Original Research Article

Study of the thermal and mechanical performance of laterite blocks mixed with Néré pod for the thermal insulation of buildings.

Abstract

This paper presents an experimental study on the characterization of local materials used in the construction of buildings. These materials are laterite blocks associated with rates ranging between 0% and 16%, with a pace of 4% of Néré pod. We observed that the thermal conductivity decreases and as the Néré pod rate increases. But it gets stabilized at 14-16% with a corresponding value of $0,427W/(m.K)$. The compressive strength is observed for these same value rates of Néré pod. We found that the compressive strength of the various formulations decrease as the additive rate increases; it decreases by $10,43\%$ when we add 4% of Néré pod and by 41.96% when adding 8% of Néré pod. We find that the compressive strength improves when the Néré pod dosing rate is higher than 8%. In this case it is reduced by 19.6%. This rate is 15.63% when we had 12% and 16% of Néré pod respectively. The ripening of the various formulations was also observed, particularly the LG8%; As a result, the thermal conductivity and the compressive strength increase with the length of stay of the Néré pod in the laterite. However, the 9th day remains the maximum duration of ripening which improves the compressive strength of the LG8% formulation as it increases from $1,38MPa$ at day 0 to $1,874MPa$ in the 9th day; this value is reduced by 43% at the 12th day of ripening. The decrease in compressive strength in the 12th day is probably due to the decay of plant material, i.e. the Néré pod.

Keywords: Néré pod, thermal conductivity, maturing, asymmetric hot plan, mechanical characteristics, volumetric heat capacity, thermal effusivity.

Nomenclatures

LG%: Laterite plus % of Néré pod.

Wp : Plastic Limit (%　　　)

Rcm : Compressive strength (MPa)

WL: Liquid limit (%)

E: effusivity $(J.m^{-2}K^{-1}S^{-\frac{1}{2}})$

F: Strength (N)

L = Laplace Transformed

λ : Thermal Conductivity $(W/m.K)$

LS: Simple Laterite

Rc; Contact Resistance $(K.W^{-1})$

Jr : Day.

Cs: Thermal Capacity of the Probe $(J.m^{-2}.K^{-1})$

Φ : Thermal Inflow (W)

α : Thermal Diffusivity $(m^{2}.s^{-1})$

t: Temperature. (°C)

θ : Laplace Transformed Temperature

P : Laplace Variable

e = Thickness (m)

R^2 : Linear Regression Coefficient.

1-INTRODUCTION

Energy consumption in buildings worldwide represents nearly 40% of the total energy consumption. It is responsible for 25% of total carbon dioxide (CO2) emissions [1]. In Sub-Saharan Africa, this consumption is between 50-70% [2]. In Burkina Faso, power consumption in buildings accounts for nearly 30-75% of all low voltage power consumption. [3] This consumption can be reduced by simple and inexpensive passive techniques. In the context of sustainable development, new regulations for thermal insulation in building industry, lead researchers to find new materials to build energy saving systems. This research was rapidly directed toward the use of materials derived from plant material. These come either directly from the processing of the cultivated products or from the development of their waste. It seems useful to identify local materials that improve thermal insulation and whose production cost is low. The will to ensure the preservation of the environment, the need to design a low-cost housing for developing countries and the need to find suitable materials for thermal insulation led us to conduct a thorough study of some local building materials. The subject of our study is the development of the Néré pod obtained from the fruit of a Sahelian tree, the Parkia biglobosa. Several methods used to assess thermal conductivity are known, and the works on the characterization of thermal properties of materials have been published. Bal et al [4] in 2011 adopted a system of asymmetric hot plan to determine the thermal characteristics of laterite mixed with millet pod. Younoussa Millogo et al [5] studied the physical and mechanical properties of compressed adobe blocks and reinforced with Hibiscus

Sabdarifa fibers. They find that with 0.02% to 0. 06% of 30cm fiber mass, the pores in the blocks of compressed adobes are reduced and their mechanical properties are improved.

