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Thermophysical, Mechanical and Durability Characterization of Adobe Bricks Reinforced with Fonio (*Digitaria exilis*) Sounds

Colbert Babé[1*], Etienne Yanné[2], Souaibou[2], Mojonda[2], Lémankréo Bakaiyang[3], Bernard Kola[1,4], Gustave Assoualaye[1], Layndé Tawé[3], Raidandi Danwé[2], Dieudonné Kidmo Kaoga[1], Noël Djongyang[1]

[1]Department of Renewable Energy, National Advanced School of Engineering of Maroua, University of Maroua, Maroua, Cameroon
[2]Department of Civil Engineering and Architecture, National Advanced School of Engineering of Maroua, University of Maroua, Maroua, Cameroon
[3]University Institute of Wood Technology, University of Yaoundé I, Yaoundé, Cameroon
[4]Energy Rsearch Laboratory, Institute of Geological and Mining Research, Yaoundé, Cameroon
Email: *babecolbert@gmail.com

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Abstract

Buildings constructed using modern materials such as cement are energy-intensive, facilitate heat transfer and thus promote warming inside the building. However, the Sudano-Sahelian regions have a hot climate occupying a large period of the year, thus requiring not only sustainable construction materials, but also which provide thermal comfort in the building by limiting the energy demand for air conditioning. These qualifications are important for sub-Saharan African countries in general and those of the Sudano-Sahelian zone in particular, which need ecological materials with good thermal performance to limit heating inside buildings. This study is an energy recovery of agricultural waste in buildings with a view to offering the populations of the northern regions of Cameroon suitable materials at lower cost for the construction of buildings. The soil used for this study was extracted from the locality of Yagoua where the populations make abundant use of mud bricks. Fonio waste was incorporated at low levels into the earth bricks, particularly at 0%, 1%, 2%, 3%, and 4%, with a view to strengthening their thermophysical and mechanical properties. The results obtained indicate that earth bricks reinforced with 4% waste showed better thermal and mechanical insulation properties compared to other formulations with an improvement of 16% and 78% respectively compared to the unreinforced samples. This research allows us to conclude that fonio waste can be used practically without expense in the building with a view to its energy recovery and will promote not only thermal comfort and the limitation of the energy supply for air conditioning, but the construction of more sustainable buildings with a cleaner environment.

Keywords

Durability, Thermal Comfort, Building, Soil, Fonio Faste

1. Introduction

The construction sector has always been a changing sector due to technological evolution and rapid population growth. Habitats built with modern or local materials sometimes do not meet the needs of the occupants because of the unskilled workforce of the builders and the lack of sufficient and available knowledge on the use of these building materials [1]. Similar to the development of renewable energy to compensate for the decrease of fossil fuels, building energy consumption has become increasingly studied and mediated. The building construction field uses more energy and contributes to more discharges of cement produce, which represents 5% of the total CO_2 output [2]. Therefore, it is very necessary to adopt a global approach in this industry for the material and building life cycles and create this approach as a sustainable development perspective. Reflections must be made on several scales and considering architectural aspects, such as raw materials, materials, structure elements (wall), and building. Since man has been building, earth has been and remains one of the main building materials [3]. It is the simplest material that we have at our disposal, for reasons of proximity, social and abundance [4]. It is also appreciated for its environmental and social benefits that encourage its use as an important alternative material for the building industry [5] [6]. It was proven that there is at least an earthen wall configuration, which presents better performance than conventional wall (hollow concrete block wall) [7]. These qualifications are important for the sub-Saharan African countries, which require ecological materials with a good thermal performance to limit the heating inside buildings [8]. Unfortunately, this technique, with its many advantages, tends to disappear in many countries in favour of concrete construction, a type of architecture that does not seem to be adapted to the all contexts [9]. In fact, Modern materials are expensive and responsible for pollution and most of these materials promote heating in buildings and therefore less suitable for the Sudano-Sahelian regions. In Europe, cementitious materials, well refer to the image of development, richness, solidity and durability and are well suited for humid and temperate climates [9]. However, in tropical sub-Saharan Africa, the temperature is practically hot all year round. Populations need comfortable indoor temperatures in habitats in order to peacefully carry out their activities [10].

This paper aims to promote earthen construction through the valorization of local building materials by solving two important problems: on the one hand, elaboration of a low-cost material adapted for the construction of habitats in the Sudano-Sahelian zone of Cameroon and, on the other hand, preservation of the environment through the recovery and use of plant waste responsible for pollution.

Previous studies on earth bricks using fibers as reinforcements in the area of this study concern millet, rize, and neem fibers [11]-[13]. Until now, no studies have examined adobes using fonio fibers in the Sudanese-Sahelian zone of Cameroon, from thermophysical and mechanical characterization and sustainability standpoints. As a result, it is difficult to know and forecast its long-term behavior. The lack of data about thermal, mechanical, and sustainability characteristics of the earthen wall in the Sudanese-Sahelian regions of Cameroon constitute the main obstacle to their spreading. In some cases, for example, unsuitable building materials create catastrophic circumstances for the building due to weather variations (rain, heat, wind) and other attacks (friction) during its lifetime. Consequently, damage recorded in some earthen wall during the rainy season and the lack of comfort inside the house during the dry season is sometimes the results of unknown thermal, mechanical, and durability behaviors.

