

A New Simplified Model for Predicting of Water Content Effects on Thermal Conductivity of Hygroscopic Materials Buildings

André Talla

Department of Industrial and Mechanical Engineering, National Advanced School of Engineering, Yaounde, Cameroon

Email address:

andre_talla@yahoo.fr

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Abstract: The aim of this paper was to predict the thermal conductivity of local composite materials, particularly used as building materials in Sub-Saharan countries, as a function of their water content. In this work, 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. Two composite materials were successfully tested providing good fitting and prediction results. Calculated and experimental values of thermal conductivity were in good agreement, with a maximum standard error of $0.037 \text{ Wm}^{-1}\text{K}^{-1}$ for the three hygroscopic materials. In spite of its simplicity, this model leads to a more accurate representation than other classical models of the measured variations of the thermal conductivity of hygroscopic materials with the water content.

Keywords: Hygroscopic Material, Water Content, Simplified Model, Thermal Conductivity, Porosity, Density

1. Introduction

The local composite materials were used since the fifties, because of their low cost, initially to bring an economic and social response to the production of a habitat intended for the most stripped populations. Today, these building materials interest as well the poor countries as the industrialized countries. The process is traditionally used in several Sub-Saharan countries, particularly in Cameroon where compressed soil building blocks or insulating material mixed with a building material were very used as building materials.

Some studies concerning the thermal properties of earth-based materials have already been published. Raghavan and Martin [1] developed a model for the prediction of the conductivity of a random distribution of spheres in a continuum of different materials but the water content is not considered. Bouguerra et al. [2] 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 [3] studied the thermal properties of stabilized soil building blocks but they did not investigate the influence of the water content. Meukam et al. [4] 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. [5] studied the thermal properties of coconut fiber-based soil-cement blocks and Omubo- Pepple et al. [6] 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 [7] concerning unfired clay bricks with straw and wood chippings. Bal et al. [8] 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. They considered the composite material as solid grains in contact with air and liquid water filling the vacuum volume. Moreover, the grains are considered weakly porous with an internal porosity filled with air and liquid water. The interest of the model suggested by these authors, resides in the fine comprehension of the elementary mechanisms.

Since the local composite materials in particular are used for building and are exposed to very different meteorological

conditions, it is very important to know how their thermal conductivity vary with the water content. To be able to predict their thermal behaviour in various meteorological conditions, the aim of this study was to develop a simplified model enabling the calculation of the thermal conductivity as a function of the water content X and to valid it experimentally for some local composite materials.

2. Mathematical Models

2.1. Thermal Conductivity Models

Generally, a homogeneous composite material is composed of a solid phase (d), of water (w) and of air (a). By considering m as mass and V as volume, its composition is defined by the following parameters:

- Dry basis water content:

$$X = \frac{m_w}{m_d} \quad (1)$$

- Global porosity of the material:

$$\varepsilon = \frac{V_w + V_a}{V} = \varepsilon_a + \varepsilon_w \quad (2)$$

where

$$\varepsilon_w = \frac{V_w}{V}, \varepsilon_a = \frac{V_a}{V} \text{ and } V = V_d + V_w + V_a \quad (3)$$

According to Wiener [9], 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:

$$\lambda = \frac{1}{\frac{\varepsilon_d}{\lambda_d} + \frac{\varepsilon_a}{\lambda_a} + \frac{\varepsilon_w}{\lambda_w}} \quad (4)$$

where $\varepsilon = \varepsilon_a + \varepsilon_w$

- The parallel model:

$$\lambda = \varepsilon_d \lambda_d + \varepsilon_a \lambda_a + \varepsilon_w \lambda_w \quad (5)$$

- Hashin and Shtrikman models:

