Physical, thermal and mechanical properties of adobes stabilized with fonio (Digitaria exilis) straw

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Abstract

This study deals with the influence of fonio straw on the physical, thermal and mechanical properties of adobes. The raw materials (soil and fonio straw from Burkina Faso) were characterized from the chemical (ICP-AES), mineralogical (XRD, DSC-TGA, IR), geotechnical (particle size distribution, Atterberg limits, methylene blue value) and microstructural (SEM-EDS) points of view. The physical (thermal conductivity, capillarity water absorption, porosity, erodibility) and mechanical (compressive and flexural strength) properties of the adobes were studied with specific attention paid to their damage and fracture behavior. Because of the biochemical composition of fonio straw (presence of quasi-crystalline cellulose and hemicelluloses, which are hydrophilic compounds), its association with the clay matrix increased water absorption and was accompanied by a significant porosity due to the air trapped during mixing. The insulating character of the cellulose and the low density resulting from the high porosity contributed to an appreciable reduction of the thermal conductivity of these adobes. The use of small amounts of fonio straw improved the mechanical properties of the adobes and made them less brittle. This improvement was linked to the good adhesion between fonio straw and the clay matrix, greatly reduced propagation of fissures in the composites and the high tensile strength of fonio straw because of its cellulose content. Thus, fonio-straw-reinforced adobes have interesting properties for use as cheap construction materials in the Sahelian zones and could contribute significantly to the thermal comfort of the inhabitants in this hot climate.

Keywords: Fonio straw; Adobe; Microstructure characterization; Physical and mechanical properties; Thermal comfort.

1. Introduction

The subsoil is rich in mineral resources that have long been exploited for the construction of habitats. The recent enthusiasm for concrete is explained not only by objective considerations (good mechanical properties, durability, standardized methods of implementation) but also by the idea of modernity associated with it. However, building habitats with concrete is expensive in developing countries (whether the cement is imported or produced locally) and has a high environmental impact. This impact is due to the use of clinker, the production of which consumes a lot of energy (clinker is produced by the calcination of a mixture of clay and limestone at 1450°C) and to the pollution related to its manufacture (the production of cement is responsible for about 10% of greenhouse gas emissions) [1].

It appears that the use of adobes (unfired earth bricks molded by hand from soil plastic paste without pressure) is one solution for sustainable construction. However, natural adobes present drawbacks, such as relatively poor mechanical properties (especially low tensile strength and brittle behavior) and poor resistance to water. Recent studies of adobes reinforced with coir, oil palm fibers and sisal fibers have shown that the incorporation of these fibers reduces the formation of cracks during drying and improves durability [2]. Many researchers have investigated the effects of plant fibers on the properties of building materials [3-10]. Millogo et al.'s work focused on improving the mechanical properties and decreasing the thermal conductivity of adobes by reducing the porosity through the addition of kenaf fibers (*Hibiscus Cannabinus*) [7]. Ghavami et al. studied the influence of sisal fibers, and coir content and length on the characteristics of cement concrete blocks [10]. It appears that the beneficial effect of the presence of the fibers shows itself mainly in the post-cracking domain.

However, the fibers used for these various studies (coir, oil palm fibers, sisal fibers) are not abundantly available in sub-Saharan countries like Burkina Faso. For this reason and because of its specific strength, its abundance and annual availability at low cost (practically free), fonio straw was chosen for this study. It should be remembered that this agricultural by-product used to be mixed with water and earth for the manufacture of adobe in rural areas, where the problem of sustainable housing is persistent. The cultural use of adobe stabilized by fonio straw (FS-adobe) for building purposes still exists, but the practice must be seriously improved. This is one of the objectives of the present work.

Very few studies have been reported on the correlation between microstructure and physical properties (such as density, closed porosity, thermal conductivity, water absorption and wet durability) of adobes stabilized with plant fibers, and still fewer for those using fonio straw [5]. To the best of our knowledge, the mechanisms implied in adobe stabilization with natural fibers have not been investigated yet. The present work studies the influence of fonio straw on some building materials widely used in developing countries. Special attention is paid to the microstructure of FS-adobe and the data are correlated with the mechanical and physical properties.

2. Materials and procedures

2.1. Raw materials

The soil used in this study came from Korsimoro (latitude 12°49' north, longitude 1°04' west) in north-central Burkina Faso. It was a reddish brown colored soil with some light brown parts. This clayey raw material from the locality of Korsimoro was chosen for the study because of its abundance and its traditional utilization for the manufacture of good quality adobes by the local population. This raw material is also currently used by a local Burkina Faso adobe manufacturing company (POCERAM). Fonio (*Digitaria exilis*) belongs to the Poaceae family. It is an ascending annual herb about 80 cm in height. It has alternate simple leaves and a glabrous, smooth, striated sheath; the membranous ligule is broad and approximately 2 mm long; the linear limb narrows gradually to a glabrous acute apex, 5-15 cm × 0.3-0.9 cm [11-13]. In the tropical climate of West Africa, with a dry season (25-30°C) and rainfall of 800 mm to 1000 mm, fonio has been grown for centuries. It is usually grown on light soils (sandy to stony soil) without crop rotation. The late varieties are particularly well suited to poor soils. Richer soils could be used for the early varieties.

Long marginalized because of the fineness of its grains, which are difficult to sort from grains of sand, fonio is now experiencing renewed interest as consumers appreciate its flavor and its nutritional qualities.

The fonio straw used here for the reinforcement of adobes came from Peni (10°57' north, 4°28' west) in the “Hauts Bassins”, region of Burkina Faso. This area was selected because of the abundance of Fonio straw in this zone. Figure 1 presents dried fonio-straw.

Figure 1: Fonio-straw

2.2. Manufacture of adobe

The clayey soil used for making adobes was crushed in a grinding machine to obtain particles with sizes < 5 mm. This procedure is usually used to homogenize soli before the manufacture of adobes or compressed earth blocks (CEB) and is also used in the industrial manufacture of extruded bricks. This step needs a quantity of energy that is negligible in comparison to that used for the grinding of cement, for example.

The dried fonio straw was cut manually (maximum length 1 cm so as to obtain a homogenous mixture between straw and soil) then mixed into the clayey soil without any preferential orientation. The adobes were manufactured using a mixture of soil and 0.2, 0.4, 0.6, 0.8 or 1% by weight of fonio straw.

The soil was mixed for twenty minutes with 24% of water by dry weight of soil to obtain a homogeneous mixture having suitable plasticity for molding adobes. The amount of water (w(%)) was calculated by applying relation (1):

$$w(\%) = (w_L+w_P)/2 \quad (1)$$

This value, which is the average of the Atterberg liquidity (w_L) and plasticity (w_P) limits, has been used in previous work [14]. The mixture was put into 4x4x16 cm^3 prismatic molds in two layers and manual compaction was applied for each layer (30 shocks). Manual compaction was used with a view to popularizing the manufacture of adobes in Burkina Faso, especially in rural areas where sophisticated equipment is not available. The specimen size is in accordance with the standards for cement mortars, which are often used in studies on adobes, in the absence of specific standard. The samples were then dried in the shade (30±5°C) in the open air for 24 h before demolding. Then they were dried again in the shade for 21 days before testing in order to avoid thermal shocks which could cause cracks in the clayey matrix. This curing time is that used by traditional adobe manufacturers and was chosen in recent studies that have given good physical and mechanical properties [7,14].

