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Abstract: The main objective of this study was to manufacture resistant, durable adobes having low thermal conductivity. For this purpose, a moderately plastic clayey soil from Korsimoro (Burkina Faso) was used to manufacture adobes reinforced with up to 1 wt.% of rice husks. The chemical and microstructural characteristics of the rice husks were evaluated, as were the physical, mechanical and microstructural characteristics of the adobes that were manufactured. The incorporation of rice husks in the clayey matrix increased the compressive strength of adobes and decreased their thermal conductivity. From a durability point of view, the addition of rice husks in adobes decreases the capillary absorption and improves the resistance to water erosion, due to the good adhesion of rice husks with the clayey matrix. According to standards related to building materials, adobes manufactured with at most 0.4 wt.% are suitable for the construction of resistant and durable dwellings that provide acceptable thermal comfort.

Keywords: Clayey soil; Rice husks; Adobe; Microstructure; Physical and mechanical properties; Thermal comfort; Burkina Faso.

Research Highlights

Friction between rice husks and clay molecules creates hydrogen bonds.
Rice husks in clayey matrix significantly reduce water absorption.
Rice husk additions to a clayey matrix improve mechanical strength of adobes.
Rice husk additions to a clayey matrix decrease thermal conductivity of adobes.
Stabilization by rice husks improves adobe water resistance.

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1. Introduction

In Africa, and particularly in Burkina Faso, shantytown or village people commonly use adobes (hand-moulded bricks) and compressed earth bricks (CEB) to build their houses. Some prefer concrete blocks, which are used mainly in urban areas, because of their good mechanical strength and water resistance. However, concrete blocks have economic and environmental disadvantages as Portland cement, which is widely used in Burkina Faso and produced by cement industries, is expensive because clinker is imported and the cement constituents have to be ground.

It thus appears that the use of adobes is a possible solution to sustain construction for populations in low-income developing countries. However, raw adobes encounter problems in terms of both mechanical strength and durability, especially water resistance. These problems are linked to poor cohesion of the clayey matrix particles and to the formation of large numbers of pores during the elaboration of adobes. In order to resolve these problems, some recent works on adobes reinforced with plant fibres of coconut, oil palm, sisal or kenaf, and with organic polymers, have shown that the addition of these additives to the clayey matrix reduces cracks and improves adobe durability (Millogo et al., 2014; Vandna et al., 2015; Danso et al. 2015). Millogo et al. (2014) investigated the influence of kenaf fibres on physical and mechanical characteristics of Pressed Adobe Blocks (PABs). Considering these works, it has been concluded that adding 0.2-0.4 wt.% of kenaf fibres improves the physical and mechanical properties of PABs, except for thermal conductivity, which increases with the amount of kenaf fibres because of their high cellulose content. The improvement of the other physical and mechanical characteristics is due to the strong adherence of the fibres to the clayey matrix, which prevents the propagation of cracks, and to the high bending strength of kenaf fibres due to their richness in cellulose. Vandna et al. (2015) report that the compressive strength of soil increases by between 131% and 145% with the addition of *P. roxburghii* fibre and by 225%-235% with the addition of *G. optiva* fibre in cubic and cylindrical samples, respectively. Danso et al. (2015) investigated the influence on some physical and mechanical properties (water absorption density, erosion, shrinkage, compressive and tensile strengths) when various weight proportions of agricultural waste fibres were added to soil blocks. This scientific work concluded that the addition of 0.5 wt.% of such fibres improved the physical, mechanical and durability properties of the soil blocks.

Other studies have shown that the nature of the clayey soil, the length of the fibres and the procedure used to manufacture the building materials significantly influence the physical and mechanical characteristics of earth building materials (Ghavami et al., 1999; Mesbah et al., 2004; Akil et al., 2011; Alavéz-Ramirez et al., 2012; Bachir et al. 2014; Millogo et al., 2014; Millogo et al., 2015). In addition, physical parameters such as water absorption by capillary action, closed porosity, erodibility, apparent density and thermal conductivity of building materials, which are very important parameters in the construction field in Africa, particularly in tropical areas, remain under-exploited in research work on building materials.

To the best of our knowledge, the scientific literature on the stabilization of adobes by non-calcined rice husks is very sparse and very little research has been devoted to the clay matrix-rice husk interaction mechanism, although it is very important to know its effect on the physical and mechanical properties of adobes. Likewise, the impact of rice husks on the thermal properties and the water resistance of adobes has not been the subject of scientific study. The present study

concerns the effect of rice husks (FKR 45N variety) on the microstructural, physical and mechanical properties of adobes. Particular emphasis will be placed on the thermal conductivity and on the erodibility of the adobes elaborated.

2. Materials and methods

2.1. Raw clayey material

The raw material (mineral matrix) used in this work has been the subject of several previous works (Ouedraogo et al., 2017; Dao et al., 2017; Ouedraogo et al., 2019). This clayey raw material, called Kors, was collected in Burkina Faso from the clay site of Korsimoro (12°79' N - 1°09' W). This clayey site is exploited by the indigenous people for manufacturing adobe bricks and by the POCERAM company for pottery and fired bricks.

The complete particle size distribution of the KORS clayey soil (Fig. 1) was determined by sieving (particles of diameter ≥ 80 µm) and sedimentometry (particles of diameter < 80 µm) according to NF P 94-056 and NF P 94-057. The particle size distribution curve of the sample shows that KORS consists of 4.7 wt.% coarse sand, 37.9 wt.% fine sand, 22.7 wt.% silt and 29.9 wt.% clay (Dao et al., 2018).

The Atterberg limits and methylene blue value of the soil were determined following NFP 94-051 and NF P 94-068 standards respectively.

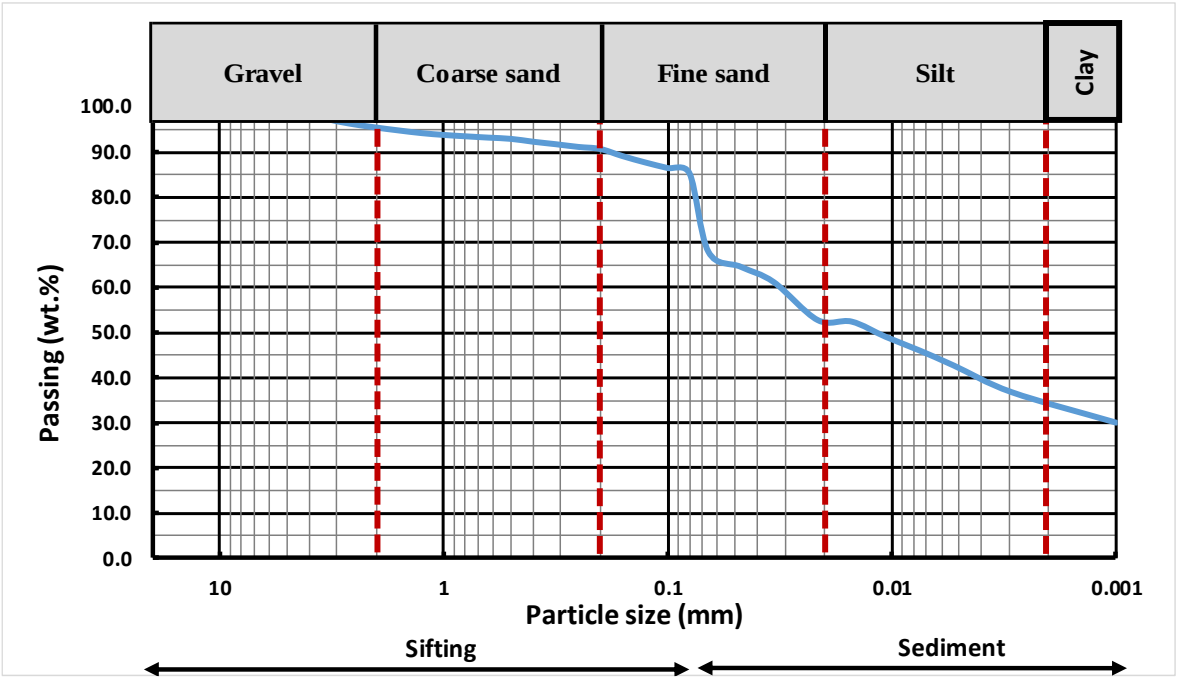

Figure 1: Particle size distribution of KORS (Ouedraogo et al., 2019)

Considering the value of the methylene blue test (V_{BS} = 5.17 g/100g), KORS can be classified as a clay with a silty character, of medium plasticity (Millogo, 2012). This nature of the KORS clay is confirmed by the Atterberg limits: liquidity limit (W_L = 31%), plasticity limit (W_P = 17%) and

plasticity index (I_P = 14%). Considering the spindle of plasticity indices of earth used for brick manufacture (Millogo, 2012), KORS is suitable for the manufacture of raw earth bricks (adobes).

Table 1 presents the results of the chemical analysis of the Kors sample.

