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Experimental study and simulation of the thermal behavior of recovered Iroko wood flour bricks stabilized with recovered high density polyethylene resin

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ABSTRACT: The use of new materials for thermal comfort is becoming more and more a priority in the construction of comfortable and economical homes. It is in this context that, in our previous work, we developed bricks based on Iroko wood flour compressed and stabilized with recycled High Density Polyethylene (HDPE) resin. There are six samples with respective contents of 10, 20, 30, 40, 50 and 60%. This article aims to present an experimental study followed by a simulation using the Cast3M calculation code of their thermal behavior. To do this, we first determined their thermophysical properties which are thermal conductivity, specific heat and thermal diffusivity. Then, after a study of the depth of heat diffusion in the different samples, we moved on to the simulation phase. It focused on the analysis of the effects of the HDPE rate, the thickness of the bricks and the air temperature. As results, the values of thermal conductivity, specific heat and thermal diffusivity, for all the composites, vary respectively from 0.310 to 0.365 $W.m^{-1}.K^{-1,}$ from 2.691 to 2.460 $kJ.kg^{-1}.K^{-1}$ and from 1.662 to 1.981.10-7$m^2.s^{-1}$. Thermal conductivity, thermal diffusivity and diffusion depth increase with increasing HDPE content; while the specific heat decreases. It also appears that for the temperature of 45°C imposed for a thickness greater than 2.7 cm, it is necessary to wait a time greater than at least 22 hours to reach a stationary state on the opposite side. From all of the above, it could be affirmed that the elaborate bricks have intrinsic capacities to be used in the construction of thermally comfortable habitats in local temperature conditions such as those of the Ivory Coast.

KEYWORDS: Iroko wood, PEHD, Bricks, Thermal, simulation, Cast3M.

1 INTRODUCTION

Global energy consumption in buildings represents approximately 40% of total energy consumption [1]. In sub-Saharan Africa, this consumption is of the order of 50 to 70% [2]. Indeed, to improve thermal comfort in a hot country like Ivory Coast, the use of air conditioning is necessary. However, savings can be made if the choice of construction materials takes into account the thermal comfort of buildings in order to reduce air conditioning needs [3]. To improve this comfort in buildings and reduce energy consumption, it is more than necessary to use particularly efficient materials, providing good thermal insulation. It is in this context that we have developed composites based on compressed Iroko wood flour and stabilized by recovered HDPE resin. The study involved six samples with respective proportions equal to 10, 20, 30, 40, 50 and 60%. The mechanical and hydraulic behaviors were evaluated in our previous studies [4]. In this work, the objective is to determine the thermophysical properties and simulate the thermal behavior using the Cast3M calculation code. To do this, we first evaluated thermal conductivity, specific heat and thermal diffusivity. The values obtained will then allow us to study the diffusion time in the bricks before carrying out a simulation. This last step focused on the influences of HDPE content, air temperature and brick thickness. The results show that the values of thermal conductivity, specific heat and thermal diffusivity, for all the composites, vary respectively from 0.310 to 0.365 $W.m^{-1}.K^{-1,}$ from 2.691 to 2.460 $kJ.kg^{-1}.K^{-1}$ and from 1.662 to 1.981.10-7$m^2.s^{-1}$. We also note that the conductivity values are close to those found in the work of Jamil et al. [5] and Emmanuel et al [3]. In addition, thermal conductivities are lower than those of compressed bricks stabilized with cement, sawdust and pozzolan, whose average values are between 0.55 to 0.95 $W.m^{-1}.K^{-1}$ [6].

According to the above, these composites could be used in the construction of economical and comfortable habitats with a compromise between mechanical, water and thermal conditions in thermal conditions like those of Côte d'Ivoire.

2 Presentation Of Study Materials

The samples studied in this work are composite bricks made from compressed Iroko wood flour and stabilized with recycled HDPE resin. They were developed during our previous work [4]. Figure 1 and Table 1 respectively present the photos and the different HDPE contents.

Table 1. Sample nomenclature

%PEHD	10	20	30	40	50	60
Samples names	CBP10	CBP20	CBP30	CBP40	CBP50	CBP60

Fig. 1. Photographs of the bricks

In this work, the specimens are homogeneous and isotropic as revealed by our previous studies [4].

3 Methods

3.1 Thermophysical Properties

Knowledge of the thermophysical properties of materials is essential for the analysis of their behavior. Indeed, one of the aspects for choosing one material over another is its ability to propagate or store heat. In this part of the study, it is a question of measuring the thermophysical characteristics which are thermal conductivity, specific heat and thermal diffusivity.

