Research Article
Study of Thermo-physical and Mechanical Properties of Clay from the Quarry of BANGA BANA

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Abstract: Clay is currently experiencing a renewed interest following energy crisis and that of housing. It is therefore important to estimate the thermo-physical and mechanical parameters of this material which is used among things as building material. We present in this study, the results of the thermo-physical and mechanical properties of clay from BANGA BANA quarry, mixed with cow dung. BANGA BANA is a neighborhood in the city of Niamey in Niger, located on the right bank of the Niger River. This mixture is used to make bricks for the construction of houses in Niamey. The results obtained show that the conductivity and effusivity of this clay decrease depending on the content of cow dung. Regarding resistances to compression, they are present to a maximum when they are represented depending on the percentage of cow dung. The stabilization of the mixture is obtained by adding cement.

Keywords: Compressive strength, flexural strength, thermal conductivity, thermal effusivity

INTRODUCTION

The objective of this study is to determine the thermo-physical and mechanical characteristics of clay taken from the quarry of BANGA BANA. The method used is that of the hot plat method. This clay mixed with cow dung is used in construction and insulation of homes in this neighborhood of Niamey. We limited our study to the rates of cow dung from 0 to 20% because beyond 20%, the obtained mixture becomes very friable. Variations of resistance to bending and compression are determined based on the percentage of cow dung. To fight against the destruction by water of the bricks made from this clay, stabilization with cement is done.

Principle of thermo-physical properties measurement:
Presentation of the method: The used technique of measuring thermo-physical characteristics is the method of warm up. The method consists in sending a constant level of heat flow through a probe whose surface is in contact with a face of the sample and we note the change in the temperature Ts (t) at the center of this probe (Marechal and Devisme, 1978).

The objective is to estimate the thermal diffusivity E and thermal conductivity λ by using direct models.

For this, a simulation with a 3D model of the behavior of a hot plate method 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 a three-dimensional system. This equation is solved using a separation of variables after Laplace transform is m. By using the formalism of quadripoles, it leads to a Laplace transformers' of the temperature. Then the model is simplified by considering a unidirectional propagation of heat flow.