Table 1: Chemical composition of KORS (Ouedraogo et al., 2019)

Oxides	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	PF	Total
wt.%	66.13	14.38	6.68	0.15	0.45	0.41	0.24	1.00	1.09	0.06	8.93	99.53

The KORS sample had a high silicon oxide, an acceptable alumina, and a significant iron oxide content, which gave it a greyish tint. In view of these results, the sample appears to be rich in quartz and clay minerals and would also contain iron minerals.

X-ray diffraction analysis (Fig. 2) confirmed the presence of quartz (SiO_2), kaolinite ($Al_2(Si_2O_5)(OH)_4$), goethite α-FeO(OH) and muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$) in KORS samples.

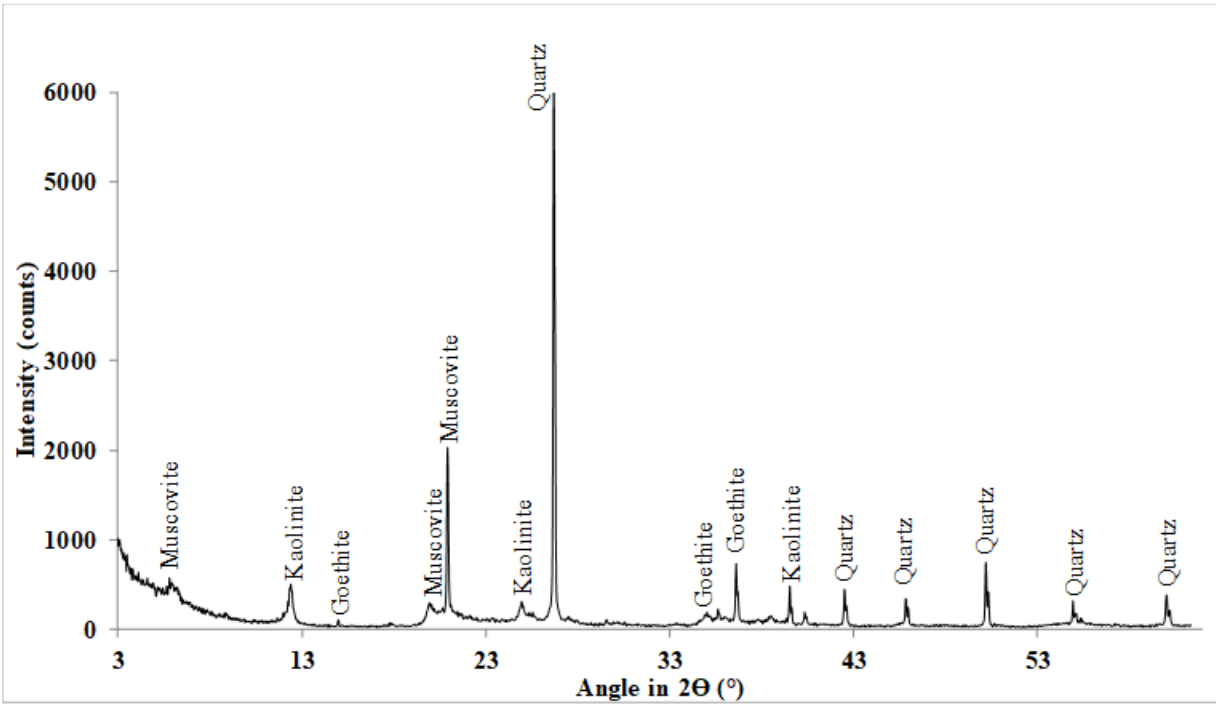

Figure 2: KORS X-ray diffraction (Ouedraogo et al., 2019)

From the results of chemical analysis and X-ray diffraction, the mineral phases reported in Table 2 were quantified using the technique described by Millogo et al. (2014) and Ouedraogo et al. (2019). This technique consists of calculating the amount T(a) of oxide (wt.%) of chemical element "a" using the following relation (1)

$$T(a) = \Sigma\, Mi.Pi\,(a) \qquad (1)$$

where Mi is the amount (wt.%) of mineral "i" in the material under study and Pi(a) is the proportion of oxide "a" in the mineral "i".

Table 2: Mineralogical composition of KORS

Mineral	Kaolinite	Muscovite	Goethite	Quartz	Balance
wt.%	32	4	7	49	8

The KORS sample is rich in quartz and clay minerals (kaolinite, muscovite) and contains goethite.

The mineralogical composition of the sample was completed by DSC-TGA and infrared spectrometry. The DSC-TGA curves of the KORS sample are given in Figure 3 (Ouedraogo et al., 2019). The analysis of DSC-TGA curves shows an endothermic peak at 100 °C due to the loss of hygroscopic or hydration water. This endothermic phenomenon is associated with 1.2 wt.% loss of mass. The endothermic peak at 399 °C is related to the transformation of goethite into hematite. The very pronounced endothermic peak at 518 °C is due to the dehydroxylation of kaolinite and its transformation into an amorphous phase called metakaolinite. The loss of mass due to this thermal accident is 3.4%.

The endothermic peak at 576 °C can be attributed to the transformation of quartz α into quartz β. Finally, the exothermic peak at 920°C is due to the structural reorganization of metakaolinite.

The infrared spectrum of KORS (Fig. 4) shows vibration bands of quartz (Si-O vibration at 1030 cm^{-1}); kaolinite: 3620, 3650 and 3690 cm^{-1} (O-H elongation vibrations); 1116, 1005 cm^{-1} (Si-O vibrations); 914 cm^{-1} (Al-OH deformation vibration) and hygroscopic water at 1637 cm^{-1}. The absence of the 3672 cm^{-1} kaolinite band shows that the kaolinite in the sample has low crystallinity (Farmer 1974; Madejova and Komadel 2001; Ouedraogo et al., 2019).

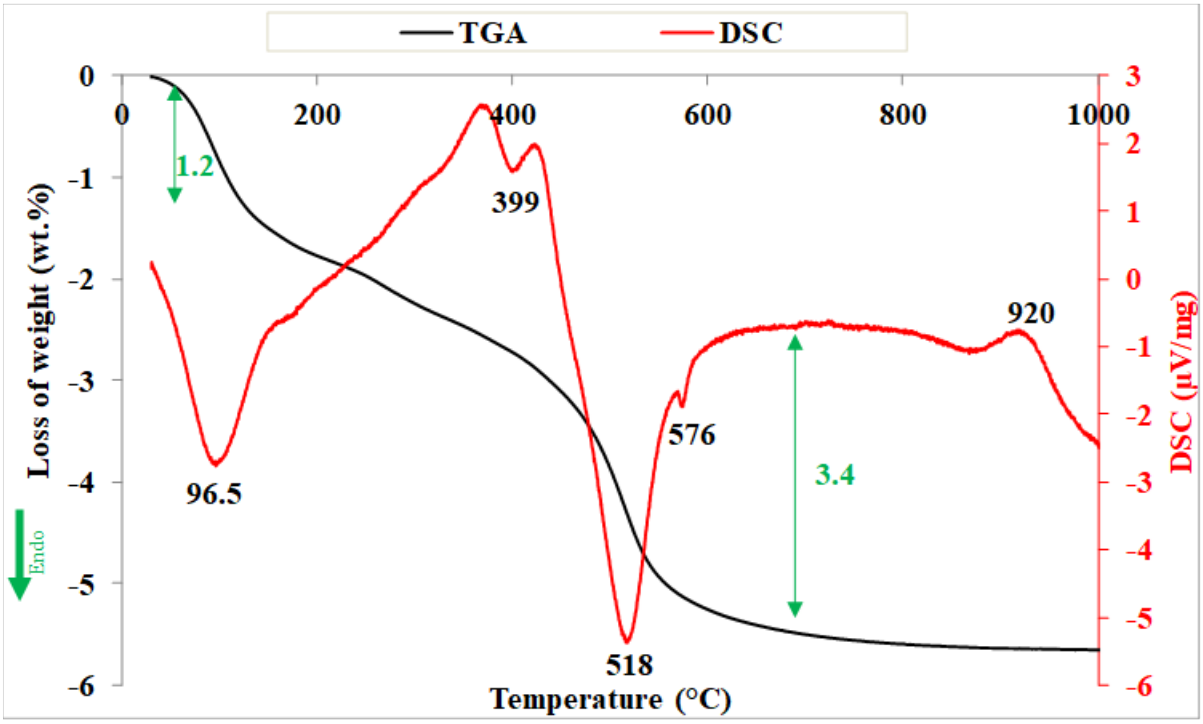

Figure 3: DSC-TGA curves of the KORS sample (Ouedraogo et al., 2019)