To do this, we use the KD2-Pro double needle probe [7]. In order to solve the heat transfer equation by the transient linear heat source propagation method in a semi-infinite medium, the Craslaw and Jaeger model is used by this device. This equation is published in IEEI standards |8]. This method has a simple instrumentation which allows rapid measurement. It also offers the possibility of working in-situ in various hygrometric conditions [3]. All operations are performed 20 times on each of 6 samples.

Error calculations were carried out on the measurements according to the following formula:

$$Error = \frac{v_{exp} - v_{theo}}{v_{\mathrm{e}}} \quad (1)$$

Where v_{exp}d v_{theo} are respectively the experimental and theoretical values of the measured quantity, Error is the error in the measurements.

3.2 Heat Diffusion Time

Thermal diffusivity characterizes the propagation of heat in a material. It is the ratio of thermal conductivity and specific heat mass:

$$\alpha = \frac{\lambda}{\rho C_p} \quad (2)$$

Where α ($m^2.s^{-1}$) is the thermal diffusivity, λ ($W.m^{-1}.K^{-1}$) the thermal conductivity, Cp ($KJ.kg^{-1}.K^{-1}$ the specific heat mass and ρ ($kg.m^{-3}$) the density of the test piece.

It therefore determines the speed with which heat propagates in a material. The product of the surface heat capacity by the thermal resistance defines the relationship between the stressed thickness and the heat diffusion time inside the material [9].

$$t = Q_s R \tag{3}$$

$$t = e\rho C_p \frac{e}{\lambda} \tag{4}$$

$$t = \frac{e^2}{\alpha} \tag{5}$$

$$e = (\alpha t)^{\frac{1}{2}} \tag{6}$$

Where t (h) the travel time, Qs ($J/m^2.K$) surface heat capacity, R (m^2. K/W) thermal resistance and e (m) the thickness of the brick.

We will make graphical representations of the functions e (t) for times ranging from 0 to 5.104 seconds; for each type of brick.

3.3 Simulation Of Heat Propagation

At this stage, simulations of heat propagation are carried out by illustrating the influences of the HDPE content, the thickness of the sample and the air temperature on the temperature level over time. The bricks are parallelepiped shapes with dimensions Hxlxe = 20x10x3 cm^3 placed in air at temperature T_i. We associate a Cartesian frame of reference (xoy) with the physical model. The axis [ox) is counted positive from left to right and the axis [oy) is perpendicular in the opposite direction to that of gravity (Fig. 3.).

The bricks have an initial uniform temperature by default equal to To=25°C for a relative humidity of 72%. From the time t=0 seconds to t=5.104 seconds, they are subjected to a heat input T_i greater than To on the face Si, taken as the exterior face. This results in a transfer of heat by conduction in the material of the wall Si in contact with the superheated air on the face S_f, taken as the interior face. We then witness an evolution of the temperature of S_f.

The simulation is done using the Cast3M calculation code. The elements used are of type QUA4 appropriate to the geometry of the bricks in a plan study. The height H and the thickness e are respectively meshed with 30 and 10 elements. A preliminary study showed a deviation of the system beyond these values and becomes unstable (Fig. 2. and 4.)

We will accept the following hypotheses:

- Heat transfer is two-dimensional,
- The bricks are homogeneous and isotropic,
- The thermophysical properties are constant,
- Deformations over time are assumed to be negligible.

To study the influence of the HDPE rate, temperature measurements are taken 20 times from each sample. The same goes for the other measures.

Regarding the effect of thickness, we vary it by 1 cm, 1.5 cm, 2 cm, 2.5 cm and 2.7 cm. It focused on the CBP10 sample. A preliminary study showed that beyond 2.7 cm, the maximum temperature Tmax=Ti is not reached for approximately one day (24 hours).

The data obtained by the calculation in the Cast3M calculation code are reported in MatLab to make graphical representations which will be the subject of analysis.

