

Experimental study of the thermo-physical properties of lateritic blocks used in the habitat in dry tropical climate.

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 is done with the hot plane device and the asymmetrical method was used. All the samples studied have thermal conductivities less than $0.6 \text{ W.m}^{-1}.\text{K}^{-1}$ and thermal diffusivities lower than $3 \cdot 10^{-7} \text{ m}^2.\text{s}^{-1}$. These results show that the materials have good thermal performance.

Keywords: Laterite blocks, Asymmetric hot plan model, Thermal conductivity, thermal diffusivity, Thermo-physical properties.

1. INTRODUCTION

The traditional African society built with "the means of edge" in complete autarky while the modern society realizes its works using Western techniques. This leads to the importation of some construction products. In Burkina Faso, the proportion of manufactured imports related to the building and public works sector is currently around 45% [1]. This constitutes huge currency losses for the country. The solution to this problem could be in the use of local building materials. The qualitative mode of urban development and the appropriated implementation of habitat are determining factors of high environmental quality. Housing and its urban context appear more and more in Africa as an important tool of globalization referred 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 in the majority of African countries, the most of buildings are built with local materials and this for almost all the rural populations who are 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 P. [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 E 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 BK 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 AK et al [8, 9]) for the use of laterite blocks as masonry elements in traditional construction. In Africa, this material represents a significant resource, used alone or associated with a concrete structure for the realization of habitats. The physico-mechanical properties have been studied to disassemble 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 plane using the asymmetrical method.

2. MATERIALS AND METHODS

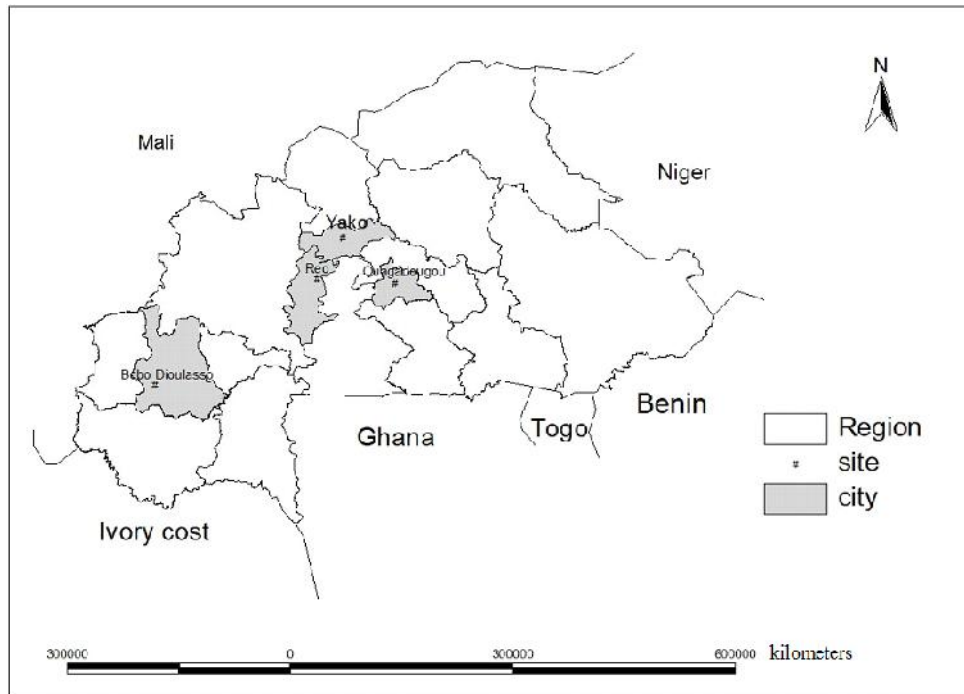
2.1. Laterite block

The laterite block or lateritic stone is a masonry element: of more or less regular dimensions and characteristics, it is obtained by manual or mechanical cutting of the cuirass or the carapaces of the lateritic rocks. Laterites are products of intense weathering and consist of a mineral assemblage that can be made of goethite, hematite, mineral compound, kaolinite and quartz. The ratio $\text{SiO}_2 / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ 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 tender in the fresh state and becomes hard when exposed to the air [13]. The size of bricks used for thermal tests is 10 cm x 10 cm x 2.5 cm.

