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Full Length Research Paper

Mass diffusivity measurements of two cement based materials

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The main purpose of a building is to ensure thermal comfort to its occupants. The present work is a contribution to the improvement of the comfort and relates to the characterization of local materials used in Benin. The authors determined the mass diffusivity of the wood composite material and cement-stabilized laterite, as a function of its water content. The experimental device is designed around a magnetic suspension balance. This precision balance can operate without direct contact with the specimen. The temperature and the relative humidity of the measuring chamber are controlled. The mass of the sample is measured at intervals of 30 s. The diffusivity is obtained from the slope of the transient mass change data. From the analysis of the results, it follows that the cement-stabilized laterite has a mass diffusivity lower than that of the wood composite material. Also, the materials studied can allow the realization of hygrothermic buildings with low cost.

Key words: Heat, humidity, composite wood-cement, stabilized laterite, slope method, mass diffusivity.

INTRODUCTION

The use of laterite stabilized with cement or cement-sawdust composite in construction, allows the building insulation and control of indoor temperature and relative humidity. This helps to minimize the energy consumption of the building. These materials are hygroscopic and they perform as natural regulator of moisture in the housing. Simultaneous heat and mass transfers inside hygroscopic materials need to be controlled and taken into account when designing the building. This allows achieving adequate and sustainable life as pointed out by Houngan (2008).

This paper focuses on the determination of the mass

diffusivity of laterite stabilized with cement and composite cement-sawdust as a function of the water content. Finally an explanation was proposed for non-fickian behavior of the materials as (Olek et al., 2011) observed for high relative humidity.

MATERIALS AND METHODS

Sample preparation

Samples of cement stabilized laterite and wood-cement

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Table 1. Materials dimensions and measurement conditions.

Material	Thickness (mm)	Section (mm × mm)	Temperature (°C)	Relative Humidity (%)
Wood cement	5.0	20.0 × 20.0	30.0	0 – 90
Stabilized laterite	5.0	20.0 × 20.0	30.0	0 – 90

Table 2. Materials composition (Tcheouali, 2002; Tch ouali et al., 2002).

Material	Water (kg)	Cement (kg)	Sawdust (kg)	Laterite (kg)
Wood cement	15.0	10.0	8.8	-
Stabilized laterite	12.0	5.0	-	20.0

Table 3. Characteristics of the composed portland cement used.

Commercial name	CPJ 35		
Color	Gray		
Absolute density	3.1		
Apparent voluminal mass (kg/l)	1.17		
Setting time	3 h		
Grains diameter	80 µm		
Specific area	3100		
Real resistance class at 28 days	32 MPa		
Constitutive element of cement	Clinker (65%)	Gypsum (5%)	Pozzolana (30%)

composite used for sorption measurements are of parallelepiped shape (Table 1); the composite material composition is given on Table 2. The cement used is the composed Portland cement CPJ 35 from CIMBENIN factory in Benin. Its characteristics are presented in Table 3.

Experimental set

The experimental device showed on Figure 1. It allows to measure the kinetics of the adsorption/desorption processes. The principle is based on a regular weighing of the sample introduced into a chamber with well-defined climate conditions of temperature and relative humidity. These parameters are controlled using an electronic scale with magnetic suspension as described by Dreisbach and Losch (2000) and (Lee et al., 2013). The balance is used to perform regular calibrations of the system during measurements. This avoids drifts and do not affect the experimental conditions. Measuring cell relative humidity is controlled using two electronic mass flow controllers connected to a humidity generator.

Saturated air and dry air are mixed at predetermined proportions to obtain the desired relative humidity. The mixture flow is then injected through an insulated tube into the measuring chamber. The laminar flow which takes place ensures the stability of the measures.

The temperature of the system is controlled with water supplied by a thermocryostat which operates at a maximum flow rate of 18 L/min and temperature ranging from -25°C and 150°C. The measuring cell and humid air generator are thermally insulated with

polymethyl methacrylate and a layer of polyurethane foam; this ensure thermal stability at ±0.02°C. A Honeywell « 3602 C » sensor is used to measure temperature and relative humidity inside the measuring chamber. A J type thermocouple is used to control environmental conditions. The device is controlled and managed by a computer.

