



Measurement and Modelling of Water Content Effects on Thermal Properties of Compressed Soil Building Blocks

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Author's contribution

This work was carried out in collaboration between author and National Advanced school of Engineering, University of Yaounde I. Author AT designed the study, carried out the samples, wrote the protocol, wrote the first draft of the manuscript, managed the analyses of the study and managed the literature searches. Author read and approved the final manuscript.

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ABSTRACT

Aims: The aim of this paper was to determine the thermal conductivity and the thermal effusivity of the compressed soil building blocks as a function of their water content.

Study Design: Samples with dimensions 53×40×20 mm³ were produced for experiment. Eight containers and an oven were used to determine the equilibrium moisture content. The thermal properties of samples were obtained using a symmetrical hot strip method device.

Place and Duration of Study: University of Yaounde I and National Advanced School of Engineering, Laboratory of Energizing, Water and Environment, between March 2014 and October 2014.

Methodology: Thereafter, sorption isotherm of this building material was determined using the gravimetric static method of saturated salt solutions at 30°C (ambient average temperature), and GAB equation was applied to discuss the results. Then, a symmetrical hot strip method device was used to measure the thermal conductivity and the thermal effusivity of these samples, with their

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water content varying from 0 to a maximum value of $0.139 \text{ kg}_w \cdot \text{kg}_{db}^{-1}$. An adapted device was developed to prevent water evaporation on the lateral faces of the samples.

Results: Both thermal conductivity and thermal effusivity were modelled and the experimental results were processed to evaluate these thermal properties of compressed soil building blocks. A new simplified model, based on a physical approach with assumption of an ideal shrinkage of the material during the evaporation of water, was built.

Conclusion: Calculated and experimental values of thermal properties were in good agreement, with a maximum standard error of $1.671 \text{ Wm}^{-2} \text{ K}^{-1} \text{ s}^{1/2}$ for thermal effusivity and of $0.024 \text{ Wm}^{-1} \text{ K}^{-1}$ for thermal conductivity. The suitability of this model for other buildings material will be further studied.

Keywords: Compressed soil building blocks; water content; model; thermal effusivity; thermal conductivity.

ABBREVIATIONS

Letters

A, B, C, D	Quadrupolar terms
Q	Heat flux density (Wm^{-2})
Rc	Thermal resistance ($\text{Km}^2 \text{W}^{-1}$)
T	Temperature (K)
a	Thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
c_p	Specific heat of the heating element ($\text{Jkg}^{-1} \text{K}^{-1}$)
x, y	Spatial coordinates
ρ	Laplace parameter
t	Time (s)
E	Thermal effusivity ($\text{Wm}^{-2} \text{ K}^{-1} \text{ s}^{1/2}$)
S	Area (m^2)
e	Thickness (m)
X	Dry basis water content ($\text{kg}_w \text{ kg}_{db}^{-1}$)

Greek letters

λ	Thermal conductivity ($\text{Wm}^{-1} \text{K}^{-1}$)
φ	Laplace-Fourier transform of the heat flux density
τ	Laplace-Fourier transform of the temperature
ϕ	Laplace transform of the heat flux density
θ	Laplace transform of the temperature
ρ	Density (kgm^{-3})
α, ω	Fourier parameter

Subscripts

s	Heating element
m	Measured
0	Initial
2	Aluminium block
θ	Laplace transform of the temperature
c	Specific heat ($\text{Jkg}^{-1} \text{K}^{-1}$)
ρ	Density (kgm^{-3})
α, ω	Fourier parameter

1. INTRODUCTION

The compressed soil building blocks were used since the fifties, initially to bring an economic and social response to the production of a habitat intended for the most stripped populations. Today, this building material interests as well the poor countries as the industrialized countries. This process is traditionally used in several Sub-Saharan countries, particularly in Cameroon where compressed soil building blocks were very used as building materials.

Some studies concerning the thermal properties of earth-based materials have already been published. Bouguerra et al. [1] studied the influence of the water content on the thermal properties of wood cement-clay based composites. Nevertheless, only thermal effusivity was investigated. Adam and Jones [2] studied the thermal properties of stabilized soil building blocks but they did not investigate the influence of the water content. Meukam et al. [3] studied the evolution of the thermal properties of stabilized soil building blocks with pouzzolane or sawdust addition as a function of the water content. Nevertheless, no interpretation of the results based on the structure of the material was presented and no predicting model was proposed. Khedari et al. [4] studied the thermal properties of coconut fiber-based soil-cement blocks and Omubo- Pepple et al. [5] studied cement stabilized lateritic bricks with sea shell addition but the influence of the water content was not investigated in these two studies. The same remark may be done concerning the work of Goodhew and Griffiths [6] concerning unfired clay bricks with straw and wood chippings. Bal et al. [7] studied the evolution of the thermal conductivity of laterite based bricks with millet waste additive as function of water content with interpretation of the results based on the structure of the material. Nevertheless, no interpretation of the results based on the sorption isotherm of the material was presented.

The aim of this study was first to determine the sorption isotherm of compressed soil building blocks at 30°C (ambient average temperature in wet tropical zone). Since these bricks are used for building and are exposed to very different meteorological conditions, it is also very important to know how their thermal properties vary with the water content. Thus, the variation of their thermal conductivity and their thermal effusivity with the water content has been experimentally determined.

Finally, to be able to predict their thermal behavior in various meteorological conditions, a model enabling the calculation of the thermal conductivity and of the thermal effusivity as a function of the water content X has been developed and experimentally validated.