Knowing the temperature in the Laplace space, we return to the determination of the temperature in the real space using the STEHFEST or Fourier methods which are numerical methods. In practice, we obtain a thermo gram of the form T = f (√T) (Fig. 1) which permits determining a value of the effusivity or conductivity that we compare to that which was used in the 3D simulation. The curve is obtained by a quadripole type modeling for the case where the surface of the probe is lower than that of the sample. When the medium is semi-infinite and when the propagation of heat is unidirectional, the linear part of the curve helps to deduce the thermal effusivity by determining its slope. When the medium is semi-infinite and when the heat transfer is 2D, exploitation of the curve with a 2D model makes possible to estimate thermal conductivity.
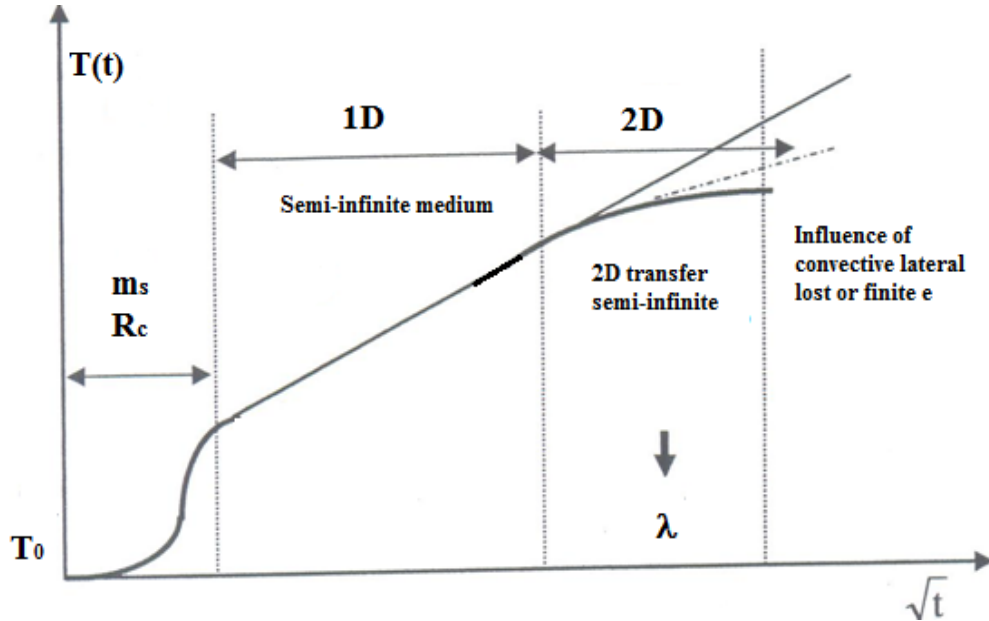
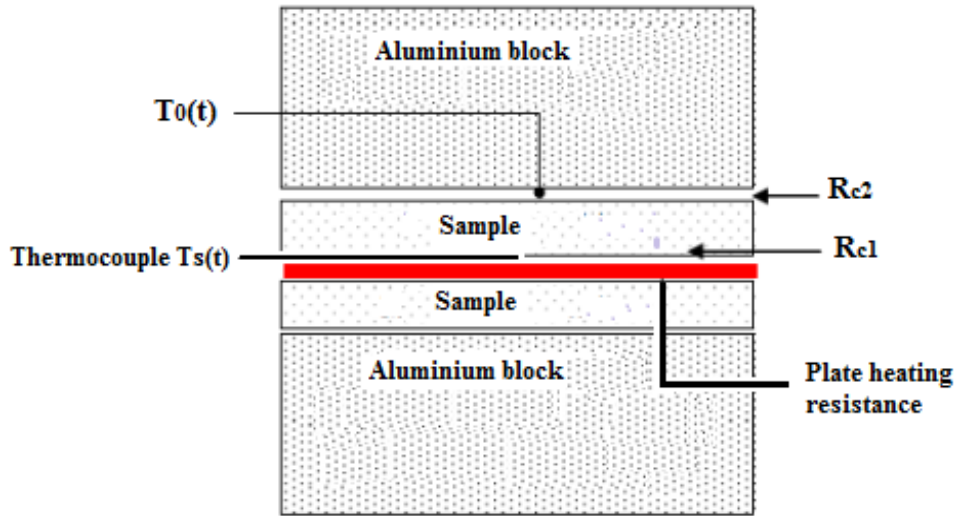Fig. 1: Representation of temperature based on time square root

Fig. 2: Mounting of the sample in the hot plate method measuring apparatus

METHODOLOGY

3D complete model of hot plat method: The diagram (Fig. 2) indicates the mounting of the samples in the measuring apparatus of the hot plate method type. The device comprises a planar heating element (probe) of low thermal resistance inserted between two identical samples of the material to be characterized and two isothermal aluminum blocks of the section identical to that of the samples (Bal *et al*., 2013; Jannot *et al*., 2009). One assumes that the mass of the aluminum block is sufficient so that the temperature remains constant for the duration of the experiment. The probe of thickness e_s, width $2b$, length $2c$, density ρ_s and

specific capacity c_s is submitted to a constant flux density of heat $\phi 0$. Samples are considered homogeneous and isotropic. The dimensions of each sample are:

* Width: $2b$
* Length: $2c$
* Thickness: e

We note R_c the thermal contact resistance between the probe and the heated surface of the sample. We recorded the temperature $T_s(t)$ in the center of the heating element and $T_0(t)$ of the aluminum block. The temperature $T_s(t)$ is measured in a time interval during
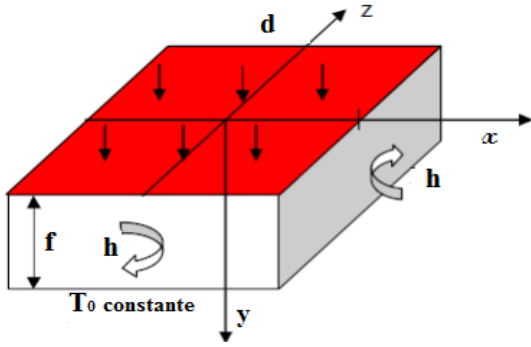
Fig. 3: Diagram of the modeled system

which the transfer of heat at the center of the heating element is unidirectional. A 3D modelisation permits to define this time interval, a simplified 1D model is then used to produce parameter estimation on that time interval.

