

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 Pierre 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. Emmanuel 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 Kossi 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 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

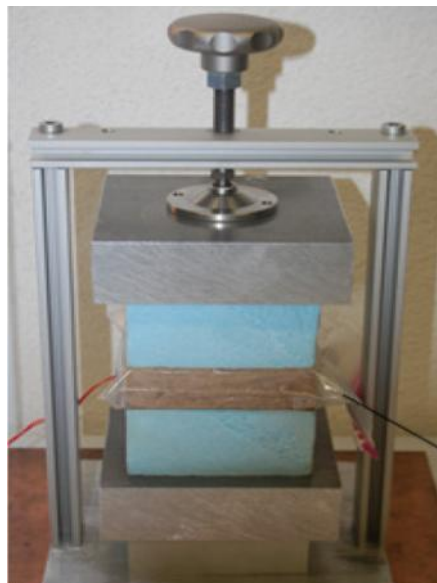
The laterite block or lateritic stone is a masonry element: of more or less regular dimensions and characteristics, it is obtained by manual or mechanical cutting of the cuirass or the carapaces of the lateritic rocks. Laterites are products of intense weathering and consist of a mineral assemblage that can be made of goethite, hematite, aluminum hydroxide, 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 $10 \times 10 \times 2.5 \text{ cm}^3$.

2.2. Method and Assessment of thermal and mechanical caractéristique 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

63 dimension stone from tree quarries (quarries of Bobo-Dioulasso, Réo and Yako) in Burkina
64 Faso.

65 2.3. Method used to measure the thermo-physical properties of materials



66
67 **Fig.1. Asymmetric Hot Plan**
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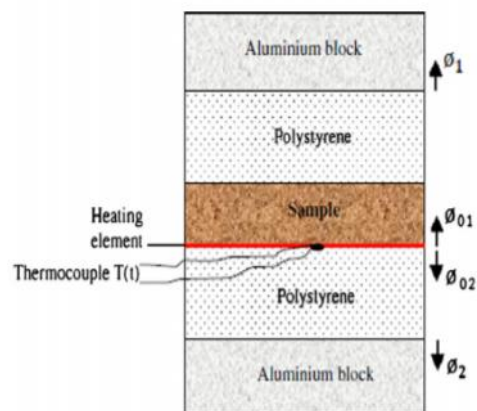


Fig. 2. Simplified Hot Plan Model

69 An experimental study of the effusivity and thermal conductivity was mainly conducted using
70 the method of the asymmetric hot plan in a transitory regime. Fig.1 shows the asymmetric
71 experimental device.

72 The method is based on temperature measurement at the center of the heating device with a
73 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
74 heating device area is thus around 2 %. We must add the uncertainty to the sample thickness
75 estimated at 1 % and to the heat flux produced in the heating device, estimated at 0.5 %. The
76 sum of these uncertainties leads to an overall uncertainty rate of 3.5 % to which must be
77 added the estimation error due to noise measurement on ΔT and the errors due to phenomena
78 that have not been taken into account in the model. Most of the heat dissipated into the
79 heating device which electric resistance $R_e = 40 \Omega$, passes through the upper part of the
80 heating device. A plan heating device sharing the same section with the sample is placed
81 under it. K-type thermocouple comprising two cords of 0.005 mm diameter is placed at the
82 underside of the heating device. The sample is placed between a 40 mm thick two blocks of
83 extruded polystyrene set between two 40 mm thick aluminum blocks. A heat flow is sent from
84 the heating device. The temperature evolution $T(t)$ is recorded at every each 0.1 s . The

85 presence of the thermocouple does not increase the contact resistance between the heating
 86 device and the polystyrene. Since polystyrene is an insulating material. this thermal resistance
 87 will be marginal. The system is modeled with the unidirectional transfer hypothesis (1D) at
 88 the center of the heating device and the sample during the measurement. This hypothesis is
 89 checked with 3D simulation using the COMSOL and residues analysis: the difference
 90 between the temperature provided by the theoretical model $T_{\text{mod}}(t)$ and that provided by the
 91 experience $T_{\text{exp}}(t)$, to determine the time t_{max} at which the unidirectional hypothesis (1D) is
 92 checked. Given the very low value of the heat flow reaching the aluminum blocks through the
 93 polystyrene and their high capacity. the temperature is assumed to be equal and constant. By
 94 applying the quadrupole formalism [14] on the device shown in figures 1 and 2, and by using
 95 the temperature of the side before the sample $T_I(t)$. On the sample side, we may write.