2. MATERIALS AND METHODS

2.1 Samples Preparation

The clay used was extracted directly from the soil in the region of Center in south Cameroon. The raw clay was sieved so that the maximum grain size was 1 mm and then it was kept into sealed recipients. The clay is first mixed with a little water until mixing lead to a homogeneous paste, to allow cohesion during the compaction. This paste is pressed in a mould with internal dimensions $53 \times 40 \times 20 \text{ mm}^3$ with a constant pressure around 1 bar. After removal from mould, samples are set into seal plastic bags for several days to obtain and uniform water content. These samples can be seen on the view in Fig. 1. The gravimetric static method was used to measure the sorption equilibrium moisture content of samples. Eight airtight cylindrical plastic containers, 115 mm diameter and 135 mm height, containing saturated salt solutions were placed in an electric oven to provide constant temperature and relative humidity environments. The digital temperature controller, on control panel of electric oven, provided the desired temperature (accuracy 0.1°C). A mini fan of 60-mm (3 V, 0.25 A) was fitted inside the plastic container to provide continuous stirring of the air inside the container. The values for water activity of the saturated salt solutions were obtained from Greenspan [8] and these are listed in Table 1. The water activity range of 0.034–0.936 were selected for this study. The samples were removed from the bag and placed inside eight airtight cylindrical plastic boxes each, and suspended over the saturated salt solutions in each container. The containers were then placed in the oven at a desired constant temperature and allowed to equilibrate with the environment inside the containers. Fig. 2 shows the schematic diagram of the experimental apparatus [9]. The selected temperature was 30°C with an accuracy of 0.1°C variation. The weight of each sample was recorded at 48 h intervals by taking out the sample from the container very fast and then replacing the sample in the container. The weight recording period was about 15 to 20 s for each sample. This procedure was continued, for many days, until the weight

was constant; their mass variation became less than 0.1 g. The equilibrium moisture content X_{eq} of each sample was then determined, after determination of their thermal properties, by the oven-drying method at 102°C for 48 h. The different thermal conductivities and thermal effusivities measurements were realized when the weights of samples were constants. The last thermal properties measurements were done with each dried samples.



Fig. 1. Pictures of compressed soil building blocks used as samples

2.2 Thermal Conductivity Measurement Method

The thermal conductivity and the thermal effusivity were measured using the hot strip method frequently used by other researchers to measure thermal properties [10,11]. This method consists in using a simple electric resistance of rectangular form on which was laid out a thermocouple made up of wire of low diameter. The temperature measurement was taken in the center of resistance; so, the thermal losses by electric wire at extremities of resistance were not taken into account. The resistance was inserted

between two samples of plane surface of material to characterize. Dimensions of these samples were such as the disturbance caused by the level of heat flow imposed on the resistance does not reach to its faces throughout measurement (assumption of the semi-infinite surrounding). The ratio length/width of resistance was selected so that the heat transfer to the center of resistance can be considered bidirectional during a time lower than 180 s. Recorded temperatures to the beginning of the heating (during time when the transfer of heat to the center of the resistance remains one-way) was used to consider the thermal effusivity by the hot plane method. A complete modeling of the bidirectional transfers in the samples, associated with a method of estimate of parameters, enabled to use the recorded temperatures between 0 and 180 s to estimate the thermal conductivity.

Since we was obtained two identical samples having exactly the same water content, using saturated salt solutions method to determine the equilibrium moisture content, a symmetrical experimental device represented in Fig. 3 was chosen. A strip heating element having the dimensions $53 \times 12 \times 0.22 \text{ mm}^3$ was inserted between two samples with a 20 mm thickness each one. A type K thermocouple made with two wires with a 0.005 mm diameter was stuck on the upper face of the heating element. This disposal is placed between two isothermal aluminum blocks with a thickness 40 mm and the same $53 \times 40 \text{ mm}^2$ cross-section as the samples. A tightening device enabling pressure control and the measurement of the thickness of the device inserted between the aluminum blocks. A heat flux step is sent into the heating element and the transient temperature $T(t)$ is recorded. The presence of the thermocouple increases the

Table 1. Saturated salt solutions used to establish the water activity at different levels from 0.06 to 0.982 (adapted from Greenspan, 1977)

Solution	Water activity at various temperature						
	10	15	20	25	30	35	40
Cesium fluoride (CsF)	0.049	0.043	0.038	0.034	0.030	0.027	0.024
Lithium bromide (LiBr)	0.071	0.069	0.066	0.064	0.062	0.060	0.058
Lithium iodide (LiI)	0.206	0.196	0.186	0.176	0.166	0.156	0.146
Magnesium chloride (MgCl ₂)	0.335	0.333	0.331	0.328	0.324	0.321	0.316
Sodium bromide (NaBr)	0.622	0.607	0.591	0.576	0.560	0.546	0.532
Sodium nitrate (NaNO ₃)	0.775	0.765	0.754	0.743	0.731	0.721	0.710
Potassium chloride (KCl)	0.868	0.859	0.851	0.843	0.836	0.830	0.823
Potassium nitrate (KNO ₃)	0.960	0.954	0.946	0.936	0.923	0.908	0.890

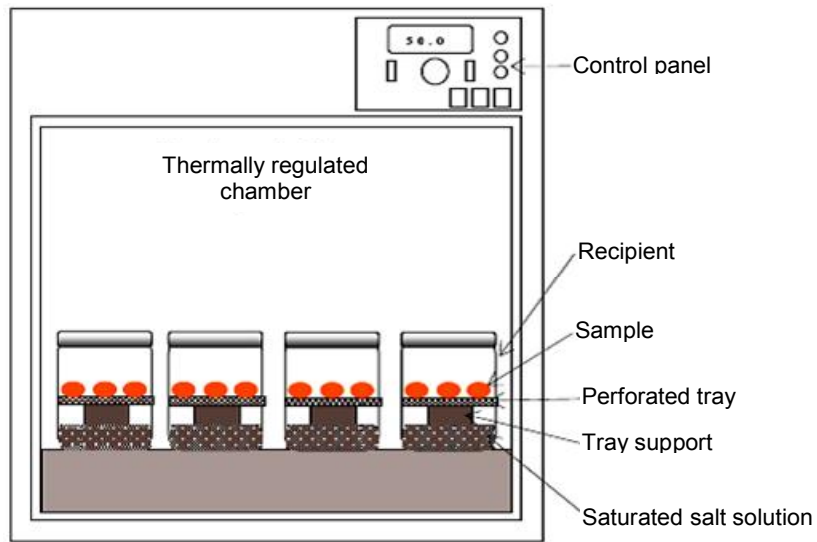


Fig. 2. Schema diagram of the experimental device for equilibrium moisture content [9]

