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Thermo-physical Properties of the Clay of Balkuy Combined with Millet Pods for the Thermal Insulation of Building Envelopes

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Authors' contributions

This work was carried out in collaboration among all authors. Author TB conceptualization, writing original draft. Author BKI resources software. Author MB resources, validation, data curation, supervision and project administration. All authors read and approved the final manuscript.

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ABSTRACT

The empirical and traditional use of millet waste mixed with clay to make bricks is widespread in the Sahel region, particularly in Burkina Faso. The aim of this study is to characterize the thermal properties of these composite bricks according to the content of millet pod. Adding an insulator to a building material is one of the simplest and oldest methods to improve its thermal properties. In this work, we report on the thermal properties of clay taken from the site of BALKUY, geographical

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coordinates (Latitude: 12.30 North; Longitude: -1.47 West) south of OUAGADOUGOU, which we mixed with millet pod at rates ranging from 0 to 4%, in steps of 1. The respective addition for rates ranging from 1% to 4% reduces thermal conductivity respectively by 31.57%; 41.03%; 43.49%; and 54.54%. The rate of millet also has an effect on the thermal diffusivity of the sample. Indeed, the respective addition between 1% and 4% per step of 1 reduces the thermal diffusivity by 81.51%; 93.26%; 93.46% and 94.44%. When 1% of millet pod is added to the clay, the mechanical strength increases 6.55 times. It reaches 6.95 times when 2% of millet pod is added to the clay. Then, it rises from 7.35 to 7.40 when 3% and 4% of millet pods are added to the clay. The addition of the millet pod therefore improves the compressive strength. The optimum value for the millet pod content is 3%.

Keywords: Thermal conductivity; Volumic heat capacity; energy saving; thermal diffusivity; millet pod; compressive strength; KD2-Pro thermal properties instrument.

NOMENCLATURE

GPM: Millet pod
Ar0: 100% clay
ArGPM1: Clay99% +1% GPM
ArGPM2: Clay98%+2% GPM
ArGPM3: Clay97%+3%GMP
ArGPM4: Clay96%+4%GPM

1. INTRODUCTION

In recent years, the issue of rational energy use has emerged as a response to its increasing cost and catastrophic consequences on the environment. All sectors are concerned and must be taken into consideration. Heating and air-conditioning systems consume large quantities of energy to ensure comfortable thermal conditions inside buildings. Calculating energy requirements depends heavily on the thermal properties of the building envelope, which are often assumed to be constant. Walls are made of building materials, which are generally porous environment capable of absorbing, containing and exchanging damp, as well as heat. An interaction develops between heat and damp transfer and the various transport properties. The absence of detailed data on thermo-physical properties can lead to operating difficulties and inadequacies [1].

This work is aimed to make local building materials available, more and better used by the poorest populations, in order to reduce energy consumption while preserving thermal comfort in Sahelian buildings.

2. MATERIALS AND METHODS

2.1 Sample Preparation

The clay powder is directly extracted from the soil in the BALKUY region. The crushed sample is then sieved to obtain granules with a maximum diameter of 1 mm. It is then mixed with small millet waste in percentages of 0%, 1%, 2%, 3% and 4%. Mixing is done using a mixer. Water is added until a homogeneous paste is obtained, which is then pressed into a mould with internal dimensions of 10×10×2.5 cm3. Table 1 shows the composition of our samples. Figs. 1 and 2 show photos of our samples, which are pierced by holes 1.27 cm in diameter, to accommodate the needles of the measuring device.

Fig. 1 shows the raw and wet millet pod used to mix the clay.

Fig. 2 shows the different clay samples associated with millet pods.