2.2. Method and Assessment of thermal and mechanical characteristic of the various formulations

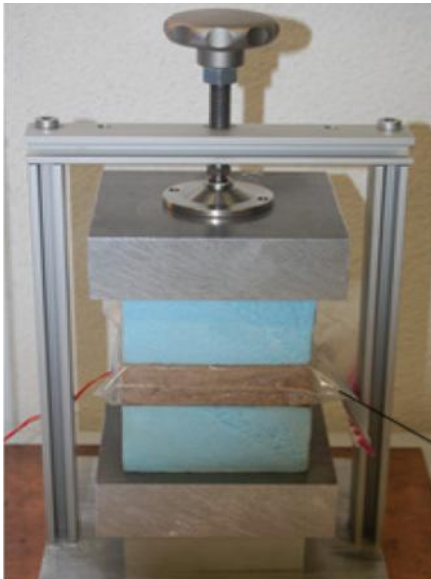
We used the method of asymmetric hot plan available to Applied Energy Laboratory of the Polytechnic School of Dakar (L.E.A) to determine the thermal properties of laterite dimension stone from tree quarries (quarries of Bobo-Dioulasso, Réo and Yako) in Burkina

64 Faso, west African country. Fig. 1 presents the map of the country with the three cities and
 65 the capital (the city of Ouagadougou).

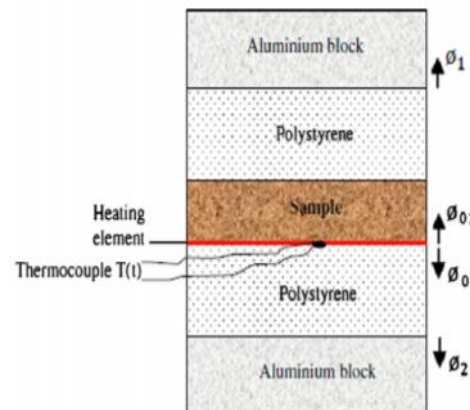


66
 67 **Fig. 1. Map of Burkina Faso**

68 **2.3. Method used to measure the thermo-physical properties of materials**



69
 70 **Fig.2. Asymmetric Hot Plan**



71 **Fig. 3. Simplified Hot Plan Model**

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

75 The method is based on temperature measurement at the center of the heating device with a
 76 heated surface $100 \pm 1 \text{ mm} \times 100 \pm 1 \text{ mm}$ and a thickness $0.22 \pm 0.01 \text{ mm}$. The uncertainty in the
 77 heating device area is thus around 2 %. We must add the uncertainty to the sample thickness
 78 estimated at 1 % and to the heat flux produced in the heating device, estimated at 0.5 %. The
 79 sum of these uncertainties leads to an overall uncertainty rate of 3.5 % to which must be
 80 added the estimation error due to noise measurement on ΔT and the errors due to phenomena
 81 that have not been taken into account in the model. Most of the heat dissipated into the
 82 heating device which electric resistance $R_e = 40 \Omega$, passes through the upper part of the
 83 heating device. A plan heating device sharing the same section with the sample is placed
 84 under it. K-type thermocouple comprising two cords of 0.005 mm diameter is placed at the
 85 underside of the heating device. The sample is placed between two 40 mm thick blocks of
 86 extruded polystyrene and the set is placed between two 40 mm thick aluminum blocks. A heat
 87 flow is sent from the heating device. The temperature evolution $T(t)$ is recorded at every each
 88 0.1 s . The presence of the thermocouple does not increase the contact resistance between the
 89 heating device and the polystyrene. Since polystyrene is an insulating material. this thermal
 90 resistance will be marginal. The system is modeled with the unidirectional transfer hypothesis
 91 (1D) at the center of the heating device and the sample during the measurement. This
 92 hypothesis is checked with 3D simulation using the modeling and simulation software
 93 COMSOL and residues analysis: the difference between the temperature provided by the
 94 theoretical model $T_{\text{mod}}(t)$ and that provided by the experience $T_{\text{exp}}(t)$, to determine the time
 95 t_{max} at which the unidirectional hypothesis (1D) is checked. Given the very low value of the
 96 heat flow reaching the aluminum blocks through the polystyrene and their high capacity. the
 97 temperature is assumed to be equal and constant. By applying the quadrupole formalism [14]
 98 on the device shown in figures 1 and 2, and by using the temperature of the side before the
 99 sample $T_l(t)$. On the sample side, we may write,

