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Formulation and Thermomechanical Characterization of Earth-based Biosourced Composites: Cases of Clay-*Hibiscus cannabinus L.* Fiber, Clay-sawdust and Clay-*Oryza sativa* Husk

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This work concerns the technical study of implementation, thermal and mechanical characterization of a composite material based on clay and plant fibers, in order to meet the need for bioclimatic and sustainable houses. The objective was to find the proportions of clay and fibers to obtain a mixture that would give better thermal properties. A characterization of the thermal properties was made thanks to the KD2 Pro analyzer on samples of various formulas of mixture clay-plant fibers. The results obtained showed that the thermal properties such as thermal conductivity and thermal diffusivity of the clay-fiber mixture samples decrease with the increase of the fiber content in the mixture. Thus, the thermal conductivity of the samples varies from 0.85 to 0.65 W/m.K; from 0.88 to 0.72 W/m.K and from 0.83 to 0.75 W/m.K respectively with *Hibiscus cannabinus L.* fiber, sawdust and *Oryza sativa* husk. As for the thermal diffusivity, it varies from 0.37 to 0.25 mm^2/s; from 0.45 to 0.30 mm^2/s and from 0.47 to 0.27 mm^2/s respectively with the addition of *Hibiscus cannabinus L.* fibers, sawdust and *Oryza sativa* husk. In sum, the earth samples stabilized with *Hibiscus cannabinus L.* fibers offer better thermal properties for the construction of bioclimatic houses.

Keywords: Composite material; bioclimatic houses; thermal conductivity; thermal diffusivity.

1. INTRODUCTION

Issues related to global warming, the reduction of greenhouse gas emissions, the excessive consumption of fossil fuels and, more generally, the need to adopt lifestyles more in line with the notion of sustainable development are increasingly present in decisions and analyses and affect most sectors of activity and development. The building industry is no exception to this awareness and has been undergoing considerable changes over the last years, in particular with the increasingly intense implementation of eco-construction principles and techniques. The building consumes energy during the manufacture of materials (cement, brick, sand, tiles, ...) and during its life cycle. On a global scale, the building sector represents 30 to 40 % of total energy consumption and a large share of anthropogenic environmental impacts [1]. As a result, it has great potential for improvement in both energy and environmental terms. To meet these energy and environmental challenges, several solutions can be implemented in a complementary manner. These solutions, applied to the building, lead to work simultaneously on the energy consumption of the building, its structure and its various equipment, from the design phase. It is in this context that this study is being carried out. It is particularly in line with the research of new and innovative techniques of energy saving as eco materials for new buildings, hence the interest of this work. The objective is to develop formulas of Eco materials produced from local resources (clay and vegetal fiber) with a good compromise between mechanical and thermal resistance. This will contribute to the thermal comfort in the building in the strongly Sunny zones like Sahelian countries.

Sahelian countries have with a hot and dry tropical climate; They usually have abundant amounts of clay materials likely to be used for the formulation of bio-based construction composites. Indeed, in these regions, the most used techniques for construction are those of hand-made mud bricks and compressed earthen bricks (BTC). Some research has been conducted in the past years about the materials and the earthen construction techniques aiming at a better use of this local, abundant and easily recyclable natural resource. But the raw adobes are facing some issues of mechanical resistance and water retention. To solve this issue, many scientific work has been conducted on the incorporation of the plant fibers in clay-based composite materials [2–5].

Millogo et al. [3] studied the thermal behavior of earth and *Hibiscus Cannabinus L.* fibers composites and found that the thermal conductivity decreases with the increase of the contents and the lengths of the fibers. They concluded that this decrease is related to the decrease in the density of the composite. Labat et al. [6] have shown that earth-straw composite could have a density between 241 and 531 kg/m^3 with a thermal conductivity varying from 0.071 to 0.12 W/(m.K). They concluded that the addition of plant fibers to the earth reduces the density leading to a reduction of the conductivity. It has been demonstrated that the insulating boards formulated with *Hibiscus Cannabinus L.* rods have mechanical characteristics (flexural modulus and tensile strength) superior to those required by the standard XP P13 - 901 (2 MPa) [7]. On the other hand, their thermal characteristics, especially the thermal conductivity is lower than 0.12 W/(m.K) which is the value recommended by the ANSI A208-1, 1999 standard. Thus, the thermal conductivity decreases with the addition of *Hibiscus Cannabinus L.* fibers and this is mainly due to the presence of cellulose in the fibers which is a good thermal insulator [8].

Furthermore, in an international context marked by an increasing need for energy and by climatic disruption, the conception of sustainable bioclimatic habitats with low energy consumption for the populations of the developing countries with low income is a necessity. So, on the basis of the interactions between the envelope of the habitats and their environment whose effects are not necessarily expected or considered at first, we oriented our research towards the formulation of clay and *Hibiscus Cannabinus L.* fiber-based materials, rice husk and sawdust in order to improve the mechanical strength and the thermal properties.