Table 1. Composition of formulations

Formulation	Clay (%)	GPM content (%)	Mass of water
Ar0	100	0	140g
ArGPM1	99	1	149g
ArGPM2	98	2	153g
ArGPM3	97	3	160g
GPM (100%)	0	100	150g

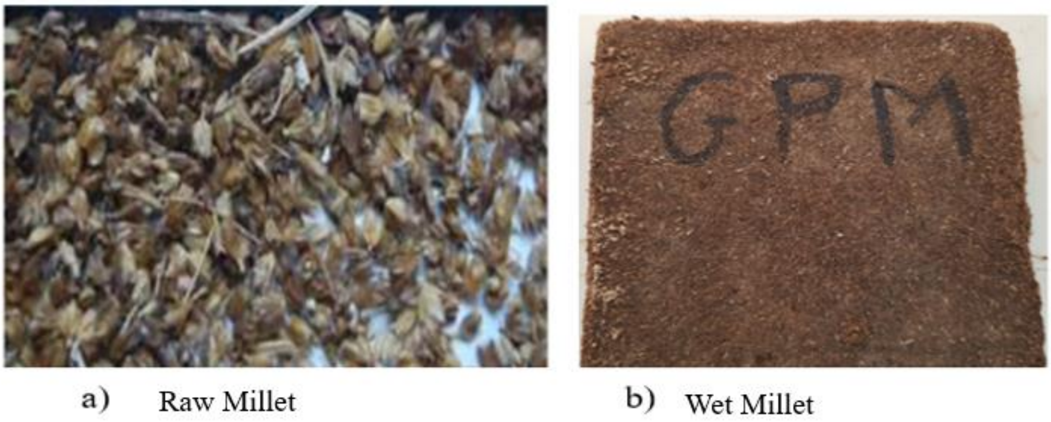

Fig. 1. Photo Millet pod

Fig. 2. Photo of materials

The geotechnical properties of the clay studied are as follows: Wp =12%; WL =43% and Ip =31%; Wp, WL and I p are the plasticity limit, liquidity limit and plasticity index respectively. The value of Ip indicates that the clay has strong plasticity, and a high swelling potential, as its plasticity index ranges from 22 to 35 depending on the swelling potential according to BRE [2]. The sieve and sedimentation particle size curves are shown in Figs. 3 and 4 respectively. Table 2 summarizes the geotechnical study of the clay used in our study.

Table 2. Geotechnical study of clay

Features	Clay
Maximum dimension Dmax (mm) (100% throughput)	8
2 mm sieve rejects (%)	2.6
Passes at 0.08 mm (%)	74.7
Liquidity limit ωl (%)	43
Plasticity limit ωp (%)	12
Plasticity index IP(%)	31
Absolute density (g/cm)3	2.53

Maximum dimension Dmax 8 mm < 50mm and Passes to 0.08 mm is 74.7% > 35%, making it a type A soil (fine soils). Plasticity index: 25<31<40, making it an A3 soil. Type A3 soils: clays and marly clays, very plastic silts [3].

The granulometric analysis by sedimentometry obtained in Fig. 4, completes the granulometric analysis in Fig. 3. *Sedimentometry is* a test that complements granulometric analysis by soil sieving. It applies to elements with a diameter of less than 80um. In our case, we have very fine clay, as shown in Fig. 4.

2.2 Materials, Methods and Operating Principle of the KD2-Pro

Thermo-physical properties of materials are quantities that characterize the behavior of materials. Some of these properties represent a body's ability to propagate and/or to store heat. Thermo-physical characteristics such as thermal conductivity, thermal diffusivity and specific heat per volume were measured using the KD2-pro instrument, a double-needle probe developed by DECAGON [4]. This device uses the model proposed by CRASLAW and JAEGER [5] to solve the heat transfer equation by the transient linear heat source propagation method in a semi-infinite environment. This equation has been published in IEEI standards [6]. The advantages of this type of method are essentially the simplicity of the apparatus, the speed of measurement and the ability to operate in situ under any hygrothermal conditions. Thermal effusivity is determined from thermal conductivity and volumetric heat capacity. Mass heat is obtained from density and heat density. The principle of this method is to calculate thermal conductivity (λ), thermal diffusivity (α) and thermal resistivity (R) by analyzing heat dissipation from a linear heat source subjected to a known tension.