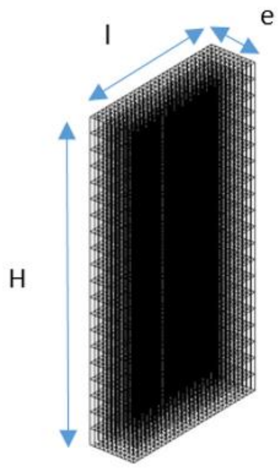

Fig. 2. 3D mesh view of the brick

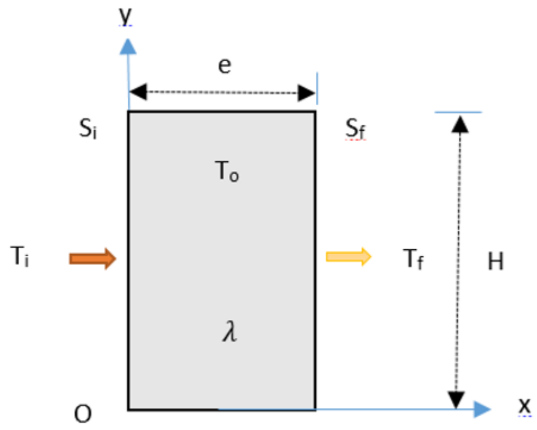

Fig. 3. Physical model

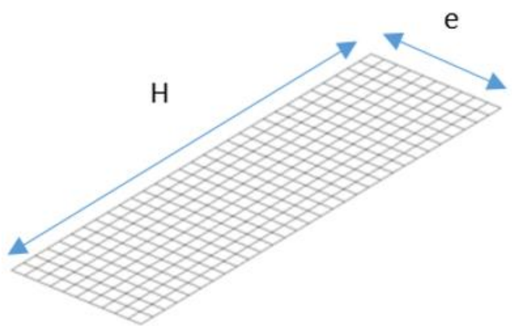

Fig. 4. 2D meshed view of the brick

4 Results And Discussions

4.1 Thermophysical Properties

Table 2 provides the experimental and theoretical values of thermal conductivities, specific heats and thermal diffusivities of the 6 different brick samples. We notice that the increase in density increases the thermal conductivity and thermal diffusivity. However, it reduces the specific heat.

Figure 5 shows an increase in conductivity as the HDPE content increases. This increase is due to the fact that the presence of HDPE resin in the matrix reduces porosity and air pockets at the interstices [4]. This results in a reduction in the thermal resistance of the material [9]. However, in Figure 6, we see a decrease in the specific heat with the increase in the HDPE content. The increase in conductivity automatically leads to a decrease in heat because the two quantities are inversely related. Figure 7 also shows that the thermal diffusivity increases with increasing HDPE content. This is completely normal because the increase in conductivity makes the composite more and more diffusive.

Thermal conductivities vary from 0.3 to 0.365 $Wm^{-1}K^{-1}$ for all samples. These values are close to those found by Y. Jamil et al. [5] and Emmanuel O [3]. They are lower than those of compressed bricks stabilized with cement, sawdust and pozzolan, whose average values are between 0.55 and 0.95 $Wm^{-1}K^{-1}$ [6]. This shows their good thermal resistance.

Table 2. Experimental and theoretical values of thermophysical properties

Samples	ρ (kg/m³)	λ(W.m⁻¹.K⁻¹)			C_p (kJ.kg⁻¹.K⁻¹)			α(10⁻⁷.m².s⁻¹)		
		Exp. Val.	Theo. Val.	Error	Exp. Val.	Theo. Val.	error	Exp. Val.	Theo. Val.	Error
CBP10	691.23	0.310	0.302	0.026	2.691	2.660	0.011	1.662	1.642	0.012
CBP20	709.11	0.319	0.314	0.015	2.642	2.620	0.008	1.710	1.690	0.011
CBP30	721.91	0.333	0.327	0.018	2.61	2.580	0.011	1.780	1.755	0.014
CBP40	741.20	0.342	0.339	0.008	2.573	2.540	0.012	1.850	1.800	0.027
CBP50	766.97	0.360	0.352	0.022	2.524	2.500	0.009	1.905	1.835	0.038
CBP60	816.68	0.365	0.364	0.002	2.491	2.460	0.012	1.981	1.871	0.058

Theoretical Value: Theo. Val., Experimental Value: Exp. Val.