The temperature at a point of coordinates (x, y, z, t) (Fig. 3) verifies the following equation:

$$\frac{\partial^2 T(x,y,z,t)}{\partial x^2} + \frac{\partial^2 T(x,y,z,t)}{\partial y^2} + \frac{\partial^2 T(x,y,z,t)}{\partial z^2}$$
$$= \frac{1}{a}\frac{\partial T(x,y,z,t)}{\partial t} \qquad (1)$$

With the boundary conditions:

$$-\lambda \frac{\partial T(x,0,z,t)}{\partial y} = \frac{T_s(x,0,z,t) - T(x,0,z,t)}{R_c} \qquad (2)$$

$$T(x,e,z,t) = 0 \qquad (3)$$

$$\frac{\partial T(0,y,z,t)}{\partial x} = 0 \qquad (4)$$

$$\frac{\partial T(x,y,0,t)}{\partial z} = 0 \qquad (5)$$

$$-\lambda \frac{\partial T(b,0,z,t)}{\partial x} = h_2[T(b,y,z,t) - T_i] \qquad (6)$$

$$-\lambda \frac{\partial T(x,y,c,t)}{\partial z} = h_1[T(x,y,c,t) - T_i] \qquad (7)$$

$$T(x,y,z,0) = T_i \qquad (8)$$

$$\phi_0 = \rho_s e_s c_s \frac{\partial T_0}{\partial t} + \frac{T_s(x,0,z,t) - T(x,0,z,t)}{R_c} \qquad (9)$$

We note: ΔT (x, y, z, t) = T (x, y, z, t) - T_0 et L [ΔT (x, y, z, t)] = θ (x, y, z, p).
The flux density is fixed as follows:

If x<b; ϕ_0 (t) = ϕ_0
If x>b; ϕ_0 (t) = 0

We write temperature after the Laplace transformation as product of independent variable functions according to relation: θ (x, y, z, p) = X (x, p) Y (y, p) Z (z, p).

The solution of the heat equation obtained by substituting of T (x, y, z, t) by θ (x, y, z, p) in Eq. (1) can be written:

$$\theta(x,y,z,p) =$$
$$\sum_{p=1}^{\infty}\sum_{q=1}^{\infty}\frac{\Phi_0(p)\frac{\sin(\alpha_p b)}{\alpha_p}\frac{\sin(\delta_q c)}{\delta_q}\cos(\delta_q x)\text{ch}[\gamma_{pq}(e-z)]}{G_{pq}\left[\frac{\sin(2\alpha_p b)}{4\,\alpha_p} + \frac{b}{2}\right]\left[\frac{\sin(2\delta_q c)}{4\,\delta_q} + \frac{c}{2}\right]} \qquad (10)$$

The solution at the center of the heated face will be:

$$\theta(0,0,0,p)$$
$$= \sum_{p=1}^{\infty}\sum_{q=1}^{\infty}\frac{\Phi_0(p)\frac{\sin(\alpha_p b)}{\alpha_p}\frac{\sin(\delta_q c)}{\delta_q}\text{ch}(\gamma_{pq}e)}{G_{pq}\left[\frac{\sin(2\alpha_p b)}{4\,\alpha_p} + \frac{b}{2}\right]\left[\frac{\sin(2\delta_q c)}{4\,\delta_q} + \frac{c}{2}\right]} \qquad (11)$$

with,

$$\gamma_{pq}^2 = \frac{p}{a} + \alpha_p^2 + \delta_p^2$$
$$G_{pq} = [\lambda\,\gamma_{pq}(1 + R_c\rho_s c_s\,e_s\,p]\,sh\,(\gamma_{pq}\,e)$$
$$+\rho_s c_s\,e_s\,p\,ch\,(\gamma_{pq}\,e)$$

The proper values δ_c are solutions of the transcendental Eq. (16).
The proper values δ_b are solutions of the transcendental equation:

$$\delta b\tan(\delta b) = H_x\text{ avec = with } H_x = \frac{hb}{\lambda}$$

For a level flow:

$$\Phi_0(p) = \frac{\phi_0}{p} \qquad (12)$$

Asymmetrical hot plate model: The mountings used are not exactly symmetrical, in fact, two samples of the same size may differ in composition and water content, so it is more convenient to use an asymmetric mounting with a single sample (Fig. 4).