$$96 \quad \begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & Rc_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} \quad (1)$$

$$97 \quad C_s = \rho_s c_s e_s$$

$$98 \quad \begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} = \begin{bmatrix} ch(qe) & \frac{sh(qe)}{\lambda q S} \\ \lambda q S sh(qe) & ch(qe) \end{bmatrix}; \quad \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = \begin{bmatrix} ch(q_i e_i) & \frac{sh(q_i e_i)}{\lambda q_i S} \\ \lambda q_i S sh(q_i e_i) & ch(q_i e_i) \end{bmatrix}$$

$$99 \quad \text{with } q = \sqrt{\frac{p}{a}} \quad \text{et} \quad q_i = \sqrt{\frac{p}{a_i}}$$

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

$$101 \quad \begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ C_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & Rc_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} ch(qe) & \frac{sh(qe)}{\lambda q S} \\ \lambda q S sh(qe) & ch(qe) \end{bmatrix} \begin{bmatrix} ch(q_i e_i) & \frac{sh(q_i e_i)}{\lambda q_i S} \\ \lambda q_i S sh(q_i e_i) & ch(q_i e_i) \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_1' \end{bmatrix} \quad (2)$$

$$102 \quad \text{By developing the previous matrix product (01), then we get } \Phi_1 : \Phi_1 = \theta_1 \frac{D}{B} \quad (3)$$

$$103 \quad \text{Concerning the (polystyrene) insulator, we have } \begin{bmatrix} \theta_1 \\ \Phi_2 \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi_2' \end{bmatrix} \quad (4)$$

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

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

$$106 \quad \theta_1 = \frac{\phi_0}{p} \left(\frac{1}{\frac{D}{B} + \frac{D_i}{B_i}} \right) \quad (5)$$

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

$$108 \quad T_1(t) = L^{-1} \left(\frac{\phi_0}{p} * \frac{1}{\left(\frac{D}{B} + \frac{D_i}{B_i} \right)} \right) \quad (6)$$

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

$$111 \quad \theta_0 \approx \frac{\Phi_0}{p} \frac{1}{\left(CP + E\sqrt{P} \right) \left(1 - R_{C1}E\sqrt{P} \right) + \left(CP + E_i\sqrt{P} \right) \left(1 - R_{C2}E_i\sqrt{P} \right)} \quad (7)$$

112 This relationship becomes

$$113 \quad \theta_0 \approx \frac{\Phi_0}{p} \frac{1}{(E + E_i)\sqrt{P} + p[C - R_{C1}E^2 + C - R_{C2}E_i^2]} \quad (8)$$

$$114 \quad \text{Again: } \theta_0 \approx \frac{\Phi_0}{p^{3/2}(E + E_i)} \frac{1}{1 - \frac{(2C - R_{C1}E^2 - R_{C2}E_i^2)\sqrt{p}}{E + E_i}} \quad (9)$$

$$115 \quad \text{And finally : } \theta_0 \approx \frac{\Phi_0}{p^{3/2}(E + E_i)} \left[1 + \left(\frac{R_{C1}E^2 + R_{C2}E_i^2}{E + E_i} - \frac{2C}{E + E_i} \right) \right] \sqrt{p} \quad (10)$$

116 By performing the Laplace inverse transform, one obtains

$$117 \quad T_0(t) = \Phi_0 \left[\frac{R_{C1}E^2 + R_{C2}E_i}{(E + E_i)^2} - \frac{2(\rho ce)_s}{(E + E_i)^2} \right] + \frac{\Phi_0}{(E + E_i)\sqrt{\pi}} \sqrt{t} \quad (11)$$