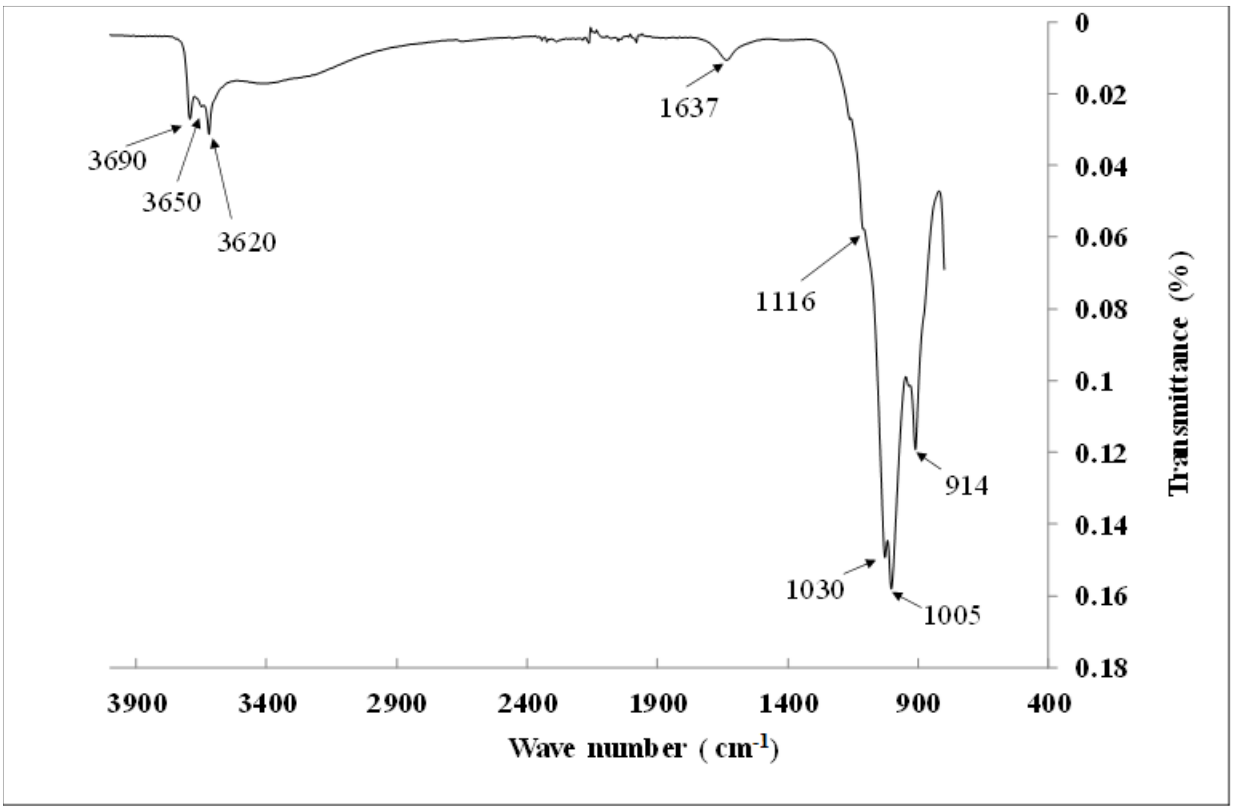

Figure 4: Infrared spectrum of the KORS sample (Ouedraogo et al., 2019)

2.2. Plant aggregates

The plant aggregates used in this work were rice husks (Fig.5). They were taken from the village of Bama, located 30 kilometres from the town of Bobo Dioulasso in western Burkina Faso. The rice husks came from FKR 45N variety rice plants from INERA's Bobo-Dioulasso experimental rice field.

Rice husks are a by-product of rice processing and form a vegetable aggregate that is used as mulch for gardens, bedding in poultry houses, or fuel. The rice husk ashes can be used in the production of cement and refractory materials.

However, after the rice harvest, rice husks are considered as a non-recyclable waste even though the thermal insulating property of the cellulose (0.037-0.042 $W.m^{-1}.K^{-1}$ (Bouchie et al., 2013)) contained in rice husks could be used to produce construction materials with good thermal regulation that could constitute a valuable reuse of this waste.

Figure 5: Rice husks

Some authors have reported the elemental chemical composition and the proportion of rice husk ash for different rice varieties. These results are gathered together in Table 3.

Table 3: Chemical composition and proportion of ash of different varieties of husk rice

Reference	C (wt.%)	H (wt.%)	O (wt.%)	N (wt.%)	S (wt.%)	Ash (wt.%)
Beagle (1978)	42.12	5.35	31.72	0.49	0.07	20.29
Kaupp (1984)	41	5	37.6	0.6	-	15.5

Kaupp (1984) reported an amount of silica between 95% and 97% in the ash. The work carried out by Beagle (1978) on several rice varieties, reports that the ash contains 90.2- 96.9 wt.% SiO_2, 0.58-3.15 wt.% K_2O, 0.25-2.70 wt.% CaO, 0.24-0.57 wt.% P_2O_5, 0.015-0.67 wt.% MgO, trace to 0.08 wt.% Al_2O_3, trace to 1.01 wt.% Fe_2O_3, 0.34-0.78 wt.% Na_2O and 0.27-2.70 wt.% SO_3.

The work of Kaupp (1984) and Beagle (1978) gives an idea of the chemical constituents of rice husk in general. The average length of the FKR 45N rice husk is 8 mm (Figure 5). Bulk loose density was determined by drying the rice husks at 60 °C for 3 days. The bulk density of the rice

husks was evaluated at 114 kg/m^3. This density is within the range given by Mansaray and Ghaly (1997) who studied six rice varieties, the rice husk bulk densities of which ranged from 86 to 114 kg/m^3.

2.3. Manufacture of adobes

The first step in manufacturing the adobes was to grind the KORS clay earth to a particle size of less than 5 mm. After grinding, the adobes were manufactured by mixing KORS and rice husks to obtain 0.2, 0.4, 0.6, 0.8 and 1 wt.% contents of dry clay soil.
KORS and rice husks were mixed with water in the proportion of approximately 24 wt.% of dry KORS, for about twenty minutes. The homogeneous mixture obtained was placed in a two-layer mould (40x40x160 mm^3) with manual compaction applied for each layer (30 shocks). After drying for 24 hours in the shade (30±5°C) and in the open air, the specimens were demoulded and dried again in the shade for 21 days. The specimens that were characterized had undergone a cure time of at least 21 days.

2.4. Experimental methods

X-ray diffraction (XRD), differential scanning calorimetry and thermogravimetric analysis (DSC-TGA) were used to determine the mineralogical composition of KORS samples and rice husks. The diffractometer used was a Siemens D5000 equipped with a monochromatic lamp having a cobalt anticathode and using the Kα line (λ= 1.789 Å). The DSC-TGA thermograms were made on a Netzsch SATA 449 F3 Jupiter device with a temperature rise rate of 10 °C/min to 1000 °C.
The Fourier Transform Infrared spectra were obtained using a Perkin Elmer UATR 1 Frontier FT-IR spectrometer operating between 4000 and 550 cm^{-1}.
Scanning Electron Microscopy (SEM) observation and energy dispersive spectrometry (EDS) on the surfaces of rice husks were performed using a JEOL 6380 LV apparatus equipped with a backscattered electron detector. The fracture surfaces of the adobes were analysed on a Keyence VH-5911 video microscope.
Water absorption by rice husk and the absorption kinetics were measured on 1g samples previously dried at 60 °C for 3 days. The absorption coefficient was determined by immersing the samples in water for various periods of time: 5 min, 15 min, 30 min, 1 h, 24 h, 48 h and 72 h.
The thermal conductivity of the adobes was measured with a TR-1 probe (2.4 mm diameter and 10 cm length, working range between 0.1 and 4 W.m^{-1}K^{-1}) connected to the KD2 Pro thermal properties analyser. The probe was inserted into a hole in the specimen in such way that it was not in contact with the air (C25W/P442, 1981). This method of measuring of thermal conductivity is applicable for any water content in the clay matrix (Decagon, 2006).
The test (Fig. 6) for the determination of the water absorption coefficient (A) was carried out on prismatic specimens (4 cm x 4 cm x 16 cm) at a temperature of 20 °C according to standard NF EN 1015-18. This test was performed on three adobe samples for each specimen formulation after drying at 105°C for 3 hours. The lower surface of the specimens was protected with filter paper to avoid loss of particles during this test. The specimens were placed on the side of the

protected surface in a beaker containing a bed (cloth) soaked in water. After a given time, the mass of the specimen was measured, giving the amount of water absorbed by the specimen.