It is preferable to ensure that the material has the main characteristics required, such as thermal, mechanical and durability behaviors before using it as a building material. This paper focuses on the characterization of thermal and mechanical properties as well as durability of adobe bricks used as building materials in the locality of Yagoua (far north region of Cameroon).

Since adobe bricks used in this locality are produced without sophisticated equipment, this study uses a manual method, which is based mainly on the technique used in the field by craftsmen. To characterize adobe bricks, we formulated samples from the soil extracted from the production site and since the artisans use reinforcements randomly, we chose five different adobe samples, with 0%, 1%, 2%, 3%, and 4% of fonio wastes. The samples are characterized by thermal mechanical and durability laboratory tests.

2. Materials

2.1. Soil

The soil used for this study is taken from a production site in Yagoua (Djenseng), Far North Region of Cameroon and near the border with Chad (Bongor) (**Figure 1**). This soil was chosen because of its abundant use in the production of adobe bricks by the local population. Moreover, this locality is chosen because of the frequent housing problems underlined in this locality due to the collapse of the houses linked to the severe weather. It's dark brown earth. A previous study carried out on this soil indicated that it is suitable for the formulation of mud bricks [11].

2.2. Fibers

Fonio is a so-called minor cereal, which, after harvesting in the countryside, undergoes a threshing process that separates it from its lemellae. Fonio, which is grown on sandy or stony soils, is resistant to drought and heavy rainfall. It is mainly found everywhere in the Sahelian regions of Africa, particularly in Guinea, Mali, Benin, Burkina Faso, Togo, Niger, Cameroon… Fonio is much smaller than other commonly grown cereals. The paddy grain is ovoid in shape and is only 1 to 1.5 mm long. The mass of 1000 fonio grains is about 0.5 g. The bran obtained after slaughter is generally considered waste. They are very rarely eaten by some anime and are very often abandoned in the wild (**Figure 2**). Very recently, some craftsmen have started to value them in mud bricks in order to improve their properties in order to have more comfortable buildings [14].

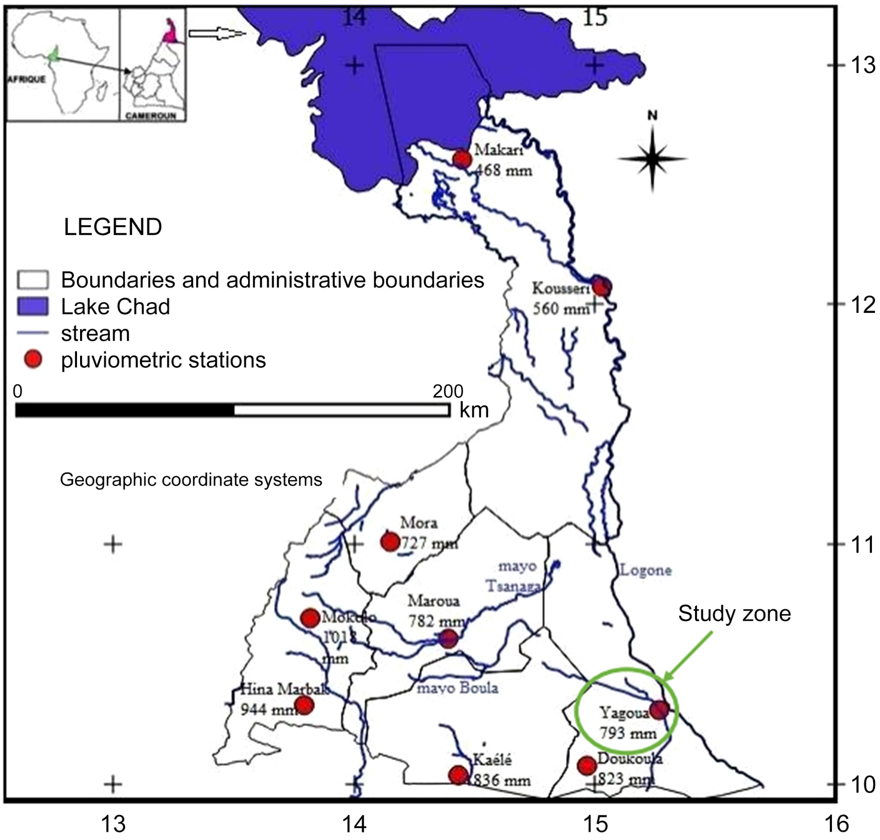


Figure 1. Geographic localization of the study zone.

Fonio field and harvest Threshing fonio Fonio sound (waste used)

Figure 2. Procedure for obtaining the sound of the fonio.

The physical properties of sound fonio used for this study are presented in **Table 1**.

Table 1. Physical properties of fonio fiber.