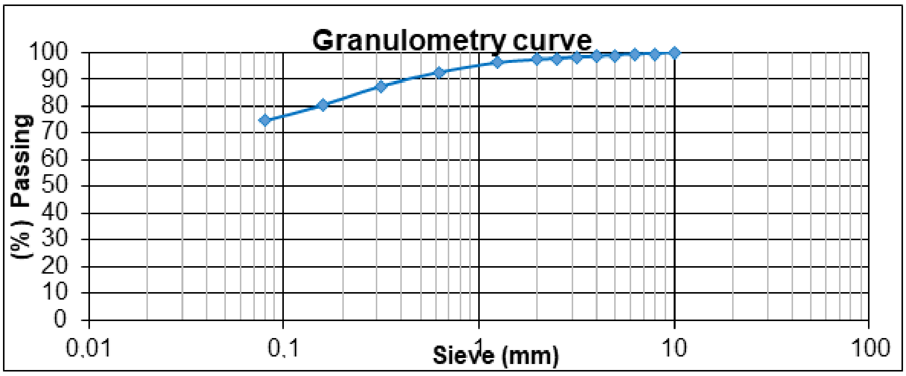

Fig. 3. Clay sieve particle size distribution

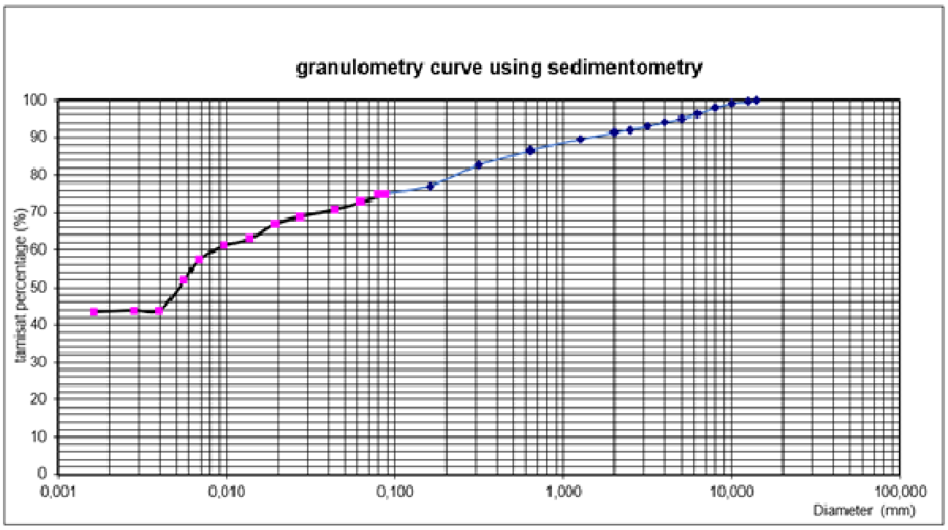

Fig. 4. Sedimentometric particle size distribution curve for clay

The equation for radial heat conduction in a homogeneous, isotropic cylindrical medium proposed by [5] is as follows:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + r^{-1}\frac{\partial T}{\partial r}\right) \tag{1}$$

Where: T (K) is temperature, t (s) is time, α (m2 /s) is thermal diffusivity, and r(m) is radial distance.

When the linear heat source is introduced into the medium, the temperature increase from an initial temperature T0, at a distance r from the source axis proposed by [5] is:

$$\Delta T = T - T_0 = \left(\frac{q}{4\pi \cdot K}\right)Ei\left(\frac{-r^2}{4\alpha \cdot t}\right) \tag{2}$$

