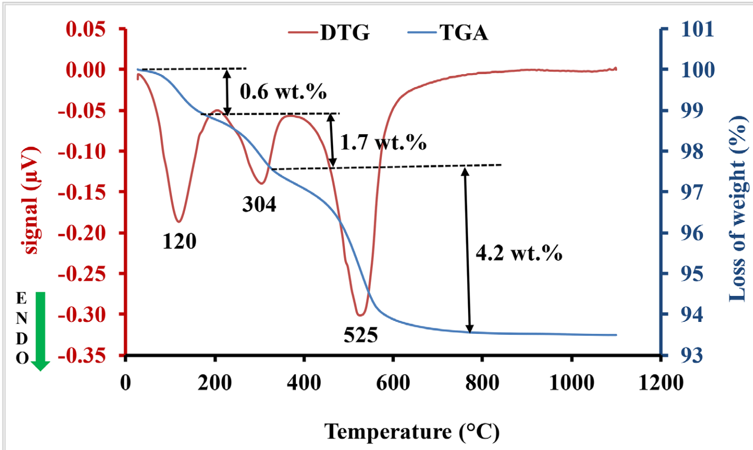

Figure 7. KOF clay DTG-TGA curves.

The semi-quantitative mineralogical composition determined using relation 1 indicates that KOF clay consists mainly of quartz (61 wt.%) and kaolinite (22 wt.%). It also contains significant proportions of illite (7 wt.%) and goethite (6 wt.%). Amorphous minerals and/or organic compounds (probably carbonates) constitute the remaining 4 wt.% [2]. These results corroborate the geotechnical data and confirm the predominance of a clay fraction associated with a sandy fraction (primarily quartz).

3.2. Physico-Mechanical Performances and Durability of Adobe Bricks Mixed with Kenaf Fibres

Tests were carried out to measure apparent density, closed-porosity, thermal conductivity, compressive strength, three-point flexural strength, capillary water absorption, and spray tests in order to evaluate the physical and mechanical performances and durability of the formulated adobe bricks. For each parameter studied, four test specimens per formulation were used under the same conditions to carry out the various tests. To assure their reliability and take into account measurement variance, the values obtained for these various attributes are the arithmetic means of the different tests performed for each formulation.

The outcomes of closed porosity and the apparent density of adobe bricks enhanced with kenaf fibres are illustrated in Figure 8. The differences between these two parameters are inverse. Soré *et al.* [37] indicate that an earth block is more pores the denser it is and vise versa. Apparent density of the raw earth bricks ranges from 1.76 to 1.62 g.cm^{-3} and decreases gradually with the addition of kenaf fibres. The reason for this decrease is that lighter kenaf fibres, with a density of 1.05 g.cm^{-3}, have partially replaced the clay matrix, that possesses a density of 2.65 g.cm^{-3}. The values obtained are similar to those described in the literature for plant-fibre-reinforced adobe bricks [6] [24] [38] [39]. In fact, Laborel-Préneron *et al.* [6] observed apparent density values ranging from 1.81 in 1.01 g.cm^{-3} in the case of adobe bricks stabilised with fibres or plant aggregates. The apparent density results for the raw earth bricks incorporating kenaf fibres are consistent with those observed in previous studies. The closed porosity of the raw earth bricks increases with rising kenaf fibre content, rising from 33.4 to 38.7%. This increase is explained by the addition of fibres to the clay soil, that promotes internal voids to form during compaction. In fact, the accumulation and arrangement of the fibres generate pores distributed throughout the material. These pores, which are mainly filled with air, can also be penetrated by water. The results obtained are comparable to those reported in several previous studies. For example, Lawane *et al.* [40], in their work on compressed blocks of coal bottom ash stabilised with lateritic soils from Niger, measured porosities ranging from 33 to 40%. Similarly, Ouédraogo *et al.* [10], studying adobe bricks reinforced with kenaf fibres, observed closed porosity values ranging from 28 to 32%. The findings recorded to the current research therefore fall into the typical range in results generally reported in the literature.