THEORY OF DETERMINATION OF DIFFUSION COEFFICIENT BY THE SLOPE METHOD

According to Fick's second law, the diffusion equation in the samples of the materials tested can be written as (Crank, 1975; Tamene, 2012; Belkaid, 2012; Remond and Almeida, 2011):

$$\frac{\partial X}{\partial t} = \text{div}(\overline{\overline{D}} \text{grad}X) \quad (1)$$

with X being the water content, t the time and $\overline{\overline{D}}$ the mass diffusivity tensor.

For a one-dimensional transfer depending on the thickness of the sample, and assuming that D is constant over this thickness and on each level or increment of relative humidity, the above equation becomes:

$$\frac{\partial X}{\partial t} = D \frac{\partial^2 X}{\partial x^2} \quad (2)$$

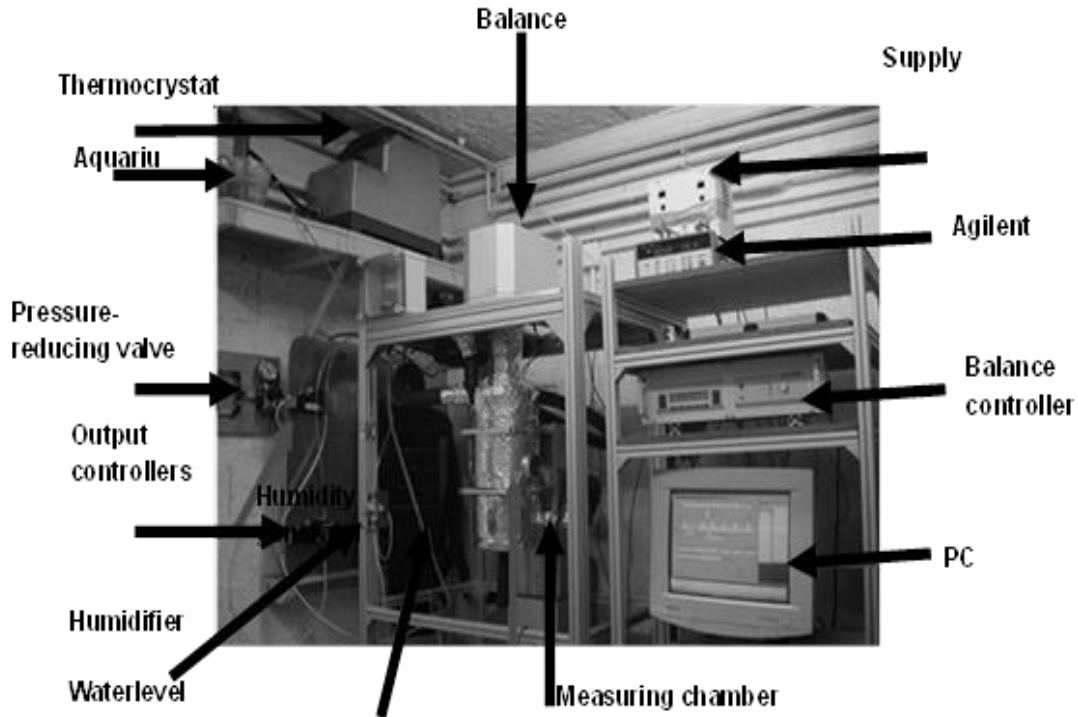


Figure 1. The experimental device.

Assuming that water content is always very close to the equilibrium value on the sample exchange face, initial and boundary conditions are the following:

- at $t=0, \forall x, X = X_i$ initial water content of hygroscopic material;
- for $t>0, |X|_{x=0 \text{ et } x=L} = X_f$ final water content of the sample.

Let's define the dimensionless water content X^* by:

$$X^* = \frac{X - X_i}{X_f - X_i} \quad (3)$$

When the authors consider (3), Equation (2) can be rewritten:

$$\frac{\partial X^*}{\partial t} = D \frac{\partial^2 X^*}{\partial x^2} \quad (4)$$

By neglecting the resistance to external mass transfer, initial and boundaries conditions become:

$$t>0, X^*|_{x=0 \text{ and } x=L} = 1 \quad (5)$$

Assuming that the medium is semi-infinite, the partial differential Equation (4) associated with boundary conditions (5) can be described in terms of a single variable

$$\eta = x/\sqrt{4Dt}$$

Some transformations, the solution of Equation (4) appears in the form:

$$X^* = 1 - \text{erf}(\eta) \text{ where } \text{erf}(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\eta \text{erf}(-\eta^2) d\eta \quad (6)$$

erf is the error function.

The flux density which passes through an exchange side of the sample is given by Fick's law:

$$q = -\rho D \left. \frac{\partial X}{\partial x} \right|_{x=0} \quad (7)$$

ρ is the specific gravity of the dry environment.

