Experimental Study of the Thermo-physical Properties of Lateritic Blocks Used in the Habitat in Dry Tropical Climate

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Authors' contributions

This work was carried out in collaboration between all authors. Authors EO, OC and BKI designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors EO, AO and PFK managed the analyses of the study. Authors EO, BKI and OC managed the literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

This article presents an experimental study on the thermo-physical characterization of local materials used in building construction. These materials are laterite cut blocks from three different quarries. The characterization was done with the hot plate device and the asymmetrical method was used. All the samples studied have thermal conductivities less than 0.6 $W.m^{-1}.K^{-1}$ and thermal diffusivities lower than $3*10^{-7}$ $m^2.s^{-1}$. These results show that the materials have good thermal performance.

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1. INTRODUCTION

The African traditional society built with "the means of edge" in complete autarky while the modern society designs its houses by using Western techniques. This leads to the importation of some construction products. In Burkina Faso, the proportion of manufactured goods imported for the building and public works sector is currently around 45% [1]. This constitutes huge currency losses for the country. The solution for this problem could be the use of local building materials. The qualitative mode of urban development and the suitable implementation of settlement are determining factors of high environmental quality. Housing and its urban context appear more and more in Africa as an important tool of globalization referring to Western modernity, which is de facto considered as the only modernity. The development practiced, however, is characterized by dualistic implementations between tradition and modernity. In Burkina Faso, as well as in the majority of African countries, the most of buildings are built with local materials and this for almost all the rural populations who represent the majority of the population of the country. It may then seem abusive to talk about valuing natural local materials. However, the use of cement blocks is becoming more common in the housing of cities in the country and tends to reach the villages. And local materials suffer from bad reputations due to their resistance and their sensitivity to water. But, they can be improved by stabilization. The results of the work of Meukam [2] show that the addition of cement or sawdust to the soil improves the mechanical and thermo-physical properties of bricks. He also showed that compressive strength and thermal conductivity increase as the cement content increases. Ouedraogo et al. [1,3] have shown that the stabilization of compressed earth blocks with cement and / or paper improves their thermo-physical and mechanical properties. The work of Imbga et al. [4,5,6] showed that the stabilization of laterite at the nere pod, cement and lime improved the mechanical and thermal characteristics. Although lateritic soils have been studied extensively for use in road and track construction [7], lateritic rocks have been somewhat less studied. In India, a number of studies have been conducted leading to the development of a standard (Kasthurba et al. [8,

9]) for the use of laterite blocks as building elements in traditional construction. In Africa, this material represents a significant resource, used alone or associated with a concrete structure for the design and construction of housing. The physico-mechanical properties have been studied to prove the potential of this material for light constructions [10,11]. The work carried out as part of this research will help to overcome the lack of data on the thermo-physical properties of lateritic blocks. The characterization is done using the hot plate using the asymmetrical method.

2. MATERIALS AND METHODS

2.1 Laterite Block

The laterite block or lateritic stone is a building element: more or less regular size and characteristics, it is obtained by manual or mechanical cutting of the cuirass or the carapaces of the lateritic rocks. Laterite is the result of intense wetting and consists of a mineral blending that can be made of goethite, hematite, mineral compound, kaolinite and quartz. The ratio SiO_2 / (Al_2O_3 + Fe_2O_3) compared to that of the source rock must be such that the lateritic formation does not contain more silica than that which is retained in quartz and that which is necessary for the formation of kaolinite [12]. It is softer in the fresh state and gets harder when exposed to the air [13]. The size of bricks used for thermal tests is 10 *cm* x10 *cm* x 2.5 *cm*.

2.2 Method and Assessment of Thermal and Mechanical Characteristics of the Various Formulations

We used the method of asymmetric hot plan available to Applied Energy Laboratory of the Polytechnic School of Dakar (L.E.A) to determine the thermal properties of laterite dimension stone from three quarries (quarries of Bobo-Dioulasso, Reo and Yako) in Burkina Faso, a west African country. Fig. 1 presents the map of the country with the three cities and the capital (the city of Ouagadougou).