2.3. Experimental procedures

2.3.1 Physical, chemical and mineralogical characterization of raw materials

The size distribution of the soil mixtures was analyzed using two techniques: the coarser fraction (≥ 80 μm) was analyzed by wet sieving, and the finer fraction (< 80 μm) by means of pipette analysis according to standard NF P 94-057 (method based on measurement of the sedimentation time of solid particles in suspension in a solution of water mixed with sodium hexametaphosphate as a deflocculating agent). The geotechnical characteristics of the soils were determined by measuring the Atterberg limits and the methylene blue value [15, 16].

The chemical composition of the raw materials was estimated on digested crushed samples of size < 80 µm by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES).The loss on ignition was evaluated after sample calcination above 1000°C.

X-ray diffraction (XRD), differential scanning calorimetry (DSC) and thermal gravimetric analysis (TGA)) were implemented to assess the mineralogical composition of the soil. The XRD apparatus used was a Brüker D 5000 power X-ray Diffractometer equipped with a copper anticathode Kα (λ=1.54 Å) monochromator.

DSC-TGA was carried out on crushed samples of the soil heated to 1000°C at a constant rate of 10 °C/min using a Netzsch SATA 449 F3 Jupiter apparatus.

The infra-red (IR) spectra were obtained using a Perkin Elmer UATR1 Frontier FT-IR spectrometer in the 4000 and 550 cm^{-1} ranges.

A JEOL 6380 LV equipped with a backscattered electron (BSE) detector was used for SEM observations on fonio straw and the microstructure of the adobes was studied using a Keyence VH-5911 video optical microscope.

2.3.2 Physical, thermal and mechanical characterization of adobes

The compressive and the flexural strengths were measured using a Controlab-type hydraulic press equipped with a 200 kN capacity load cell. The tests were run at a displacement rate of 0.5 mm/min, according to standard XP P13-901 [17].

The thermal conductivity (λ) of the samples was measured with a TR-1 probe (2.4 mm in diameter; 10 cm long, measurement range between 0.1 and 4 $W.m^{-1}.K^{-1}$) connected to a KD2 Thermal Pro Properties Analyzer device. The probe was introduced into a hole made in the center of a small face of the specimen to prevent contact with the air [18,19].

The test for determining the capillarity water absorption coefficient (A) was carried out on prismatic samples (4x4x16 cm^3) dried at 60°C for 24 hours in an oven. The capillarity water absorption coefficient (A) was evaluated as the slope of the mass flow of absorbed water plotted versus the square root of the exposure time:

$$A = \frac{m_1 - m_0}{S.\sqrt{t}} \quad (2)$$

In relation (2), m_0 is the weight of the dry sample, m_1 is the weight of the sample soaked in water for a duration, t, equal to 600 seconds, S is the base surface area (4x4 cm²) of the sample. The capillarity water absorption was determined according to XP P13-901 [17].

The apparent density was measured using hydrostatic weighing of samples covered with paraffin. The apparent density was calculated using relation (3):

$$d = \frac{m_0}{\left(m_1 - m_2 - \left(\frac{m_1 - m_0}{d_p}\right)\right)} \quad (3)$$

where m_0 is the weight of dry sample, m_1 is the weight in air of the dry sample coated with paraffin, m_2 is its weight in water and d_p is the paraffin density.

The porosity (η) of the adobe was deduced from the measurements of the apparent densities of adobes (d_a) and their absolute densities measured with a pycnometer (d_{ab}) using relation (4):

$$\eta = \left(1 - \frac{d_a}{d_{ab}}\right) * 100 \quad (4)$$

To appreciate the behavior of adobes in a wet environment, the spray test was carried out on unreinforced adobe and FS-adobes. For this test, the specimens were tilted by 30° relative to the vertical plane and water at a pressure of 2 bars was sprayed onto the surface in fine droplets for 10 minutes. The loss of weight of the specimens was measured at the end of the test.

Each value reported for the physical and mechanical test represents the average value for three tested specimens and the error bars associated on the figures indicate the standard deviation.

3. Results and discussion

3.1. Mineralogical and chemical characterization of the soil

The chemical composition of the soil is given in Table 1.

Table 1: Chemical composition of the soil used in this study (L.O.I.: Loss on Ignition)

Oxides	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	L.O.I.
Wt.%	66.13	14.38	6.68	0.15	0.45	0.41	0.24	1.00	1.09	0.06	8.93

Table 1 shows that the soil used for this study was an aluminosilicate with a significant amount of quartz and a non-negligible amount of iron oxide.

The XRD study (Figure 2) showed the presence of quartz (SiO_2), kaolinite ($Al_2(Si_2O_5)(OH)_4$), goethite α-FeO(OH) and muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$).

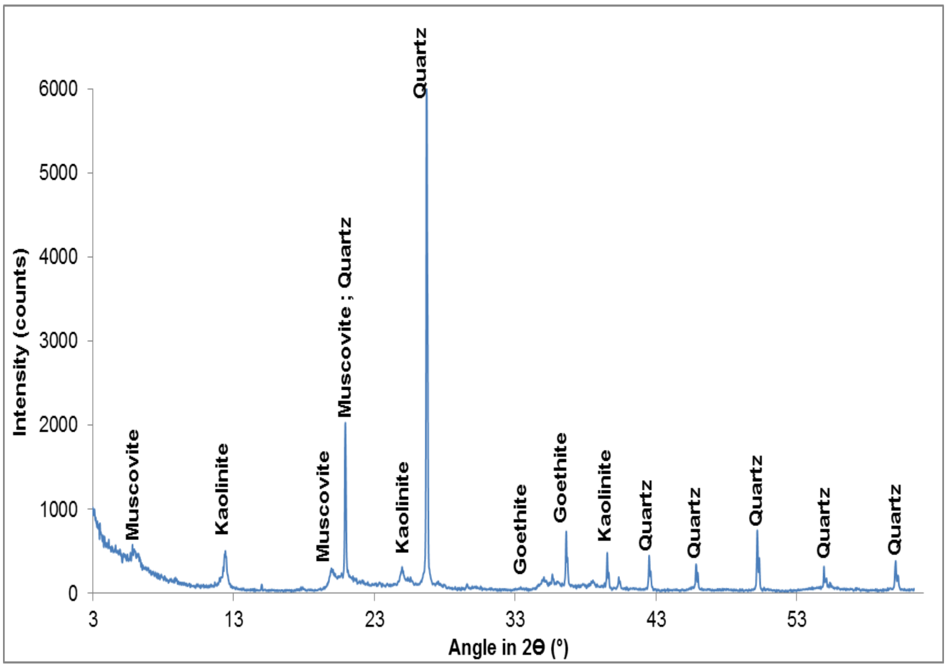

Figure 2: XRD pattern of the soil

The mineralogical composition of the sample was obtained using the results of X-ray diffraction and the chemical analyses. Relation (5) was used to calculate the amount T (a) of oxide (wt.%) of chemical element “a”:

$$T(a) = \sum M_i P_i(a) \quad (5)$$

where M_i is the amount (in wt.%) of mineral i in the material under study containing the element i, and P_i (a) is the proportion of element a in the mineral i [20]

Based on XRD and chemical results and applying relation (4), the soil was found to be composed of kaolinite (28 wt.%), muscovite (9 wt.%), goethite (7 wt.%) and quartz (49 wt.%). The presence of the minerals identified by XRD was confirmed by the DSC-TGA results. The DSC-TGA curves (Figure 3) showed an endothermic peak around 100 °C due to the loss of hygroscopic water, which led to a weight decrease of about 1.2%. The endothermic peak around 399 °C in Figure 3 corresponds to the transformation of goethite into hematite. A high endothermic peak is observable around 518 °C and is due to the dehydroxylation of kaolinite [21] to form metakaolinite (an amorphous phase) [22] with a loss of weight of 3.4%. The reaction associated with this dehydroxylation is:

$$Si_2Al_2O_5(OH)_4 \text{ (kaolinite)} \rightarrow Si_2Al_2O_7 \text{ (metakaolinite)} + H_2O.$$

The endothermic peak at 576 °C corresponds to the allotropic transformation of quartz α into quartz β and that at 920 °C is due to the structural reorganization of metakaolinite.