Thereafter, for isotropic mixtures, Hashin and Shtrikman [10] shown that the effective thermal conductivity is independent of pore structure and a refined analysis lead to the Hashin–Shtrikman's bound adapted by Tong et al. [11] to a three phase mixture as:

$$\lambda_{min} = \lambda_a + \frac{3\lambda_a[\varepsilon_w/(1+f_{w-a})+\varepsilon_d/(1+f_{d-a})]}{\varepsilon_a+\varepsilon_w f_{w-a}/(1+f_{w-a})+\varepsilon_d f_{d-a}/(1+f_{d-a})} \quad (6)$$

$$\lambda_{max} = \lambda_a + \frac{3\lambda_a[\varepsilon_w/(1+f_{w-d})+\varepsilon_a/(1+f_{a-d})]}{\varepsilon_d+\varepsilon_w f_{w-d}/(1+f_{w-d})+\varepsilon_a f_{a-d}/(1+f_{a-d})} \quad (7)$$

where

$$f_{w-a} = \frac{3\lambda_a}{\lambda_w - \lambda_a} \quad (8a)$$

$$f_{d-a} = \frac{3\lambda_a}{\lambda_d - \lambda_a} \quad (8b)$$

$$f_{w-d} = \frac{3\lambda_d}{\lambda_w - \lambda_d} \quad (8c)$$

$$f_{a-d} = \frac{3\lambda_d}{\lambda_a - \lambda_d} \quad (8d)$$

In the literature, several authors proposed models, as a function of the parallel configuration and of the series configuration, to estimate the effective thermal conductivity of a composite material. Among these authors, we can notice:

- The Beck's model [12]

$$\lambda = \sqrt{\lambda_{series} \lambda_{parallel}} \quad (9)$$

- The Krischer's model [13]

$$\lambda = \frac{\lambda_{series} \lambda_{parallel}}{A \lambda_{series} + (1-A) \lambda_{parallel}} \quad (10)$$

where A is a constant depending on material.

- The Woodside and Mesmer's model [14]

$$\lambda = \lambda_{series}^\alpha \lambda_{parallel}^{1-\alpha} \quad (11)$$

But among these models, the model of Ingersoll [15] and that of Bal et al. [8] were the more physical models.

- Ingersoll [15]

This author considered that, water in a parallel arrangement with air is in series with the solid structure:

$$\lambda = \left(\frac{1-\alpha}{\lambda_d} + F \frac{\alpha}{\lambda_{a,w}} \right) \quad (12)$$

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

- Bal et al. [8]

$$\lambda = \frac{V_{i+g} \lambda_{i+g} + V_v \lambda_v}{V_i + V_g + V_v} \quad (13)$$

where

$$\lambda_{i+g} = \frac{V_g + V_g + V_v \lambda_v}{\frac{V_i}{\lambda_i} + \frac{V_g}{\lambda_g}} \quad (14a)$$

$$\lambda_v = \lambda_i = \frac{\lambda_w V_{iw} + \lambda_a V_{va}}{V_{vw} + V_{va}} \quad (14b)$$

$$\lambda_g = \frac{\lambda_s V_s + \lambda_w V_{gw} + \lambda_a V_{ga}}{V_s + V_{gw} + V_{ga}} \quad (14c)$$

$$V = \frac{(1+X)(1+Y)}{\rho_s(X,Y)} \quad (15a)$$

$$V_s = (1 - \varepsilon)V \quad (15b)$$

$$V_{gv} = \frac{\varepsilon_g V_s}{1 - \varepsilon_g} \quad (15c)$$

$$V_w = \frac{X(1+Y)}{\rho_w} \quad (15d)$$

$$V_{va} = \frac{\varepsilon V - V_g - (V_w - V_{gw})}{1 + \alpha} \quad (15e)$$

The modelled thermal conductivity λ can be calculated if the porosity ε and the densities ρ_s , ρ_w have been previously measured. Moreover the unknown parameters λ_s , ε_g and α of the model must be identified.

With this model we have the fine comprehension of the

elementary mechanisms. However, its use is not always suitable, in particular in the case of an application with for goal the taking into account of thermal conductivity in the energy saving in the building in unfavourable period. Moreover, to consider porosity as a parameter supposes that the material does not undergo shrinkage during decreasing of its water content.