2.3 Method Used to Measure the Thermo-physical Properties of Materials

The Fig. 2 presents the experimental device and the Fig. 3 shows the simplified model of this device.
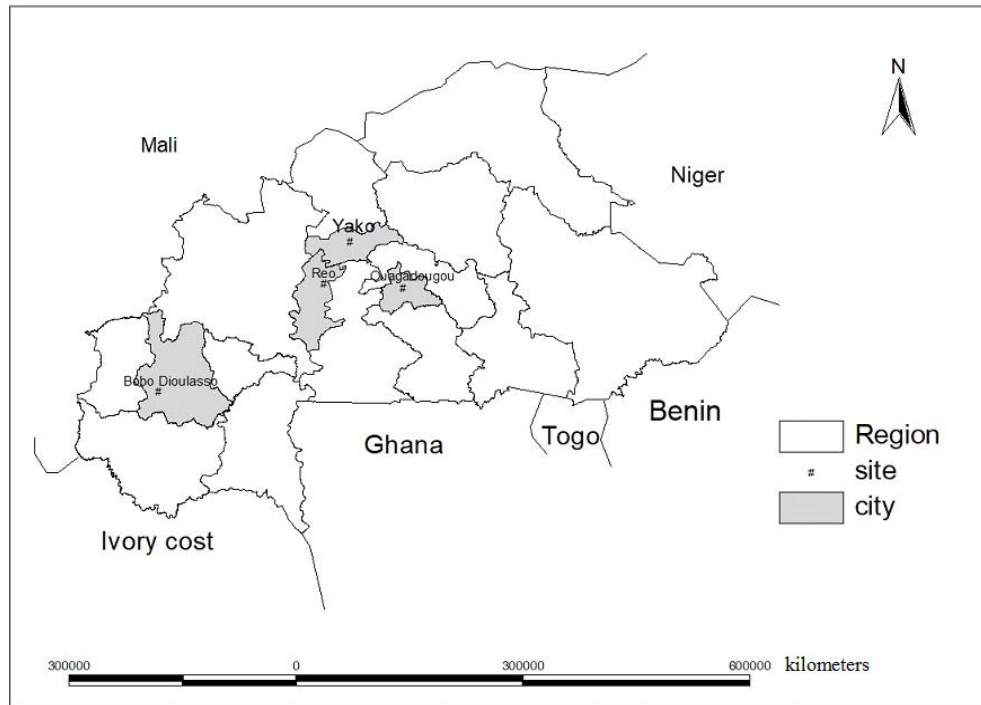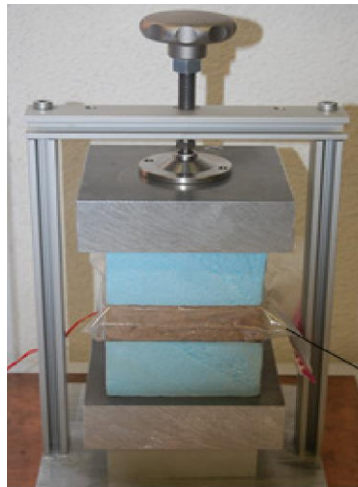
Fig. 1. Map of Burkina Faso

Fig. 2. Asymmetric hot plan

An experimental study of the effusivity and thermal conductivity was mainly conducted using the method of the asymmetric hot plate in a transitory regime. Fig. 2 shows the asymmetric experimental device.

The method is based on temperature measurement at the centre of the heating device with a heated surface $100 \pm 1 mm \times 100 \pm 1 mm$ and a thickness $0.22 \pm 0.01 mm$. The uncertainty in the heating device area is thus around 2%. We must add the uncertainty to the sample thickness estimated at 1 % and to the heat flux produced in the heating device, estimated at 0.5%. The sum of these uncertainties leads to an overall uncertainty rate of 3.5% to which must be added the estimation error due to noise measurement on ΔT and the errors due to phenomena that
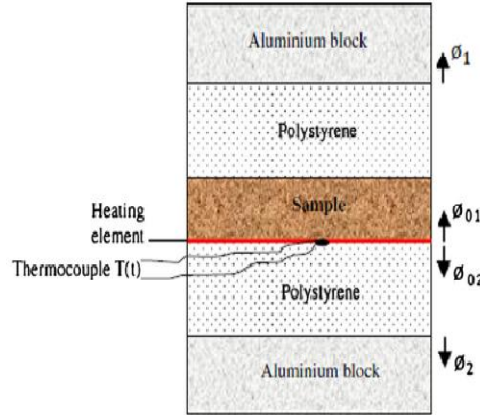
Fig. 3. Simplified hot plan model