In this formula, q (W/m) is the heat produced over a unit length in a unit time, K (W/mK) is the thermal conductivity of the medium, and Ei is the exponential integral function. The expression of Ei is given by [7] :

$$-E_i\left(-\frac{r^2}{4\alpha.t}\right) = \int_a^\infty\left(\frac{1}{u}\right)\exp(-u)du = -\gamma - \ln\left(\frac{r^2}{4\alpha.t}\right) + \left(\frac{r}{4\alpha.t}\right) - \left(\frac{r^2}{8\alpha.t}\right) + ... \tag{3}$$

Where γ is the Euler constant (γ=0.5772)

Taking the first two terms of equation (03) we have:

$$\begin{aligned} -E_i\left(-\frac{r^2}{4\alpha.t}\right) &= \int_a^\infty\left(\frac{1}{u}\right)\exp(-u)du = -\gamma - \ln\left(\frac{r^2}{4\alpha.t}\right) \\ -\gamma - \ln\left(\frac{r^2}{4\alpha.t}\right) &= -\gamma - \ln\left(\frac{r^2}{4\alpha}\right) - \ln\left(\frac{1}{t}\right) \\ -\gamma - \ln\left(\frac{r^2}{4\alpha}\right) - \ln\left(\frac{1}{t}\right) &= \ln(t) - \gamma - \ln\left(\frac{r^2}{4\alpha}\right) \end{aligned} \tag{4}$$

By introducing equation (04) into equation (02), we obtain equation (05)

When t is large enough, by approximation, we have :

$$\Delta T = T - T_0 = \frac{q}{4\pi K}\left(\ln(t) - \gamma - \ln\left(\frac{r^2}{4\alpha}\right)\right) \tag{5}$$

This equation shows that the relationship between ΔT is linear with a slope $m = \frac{q}{4\pi\lambda}$. The slope m, plotted on a graph T as a function of $\ln(t)$, can be used to calculate conductivity using the following formula.

$$\lambda = \frac{q}{4\pi m} \tag{6}$$

The hypotheses used in this theory are as follows:

The probe is a heat source.

The environment is isotropic and homogeneous, so λ does not depend on T.

The initial temperature, T_0 is uniform.

The needle consists of a thermistor and a heating element. To measure the thermal properties of a part, the needle is inserted into the part. At the beginning of the measurement, the microcontroller waits 90 seconds for the temperature to become homogeneous. Next, an electric current of known intensity is passed through the heating element, whose electrical resistance is known. The microprocessor then calculates the power supplied to the heating element. The thermistor is used to measure the temperature variation during the 30 seconds of heating.

The thermal parameters of the part are calculated using data on temperature variations as a function of time. We used the double-needle KD2 Pro (Fig. 5) to estimate the thermo-physical characteristics of our materials. The manufacturer's measurement uncertainties for thermal conductivity are ±5% [8].

Fig. 5. KD2-Pro measuring instrument

3. RESULTS AND DISCUSSION

3.1 Experimental Thermal Conductivity of Clay Combined with Millet Pods at Different Dosage Rates

The results of the experimental thermal conductivity of the different formulations obtained by KD2-Pro, allow us to draw the following curve:

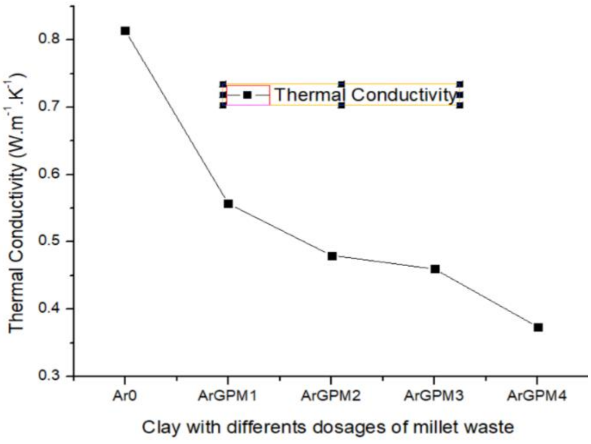

Fig. 6. Thermal conductivity of clay combined with millet pods at different dosages