The change in the sample mass versus time corresponds to the integration of the flow between initial time zero and t:

$$\Delta m(t) = \int_0^t S \cdot q dt \quad (8)$$

S is the section area of the sample.

Considering the whole thickness of the sample (both sides) and Equations (6), (7) and (8), the analytical solution (9) shows that the mass increase in the sample varies as the square root of time.

$$\frac{\Delta m(t)}{\Delta m_{max}} = \frac{4}{L} \sqrt{\frac{D}{\pi}} \sqrt{t} \quad (9)$$

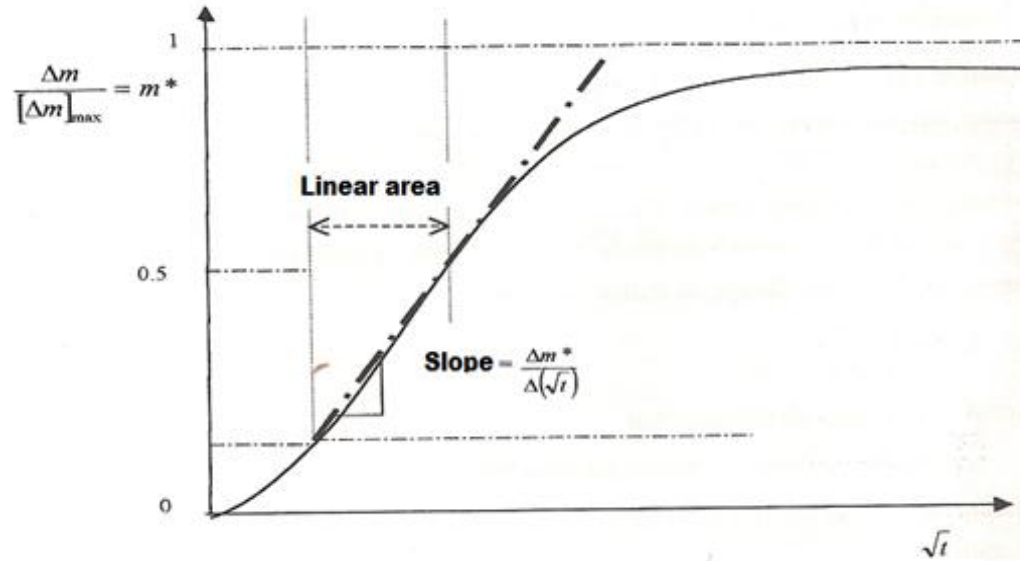


Figure 2. Determination of the diffusion (Wadso, 1993).

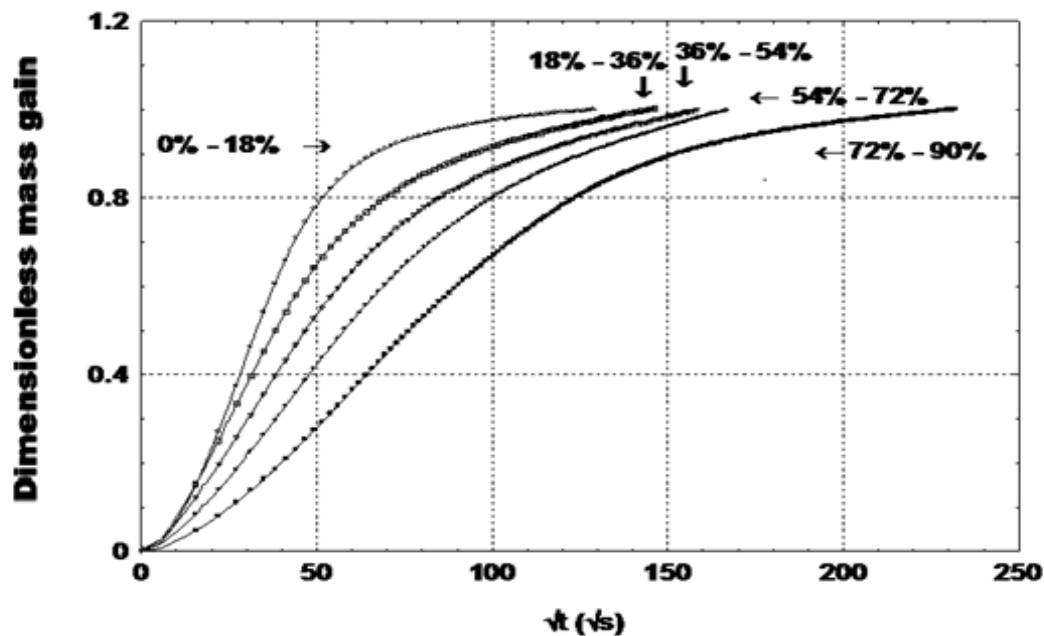


Figure 3. Dimensionless mass increase of wood-cement composite.