1D simplified model: Quadripole formalism is applied independently on two systems (Bal *et al*., 2012):

- **First system:** Spread of heat flux Φ_1 in the direction sample-probe-insulator
- **Second system:** Spread of heat flux Φ_2 going on the opposite side probe-insulation

The total heat flux is the sum of flux pointing in each direction (Fig. 5):

$$\Phi_0 = \Phi_1 + \Phi_2 = \frac{\varphi_0}{S} \qquad (13)$$

For the first system, the application of the quadripole formalism leads to the following relationship:
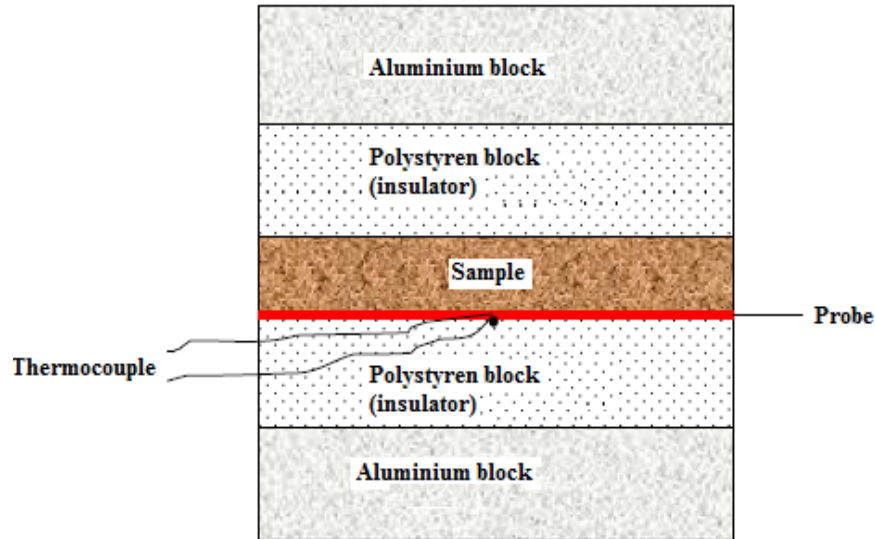
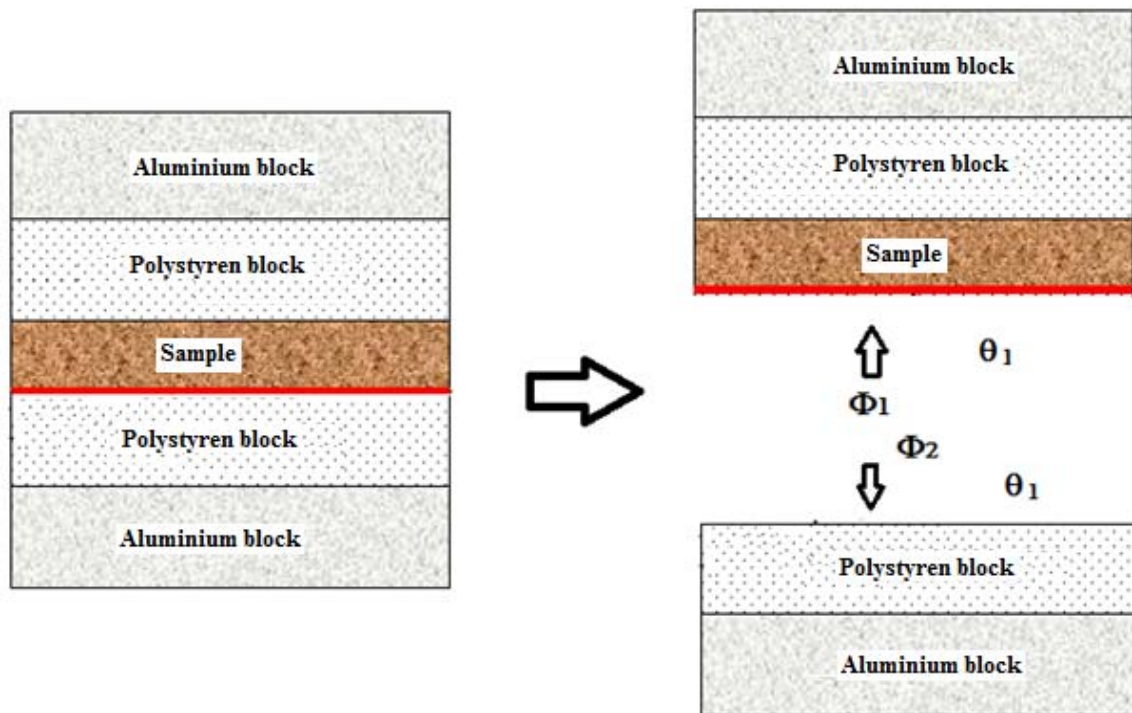Fig. 4: Diagram of experimental asymmetrical hot plate method