Physical properties	values
Bulk density (g/cm^3)	0.40
Length (mm)	0.8 - 1.5

2.3. Manufacture of Specimens

The clayey soil used to produce adobes is dried up first and crushed afterward to obtain particles with a maximum grain size of 5 mm. Five compositions from the combination of dried powder of raw material with 0%, 1%, 2%, 3% and 4% by weight of fonio fibers content. Soil is mixed with plant fibers for fifteen minutes with 22% of water by dry weight of soil until it becomes a homogeneous mixture. The clayey paste is covered with plastics at room temperature for three days to promote the fermentation of fibers. The mixture (soil + fibers) is laid in $4 \times 4 \times 16\ \text{cm}^3$ prismatic and $10 \times 10 \times 3\ \text{cm}^3$ cubic mold in three layers and each layer is pressed manually with twenty shocks and progressively another layer is added until the mold is full after the third layer. The specimens are first kept in the shade (22˚C ± 5˚C) in ambient air for 24 h with a humidity of 60% before being demolded to dry. Before carrying out the various tests, the samples are first left in the shade for at least 21 days. Shade drying has been adopted to have samples without any cracks. After drying, the specimens are subjected to mechanical, durability and thermal characterizations.

2.3.1. Thermal Characterization Methods

The experimental device schematized in **Figure 3** includes: A thin flat heating element on which is fixed a type K thermocouple (diameter wires 0.08 mm) inserted between two samples of identical dimensions of the material to be characterized, two isothermal aluminum blocks 4 cm thick with a section identical to that of the samples, a clamping device to control the clamping pressure and the thickness of the inserted device between the aluminum blocks.

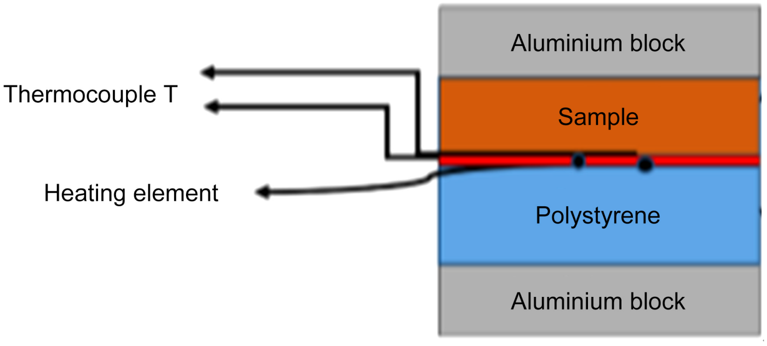


Figure 3. Hot plane method.

The heating element is subjected to a flux step and the temperatures $T_s(t)$ are recorded at the center of the heating element and $T_0(t)$ aluminum blocks. The exploitation of the recording of $T_s(t)$ carried out on a time interval during which the transfer to the center of the heating element is 1D. 3D modeling makes it possible to define this time interval, a simplified 1D model is then used to make an estimate parameters over this time interval.

1D simplified models

The following assumptions are considered: The contact resistances and the thermal resistance of the heating element are negligible compared to the sample resistance , the transfer is 1D at the center of the system for the duration of the experiment, the following temperature gradient Oz is zero in the heating element (thin) and the temperature $T_0(t)$ remains constant.

A probe with a maximum thickness of $2e_s = 0.3$ mm and a thermal conductivity of the order of 0.15 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ has thermal resistance:

$$\frac{e_s}{\lambda_s} = 10^{-3}\,\text{m}^2\cdot\text{K}\cdot\text{W}^{-2} \tag{1}$$

To satisfy the first hypothesis, we will consider that the cases where $\frac{e_s}{\lambda_s} \gg 10^{-3}\,\text{m}^2\cdot\text{K}\cdot\text{W}^{-2}$.

A 1D quadripolar modeling of the system makes it possible to write [13]-[17]:

$$\begin{bmatrix} \theta_S \\ \frac{\varphi_0}{p} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_S p & 1 \end{bmatrix} \begin{bmatrix} A & B \\ C & B \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1 \end{bmatrix} \tag{2}$$

When: $A = D = \cosh\left(\sqrt{\frac{p}{a}}e\right)$; $B = \dfrac{\sinh\left(\sqrt{\frac{p}{a}}e\right)}{\lambda S\sqrt{\frac{p}{a}}}$; $C = \lambda S\sqrt{\frac{p}{a}}\sinh\left(\sqrt{\frac{p}{a}}e\right)$

With: θ_s is a Laplace transform of the difference $T_s(t) - T_0(t)$, ρ_s is a Density of the heating probe, c_s is a mass heat capacity of the heating probe, λ is a thermal conductivity of the material to be characterized, a the thermal diffusivity of the material to be characterized, p Laplace variable and S is the surface of sample and heating element. $C_s = \rho_s c_s e_s S$.

This allows to write [18] [19]:

$$\theta_S(p) = \varphi_0 \frac{B}{BC_S p + D} \tag{3}$$

The temperature $T_s(t)$ in real space is obtained by inverse Laplace transformation which is carried out by De Hoog's algorithm or Stehfest's method:

$$\Delta T(t) = T_S(t) - T_0(t) = L^{-1}\left[\theta_S(p)\right] \tag{4}$$

At very long times we get:

$$T_S(t = \infty) - T_0(t) = \frac{\Phi_0}{\frac{\lambda}{e}} \tag{5}$$

This relation makes it possible to obtain in a very simple a value of the thermal conductivity λ from the value of $\Delta T_{\exp}$ obtained when the regime permanent is reached.