2. MATERIALS AND METHODS

2.1 Raw Materials

2.1.1 Clay

Clay is one of the main construction materials used for thousands of years in various regions of the world with different methods according to its features. The clay earth used in this work has been extracted from a pit in Malgsombo in the center region (township of Saaba) of Burkina Faso. These are white clay (MSB-BL), red clay (MSB-RG), weak clay or sandy clay (MSB-FB), strong clay (MSB-FR) and the mixture (MSB-ME). The grain size of five (05) samples of this earth has been determined by sifting and by sedimentometry respectively according to NF P 94-056 and NF P 94-057 standards. The thickness of these five (05) samples has been respectively determined through the determination of Atterberg limits and methylene blue value according to NF P 94-051 and NF P 94-068 standards.

2.1.2 *Hibiscus cannabinus L.* fibers

Hibiscus cannabinus L. is a yearly plant, with a summery growth belonging to the *Malvaceae* family [9]. This is a plant of the cotton family, whose fibers are extensively used in Burkina Faso to fabricate bags and ropes. These fibers have been recently used in new sectors such as in construction, insulation and automobile. *Hibiscus cannabinus L.* has long been used to manufacture a range of products, including clothing, paper and industrial products in industrialized countries [7]. The fiber of *Hibiscus cannabinus L.* used in this work was collected in the west central region of Burkina Faso. Fig. 1 shows the image of the *Hibiscus cannabinus L*. plant.

2.1.3 *Oryza sativa* husk

Rice husk is a co-product derived from the transformation of *Oryza sativa (*rice*)*. It consists of the set of bracts or lemmas that wrap the grain. After protecting the seed during its growth, the husk can be used as reinforcement in construction materials (mud bricks). In addition, many studies have shown that rice husk composites have better mechanical characteristics (tensile strength 32 N/m^3) and a density ranging from 86 to 114 kg/m^3 [10]. Fig. 2 shows the image of the *Oryza sativa* husk. The rice husk used in this work was collected from a local rice husking plant.

Fig. 1. *Hibiscus cannabinus L.*

Fig. 2. ***Oryza sativa*** **husk**

Fig. 3. Sawdust

2.1.4 Sawdust

Wood is one of the most used materials by man. The residues of timber cuttings and transformation represent one of the main biomasses studied for the absorption of metals and constitute almost 40% of the total mass of the timber. Unfortunately, these wastes are not sufficiently valued and are then considered as final wastes [11]. They are generally incinerated leading to an important release of carbon dioxide (CO_2), otherwise, left on the spot causing health issues in cities.

Sawdust possesses an important intrinsic porosity, due to the presence of capillaries. Clay constitutes a fine mineral. The mixture of these constituents of very different nature and features give a material whose porosities will be variable according to the volumetric concentrations of each constituent. Fig. 3 shows the image of the sawdust. In this work sawdust has been collected from local sawmills.

2.2 Measurement Equipment

2.2.1 KD2 Pro analyzer

The KD2 Pro analyzer is a portable device developed by DECAGON Inc. This device complies with the standard IEEE 442-1981 and ASTM D5334-08 and can be used at the laboratory or on the field. Its principle is based on the method of the hot wire. Some research on the thermal properties of soil and other porous materials during 30 years permitted the construction of this very sophisticated analyzer for the measurement of the thermal properties. The analyzer is very sensitive because a person's movement in the laboratory or the heat of the sun on the field affects the accuracy of the measurement of the thermal properties [12]. Fig. 4 shows the image of the KD2 Pro analyzer and its sensors.

The KD2 Pro analyzer is delivered with three sensors “SH-1”, “TR-1” and “KS-1”.

Every sensor is specific to a type of given material. The SH-1 sensor adapted to solid and granulated materials, used in our case, measures the conductivity, the diffusivity, the resistance and the calorific capacity. It is a sensor with double needles of 1.3 mm of diameter out of 60 mm of length spaced 6 mm.

2.2.2 Mechanical press

The device used for the compression test is a hydraulic press type Instron 8516 with a capacity of 100 kN. This test is governed by the standard NF EN 14617-15. Fig. 5 shows the picture of mechanical press.

Fig. 4. The measuring device of the thermal features: KD2 Pro

Fig. 5. Mechanical press

2.3 Methods and Experimental Procedures

From previous research, it appears that the fiber incorporation improve the properties of the materials such as cement, concrete, BTC [13]. For this purpose, in this work, we intend to investigate different formulas of composite materials from clay and *Hibiscus Cannabinus L.* fiber, rice husk and sawdust. In order to make a comparative study of the composites reinforced by these three fibers, we have carried out a uniform dosage of 0.2%; 0.5%; 1%; 1.5%; 2%; 2.5% and 3%. The mass m_i corresponding to the percentage of the input i required for the different dosages was determined using the relation:

$$m_i = \frac{P_i \times m_0}{100} \quad \text{(E.1)}$$

m_0 is the earth mass considered and P_i the percentage of the incorporated organic material i. The different masses are measured with a digital scale of 0.001 g precision.

Thus, the test samples were designed with these various proportions and for the sake of symmetry, all samples were formulated with approximately the same dimensions. Table 1 shows the different proportions of the components used in each formula.

