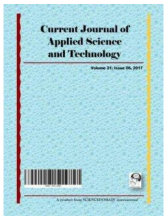

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New Materials for Thermal Insulation in Rural Construction

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Authors' contributions

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

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ABSTRACT

This article presents a study on thermo-physical characterisation of local materials used in the building. The simulation with Energy Plus software made it possible to evaluate the energy performance of a building. The studied materials are lateritic blocks which were not stabilised and those stabilised with the nere pod, cement and lime. Simulation makes it possible to determine the performance of the building and to evaluate the thermal comfort. The asymmetric hot plate method was used to determine the properties of the different types of samples. The values of the thermal

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conductivities of the different bricks vary from 0.427 to 0.814 $W.m^{-1}.K^{-1}$, they are relatively weak. These materials feet better for thermal insulation of buildings. This work aims to develop a new composite material, to improve their thermophysical property. Nere pod stabilisation saves on 20 to 43% energy depending on the mixing rate compared to mere laterite. The decrement factor and the time lag are better when the wall thickness increases. For the purpose of reducing the building energy consumption, this composite material is intended to be used in walls or false ceilings.

Keywords: Thermal insulation; asymmetric hot plan model; thermophysical properties; the economy of energy; nere pod; decrement factor; time lag.

1. INTRODUCTION

The use of a composite material requires first of all knowledge of its thermophysical properties, especially if it is about the natural, lasting and environmental material. This study allows determining the thermophysical characteristics of new types of materials based on laterite and clay mix with nere pod, lime and cement. For this work, we used the method of the hot plan transitional to determine the thermal effusivity and the method of the hot plan in regime permanent to determine thermal conductivity. Studies have already been done and published on materials at the root of clay and alfa fibres. The results obtained by Hamour et al. [1] show that the addition of alfa fibre treated and untreated in the matrix makes it possible to improve the mechanical properties of the materials. For thermal properties, the stabilisation with treated and untreated alfa fibres improves thermal stability. The results obtained by Elhamdouni et al. [2] show that increasing the content of alfa fibres improves the thermal properties, they have obtained samples that are more insulating. Oushabi et al. [3] showed that composite materials (PU-DPP) have good mechanical and thermal performance compared to insulating materials available on the market. So, the (PU-DPP) is a good isolate because it is inexpensive and safe. Laaroussi et al. [4] studied the thermal properties of samples stabilised with alfa fibre. The results obtained show that increasing the levels of alfa fibres improves the thermal properties. This makes the sample more insulating and allows to save on energy. Also, Meukam [5] determined the mechanical and thermal properties of stabilised earth bricks with the aim of using in the building. They showed the dependence on thermal conductivity and thermal diffusivity of these materials depending on whether water content remains low. These results also show that made-up clay bricks can be used in building construction without presenting a high risk of cracking. Bahloul al [6] assessed the effect of alfa fibres on the values of the mechanical and thermal resistance of mortar of cement. Imbga et al. [7] determined the thermal and mechanical performance of laterite blocks stabilised with nere pod for the thermal insulation of buildings. Thermal conductivity decreases as the Nere pod rate increases. The mechanical strength is reduced depending on the dosage rate which enables to conclude that the Nere pod does not stabilise laterite. The stay time of the nere pod in the laterite impacts the thermal and mechanical performance. They have found that the thermal conductivity and the compressive strength increase depending on the maturing time of the nere pod. Imbga et al. [8] have determined the thermophysical properties of various formulations with laterite and slaked lime. The value of the thermal conductivity decreases when the lime rate is lower than 4% and increases for rates higher than 4%. The thermal conductivity was 0.623 $W.m^{-1}.K^{-1}$ for a rate of 4%; it increases to 21.13% for 16% of lime used. Recent studies were carried out by Azakine al [9] on earth blocks stabilised with lime. The results of the thermal properties of the various formulations were measured using the hot wire method. They obtained 0.59 $W.m^{-1}.K^{-1}$ for a 4% lime rate, 0.62 $W.m^{-1}.K^{-1}$ for a rate of 8% and 0.68 $W.m^{-1}.K^{-1}$ for a rate of 12% of lime used as a stabiliser of cement and lime increase. However, it decreases when the rates of the sawdust increase. Moreover, thermal resistance decreases according to the percentages of lime and cement and increases according to the percentages of the sawdust. Bodian al [10] have determined the mechanical and thermal properties of unfired and fired clay soil bricks made from a mixture of clay soil and laterite. The thermal conductivity and thermal effusivity were measured by the asymmetric Hot plate method. The results show that the variation of thermal conductivity with laterite percentage has the same shape for unfired and fired bricks. Cherki al [11] carried out an experimental study about the thermal properties of a cork-gypsum composite by using the asymmetrical Hot plate method. They demonstrated that the composite material is three times more insulating and twice lighter than cork-free gypsum. Boumhaout al [12] aimed to study the thermomechanical characterisation of composite materials made from mortar and date palm fibre meshes. Their objective was to evaluate the thermal insulation properties as well as the mechanical performance of this material for insulation of buildings. The volume percentage of date palm fibre meshes in the samples varied from 0% to 51%. The results show that the values of thermal conductivity decrease as the fibres rate increases. While thermal conductivity of the mortar reference is 0.795 $W.m^{-1}.K^{-1}$ it drops to 0.243 $W.m^{-1}.K^{-1}$ for the reinforced mortar fibre 51% composite material which corresponds to a decrease of about 70%.