However, by adding 0.08% of 60mm fiber mass, this produces a negative impact on the compressive strength. Makinta Boukar [6] in 2013 studied the thermal behavior of the clay-cow dung mixture with the asymmetrical hot plan and determined the compressive strength of clay-cow dung mixture; it appears that the thermal conductivity decreases by progressively increasing the volume of cow dung and the mechanical strength increases when the dosage rate is lower than 8%, and decreases when it is higher than 8%. N Laaroussi et al [7] in 2013 used the hot plate method in a permanent regime to assess the thermal conductivity of small size clay bricks produced by Slaoui in Morocco. IMBGA et al [8] in 2014 showed that adding Cymbogogon Schoenantus Spreng fibers to the adobe reduces the thermal conductivity. The result shows that this 3% increase enables to obtain a composite material whose thermal conductivity offers a thermal comfort in the building constructed with these local materials.

2-Methods and Materials

2-1 Laterite and Négé Pod.

The laterite we used comes from a company located in the Gandigal region in Senegal. The diameter of its grain is lower than or equal 4mm.

Atterberg limits and the size of the laterite studied, were studied by Sekou Bodian [9]

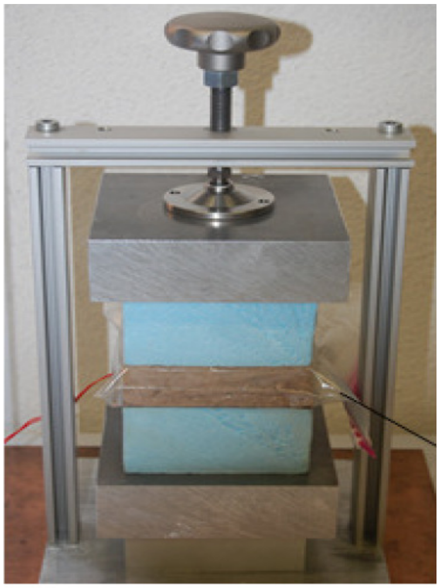
WP=16.02%   WL=33.07%   Ip=17.02%. The fineness modulus is 2.476.

Néré fruits were heated to very high temperatures to eliminate moisture, then crushed to obtain a Néré pod flour lower than or equal to 1.25 mm. the size of bricks used for thermal tests is $10*10*2,5cm^3$.

2-2 Method and Assessment of thermal and mechanical characteristique of the various formulations.

We used the method of asymmetric hot plan available to Laboratoire Energétique Appliquée (L.E.A) de L' Ecole Supérieure Polytechnique de Dakar to determine the thermal properties of laterite, to which we gradually added 4%, 8% , 12%, 14% and finally 16% of Néré pod in order to observe the evolution of thermal and mechanical properties of these formulations .

I-3 Method used to measure the thermophysical properties of materials



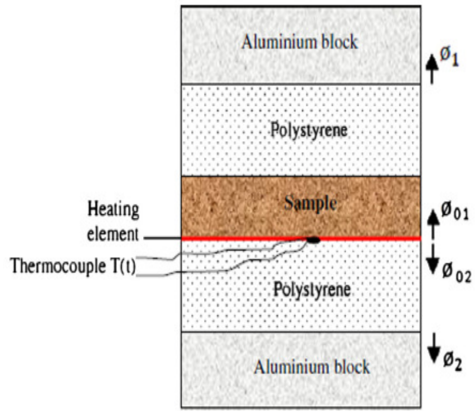


Figure 1 :Asymmetric Hot Plan **Figure2 : Simplified Hot Plan**
Model

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

The method is based on temperature measurement at the center of the heating device with a heated surface $100 \pm 1mm$ $*100 \pm 1mm$ and a thickness $0,22 \pm 0,01mm$. 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 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 plan heating device sharing the same section with the sample is placed under it. K-type thermocouple comprising two cords of $0,005mm$ diameter is placed at the underside of the heating device. The sample is placed between a $40mm$ thick two blocks of extruded polystyrene set between two $40mm$ 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 center of the heating device and the sample during the measurement. This hypothesis is checked with 3D simulation using the COMSOL and residues analysis: the difference between the temperature provided by the theoretical model $T_{\mathrm{mod}}(t)$ and that provided by the experience $T_{\exp}(t)$, 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 [10] on the device shown in Figure 1 & 2, and by using the temperature of the side before the sample $T_1(t)$:

$$\begin{bmatrix}\theta_1\\ \Phi_1\end{bmatrix}=\begin{bmatrix}1 & 0\\ C_s p & 1\end{bmatrix}\begin{bmatrix}1 & Rc_1\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_e & B_e\\ C_e & D_e\end{bmatrix}\begin{bmatrix}A_i & B_i\\ C_i & D_i\end{bmatrix}\begin{bmatrix}0\\ \Phi_1^{'}\end{bmatrix}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}\begin{bmatrix}0\\ \Phi_1^{'}\end{bmatrix} \qquad (01)$$