$$100 \quad \begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & Rc_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} \quad (1)$$

$$101 \quad C_s = \rho_s c_s e_s$$

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

$$\text{with } q = \sqrt{\frac{p}{a}} \quad \text{et} \quad q_i = \sqrt{\frac{p}{a_i}}$$

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

$$\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & R_{C1} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} ch(qe) & \frac{sh(qe)}{\lambda q S} \\ \lambda q S sh(qe) & ch(qe) \end{bmatrix} \begin{bmatrix} ch(q_i e_i) & \frac{sh(q_i e_i)}{\lambda q_i S} \\ \lambda q_i S sh(q_i e_i) & ch(q_i e_i) \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} \quad (2)$$

$$\text{By developing the previous matrix product (01), then we get } \Phi_1 : \Phi_1 = \theta_1 \frac{D}{B} \quad (3)$$

$$\text{Concerning the (polystyrene) insulator, we have } \begin{bmatrix} \theta_1 \\ \Phi_2 \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_2' \end{bmatrix} \quad (4)$$

$$\text{by developing the previous matrix product, we have } \Phi_2 : \Phi_2 = \theta_1 \frac{D_i}{B_i} \text{ with } \Phi_0 = \Phi_1 + \Phi_2 = \frac{\phi_0}{S}.$$

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

$$\theta_1 = \frac{\phi_0}{p} \left(\frac{1}{\frac{D}{B} + \frac{D_i}{B_i}} \right) \quad (5)$$

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

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

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

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

This relationship becomes

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

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

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

By performing the Laplace inverse transform, one obtains

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

When P approaches zero (long time), the curve $T = f(\sqrt{t})$ 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 center of the heating device in the Laplace area becomes:

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

And after inversion with longer time we have:

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

The principle of the method is to determine the value of the effusivity E, the thermal conductivity λ of the sample and the contact resistance R_c that minimize the Mean Squared

Error of the sum $\psi = \sum_{j=0}^N \left[\Delta T_{\text{exp}(t_j)} - T_{\text{mod}(t_j)} \right]^2$ (9) between the theoretical curve

$T_{c \text{ mod}(t)} = T_{c \text{ mod}}(0, t)$ and the experimental curve $\Delta T_{c \text{ exp}} = T_{c \text{ exp}}(0, t) - T_{c \text{ exp}}(e, t)$ in the

Levenberg-Marquardt-like algorithm program [16]. θ_l is the Laplace temperature transformed $T_l(t)$; 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 plan 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 $T = f(\sqrt{t})$. It permits determining a value of the effusivity or conductivity that we compare to that obtained the 3D simulation. The curve is obtained by quadrupole type modeling for the case where the surface of the probe is lower than that 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.

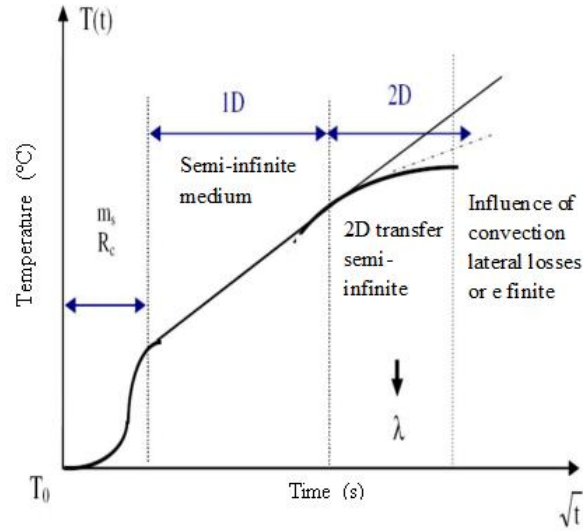


Fig. 4. Thermogram of $T = f(\sqrt{t})$

3. RESULTS AND DISCUSSION

The curves $T_{h\text{ consol}} = f(t)$ obtained from this simulation are represented in fig. 5. In a 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 $h = 10 \text{ W.m}^{-2}.\text{K}^{-1}$ (3D transfer). The analysis of this curves show that, the time during which the temperature relative different $\frac{T_{h=0}(t) - T_{h=10}(t)}{T_{h=0}(t)}$ is lower than 1 % is around 400 s (fig. 5).