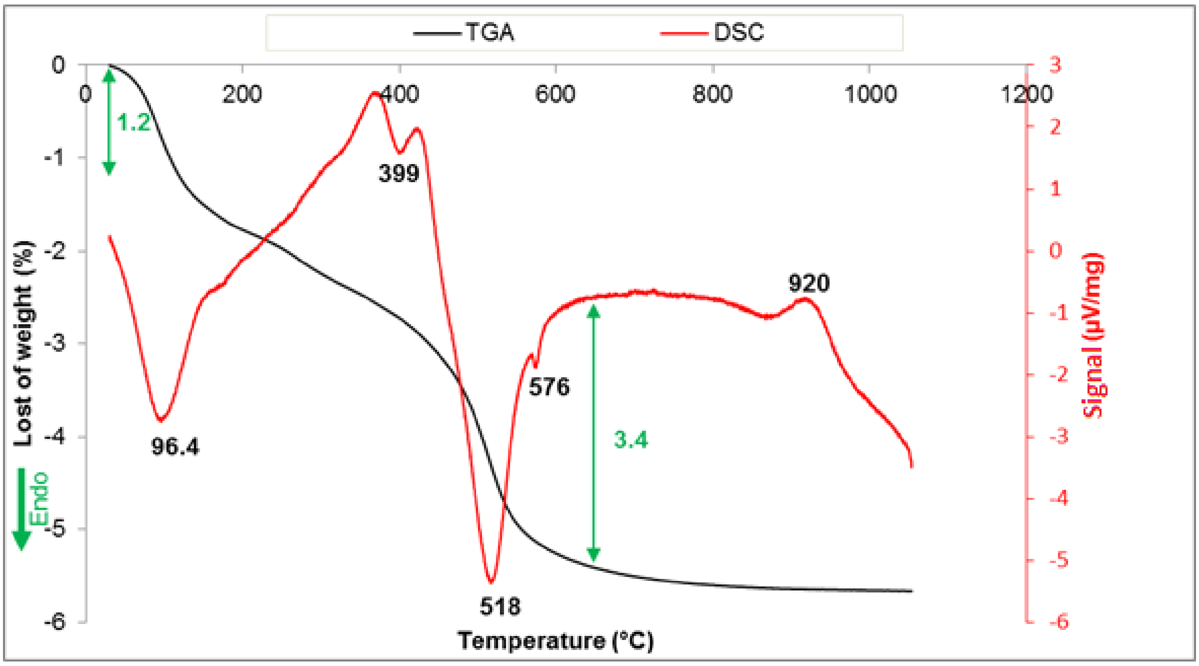

Figure 3: DSC and TGA of the soil

The particle size distribution of the soil (Figure 4) shows that d_{50} and d_{90} were 6 and 200 µm, respectively. The liquid limit (w_L), plasticity limit (w_P) and the plasticity index (PI) of the sample studied were 31, 17 and 14%, respectively. Taking the value of the methylene blue test (V_{BS} = 5.17 g / 100 g) into account, it can be concluded that the sample was a clayey material with silty behavior and medium plasticity, which is consistent with the particle size distribution determined. Regarding the values of plasticity indices recommended for the manufacture of adobes [22], the soil from Korsimoro can be considered as suitable for the manufacture of adobe. This type of soil is commonly found in the West African sub-region.

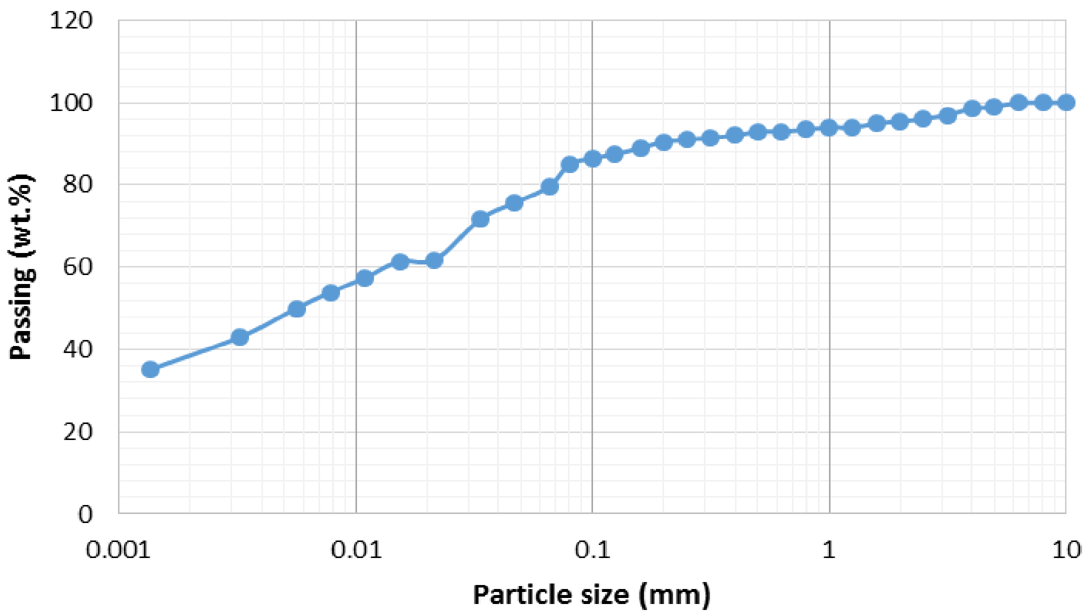

Figure 4: Particle size distribution of the soil

3.2. Microstructural characterization of fonio straw

The SEM micrograph of the fonio straws in Figure 5a shows veins oriented parallel to the axis of the straw. This grooved structure of the fibers may favor their mechanical coupling with the matrix and this may influence the post-peak behavior of the composite. The EDS analysis spectrum (Figure 5b) of dried and crushed fonio straw reveals a very large amount of carbon but also non-negligible proportions of clay minerals, quartz, potassium and magnesium oxides, probably as contaminants in the fonio straw.