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

$$121 \quad E + E_i = \frac{\Phi_0}{\beta\sqrt{\pi}} \quad (12)$$

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

$$124 \quad \theta_s(0,0,p) = \frac{\Phi S}{2p} \frac{1 + R_c E S \sqrt{P}}{m_s c_s p + [R_c m_s c_s p + 1] E S \sqrt{P}} \quad (13)$$

125 And after inversion with longer time we have:

$$126 \quad T_s(0,0,t) = \Phi \left[R_c - \frac{m_s c_s}{E^2 S^2} \right] + \frac{2\Phi\sqrt{t}}{E S \sqrt{\pi}} \quad (14)$$

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

129 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

130 $T_{\text{cmod}(t)} = T_{\text{cmod}}(0,t)$ and the experimental curve $\Delta T_{\text{cexp}} = T_{\text{cexp}}(0,t) - T_{\text{cexp}}(e,t)$ in the
 131 Levenberg-Marquardt-like algorithm program [16]. θ_l is the Laplace temperature
 132 transformed $T_l(t)$; Φ_1 is Laplace transformed of the heat flow from the probe toward the
 133 sample above; Φ_2 is Laplace transformed of the heat flow from the probe to the insulator
 134 (polystyrene) located at the bottom; Φ_0 is the sum of Laplace transformed of the total flux
 135 released by the probe to the sample (on top) and to the insulator (polystyrene) underneath;
 136 $C_s = \rho_s e_s c_s$ is the heat capacity per unit area of the probe; R_c is the contact resistance
 137 between the sample and the probe; e_i et e are the thicknesses of the insulator and the sample
 138 respectively; a_i is the thermal diffusivity of the polystyrene.

139 For this, a simulation with the 3D model of the behavior of the hot plan model is made, in
 140 which intervene the lateral transfer of heat. It provides a theoretical representation of the
 141 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. 3) 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.

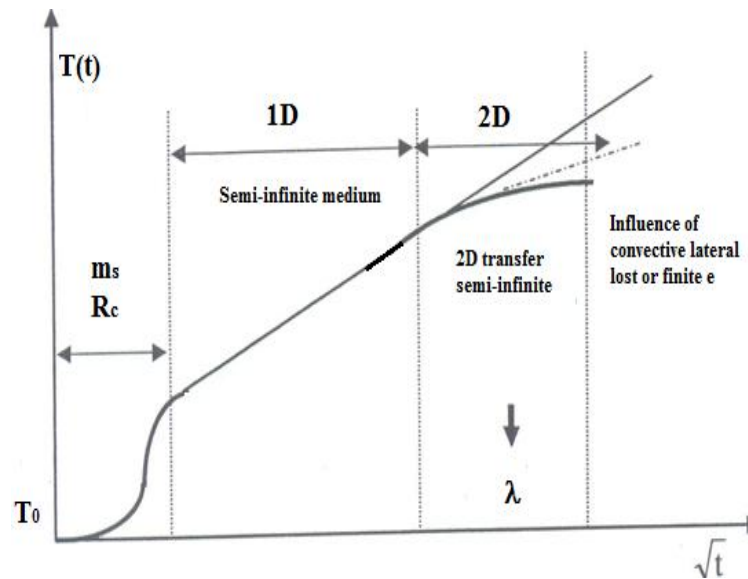
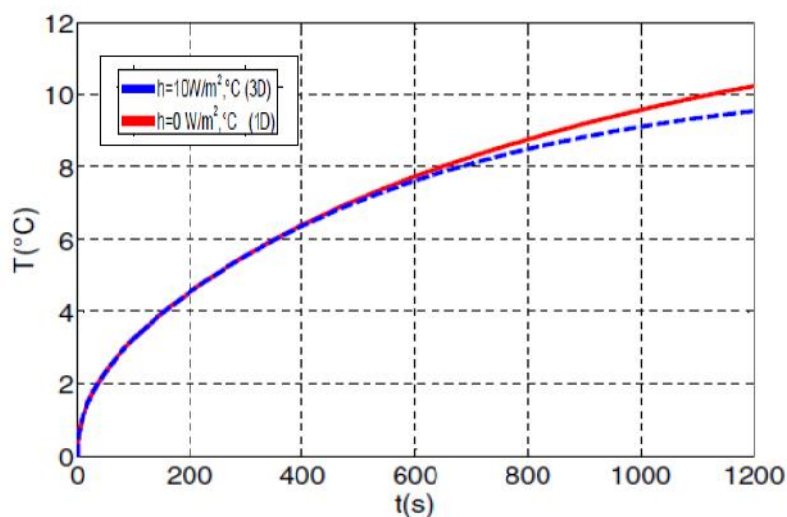