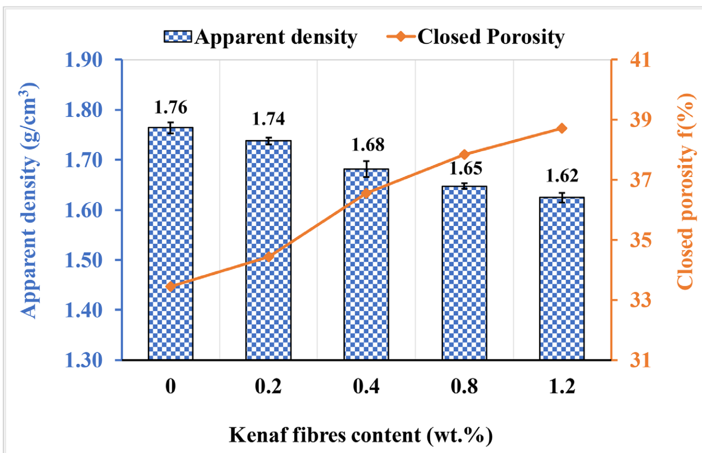

Figure 8. Closed porosity and Apparent density of adobe bricks amended by kenaf fibres.

The change in the adobe bricks thermal conductivity values with the addition in kenaf fibres is presented in **Figure 9**. The results show that thermal conductivity decreases gradually with the kenaf fibres amount gets higher. The composite materials increased closed porosity is the primary cause of this decrease. Indeed, addition of kenaf fibres creates more air-filled voids in the clay matrix. However, as air is a poor heat conductor, it slows down heat transfer through the earthen bricks, thereby reducing their thermal conductivity [5]. Furthermore, kenaf fibres contain cellulose, a molecule with good thermal insulation properties, which also contributes to this improvement in thermal performance [11]. These findings are in line with a study by Millogo *et al.* [41], which found that compressed adobe blocks reinforced with 6 cm kenaf fibres had a higher decrease in thermal conductivity than those with 3 cm fibres. Similarly, Khedari *et al.* [42] observed that a decrease in thermal conductivity occurs when the amount of coconut fibre in compressed adobe bricks is increased. The thermal conductivity values for compressed bricks of earth reinforced by kenaf fibres in Benin described by Laibi *et al.* [43] are higher than those observed in this work. This disparity could be caused by both the kind, size, and content of the fibres utilized as well as the degree of block compaction. Indeed, compressed earth blocks are generally less porous than raw earth bricks, which facilitates heat transfer and results in higher thermal conductivity. The low thermal conductivity observed is a significant advantage for dwellings located in hot, dry climates, particularly in the Sahel. It reduces the necessity for ventilation as well as air conditioning while also improving interior thermal comfort. This reduction in energy consumption is a major benefit for developing countries, where energy costs remain high.

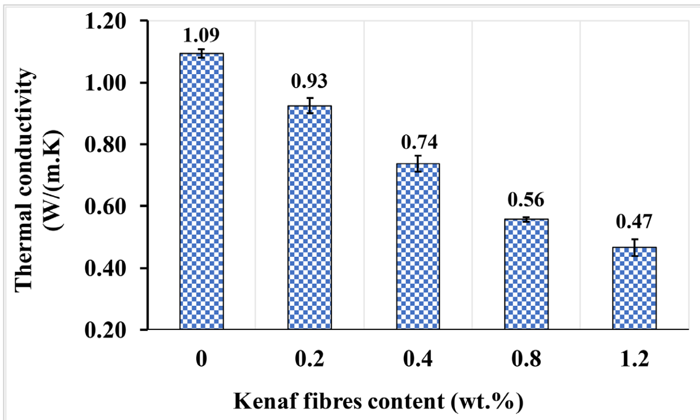

Figure 9. Thermal conductivity values of adobe bricks with the incorporation of kenaf fibres.