2. MATERIALS AND METHODS

2.1 Clay and Laterite

We have used clay from the district of karpala in Ouagadougou (Burkina Faso). The laterite we used comes from a countryside located in the Gandigal region in sénégal. Its diameter is lower than or equal 4 mm. Atterberg limits and size of laterite studied were studied by Bodian [13].

W_p = 16.02 %, W_L = 33.07 %, I_p = 17.02% and the fineness modulus is 2.476

Where, W_P is the limit of plasticity, W_L is the limit of liquidity and I_P is the plastic index.

2.2 Nere Pod

The nere pod is used because they are available and inexpensive.

2.3 Preparation of Samples

For this study, we used four (04) types of samples of the same size. These samples are in laterite and laterite stabilised with nere pod, lime and cement. To evaluate the influence of stabilisers (nere pod, lime and cement) on thermo-physical properties, several mixtures were made by varying the levels of these stabilisers. For characterisation, we used bricks in the dry state.

2.4 Theoretical Approach of Determination of Thermo-physicals Properties

2.4.1 Method of determination of thermal conductivity

Thermal conductivity is determined by the hot plan method in the permanent regime developed by Jannot et al. [14]. This method is based on the determination of the values of the temperature in the centre of the heating plate inserted between the material to be characterised and the thermal insulating in polyethene. Fig. 1 illustrates the fundamental scheme of the method. The brick of size 100 *mm**100 *mm**25 *mm* is put on a heating