have not been taken into account in the model. Most of the heat dissipated into the heating device which electric resistance $R_e = 40\Omega$, passes through the upper part of the heating device. A plate heating device sharing the same section with the sample is placed under it. K-type thermocouple comprising two wires of 0.005 *mm* diameter is placed at the underside of the heating device. The sample is placed between two 40 *mm* thick blocks of extruded polystyrene and the set is placed between two 40 *mm* thick aluminum blocks. A heat flow is sent from the heating device. The temperature evolution $T(t)$ is recorded at every each 0.1 *s*. The presence of the thermocouple does not increase the contact resistance between the heating device and the polystyrene. Since polystyrene is an insulating material. This thermal resistance will be marginal. The system is modeled with the unidirectional transfer hypothesis (1D) at the centre of the heating device and the sample during the measurement. This hypothesis is checked with 3D simulation using the modeling and simulation software COMSOL and residues analysis: the difference between the temperature provided by the theoretical model $T_{\mathrm{mod}}(t)$ and that provided by the experience $T_{\mathrm{exp}}(t)$, to determine the time t_{max} at which the unidirectional hypothesis (1D) is checked. Given the very low value of the heat flow reaching the aluminum blocks through the polystyrene and their high capacity. the temperature is assumed to be equal and constant. By applying the quadrupole formalism [14] on the device shown in Figs. 1 and 2, and by using the temperature of the side before the sample $T_1(t)$. On the sample side, we may write:

$$\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & Rc_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} \tag{1}$$

$$C_s = \rho_s c_s e_s$$

$$\begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} = \begin{bmatrix} ch(qe) & \dfrac{sh(qe)}{\lambda q S} \\ \lambda q S\, sh(qe) & ch(qe) \end{bmatrix} ; \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = \begin{bmatrix} ch(q_i e_i) & \dfrac{sh(q_i e_i)}{\lambda q_i S} \\ \lambda q_i S\, sh(q_i e_i) & ch(q_i e_i) \end{bmatrix}$$

with $q = \sqrt{\dfrac{p}{a}}$ et $q_i = \sqrt{\dfrac{p}{a_i}}$

The formula (1) leads to the following formula (2):

$$\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & Rc_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} ch(qe) & \dfrac{sh(qe)}{\lambda qS} \\ \lambda qS\,sh(qe) & ch(qe) \end{bmatrix} \begin{bmatrix} ch(q_i e_i) & \dfrac{sh(q_i e_i)}{\lambda q_i S} \\ \lambda q_i S\,sh(q_i e_i) & ch(q_i e_i) \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} \quad (2)$$

By developing the previous matrix product (01), then we get Φ_1 :

$$\Phi_1 = \theta_1 \frac{D}{B} \quad (3)$$

Concerning the (polystyrene) insulator, we have

$$\begin{bmatrix} \theta_1 \\ \Phi_2 \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_2' \end{bmatrix} \quad (4)$$

by developing the previous matrix product, we have Φ_2 : $\Phi_2 = \theta_1 \dfrac{D_i}{B_i}$ with $\Phi_0 = \Phi_1 + \Phi_2 = \dfrac{\varphi_0}{S}$.

So $\Phi_0 = \theta_1 \left(\dfrac{D}{B} + \dfrac{D_i}{B_i} \right)$ and then we draw the value of θ_1 using the relation:

$$\theta_i = \frac{\phi_0}{p} \left(\frac{1}{\dfrac{D}{B} + \dfrac{D_i}{B_i}} \right) \quad (5)$$

With the inverse transformed [15], the relation (5) enables to get.

$$T_1(t) = L^{-1} \left(\frac{\phi_0}{p} * \frac{1}{\left(\dfrac{D}{B} + \dfrac{D_i}{B_i} \right)} \right) \quad (6)$$

Simplification of the model nothing that $\lambda q = \sqrt{pE}$ and $\lambda_i q = \sqrt{pE_i}$. The size is written when the time is long.