Figure 10 represents the curves for adobe bricks compressive and three-point bending resistance in a function of the proportion of kenaf fibres. An analysis of this graph reveals that the compressive resistance increases up until an optimal value of 0.4 wt.% of kenaf fibres. The compressive resistance reduces as the percentage of kenaf fibres exceeds 0.4 wt.%. This improvement in strength is caused by the kenaf fibres high adherence to the clay matrix due to their rough surface, as well as the fibres' ability to stop cracks from propagating [5] [41]. A decrease in compressive resistance when a mass fraction of kenaf fibres exceeds 0.4 wt.% is due to the fibres becoming distributed in clumps within the clay matrix because of their high number. In this case, the composite becomes more porous, which significantly affects the compressive resistance. A compressive resistance trend is identical to that of adobe bricks reinforced with the same kenaf fibres and made from clay from the Isère Valley [41]. The compressive resistance values of the adobe bricks studied are higher than those of the raw earth bricks made from clay from the Isère Valley [41]. This result is caused by the two samples different mineral compositions, particularly the amounts of quartz and clay-based minerals.

Although both clays contain almost the same mineral phases (kaolinite, quartz, illite and goethite) [8], Kofila sample is lower in clay minerals but richer in quartz, which is an effective degreaser. This result is well justified, as the compressive resistance for the raw material from Kofila has risen relative to that of the raw material from the Isère Valley, which contains 0.2 wt.% of kenaf fibres [41]. The study compressive resistance results are good because they are inside the same range as those found in the literature for adobe bricks reinforced with plant-based aggregates or fibres [5] [6] [14] [44]. Taking into account the current standards for building materials (which are primarily based on compressive resistance, which must exceed 2 MPa) [45], raw earth blocks made from Kofila clay are suitable for use in housing construction.

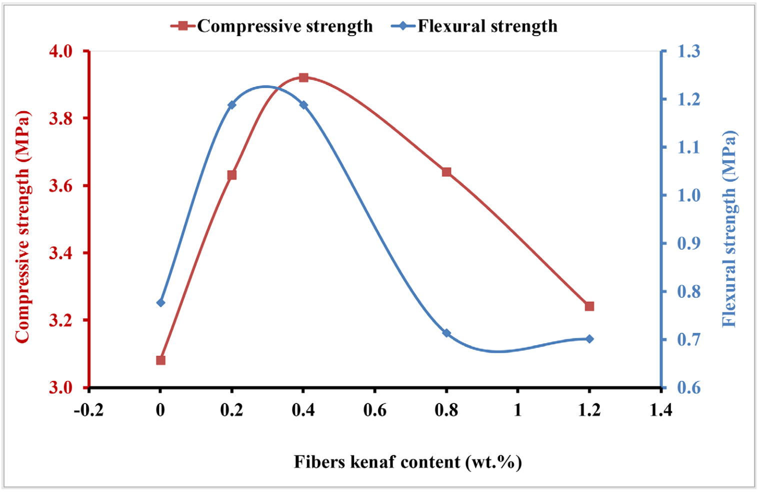

Figure 10. Compressive and three-point bending strengths of adobe bricks in a function of the proportion of kenaf fibres.