Fig. 5: Diagram showing the propagation of heat from the probe

$$\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = [M_1][M_2][M_3][M_4][M_5] \begin{bmatrix} 0 \\ \Phi'_1 \end{bmatrix}$$
$$= \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \Phi'_1 \end{bmatrix} \tag{14}$$

The matrices M_1, M_2, M_3 and M_4 have for expressions:

$$M_1 = \begin{bmatrix} 1 & 0 \\ C_p & 1 \end{bmatrix}$$

M₁: Corresponding to half the thickness of the probe:

$$M_2 = \begin{bmatrix} 1 & R_{C1} \\ 0 & 1 \end{bmatrix}$$

M₂: Corresponding to the thermal resistance of contact between probe and material, to be characterized, with Rc_1 the thermal resistance of contact between the probe and the material:

$$M_3 = \begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} = \begin{bmatrix} ch(qe) & \frac{1}{\lambda qS} sh(qe) \\ \lambda qSch(qe) & ch(qe) \end{bmatrix}$$

M₃: Corresponding to the material to be characterized (here the sample) of e thickness and λ thermal conductivity. We note: $q = \sqrt{\frac{p}{a}}$:

$$M_4 = \begin{bmatrix} 1 & R_{C2} \\ 0 & 1 \end{bmatrix}$$

M₄: Corresponding to the resistance of contact between sample and insulation Rc₂:

$$M_5 = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}$$
$$= \begin{bmatrix} ch(q_i e_i) & \frac{1}{\lambda q_i S} sh(q_i e_i) \\ \lambda_i q_i S\, ch(q_i e_i) & ch(q_i e_i) \end{bmatrix}$$

M₅: Corresponding to the insulation of e thickness and λᵢ thermal conductivity Noting: $q_i = \sqrt{\frac{p}{a_i}}$.

By developing the matrix product of the relationship 14, a system of two equations with two unknowns is obtained. By solving this system, we will have:

$$\Phi_1 = \theta_1 \frac{D}{B} \tag{15}$$

By considering the second system, with the subscript i referring to the insulation, we can write:

$$\begin{bmatrix} \theta_1 \\ \Phi_1 \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \Phi'_1 \end{bmatrix} \tag{16}$$

After the matrix product development and resolution of the system of two equations obtained, we will have:

$$\Phi_2 = \theta_1 \frac{D_i}{B_i} \tag{17}$$

Using the relation (3.33), one obtains:

$$\Phi_0 = \theta_1 \left(\frac{D}{B} + \frac{D_i}{B_i}\right) \tag{18}$$

The Expression of θ₁ is deduced by the relationship:

$$\theta_1 = \frac{\phi_0}{p} \frac{1}{\left(\frac{D}{B} + \frac{D_i}{B_i}\right)} \tag{19}$$