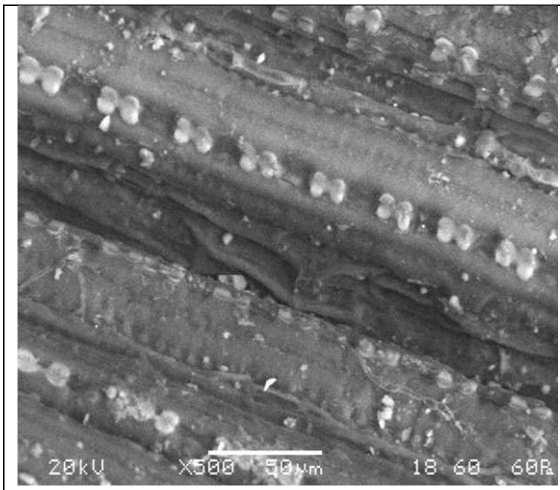

Figure 5a: SEM micrographs of fonio straw

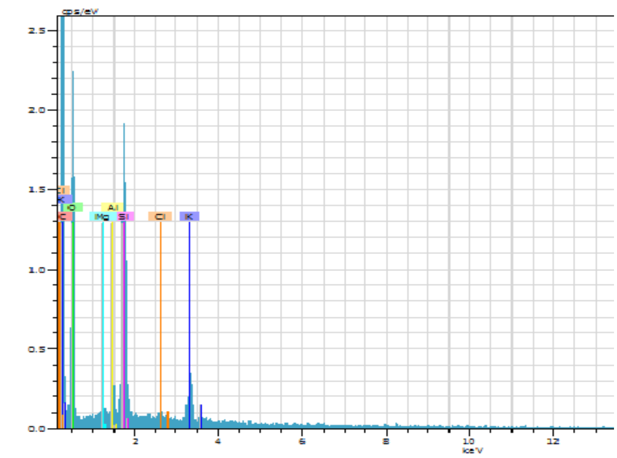

Figure 5b: EDS analysis spectrum of fonio straw

The infrared spectrometry of the fonio straw (Figure 6) shows the vibrations of OH groups of the cellulose [23], aliphatic C-H, C=O of the carboxyls contained in the hemicelluloses [23, 24], C=C-C of the aromatic ring structures [25-27], the deformation of the acetyl groups (xylans) of lignins and the antisymmetric elongation of C-O-C from cellulose and hemicelluloses.

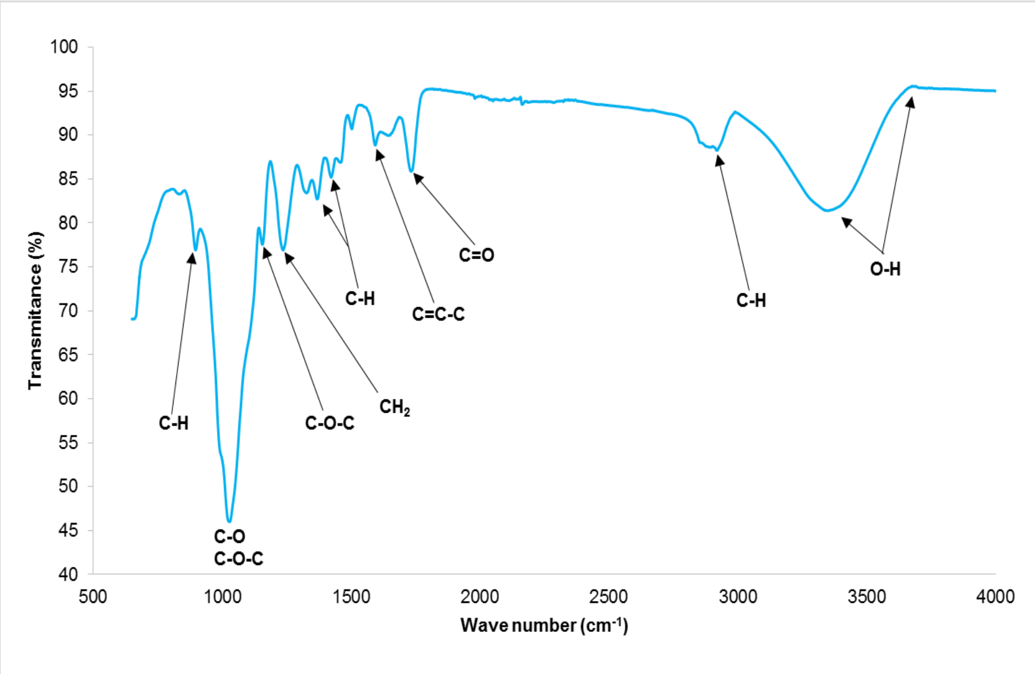

Figure 6: Infrared spectrum of the fonio straw

The presence of cellulose was confirmed by XRD carried out on fonio straw crushed to a size < 80 µm (Figure 7).

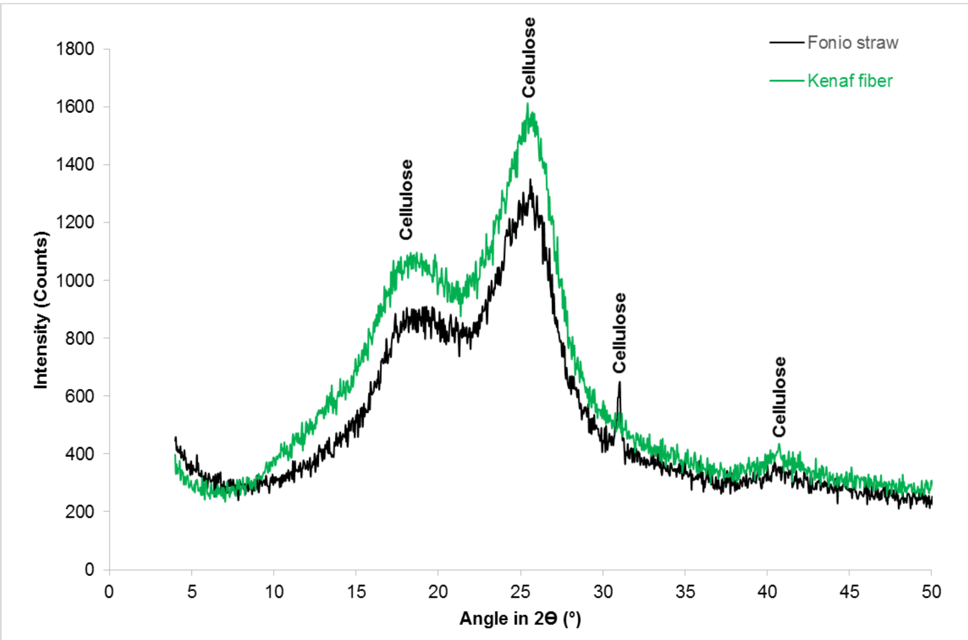

Figure 7: XRD pattern of the fonio straw compared to kenaf (*Hibiscus Cannabinus*) [28]

A comparison with the X-Ray Diffraction pattern of kenaf [28] confirmed that the crystal substance observed in the fonio straw was mainly composed of cellulose. This presence of a large amount of cellulose gives fonio straw its apparent stiffness when it is dried.

The molecular compounds identified by infra-red spectrometry are presented in Figure 8.