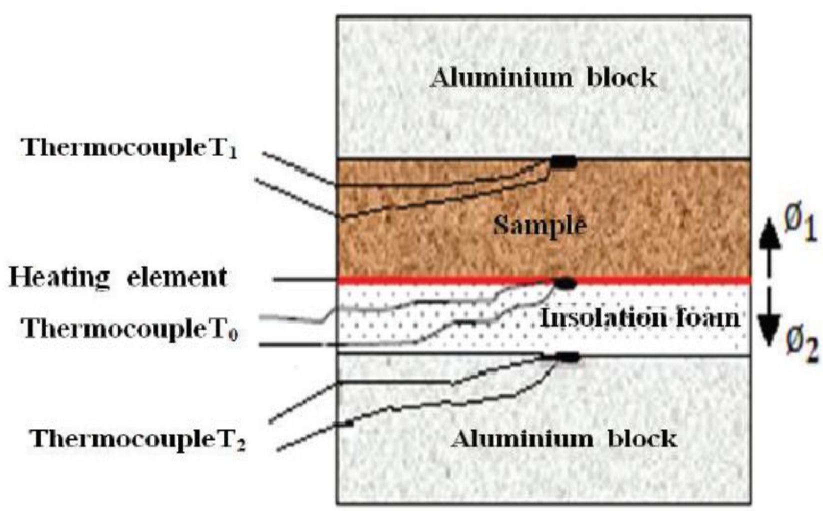

Fig. 1. Experimental mounting of the hot plate method

plate of section 100±1*mm**100±1*mm* and a thickness 0.22±1.01*mm* equal to that of the sample. The uncertainty in the heating device area is thus around 2% 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 $R_e = 40\,\Omega$. The temperature evolution recorded at every each 0.1s. The presence of the thermocouple does not increase the contact resistance between the heating element and the polystyrene. Since polystyrene is an insulating material, this thermal resistance will be marginal. The system is modelled with the unidirectional transfer hypothesis $(1D)$. At the centre of the heating element and the sample during the measurement. This hypothesis is checked with a $(3D)$ simulation using comsol and residues analysis: the difference between the temperature provided by the theoretical model $T_{\text{mod}}(t)$ and provided by the experiment $T_{\exp}(t)$. They put, under the heating element, an insulating foam of size $100\,mm \times 100mm \times 40mm$. So that the great part of the heat flux emitted by the hot plate passes into the sample, the brick is placed between this plate and the thermal insulation. this allows the system to reach a thermal balance as quickly as possible.

One thermocouple is placed in the centre of the lower face of the hot plate to determine the temperature values T_0. The second thermocouple placed on the unheated face of the sample and the third on the unheated face of the thermal insulation is used respectively to determine the temperatures T_1 and T_2. With this shape, we can write:

$$\Phi = \Phi_1 + \Phi_2 \quad (1)$$

with $$\Phi_1 = \frac{\lambda_1}{e_1}(T_0 - T_1) \quad (2)$$

and $$\Phi_2 = \frac{\lambda_2}{e_2}(T_0 - T_2) \quad (3)$$

Φ_1 is the heat flux through the material, Φ_2 is the heat flux through the thermal insulation. Φ is the total flux emitted by the heating element, λ_1 is the thermal conductivity of the sample as we seek to determine, e_1 is the thickness of the sample, λ_2 and e_2 are successively thermal conductivity and thickness of the thermal insulation. The heating plate is an electrical resistance *R* dissipating heat flux by Joule effect when it is crossed by an electric current electrique (*I*) under of voltage (*U*), so:

$$\Phi = \frac{U^2}{R.S} \quad (4)$$

Combining equation 1 and 2, we have:

$$\lambda_1 = \frac{e_1}{T_0 - T_1}\left[\frac{U^2}{R.S} - \frac{\lambda_2}{e_2}(T_0 - T_2)\right] \quad (5)$$

Equation 5 allows determining the thermal conductivity when the system reaches the steady state regime.

2.4.2 <u>The method of determining thermal effusivity</u>

Thermal effusivity is determined using the hot plane method in transient regime [15]. We use the asymmetric experimental device (represented on the Fig. 2). An element of a heating plan having the section of $100 \pm 1\,mm \times 100 \pm 1\,mm$ is put under the sample. One thermocouple of type K made with two wires of a 0.005 *mm* diameter is glued together on the lower face of the heating element. This arrangement is placed between two thermal insulation in polystyrene having a thickness of 40 mm fixed between two aluminium plate with a thickness of 40 *mm*.

The heat flux sent by the heating plate and the transitional temperature *T (t)* are recorded. It is assumed that the thermocouple in contact with the insulation does not increase the thermal contact resistance between plate and polystyrene, this thermal resistance is neglected. The system is modelled using the unidirectional heat transfer assumption (*1D*) at the centre of the sample. Temperatures are assumed constant at the level of the aluminium blades because the value of the heat flux passing through the polystyrene is very low.