Simplification of the model:
Noting that:
$\lambda q = \sqrt{p} E\, et\, \lambda_i q_i = \sqrt{p} E_i$; the size θ₁ is written when the time is long (p tending to zero):

$$\theta_1 \simeq \frac{\phi_0}{p}$$
$$\frac{1}{(C\,p + E\,\sqrt{p})(1 - R_{c1} E\sqrt{p}) + (C\,p + E_i \sqrt{p})(1 - R_{c2} E_i \sqrt{p})} \tag{20}$$

This Relationship becomes:

$$\theta_1 \simeq \frac{\phi_0}{p^{3/2}(E+E_i)} \left[1 + \left(\frac{R_{c1}E^2 + R_{c2}E_i^2}{E+E_i} - \frac{2C}{E+E_i}\right)\right] \sqrt{p} \tag{21}$$

By performing the Laplace inverse transform, one obtains:

$$T_1(t) = \Phi_0 \left[\frac{R_{c1}E^2 + R_{c2}E_i^2}{(E+E_i)^2} - \frac{2(\rho c)_s e}{(E+E_i)^2}\right] + \frac{\phi_0}{(E+E_i)\sqrt{\pi}} \sqrt{t} \tag{22}$$

When p approaches zero (long time), the curve $T_1(t) = f(\sqrt{t})$ tends towards a straight line. The inertia of the probe and the contact resistance has a negligible effect on this temperature. To determine the thermal effusivity, the slope β of the line is used. This will provide:

$$E + E_i = \frac{\Phi_0}{\beta \sqrt{\pi}} \tag{23}$$

The determination of the parameters E, λ, ρ_c and a is obtained using the full model. We find that on a time interval, the experimental curve is coincident with that produced by the full model.

Methods of mechanical properties measurement: To build a home, it is necessary to know the resistance of the bricks which compose it, to the efforts of traction and compression. Compression refers to the load carried by the material (bricks, for example) while the traction mainly concerns the reinforced concrete structures such as posts and lintels.

Compressive strength: The compressive strength is measured by compressing a test tube placed between the plates of a press. A force is applied to the axis of the specimen. The intensity of this force is increased until failure of the test tube (Fig. 6).
The resistor R_c, expressed in MPa, is given by the following relationship:

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

With,
F: Maximum value of the intensity of the applied force, in N
S: Surface of the section of the test tube in m²

Tensile strength in bending: To measure the tensile strength in bending, the test tube is placed along its height, between the platens of a press (Fig. 7). A force is applied on the test tube (Gaye *et al.*, 2001). When the intensity of this force increases, there will be elastic deformation and rupture of the specimen.
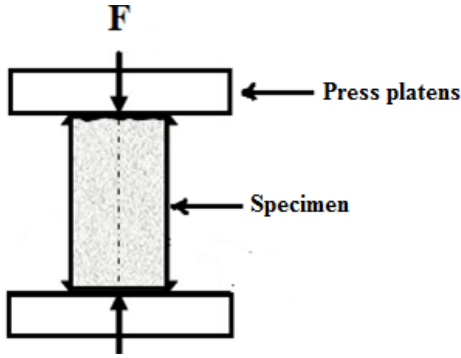
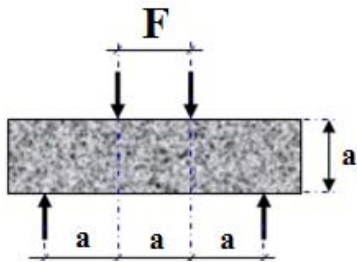Fig. 6: Device for measuring the compressive strength

Fig. 7: The device for measuring the tensile strength in bending

According to NF P 18-40, for samples of size 7×7×28 or 10×10×40 cm^3 (side a = 7 or 10 cm and length 4a), the tensile stress by bending, considering a linear elastic behavior for the material is given by the formula (6):

$$R_t = \frac{3F}{a^2} \tag{24}$$

For pure tensile stress, some authors propose a correction factor of 0.6. There is thus:

$$R_t = \frac{1,8\,F}{a^2}$$

RESULTS AND INTERPRETATIONS

For the measurement of thermo-physical characteristics of the material, we use the asymmetric hot plate method.