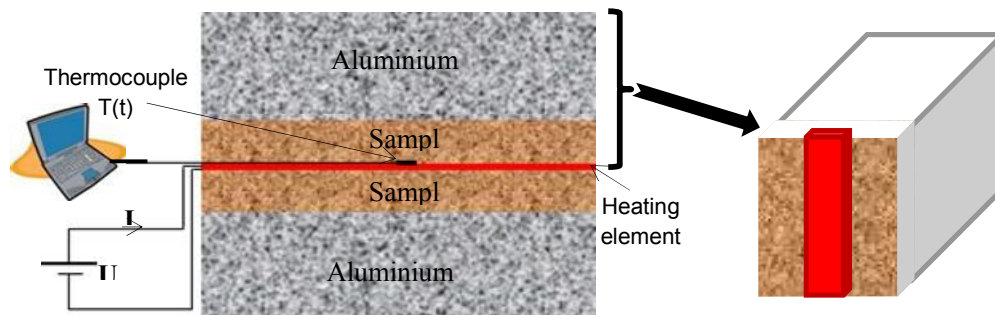


Fig. 3. Schema of the experimental hot strip device

thermal contact resistance between the heating element and the upper sample. Furthermore, since polystyrene is an insulating material, this thermal contact resistance was taken into account in the complete model. The system is modeled with the hypothesis that the heat transfer was carried out in two dimensions (2D) from the center of the two samples during the experiment.

Nevertheless, since wet materials have to be characterized, the problem of surface water evaporation must be addressed. Without special care, the evaporation that will occur on the lateral face of the heated sample will increase the convection heat transfer coefficient. The result would be that the time during which the heat transfer at the center remains 2D would be

shortened. To avoid this problem, the samples have been placed in sealed thin plastic bags (polyethylene with a thickness 0.05 mm) in which the air reaches an equilibrium humidity with the sample, preventing surface evaporation. It has been shown that this disposal has no influence on the measurement result [7]. Fig. 3 shows the schema of the experimental hot strip method device. We consider, like the laterite based bricks with millet waste additive, that the thermal resistance of the plastic bag is negligible compared with the samples thermal resistance [7]. Considering the problem symmetry, only the half of the geometry, which can be seen in Fig. 4, was studied.

Within these hypotheses, one can write the following quadrupolar matrix relation [12,13]:

$$\begin{bmatrix} \tau_m(\alpha_n, 0, p) \\ \varphi_m(\alpha_n, 0, p) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ (\rho c_p)_s e_s p & 1 \end{bmatrix} \begin{bmatrix} 1 & R_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} \begin{bmatrix} \tau(\alpha_n, e_s + e, p) \\ \varphi(\alpha_n, e_s + e, p) = \lambda_2 \sqrt{\frac{p}{a_2} + \alpha_n^2} \tau(\alpha_n, e_s + e, p) \end{bmatrix} \quad (1)$$

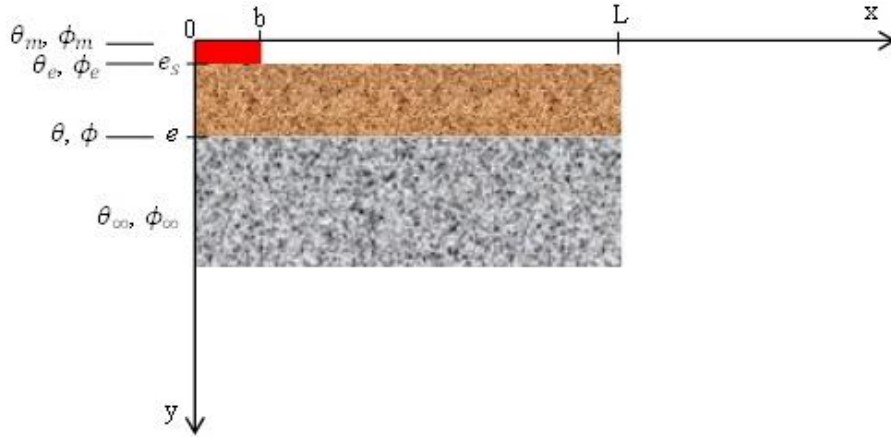


Fig. 4. Schema of the geometry of problem

This system leads, after resolution, to complete model:

$$\tau_m(\alpha_n, 0, p) = \frac{[A'_n + B'_n \lambda_2 \sqrt{\frac{p}{a_2} + \alpha_n^2}] \varphi_m(\alpha_n, 0, p)}{C_n + A'_n (\rho c_p)_s e_s p + \lambda_2 L \sqrt{\frac{p}{a_2} + \alpha_n^2} [A'_n (\rho c_p)_s e_s p + D_n]} \quad (2)$$

With:

$$\varphi_m(\alpha_n, 0, p) = \frac{Q \sin(\alpha_n b)}{p} \frac{1}{\alpha_n}, \quad \alpha_n = \frac{n\pi}{L} \quad (3)$$

$$\begin{aligned} A'_n &= D_n = A_n + R_c C_n = ch \left[\sqrt{\left(\frac{p}{a} + \alpha_n^2\right)} e \right]; \\ B'_n &= B_n + R_c D_n = \frac{1}{\lambda \sqrt{\left(\frac{p}{a} + \alpha_n^2\right)}} sh \left[\sqrt{\left(\frac{p}{a} + \alpha_n^2\right)} e \right]; \\ C_n &= \sqrt{\left(\frac{p}{a} + \alpha_n^2\right)} sh \left[\sqrt{\left(\frac{p}{a} + \alpha_n^2\right)} e \right] \end{aligned} \quad (4)$$

$\tau_m(\alpha_n, 0, p)$ is the Laplace-Fourier transform of the temperature $T(t)$ measured, p is the Laplace parameter, $\varphi_m(\alpha_n, 0, p)$ is the Laplace-Fourier transform of the heat flux density living the heating element, Q is the heat flux density produced in the heating element,

c_p is specific heat of the heating element, R_c is the thermal contact resistance between the heating element and the sample, $\tau(\alpha_n, e_s + e, p)$ is the Laplace-Fourier of the temperature on the upper aluminum block, $\varphi(\alpha_n, e_s + e, p)$ is the Laplace-Fourier transform of heat flux density on the aluminum block.