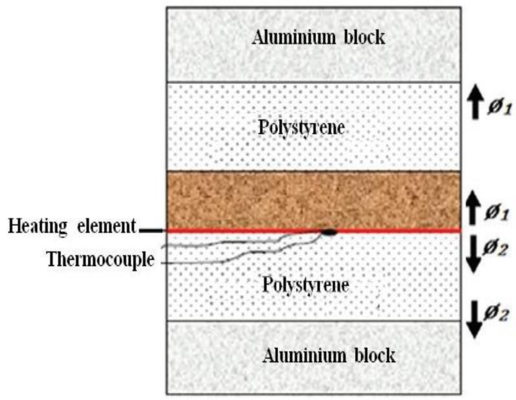

Fig. 2. Schema of the experimental plate

Within these hypotheses one can write:

Using the temperature of the side before the sample $T_1(t)$:

$$\begin{bmatrix}\theta_1\\ \Phi_{01}\end{bmatrix}=\begin{bmatrix}1 & 0\\ C_s p & 1\end{bmatrix}\begin{bmatrix}1 & Rc_1\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_e & B_e\\ C_e & D_e\end{bmatrix}\begin{bmatrix}A_i & B_i\\ C_i & D_i\end{bmatrix}\begin{bmatrix}0\\ \Phi_1'\end{bmatrix}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}\begin{bmatrix}0\\ \Phi_1\end{bmatrix} \quad (6)$$

$$C_s = \rho_s c_s e_s \quad (7)$$

$$\begin{bmatrix}A_e & B_e\\ C_e & D_e\end{bmatrix}=\begin{bmatrix}ch(qe) & \dfrac{sh(qe)}{\lambda qS}\\ \lambda qS\, sh(qe) & ch(qe)\end{bmatrix} \quad (8)$$

$$\begin{bmatrix}A_i & B_i\\ C_i & D_i\end{bmatrix}=\begin{bmatrix}ch(q_i e_i) & \dfrac{sh(q_i e_i)}{\lambda q_i S}\\ \lambda q_i S\, sh(q_i e_i) & ch(q_i e_i)\end{bmatrix} \quad (9)$$

$$q=\sqrt{\frac{p}{\alpha}} \quad (10)$$

$$q_i=\sqrt{\frac{p}{\alpha_i}} \quad (11)$$

Concerning the (polystyrene) insulator. we have

$$\begin{bmatrix}\theta_1\\ \Phi_{02}\end{bmatrix}=\begin{bmatrix}A_i & B_i\\ C_i & D_i\end{bmatrix}\begin{bmatrix}0\\ \Phi_2\end{bmatrix} \quad (12)$$

With $\Phi_0 = \Phi_{01} + \Phi_{02} = \dfrac{\varphi_0}{p}$ (13)

Where *θ*, *Φ_{01}*, *Φ_{02}*, *Φ_0*, *Φ_1* et *Φ_2* are respectively the symbols of Laplace transforms: the temperature, the heat flux density coming from the heating element (upstream), the thermal flux density coming from the heating element (downstream), the total flux produced in the heating element, the thermal flux density entering the upper aluminium block, the thermal flux density entering the lower aluminium block.

θ the thermal flux density produced in the heating plate, *Cs* the surface heat capacity of the heating plate and *Rc* the thermal contact resistance between the plate and the material.

λ_i the polystyrene thermal conductivity, a_i *and* a are successively the thermal diffusivity of polystyrene and sample. e_i *and* e are successively the thickness of polystyrene and sample.

Combining equation 4 and 5, the system leads to:

$$\theta(p)=\frac{\Phi_0(p)}{\dfrac{D}{B}+\dfrac{D_i}{B_i}} \quad (14)$$

This method makes it possible to determine the value of the thermal effusivity. The thermal conductivity λ of the block and the contact resistance *Rc* that minimise the Mean Squared.