The principle of the proposed method is to estimate the values of the parameters λ and incidentally ρc and $\rho_s c_s$ which minimize the sum of squared deviations:

$$\psi = \sum_{i=0}^{n} \left[\Delta T_{\exp}(t_i) - \Delta T_{\text{mod}}(t_i) \right]^2 \tag{6}$$

between the experimental curve and the theoretical 1D curve over a time interval over which the transfer is 1D at the center of the heating element [18]. The minimization of the sum ψ is carried out using the Levenberg-Marquart algorithm.

For thermal properties measurement, samples are first put in an oven for 48 hours and kept in plastic for 48 hours before carrying out the tests. These bricks are made of cubic pieces of 10 × 10 × 3 cm^3, each.

2.3.2. Compressive and Flexural Strength Tests

For each formulation, three samples, of 4 × 4 × 16 cm^3 each, are used for the uniaxial compression test according to standards NF P18-406 and the six half specimens obtained after the uniaxial compression test are considered to determine the 3-point bending [20] [21]. The compressive and flexural strengths are measured, using a hydraulic press equipped with a 200 kN load, at a controlled displacement rate of 0.5 mm/min.

The compressive strength is calculated by [22]:

$$R_c = \frac{F}{S} \tag{7}$$

where F is the maximum loading force (N), S is the section (mm^2).

The 3-point bending resistance is determined as given [23]:

$$R_f = \frac{1.5 F_f l}{b^3} \tag{8}$$

where F_f is the maximum loading force applied in the middle of the sample (N), l is the length (distance between supports, mm), b is the side of the prism square section (mm).

2.3.3. Durability Test

The test to determine the capillarity water absorption coefficient (A) is carried out on cubic samples (4 × 4 × 16 cm^3), dried up in an oven, at 105˚C for 24 hours. The water absorption coefficient (A) is determined as the drop of mass absorbed water by the sample plotted versus the square root of the time. The adobe samples are weighted using an electronic balance with 0.01 g precision. The value of the water absorption coefficient (A) is determined by the relation [24]:

$$A = \frac{m_1 - m_0}{S\sqrt{t}} \tag{9}$$

where m_0 is the mass of the dry sample, m_1 is the mass of the sample immersed in water, t is time of immersion equal to 600 seconds, and S is the base surface area (4 × 16 cm^2) of the sample. The capillarity water absorption was determined according to the literature [25] and the view of the samples as show in **Figure 4**.

Figure 4. Water absorption test by capillarity of adobes.

For erosion tests, three prismatic adobe samples of 4 × 4 × 16 cm^3 of each formulation are used to simulate the erosion impact of rain for 10 min with a flow rate of 5 l/min. The samples are tilted at an angle of 30˚ to the horizontal. The spray is positioned around 120 mm in height above the sample. The coefficient of erosion test expressed as a percentage of loss material after the erosion test and is given in equation below [26]:

$$CE = \frac{m_0 - m_s}{m_0} * 100 \tag{10}$$

where m_0 is the mass of dried adobes and m_s the mass of the adobes exposed to the erosion test and dried at 105˚C for a duration of 24 h.

3. Results and Discussion

3.1. Specific Heat of Adobes Reinforced with Fonio

The specific heat $C_{\exp}$ is determined from the heat capacity $(\rho C)_{\exp}$ measured using the hot plate device and the density.

Figure 5 shows different values of bricks as in terms of fonio. The results show that the effective temperature increases due to the increase in fonio in the bricks. These values are 1034; 1070; 1115; 1168 and 1217 J·kg^{-1}·K^{-1} with 0%, 1%, 2%, 3%, and 4% fonio added. The specific heat of an object is the energy given to raise the temperature of one part of the object by 1 Kelvin, and we see a 17% difference in specific heat between actual bricks and bricks containing 4% agricultural residues.

These results are consistent with the authors' view that the more an object is heated, the more it burns [27] [28]. The specific heat capacity of adobes increases when their density decreases, since the fibers plants have a higher capacity than mineral elements.

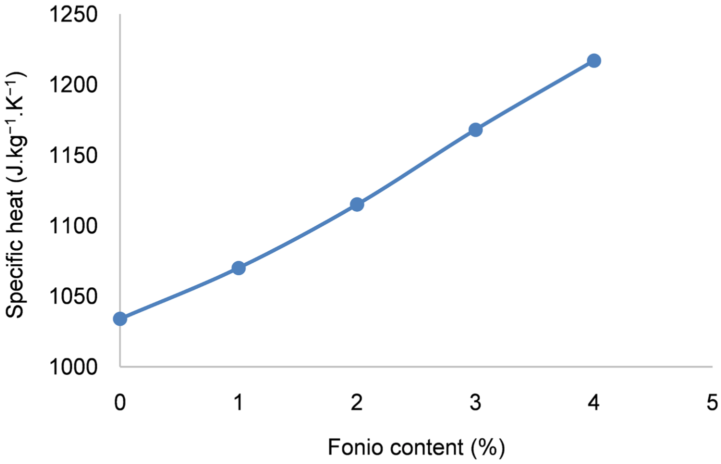


Figure 5. Specific heat of bricks as function of fonio (%).

3.2. Thermal Diffusivity

Figure 6 shows that the temperature change follows the temperature difference and decreases with increasing addition rate. In addition to low temperature, insulating materials must also have good ability to reduce thermal diffusion [29].