Fig. 6, shows that the thermal conductivity of the clay without the millet pod is 0.814 (W/m. K). This value is very close to that found by IMBGA et al [9] on Kaolinite clay and is 8.35% higher than that found by Fatima et al [10]. Marthe DIATTA [11] determined the thermal conductivities of two clays, MN and NM1, using the Hot Disk TPS 2500. The estimated thermal conductivities are 0.46 and 0.72 (W/m.K) respectively. The chemical and mineralogical compositions of the NM and MN1 clays are fairly similar, consisting mainly of kaolinite, quartz and illite. Thermal conductivity is 14% lower than our measurements. Fig. 6 shows that thermal conductivity decreases as the proportion of millet in the clay mixture increases. The addition of 1%, 2%, 3% and finally 4% reduces thermal conductivity by 31.57%, 41.03%, 43.49% and 54.54% respectively. The addition of GPM creates pores which the quantity increases according to the GPM content in the clay. The pores contain air, and air has a low conductivity, which explains why the thermal conductivity of the mixture decreases as the GPM content in the clay matrix increases. BAL et al [12] determined the volumetric heat capacity of laterite associated with small millet pods, according to water content, using the hot plane method. The results show that the volumetric heat capacity increases as a function of water content, and also as a function of the proportion of small millet pods in the laterite. Experimentally measured values of heat capacity by mass and density are $C_{mil} = 2019 J / Kg.K$ with $\rho_{mil} = 1164 Kg / m^3$. Laroussi et al [13;14] determined the thermal properties, using the hot plane asymmetry method, of clay taken from a Sloui industry in Morocco. The thermal conductivity value found was $0,35 W / m.K$. This value is very close to that found using the box method IMBGA et al [15]. A Michot et al [16] determined the thermal conductivity and specific heat of Kaolin clay using the laser flash technique. Using this method, the thermal conductivity value found was $0,3 W / m.K$ for a temperature below 1050°C, and this value increased as the temperature rose, reaching $3,2 W / m.K$ when the temperature was $1400°C$. The thermal conductivity of clay therefore depends on its nature, and the chemical composition of the clay concerned.

3.2 Evolution of the Thermal Diffusivity of a Mixture of Clay and Millet Pods

The thermal diffusivity of our different formulations, obtained from experimental measurements, enables us to draw the curve shown in Fig. 7.

Fig. 7, shows a rapid decrease in values between 100% clay and clay combined with 1% millet pod. this value remains almost constant from the addition of 2%, 3% and 4%. the thermal diffusivity of the clay without the millet pod is 4.098 10-4 m2. s-1. this value is reduced by 81.51% when 1% of millet pod is added to the clay. the addition of 2%, 3% and 4% respectively reduces thermal diffusivity by 93.26%, 93.46% and 94.44%.

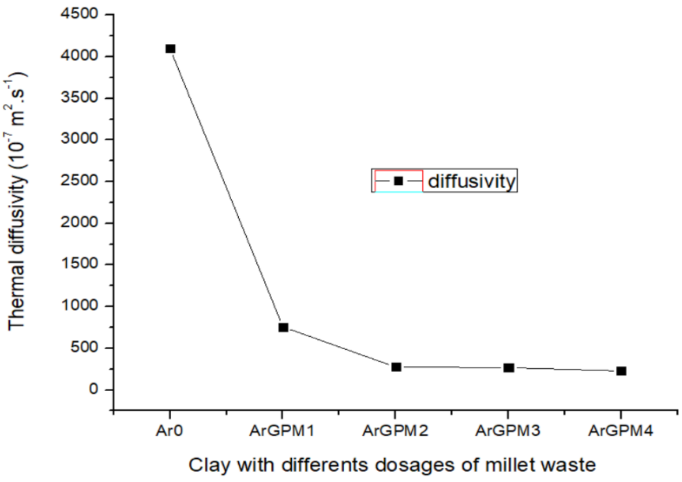

Fig. 7. Thermal diffusivity of clay associated with small millet pods at different rates

3.3 Evolution of the Volumetric Heat Capacity of the Clay Mixture and the Millet Pod

The curve in Fig. 8 shows the variations in the volumetric heat capacity of the mixture of clay and small millet pods at different dosage rates.