2.2. Proposed Models

The most physical models suggested in the literature were not explicitly a function of the water content. To elaborate on the proposed models, we considered that the material was constituted of a solid structure with density ρ_d and volume V_d , pores of which are occupied by water liquid with density ρ_w and volume V_w then humid air with density ρ_a and volume V_a .

Furthermore, by considering m as the hygroscopic material mass at a given time, m_w its water liquid mass, m_v its water vapour mass, m_a its humid air mass, m_{as} its drying air mass and m_d its solid structure mass, it can be written that:

$$m_a = m_v + m_{as} \quad (16a)$$

$$V_a = V_v + V_{as} \quad (16b)$$

$$\rho = \frac{m_d + m_w + m_a}{V_d + V_w + V_a} \quad (17a)$$

$$\rho_a = \frac{m_v + m_{as}}{V_v + V_{as}} \quad (17b)$$

$$\rho_w = \frac{m_w}{V_w} \quad (17c)$$

$$\rho_d = \frac{m_d}{V_d} \quad (17d)$$

$$x = \frac{m_a}{m_w + m_a} \quad (18a)$$

$$\alpha = \frac{m_a}{m_d} \quad (18b)$$

$$\beta = \frac{\rho_w}{\rho_d} \quad (18c)$$

$$\gamma = \frac{\rho_a}{\rho_d} \quad (18d)$$

ρ_a, ρ_w, ρ_d : densities of humid air, liquid water and solid material respectively;

x : mass fraction of the humid air in the fluid phase.

2.2.1. Complete Model

We supposed water liquid, in a series arrangement with humid air, was in parallel with the solid structure. Thus, by considering the equivalent represented in figure 1, the equivalent thermal resistance R of the material is:

$$\frac{1}{R} = \frac{1}{R_d} + \frac{1}{R_{w,a}} \quad (19)$$

where

$$\frac{1}{R_{w,a}} = \frac{1}{R_w + R_a} \quad (20a)$$

$$R = \frac{e}{\lambda S} \quad (20b)$$

$$R_d = \frac{e_d}{\lambda_d S_d} \quad (20c)$$

$$R_w = \frac{e_w}{\lambda_w S_w} \quad (20d)$$

$$R_a = \frac{e_a}{\lambda_a S_a} \quad (20e)$$

$$S = S_s + S_w \quad (21a)$$

$$S_w = S_a \quad (21b)$$

$$e = e_d = e_{w,a} = e_w + e_a \quad (21c)$$

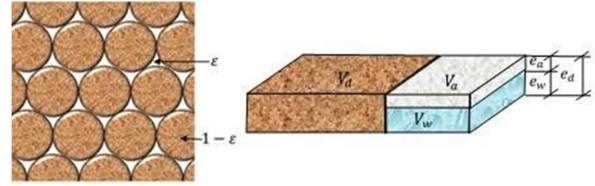


Figure 1. Model of the elementary volume of the material.

Using relations (19) to (21), the equivalent thermal conductivity of the material is:

$$\lambda = \varepsilon_d \lambda_d + \varepsilon \lambda_{w,a} \quad (22)$$

$$\varepsilon_d = \frac{V_d}{V} = 1 - \varepsilon \quad (23a)$$

$$\lambda = \varepsilon_d \lambda_d + \varepsilon \lambda_{w,a} = \lambda = \lambda_d + \varepsilon (\lambda_{w,a} - \lambda_d) \quad (23b)$$

In other respects, water liquid was in a series arrangement with humid air so that:

$$\varepsilon'_w = \frac{V_w}{V_w + V_a} \quad (24a)$$

$$\varepsilon'_a = \frac{V_a}{V_w + V_a} \quad (24b)$$

$$\lambda_{w,a} = \left(\frac{\varepsilon'_w}{\lambda_w} + \frac{\varepsilon'_a}{\lambda_a} \right)^{-1} \quad (24c)$$