$$C_s=\rho_s c_s e_s$$

$$\begin{bmatrix}A_e & B_e\\ C_e & D_e\end{bmatrix}=\begin{bmatrix}ch(qe) & \dfrac{sh(qe)}{\lambda qS}\\ \lambda qS\,sh(qe) & ch(qe)\end{bmatrix},\begin{bmatrix}A_i & B_i\\ C_i & D_i\end{bmatrix}=\begin{bmatrix}ch(q_ie_i) & \dfrac{sh(q_ie_i)}{\lambda q_iS}\\ \lambda q_iS\,sh(q_ie_i) & ch(q_ie_i)\end{bmatrix}\text{with}$$

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

The formula (01) leads to the following formula (02) :

$$\begin{bmatrix}\theta_1\\ \Phi_1\end{bmatrix}=\begin{bmatrix}1 & 0\\ C_s p & 1\end{bmatrix}\begin{bmatrix}1 & Rc_1\\ 0 & 1\end{bmatrix}\begin{bmatrix}ch(qe) & \dfrac{sh(qe)}{\lambda qS}\\ \lambda qS\,sh(qe) & ch(qe)\end{bmatrix}\begin{bmatrix}ch(q_ie_i) & \dfrac{sh(q_ie_i)}{\lambda q_iS}\\ \lambda q_iS\,sh(q_ie_i) & ch(q_ie_i)\end{bmatrix}\begin{bmatrix}0\\ \Phi_1^{'}\end{bmatrix}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}\begin{bmatrix}0\\ \Phi_1^{'}\end{bmatrix}(02)$$

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

$\Phi_1=\theta_1\dfrac{D}{B}$ (03). Concerning the (polystyrene) insulator, we have $\begin{bmatrix}\theta_1\\ \Phi_2\end{bmatrix}=\begin{bmatrix}A_i & B_i\\ C_i & D_i\end{bmatrix}\begin{bmatrix}0\\ \Phi_2^{'}\end{bmatrix}$ (04) by developing the previous matrix product, we have Φ_2 : $\Phi_2=\theta_1\dfrac{D_i}{B_i}$

with $\Phi_0 = \Phi_1 + \Phi_2 = \frac{\varphi_0}{S}$. 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 $\theta_i = \frac{\phi_0}{p}\left(\frac{1}{\frac{D}{B} + \frac{D_i}{B_i}}\right)$ (05) .

With the inverse transformed [11], the relation (5) enables to get.

$$T_1(t) = L^{-1}\left(\frac{\phi_0}{p} * \frac{1}{\left(\frac{D}{B} + \frac{D_i}{B_i}\right)}\right) \quad (06)$$

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

$$\theta_s(0,0,p) = \frac{\Phi S}{2p}\frac{1 + R_c ES\sqrt{P}}{m_s c_s p + [R_C m_s c_s p + 1]ES\sqrt{P}} \quad (07)$$

and after inversion with longer time we have : $T_s(0,0,t) = \Phi\left[R_c - \frac{m_s c_s}{E^2 S^2}\right] + \frac{2\Phi\sqrt{t}}{ES\sqrt{\pi}}$ (08)

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 $\psi = \sum_{j=0}^{N}\left[\Delta T_{\exp(t_j)} - T_{\mathrm{mod}(t_j)}\right]^2$ (9) 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 [12]. 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.

3- Results and discussions on thermal performances.

3-1 Characteristic of thermal performances.

Table 1 : Variation of the thermal conductivity recorded and thermal effusivity of the laterite materials mixed with the Néré pod

materials	$\lambda(W/mK)$	$\frac{\Delta\lambda}{\lambda}\%$	$E(J/m^2.K.s^{1/2})$	$\frac{\Delta E}{E}\%$
LS	0.75	0.121	1277.561	0.027
LG4%	0.603	0.226	1160.735	0.017
LG8%	0.552	0.175	1082.955	0.053
LG12%	0.483	0.24	1056.508	0.013
LG14%	0.428	0.113	1005.946	0.016
LG16%	0.427	0.118	975.1414	0.019