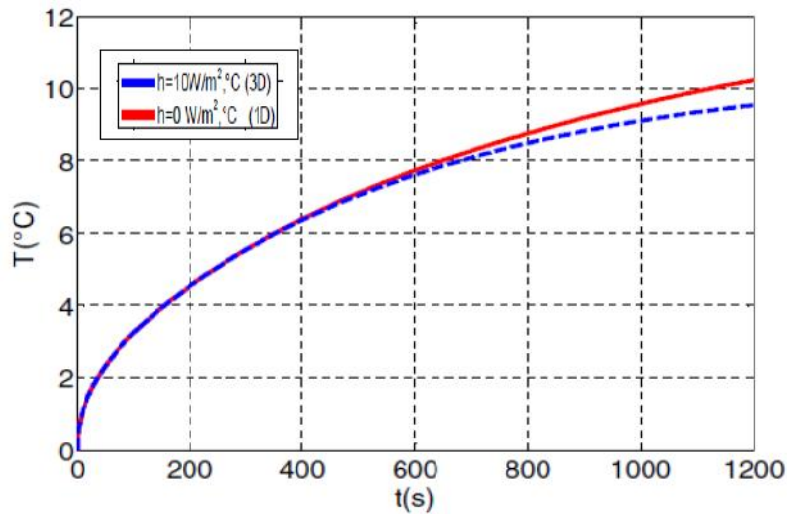


Fig. 5. Thermograms of temperature for material soved by comsol

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.

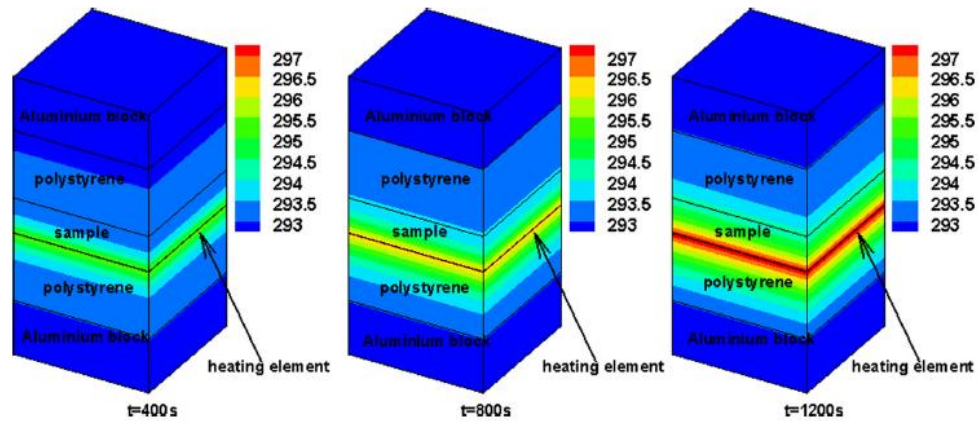


Fig. 6. Heat diffusion in materials (negligible convection, $h = 0 \text{ W.m}^{-2}.\text{K}^{-1}$)