Finally, thermal conductivity of material can be obtained using these two equations:

$$\varepsilon = \frac{\alpha\beta + \gamma X}{\alpha\beta + \beta\gamma + \gamma X} \quad (25a)$$

$$\rho = \rho_d \frac{\beta\gamma(1+X+\alpha)}{\alpha\beta + \beta\gamma + \gamma X} \quad (25b)$$

$$\lambda_{w,a} = \left\{ \frac{1}{\rho_d + x(\rho_w - \rho_d)} \left[\frac{\rho_d(1-x)}{\lambda_w} + \frac{\rho_w x}{\lambda_a} \right] \right\}^{-1} \quad (26)$$

For this complete model, the unknown parameters that must be identified are thus: $\lambda_d, \lambda_a, \alpha, \beta$ and γ . Out of four parameters to be identified, the model presents two variables X and x to determine from the independent experiments. This leads us to elaborate a simplified model by using some assumptions.

2.2.2. Simplified Model

We assumed that vaporization front view was at the border

of material. Therefore, we have an ideal shrinkage of the material during the evacuation of water. Thus, the pores were only occupied by liquid water and in this case:

$$x = 0 \quad (27a)$$

$$\alpha = 0 \quad (27b)$$

$$\varepsilon = \frac{x}{\beta+x} \quad (28a)$$

$$\rho = \rho_d \frac{\rho_w(1+x)}{\rho_w + \rho_d x} \quad (28b)$$

Finally, only water liquid was in parallel with the solid structure. We obtained so:

$$\lambda_{mod} = \lambda_d + \frac{x}{\beta+x} (\lambda_w - \lambda_d) \quad (29)$$

For this simplified model, the unknown parameters that must be identified are thus λ_d and β .

The parameters are estimated by minimizing the sum S of the quadratic errors between the experimental thermal conductivity λ and the values calculated with equation (29):

$$S = \sum_{i=1}^n \left(1 - \frac{\lambda_{mod}}{\lambda} \right)_i^2 \quad (30)$$

where n is the number of measurements for contents.

$$R^2 = 1 - \frac{\sum_{i=1}^n (\lambda_i - \lambda_{mod_i})^2}{\sum_{i=1}^n (\lambda_i - \bar{\lambda})^2} \quad (31)$$

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:

$$MRD(\%) = \frac{100}{n} \sum_{i=1}^n \left| 1 - \frac{\lambda_{mod_i}}{\lambda_i} \right| \quad (32)$$

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

2.3. Sensitivity of Simplified Model Parameters

The sensitivity of the simplified model parameters λ_d and β is deduced from relations (34) and (35) respectively.

$$SE = \sqrt{\frac{\sum_{i=1}^n (\lambda_i - \lambda_{mod_i})^2}{n}} \quad (33)$$

$$\frac{k}{100} \lambda_d \frac{\partial \lambda}{\partial \lambda_d} = \frac{k}{100} \lambda_d \frac{\beta}{\beta+x} \quad (34)$$

$$\frac{k}{100} \beta \frac{\partial \lambda}{\partial \beta} = \frac{k}{100} \beta \frac{\lambda_d - \lambda_w}{(\beta+x)^2} \quad (35)$$

These two formulas represent the variation of the estimated value of λ induced by a relative variation of $k\%$ of respectively the parameters λ_d and β from their nominal values.

3. Results and Discussion

3.1. Experimental Results

The validation of the elaborate model was based on three types of materials: an isotropic homogeneous material (compressed soil building blocks), an isotropic composite material (laterite based bricks with 0.0611 kg_{mi}.kg_{la}⁻¹ millet waste) and an orthotropic homogeneous material (wood of oak). The experimental values of the thermal conductivity λ are obtained by Talla [16] for compressed soil building blocks, Bal et al. [8] for laterite based bricks with 0.0611 kg_{mi}.kg_{la}⁻¹ millet waste and Nadeau and Puiggali [17] for wood of oak the thermal. Figure 2 represents the experimental values of the thermal conductivity obtained for these three materials for different values of the water content (between 0 and 0.139 kg_w.kg_{db}⁻¹, 0 and 0.054 kg_w.kg_{db}⁻¹, 0.025 and 1.068 kg_w.kg_{db}⁻¹ respectively).