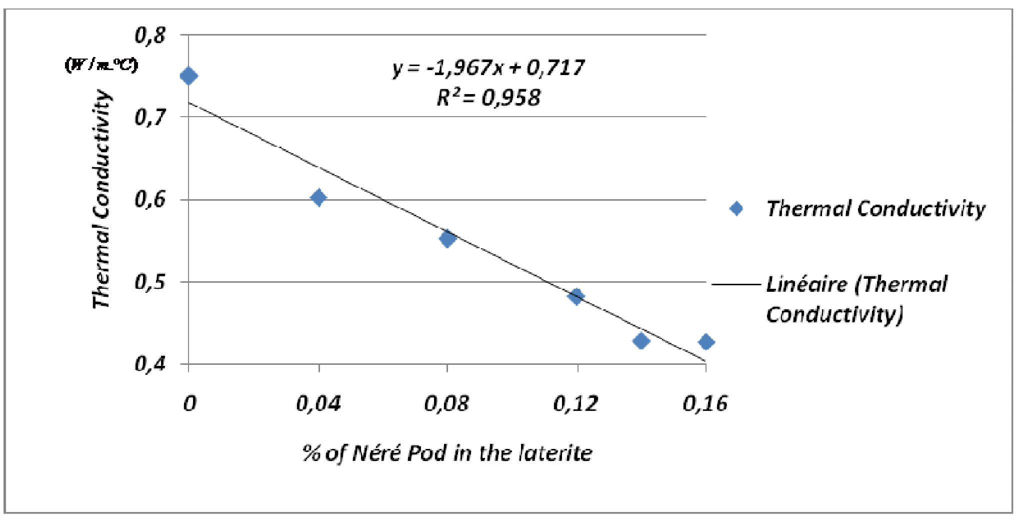


Figure3 : Thermal conductivity variation according to the Néré pod dosage rate in the laterite

The analysis of the results shows a decrease in thermal conductivity and thermal effusivity of materials depending on the dosage rate of the Néré pod.

The conductivity of the laterite without adding Néré pod is $0.75 W/m.K$. This value is reduced by 19.6% when adding 4% of Néré pod and 35.6% when adding 12% Néré pod. But this reduction stabilizes when the mass of Néré pod is between 14% and 16%, accounting for 43.06% reduction of the thermal conductivity when we add 16% of Néré pod. Indeed, Néré pod associated with laterite creates an empty space filled with air in the composite matrix, and this air is an insulator; the more the dosage rate of Néré pod increases in the solid matrix, the more empty spaces are created within it; the air volume increases in this solid and decreases the thermal conductivity progressively as the dosage rate increases

3-2 Thermal conductivity evolution according to the bulk density of the various formulations.

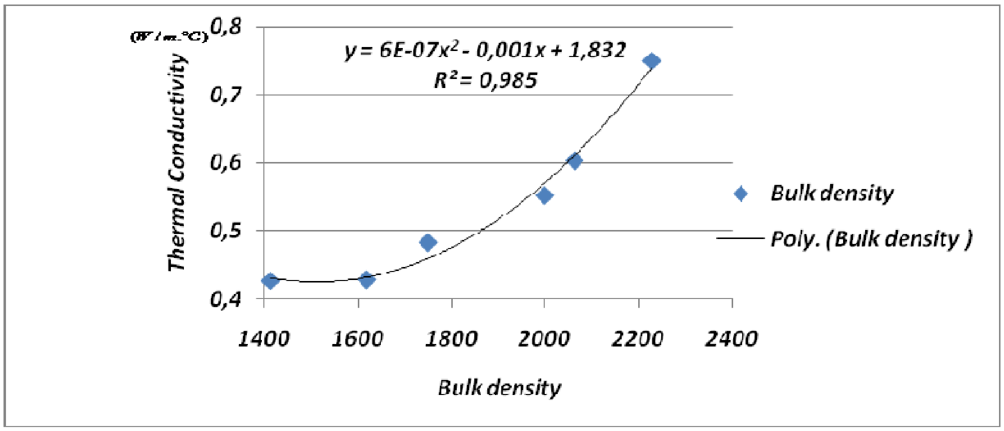


Figure 4 : Evolution of the thermal conductivity according to the bulk density of formulations.