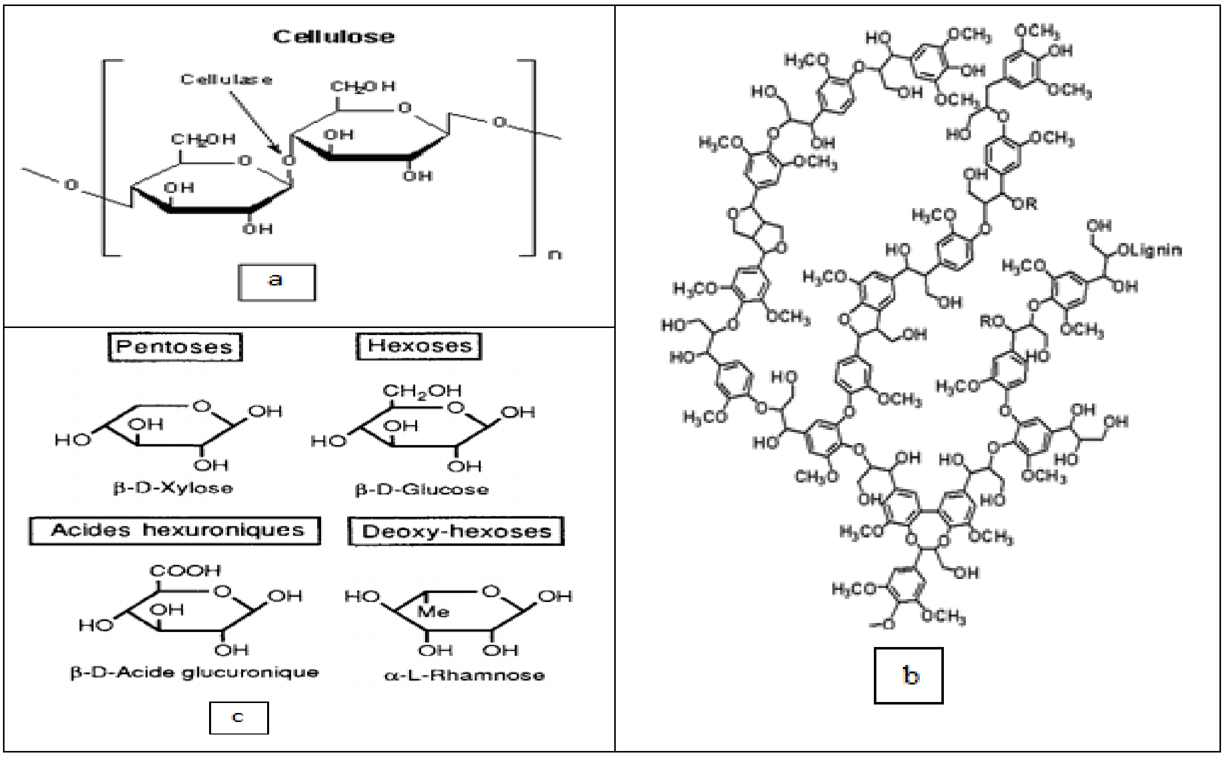

Figure 8: Molecular compounds in the fonio straw (a: cellulose, b: lignin, c: structures of sugars composing hemicelluloses)

This figure shows the presence of free hydrogen and electronic doublets of oxygen atoms in fonio straw. Each microfibril is made up of 30-60 individual chains of cellulose disposed in superimposed planes. A significant number of hydrogen bonds inside and between the cellulose chains stabilize the unit [29] and give it high mechanical resistance. These microfibrils are the main constituents of the primary plant cell wall. Crystallized cellulose has a relatively high modulus of elasticity (90-137 GPa) compared, for example, with that of glass fibers (75 GPa). Thus, high cellulose crystallinity is an indicator of high mechanical properties [30].

All these results show the potential of fonio straw for the reinforcement of a brittle matrix such as adobe.

3.3 Physical and mechanical characteristics of adobes

3.3.1 Flexural and compressive strength

The 3-point bending load-displacement curve of the adobe reinforced with 0.2 wt.% of fonio straw is compared to that of unreinforced adobe in Figure 9.

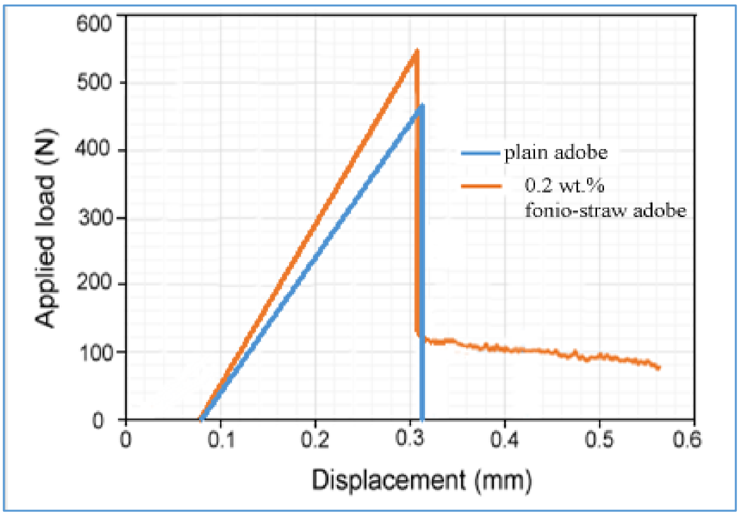

Figure 9: 3-point bending behavior of unreinforced adobe and FS-adobe (0.2%wt)

Both materials showed a linear elastic behavior up to the ultimate deformation, at which the cracking of the clayey matrix occurred from a structural defect. This led to a catastrophic rupture of the unreinforced adobe (into two distinct parts). Although the first matrix cracking in FS-adobes occurred at the same deformation as in unreinforced adobe, it did not result in complete failure. After a first phase of sudden propagation from the maximum load, the crack extended in a controlled manner.

The compressive and flexural strengths of adobes are presented in Figure 10.

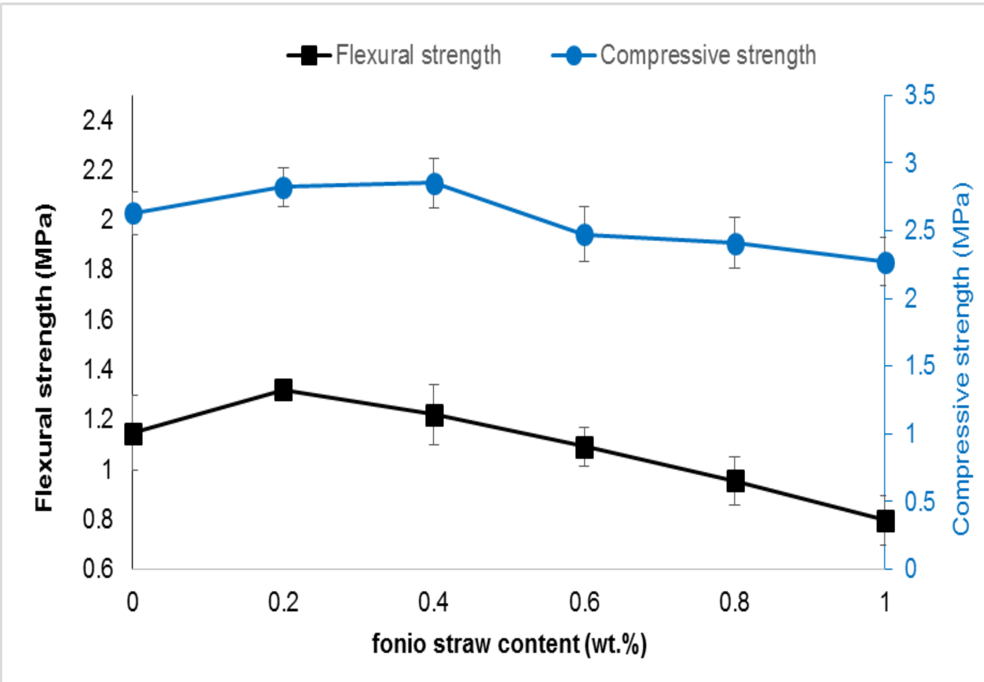

Figure 10: Compressive and flexural strengths of FS-adobes

The flexural strength of adobes increased with fonio straw addition up to 1.3 MPa for 0.2 wt.%. Globally the same tendency was observed by Danso et al. [31] on soil building blocks manufactured with soils from Ghana reinforced by bagasse, coconut and oil palm fibers.