3.2. Validation of Proposed Model

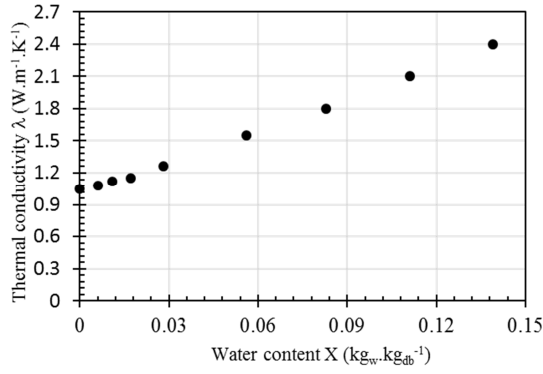
The parameters λ_d and β of proposal model were determinate, for these three materials, by minimization of the sum of the quadratic differences (equation (30)) between the theoretical value of thermal conductivity λ_{mod} calculated using equation (29) and the experimental values λ . Table 1 shows the parameters of this model fitted to the experimental thermal conductivities data of materials tested. In the same table, we have the values of the regression coefficient (R^2), the mean relative deviation (MRD) and the standard error (SE) resulting from equations (31) to (33).

Table 1. Estimated parameters of the new model for the thermal conductivity of compressed soil building blocks and comparison with experimental data.

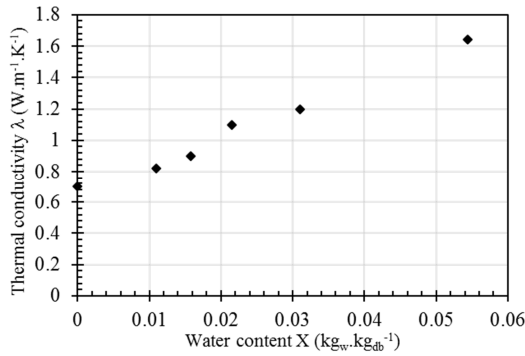
Parameters	CSBB ⁽²⁾	LBB ⁽³⁾ with 0.0611 kg _{mi} .kg _{la} ⁻¹ millet waste additive	Wood of oak
λ_w (Wm ⁻¹ K ⁻¹)	0.612	0.612	0.612
λ_w (Wm ⁻¹ K ⁻¹)	1.016	0.674	0.135
β	0.973	0.670	1.474
MRD (%)	1.01	3.61	4.78
R^2	0.998	0.985	0.979
SE (Wm ⁻¹ K ⁻¹)	0.021	0.037	0.017

⁽²⁾CSBB: Compressed soil building blocks

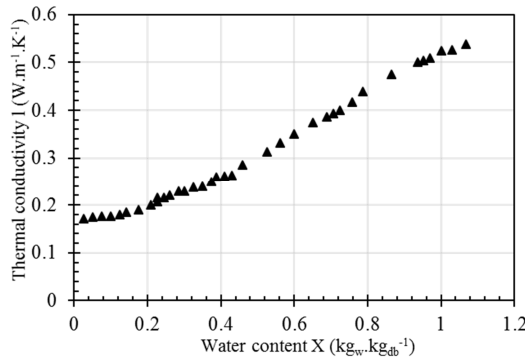
⁽³⁾LBB: Laterite based bricks



(a) Compressed soil building blocks, Talla [16]



(b) Laterite based bricks with 0.0611 kgmi.kgla⁻¹ waste additive, Bal et al. [8]



(c) wood of oak, Nadeau and Puiggali [17]

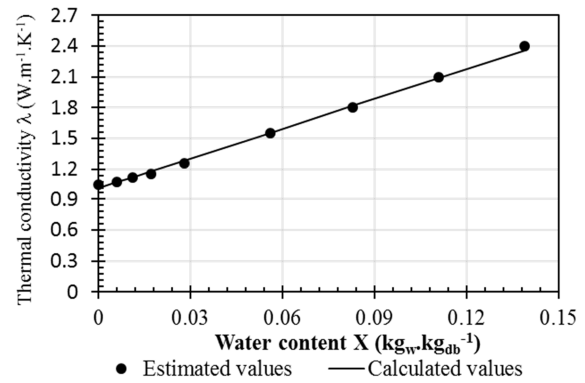
Figure 2. Experimental results of thermal conductivity for different materials.