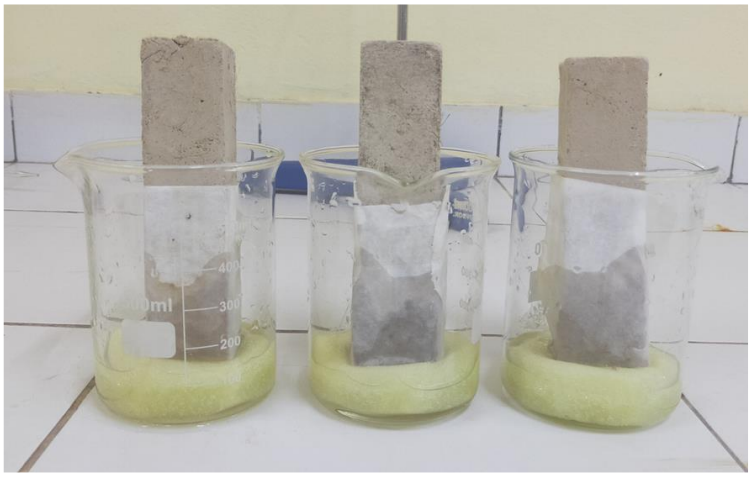

Figure 6: Capillary water absorption of an adobe

The test to determine the water absorption coefficient (A) was carried out on prismatic specimens (40x40x160 mm^3) dried at a temperature of 60 °C for 24 hours (NF EN 1015-18). The water absorption coefficient (A) was determined by following the mass of water absorbed by the adobe as function of time and base area. The value of the water absorption coefficient (A) was determined using relation (2):

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

with m_0: mass of dried adobe
m_1: mass of the adobe soaked in water for a time t
S: lower surface (40x40mm^2) of the adobe
t: absorption time in seconds

The mechanical properties of compressive (NF P18-406) and flexural (NF P 15-451) strengths were determined using a Controlab multifunction press with a speed of 0.5 mm/min and maximum load of 200 kN.
The erosion of the adobes by rainwater was simulated through a spray test device that sprayed the adobes continuously for 10 minutes with water at constant pressure and flow rate. The watering system was placed 120 mm above a plane inclined at about 30° to the horizontal, on which the adobes were placed. This method was inspired by Millogo et al. 2014. The percentage of material loss (C_E) measured at the end of the test determined the degree of erosion (or erodibility), which was estimated by an erosion coefficient given by relation (3).

$$C_E = \frac{(M_0 - M_S)}{M_0} X100 \qquad (3)$$

where M_0 is the mass of the air-dried adobe before the test and Ms is the mass of the air-dried adobe after erosion.

3. Results and discussion

3. 1. Physical, Chemical and microstructural characteristics of rice husks

The relative moisture content of the rice husk was determined by placing 1 g of rice husk in an oven at 60 °C for 24 hours. The difference in mass indicated a moisture content of 17.15%. After this study, the sample was immersed in water to measure its absorption rate. The water absorption of the rice husks was plotted as a function of time. The water uptake curve shows an increase in this parameter with time for 48 hours, at which point the curve stabilizes, showing water saturation of the rice husks. The plot of this study gives the following graph (Fig. 7):

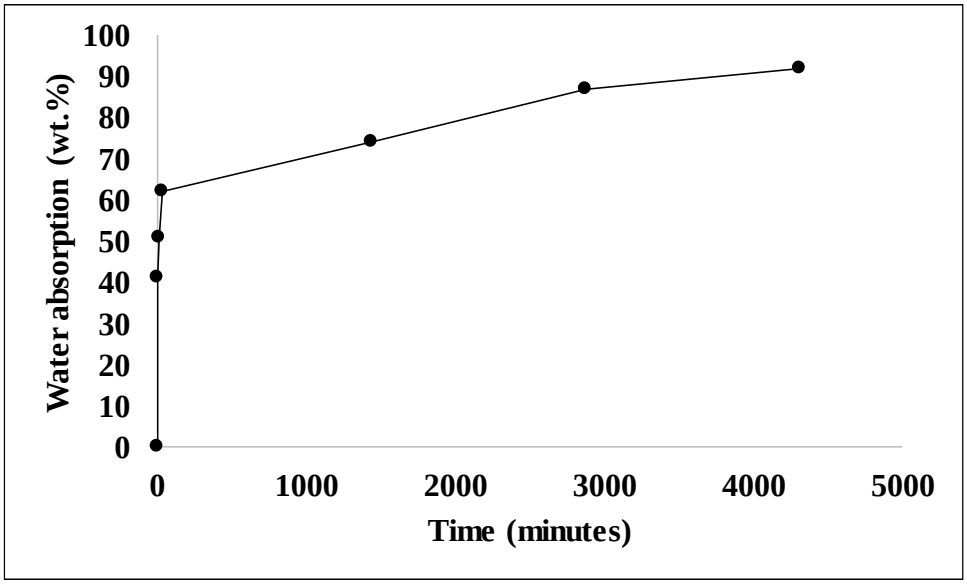

Figure 7: Water absorption of rice husk

The water absorption value after 48 h (2880 minutes) was about 88%. The increase in water absorption with time was due to the presence of a hollow cavity in the rice husk. This increase was small compared to that found with kenaf fibres (230% – Ouedraogo et al., 2017) and coir (163% – Nkotto et al., 2020). On the other hand, results obtained were similar to those of Cesar et al. (2009), who used *Agave lecheguilla* fibres impregnated with protective solutions such as kerosene, polyvinyl (5 to 10 wt.%) and xylene (20 to 40 wt.%) under the same conditions as in our study.

The water absorption was mainly at the surface and in the hollow cavity because ice husk does not have porosities; it is compact and rigid.

The low water absorption value could be an advantage for the ageing of the composites with the clay material.

The biochemical composition of the rice husk reported by Morgan (2015) is shown in Table 4.

Table 4: Mineralogical composition of rice husk (Morgan, 2015)

Cellulose (wt.%)	Hemicelluloses (wt.%)	Lignins (wt.%)	Silica (wt.%)
25-35	18-21	26-31	15-25

It appears from Morgan's study that rice husk is not rich in cellulose but is richer in lignin than other plant fibres, as presented in Table 5.

Table 5: Biochemical composition of some vegetal fibres (Akil et al., 2011, Ismail et al., 2011, Godin et al., 2010, Morel et al., 1997, Millogo et al., 2014**)**

Vegetal Fibres	Cellulose (wt.%)	Hemicelluloses (wt.%)	Lignins (wt.%)
Kenaf	71	20	4
Flax	71	19-20.6	2.2
Hemp	70-74	18-22.4	3.7-5.7
Jute	61-71	14-20	12-13
Sisal	63-64	12.0	10-14
Cotton	85-90	5.7	-

The hemicellulose content of all these plant materials is of the same order of magnitude, except for coton (Ouedraogo et al., 2017). In contrast to the other vegetal fibres, rice husks contain a significant amount of silica. This high silica content prevents rice husks from degrading naturally like other vegetal materials, which is a problem for farmers, who cannot use them to amend their soils (Garba et al., 2020).

The scanning electron microscopy observation of the rice husk (Fig. 8.a) shows "hooks" on the surface, which appear to be solid. The rough, hooked surface of the rice husks will promote good adhesion with clay particles (Ouedraogo et al., 2017, Ouedraogo et al., 2019, Bamogo et al., 2020). This will help to strengthen the adobes containing rice husk. Chemical analysis by Energy Dispersive X-ray spectrometry (Fig. 8.b) carried out on dried and ground rice husks showed that they contained high levels of carbon (16.89 wt.%) and silica (23.48 wt.%), which gave the husk its solid appearance, and also a significant proportion of aluminium, potassium and magnesium oxides.

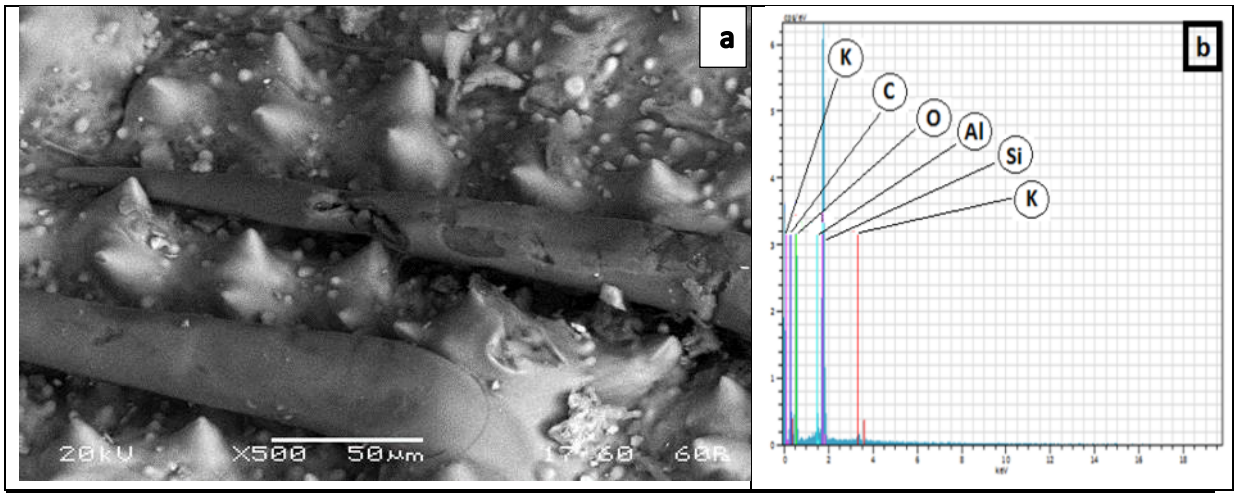

Figure 8: Scanning electron microscopy (a) and EDS analyses (b) of the rice husk

The Fourier Transform Infrared spectrum of raw and processed rice husks (Fig. 9) shows the presence of OH groups (3677 cm^{-1}), celluloses (Le Troedec et al. 2008), C-H aliphatics (2988, 2920, 1377, 1157, 895 and 794 cm^{-1}), and carboxyles C=O (1731 cm^{-1}) present in hemicelluloses (Huo et al., 2013; Fernandez et al. 2007), C=C-C (1607 and 1513 cm^{-1}) of the aromatic ring (Blanchart et al., 2010), deformation of xylan groups of lignins (1230 cm^{-1}) and antisymmetric stresses C-O-C (1160 and 1036 cm^{-1}) of celluloses and hemicelluloses.