where $\Delta m(t)$ and Δm_{max} represent the increase (or decrease)

of the sample mass at time t and at equilibrium. From Equation (9), it is possible to determine D with the experimental measures: the assumption of semi-infinite medium is only valid for "short time".

After observation of the linear part of the curve of the dimensionless mass plotted versus the square root of time, we determined the slope by considering the part of the curve between 0.1 and 0.5 for dimensionless mass (Figure 2).

Figure 3 shows the dimensionless mass increase of the

cement-wood composite vs square root of time for each range of water content.

RESULTS

The kinetics of sorption

The tests are performed in unsteady state. Samples

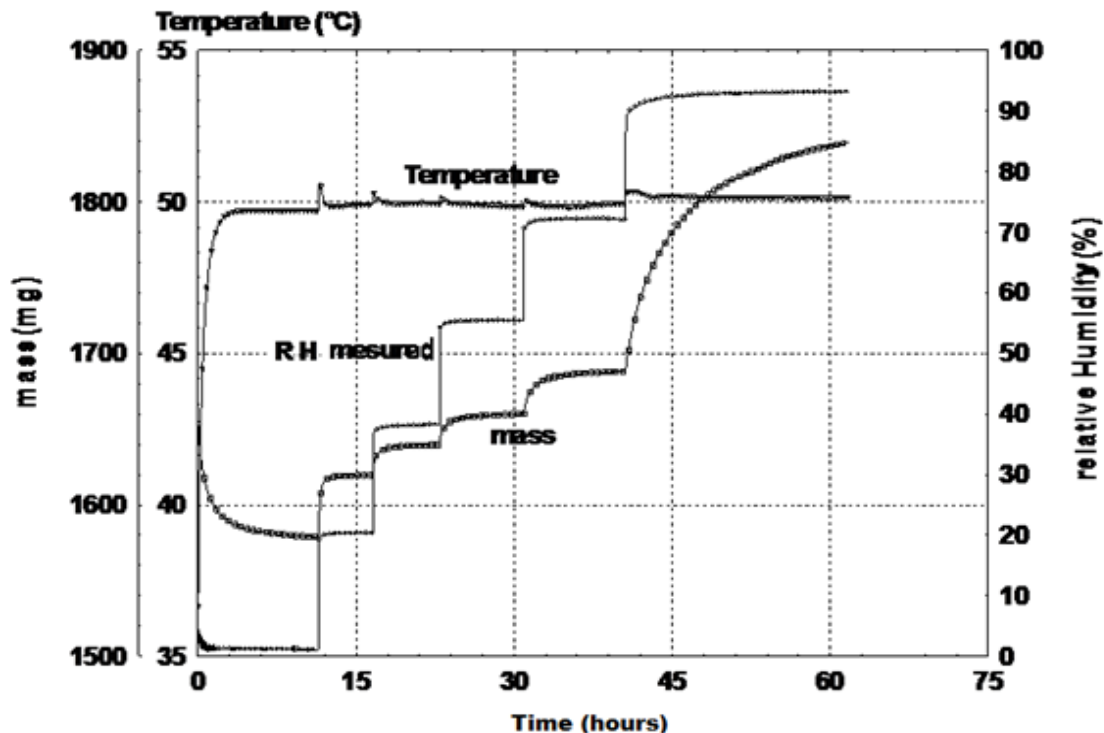


Figure 4. Kinetics of sorption of wood-cement composite.

previously are brought to equilibrium in a controlled relative humidity environment, (0 or 90%) in the climatic chamber. Then, they undergo a sudden change of this parameter: Higher humidity for adsorption and lower for desorption processes which follows the weighing of the sample mass at given time step.

Figures 4 and 5 show respectively the kinetics of adsorption process of the composite cement-sawdust and the stabilized laterite at 30°C for various levels of relative humidities (0, 18, 36, 54, 72, 90%). It is shown on these graphs a complete concordance between the given theoretical humidity and that measured. The temperature is very stable; this is a necessary factor for reliable kinetics of sorption.