$$\theta_0 \approx \frac{\Phi_0}{p} \frac{1}{\left(CP + E\sqrt{P}\right)\left(1 - R_{C1}E\sqrt{P}\right) + \left(CP + E_i\sqrt{P}\right)\left(1 - R_{C2}E_i\sqrt{P}\right)} \quad (7)$$

This relationship becomes

$$\theta_0 \approx \frac{\Phi_0}{p} \frac{1}{(E + E_i)\sqrt{P} + p\left[C - R_{C1}E^2 + C - R_{C2}E_i^2\right]} \quad (8)$$

Again:

$$\theta_0 \approx \frac{\Phi_0}{p^{3/2}(E + E_i)} \frac{1}{1 - \dfrac{\left(2C - R_{C1}E^2 - R_{C2}E_i^2\right)\sqrt{p}}{E + E_i}} \quad (9)$$

And finally :

$$\theta_0 \approx \frac{\Phi_0}{p^{3/2}(E + E_i)} \left[1 + \left(\frac{R_{C1}E^2 + R_{C2}E_i^2}{E + E_i} - \frac{2C}{E + E_i} \right)\right]\sqrt{p} \quad (10)$$

By performing the Laplace inverse transform, we obtain

$$T_0(t) = \Phi_0 \left[\frac{R_{C1}E^2 + R_{C2}E_i}{(E + E_i)^2} - \frac{2(\rho ce)_s}{(E + E_i)^2} \right] + \frac{\Phi_0}{(E + E_i)\sqrt{\pi}}\sqrt{t} \quad (11)$$

When P approaches zero (long time), the curve $T = f\left(\sqrt{t}\right)$ tends towards a straight line. The inertia of the probe and the contact resistance has a negligible effect on this temperature. To determine the effusively, the slop β of the line is used. This will provide.

$$E + E_i = \frac{\Phi_0}{\beta\sqrt{\pi}} \quad (12)$$

For the whole time, we used the unidirectional hypothesis (1D). Temperature at the centre of the heating device in the Laplace area becomes:

$$\theta_s(0,0,p) = \frac{\Phi S}{2p} \frac{1 + R_c ES\sqrt{P}}{m_s c_s p + \left[R_c m_s c_s p + 1\right]ES\sqrt{P}} \quad (13)$$

And after inversion with longer time we have:

$$T_s(0,0,t) = \Phi \left[R_c - \frac{m_s c_s}{E^2 S^2} \right] + \frac{2\Phi\sqrt{t}}{ES\sqrt{\pi}} \quad (14)$$

The principle of the method is to determine the value of the effusivity E, the thermal conductivity

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λ of the sample and the contact resistance R_C that minimize the Mean Squared Error of the sum

$$\psi = \sum_{j=0}^{N} \left[\Delta T_{\exp(t_j)} - T_{\mathrm{mod}(t_j)} \right]^2 \quad (9) \text{ between}$$

the theoretical curve $T_{c\,\mathrm{mod}(t)} = T_{c\,\mathrm{mod}}(0,t)$ and the experimental curve $\Delta T_{c\exp} = T_{c\exp}(0,t) - T_{c\exp}(e,t)$ in the Levemberg-Marquardt-like algorithm program [16]. θ_1 is the Laplace temperature transformed $T_1(t)$; Φ_1 is Laplace transformed of the heat flow from the probe toward the sample above; Φ_2 is Laplace transformed of the heat flow from the probe to the insulator (polystyrene) located at the bottom; Φ_0 is the sum of Laplace transformed of the total flux released by the probe to the sample (on top) and to the insulator (polystyrene) underneath; $C_s = \rho_s e_s c_s$ is the heat capacity per unit area of the probe; R_c is the contact resistance between the sample and the probe; e_i et e are the thicknesses of the insulator and the sample respectively; a_i is the thermal diffusivity of the polystyrene.