Fig. 8 shows that the volumetric heat capacity of the clay decreases as the proportion of millet pods increases. It decreases by 63.37%, 69.99%, 75.12% and 89.27% respectively, when 1%, 2%, 3% and 4% of millet pods are added to the clay.

4. COMPRESSIVE STRENGTH

Mechanical tests were carried out on three 4x4x16 cm3 prismatic samples, in accordance with the operating methods specified in EN 196-1 [17], using the mechanical press (Fig. 9).

Fig. 10 shows a photo of the specimens that have been characterized. They are made in a 4×4×16 cm3 mould, dried under laboratory conditions for 28 days (cure time) before being crushed by the press.

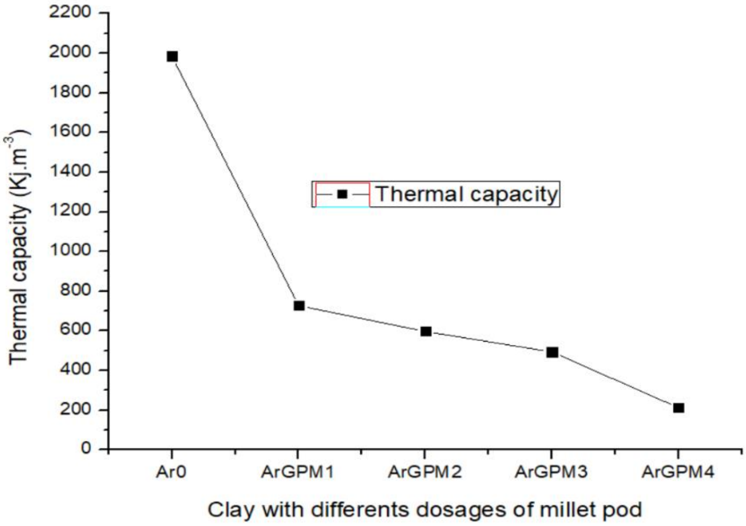

Fig. 8. Heat capacity by volume of the clay mixture combined with small millet pods at different dosage rates