After the determination of the different proportions and the elimination of the stones and dead leaves of the earth, a homogeneous dry mixture with the inputs according to the set dosages has been made. Then, the mixture is soaked in a well-definite quantity of water during 24 hours. After the 24 hours and before moving to the formulation, the mixture is mixed while adding water progressively until the desired consistency. The quantity of necessary water is determined by adding the quantities of water of the two (02) phases (soaking and mixture). Finally, the mixture is molded in two (02) molds of respective dimensions 18.5x9x9 cm^3 and 16x4x4 cm^3. After demolding, the bricks covered with fiber bags are dried in a shed to avoid rapid drying that could lead to cracks. The different steps of the formulation of the test samples are summarized in Fig. 6.

Table 1. Formulas of the test samples

Mass of clay (kg)	Fiber ratio (%)	Mass of fiber (kg)	The samples formulated	
			18.5*9*9 cm^3	16*4*4 cm^3
7	0.2	0.014	3	6
7	0.5	0.035	3	6
7	1	0.07	3	6
7	1.5	0.105	3	6
7	2	0.14	3	6
7	2.5	0.175	3	6
7	3	0.21	3	6

Fig. 6. Production diagram of test samples

3. THERMAL AND MECHANICAL CHARACTERIZATION

3.1 Technical and Procedure of the Mechanical Compression Test

This involves submitting a sample of brick to compression until it reaches its breaking point. The objective is to determine the nominal resistance in dry and wet compression of compressed earthen blocks. The test consists in placing the test sample between the press plates and to apply the load continuously with a speed of 0.05mm/s until the sample is completely broken. The maximum load supported by the sample during the test is then recorded. The compressive strength of the blocks is given by the equation 2:

$$R_c = 10\frac{F}{S} \tag{E.2}$$

where:

R_c : compressive strength in MPa ;

F : maximum load supported by the two bricks in kilo newtons (kN) ;

S : average area of the test faces in square centimeters (cm^2).

The compressive strength of the blocks is the arithmetic average of the strengths of at least three trials test performed on samples of the same formula.

3.2 Technical and Procedure of Three-Point Bending Test

The three-point bending test is carried out on samples of dimensions 4x4x16 cm^3. The principle of this test is to measure the metric parameters (length, width and thickness) of the test sample with a grouting foot. Then, the sample is placed on two supports spaced by a length l according to the size of the sample and perpendicular to its length. In the axis above the sample, parallely to the short side, another support is placed on top of a plate on which an increasing force is exerted until the sample breaks. The value of the breaking load is recorded and the bending strength of the sample under test is determined by applying the following relationship:

$$R_f = \frac{3Fl}{2bh^2} \tag{E.3}$$

F : load at break of the block in bending in kilonewtons (kN)

l : length between the two supports in millimeters (mm)

b : basis of the straight section of the block in millimeters (mm)

h : height in millimeters (mm)

R_f : bending strength in megapascals (MPa)

3.3 Operating Mode of the KD2 Pro Analyzer

The procedure consists of piercing two parallel holes at the level of the needles of the sensor. The holes must neither be too big, to avoid the losses of heat during the measurement, nor too small because the needles must be completely inserted in the sample. The duration of the measurement depends on the volume of the sample, the more the sample is voluminous the more a long time is necessary to have precise results. In our work, we took five (05) minutes for the measuring time. To take into account the thermal gradient, fifteen (15) minutes of break are observed between two successive measurements. To carry out a measurement, it is necessary to insert the needles in the holes after applying the thermal frost.

3.4 Evaluation of Measurement Errors

The measurement errors are calculated by applying the standard deviation. this is done by repeating the measurement at least three times on three samples of the same formula. then we calculate the mean value from which we evaluate the error of the measurement. The function standard deviation uses this relation:

$$Sd = \frac{\sqrt{\left(X_i - \overline{X}\right)^2}}{N * \overline{X}} \tag{E.4}$$

$\overline{X}$: average of the measurements on a sample

N : number of samples

X_i : value of a measurement

4. RESULTS AND DISCUSSIONS

4.1 Properties of Clay Used

Fig. 7 shows the results of particle size analysis. From this figure, we note that these soils have a similar granulometry and are all contained in the ideal spindle recommended by CRAterre to be used as building material for earth bricks. The MSG-BL clay has a fine fraction of 47.85 %, a clay fraction of 20.61%.

Table 2 the results of particle size and argility analysis. From this table, we note that the MSG-BL clay has a methylene blue value in the range [6;8]. The plasticity index of this clay is in the range [20;40]. This clay obeys the requirements in terms of granularity and its relatively high clay fraction will favor its adhesion with the additives that are the vegetable fibers. Moreover, the grading curve of this clay is in the ideal range of CRAterre for soils that can be used in the manufacture of BTC or adobes [14]; therefore MSB-BL clay is suitable for the manufacture of mud bricks [15,16].