Fig. 3. Thermogram of $T = f(\sqrt{t})$

3. RESULTS AND DISCUSSION

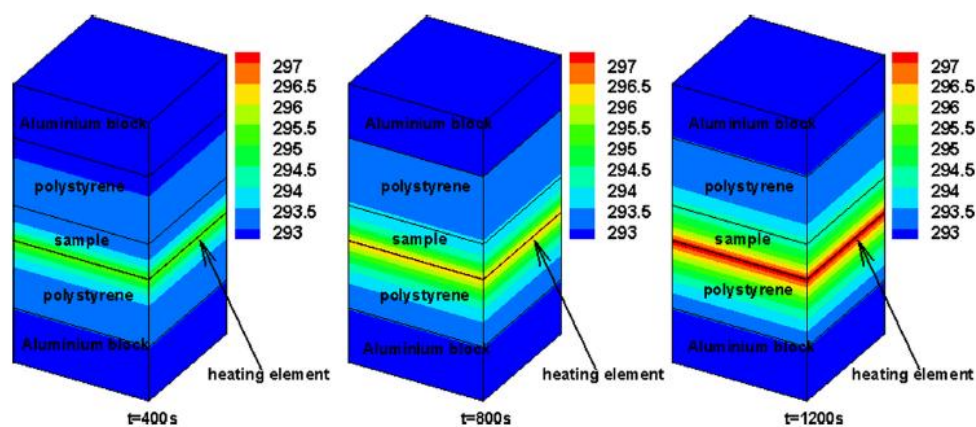
The curves $T_{h\,consol} = f(t)$ obtained from this simulation are represented in figure 4. In a first step, we neglected the lateral losses between the blocks and the polystyrene, the negligible convective transfer coefficient (1D transfer), then we considered the convection with a coefficient $h = 10\, W.m^2.K^{-1}$ (3D transfer). The analysis of this curves show that, the time

162 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
 163 400 s (fig. 4).



164
 165 **Fig. 4. Thermograms of temperature for material soved by comsol**

166 Fig. 5 and Fig. 6 respectively show the propagation of heat in the experimental setup during
 167 measurements when the thermal convection is negligible and with thermal convection. It is
 168 obtained by modeling this device with Comsol.



169
 170 **Fig. 5. Heat diffusion in materials (negligible convection, $h = 0 \text{ W.m}^2.\text{K}^{-1}$)**

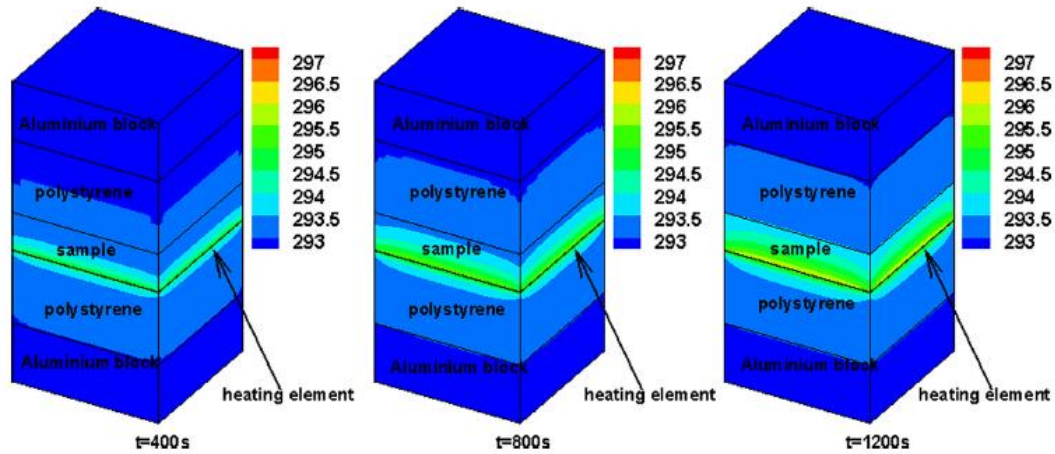


Fig. 6. Heat diffusion in materials (with convection, $h = 10 \text{ W.m}^2.\text{K}^{-1}$)

Figure 7 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.