The authors also note that 10 h at least is required for a 5 mm thickness laterite sample stabilized with cement to become stable (Figure 3). It should also be noted that when the relative humidity increases, the time needs to reach stabilization becomes higher. This can be explained by non-Fickian phenomena (Olek et al., 2011; Remond and Almeida, 2011; Patrick et al., 2015), which are due to the behavior of macromolecules layers. For high water contents, a molecular reorganization is required to free the sorption regions. This phenomenon is also present on the kinetics of sorption of wood-cement composite (Figure 4). From these kinetics, it is possible to deduce the mass diffusivity of samples in a transient regime.

Tables 4 and 5 present the mass diffusivity values of

the two composites, wood-cement and laterite stabilized with cement; this mass diffusivity is computed in adsorption. Figure 6 illustrates the variations of mass diffusivity obtained for these two materials as function of the water content at a temperature of 30°C.

DISCUSSION

The analysis of the Figure 6 shows that the mass diffusivity of cement-wood composite decreases when the water content increases. As for the material of laterite stabilized with cement, the author find that the mass diffusivity in adsorption increases with the water content, reaching a maximum around 1.8% of water content and then decreases with the water content. Mass diffusivities of the composite wood-cement for different water contents are higher than those of the stabilized laterite in adsorption at a temperature of 30°C (Figure 6). These differences may be related to the composition of the cement matrix of these materials. In fact, the cement-wood composite has a low density and higher porosity according to Baroghel-Bouny (2007), than the laterite stabilized with cement.

The values of mass diffusivities obtained experimentally with these materials are in the range of 10^{-10} to 2×10^{-9} m²/s, these values indicate that moisture transfers in these materials involve very slow process.

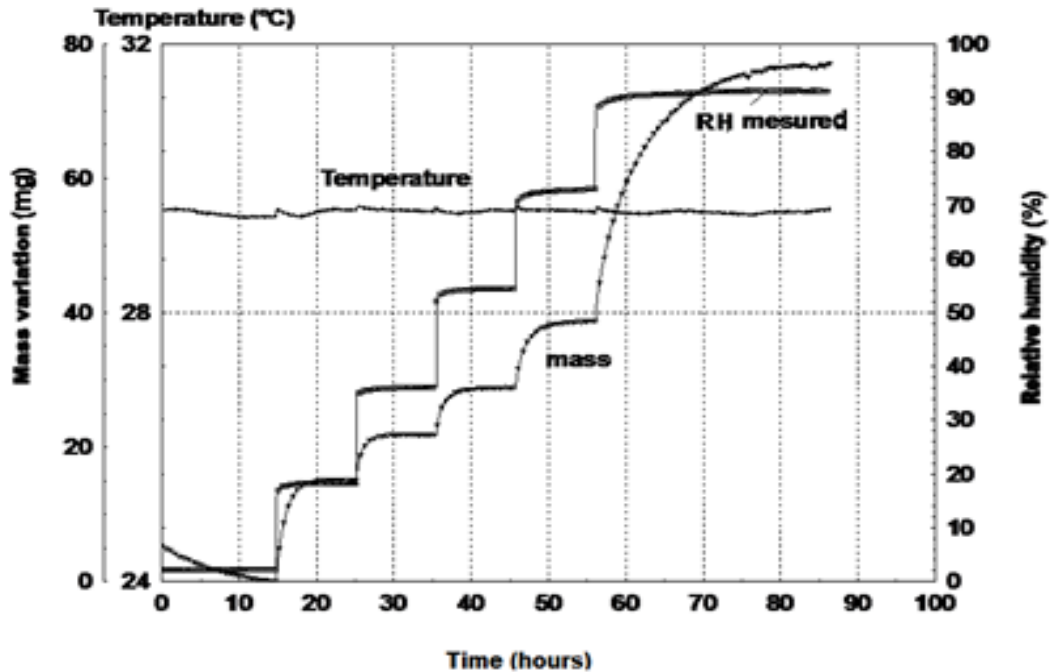


Figure 5. Kinetics of sorption of stabilized laterite.

Table 4. Mass diffusivity in adsorption for cement-wood composite.

Wood-cement composite, thickness 5.07 mm adsorption		
Increment of RH at T = 30°C (%)	Equilibrium water content (%)	Diffusivity ($D \times 10^{-10} \text{ m}^2/\text{s}$)
0-18	2.8	21 ± 0.9
18-36	3.7	11 ± 0.7
36-54	4.7	7 ± 0.4
54-72	6.3	5 ± 0.2
72-90	10.2	3 ± 0.1

Table 5. Mass diffusivity in adsorption for stabilized laterite.