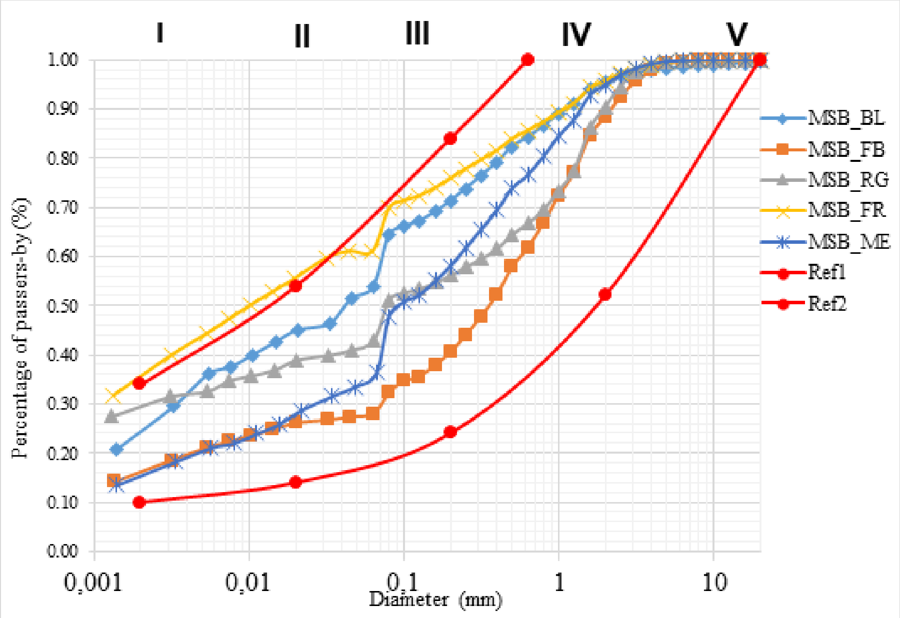

Fig. 7. Particle size analysis through sifting and sedimentometry

Table 2. Atterberg limits and methylene blue value of the studied lands

Samples	Atterberg Limits				Blue Value (BV)
	Liquidity limits W_L (%)	Plastic Limit W_P (%)	Plastic Index IP (%)	Withdrawal limit W_S (%)	
MSB-RG	62	30	32	18.66	5.99
MSB-ME	49	24	25	16.17	8.26
MSB-BL	52	26	26	17.36	7.66
MSB-FR	53	25	28	19.09	7.50
MSB-FB	51	26	25	17.63	9.33

4.2 Mechanical Properties

4.2.1 Compressive strength

Compressive strength is often used to evaluate the stiffness potential of stabilized bricks. Table 3 shows all the results obtained on dry compressive strength. These results concern the three types of fibers (*Hibiscus cannabinus L.*, sawdust and *Oryza sativa* husk) and the seven (07) dosages (0.20; 0.50; 1.00; 1.50; 2.00; 2.50 and 3.00%).

To better appreciate the effects of the addition of stabilizers on the compressive strengths of stabilized adobes, the results of Table 3 are presented in Fig. 8 where the relative errors due to the measurements are shown.

Table 3. Values of compressive strengths according to the ratio and the nature of the fibers

Fiber ratio (%)	Values of compressive strength Rc (MPa)		
	Hibiscus cannabinus L.	**Sawdust**	***Oryza sativa* husk**
0.2	6.87 ± 0.03	3.38 ± 1	4.13 ± 0.72
0.5	7.62 ± 0.07	4.51 ± 0.08	4.21 ± 0.21
1	8.19 ± 0.46	4.83 ± 0.3	4.66 ± 0.44
1.5	8.58 ± 0.57	5.08 ± 0.73	4.75 ± 0.54
2	8.78 ± 0.54	5.25 ± 0.2	4.78 ± 0.19
2.5	8.99 ± 0.39	5.48 ± 0.63	4.81 ± 0.31
3	9.09 ± 0.33	5.56 ± 0.49	5.05 ± 0.22

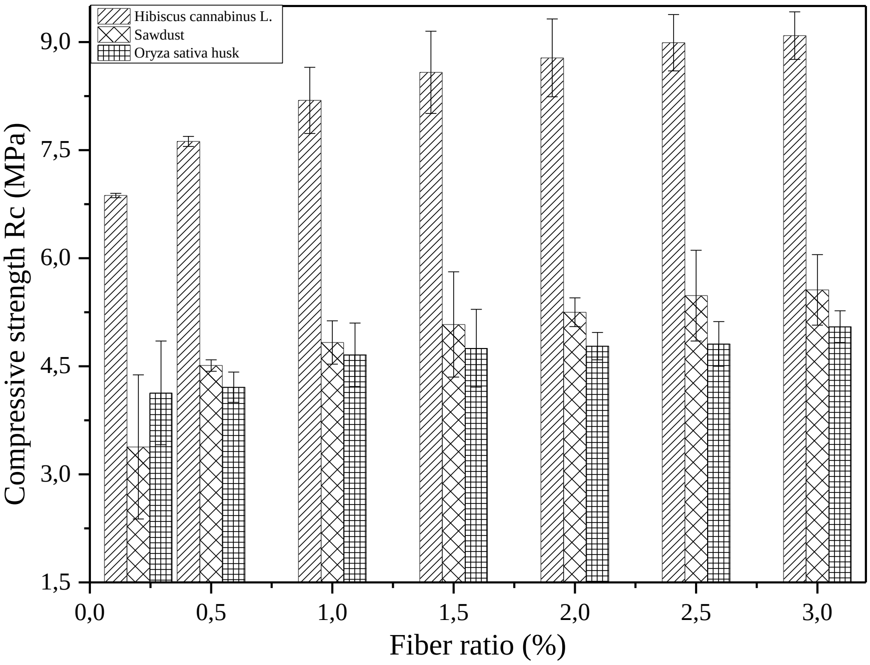

Fig. 8. Compressive strength Rc (MPa) according to the type and fibers ratio in mixture