The diffractogram of rice husks (Fig. 10) shows that the only crystalline substance they contain is cellulose (Millogo et al., 2015).

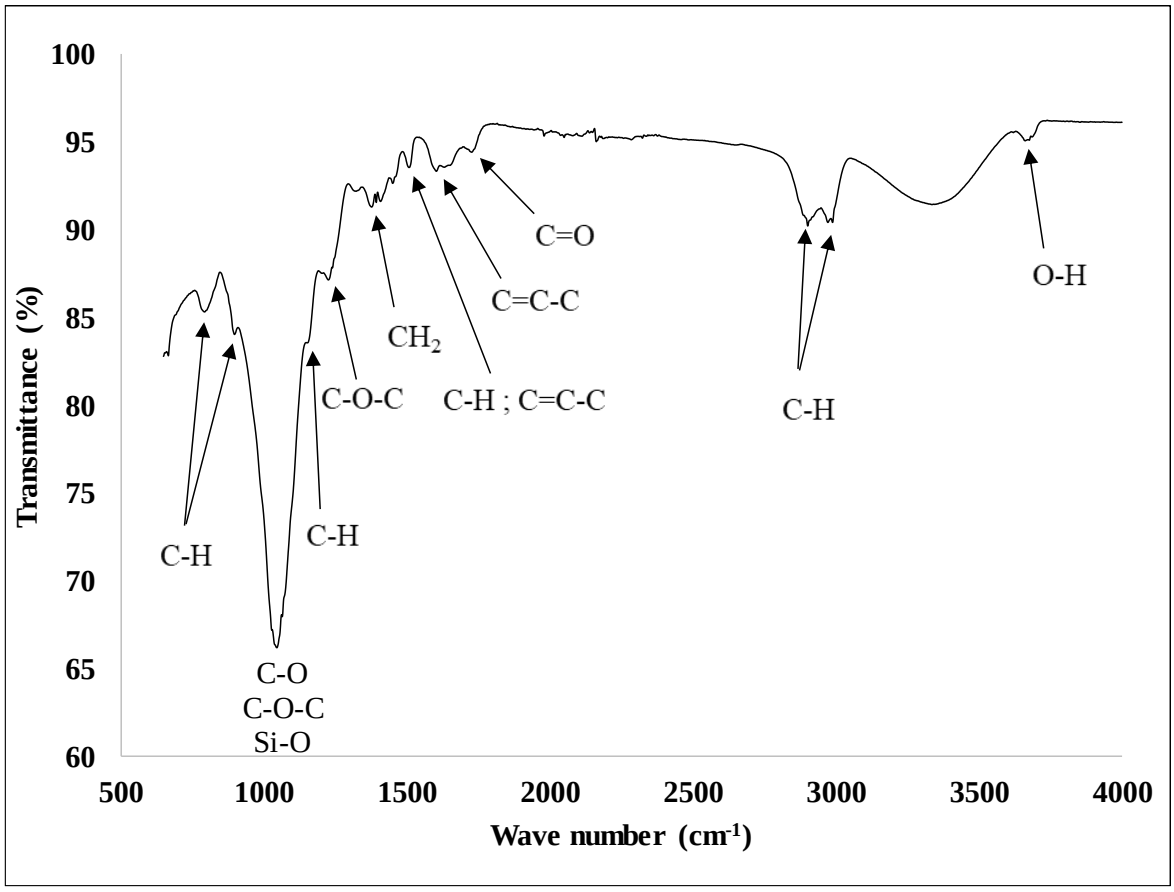

Figure 9: Infrared spectrum of the rice husks

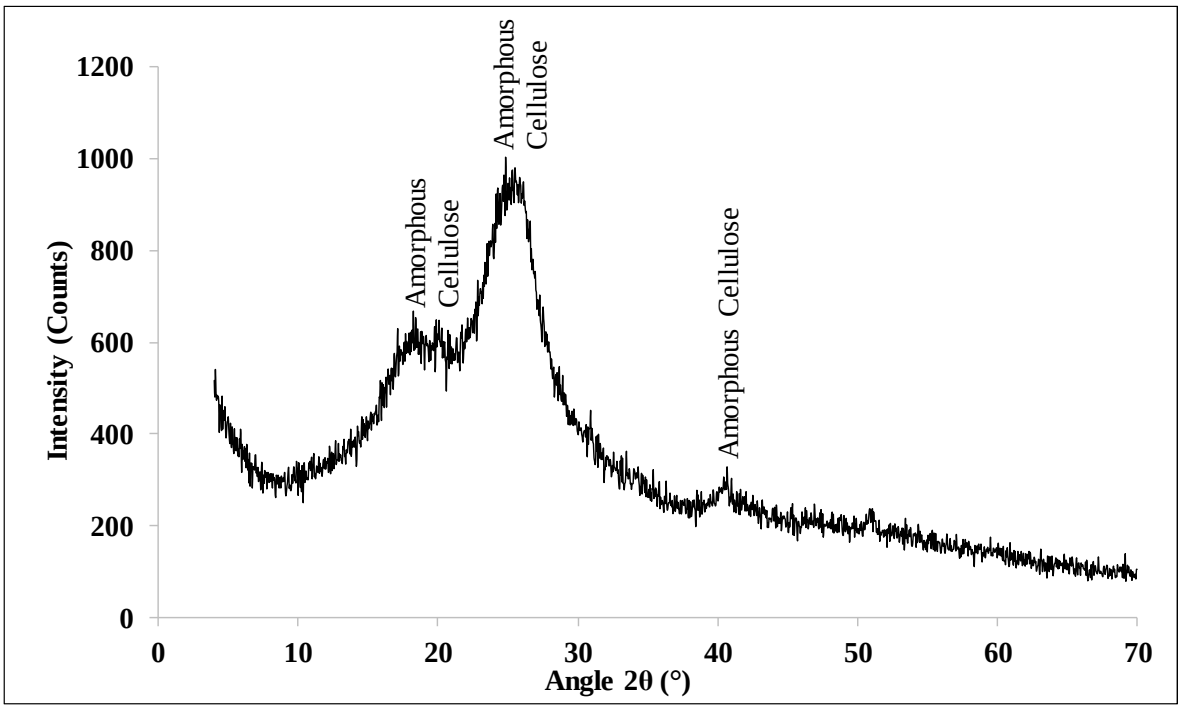

Figure 10: Diffractogram of rice husks

3.2. Density and microstructure of adobes reinforced with rice husks

As the density of rice husks is considerably lower than that of the KORS clay soil, a decrease in the bulk density of the adobes is observed with increasing rice husk content in the clay matrix (Fig. 11).