The error of the sum $\psi = \sum_{j=0}^{N}\left[\Delta T_{\exp(t_j)} - T_{\mathrm{mod}(t_j)}\right]^2$ (15) between the theoretical curve $T_{c\,\mathrm{mod}(t)} = T_{c\,\mathrm{mod}}(0,t)$ (16) and the experimental curve $\Delta T_{c\exp} = T_{c\exp}(0,t) - T_{c\exp}(e,t)$ (17) in the Levenberg-Marquardt-like algorithm program [16].

3. RESULTS AND DISCUSSION

The results of the thermophilic characterisation of the different samples depending on the percentage of nere pod, lime and cement are shown in Table 1.

Table 1 shows that the thermal conductivity of laterite decreases as the nere pod level increases. It is reduced when nere's pod is added to the laterite and if nere's pod is added to the laterite. It can be seen that the thermal effusivity also decreases as the nere pod rate increases in the laterite. It is reduced when we add $8\,\%$ and 23.67 % of nere pod. The materials LG14%, LG16%, LG12% have lower thermal conductivities than the brick in straw-clay (3%) formulated by Toguyeni et al. which have a good thermal performance [17].

Table 2 indicates that thermal effusivity and thermal conductivity decrease as the clump rate increases in the clay. Thermal effusivity decreases with the addition of cement and clay seed in the clay and when cement and clay seed are added to the clay. However, the capacity of the heated volume increases when the rate of néré pod increases in the clay.

The results in Table 3 indicate that the addition of the cement in the laterite-chalk mix increases the thermal conductivity compared to the addition of the pearl pod.

Consider two envelopes of the same habitat that are subjected to the same temperature gradient. We can write the following relation:

$$\frac{\Phi_{Laterite + x\%\,gn}}{\Phi_{Laterite}} = \frac{\lambda_{Laterite + x\%\,gn}}{\lambda_{Laterite}} \quad (18)$$

Table 1. Thermophysical properties of laterite plus the different pod of nere

Material	$\lambda(W/m.K)$	$\frac{\Delta\lambda}{\lambda}\%$	$E(J/m.K.S^{1/2})$	$\frac{\Delta E}{E}(\%)$
LS	0.750	±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	±0.240	1056.508	±0.013
LG14%	0.428	±0.113	1005.946	±0.016
LG16%	0.427	±0.118	975.141	±0.019

Table 2. Thermal properties of Karpala clay stabilised with cement and Nere's pod

Material	$E(J/m^2.K.s^{1/2})$	$\frac{\Delta E}{E}(\%)$	$\lambda(W/mK)$	$\frac{\Delta\lambda}{\lambda}(\%)$	$\rho c(KJ/m^3.K)$	$\frac{\Delta\rho c}{\rho c}(\%)$
Clay	1269.447	±0.183	0.814	±0.173	1985.900	±0.539
Clay96%C4%	1125.987	±0.018	0.572	±0.165	2225.730	±0.201
Clay92%G4%C4%	1069.651	±0.068	0.544	±0.129	2104.479	±0.265
Clay88%G8%C4%	985.146	±1.930	0.443	±0.434	2194.722	±4.294

Table 3. Thermophysical properties of laterite stabilised with cement, lime and nere pod

Material	$\lambda(W/mK)$	$\frac{\Delta\lambda}{\lambda}(\%)$	$\rho c(KJ/m^3.K)$	$\frac{\Delta(\rho c\%)}{\rho c}$
La92%lime4%G4%	0.458	± 0.367	2079.561	± 0.399
La92%lime4%C4%	0.509	± 0.367	1871.197	± 0.399
La96%C4%	0.611	± 0.183	2605.126	± 0.219
LaG4%	0.603	±0.226	2234.337	± 0.260

This relationship allows us to estimate energy saving by using composite materials by the following relation

$$Es = 100\left(1 - \frac{\lambda_{Laterite+x\%gn}}{\lambda_{Laterite}}\right) \quad (19)$$

$\lambda_{Laterite+x\%gn}$: Thermal conductivity of the laterite mix + a percentage of néré pod; *Es*: economy of energy.