The results of the destructive compressive test, of the samples of earth bricks stabilized in cold by vegetable fibers, presented in Table 3 and on Fig. 8 confirmed that these fibers are good stabilizer. Through these results, we observe the evolution of the compressive strength of the bricks according to the rate of fibers in the mixture. Thus, for fiber contents of 0.2 %, 0.5 %, 1 %, 1.5 %, 2 %, 2.5 %, and 3 %, we obtained compressive strengths that ranged from 6.87 MPa to 9.09 MPa; from 3.38 MPa to 5.56 MPa; and from 4.13 MPa to 5.05 MPa, respectively, for *Hibiscus cannabinus L.*, sawdust, and *Oryza sativa* husk fibers. The optimal compressive strength is obtained with a dosage of 3% of *Hibiscus cannabinus L.* fibers. We note in particular that for these fibers the values are clearly higher than for the other fibers; but this variation is small after a dosage of 1.5 % *Hibiscus cannabinus L.* fibers. According to the values found in the literature [18], earthen bricks stabilized with the two other fibers are also satisfactory. These results are in good agreement with the conclusions of the study by other authors on lateritic mud bricks in Burkina Faso [17]. In this study, they showed that the compressive strength of unstabilized earthen bricks ranges from 0.38 MPa to 4.87 MPa.

Our results remain in relative agreement with those found by other authors on a study done on the compressive strength of earth blocks stabilized with hydrated lime and fiber [18]. They found that the compressive strength of these blocks reached 8.63 MPa after 45 days of cure. By referring to the CRAterre prescription, which recommends a threshold stress of at least 4MPa for the construction of stabilized or unsterilized not earthen bricks, we can conclude that our materials are suitable for use as masonry elements [19]. Moreover, in Burkina Faso, the standard NBF 02-003/2009, concerning the physical-mechanical and hydric properties of cement-stabilized earthen blocks, recommends a compressive strength of at least 6 MPa for load-bearing multi-storey structures, 4 MPa on the first floor and 2 MPa for no-load-bearing structures.

4.2.2 Three-point bending strength

Table 4 shows the results of the destructive three-point bending test of cold-stabilized earthen bricks with the three types of plant fibers (*Hibiscus cannabinus L.*, sawdust and *Oryza sativa* husk).

In order to fully appreciate the effects of the addition of plant fibers on the three-point bending strengths of the stabilized samples, the results of Table 4 are presented in Fig. 9.

Although masonry units are often subjected to compressive stresses, they are sometimes stressed in bending. The study of the response of bricks to bending stresses is therefore of great importance. Table 4 and Fig. 9 show the complementary results of destructive testing of the study samples. According to these results, it can be seen that the bending strength of composites based on these three types of fibers has a similar evolution. For composites reinforced with *Hibiscus cannabinus L.* fibers, it increases from the ratio of 0.2 % to the ratio of 1.5 % and decreases from this ratio to the ratio of 3 %. We note that the values of bending strength of composites based on *Hibiscus cannabinus L.* fibers are higher than those of composites based on sawdust and *Oryza sativa* husk. This can be justified by the fact that *Hibiscus cannabinus L.* fibers have a high tensile strength.

Table 4. Values of bending strength according to the rate and nature of the fibers

Fiber ratio (%)	Values of bending strength R_f (MPa)		
	Hibiscus cannabinus L.	**Sawdust**	***Oryza sativa* husk**
0.2	1.20 ± 0.13	1.12 ± 0.08	**1.00 ± 0.05**
0.5	1.22 ± 0.15	**1.15 ± 0.10**	0.97 ± 0.03
1	1.28 ± 0.21	1.03 ± 0.08	0.95 ± 0.13
1.5	**1.45 ± 0.26**	0.98 ± 0.08	0.88 ± 0.10
2	1.13 ± 0.10	0.92 ± 0.10	0.80 ± 0.05
2.5	1.07 ± 0.13	0.87 ± 0.08	0.75 ± 0.18
3	0.92 ± 0.10	0.77 ± 0.08	0.65 ± 0.05