This value was relatively high, compared with that of adobes reinforced sisal fiber of 2 cm or 5 cm (respectively 0.23 and 0.25 MPa) [2]. The increase was mainly due to the high tensile strength of fonio straw because of its crystalline cellulose molecule content.

In the same way, the addition of the fonio straw increased the compressive strength of the adobes up to a mass content of 0.4% because the presence of fonio straw in the adobes prevented the propagation of cracks and thus increased the compressive strength of the adobe. Similar results have been reported by Danso et al. [31] on the reinforcement of soil building blocks with bagasse, coconut and oil palm fibers. The influence of fonio straw on mechanical properties is significant because of the good adhesion of the fibers to the clay matrix, thanks to the roughness of their surface (Fig. 5a).

Flexural and compressive strengths of the FS-adobes decreased smoothly when the straw content was raised. This loss of mechanical strength was correlated with the increase in porosity due to the agglomeration of fibers for high straw contents, which can be observed on the video optical microscopy images of the adobes presented in Figures 11 (c and d).

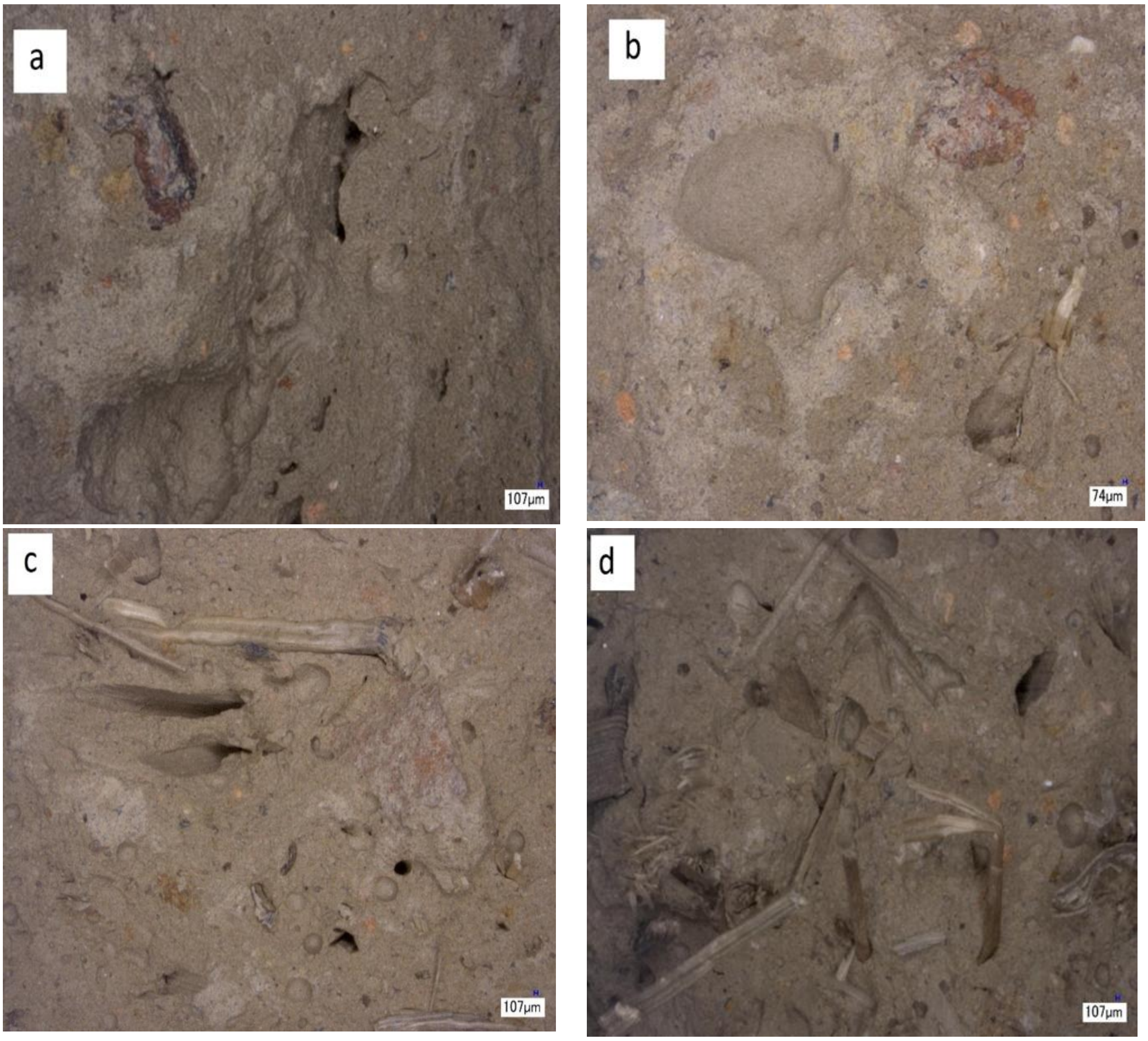

Figure 11: Video microscope images of adobes (a: without straw, b: 0.2 wt.% fonio straw, c: 0.8 wt.% fonio straw and d: 1.0 wt.% fonio straw

The adobes reinforced with 0.2 wt.% of fonio straw seemed less porous (Figure 11b), without cracks, with small sized pores and zones devoid of straws. This addition helped to improve flexural strength, but the fact remains that the straw distribution should be improved. For fonio straw contents higher than 0.2 wt.%, Figures 11c and 11d reveal a structural heterogeneity increasing with fonio straw ratio: fonio straws have piled up and big pores are present in the adobes (Figure 11d), which could explain the reduction of mechanical properties observed in Figure 10.

The results obtained in this study were compared with those of Pressed Adobe Blocks (PABs) reinforced with 30 mm lengths of *Hibiscus cannabinus* fibers [28]. This comparative study is presented in Table 2.

Table 2: Comparison of mechanical properties of PABs and FS-adobes

Fiber content (%)		0	0.2	0.4	0.6	0.8	1.0
PABs reinforced with kenaf fibers	Flexural strength (MPa)	0.9	1.9	1.5	-	1.4	-
	Compressive strength (MPa)	2.3	2.6	2.8	-	2.6	-
FS-adobes	Flexural strength (MPa)	1.1	1.3	1.2	1.1	1.0	0.8
	Compressive strength (MPa)	2.6	2.8	2.9	2.5	2.4	2.3

This table shows the greater contribution of fonio straw compared to kenaf fibers in the stabilization of adobes in the case of compressive strength. The compressive strengths of the adobes are better than those of the PABs, probably because of a better distribution of the fonio fibers in the clay matrix.