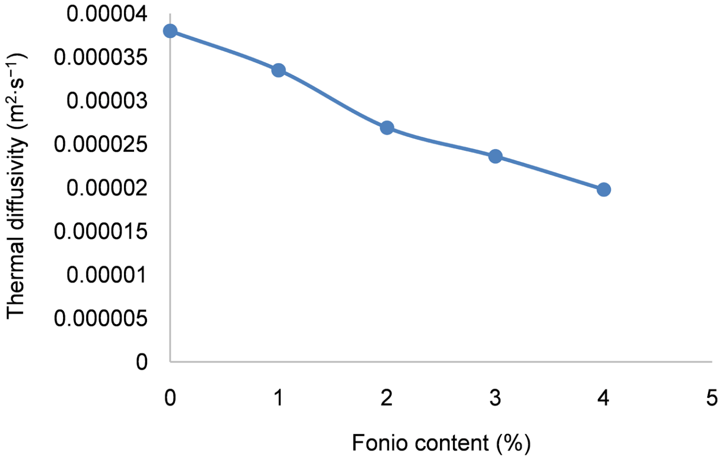


Figure 6. Thermal diffusivity of bricks as function of fonio (%).

In **Figure 6**, it can be seen that the thermal diffusivity decreases with the addition of fonio fibers. A drop of 10% in thermal diffusivity between the reference brick (3.80×10^{-5} $m^2 \cdot s^{-1}$) and that having 4% fonio (1.98×10^{-5} $m^2 \cdot s^{-1}$) is obtained. This reduction is due to the pores in the fonio and their shape acting on the temperature within the group, helping to reduce the vulnerability of the compost and heat conduction. **Table 2** reported differents values of thermal properties.

The porosity rate, the percentages of fiber addition, the composition of materials are all factors that influence the thermal performance of composite. In addition to low heat, thermal insulation should also have a good ability to reduce heat transmission [30] [31].

Table 2. Thermal properties of different samples.

Sample	λ (W·m^{-1}·K^{-1})	ρc (J·m^{-3}·K^{-1})	α (m^2·s^{-1})
Bricks + 0% fonio	0.96	1.90×10^5	3.80×10^{-5}
Bricks + 1% fonio	0.96	1.91×10^5	3.35×10^{-5}
Bricks + 2% fonio	0.94	1.94×10^5	2.69×10^{-5}
Bricks + 3% fonio	0.89	1.96×10^5	2.36×10^{-5}
Bricks + 4% fonio	0.81	1.98×10^5	1.98×10^{-5}

3.3. Thermal Conductivity of Samples

One of the most important aspects for buildings in hot climate environments is the assessment of the behaviour of its building materials in the face of heat. This behavior is evaluated by thermal conductivity, which is the most important thermophysical parameter. It provides information on the ability of the material used in the building envelope, particularly in the load-bearing wall, to be easily or not penetrated by heat.

The following Figure 7 shows the evolution of the thermal conductivity of adobe bricks reinforced with 1%, 2%, 3% and 4% of fonio fiber waste.

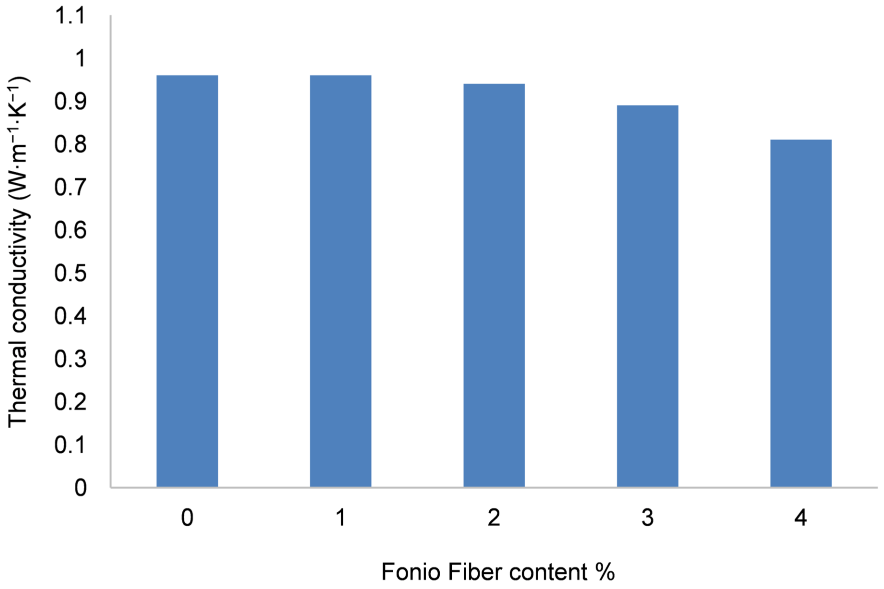


Figure 7. Evolution of thermal conductivity in function of fonio fiber's content.

Figure 7 illustrates the effect of adding fonio fibres to the mud bricks. The addition of 0%, 1%, 2%, 3%, and 4% in the soil matrix contributes to a gradual decrease in its thematic conductivity. Indeed, the new thermal conductivity values after adding 0%, 1%, 2%, 3% and 4% are 0.96 respectively; 0.96; 0.89; 0.81 (W·m^{-1}·K^{-1}).