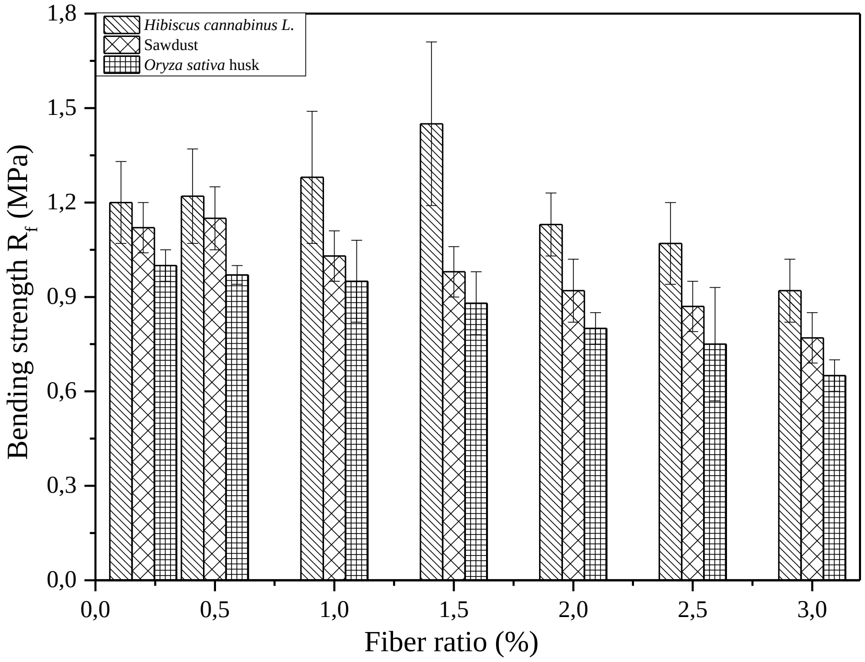

Fig. 9. Evolution of the bending strength according to the ratio and the type of fibers

Table 5. Thermal properties of soil + *Hibiscus cannabinus L.* fiber mixture samples

Samples	λ (W/m.K)	Cp (J/kg.K)	α (mm^2/s)	E ($J/s^{1/2}.m^2.K$)
MSB-K0.2	0.85 ± 0.02	1312.86 ± 19.16	0.37 ± 0.01	1409.93 ± 37.96
MSB-K0.5	0.73 ± 0.04	1405.63 ± 135.45	0.36 ± 0.02	1284.12 ± 78.20
MSB-K1	0.73 ± 0.01	1223.12 ± 149.87	0.36 ± 0.04	1231.84 ± 59.03
MSB-K1.5	0.75 ± 0.03	**1133.88 ± 62.91**	0.34 ± 0.005	**1195.79 ± 67.43**
MSB-K2	0,71 ± 0,01	1162.85 ± 2.94	0.31 ± 0.03	**1188.44 ± 10.54**
MSB-K2.5	0.69 ± 0.01	1653.93 ± 35.59	0.27 ± 0.01	1376.54 ± 10.78
MSB-K3	0.65 ± 0.02	1644.36 ± 65.45	0.25 ± 0.02	1316.03 ± 43.75

Table 6. Thermal properties of soil + sawdust mixture samples

Samples	λ (W/m.K)	Cp (J/kg.K)	α (mm^2/s)	E ($J/S^{1/2}.m^2.K$)
MSB-SB0.2	0.88 ± 0.02	1614.97 ±16.81	0.45 ± 0.04	1561.94 ± 22.16
MSB-SB0.5	0.82 ± 0.01	1319.40 ± 98.60	0.37 ± 0.02	1349.26 ± 29.30
MSB-SB1	0.79 ± 0.08	**1051.58 ± 58.89**	0.41 ± 0.01	1178.56 ± 27.11
MSB-SB1.5	0.76 ± 0.05	1248.44 ± 29.90	0.37 ± 0.02	1270.56 ± 53.92
MSB-SB2	0.75 ± 0.03	833.50 ± 42.48	0.36 ± 0.01	**1028.89 ± 60.69**
MSB-SB2.5	0.74 ± 0.02	1275.33 ± 25.89	0.34 ± 0.01	1245.52 ± 32.04
MSB-SB3	0.72 ± 0.01	1630.49 ± 96.94	0.30 ± 0.03	1382.17 ± 43.84

For all *Oryza sativa* husk and sawdust contents in the mixture, the bending strength of the composites is not improved, it is even significantly reduced when the fiber content in the mixture has increased. For these fibers the values remain the lowest and have an ambiguous evolution. The optimal bending strength is reached for a dosage of 1.5 % of *Hibiscus cannabinus L.* fibers in the mixture, whether 1.45 MPa.

In general, we find that the bending strength decreases when the fiber content in the mixture increases. This finding is most noticeable in the sawdust and rice husk composite samples. This phenomenon can be justified by the fact that the presence of fibers increases the porosity of the bricks. A low porosity improves the mechanical tenacity of stabilized earthen bricks [20]. The porosity increases strongly with the addition of fibers in the matrix whatever the length of the fibers because the fact that the fibers play a role of air entrainment during the mixing stage of the "soil+fiber" mixture [21].

Although our results are relatively low, we note that the values found are higher than the bending strengths of non-fibrous earthen bricks (0.9MPa) found by [22] and those of cement block bricks (1.11 MPa) found by [23].

4.3 Thermal Properties

The thermal properties of samples of biosourced clay-based materials, characterized by the KD2 Pro analyzer, are presented in the Tables 5,6 and 7. Indeed, we present in these tables the main thermal properties that allow to qualitatively appreciate the thermal performance of a building material. These are thermal conductivity, thermal capacity, diffusivity and thermal effusivity.