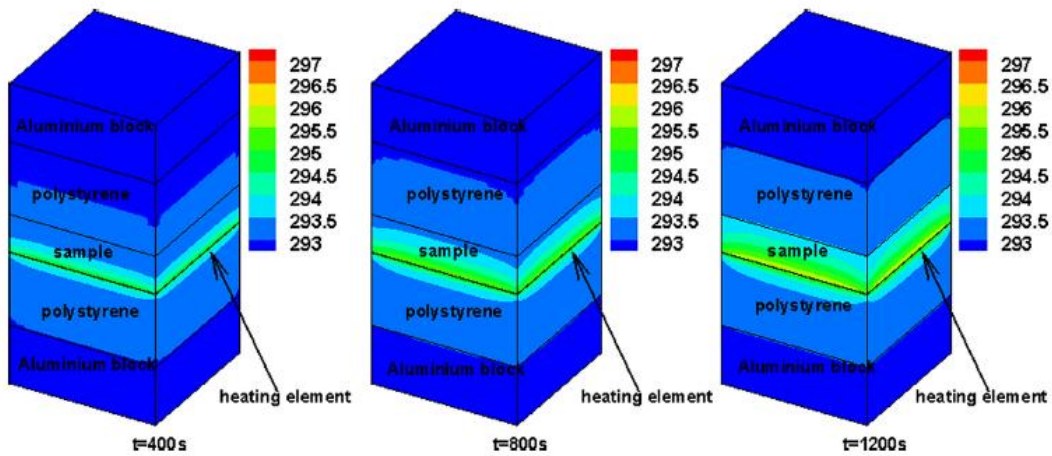


Fig. 7. Heat diffusion in materials (with convection, $h = 10 \text{ W.m}^{-2}.\text{K}^{-1}$)

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 resume the estimate in case these latter would not be flat.

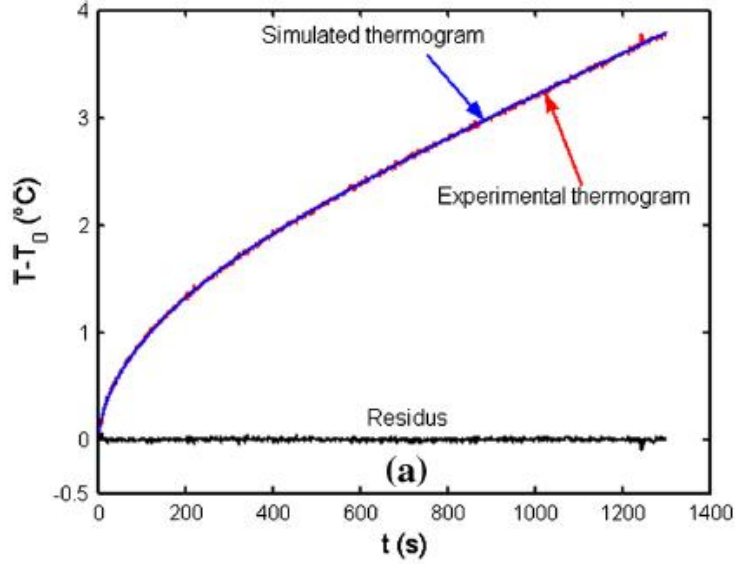


Fig. 8. Curves of theoretical and experimental values of temperatures and those of residues

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.

Table1: Thermo-physical properties of the laterite blocks

Properties	Bobo-Dioulasso	Réo	Yako
Thermal conductivity ($\text{W.m}^{-1}.\text{K}^{-1}$)	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 ($\text{J.kg}^{-1}.\text{K}^{-1}$)	1027.853 ± 25.698	1143.945 ± 28.569	982.562 ± 24.565
Thermal diffusivity ($10^{-7} \text{ m}^2.\text{s}^{-1}$)	2.973 ± 0.074	2.145 ± 0.053	2.783 ± 0.070
Thermal effusivity ($\text{J.m}^{-2}.\text{K}^{-1}.\text{s}^{-1/2}$)	1059.363 ± 26.483	958.676 ± 23.967	889.043 ± 22.215

The values of the thermal conductivities vary from 0.444 to $0.577 \text{ W.m}^{-1}.\text{K}^{-1}$, we can say that the conductivity values are close to those measured by Ouedraogo E 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 E 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 m².s⁻¹). We also find that the values of thermal effusivity are relatively low. The blocks will then see their surface temperatures close quickly.

4. CONCLUSION

The experimental study on the thermo-physical characterization made it possible to determine the properties of the laterite blocks cut from three (03) quarries (Bobo-Dioulasso, Reo and Yako) in Burkina Faso. The use of the asymmetrical method of the hot plane 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 m².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 construction of energy-efficient buildings. And especially the design of buildings for better thermal comfort.

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