Experimental device: It comprises a 10×10 cm area probe, powered by a direct current generator of mark TTI (THURBY THANDAR INSTRUMENTS) with 32V-3A characteristics. A type of K thermocouple, consisting of wires of 0.05 mm in diameter, placed under the probe allows measuring the temperature in the center thereof. The probe is placed below the sample. The sample is a small clay brick with the same surface area as the probe and 3 cm thick. The sample-probe-thermocouple as a whole is placed between two blocks of polystyrene foam of 5.9 cm thick. The outer surface of each block of polystyrene foam is in contact with the surface of an aluminum block of 4 cm thickness, to obtain a fixed temperature on this surface.

The acquisition of the temperature measurements is provided by the data logger of the brand AGILENT BENCHLINK DATA LOGGER 34970A coupled to a computer of the HP VECTRA brand (Fig. 8).
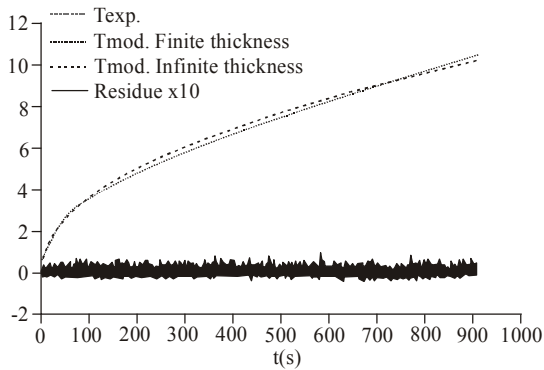

Fig. 8: Experimental device

Fig. 9: Residue curve showing the consistency between the experimental curve and that given by the model

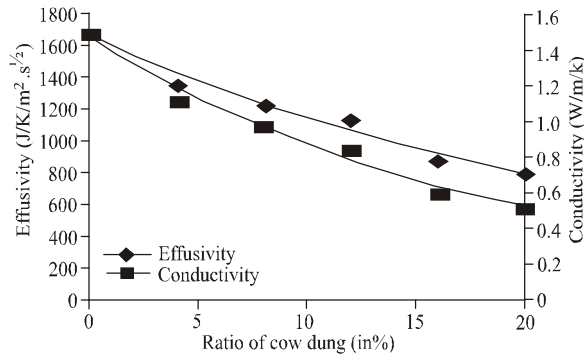Fig. 10: Photograph of a sample

Fig. 11: Evolutions of effusivity and conductivity of the clay based on percentage of cow dung

To standardize the probe, we used a reference material, a block of PVC whose thermal characteristics and dimensions are well known: 10×10 cm surface thickness: 1.5 cm, conductivity: 0.184 W/m/K, diffusivity: $1.21/10^7 \, m^2/sec$.

This experimental device allows the simultaneous determination of the thermal effusivity and thermal conductivity of the sample.

Fig. 12: Photograph of a test tube to measure the mechanical strength (top view)
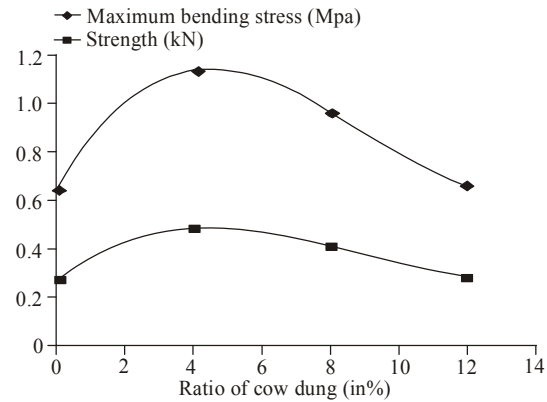

Fig. 13: Evolutions of strength and maximum bending stress of clay depending on the rate of cow dung
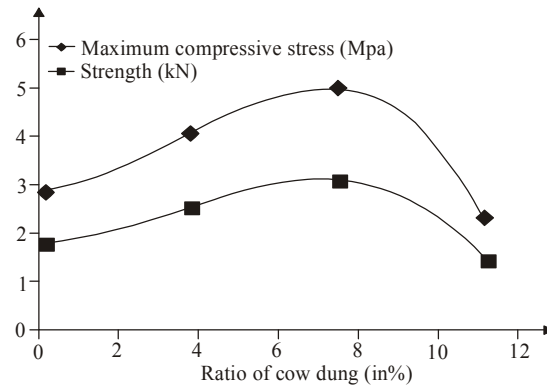
Fig. 14: Evolutions of strength and maximum compressive stress of clay based on the rate of cow dung

Residues analysis: The theoretical curve, the experimental curve of the temperature versus time and the residue curve are represented by Fig. 9. Consistency between the experimental value and the theoretical value of the temperature is determined if residues (horizontal band) are centered on zero.