Unlike the compressive strength, the flexural strength of FS-adobes is relatively low compared to that of the PABs, because of the higher cellulose content of kenaf, which increases the tensile strength of fibers and therefore the flexural strength of PABs that contain them.

The flexural strength evolution of FS-adobes was similar to that of adobes elaborated with the same soil (from Korsimoro) reinforced by one variety of kenaf fibers *(Hibiscus Altissima)* 3 cm long [32]. For these two studies, the optimum amount of fibers for flexural strength was 0.2 wt.%. Also, the compressive strength of FS-adobes and adobe reinforced by kenaf fibers *(Hibiscus Altissima)* showed the same evolution. Adobes reinforced by kenaf fibers had high resistance because of the larger amount of cellulose in kenaf fibers than in fonio straw.

The importance of fonio straw incorporation is that it mechanically reinforces adobes and prevents the propagation of cracks, thus increasing FS-adobes' ductility. These phenomena are probably due to the formation of hydrogen bridges between hydrogen atoms and free doublets of oxygen atoms present in the two raw materials [33].

3.3.2 Porosity and thermal conductivity of adobes

The porosity and the thermal conductivity of the FS-adobes are presented in Figure 12.

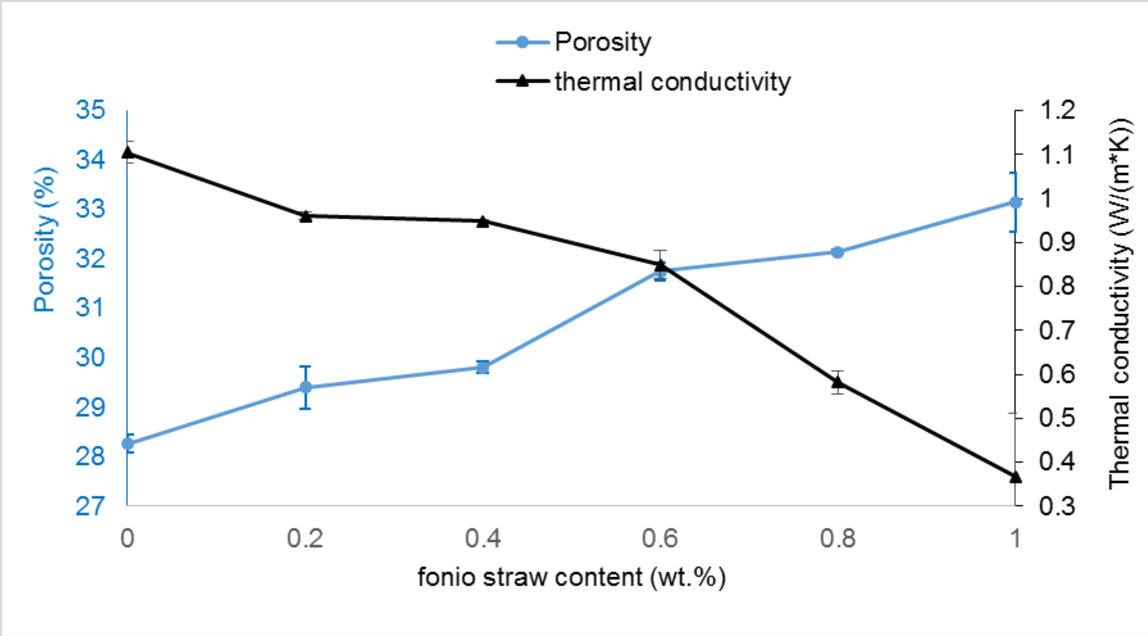

Figure 12: Porosity and thermal conductivity of FS-adobes

The addition of fonio straw in the adobe leads to an increase in closed porosity. The thermal conductivity decreases when the fonio straw content is raised: a decrease of 67% is observed for the adobe containing 1 wt.% of fonio straw. This decrease could be explained by the combined effects of higher porosity and the use of reinforcement having low thermal conductivity due to the presence of cellulose, which is a good thermal insulator.

The thermal conductivity of FS-adobes was lower than that measured by Laibi et al. [34] on CEB stabilized with kenaf fibers from Benin. This difference was related to the manufacturing procedure: the CEB were less porous than adobes because they were compacted with high pressure during their manufacture. This difference of porosity can explain the difference of thermal conductivities observed between these two earth materials. Laborel-Préneron et al. [35] studied the effects of the addition of barley straw and hemp on hygrothermal properties of compressed earth blocks. In their study, the compaction effect was compensated by the finer content, which was much higher (3% wt.) than in the present study, the thermal conductivities measured during the two studies being comparable. Globally, the thermal conductivity values of FS-adobes are similar to those reported by Meukam et al. [36], who worked on unreinforced bricks and bricks reinforced by wood sawdust.

The decrease in thermal conductivity with fonio straw addition is an important result, which can be exploited by using adobes with high straw contents in building parts that are the most exposed to high heat fluxes, if their mechanical strength allows it.

3.4. Capillary water absorption and resistance to water erosion

The hydric behavior of these bio-sourced composites is an important aspect for their acceptability in building construction. The influence of plant aggregates or fibers on water absorption has been studied very rarely. Water absorption by the material is measured by immersion or capillarity [3]. Recent scientific works have shown that earth blocks stabilized by fibers do not withstand water immersion [37, 38].

The effect of fonio straw addition on water absorption of the adobes is shown in Figure 13.