For this, a simulation with the 3D model of the behavior of the hot plate model is made, in which intervene the lateral transfer of heat. It provides a theoretical representation of the temperature versus time. The heat equation and the boundary conditions are written for three dimensional systems. This equation is solved using a separation of variables after Laplace transform, and with the formalism of quadrupoles, it leads to Laplace transforms of the temperature.. Then the model is simplified by considering a unidirectional propagation of heat flow. Knowing the temperature in the Laplace space, we proceed to the determination of the temperature in the real space using the STEHFEST a Fourier method which are numerical methods. In practice, we obtain a thermogram (Fig. 4) of the form $T = f\left(\sqrt{T}\right)$. It permits determining a value of the effusivity or conductivity that we compare to that obtained by the 3D simulation. The curve is obtained by quadrupole type modeling for the case where the surface of the probe is lower than that of the sample. When the medium is semi-infinite and when the propagation of heat is unidirectional, the linear part of the curve helps to deduce the thermal effusivity by determining its slope. When the medium is semi-infinite and when the heat transfer is 2D, exploitation of the curve with 2 D model makes possible to estimate thermal conductivity.
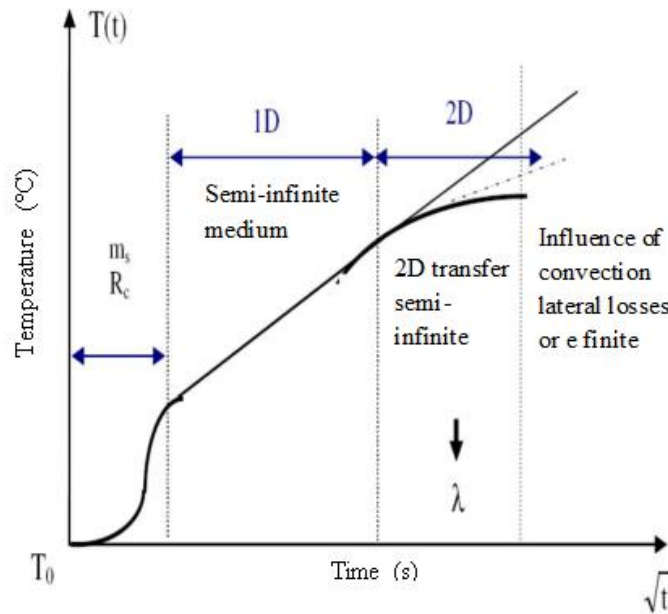

Fig. 4. Thermogram of $T = f\left(\sqrt{T}\right)$

3. RESULTS AND DISCUSSION

The curves $T_{h\,comsol} = f(t)$ obtained from this simulation are represented in Fig. 5. In the first step, we neglected the lateral losses between the blocks and the polystyrene, the negligible convective transfer coefficient (1D transfer), then we considered the convection with a coefficient h = 10 $W.m^{-2}.K^{1}$ (3D transfer). The analysis of this curves show that, the time during which the temperature relative difference $\dfrac{T_{h=0}(t) - T_{h=10}(t)}{T_{h=0}(t)}$ is lower than 1 % is around 400 s (Fig. 5).

Fig. 6 and Fig. 7 respectively show the propagation of heat in the experimental setup during measurements when the thermal convection is negligible and with thermal convection. It is obtained by modeling this device with COMSOL.

Fig. 8 shows the curves of theoretical and experimental values of temperatures and those of the residues. After simulation, we proceed to the analysis of the residues to possibly sum up the estimate in case these latter would not be flat.
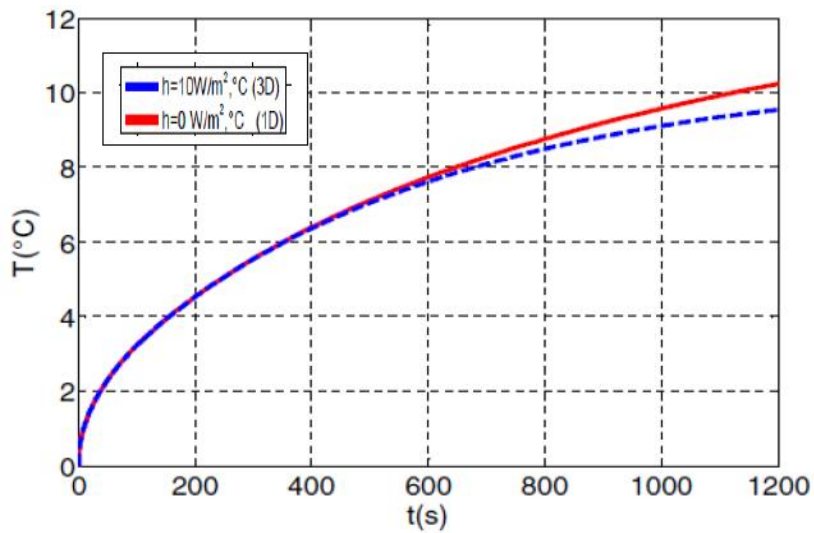