In order to fully appreciate the influence of the nature of the fiber and its proportion in the composite on the variation of the intrinsic properties of the final product, we represent the evolution curves of these properties on the Figs. 10 and 11.

Thermal conductivity, specific heat and diffusivity are the main thermal properties evaluated in this study. From a value of 0.975 W/m.K for the no-fibrous brick sample, the thermal conductivity of biosourced materials based on the same clay stabilized with *Hibiscus cannabinus L.* fibers decreases from 12.82 % to 38.24 %. For the samples of soil + sawdust mixture the decrease is from 9.74 % to 26.15 %. However, the decrease is not very clear for the soil + *Oryza sativa* husk mixture samples; the highest recorded is 23 % for these samples.

Table 7. Thermal properties of soil + *Oryza sativa* husk mixture samples

Samples	λ (W/m.K)	Cp (J/kg.K)	α (mm^2/s)	E ($J/S^{1/2}.m^2.K$)
MSB-BR0.2	0.83 ± 0.01	1186.32 ± 119.46	0.47 ± 0.01	1326.71 ± 55.14
MSB-BR0.5	0.76 ± 0.02	1198.97 ± 34.40	0.43 ± 0.01	1267.30 ± 15.34
MSB-BR1	**0.75 ± 0.10**	**867.75 ± 23.87**	0.39 ± 0.01	**1103.12 ± 70.42**
MSB-BR1.5	0.79 ± 0.001	1055.59 ± 27.14	0.36 ± 0.07	1196.14 ± 10.91
MSB-BR2	0.79 ± 0.02	1240.06 ± 49.32	0.32 ± 0.01	1319.09 ± 13.54
MSB-BR2.5	0.79 ± 0.02	1441.18 ± 157.98	0.31 ± 0.02	1433.94 ± 83.00
MSB-BR3	0.80 ± 0.05	1412.92 ± 38.71	0.24 ± 0.01	1387.46 ± 38.66