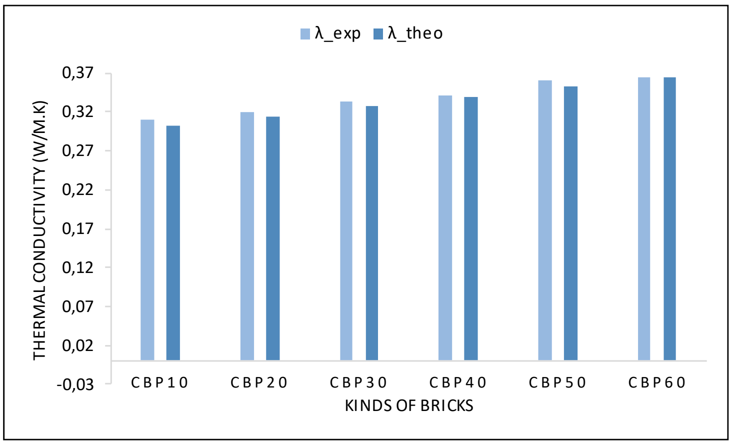

Fig. 5. Variation of experimental and theoretical thermal conductivities depending on brick type

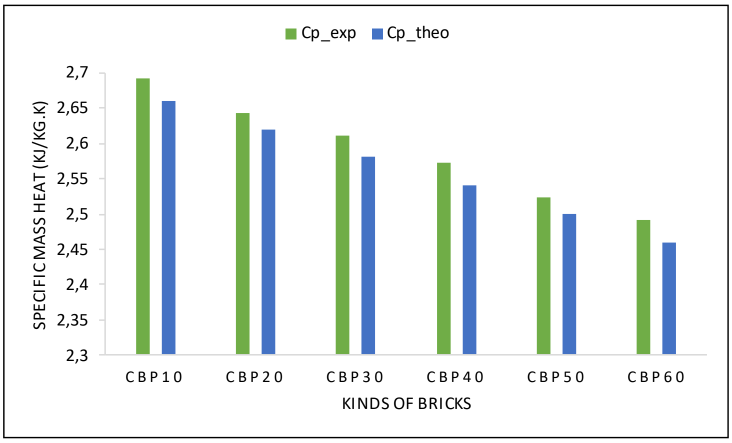

Fig. 6. Variation of experimental and theoretical specific heats depending on brick type

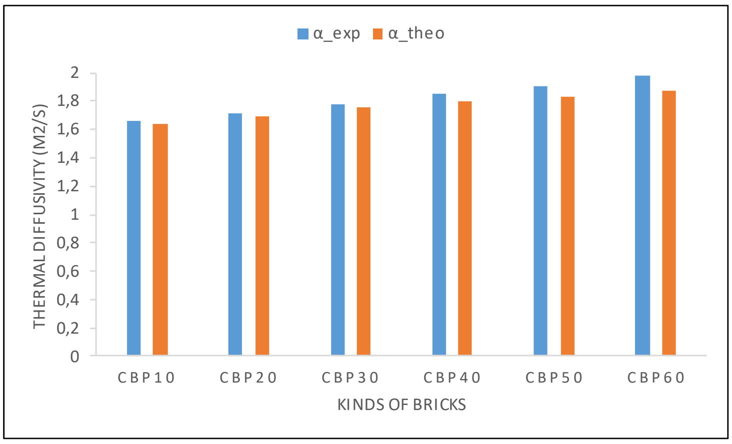

Fig. 7. Variation of experimental and theoretical thermal diffusivities depending on brick type

The errors calculated on the different measurements are low. They thus attest to the homogeneity of the samples.

4.2 Heat Diffusion Depth

Figure 8 shows the evolution of the depth of heat diffusion following the thickness of the brick over time. We note an increase in this depth over time. For a period of 12 hours, the diffusion goes from a depth of 0 to 4.8 cm maximum for all samples. The diffusion, at each moment, is larger and smaller for the CBP60 and CBP10 type bricks respectively. This means that increasing the HDPE content increases the thermal penetration capacity of the composites. For example, for an exposure time of 12 hours, the characteristic thicknesses achieved are 4.3 cm, 4.4 cm, 4.5 cm, 4.6 cm and 4.8 cm respectively for samples CBP10, CBP20, CBP30, CBP40, CBP50 and CBP60. We observe that there is not too big a difference between the diffusion behaviors of the different materials. This is well confirmed by the experimental study. From all these results, we can say that whatever the sample, the depth of heat diffusion is less than 5 cm over a daily cycle of 12 hours of sunshine. It could be said that these bricks can be considered thermal insulators on the aforementioned time scale.