λ is the sample thermal conductivity, a is the sample thermal diffusivity, e is the sample thickness, e_s is the heating element thickness, λ_2 is the aluminium thermal conductivity and a_2 is the aluminium thermal diffusivity.

By the inverse Fourier transform of equation (2), we obtain:

$$\theta_m(x, 0, p) = \frac{1}{L} \tau_{m0}(0, 0, p) + \frac{2}{L} \sum_{n=1}^{\infty} \tau_m(\alpha_n, 0, p) \cos(\alpha_n x) \quad (5)$$

Finally the inverse Laplace transformation of Eq. (5) is realized by use of the Stehfest method [14]:

$$T_s(0, 0, t) = \frac{\ln(2)}{t} \sum_{j=1}^k V_j \theta_s\left(0, 0, \frac{j \ln(2)}{t}\right) \quad (6)$$

With for $k=10$:

$$\begin{aligned} V_1 &= \frac{1}{12}; V_2 = \frac{-385}{12}; V_3 = 1279; V_4 = \frac{-46871}{3}; \\ V_5 &= \frac{505465}{6}; V_6 = \frac{-473915}{2}; V_7 = \frac{1127735}{3}; \\ V_8 &= \frac{-1020215}{3}; V_9 = \frac{328125}{2}; V_{10} = \frac{-65625}{2}. \end{aligned}$$

The principle of the method is to estimate the value of the thermal effusivity $E = \sqrt{\lambda \rho c}$ and of the thermal conductivity λ of the sample that minimize the sum of the quadratic error $\Psi =$

$\sum_{i=1}^n [T_{exp}(t_i) - T_{mod}(t_i)]^2$ between the experimental curve and the theoretical curve calculated with Eq. (6). The estimation has been done on a time interval $[0, t_1]$ for E such as the heat transfer at the center of the sample remains 1D until t_1 and on a time interval $[t_1, t_{max}]$ for λ such as the heat transfer at the center of the sample remains 2D until t_{max} .

The thermal capacity ρc is deduced from the values of the thermal effusivity E and of the thermal conductivity λ by:

$$\rho c = \frac{E^2}{\lambda} \quad (7)$$

2.3 Mathematical Models

2.3.1 Sorption isotherms using GAB model

The Guggenheim, Anderson and den Boer (GAB) model [15] was accepted as the best to represent the sorption isotherms at the International Symposium on the Properties of Water (ISOPOW) in 1983 [16] and is recommended by the European Project Group COST 90 on Physical Properties of Food [17]. The GAB equation is given by:

$$X_{eq} = \frac{X_m CKa_w}{(1-Ka_w)[1+(C-1)Ka_w]} \quad (8)$$

where X_{eq} is the amount of water and X_m is the monolayer moisture content, both generally expressed in dry basis ($kg_w kg_{db}^{-1}$), C is an energetic constant also called as Guggenheim constant [18], and K is a parameter that takes into account the difference of chemical potential between the multilayer and bulk water in the food [19;20]. C and K are given by the following equations:

$$C = C_0 \exp\left(\frac{H_m - H_w}{RT}\right) \text{ and } K = K_0 \exp\left(\frac{H_q - H_w}{RT}\right) \quad (9)$$

where H_w , H_m , H_q , are respectively, the condensation heat of pure water, the total sorption heat of the monolayer and the total sorption heat of other layers ($Jmol^{-1}$), T is the absolute temperature (K), C_0 the constant, K_0 the constant and R is the universal gas constant ($8.314 Jmol^{-1}K^{-1}$).

The parameters are estimated by minimizing the sum of the quadratic errors between the experimental equilibrium water contents X_{eq} and the values calculated with Eq. (8). For the parameter estimation the same function S used

in Talla et al. [9] was considered; the sum of the quadratic errors between the experimental equilibrium water contents X_{eq} and the values calculated with Eq. (8) was minimized:

$$S = \sum_{k=0}^n \left(\frac{X_{eq} - X_{mod}}{X_{eq}} \right)_i^2 \quad (10)$$

where n is the number of measurements for a temperature (nine in the present case).

Fit and prediction quality were analysed by the regression coefficient (R^2), the mean relative deviation (MRD) and the standard error (SE), calculated as follow:

$$R^2 = 1 - \frac{\sum_{i=1}^n (X_{eq_i} - X_{mod_i})^2}{\sum_{i=1}^n (X_{eq_i} - \bar{X})^2} \quad (11)$$

$$MRD(\%) = \frac{100}{n} \sum_{i=1}^n \left| 1 - \frac{X_{mod_i}}{X_{eq_i}} \right| \quad (12)$$

$$SE = \sqrt{\frac{\sum_{i=1}^n (X_{eq_i} - X_{mod_i})^2}{n}} \quad (13)$$

with $\bar{X} = \frac{\sum_{i=1}^n X_i}{n}$; n being the number of experiments.

Generally, the GAB model is used independently for each temperature, generating a set of values for C , X_m and K estimated from experimental data for each temperature condition – e.g. [21-24].