The variation in thermal conductivity is closely related to the thermal properties of the plant fibers. Indeed, several authors reveal in their studies that plant fibers have a thermal insulating power [8] [14]-[16]. Therefore, the abundance of plant fibers within the matrix soil makes it difficult to access heat inside the building through the wall made of earth + plant fiber composite. As a result, the gradual increase of plant fibers in the soil matrix gradually strengthens the insulating properties of the composite [8] [14]-[16]. This behavior of slowing down the movement of heat through the load-bearing wall is of paramount importance for hot regions such as the Sudano-Sahelian region of Cameroon which requires a less hot indoor climate for occupants.

Moreover, this decrease in thermal conductivity is not perceptible at 1%, which would probably be related to the low content of the vegetable fibres and the low insulating properties of the plant fibres used. However, this increase starts to be noticeable from 2% and becomes a bit more satisfying up to 4%. Overall, we realize that fonio fibers make a certain positive contribution in terms of thermal insulation in the soil matrix but this improvement is relatively small; it is 16% corresponding to the addition of 4% of plant fibers. The same authors recently found an improvement of 23% and 54% respectively with the incorporation of millet and neem fibers in the same proportions (**Table 3**). This confirms that fonio fibers have limited thermal insulation properties compared to mille, straw and neem leaf fibers [11] [12].

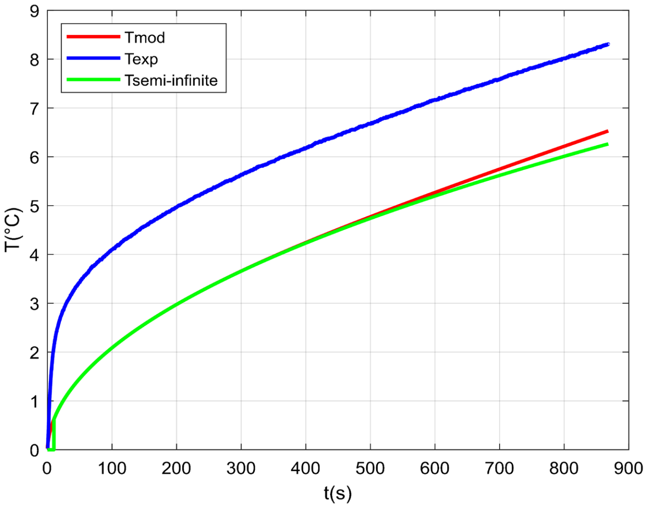
Table 3. Comparison of thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) of adobe reinforced with fonio and adobes reinforced with milled, leave and straw neem.

%	Millet	Straw	Leave	**Fonio**
0	0.96	0.96	0.96	**0.96**
1	0.91	0.90	0.74	**0.96**
2	0.85	0.85	0.65	**0.94**
3	0.80	0.80	0.52	**0.84**
4	0.74	0.74	0.43	**0.81**

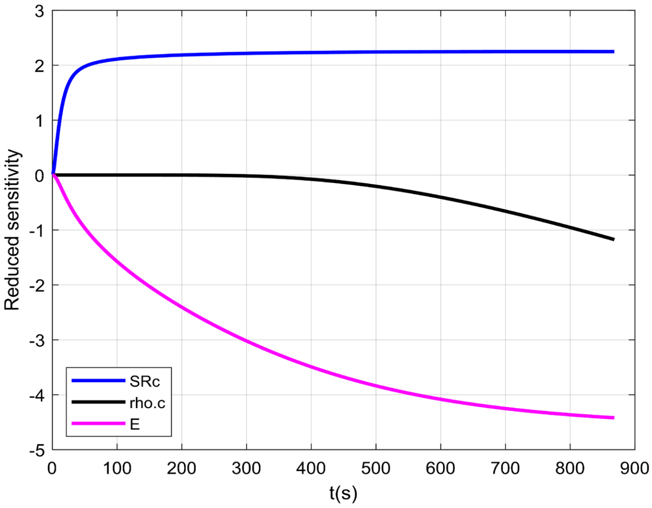
The agreement obtained between the experimental and theoretical curves is then very good as shown by the curves of the estimation of covariance, sensibility and residuals in **Figure 8**. That is a proof that the thickness/width ratio must always respect the limits set by the chart in **Figure 8** to ensure that the transfer is 1D in the center and that the contact resistances are negligible [18].

Ultimately, adobe bricks reinforced with fonio fibers from 2% limit heat transfer and are therefore better suited for buildings compared to adobe bricks without the addition of plant fibers [14] [26].

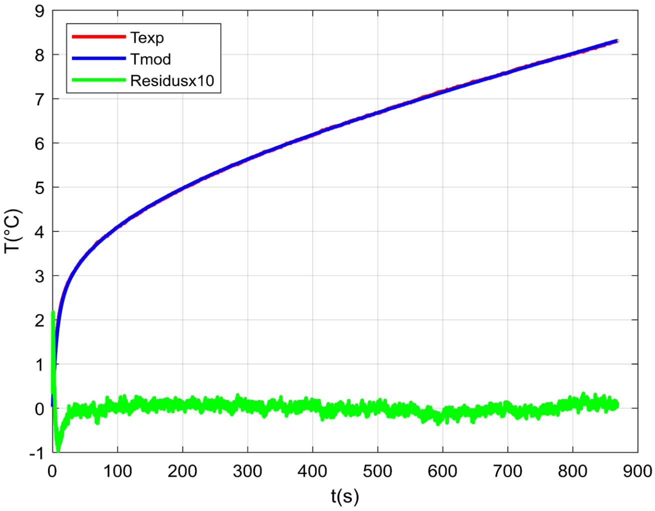
However, many other authors have shown that the less plant fibers improve thermal properties, the more they improve mechanical properties.