The three-point bending resistance of the green-earth blocks is increased by the addition of kenaf fibres up to an optimum value of 0.4 wt.% of kenaf fibres, as illustrated in **Figure 10**. Above 0.4 wt.% of kenaf fibres, the bending resistance decreases. The primary cause of this increase is the high cellulose content (70 wt.%) of kenaf fibres, which contributes to their good tensile strength [5]. The adobe bricks are made more ductile by the kenaf fibres present in the clay soil. To this end, when a raw earth bricks is subjected to bending stress, the clay matrix first breaks, followed by an increase in strength now provided by the kenaf fibres. The adobe bricks will therefore exhibit elastoplastic behaviour; this is very important for structural elements, particularly in masonry. The decrease in flexural strength in excess of 0.4 wt.% of kenaf fibres is caused by the same phenomenon for fibre bundling inside the clay soil as occurs under compression. The flexural curves for the raw earth bricks made with clay from Kofila and clay from the Isère Valley show the same trends. As with compressive strength, the results obtained with clay from Kofila are better than those with clay from the Isère Valley for the same reasons highlighted in the case of simple compression [41]. The flexural strength obtained in this study is relatively high compared with that reported by Mesbah *et al.* [46] for adobe blocks enhanced in 2 cm and 5 cm sisal fibres, when the flexural strength values were 0.23 MPa and 0.25 MPa correspondingly. The biochemical makeup of the fibres utilised is responsible for this disparity. Moreover, the kenaf fibres are generally richer in cellulose than sisal fibres, which gives them greater tensile strength. They therefore contribute more significantly to improving the flexural resistance for adobe blocks.

Generally speaking, adding kenaf fibres on adobe blocks improves their mechanical behaviour and prevents cracks from spreading under mechanical stress. Several studies in the literature [10] [46] show that this improvement may be related to the creation of hydrogen bonds among organic molecules in the kenaf fibres (polysaccharides) and the clay particles (kaolinite). However, this mechanism was not directly verified in the present study in the absence of specific interfacial characterisations. The mechanism by which these hydrogen bonds form is illustrated in **Figure 11**.

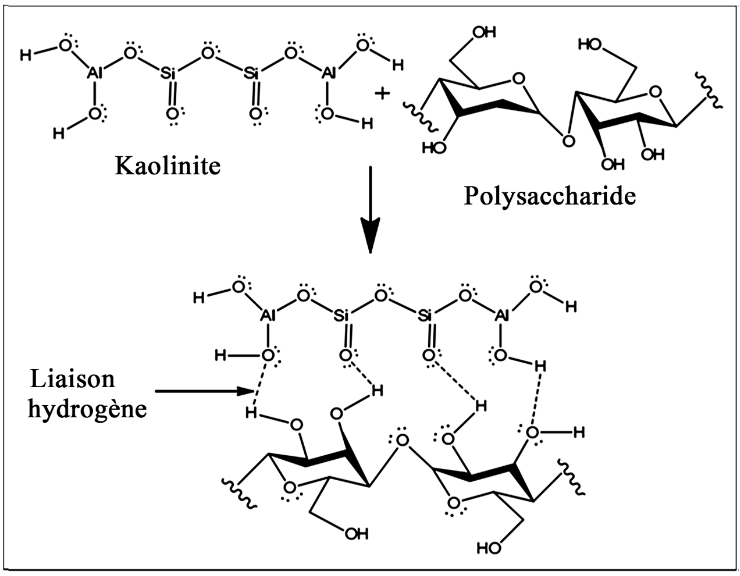

Figure 11. Mechanism of hydrogen bond formation [47].

Figure 12 shows the variance in adobe bricks capillary water absorption coefficients with a proportion of kenaf fibres amount. This parameter serves a crucial part during material processing, as the fibres absorb a major amount of the water used for mixing. Volumetric changes may also result from long-term alterations in the moisture content of the material. As shown, the capillary water absorption coefficient of adobe bricks amended with kenaf fibres increases up to an optimum value of 0.8 wt.% of kenaf fibres. Above a kenaf fibres content of 0.8 wt.%, the capillary water absorption coefficient of the adobe bricks decreases. The hydrophilic nature of kenaf fibres, which is associated with their high cellulose and hemicellulose content and promotes water retention, is mainly the cause of the rise in the capillary water absorption coefficient [10]

[48]. Conversely, the reduction of the capillary absorption of water coefficient may be attributed to the more dense packaging of the fibres within the clay soil. This fibre accumulation affects continuity in the capillary pore networks, thereby reducing the rate of water uptake within the composite material [5] [7]. A similar trend in the coefficient of capillary water absorption has been observed by several authors [7] [31] [49] when natural plant fibres are incorporated into adobe. According to this research, the rise of water absorption rates can be attributed to the high water absorption capacity of the plant fibres incorporated into clay matrix. Conversely, the decrease in this absorption is attributed to the agglomeration of the fibres, which limits their direct contact with water and slows its progression by capillary action through the adobe.