A wall with a more insulating envelope saves more energy because the percentage of energy savings increases when the conductivity is low. The performance of the envelope is determined by the decrement factor *f* (equation 20) and the time lag φ_d (equation 21).

$$f = \frac{T_{mi}^{max} - T_{mi}^{min}}{T_{me}^{max} - T_{me}^{min}} \quad (20)$$

$$\varphi_d = t_{T_{mi\,(max)}} - t_{T_{me\,(max)}} \quad (21)$$

f: decrement factor; T_{mi}^{max}: Maximum temperature of the inner wall (°C); T_{mi}^{min}: Minimum temperature of the inner wall (°C); T_{me}^{max}: Maximum temperature of the outer wall (°C); T_{me}^{min}: Minimum temperature of the outer wall (°C); φ_d: time lag (h); $t_{T_{mi(max)}}$: Time when the temperature of the inner wall is maximum (h); $t_{T_{me(max)}}$: Time when the temperature of the outer wall is maximum (h).

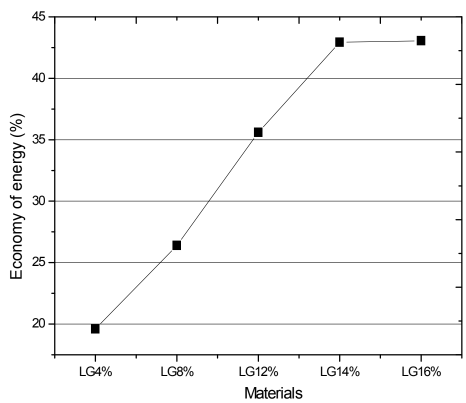

Fig. 3. Saving energy depending on the nature of the building envelope

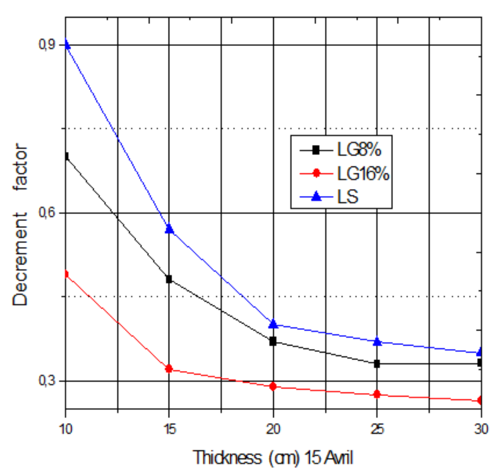

Fig. 4. Decrement factor according to the thickness

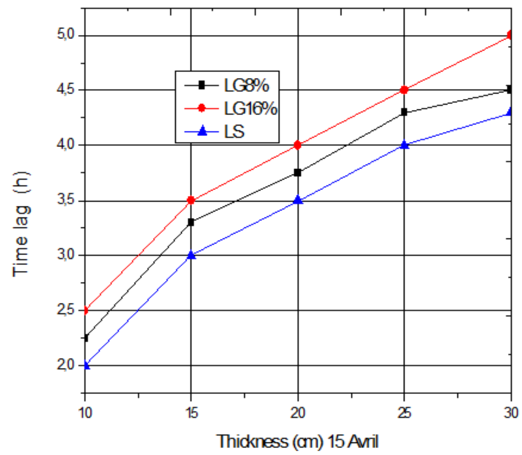

Fig. 5. Time lag according to the thickness

The decrement factors are calculated on the south wall (Fig. 5) because they are most exposed to solar radiation. The decrement factor decreases with increasing thermal capacity and wall thickness and augments with increasing thermal conductivity. The time lag (Fig. 4) increases as the thermal capacity, and wall thickness increase and the thermal conductivity decreases. Belhadj et al. [16] carried out an experimental study also on the influence of cereal fibres on the thermal properties of concrete. The thermal results from this experimental study were used to simulate using the Energy Plus software to determine the decrement factor and the time lag. Sambou [18] has shown that the thermophysical properties of the wall have important effects on the time lag and decrement factor of the thermal wave.