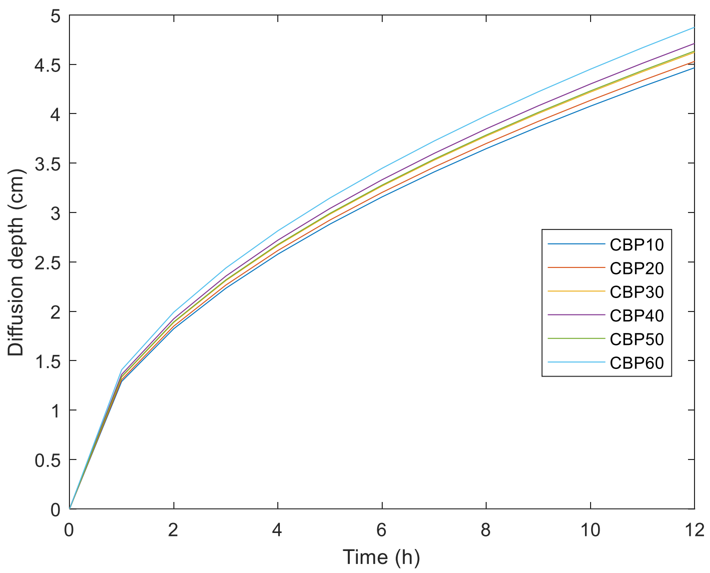

Fig. 8. Depth of heat diffusion over time

4.3 Simulation Of Heat Propagation

4.3.1 Influence Of HDPE Content

In Figure 9, the evolution of the surface temperature S_f is presented for each sample in this study. For every 6 bricks, the temperatures on this face increase over time to reach a constant value close to the temperature T_i imposed on S_i. Thus, after 9 hours 40 minutes of exposure, the bricks reach the same temperature value. We note that the increase in temperatures over time is all the more significant as the heat capacity of the material is low. However, at the S_f face, the temperature reached in steady state is all the higher as the thermal conductivity of the sample is high. This result is corroborated by the analysis of thermophysical properties.

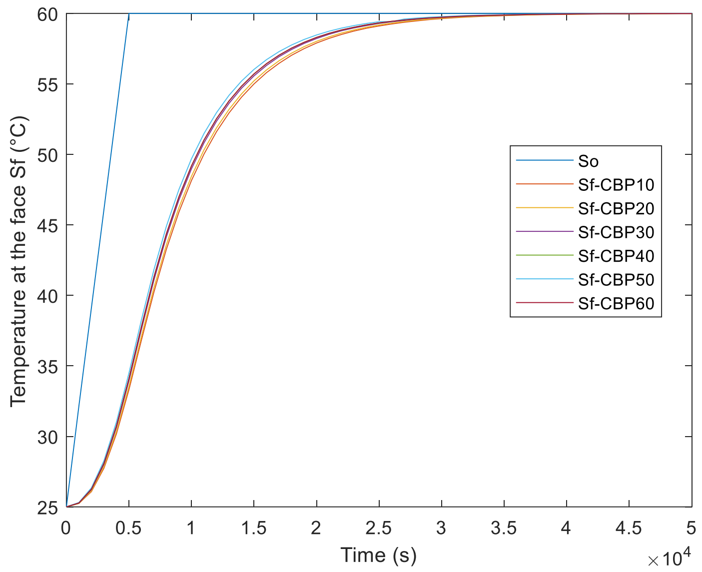

Fig. 9. Variation of temperature in the different bricks over time

4.3.2 Influence Of Brick Thickness

Figure 10 illustrates the influence of the thickness of the bricks on the propagation of heat over time on the S_f face. The test focused on the CBP10 brick. It is observed that the temperature increases with time for all thicknesses at this terminal surface.

For example, for thicknesses e=1 cm, 1.5 cm and 2 cm, the steady state, corresponding to the temperature imposed on S_i, is reached after 3 hours 20 minutes and 7 hours 46 minutes respectively. While for e = 2.5 and 2.7 cm, even after 13 hours, this state is not reached. Preliminary calculations have shown that beyond 2.7 cm, the S_f face is practically no longer influenced by the effect of the imposed temperature until 23 hours 11 minutes. All this information clearly specifies the characteristic thickness of the bricks produced.