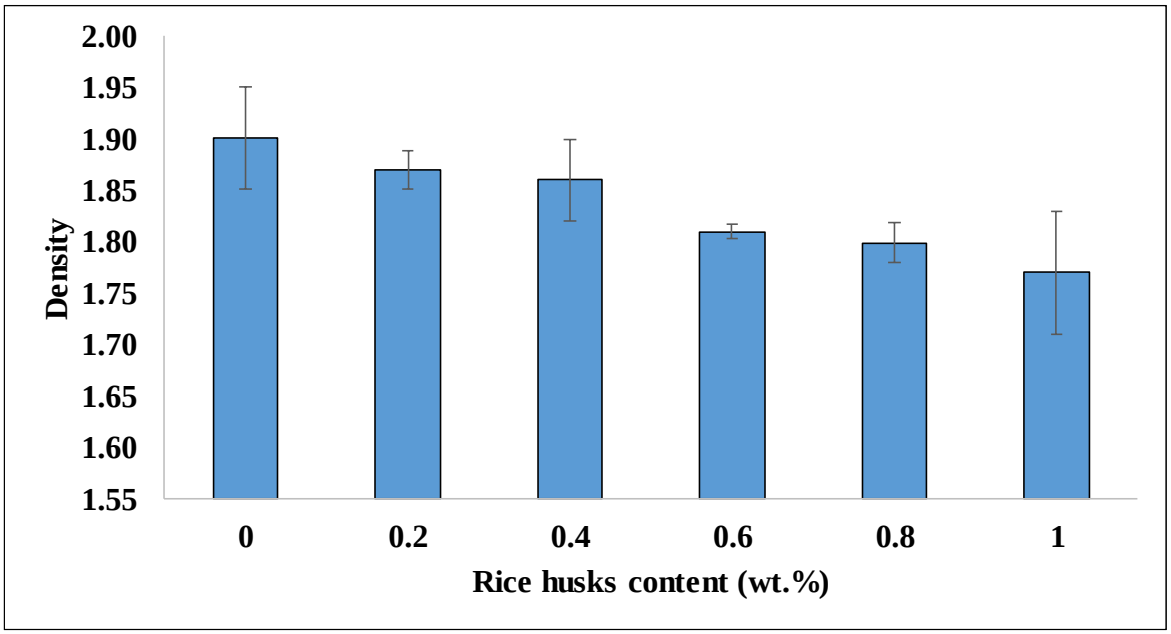

Figure 11: Density of adobes versus rice husk content

The video microscopy images of breaking natural adobe faces indicate a heterogeneous microstructure with the presence of cracks and large pores (Fig. 12.a). Such a microstructure could negatively affect the physical and mechanical properties of adobes. Adobes reinforced with 0.2 wt.% rice husks have a very homogeneous microstructure, without cracks, but there are nevertheless some small pores (Fig. 12.b). This homogeneous microstructure with low porosity could improve the physical and mechanical properties. Adobes containing more than 0.2 wt.% rice husks (Figs 12.c and 12.d) have very heterogeneous microstructures with reappearance of cracks, large pores and crowding of the rice husks in some areas, especially for a 1 wt.% rice husk content (Fig. 12.d). Such microstructures could lead to a reduction of physical and mechanical properties.

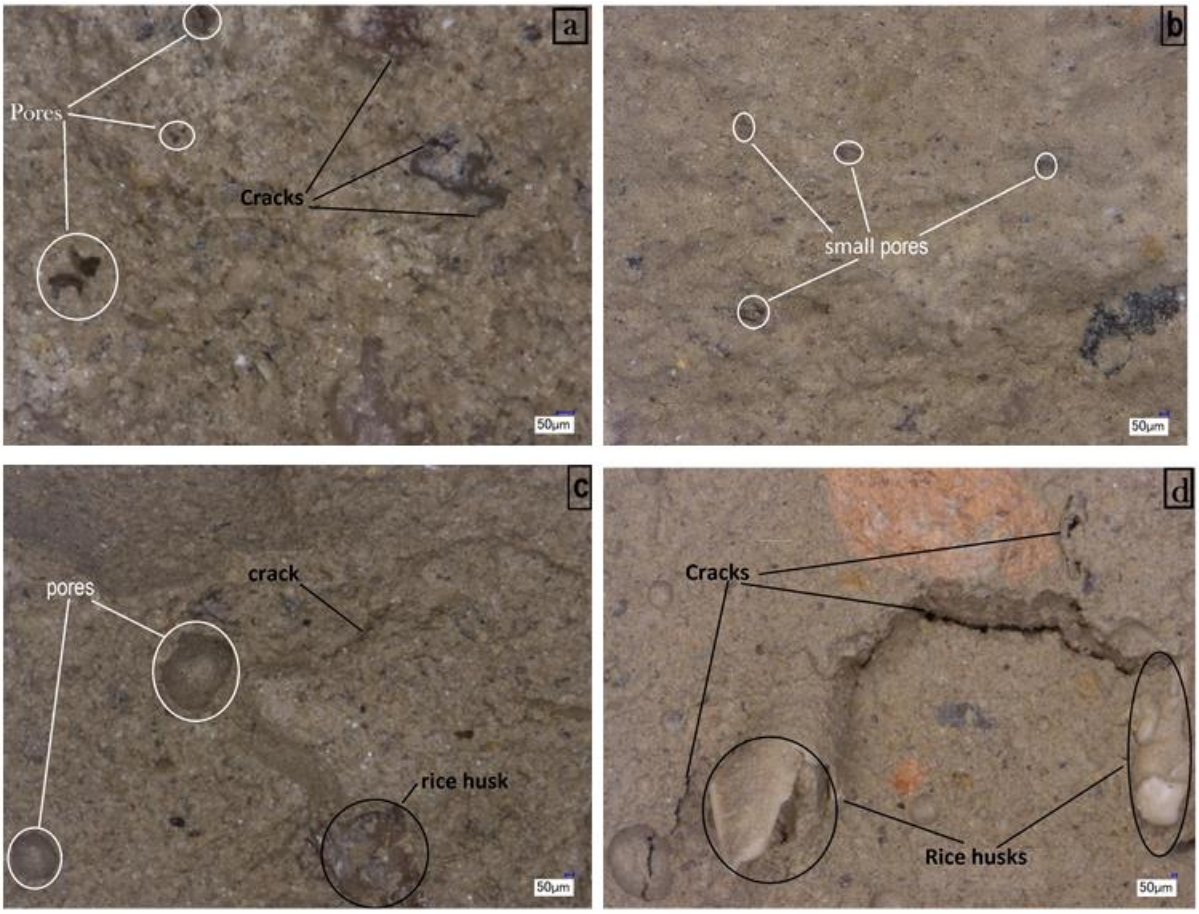

Figure 12: Video microscopy of adobe fracture surfaces: 0 wt.% (a); 0.2 wt.% (b); 0.8 wt.% (c) and 1 wt.% (d) of rice husks

At high contents (more than 0.2 wt.% rice husks), the clay matrix/plant aggregate interface shows macro cracks and pores. This observation is similar to that of Bouguerra et al. (1998), on the incorporation of wood aggregates into a cement matrix. These studies show that the matrix/wood aggregate interface presented macropores due to the structure of the aggregates.

3.3. Physical properties of adobes

3.3.1. Thermal conductivity

Figure 13 shows that the addition of rice husks decreases the thermal conductivity of the adobes.

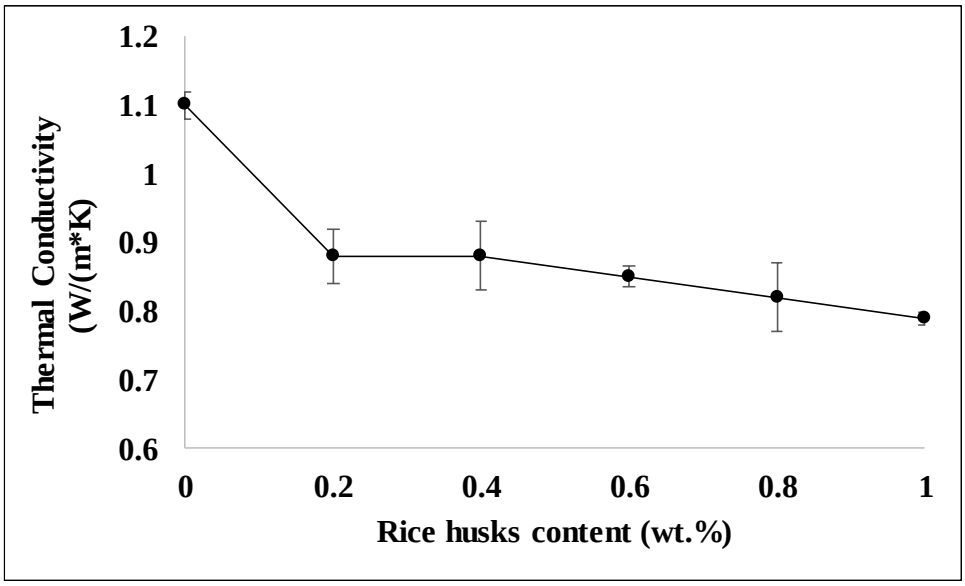

Figure 13: Thermal conductivity of adobes versus rice husk content

This result is well correlated with the video microscopy observations. The presence of many pores in the adobes reduces their heat conduction because the pores contain air, which is a good thermal insulator with a thermal conductivity of 0.02 $W.m^{-1}.K^{-1}$ at 20 °C (Strnad and Vengar, 1984). In addition, the decrease of thermal conductivity is related to the presence of rice husks containing cellulose, which is also a good thermal insulator. Compared to that of adobes stabilized by kenaf fibres (Ouedraogo et al., 2017), the thermal conductivity of adobes amended by rice husks is high. This is related to the high cellulose content of kenaf fibres compared to rice husks and is also due to the presence of more pores in adobes stabilized by kenaf fibres. Moreover, the thermal conductivity of rice-husk-reinforced adobes is lower than that of Toussiana lateritic stone blocks (0.96 $W.m^{-1}.K^{-1}$) and adobes made with Kors clay or other cement-stabilized clay soils (Dao et al., 2018; Abhilash et al., 2016; Meukam et al., 2003). The high conductivity value of cement-stabilized adobes is due to the fact that these types of adobes have homogeneous microstructures with few, mainly closed, pores. The presence of rice husks in the clayey matrix promotes the creation of pores, which contributes to a decrease in thermal conductivity through the combined effect of the presence of internal pores and the insulating nature of the cellulose contained in the rice husks.