(a) Covariance curves



(b) Sensibility curves



(c) Residues curves

Figure 8. Aspects of curves of Experimental and modeled hot plate temperature in function of time obtained for one sample: (a) Covariance curves; (b) Sensibility curves; (c) Residues curves.

3.4. Effect of Fonio on the Compressive and Flexural Strength

The effect of fonio on the Compressive and flexural strength the soil appears on **Figure 9**.

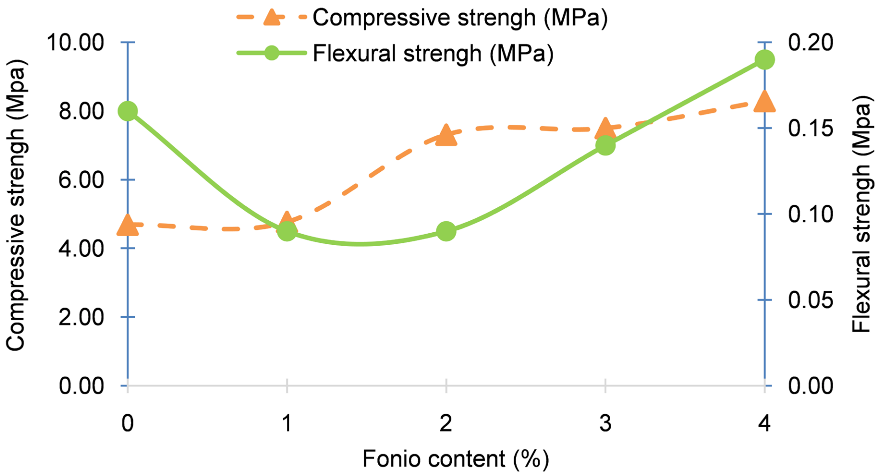


Figure 9. Effect of the fonio on the compressive and flexural strength.

As illustrated on **Figure 9**, a reading of this curve shows that compressive and flexural strengths vary according to the fonio contents incorporated into the soil matrix. We noticed an improvement of the mechanical characteristics with the addition of fonio waste.

It is quickly observed that the Compressive strength of the soil gradually increases with the fonio addition. Whatever the case, the Compresive strength values are improved, compared to soils without reinforcement. For this purpose, we obtained a resistance gain of 1.71%; 58.86%; 59.91% and 76.75%, respectively when we used 1%, 2%, 3% and 4% of fonio. As the fonio content increases, the compressive strength increases proportionately. The maximum compressive strength value is 8.29 MPa and corresponds to 4% fonio addition. At this percentage, the fonio fibers adhere better to the clay matrix, the composite obtained is more compact and resists better mechanical loads [20] [32] [33]. These results clearly show that fonio has a considerable effect on the improvement of the soil studied. The results obtained in this study show that fonio fiber waste improves compressive strength better in all proportions compared to the compressive strength values of some authors in the literature [34] [35] (**Table 4**).

Many authors tried to explain the increase of the compressive strength of soils stabilized with fibers [26] [33], this increase of the Compressive strength values is due to the reduction in the size of shrinkage cracks.

As illustrated in **Figure 9**, it can be seen that the flexural strength decreased after 1% of fonio addition before increasing with 3, 4 and 4% of fonio. Similar results were obtained by Millogo *et al.*, 2014 [26] and Danso *et al.*, 2015 [34]. In fact, some authors point out that fibers are generally known rich in cellulose (tensile strength between 300 and 500 Mpa), responsible for the increase of the

the soil + fibers mixture [36] [37].

Fonio fibre-reinforced adobes have shown exceptional capabilities in terms of mechanical strength. They can therefore be used in the building without any damage to the occupant according to the recommendations in force in the building sector [38]. However, it is also important to evaluate the behaviour of these adobes in the face of water in order to enjoy not only the thermophysical and mechanical capacities, but also a certain guarantee of performance.

Table 4. Comparison of compressive strength (MPa) of adobe reinforced with fonio and adobes reinfoced with milled, leave and straw neem.

	Millet	Straw	Leave	**Fonio**
0	4.69	4.69	4.69	**4.69**
1	4.13	6.23	5.44	**6.77**
2	6.5	6.35	5.59	**7.31**
3	421	6.1	4.27	**7.50**
4	3.66	5.85	4.09	**8.29**

3.5. Durability of Adobes

Figure 10 shows the evolution of the weigth loss before and after stabilization.