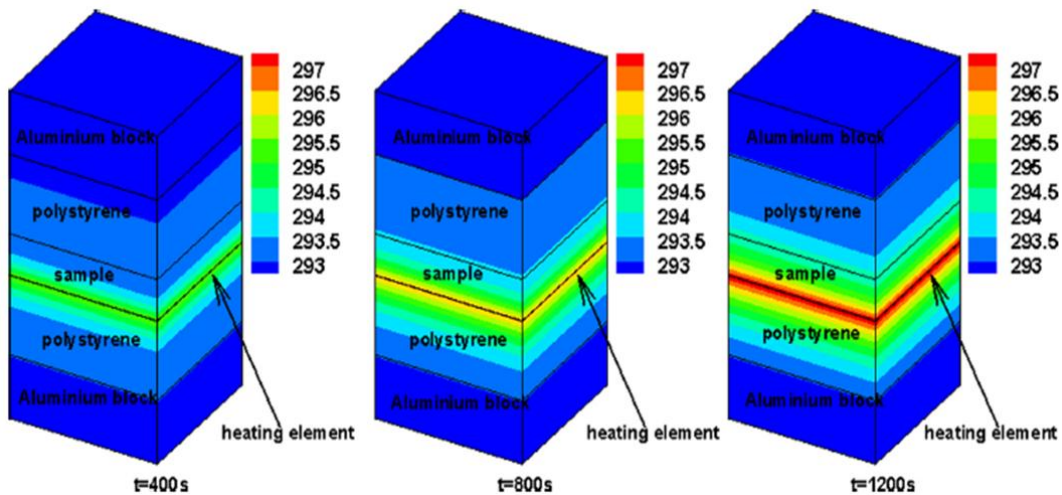**Fig. 5. Thermograms of temperature for material solved by COMSOL**

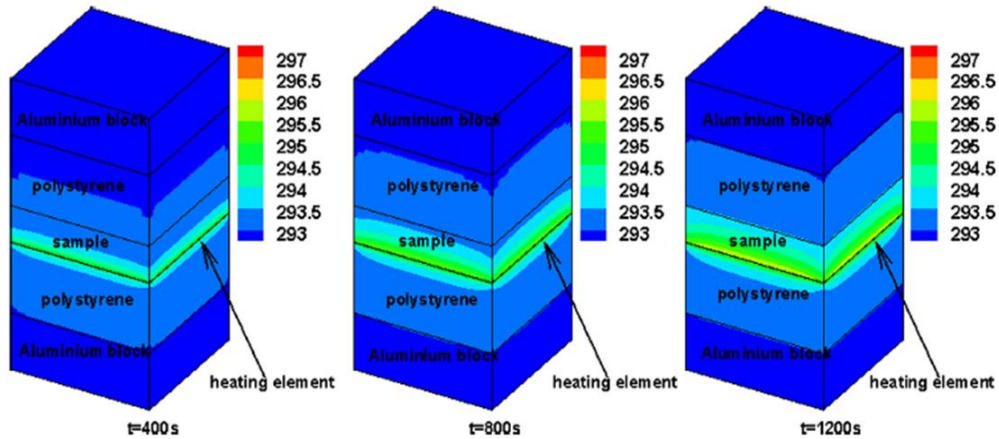**Fig. 6. Heat diffusion in materials (negligible convection, h = 0 $W.m^{-2}.K^{1}$)**