We can see that the curve increases according to bulk density of the materials. The higher the Néré pod rate, the lower the density and conductivity. The material becomes thermally more insulating. By using the relations $\alpha = \left(\frac{\lambda}{E}\right)^2$ and $E = \sqrt{\lambda \rho c}$ (09), we can draw the thermal diffusivity of the materials that shows the speed at which the thermal wave is spreading in them and the volumetric thermal capacity of materials that determine the quantity of heat stored per meter cube of the material.

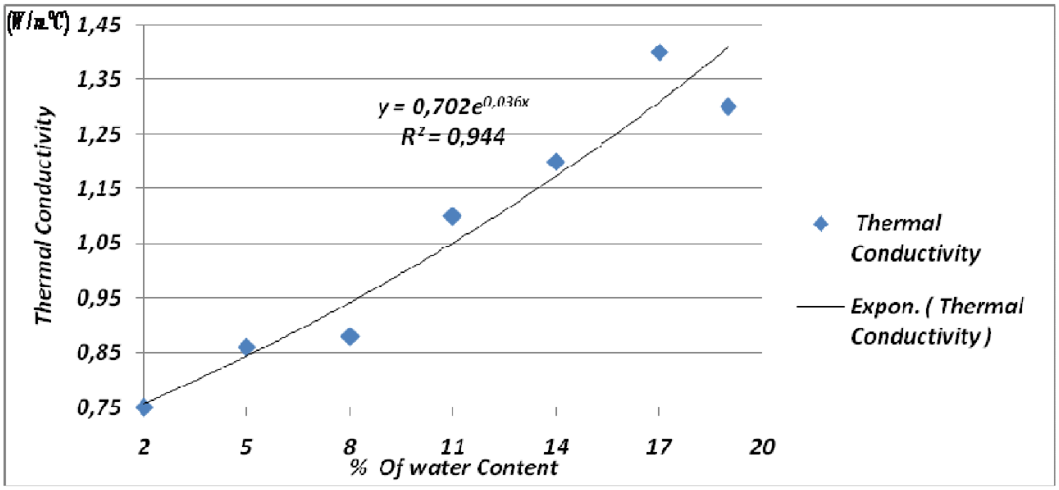


Figure 5 : Thermal conductivity according to water content.

Figure 5 shows the evolution of the thermal conductivity according to water content. It appears that the thermal conductivity increases according to water content. Indeed, the increasing humidification content of the material occurs through a gradual replacement of the air contained in the pores by water. At the same temperature, the thermal conductivity of water is much higher than that of the air ($0,6W.m^{-1}.K^{-1}$ against $0,026W.m^{-1}.K^{-1}$).

The thermal behavior of the hygroscopic material is influenced by water content which reaches its maximum value corresponding to a relative saturation state and the thermal conductivity tends to get stabilized Ezbakhe H. et al. [13]. This conductivity increase is consistent with the results found by Dos Santos [14] showing that the thermal conductivity decreases when the quantity of steam absorbed by the material decreases while increasing its porosity

Table 2 : Variation of the density of the thermal capacity and the thermal diffusivity according to the Néré pod dosage rate.

Materials	$\alpha(m^2.s^{-1})*10^{-7}$	$\frac{\Delta\alpha(\%)}{\alpha}$	$\rho c(KJ/m^3.K)$	$\frac{\Delta(\rho c\%)}{\rho c}$
LS	3.445	0.054	2176.216	0.067
LG4%	2.697	0.034	2234.337	0.192
LG8%	2.597	0.106	2124.630	0.069
LG12%	2.090	0.027	2310.992	0.212
LG14%	1.810	0.032	2364.320	0.081
LG16%	1.617	0.038	2226.933	0.080

The materials show high thermal diffusivity for low Néré pod dosing, i.e. less than 12%. However, the higher the diffusivity, the lesser the time the heat will take to get into the building.