2.3.2 Thermal conductivity models

Generally, a homogeneous composite material is composed of a solid phase (d), of water (w) and of air (a). Its composition is defined by the following parameters:

- Dry basis water content :

$$X = \frac{m_w}{m_d} \quad (14)$$

- Global porosity of the dried material ($X = 0$) :

$$\varepsilon = \frac{V_a}{V_d + V_a} \quad (15)$$

According to Wiener [25], the lowest possible value of the thermal conductivity is given by the series model and the highest is given by the parallel one:

- The series model:

$$\lambda = \frac{1}{\frac{\varepsilon_d}{\lambda_d} + \frac{\varepsilon_a}{\lambda_a} + \frac{\varepsilon_w}{\lambda_w}} \quad (16)$$

where $\varepsilon = \varepsilon_a + \varepsilon_w$

- The parallel model:

$$\lambda = \varepsilon_d \lambda_d + \varepsilon_a \lambda_a + \varepsilon_w \lambda_w \quad (17)$$

Several authors proposed to estimate the effective thermal conductivity of a mixture by a more or less complicated function of the parallel model and of the series model but the model of Ingersoll [23] was a more physical model in which water in a parallel arrangement with air is considered in series with the solid structure:

$$\lambda = \left(\frac{1-\alpha}{\lambda_d} + F \frac{\alpha}{\lambda_{a,w}} \right)^{-1} \quad (18)$$

$\lambda_{a,w}$ is the conductivity of air and water corresponding to a parallel arrangement, F and α are adjustable factors.

2.3.2 Proposed model

The physical model of Ingersoll [23] is not explicitly a function of the water content. To elaborate on the proposed model, we considered that the product is constituted of a solid structure with density ρ_d and volume V_d , pores of which are occupied by water with density ρ_w and volume V_w below air with density ρ_a volume V_a .

Contrary to the assumption of Ingersoll [26], we supposed water in a series arrangement with air is considered in parallel with the solid structure. Thus, we proposed the equivalent schema represented in Fig. 5. Thus, the equivalent thermal conductivity of the material is:

$$\lambda = \varepsilon_d \lambda_d + \frac{e^2}{\frac{e_a^2}{\lambda_a \varepsilon_a} + \frac{e_w^2}{\lambda_w \varepsilon_w}} = \lambda_d + \varepsilon_w \left[\frac{1}{\varepsilon_w^2} \left(\frac{\lambda_w}{1 + \left(\frac{\varepsilon_a}{\varepsilon_w} \right)^2 \frac{\varepsilon_w \lambda_w}{\varepsilon_a \lambda_a}} \right) - \lambda_d \right] - \varepsilon_a \lambda_d \quad (19)$$

with:

$$\varepsilon_w = \frac{e_w}{e}, \varepsilon_a = \frac{e_a}{e}, \varepsilon_d = \frac{V_d}{V}, \varepsilon_w = \frac{V_w}{V}, \varepsilon_a = \frac{V_a}{V} \text{ and } V = V_d + V_w + V_a$$

Furthermore, by considering m as the mass of the material at a given time, m_w the mass of

water contained in this material, m_a the mass of air contained in this material and m_d the mass of its solid material, it can be written that:

$$m = m_w + m_d + m_a; \quad \rho = \frac{m}{V} \quad (20)$$

Furthermore,

$$\varepsilon_d = \frac{\rho}{\rho_d} \left(\frac{1}{1+X+m_a/m_d} \right); \varepsilon_w = \frac{\rho}{\rho_w} \left(\frac{X}{1+X+m_a/m_d} \right); \varepsilon_a = \frac{\rho}{\rho_a} \left[\frac{1}{1+(1+X)/(m_a/m_d)} \right] \quad (21)$$

With assumption that $m_a/m_d \ll 1$, Eq. (21) and the development of Eq. (20) gives the following expression:

$$\varepsilon_d = \frac{\rho}{\rho_d} \left(\frac{1}{1+X} \right); \varepsilon_w = \frac{\rho}{\rho_w} \left(\frac{X}{1+X} \right); \varepsilon_a \approx 0 \text{ and } \rho = \rho_d \frac{\rho_w(1+X)}{\rho_w + \rho_d X} \quad (22)$$

Eq. (19) after simplification becomes:

$$\lambda = \lambda_d + \left(\frac{\rho_d X}{\rho_w + \rho_d X} \right) \left[\frac{1}{\varepsilon_w^2} \left(\frac{\lambda_w}{1 + \left(\frac{\varepsilon_a}{\varepsilon_w} \right)^2 \frac{\rho_a \lambda_w X}{\rho_w \lambda_a}} \right) - \lambda_d \right] \quad (23)$$

We notice that $\left(\frac{\varepsilon_a}{\varepsilon_w} \right)^2 \frac{\rho_a}{\rho_w} \approx 0$ and finally, the equivalent thermal conductivity of the material is:

$$\lambda_{mod} = \lambda_d + (\beta \lambda_w - \lambda_d) \left(\frac{X}{\gamma + X} \right) \quad (24)$$

The combination of Eqs. (7) and (24) gives the equivalent thermal effusivity of the material:

$$E_{mod} = \left[E_d^2 + (\delta E_w^2 - E_d^2) \left(\frac{X}{\nu + X} \right) \right]^{1/2} \quad (25)$$

β, γ, δ and ν are adjustable factors, depend on the porosity of material and the densities of the air and water.

The modeled thermal properties λ_{mod} and E_{mod} can be calculated using Eq. (24) and Eq. (25) if the parameter λ_d and E_d are known. The unknown parameters of the model that must be identified are thus: $\lambda_d, \beta, \gamma, E_d, \delta$ and ν .