Laterite material stabilized with cement, thickness 5.0 mm adsorption		
Increment of RH at T = 30°C (%)	Equilibrium water content (%)	Diffusivity ($D \times 10^{-10} \text{ m}^2/\text{s}$)
0-18	1.5	6.1 ± 0.5
18-36	1.8	9.6 ± 1.7
36-54	2.2	8.9 ± 1.5
54-72	2.7	5.8 ± 0.7
72-90	4.7	1.3 ± 0.1

Moreover the low variability of the diffusivity with water content for stabilized laterite highlights the complex interaction between vapor and liquid phases in the porous network of the material. Another reason for the low diffusivity of this material may be due to the absence of natural fibers in its matrix.

Conclusion

In this research, the authors have determined the mass diffusivity of construction materials according to their water content, by using the kinetics of sorption. The computation of the diffusion coefficient from an

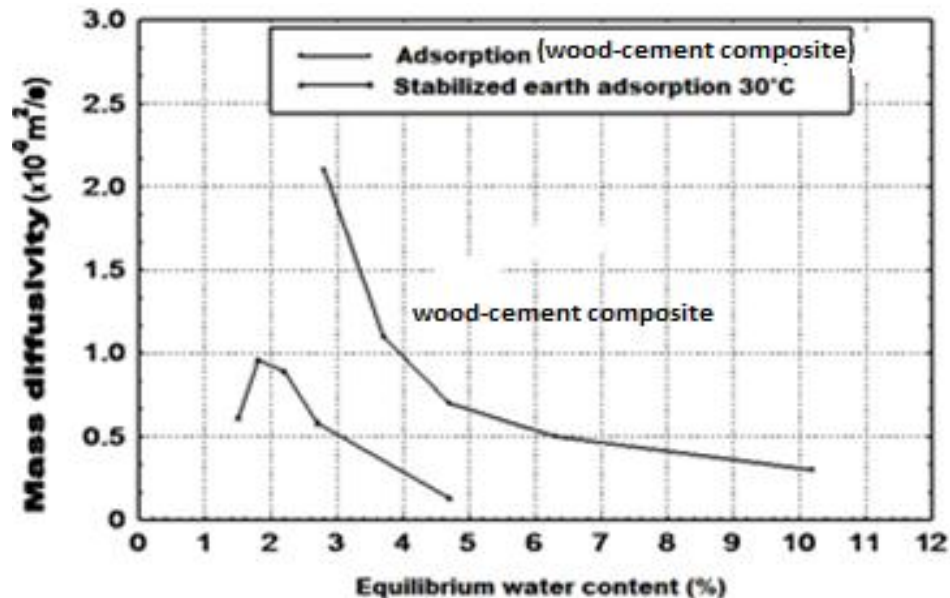


Figure 6. Variation of the mass diffusivity of the two composite materials at 30°C.

experimental sorption curve in unsteady state is made. For that the author use the slope of the curve between 0.1 and 0.5 of the dimensionless water content plotted versus the square root of the time.

For wood-cement composite we find that the mass diffusivity decreases from 2.1×10^{-9} to $0.3 \times 10^{-9} \text{ m}^2\text{s}^{-1}$ when the water content varies from 2.8 to 10.2% in adsorption at 30°C temperature. The laterite stabilized with cement has a mass diffusivity smaller than that of the wood-cement composite. Note that for the laterite material, the absence of natural fibers in its composition makes it a bit diffusive. The use of these two new construction materials could improve passive air-conditioning at a minimum cost since these aggregates are available in large quantities in Benin.

Abbreviations: **D**, Mass diffusivity (m^2s^{-1}); **L**, Sample thickness (m); **m** Mass, (kg) **pSlope** ($\text{s}^{-1/2}$); **T**, Temperature ($^{\circ}\text{C}$); **t**, Time (s); **X**, Moisture content (kg.kg^{-1}); **X***, Dimensionless moisture content xCartesian coordinate (m).

Subcripts: **dew**, Dew point; **dry**, Dry bulb; **f**, Final or equilibrium; **I**, Inlet; **p**, Specific gravity of dry environment (kg.m^{-3}); **q**, Flux density ($\text{kg.m}^{-2}\text{s}^{-1}$); **erf**, error function.

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