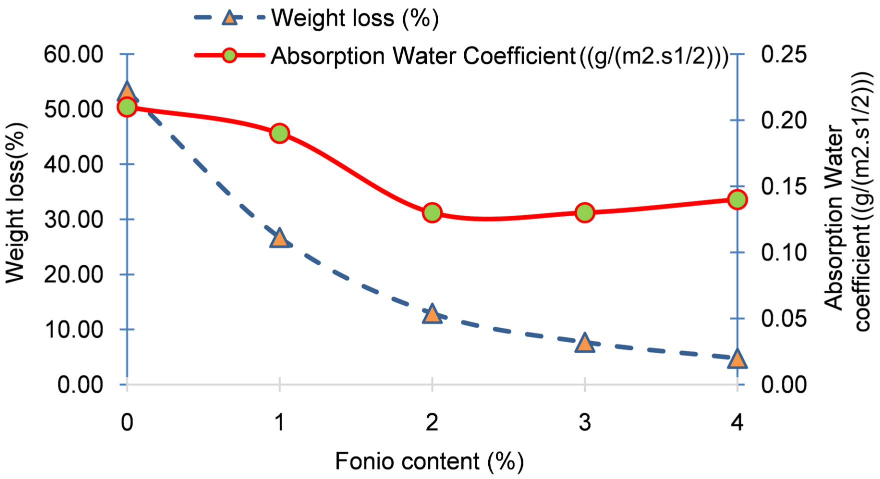


Figure 10. Effect of fonio on the weight loss.

The results show that the values of weight loss of soils decrease with the addition of fonio content. These results clearly show the beneficial effect of stabilization. The same results have been obtained by [34]. For the authors, this decrease could be explained by the high adhesion of fibers with clayey matrix.

These results sufficiently prove that soils with low mass loss are more resistant to water erosion.

This is important because it justifies that adobe bricks reinforced with fonio fibers will resist tearing due to spraying from rain. For all percentages, adobe bricks reinforced with fonio fibers gave better stability compared to millet fibers, straws and neem leaves as shown in **Table 5**.

Table 5. Comparison of erosion coefficient (%) of adobe reinforced with fonio and adobes reinfoced with milled, leave and straw neem.

Erosion coefficient (%)	Millet	Straw	Leave	**Fonio**
0	53.31	53.31	53.31	**53.31**
1	35.56	16.12	40.79	**26.71**
2	33.64	22.55	65.41	**12.94**
3	20.14	27.75		**7.68**
4	22.01	57.74		**4.76**

Since moisture is the main enemy of earthworks, the understanding of the water stability of adobes was completed by the study of the water absorption of the samples in order to assess whether or not the formulated adobes promote water absorption by capillary action.

Figure 10 shows the effect of adding fonio waste on adobe bricks. Careful observation of this curve shows a decrease in the water absorption rate for all additions 1%, 2%, 3% and 4%. This reveals that the incorporation of the different fonio fibre contents in the adobe bricks helps to improve the behaviour of the mud bricks in the face of water. Indeed, when the absorption coefficient becomes lower and lower, as is the case in **Figure 10**, the resulting composite is more resistant to water penetration and destruction [20] [25] [26]. Therefore, the addition of fonio fibers in the mud bricks enhances the durability of the mud bricks. Compared to millet and neem fibers previously studied with the same soil and with the same conditions, fonio fiber waste showed an improvement [11] [12] (**Table 6**).

Table 6. Comparison of water absorption coefficient (%) of adobe reinforced with fonio and adobes reinfoced with milled, leave and straw neem.

%	Millet	Straw	Leave	**Fonio**
0	0.21	0.21	0.21	**0.21**
1	0.19	0.11	0.25	**0.16**
2	0.13	0.16	0.28	**0.16**
3	0.13	0.24	0.33	**0.15**
4	0.14	0.29	0.25	**0.12**

Other authors have obtained similar results with similar fibers and point out that certain thin, fine and short plant fibers promote the stability of mud bricks thanks to their physical properties.

Compared to millet and neem fibers previously studied with the same soil and with the same proportions fonio fiber waste showed an improvement [11] [12].

4. Conclusions

Fonio fibre waste was used in adobe bricks in order to assess the effect of their addition from a thermophysical and mechanical point of view. The different fiber contents of 0%, 1%, 2%, 3%, and 4% brought satisfaction in general on these aspects, but more specifically, we noticed:

- A 16% improvement in thermal conductivity. Hence, future buildings constructed of mud bricks reinforced with fonio fibers will heat up less compared to mud bricks alone. This is of great advantage for climates where the temperature sometimes reaches 45˚C in the shade, such as in the Far North region of Cameroon where this study is conducted.
- Improved mechanical properties. This increase reaches 8.29 MPa with a percentage of 77%. According to the African standard cited by Boubekeur and Rigassi, 2000, mud bricks with a compressive strength between 2 and 4 MPa are recommended for non-load-bearing walls, and those with a compressive strength above 4 MPa are suitable for a load-bearing wall. Hence, earth bricks reinforced by fonio sounds will not present any disadvantage to be used as a load-bearing wall.
- From the point of view of durability, fonio fibers have shown a favorable effect both in providing stability to the mud bricks. Walls built of mud bricks reinforced with fonio fibre waste will therefore be able to withstand bad weather and even water infiltration by capillary action.

Given that the fibre-reinforced mud bricks have given satisfactory results, we would like to look forward to:

- Understanding the hygrothermal and mechanical behaviour of adobes reinforced with these fibers with mass percentages greater than 4%.
- Continuing the chemical and mineralogical study of the materials studied to improve the understanding of the thermal and mechanical behaviors of adobes.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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