4. Characteristics of the mechanical performances of the various formulations.

Test tubes have been made the same day just after the preparation of the paste. Test tubes used for simple compressive and traction tests are in parallelepiped form with the following dimension $4*4*16cm^3$. Tests were performed on the 28th day after the making of the test tubes.

$$Rc = \frac{F}{S}$$

R_C = Compressive Strength (MPa)

F = Maximum compressive strength (N)

S = Strength support area (mm^2)

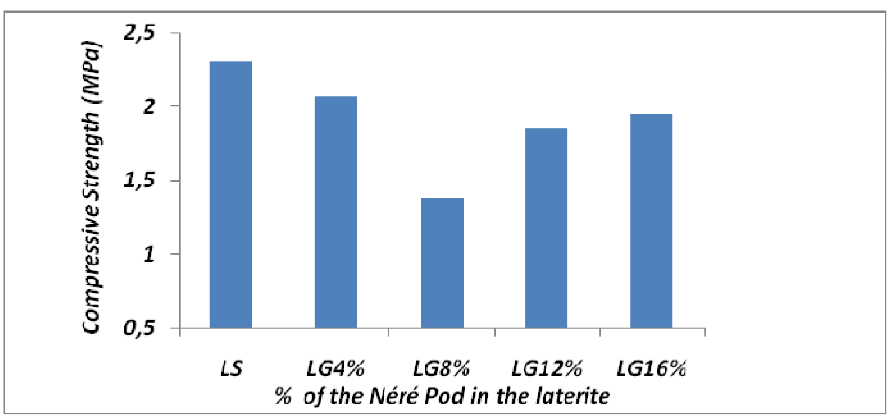


Figure6 : Variation of the mechanical resistance of test tubes according to the various % of Négé pod.

We see (Figure 6) that the mechanical strength decreases. It is 2.309 Mpa when the laterite is not stabilized. This value is found in the Hakimi work's reported by Meukam [15]. It is also comparable to the value of the mechanical strength of the laterite at 27°C obtained by Laurent Mbumbial et al [16] in (2000). It decreases by 10.43% when 4% of Néré pod is added and 41.96% when we add 8% of Néré pod. This reduction is 19.96% when we add 12% and 15.63% when we add 16%. We find that the mechanical strength is improved when the dosage of Néré pod is above 8%. In short, we can say that the Néré pod does not improve the mechanical strength of laterite. The flexural strength is very low for all laterite materials to which Néré pod is added.

5-Characteristics of the thermal and mechanical performances of the maturing of the formulation (LG8%) laterite plus 8% of Néré pod.

5-1 Characteristics of the thermal performances of the LG8%formulation

We studied the thermal and mechanical properties of the LG8% formulation composite whose blocks are made at 0 day, 3 days, 6 days 9 days and 12 days after the preparation of the paste. As a result, the thermal conductivity increases according to the number of days.

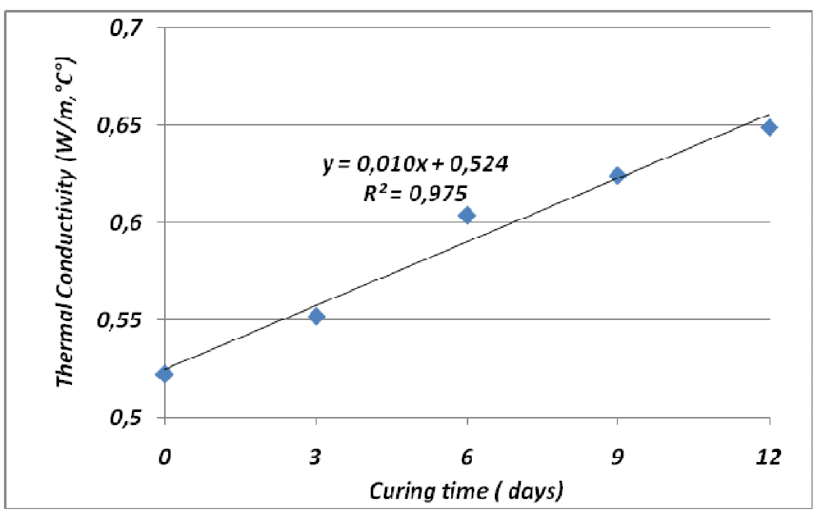


Figure 7 : Variation of the thermal conductivity according to the number of days for the maturing of the LG8%.

We find that the thermal conductivity (Figure 7) increases according to duration of the Néré pod in the laterite before the making of blocks. It increases from $0, 522 W/m.K$ when the LG8% paste is used on the same day to make the blocks to $0.551 W/m.K$, accounting for 5.26% increase on the third day of the construction of the blocks. This conductivity increases from 13.43%; 16.34% to 19.56% respectively when LG8% pastes last 6 days; 9 days and 12 days respectively before the construction of the blocks. This increase in thermal conductivity over time is due to the fact that Néré pod reacts on the laterite over time by secreting chemicals that increase its thermal conductivity. The longer the pod stays in the laterite, the higher the secretion rate and then the higher the conductivity.