3.3. Discussion

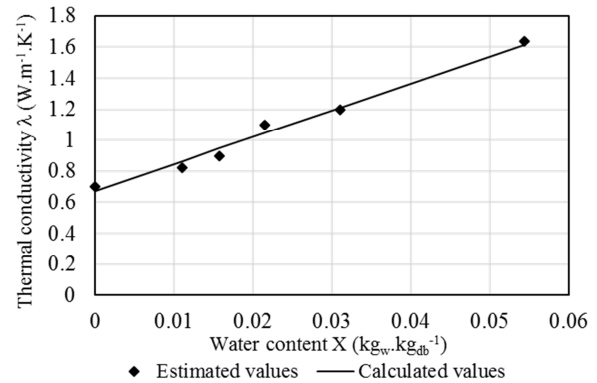
The mean relative deviation between the experimental values and the theoretical values calculated with relation (32) was 1.01%, 3.61% and 4.78% respectively for compressed soil building blocks, laterite based bricks with 0.0611 kgmi.kgla⁻¹ millet waste and wood of oak. Moreover, the regression coefficient (R^2) is 0.998, 0.985 and 0.979 in the order of materials tested. The results obtained, by using the elaborate model, are very satisfying for the two isotropic materials (compressed soil building blocks and laterite based bricks with 0.0611 kgmi.kgla⁻¹ millet waste) but less for orthotropic material (wood of oak). All the experimental and theoretical values are represented on figure 3.

The different models described by equations (4) to (13)

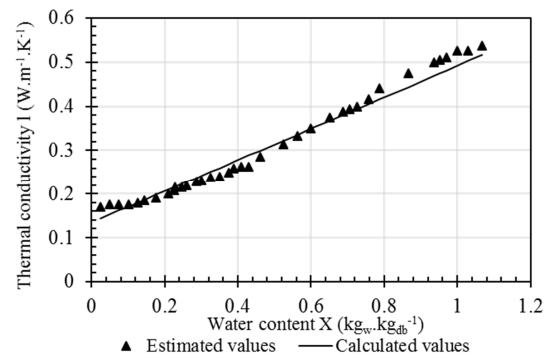
were tested by Bal et al. [8] for laterite based bricks with 0.0611 kgmi.kgla⁻¹ millet waste additive. Table 2 gives the values of the estimated parameters of each model both with the mean deviation between the experimental and the modelled values of the thermal conductivity according to these authors. The results show that, considering the classical models described by equations (4) to (12), only the Woodside and Messmer's model and the Krischer's model lead to a satisfying representation of the variation of the thermal conductivity as a function of the water content. Nevertheless, the estimated values of the thermal conductivity of the solid fraction λ_d are greater than 100 Wm⁻¹.K⁻¹. These values have not any physical meaning.



(a) Compressed soil building blocks, experimental values from Talla [16]



(b) Laterite based bricks with 0.0611 kgmi.kgla⁻¹ millet waste additive, experimental values from Bal et al. [8]



(c) wood of oak, experimental values from Nadeau and Puiggali [17]

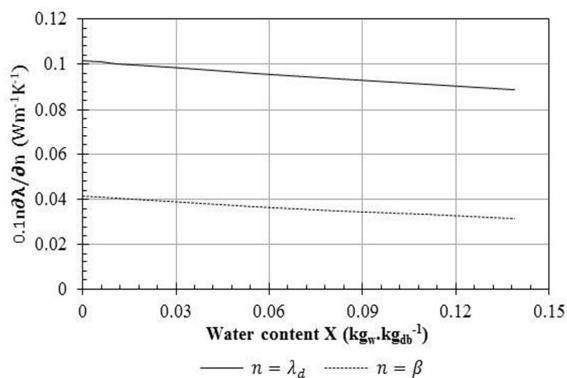
Figure 3. Experimental results and calculated of thermal conductivity for different materials.