3.3.2. Water resistance

3.3.2.1. Capillary water absorption

The coefficient of water absorption by capillarity of adobes decreases with the addition of rice husks until the husks make up 0.8 wt.% of the material (Fig. 14). This decrease is due to the low porosity of the husks (as shown in Fig. 12), and to the homogeneous microstructure, with few pores, of adobes reinforced by the rice husks. After 0.8 wt.% of rice husks, the absorption coefficient increases due to the presence of macro cracks and pores in the matrix as observed in Figure 12. This result differs from those obtained with adobes stabilized with kenaf fibres (Ouedraogo et al., 2017) due to the higher hydrophilicity of the latter, which results from their high cellulose content compared to rice husk.

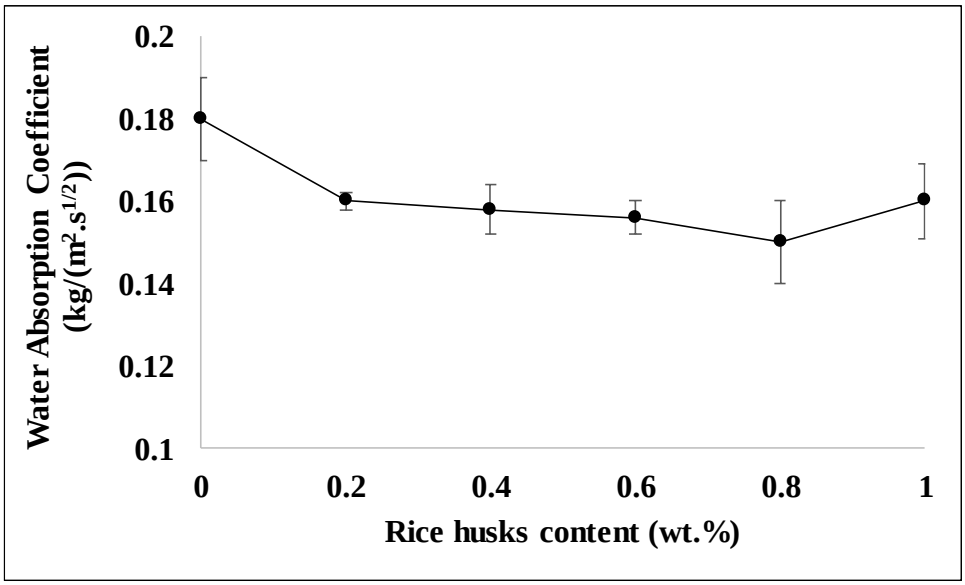

Figure 14: Capillary water absorption coefficient as a function of rice husk content

3.3.2.2. Resistance to water erosion

When comparing natural adobes with those amended with rice husks (Fig. 15), a marked loss of clay particles can be observed in adobe without rice husks. The reduced mass loss in adobes containing rice husks is due to the good cohesion between clay particles and the rough surface of the husk. This cohesion is also believed to be improved by the formation of hydrogen bonds between the free doublets of oxygen and the hydrogen of clay minerals (kaolinite and muscovite), and those of rice husks (cellulose, lignin, hemicelluloses) (Ouedraogo et al., 2019).

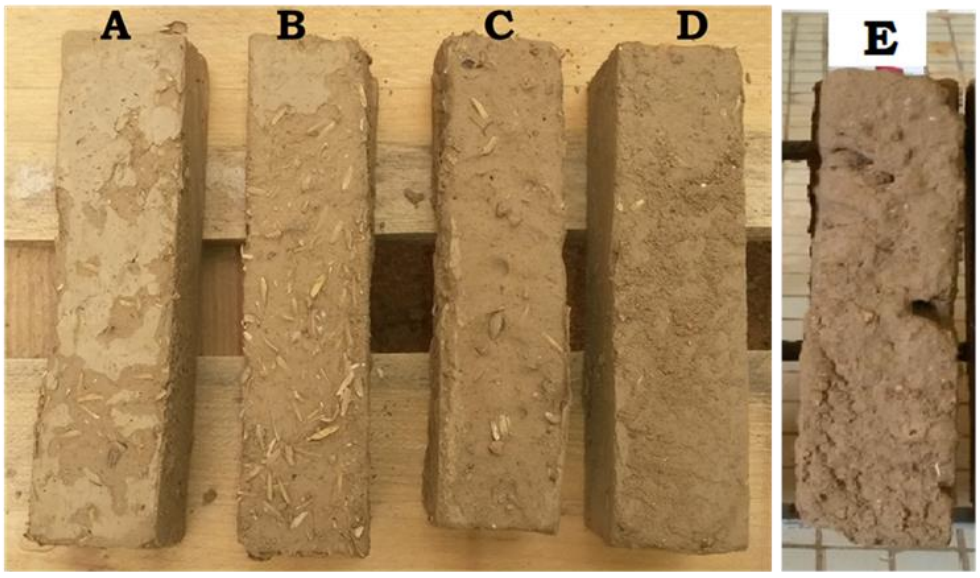

Figure 15: Adobes reinforced with rice husks after spray test ((A) 0.2 wt.%; (B) 0.6 wt.%; (C) 0.8 wt.%; (D) 1 wt.% and (E) 0 wt.%)

The erosion resistance of adobes increases with the amount of rice husks until this amount reaches 0.8 wt. % (Fig. 16). This resistance is due to the ability of rice husks (plant aggregates) to protect clay particles against water erosion. The effect of rice husks in adobes is similar to that of plant roots controlling mechanical soil erosion (Danso et al., 2015; Huat et al., 2010; Michalowski et al., 1996). The rice husks give better resistance to the adobes. Erosion is generally a surface phenomenon but it can also occur by infiltration of water into cracks and open pores. Adobes (0.2 to 0.6 wt. % rice husks) with few pores and cracks (Fig. 12.b for 0.2 wt.%) are hardly subject to erosion. Adobe with 0.8% rice husks (Fig. 12.c) has pores and cracks but the high proportion of rice husks has a marked preventive effect against erosion. However, adobe at 1% shows weak resistance to this water phenomenon because a very high supply of plant aggregates reduces the cohesive strength of the clay matrix by creating a large number of pores and cracks (Fig. 12.d). Rice-husk-reinforced adobes are more resistant to erosion than those amended by kenaf fibres (Ouedraogo et al., 2017). This result is explained by the fact that, unlike kenaf fibres, rice husks make the microstructure more homogeneous when they are incorporated in the clay matrix, as their rougher surface results in good adhesion with fewer pores.

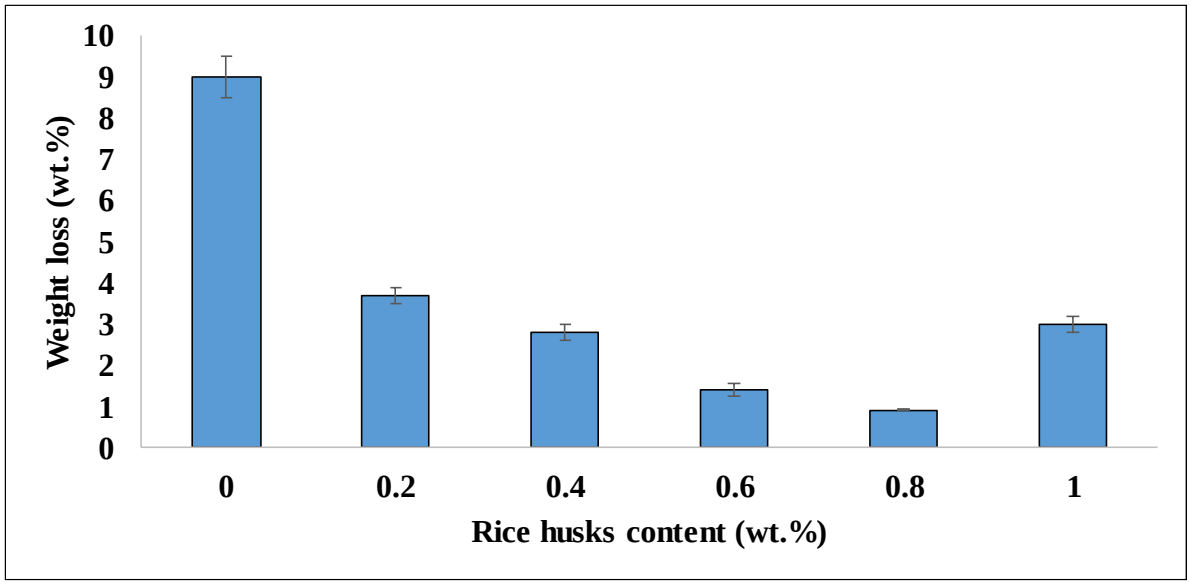

Figure 16: Mass loss of adobes reinforced with rice husks

3.4. Mechanical properties of adobes

The three-point bending strength of adobes stabilized by rice husks (Fig. 17) increased with the percentage of husks, reaching 1.25 MPa for 0.2 wt.%. This value is higher than the bending strengths adobes reinforced with sisal fibres 20 and 50 mm in length, which are respectively 0.23 and 0.25 MPa (Mesbah et al., 2004), and also of blocks of Burkina Faso lateritic stone dried outdoors, which has a strength of 1.08 MPa (Abhilash et al., 2016). This high value is, however, lower than the bending strength of the adobes reinforced with 30 mm kenaf fibres (Ouedraogo et al., 2017).