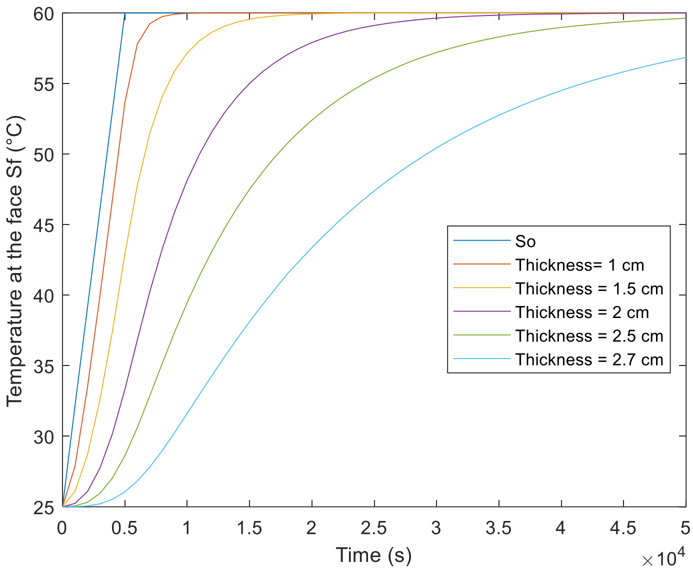

Fig. 10. Temperature variation in CBP10 brick at different thicknesses over time

4.3.3 Influence Of Air Temperature

Figure 11 shows the evolution of the temperature at the S_f face for different air temperatures at an ambient relative humidity equal to 72%. The test temperatures are: 30, 35, 40 and 45°C. It is an analysis of spatial-temporal temperature distributions. The simulation focused on the CBP10 sample. The analysis of the profiles indicates that after each increase in the imposed temperature, the temperature at the terminal surface Sf of the brick tends to increase rapidly. This elevation is the result of heat transfer by convection to the Si surface and by conduction inside the composite.

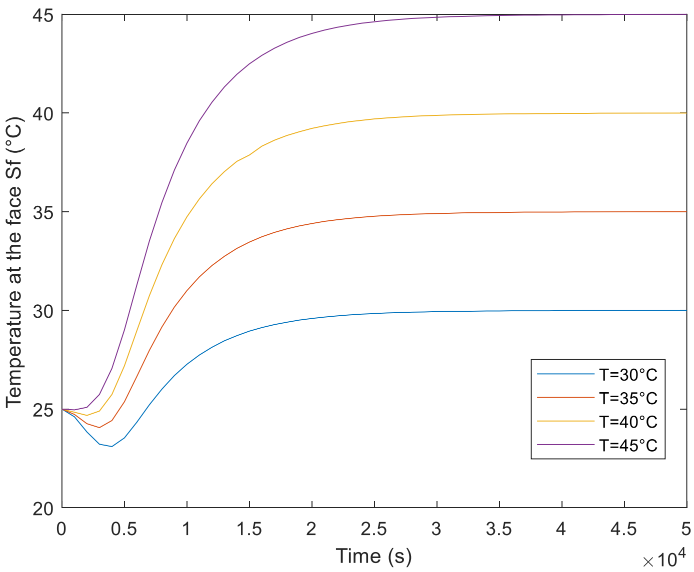

Fig. 11. Temperature variation in the CBP10 brick at different air temperatures over time

We observe a drop in temperature at the initial moments before the rapid rise in heat. Indeed, in contact with heat, the brick, through the S_i face, undergoes a structural shock which modifies the interfaces increasing the porosity. This increase in porosity promotes the release of heat instantly before the rapid rise due to the permanent presence of the T_i temperature. This drop-rise cycle of the surface temperature S_f is more remarkable for low air temperatures. This means that the larger these are, the more the cycle time is reduced.

Furthermore, in all cases, the maximum temperature is not reached before 8 hours 20 minutes of exposure.

5 Conclusion

This work consisted of investigating the thermal behavior of bricks made from Iroko wood flour compressed and stabilized with recycled High Density Polyethylene (HDPE) resin. The experimental study on the thermophysical properties indicates a good thermal performance of the bricks with a view to minimizing thermal inputs in residential buildings. For all samples, low values of thermal conductivity and diffusion depth are noted. All the bricks studied have thermal conductivities lower than 0.366 $Wm^{-1}K^{-1}$. In addition, the simulation, using the Cast3M calculation code, shows that the 3 cm thick bricks, with an imposed temperature of 60°C, do not reach a stationary state before 14 hours of exposure.

In this study, we developed new materials with a compromise between mechanical, water and thermal performances. On an ecological level, the use of these materials helps to reduce the quantity of waste that pollutes our cities. The thermal performance of the bricks produced shows that they could be used in the usual thermal conditions in Ivory Coast.

Our following article will focus on the study and simulation of the behavior of these bricks in bending by analysis of the state of stress and deformation.

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