Fig. 7. Heat diffusion in materials (with convection, h = 10 $W.m^{-2}.K^{-1}$)
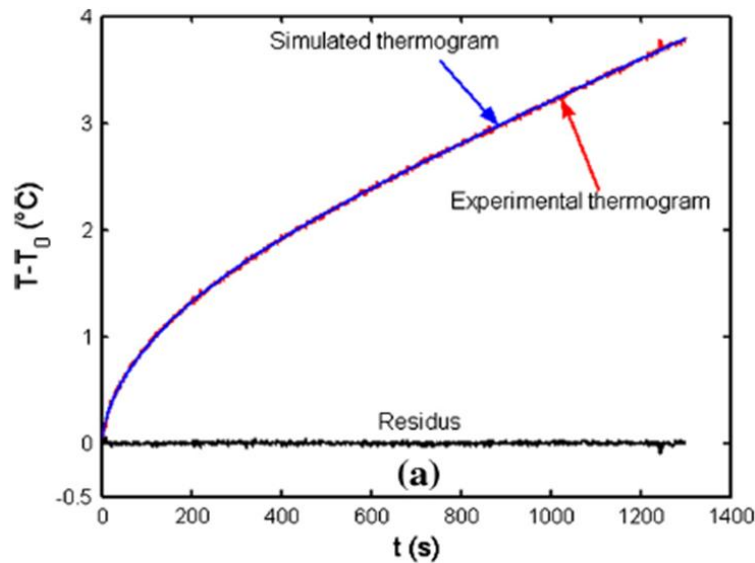

Fig. 8. Curves of theoretical and experimental values of temperatures and those of residues

The residue curve (black) shows that the experimental values are very close to the theoretical values over the estimation period. During this time, the residue is centered on zero and the transfer is unidirectional (1D).

Table 1 gives the values of the thermo-physical properties of the laterite blocks cut.

The values of the thermal conductivities vary from 0.444 to 0.577 $W.m^{-1}.K^{-1}$, we can say that the conductivity values are close to those measured by Ouedraogo et al. [1]. Also, these conductivities are lower than those of single lateritic blocks stabilized with the nere pod at 4% and 8% [5]. The low values of conductivity are

due to the high porosity of the blocks. The greater the porosity, the greater the number of pores filled with air whose conductivity is relatively very low. The values of the specific heat of the BLTs vary from 982.562 to 1143.945 $J.kg^{-1}.K^{-1}$ according to the samples. They are weaker than those of compressed earth blocks determined by Ouedraogo et al. [1]. These lateritic blocks will therefore have a low capacity for storing heat. These blocks will transmit low heat because they have low thermal diffusivities (the largest value is 2.973*10^{-7} $m^2.s^{-1}$). We also find that the values of thermal effusivity are relatively low. The blocks will then see their surface temperatures lower quickly.

Table 1. Thermo-physical properties of the laterite blocks

Properties	Bobo-Dioulasso	Reo	Yako
Thermal conductivity $(W.m^{-1}.K^{-1})$	0.577 ± 0.014	0.444 ± 0.012	0.469 ± 0.011
Density $(kg.m^{-3})$	1892.293 ± 47.305	1813.024 ± 45.327	1853.319 ± 46.323
Thermal capacity $(J.kg^{-1}.K^{-1})$	1027.853 ± 25.698	1143.945 ± 28.569	982.562 ± 24.565
Thermal diffusivity $(10^{-7}\ m^2.s^{-1})$	2.973 ± 0.074	2.145 ± 0.053	2.783 ± 0.070
Thermal effusivity $(J.m^{-2}.K^{-1}.s^{-1/2})$	1059.363 ± 26.483	958.676 ± 23.967	889.043 ± 22.215

4. CONCLUSION

The experimental study on the thermo-physical characterization made it possible to determine the properties of the laterite cut blocks from three (03) quarries (Bobo-Dioulasso, Reo and Yako) in Burkina Faso. The use of the asymmetrical hot plate method made it possible to obtain the values of these properties. All the samples studied have thermal conductivities lower than 0.6 $W.m^{-1}.K^{-1}$. And the Reo bricks have the lowest values of thermal conductivities (0.444 $W.m^{-1}.K^{-1}$) and thermal diffusivities (2.145*10^{-7} $m^2.s^{-1}$). It is therefore the best material for thermal insulation. The results show that the materials have good thermal performance. They can therefore be used for the building of energy-efficient habitats, especially the design of buildings for better thermal comfort.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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