Fig. 9. Mechanical press

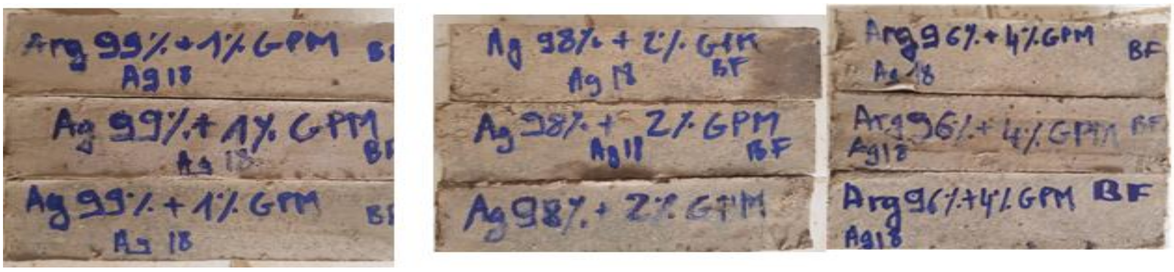

Fig. 10. Compressive strength and flexural strength test specimens

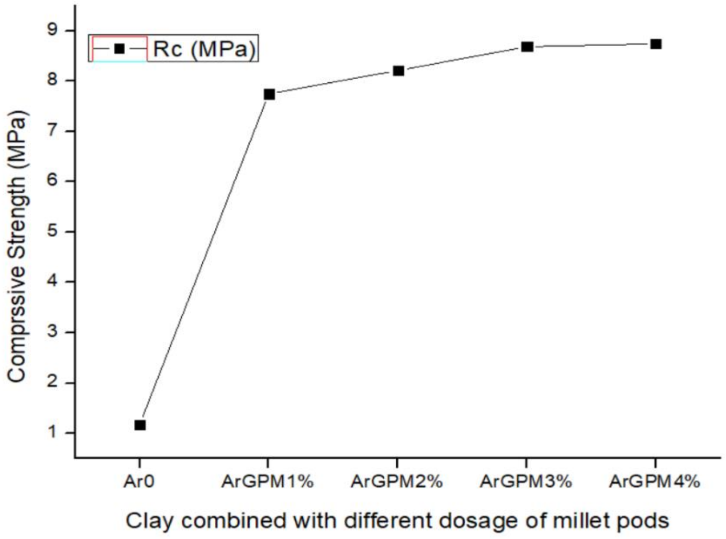

Fig. 11. Effect of pearl millet pods on the mechanical strength of clay

$R_f(MPa) = 2.34 \times 10^{-3} \times F_f(N)$

R_f: $Bending\ strength\ (MPa)$

$$R_c(MPa) = \frac{F_c(N)}{1600}$$

F_c: force of rupture(N)

R_c: $Compressive\ strength\ (MPa)$

4.1 Mechanical Characterization Results

The results obtained by the mechanical press on our specimens, dried for 28 days, enable us to draw the following Fig. 11.

Fig. 11 shows that the compressive strength of the clay without the millet pod is 1.181MPa, a value in line with that found by IMBGA et al [15], while that found by BOUKAR et al [18] is 0.641MPa. This can be explained by the fact that clays do not always have the same composition. The mechanical strength we obtained is increased 6.55 times by adding 1% of millet pod is added to the clay, and 6.95 times when 2% of millet pod is added to the clay. It rises from 7.35 to 7.40 when 3% and 4% of millet pods are added to the clay. The addition of small millet improves compressive strength. According to Fig. 10, the optimum value is 3%.

4.2 Interpretation

The rapid decrease in thermal conductivity according to the dosage rate of millet pod is due to the porosity of the sample material. The greater the quantity of small millet pods in the clay, the greater the porosity. Air being an insulator, the piece containing the most porosities, that is to say, the number of air pockets, will be the most thermally insulating. However, the addition of millet pods in the mixture increases porosity. That is why the piece containing the most small millet pods is the most thermally insulating. Thermal diffusivity expresses the ability of a material to diffuse heat, and depends on the material thermal conductivity and volumetric heat capacity. A material containing more millet pods has a low density and low conductivity, which reduces its capacity to diffuse heat.

5. CONCLUSION

In this study, we chose a mixture of millet pods and clay as the composite material. These materials are traditionally used in rural building construction. Millet pods are locally available in large quantities, are very inexpensive and easy to work with. It is a low-density product that should, in principle, have low thermal conductivity. However, its thermo-physical properties change according to the quantity of millet pods in the clay. The respective addition of 1%; 2%; 3%; and finally, 4% reduces thermal conductivity by 31.57%; 41.03%; 43.49%; and finally, 54.54%. The level of millet also has an effect on the thermal diffusivity of the formulation. Indeed, the respective addition of 1%; 2%; 3% and 4% reduces the thermal diffusivity respectively by 81.51%; 93.26%; 93.46% and 94.44%. The study of the thermal characteristics of these clay materials combined with locally produced millet pods shows and confirms that the millet pod content is an essential parameter for the evaluation of thermal parameters. The differences observed, particularly in the thermal conductivity of these composite materials, have potentially significant consequences when it comes to establishing thermal balances for buildings. Thermal conductivities vary according to the chemical composition of the different clays. When 1% of millet pod is added to the clay, the mechanical strength increases 6.55 times. It reaches 6.95 times when 2% of millet pod is added to the clay. Then, it rises from 7.35 to 7.40 when 3% and 4% of millet pods are added to the clay. The addition of millet improves compressive strength, with an optimum value of 3%.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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