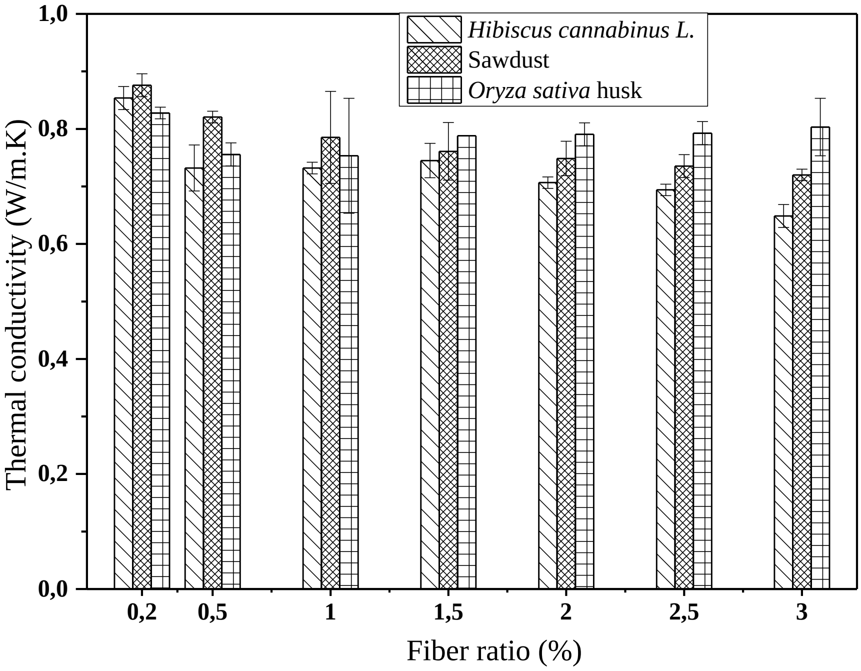

Fig. 10. Evolution of the thermal conductivity

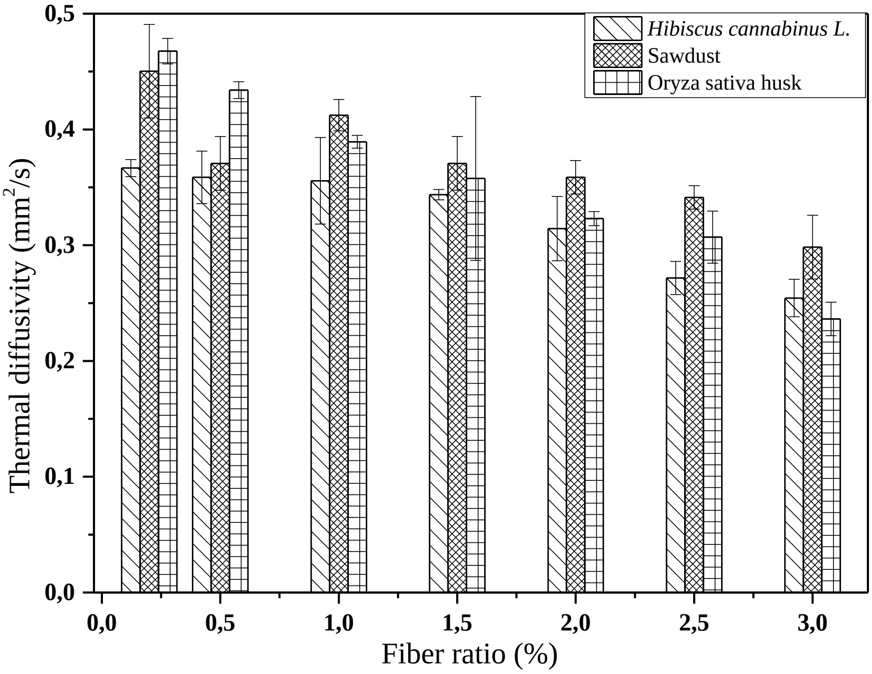

Fig. 11. Evolution of the thermal diffusivity

We note that for *Hibiscus cannabinus L.* fibers and sawdust, the decrease in thermal conductivity is linear with values that vary respectively from 0.85 W/m.K to 0.65 W/m.K and from 0.88 W/m.K to 0.72 W/m.K. The same applies to other parameters such as heat capacity and thermal diffusivity. Depending on the fiber content in the mixture, we can see that with a higher fiber content, the thermal conductivity values are a little lower, except for the case of the soil + *Oryza sativa* husk mixture samples.

From these results, we note that for all three types of fibers the thermal conductivity of the samples stabilized with 0.2 % fibers is higher than that of those stabilized with 3 % fibers. The addition of plant fibers with low thermal conductivity reduces heat transfer by conduction [24]. This mode of heat transfer in the material takes place mainly at the contact dots between the seeds forming the material, hence the small increase in the value of thermal conductivity. Indeed, the presence of fibers in the matrix leads to an increase in the porosity of the material [25]; which increases the volume of air occupied by the voids in the sample. The air being a good thermal insulator (λ_{air} =0.025104 W/m.K), the heat will propagate with difficulty in the samples, this explains the results noted with regard to the influence of plant fibers on the thermal conductivity of materials.

The results also show that the specific heat ($Cp = 1650$ J/kg.K) is obtained with 2.5% *Hibiscus cannabinus L.* fibers and the lowest thermal conductivity ($\lambda = 0.65$ W/m.K) is obtained for 3% of *Hibiscus cannabinus L.* fibers. The samples stabilized with rice husk have the highest thermal conductivities (0.83 W/m.K to 0.75 W/m.K) and a not linear evolution.

As far as thermal diffusivity is concerned, it shows a similar evolution for all samples formulated with the three types of fibers. We notice that the materials become less and less diffusive when the fiber content increases in the mixture. These results allow us to say that biosourced materials based on earth diffuse less heat and offer in this case a very good thermal inertia; which would make it possible to meet the needs for thermal comfort in bioclimatic houses. This result is confirmed in the literature for studies conducted by some authors [26].

Finally, the thermal effusivity obtained for all the samples does not have a very good configuration. Its evolution does not follow the increase of the fiber content in the mixture; it increases and decreases at the same time. Materials with a high thermal effusivity have the ability to impose their temperature; that is to say to absorb heat without heating up [27]. In comparison with conventional materials such as cinder block (E ≈ 850 $J/S^{1/2}.m^2.K$), our materials are more effusive with an optimal value found for brick stabilized with 0.2 % sawdust.

In general, we can say that the bricks we have formulated are thermally insulating due to their low thermal conductivity, high effusivity and low diffusivity. These materials will therefore be very advantageous for sub-Saharan areas with high thermal variation such as Burkina Faso.

5. CONCLUSION

The results of this study highlight the variation of the thermal and mechanical characteristics of composite materials based on clay stabilized by vegetable fibers. Indeed, the thermophysical and mechanical tests were carried out here with the aim of appreciating the importance of the stabilization of the bricks of ground with certain stabilizers that they are the fibers of *Hibiscus cannabinus L.*, the sawdust of wood and the *Oryza sativa* husk. Since the work carried out by other authors revealed that kenaf fibers improve the thermal and mechanical quality of mud bricks [3], we were interested in the influence of its proportions on the properties of the final product and to compare them with other vegetable fibers.

In general, we noted an increase in the mechanical and thermal characteristics with the increase of the ratio of fibers in the earth matrix. Thus, we note a maximum compressive strength of 9.09 MPa for 3 % of *Hibiscus cannabinus L.* fibers and a maximum bending strength of 1.45 MPa for 1.5 % of the same fiber. And for the thermal properties, we noted the low thermal conductivity (λ=0.65 W/m.K) for 3 % of kenaf and the highest thermal capacity (Cp=1650 J/kg.K) is obtained with 2.5 % of this fiber. However, the *Oryza sativa* husk reinforced composites were more diffusive with the lowest value obtained for 3 % *Oryza sativa* husk in the mixture.

In conclusion, we can say that according to these thermal properties, a housing envelope built with our materials could have a better thermal response to the solicitations of the external environment.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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