5- 2 Characteristic of mechanical performance of the LG8% formulation maturing.

Figure 8 below shows that the mechanical strength increases until the 9th day and decreases the 12th day.

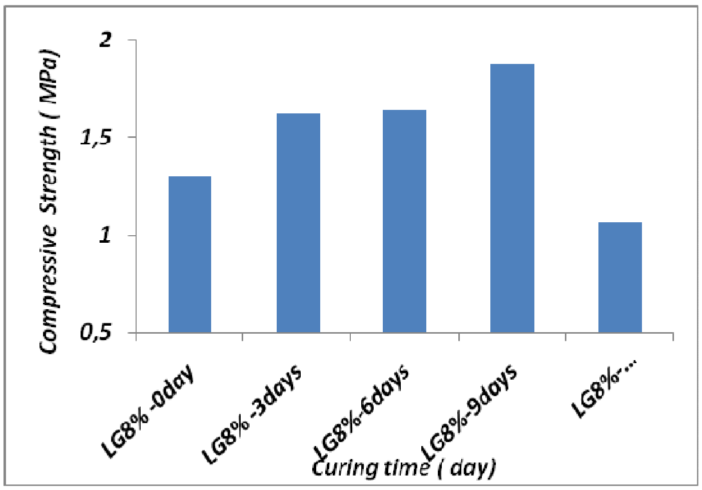


Figure8: Variation of the mechanical resistance depending on the number of days for the maturing of the Néré pod in the laterite

The optimum mechanical strength is 1.874 MPa and is obtained on the 9th day. This value is reduced by 43% on the 12th day of the maturing and 33.41% against the value of the mechanical strength of the LG8% formulation without maturing.

The decrease in the mechanical strength on the 12th day is possibly due to the decay of the Néré pod in the laterite. The mechanical strength of these various formulations was also noticed on the 12th day of the maturing of the Néré pod.

6-Thermal and mechanical characteristics of LG4%, LG8%, LG 12% formulations

6-1 Characteristics of the thermal performances.

The test tubes were made on the 1st day after the preparation of the paste and the 12th day after the preparation of laterite-Néré pod mixture.

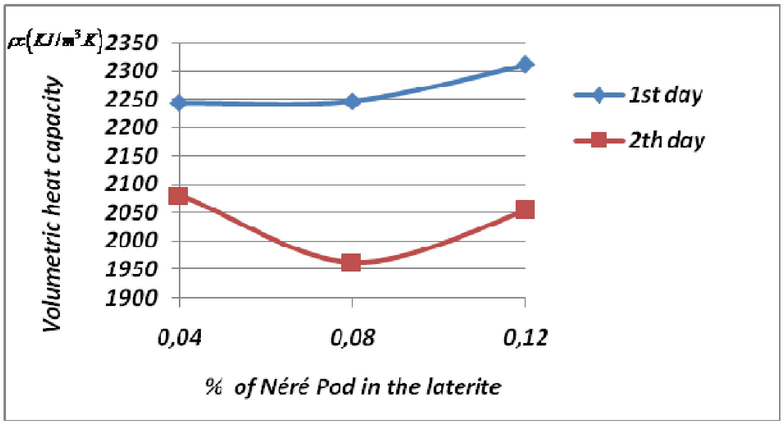


Figure 9: Change in volumetric heat capacity,

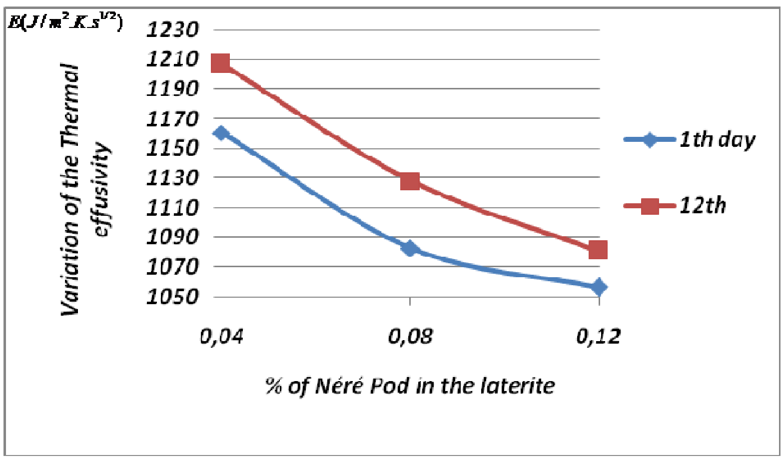


Figure 10: Variation of the thermal effusivity.