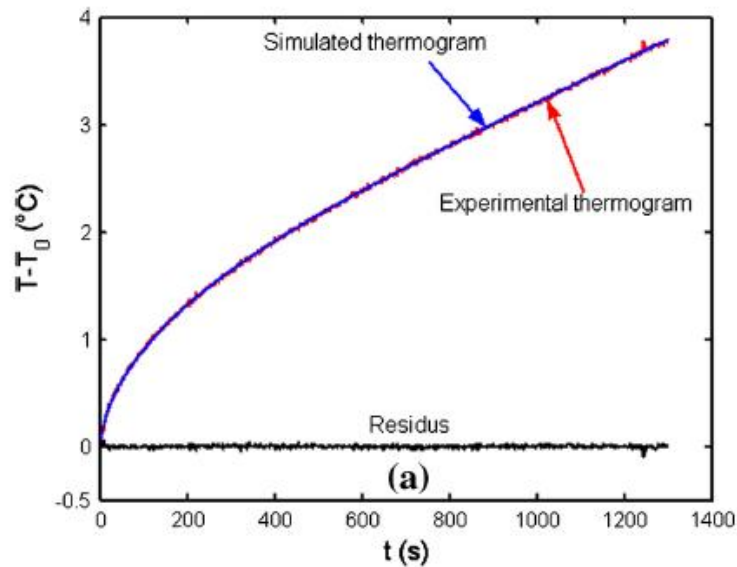


Fig. 7. Curves of theoretical and experimental values of temperatures and those of residues

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.

183

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 ($\text{J.s}^{-1/2}.\text{m}^{-2}.\text{K}^{-1}$)	1059.363 ± 26.483	958.676 ± 23.967	889.043 ± 22.215

184 The values of the thermal conductivities vary from 0.444 to 0.577 $\text{W.m}^{-1}.\text{K}^{-1}$, we can say that
 185 the conductivity values are close to those measured by OUEDRAOGO et al [1]. Also, these
 186 conductivities are lower than those of single lateritic blocks stabilized with the Nere pod at
 187 4% and 8% [5]. The low values of conductivity are due to the high porosity of the blocks.
 188 The greater the porosity, the greater the number of pores filled with air whose conductivity is
 189 relatively very low. The values of the specific heat of the BLTs vary from 982.562 to
 190 1143.945 $\text{J.kg}^{-1}.\text{K}^{-1}$ according to the samples. They are weaker than those of compressed
 191 earth blocks determined by OUEDRAOGO et al [1]. These lateritic blocks will therefore
 192 have a low capacity for storing heat. These blocks will transmit low heat because they have
 193 low thermal diffusivities (the largest value is $2.973 \times 10^{-7} \text{ m}^2.\text{s}^{-1}$). We also find that the values
 194 of thermal effusivity are relatively low. The blocks will then see their surface temperatures
 195 close quickly.

196 4. CONCLUSION

197 The experimental study on the thermo-physical characterization made it possible to determine
 198 the properties of the laterite blocks cut from three (03) quarries (Bobo-Dioulasso, Réo and
 199 Yako) in Burkina Faso. The use of the asymmetrical method of the hot plane made it possible
 200 to obtain the values of these properties. All the samples studied have thermal conductivities
 201 lower than 0.6 $\text{W.m}^{-1}.\text{K}^{-1}$. And the Reo bricks have the lowest values of thermal
 202 conductivities ($0.444 \text{ W.m}^{-1}.\text{K}^{-1}$) and thermal diffusivities ($2.145 \times 10^{-7} \text{ m}^2.\text{s}^{-1}$). It is therefore
 203 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.