Table 2. Estimated parameters of the models and mean relative deviation between experimental and modelled thermal conductivities for laterite based bricks with 0.0611 kg_{mi}.kg_{la}⁻¹ millet waste additive, Bal et al. [8]

Model	λ_d (Wm ⁻¹ K ⁻¹)	α	F	ε	ε_g	MRD (%)
Parallel	1.63	-	-	-	-	21.7
Series	8.6×10^7	-	-	-	-	91.4
HS _{min}	0.79	-	-	-	-	88.7
HS _{max}	1.90	-	-	-	-	20.5
Beck	21.7	-	-	-	-	16.2
Woodside	3.0×10^{19}	0.947	-	-	-	7.8
Krischer	141	0.0868	-	-	-	6.7
Ingersoll	1.88	0.034	1.72	-	-	15.5
Bal	3.57	0.0297	-	0.39	0.0224	4.0

Tables 1 and 2 show that the mean relative deviation of 3.6% resulting from the elaborate simplified model (3.6%) is smaller than the deviation of 4.0% given by the model of Bal et al. [8]. Moreover, the thermal conductivity of the solid fraction $\lambda_d = 0.674$ Wm⁻¹K⁻¹ resulting of the developed model corresponds to true-to-life description; the experimental value of the solid fraction obtained by Bal et al. [8] was $\lambda_d = 0.70$ Wm⁻¹K⁻¹. The value resulting from the model of these authors ($\lambda_d = 3.57$ Wm⁻¹K⁻¹) deviates relatively from the experimental value. The porosity taken as a constant in their model, when the material would undergo a shrinkage by losing water, could be a justification of this difference.

In other respects, the knowledge of the second parameter β of developed model informs us about the density of the solid fraction. If $\beta < 1$, case of isotropic materials examined in this article, the density of the solid fraction is higher than the density of water. In the contrary case, case of orthotropic material examined in our work, the density of the solid fraction is lower than the density of water.

**Figure 4.** Residual variation of λ induced by a relative variation of 10% of each parameter for compressed soil building blocks.

Formulas (34) and (35) represent the variation of the estimated value of λ indices by a relative variation of $k\%$ of respectively the parameters λ_d and β from their nominal values. For example, Fig. 4 represents this sensitivity for compressed soil building blocks. It shows that the simplified model is less sensitive to parameter β than with parameter λ_d : a relative variation of 10% on the parameter λ_d has an effect 2.45 times more significant than on the parameter β ,

on the simulated values. However, the sensitivity as of these two parameters on the simulated values of thermal conductivity is overall low: maximum 0.1 for λ_d and 0.04 for β . At last, we note that the two curves of sensitivity decrease when the water content increases.

4. Conclusion

In this work, an adapted simplified model has been developed to predict the thermal conductivity $\lambda(X)$ of the hygroscopic materials buildings as a function of water content X . Three hygroscopic materials buildings were tested and the prediction capability of this simplified model was verified. Very good results were obtained in both correlation and prediction of thermal conductivity, particularly for isotropic materials. These good results validated the fundamental assumption which guided the development of the simplified model. We assumed that the material underwent an ideal shrinkage during the evacuation of water, with front view of vaporisation at the border of sample. The new model is easy to use. The suitability of this simplified model for other hygroscopic materials buildings will be further studied.

Acknowledgements

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Abbreviations

Letters

e	thickness (m)
m	mass (kg)
V	volume (m ³)
X	Dry basis water content (kg _w kg _{db} ⁻¹)

Greek letters

λ	thermal conductivity (Wm ⁻¹ K ⁻¹)
ε	porosity
ρ	density (kgm ⁻³)

Subscripts

a	air
d	solid phase
db	dry basis
la	laterite
mi	millet waste
mod	model
w	Water phase

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