Fig. 5. Model of the elementary volume of the material

3. RESULTS AND DISCUSSION

3.1 Validation of the Method

The method was first applied to a PVC sample which properties have been measured by the flash method [27] and the tiny hot plate method [28]: $a = 1.25 \times 10^{-7} \text{ m}^2\text{s}^{-1}$ and $\lambda = 0.184 \text{ Wm}^{-1}\text{K}^{-1}$ leading to $\rho c = 1.47 \times 10^6 \text{ Jm}^{-3}\text{K}^{-1}$. The PVC sample dimensions are $53 \times 40 \times 5.9 \text{ mm}^3$. The experiment lead to the following results: $\lambda = 0.187 \text{ Wm}^{-1}\text{K}^{-1}$ and $E = 512 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-1/2}$; thus $\rho c = 1.40 \times 10^6 \text{ Jm}^{-3}\text{K}^{-1}$, so that the deviations with the previously known values are lower than 1.7% for thermal conductivity and 4.8% for thermal capacity. This result validates the measurement method with a precision better than 5%.

After being validated by these measurements, the proposed method will now be used to study the water content dependence of the thermal properties of compressed soil building blocks.

3.2 Experimental Results

3.2.1 Sorption isotherms

Sorption isotherms of compressed soil building blocks at ambient average temperature of 30°C in the water activity range of 0.030–0.923 are presented in Fig. 6. Isotherm curve was found to be sigmoid.

Table 2 shows the parameters of the GAB model fitted to the experimental sorption data of compressed soil building blocks; and the values of the regression coefficient (R^2), the mean relative deviation (*MRD*) and the standard error (*SE*). The mean *MRD* value obtained was relatively small (*MRD* < 6%), the coefficient (R^2) for the calculated curve was higher than 0.98 and the standard errors *SE* was smaller than 0.0063.

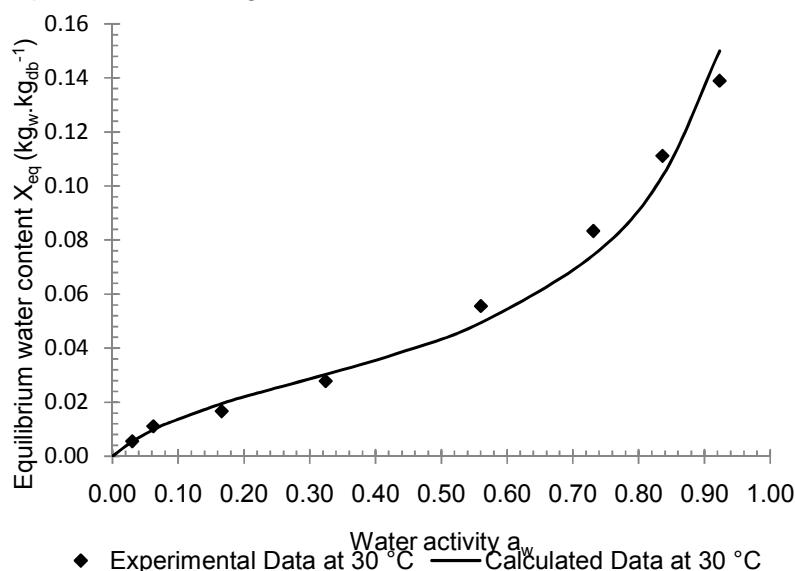


Fig. 6. Experimental and calculated isotherms of compressed soil building blocks at 30°C with GAB model

Table 2. Estimated parameters of the GAB model for the sorption isotherm of compressed soil building blocks at 30°C and comparison with experimental data

$X_m(\text{kg}_w/\text{kg}_{db}^{-1})$	C	K	MRD (%)	R^2	SE($\text{kg}_w/\text{kg}_{db}^{-1}$)
0.03	8.623	0.888	5.9	0.982	0.0062

3.2.2 Thermal properties

The experimental value of the thermal effusivity E_{exp} and the thermal conductivity λ are obtained, at ambient temperature of 30°C (fluctuation $\pm 0,5^\circ\text{C}$), by a thermal method (symmetrical hot strip) and the thermal capacity $(\rho c)_{exp}$ is deduced from the values of these two parameters. Ever since the density $(\rho_{exp} = \frac{M}{V})$ is obtained by direct measurement of the mass and of the dimensions of the sample, the specific heat c_{exp} can be deduce by: $c_{exp} = \frac{(\rho c)_{exp}}{\rho_{exp}}$ for the nine samples with nine different water contents for each of them. Fig. 7 represents the experimental values of the thermal capacity and of the specific heat obtained for this solid for nine different values of the water content (between 0 and 0.139 $\text{kg}_w \cdot \text{kg}_{db}^{-1}$).

The thermal effusivity of compressed soil building blocks may be estimated by minimization of the sum of the quadratic differences between the theoretical value E_{mod} calculated with Eq. (25) and the experimental values E_{exp} (similar relation to Eq. (10)). Table 3 shows the parameters of this model fitted to the experimental thermal effusivity data of compressed soil building blocks; and the values of the regression coefficient (R^2), the mean relative deviation (MRD) and the standard error (SE) (similar relations to Eq. (11)

to (13)). The mean MRD value obtained was very small ($MRD < 2.53\%$), the coefficient (R^2) for the calculated curve was higher than 0.98 and the standard errors SE was smaller than $1.67 \text{ Wm}^{-2}\text{K}^{-1}\text{s}^{1/2}$.

The mean relative deviation between the experimental values and the theoretical values calculated with Eq. (25) was 2.62% with a maximum relative deviation of 2.91% that is quite satisfying. All the experimental and theoretical values are represented on Fig. 8. The apparent density of the nine samples varied between $1800 \text{ kg} \cdot \text{m}^{-3}$ for the dry compressed soil building block ($X = 0 \text{ kg}_w \cdot \text{kg}_{db}^{-1}$) and 2050 kgm^{-3} for the compressed soil building block with the maximum moisture content ($X = 0.139 \text{ kg}_w \cdot \text{kg}_{db}^{-1}$). The corresponding values of the thermal conductivities varied between 1.05 and $2.40 \text{ Wm}^{-1}\text{K}^{-1}$. As described in the paragraph "Thermal conductivity measurement method", the thermal conductivity of each of the nine samples has been measured for at least nine different water contents X varying between the maximum value obtained after equilibrium in saturated salt solution and a null value. Fig. 9 represents the experimental and modeled hot strip temperature curves with an example of residues for $X = 0.139 \text{ kg}_w \cdot \text{kg}_{db}^{-1}$ obtained with the compressed soil building block samples for the different moistures content.