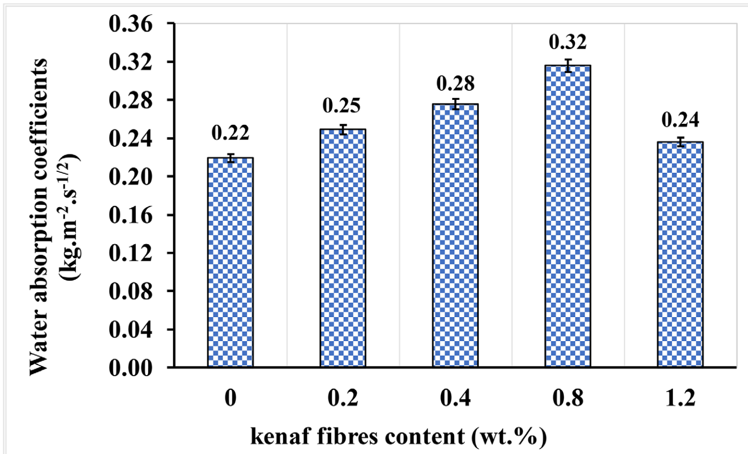

Figure 12. Capillary water absorption coefficients of adobe bricks with a proportion of kenaf fibres amount.

Figure 13 displays the mass losses on adobe bricks following the rain erosion test. The findings suggest unreinforced adobe exhibit greater mass loss than those containing kenaf fibres. The incorporation of fibres therefore significantly improves the bricks resistance to water erosion. This improvement has been attributed to the reinforcing effect of kenaf fibres, which improve adherence among the clay matrix particles and reduce porosity, particularly on the surface surface. The establishment of hydrogen bonds among the constituents of kenaf fibres (cellulose, hemicelluloses and lignin) and clay particles like illite and kaolinite may also be responsible [46] [50]. The low mass losses observed for kenaf-fibres-reinforced adobe bricks are in line with results published in previous studies [41] [51]. Fibres in the clay matrix behave similarly to planting roots, which reduce erosion and stabilise the soil [7]. Furthermore, fibres aid in making raw earth blocks more resistant against the impacts of rainwater. Such results support the performance of conventional methods using plant fibres, such straw, in earth-based building materials. They also open up prospects for the development of simple and inexpensive solutions designed to protect earthen structures against erosion.

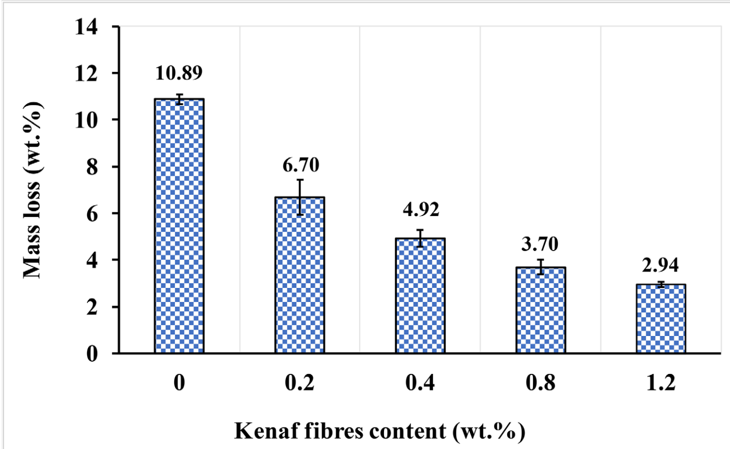

Figure 13. Mass losses of adobe bricks following the rainfall erosion test.