Presentation of results and comments:
Thermal properties: The samples (Fig. 10) have been previously placed for 48 h in an oven of 100.4°C

Table 1: Results of the measurement of the conductivity and diffusivity of clay based on the percentage of cow dung

Rate of cow dung (in %)	0	4	8	12	16	20
E (J/K/m^2 sec$^{1/2}$)	1643.820	1350.280	1227.30	1141.650	879.100	806.150
λ (W/m/K)	1.483	1.111	0.98	0.842	0.609	0.524

Table 2: Strength and maximum stress of clay on the rate of cow dung

Rate of cow dung in the sample (in %)	Bending		Compression	
	Strength (kN)	Max. stress (MPa)	Strength (kN)	Max. stress (MPa)
0	0.273	0.641	3.380	2.110
4	0.479	1.122	4.767	2.989
8	0.404	0.947	5.874	3.671
12	0.280	0.656	2.700	1.687
16	-	-	4.275	2.653

Max.: Maximum

interior temperature, so as to eliminate the amount of water they contain. They are subsequently installed over the probe in the measurement system.

For a given supply voltage, three measurements are made, we consider the average value for the characteristics of each sample. The measurement results of the characteristics of bricks clay-dung material composite are given in Table 1.

From the curves of Fig. 11, we can see that the thermal effusivity and thermal conductivity decreased with the amount of cow dung added. This is explained by the fact that the addition of the dung increases the porosity of the clay and thereby traps air which is at the basis of the decrease in conductivity.

Mechanical properties: The quality of the material also depends on its ability to bear loads. The test tubes used are of parallelepiped shape 4×4×16 cm dimensions (Fig. 12).

We have summarized in Table 2 the maximum crushing load in kN and the bending strength and compressive strength in MPa, for different contents of cow dung for this material.

It appears from Table 2 that the maximum stress and the strength increase with the addition of cow dung to a level of about 4% in the case of bending and 8% in the case of compression. Beyond these values, they decrease as confirmed by the curves of Fig. 13 and 14.

Cow dung therefore acts as reinforcement for the clay (approximately like iron acting as reinforcement for concrete) and the cohesion decreases after a certain rate causing a decrease in mechanical strength.

In the case of the sample rate of 16%, the press CONTROLAB did not yield any result for the bending following the crash of the test tube.

There is no interest from the point of view of compressive strength to make bricks whose rate of dung exceeds 8%.

Clay stabilization: After adding cow dung to clay, we find that the conductivity decreases. The material becomes, thermally, more insulating. This result in a feeling of freshness inside a room built with this material when it's hot outside and a feeling of warmth when it is cold outside. There is therefore an increase in the thermal comfort. But another factor involved: that is the fight against the degradation caused by the rains. Thus we see that, in rural areas, people are renewing the outer layer of the rooms before the first rains or strengthen during the rainy season. Should therefore make water resistant clay. An experiment with a brick whose rate of cow dung is 8% mixed with 4.8% cement leads to its stabilization.

CONCLUSION

The results of measurement of thermal conductivity and thermal effusivity of studied clay using the method of asymmetric warm up show that these two characteristics decrease when the cow dung rate increases. Cow dung contributes to the thermal insulation of a house of clay.

It is also important, in terms of habitat, to take an interest in the mechanical properties of the clay, thus we observed, after measurements, that compressive strength increases to 8% rate and then it starts to decrease. Excessive addition of cow dung therefore decreases the strength of the clay.

This clay which contains 8% of cow dung resists to water when it is stabilized with cement in a proportion of 4.8%.

This study that takes into account insulation aspect and mechanical strength aspect, contributes to improving the quality of housing in clay widely used in rural areas because of the prohibitive cost of concrete.

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