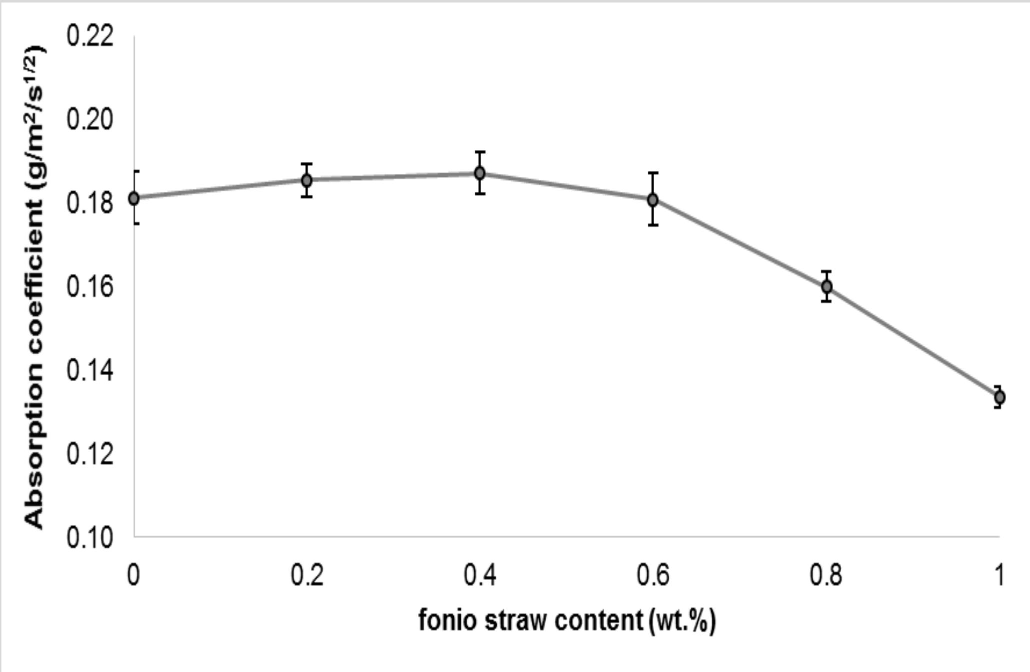

Figure 13: Capillary water absorption of FS-adobes

The capillary water absorption coefficient of adobes increases with their fonio straw content up to 0.4 wt.%. This is due to the high water absorption of the dried straw contained in such adobes. The high water absorption of soil blocks reinforced with fibers could be mainly attributed to the presence of cellulose, which is hydrophilic, in the fibers. The presence of pores in such composite materials is an additional reason for their high water absorption [39]. This phenomenon was noted by Ismail et *al.* [40], who reported the increase in water absorption of lateritic bricks with the increase in palm oil fiber content. In the same way, Algin and Turgut [41] showed that the quantity of water absorbed was proportional to the cotton waste content and Taallah et al. [4] concluded that increasing date palm fiber content to 0.2% led to an increase in water absorption and swelling.

Water absorption by fonio straws has an important effect on their adhesion with the matrix. The swelling of fibers linked to water absorption pushes away the soil and, then, after drying, the volume of fibers decreases again, creating voids around them and thus increasing the porosity [10, 42].

Beyond 0.4 wt.% of fonio straw, the formation of clusters and the increase in open porosity (Figure11d) slows down the water absorption kinetics; hence this phenomenon is strongly dependent on the microstructure of the composites. Also, with a large amount of fonio straw, fibers tend to clump together (Figure 11d) in the composite and therefore slow down water ascension.

To appreciate the behavior of adobes in a wet environment, the spray test was carried out on unreinforced adobe and FS-adobes. Figure 14 presents the evolution of weight loss of adobes after the spray test according to the amount of fonio straw added.

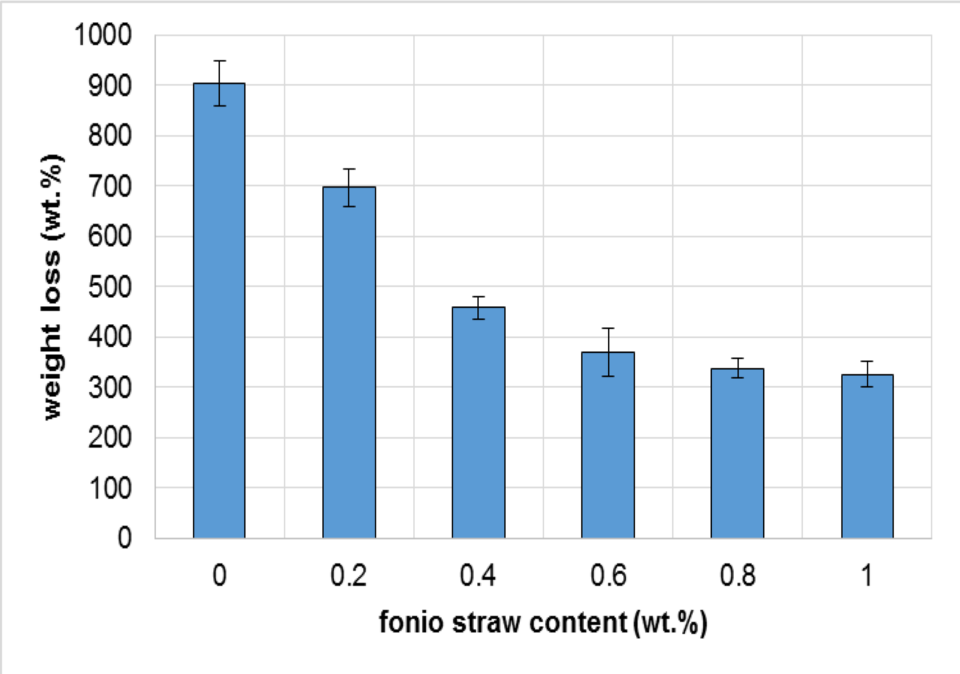

Figure 14: Weight loss of FS-adobes during the spray test

The results clearly show that the weight loss of the adobes decreases with increasing fonio straw content. In comparison with composites, unreinforced adobe is strongly eroded. These results are similar to those reported by Danso et al. [31, 39] on soil building blocks. In their works, these authors showed a significant decrease in erosion with the increase of sugarcane bagasse fiber content up to 0.5%wt, as was the case in the present study. According to the authors, this decrease could be explained by the high adhesion of fibers with clayey matrix. In contrast, Obonyo et al. [43] showed that using coir fibers in soil-cement blocks considerably decreased their durability against water. The number of studies dealing with the effects of fibers on the erosion resistance of earth bricks is too small to allow the conclusions to be generalized but, in the present study, the inclusion of the fonio straws in the soil matrix clearly increased soil resistance to water erosion.

The aspect of the adobes after the spray test are presented in Figure 15. Adobes containing fonio straw were much less sensitive to water erosion. Whatever the explanation may be, this result is very important because it justifies a technique used through the ages in rural areas, and it also suggests new methods for protecting structures in raw clay at low cost.


1 wt.% 0.8 wt.% 0.4 wt.% 0.2 wt.% unreinforced adobe

Figure 15: Aspects of adobe samples after the spray test

4. Conclusion

The chemical and mineralogical compositions of fonio straw and the physical and mechanical properties of derived adobe composites have been investigated. The important points that emerge are:

(1) The soil used in this study consisted essentially of quartz (49 wt.%), kaolinite (32 wt.%), goethite (7 wt.%) and muscovite (4 wt.%). Its geotechnical properties showed that it was suitable for the manufacture of adobe.

(2) Fonio straw has a rough surface and is rich in cellulose, hemicelluloses and lignin.

(3) A small amount of fonio straw mixed with soil leads to biosourced geomaterials that are more homogeneous, with smaller pores than the unreinforced adobe.

(4) The compressive and flexural strengths of fonio-straw-containing adobes are mainly improved by the good adherence of fibers to clay matrix and by the limitation of crack propagation thanks to the presence of straw. The water absorption of adobes mixed with fonio straw increases until a proportion of 0.4 wt.% is reached. This effect is due to the hydrophilic character of fonio straw (linked to its high cellulose content). This parameter

decreases with larger amounts of fonio straw, where the distribution of the straw in clumps reduces water ascension.

(5) The thermal conductivity of adobes decreases with the addition of fonio straw because of the insulating character of the cellulose contained in the straw and the increase in the closed porosity.

(6) Optimum physical and mechanical properties are obtained for fonio straw contents ranging between 0.2 and 0.4 wt.%.

(7) The good compressive strength of the adobes incorporating fonio straw, their good resistance to water erosion and their low thermal conductivity are very encouraging for the use of these eco-composites in the building of individual habitats in the sub-Saharan zone.

It could be interesting to complete this study by further works on the hygrothermal properties of fonio-straw-containing adobes in order to evaluate the possible beneficial effect of fonio straw addition on these properties.

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