4. Conclusions

The primary objective of this work is to produce earthen bricks with high mechanical resistance, great water durability and lower thermal conductivity, in order to improve the increase the housing quality and comfort. In order achieve this objective, a variety of analytical methods were used to characterise the Kofila clay (KOF) and determine whether it was suitable for manufacturing earthen bricks. Kenaf fibres have also been characterised to verify their compatibility as a reinforcing additive. Furthermore, the effect of incorporating kenaf fibres on durability, mechanical, and physical characteristics of the adobe bricks was investigated. Several important conclusions about the characteristics of the raw materials and the performance of the produced adobe blocks were made from the results. Chemical and mineralogical analyses have revealed that KOF clay is mainly composed of quartz (61 wt.%), kaolinite (22 wt.%), illite (7 wt.%) and goethite (6 wt.%). According to geotechnical tests, it is a medium-plasticity sandy-clay soil with characteristics appropriate to manufacture of adobe blocks. Kenaf fibres biochemical, mineralogical with microstructural characteristics showed a high cellulose content (71 wt.%), along with hemicelluloses (20 wt.%), lignin (4 wt.%), and ash (2 wt.%). Furthermore, their rough surface promotes strong adherence among the clay array and the fibres, which helps to reinforce the bricks. The test specimens were subsequently produced using mixtures of KOF clay and 1.5 cm-long kenaf fibres. Following the preparation and characterisation of the test specimens, we obtained results which showed that:

The apparent density of raw earth bricks decreases when kenaf fibres are added. The lower density of kenaf fibres (1.05 g.cm^{-3}) in comparison with particles in the clay matrix (2.65 g.cm^{-3}) is the cause of this decrease.

The closed porosity of raw earth blocks increases as the kenaf fibre content rises. This increase is explained by the fibres introduction into the clay array, promoting the creation of internal voids during compaction.

The incorporation of kenaf fibres to raw earth bricks improves their ductility because of the fibres strong adherence to the clay array and high mechanical properties. The highest three-point flexural strength is achieved with a kenaf fibres content of 0.4 wt.%. Above this value, this strength decreases. As for compressive strength, also rises to an ideal value of 0.4 wt.% of kenaf fibres before declining after that. In incorporation of fibres is particularly beneficial for these materials in terms of flexural strength.

The capillary water absorption coefficient of adobe bricks increases with the incorporation of kenaf fibres, owing to a hydrophilic character and high cellulose and hemicellulose content.

Kenaf fibres reinforced adobe bricks are highly resistant to water erosion. This enhancement results from the kenaf fibres strong adherence to the clay array and limited spread of cracks.

Thermal conductivity of adobe bricks is decreased by incorporating kenaf fibres. This reduction can be attributed to both the increased closed porosity in the earth bricks and the good insulating properties of the cellulose in the fibres.

In summary, thanks to their good mechanical strength, low thermal conductivity and good water resistance, kenaf fibres reinforced raw earth bricks are well-suited to the construction of sustainable housing. They help to regulate the internal temperature of buildings, thus enhancing the comfort levels of the residents. The use of these earth bricks can provide low-income communities with more comfortable housing whilst reducing the need for ventilation and air conditioning. This reduction in energy consumption is particularly beneficial in dry tropical regions, such as Burkina Faso, where hot periods account for a large part of the year. However, the results obtained show that a kenaf fibre content of 0.4 wt.% is the optimal formulation, as it offers the best mechanical performance whilst maintaining satisfactory physical, hydraulic and thermal properties.

Author Contributions

H.B., F.K., O.B. and **L.V.L.G.** carried out the experimental work and drafted the manuscript. **M.O., I.S., J.E.A.** and **Y.M.** contributed to the drafting of the manuscript and the validation of the experimental results. All eight authors were involved in revising the manuscript, made the final corrections and approved the published version.

Accounting

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Conflicts of Interest

Authors affirm they do not have any personal relationships or known financial conflicts of interest that could have affected the findings or conclusions in this article.

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