REFERENCES

1. Emmanuel Ouedraogo, Ousmane Coulibaly, Abdoulaye Ouedraogo, Adamah Messan, Caractérisation mécanique et thermophysique des blocs de terre comprimée stabilisée au papier (cellulose) et/ou au ciment, *Journal of Materials and Engineering Structures*. 2015; 2, 68-76.
2. Pierre Meukam, Caractérisation de matériaux locaux en vue de l'isolation thermique de bâtiments. Thèse de doctorat, Université de Yaoundé I, Cameroun, 2004.
3. Emmanuel Ouedraogo, Abdoulaye Ouedraogo and Adamah Messan, Hydro Mechanical Properties of Cement and Cellulose Stabilized Compressed Clay Bricks, *Journal of Materials Science and Engineering A*. 2014; 4 (11), 348-355.
4. IMBGA B kossi, KIENO P. Florent, OUEDRAOGO Emmanuel, Thermal and Mechanical Study of the Adobe Stabilized with Straws and /or Cement at different, *International Journal of Engineering and Innovative Technology*. October 2014; Volume 4, Issue 4, 200-204.
5. Imbga B. Kossi, Kieno P. Florent, Sambou Vincent, Ouedraogo Emmanuel, Gouba Daniel and Toure P. Moussa, Study of the Thermal and Mechanical Performance of Laterite Blocks Mixed with Néré Pod for the Thermal Insulation of Buildings, *Physical Science International Journal*. 2016; 11(2), 1-10.
6. IMBGA B kossi, SAMBOU Vincent, KIENO P. Florent and DIEYE Younouss, Thermal and mechanical study of Thermal and mechanical study of with lime for sustainable building applications in Sahel countries. *International Journal of Current Research*. 2017; 9, (01), 44609-44615.
7. Y. Millogo, J.C. Morel, K. Traoré, R. Ouedraogo, Microstructure, geotechnical and mechanical characteristics of quicklime-lateritic gravels mixtures used in road construction. *Constr. Build. Mater*. 2012; 26 (1), 663-669.
8. Kasthurba A.K., Santhanam M., Mathews M.S. «Investigation of laterite stones for building purpose from Malabar region, Kerala state, SW India – Part 1: Field studies and profile characterisation», *Construction and Building Materials*. 2007; 21, 73–82.
9. Kasthurba A.K., Santhanam M., (2005), «A Re-look into the Code Specifications for the Strength Evaluation of Laterite Stone Blocks for Masonry Purposes», *Journal of The Institution of Engineers (India)*, Vol 86, April 2005 pp 1 – 6, Kolkata, 2005.
10. Lawane A., Vinai R., Pantet A., Thomassin J.H (2011)«Characterisation of laterite stone as building material in Burkina Faso», *Journée Scientifique 2IE*, 6 Avril 2011.

- 238 11. Abdou Lawane, Anne Pantet, Raffaele Vinai, Jean Hugues Thomassin. Etude géologique
239 et géomécanique des latérites de Dano (Burkina Faso) pour une utilisation dans l'habitat. Les
240 Annales BTP. 2011; n° 1n°6.
- 241 12. Schellmann W., Discussion of “«A critique of the Schellmann definition and
242 classification of laterite”» by R.P. Bourman and C.D. Ollier (Catena Elsevier 2003. 47,117–
243 131), 77– 79.
- 244 13. Bourmana R.P., Ollier C.D. «A critique of the Schellmann definition and
245 classification of ‘laterite’», Catena Elsevier. 2002; 47, 117–131.
- 246 14. Bodian, S. ‘Comportement Thermomécanique d’une brique de Terre Crue et en
247 Terre Cuite.’ Master de Recherche. Ecole Supérieure Polytechnique (E S P) Dakar. 2011.
- 248 15. F. R. de Hoog, J. H. Knight, and A. N. Stokes. An Improved method for numerical
249 inversion of Laplace Transforms. Society of Industrial and Applied Mathematics. 1982;
250 3(3); 357-366.
- 251 16. Marquardt D. An Algorithm for least Squares estimation of non-linear parameters. Soc
252 Ind Appl Math.1963. 11, 431-41.