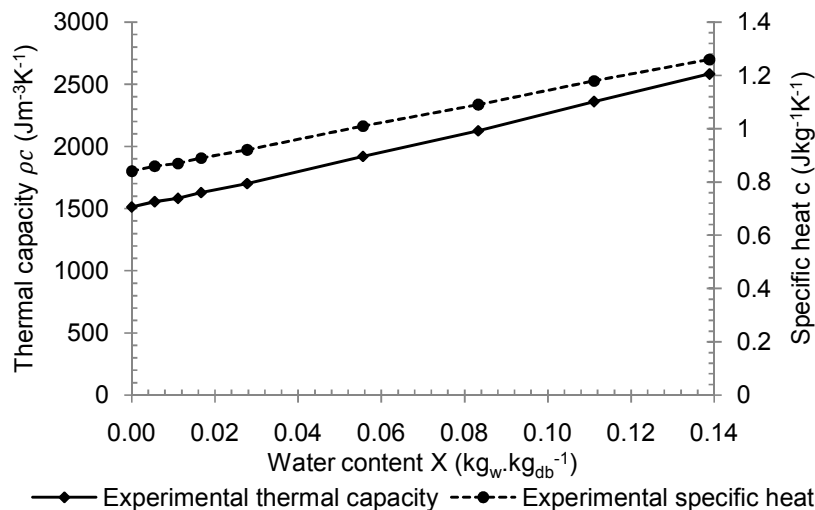


Fig. 7. Estimated thermal capacity and specific heat of compressed soil building blocks

Fig. 10 represents the experimental and theoretical values of the thermal conductivity obtained for this solid for nine different values of the water content (between 0 and 0.139 kg_w.kg_{db}⁻¹). Two main remarks can be made:

- The variation of the thermal conductivity λ is very important compared to the weak variation of the water content X: λ is multiply by 2.29 when X grows from 0 to 0.139 kg_w.kg_{db}⁻¹.
- The thermal conductivity increases quickly with the water content X for the low values of X (X < 0.056 kg_w.kg_{db}⁻¹) and then more slowly for the higher values.

The first remark leads us to consider that the thermal conductivity is weakly affected by the thermal contact resistances (very thin air layer) that can strongly increase if small water content is present in this layer.

The second remark leads us to consider that starting from a dried material, a low increase of

water content affects weakly the thermal conductivity because the water is not first placed in the thermal contact resistance but must filled the internal porosity of the solid grain. After the internal porosity of the grain is filled, a part of the water is set between the grains leading to a strong decreasing of the thermal contact resistances. The remaining part is mixed with air in the void volume between the lateral faces of the grains. So, the thermal conductivity of water has a more significant sensitivity on the thermal conductivity of dry compressed soil building blocks. These results were obtained by Bal *et al.* for laterite based bricks with millet waste additive [7].

These two remarks have led us to propose the model previously described and represented in Fig.5. The classical models described by Eq. (16) to (18) were not tested because they are not explicitly a function of the water content. The parameters of the proposed model described by Eq. (24) were estimated by applying a minimization algorithm to the sum of the

Table 3. Estimated parameters of the new model for the thermal effusivity of compressed soil building blocks and comparison with experimental data

E_d (Wm ⁻² K ⁻¹ s ^{1/2})	E_w (Wm ⁻² K ⁻¹ s ^{1/2})	δ	ν	MRD (%)	R^2	SE (Wm ⁻² K ⁻¹ s ^{1/2})
38.296	1598.477	15.609	1332.062	2.529	0.985	1.671

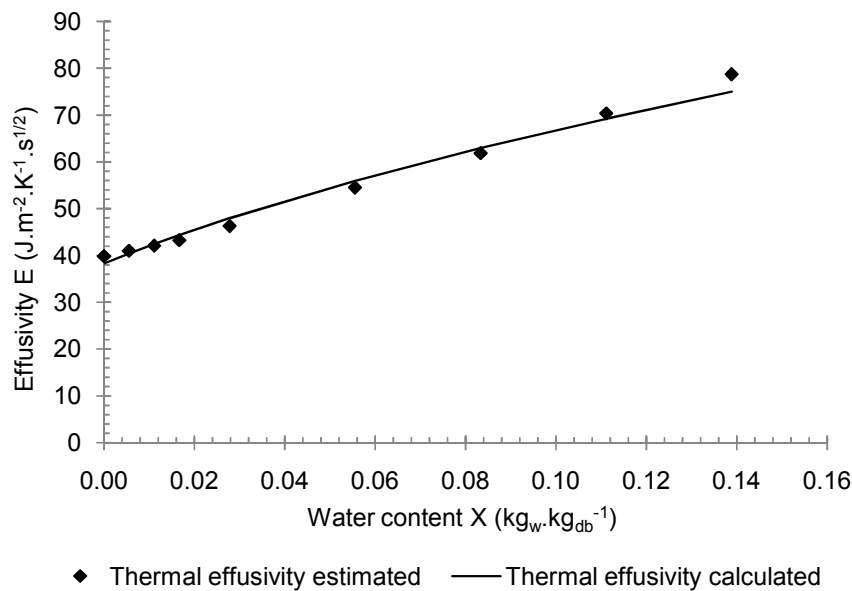


Fig. 8. Estimated and calculated thermal effusivity of compressed soil building blocks with new model

quadratic errors between the experimental and modeled thermal conductivity (similar relation to Eq. (10)). The experimental results were firstly processed by the way described in the paragraph "Thermal conductivity measurement method".