The performance of the insulation is also related to the thermal resistance of the insulation. For a new building, the thickness of the insulation may vary depending on the type of material, the nature of the wall and the level of performance. The resistance increases when the material is insulating, it also increases with the thickness of the wall. Reducing air infiltration in low-energy housing is an important lever for achieving energy performance.

The same amount of heat uniformly distributed in the wall will cause in it a temperature that depends on its thickness and the thermophysical properties of the materials used for construction (Fig. 7), the higher heat quantity a wall is receiving, the lesser its internal temperature rises, it rises all the less as the mass heat C is great. The flux density crossing the two fields is proportional to the thermal effusivity. The rate of air infiltration increases the temperature of the air during the day and refreshes it at night (Fig. 8).

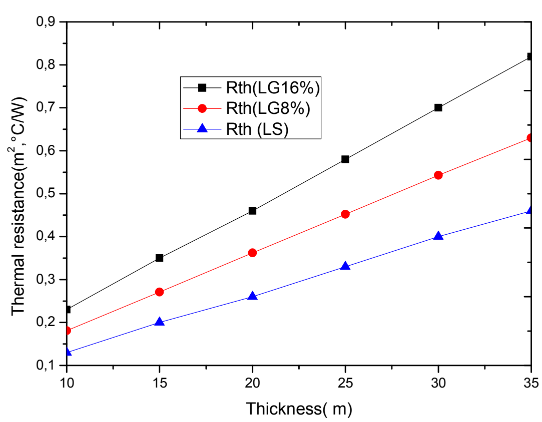

Fig. 6. Thermal resistance of stabilised materials with laterite and néré pod

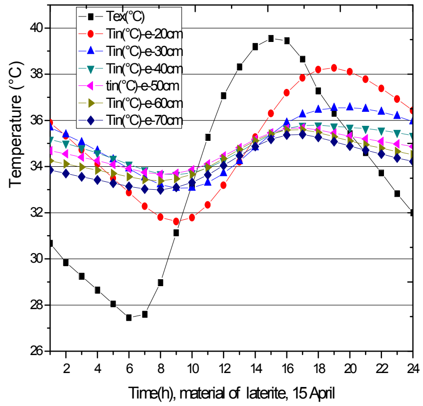

Fig. 7. Air temperature according to the thickness of the wall

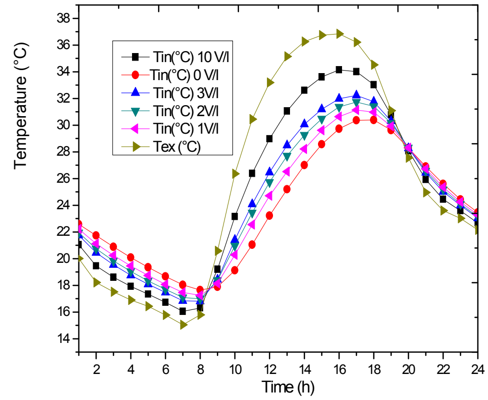

Fig. 8. Indoor air temperature according to the air infiltration rate

4. CONCLUSION

This paper presents the results of the thermophysical properties of local materials stabilised with lime, cement and néré pod by the asymmetric hot plate method. The results indicate that the values of the thermal conductivity decrease when the nere pod rate is high in laterite. The values of the thermal effusivity and those of the thermal conductivity of the mixture (clay plus cement) decrease when the rate of néré pod increases. The thermophysical results obtained were simulated under the Energy Plus software, the results coming from this simulation indicate that the thermal phase shift increases as the thermal conductivity decreases and the thickness of the wall increases. The decrement factor decreases when the thermal conductivity decreases and when the thickness of the wall is large. The indoor air temperature of a house is stable when the thermal time lag is high, and the decrement factor is low.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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