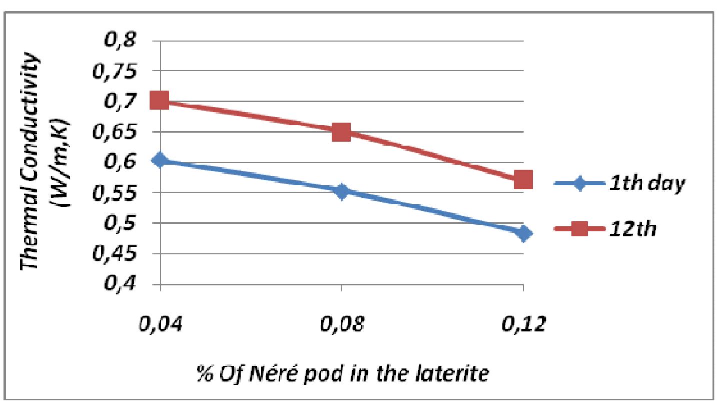


Figure11 : Variation of the thermal conductivity

The maturing time leads to the variation of the thermal properties of the various formulation materials. The Néré pod acts on the thermal properties in long-term material. The conductivity and thermal effusivity values obtained on the 12th day are higher than those obtained in day 0. However, we notice the reverse trend with the volumetric thermal capacity.

6-2 Results of the mechanical trials on the various formulations for 12 days maturing.

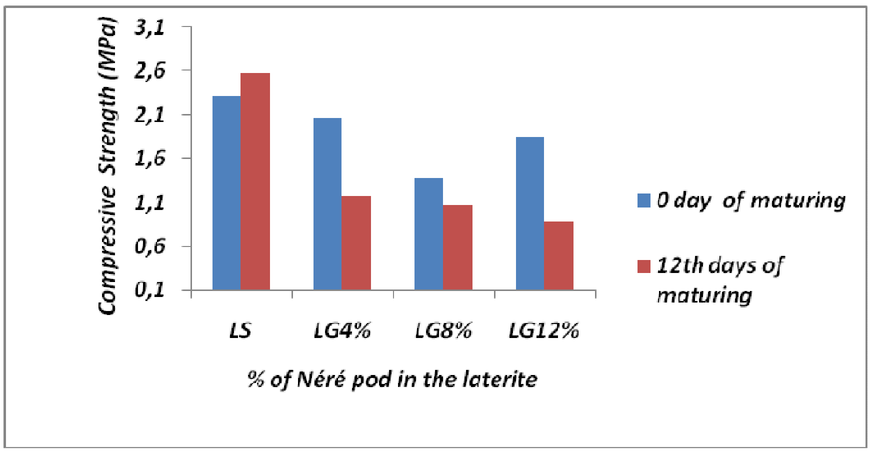


Figure 12: Mechanical strength between 0 day and the 12th day of the maturing of the laterite plus various % of Néré pod.

We notice that only the laterite without Néré pod has its mechanical strength increased by 11.69% on the 12th day of maturing. However LG4%, LG8% and LG12% formulations have their mechanical strength reduced by 42.98%, 22.60% and 51.89% respectively during this period.

Conclusion

The will to protect environment and the need to develop a low-cost housing for developing countries, has led us to undertake a thorough study of local building materials, notably the laterite blocks to which we have gradually added a variable rate of pod Néré to know all of their thermo-physical and mechanical characteristics. Thermal conductivity decreases gradually as the Néré pod rate increases. The mechanical strength is reduced depending on the dosage rate, which enables to conclude that the Néré pod does not stabilize laterite. The maturing impact was also studied during the experience on the thermal and mechanical characteristics of materials, including LG8% formulation. The length of stay of the Néré pod in the laterite impacts the thermal and mechanical performance. We have found that the thermal conductivity and the compressive strength increase depending on the maturing time of the Néré pod. Yet, this compressive strength decreases on the 12th day of maturing; this decrease of the mechanical strength is probably due to the deterioration of the Néré pod which is a plant material.

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