Table 4 gives the values of the estimated parameters of this new model with the mean deviation between the experimental and the modeled values of the thermal conductivity.

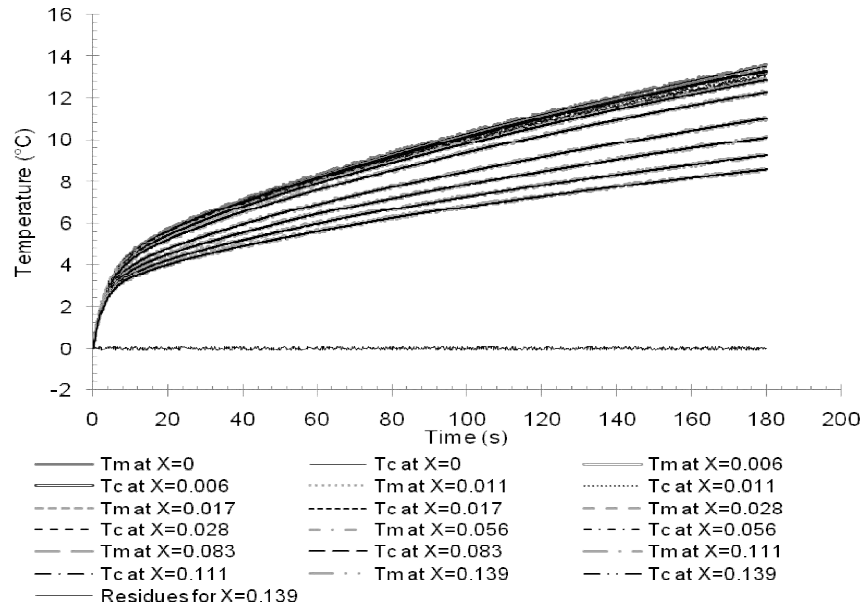


Fig. 9. Experimental and modeled hot strip temperature curves with an example of residues for $X = 0.139 \text{ kg}_w\text{kg}_{db}^{-1}$

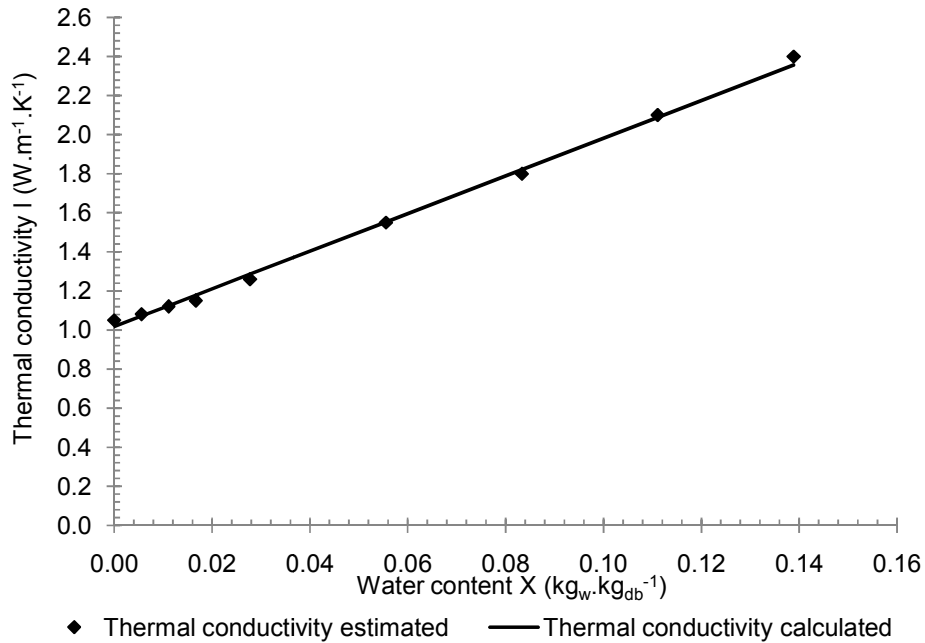


Fig. 10. Estimated and calculated thermal conductivity of compressed soil building blocks with new model

Table 4. Estimated parameters of the new model for the thermal conductivity of compressed soil building blocks and comparison with experimental data

λ_d (Wm ⁻¹ K ⁻¹)	λ_w (Wm ⁻¹ K ⁻¹)	β	γ	MRD (%)	R ²	SE(Wm ⁻¹ K ⁻¹)
1.017	0.612	20616.162	1310.248	1.39	0.997	0.024

The values of Table 4 have then been used to calculate the modeled thermal conductivity using the Eq. (24). The similar relations to Eq. (11) to (13)) were used to calculate the values of the regression coefficient (R^2), the mean relative deviation (MRD) and the standard error (SE) consigned in this table. The values are found to be in good agreement with a mean relative deviation of 1.32% between the experimental and the theoretical values. It may be noticed that the maximum relative deviation was 2.17%. This value is relatively slow and quite acceptable for samples handmade with natural materials.

4. CONCLUSION

This study presents experimental results concerning the water content dependence of thermal effusivity and thermal conductivity of compressed soil building blocks. Nine samples of compressed soil building blocks with nine different water contents (from 0 to 0.139 kg_w/kg_{db}⁻¹) have been investigated. A symmetrical hot strip method device has also been modeled and used for thermal properties measurement. In this device, a specific disposal has been used to avoid water evaporation on the lateral faces of the sample. Adapted models have been developed to predict the thermal conductivity $\lambda(X)$ and the thermal effusivity $E(X)$ of the samples as a function of water content X . Both models lead to a very good representation of the experimental results with a mean relative deviation of 2.62% for the thermal effusivity and 1.32% for the thermal conductivity. The suitability of this model for other buildings material will be further studied.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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