This was due to the cellulose content of kenaf fibers (Ouedraogo et al., 2017), which is higher than that of rice husks (Tran et al., 2014; Mansaray et al., 1999) and the great length of kenaf fibers (Ouedraogo et al.,2017) compared to the 7 mm of rice husks (Armstrong, 2001). The positive impact of rice husks on the bending strength of adobes is related to the fact that they contain a considerable amount of cellulose, a crystalline molecule with significant tensile strength (Millogo et al., 2016; Millogo et al., 2014; Ghavami et al., 1999).

This result is also due to the homogeneous microstructure without a large number of pores (Fig. 12.b) in adobes to which rice husks are added as an adjuvant, at low levels. The significant drop in bending strength observed for formulations rich in rice husks (above 0.4 wt.%) is explained by a heterogeneous distribution of the husks in the clayey matrix resulting in a microstructure that is more heterogeneous, with pores and even cracks, than adobes without adjuvants (Figs 12.c and 12.d). This way of using cellulose is also mentioned in the literature (Millogo et al., 2014) and explained by the good resistance to deformation and the small size of rice husks, which occupy the pores of the adobe, thus reducing the spread of cracks. The extent of this reinforcement mechanism depends largely on microstructural parameters, such as the size of the rice husks, the level of shear force in the rice husk/clay matrix interface, and the average breaking stress of the adobes to which the rice husks are added.

The addition of up to 0.4 wt% rice husks increases the compressive strength of the adobes (Fig. 18). This is due to good adhesion of the rice husks to the clay matrix, favoured by their rough surfaces (Fig. 8.a). The presence of rice husks in adobes prevents the propagation of cracks observed in natural adobes (Fig. 12.a). Above 0.4 wt.% rice husks, the compressive strength of adobes decreases. This is similar to findings by Becchio et al. (2009) concerning Mineralized Wood Concrete (MWC), where compressive strength was observed to be correlated with density and decreased regularly with the increase of wood aggregate content. The adobe formulations studied in the present work show high heterogeneity in the distribution of rice husks in the clay matrix (Figs 12.c and 12.d) causing a large number of pores and cracks in the adobes. The compressive strength of the adobes is better than that of the adobes reinforced with kenaf fibres (Ouedraogo et al., 2017) or fonio straw (Ouedraogo et al., 2019) using the same Kors clay. This is due to the better microstructural organization for adobes amended with rice husks than those reinforced with kenaf fibres and to the strengthening of the clay matrix by rice husks because of their high silica content.

With regard to adobes having a compressive strength greater than 2 MPa, the adobes elaborated can be used for house construction (Mbumbia et al., 2000; CID 1991; CID 2000).

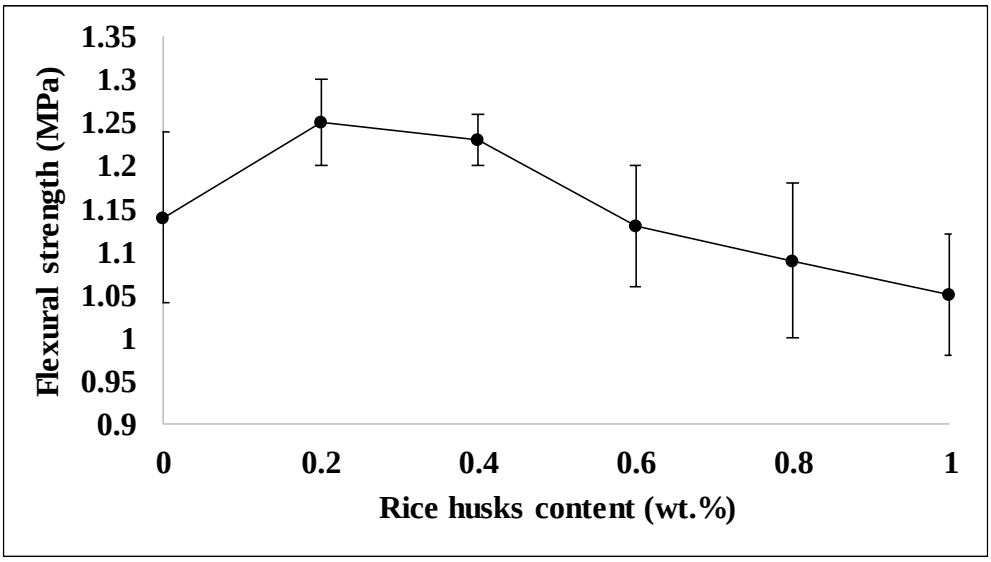

Figure 17: Flexural strength as a function of rice husk content

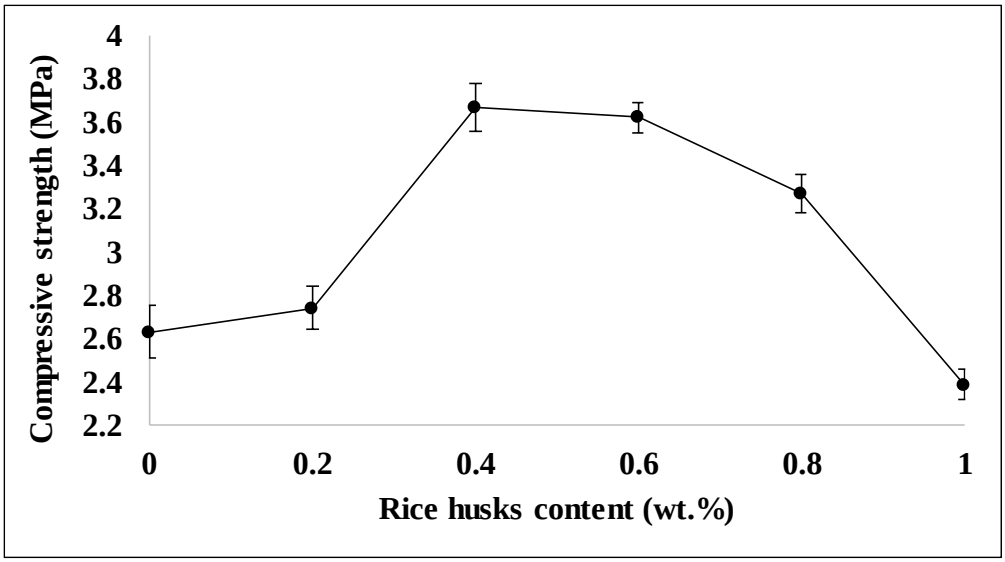

Figure 18: Compressive strength as a function of rice husk content

4. Conclusions

This paper has dealt with the manufacture of resistant, durable adobes with low thermal conductivity, using rice husks as stabilizers. A moderately plastic clayey soil composed of kaolinite (28 wt. %), quartz (49 wt. %), goethite (7 wt. %) and muscovite (9 wt. %) was used to manufacture adobes reinforced with 0.2, 0.4, 0.6, 0.8 and 1 wt.% of rice husks. The chemical and microstructural characteristics of the rice husks and the physical, the mechanical and the microstructural characteristics of the adobes produced have been evaluated.

From the results presented in this paper, the following conclusions can be drawn:

1. The presence of rice husk in the clay matrix considerably reduces capillary water absorption if the rice husk content is less than or equal to 0.8 wt. %. This decrease is due to the low porosity of rice husks and to the homogeneous microstructure of adobes reinforced by such husks.
2. The resistance to rain erosion is much improved. The mass loss of 8 wt. % for adobes amended with 0.8 wt. % rice husks could be explained by the rough surface of rice husk particles.
3. The decrease in the thermal conductivity of adobes with rice husk additions is due the presence of cellulose in rice husks (insulating material) and to the presence of closed porosity in adobes. Thermal conductivity decreases from 1.1 to 0.8 $W.m^{-1}.K^{-1}$ (corresponding to a decrease of 28%).
4. The addition of rice husks to the clay matrix improves the bending strength (1.25 MPa for 0.2 wt. %) and compressive strength (3.7 MPa for 0.4 wt. %) of adobes. This is due to the homogeneous microstructure obtained with rice husk addition, the pores being reduced thanks to the good adhesion between rice husks and clay matrix. Rice husk additions also contribute to the formation of hydrogen bonds between hydrogen and oxygen doublets of clay and rice husk molecules, thus increasing the density of composite materials and preventing the propagation of cracks. The improvement of compressive strength is also due to the large amount of silica in rice husks.
5. The results obtained in this study show that the optimal amount of rice husks to be added depends on the property in question. Considering the mechanical strength, the best results were obtained with 0.2 and 0.4 wt.% of rice husks whereas, for the water resistance, they were obtained with 0.8 wt.% of rice husks. Considering all parameters, it seems that an addition of 0.4% could be a good compromise and provide suitable material for the construction of resistant, durable and comfortable dwellings.

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