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Numerical Study of the Thermal Behavior of a Hollow Block with Phase Change Materials (PCM) in the Sahelian Zone

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Authors' contributions

This work was carried out in collaboration among all authors. Author VZ designed the study, performed the numerical and experimental analysis, wrote the protocol and wrote the first draft of the manuscript. Authors BK, GWPO, JMC and SK managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

In this work, we present a numerical study of the thermal behavior of a hollow block with or without phase change material (PCM) in the Sahelian zone.
The PCMs used in this study are RT27 paraffin and hydrated salt with a melting temperature of 27°C and 29.9°C respectively and a latent heat of fusion of 179kJ/kg and 184kJ/kg. The equations

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obtained were adimensionalized then discretized by the finite element method and solved on the COMSOL software. We were first interested in the study of the thermal phase shift, the damping and the evolution of the temperature at the level of the internal wall. In a second phase, we conducted a comparative study between hollow block containing PCM and other construction materials (adobe, BTC and BLT) used in Burkina Faso.
The numerical results obtained show that the temperature of the internal wall of a hollow block containing RT27 is lower than that of a hollow block without PCM, hollow block containing hydrated salt, BTC, BLT and adobe with respectively a temperature difference of 8.354°C; 3.39°C; 5.79°C; 3.97°C and 3.92°C and the difference in terms of phase shift is 1h18min, 6min, 24min, 42min and 6min for the hollow block containing RT27, the hollow block containing hydrated salt, BTC, BLT and adobe.
Therefore, the integration of PCM in building materials increases their thermal inertia.

Keywords: Numerical simulation; hollow block; phase change materials; thermal; COMSOL.

1. INTRODUCTION

In Burkina Faso, the walls of buildings are constructed with hollow breeze blocks. These walls are confronted with thermal disturbances during periods of heat. These are caused by strong heat received by the external faces of the walls. This generates a significant consumption of energy within the building for internal cooling. This results in high charges.

According to a study carried out by the Ministry of Energy of Burkina Faso, the amount of energy consumed per year in buildings is 470.807 MWh with a consumption index of 232kWh/m^2/year [1]. To reduce this energy consumption in a context marked by global warming and a scarcity of energy resources of fossil origin, it is necessary to consider new thermal insulation materials in building structures in order to reduce heat in buildings. To this end, some studies have focused on materials that better regulate heat transfer in buildings. Among these materials, we have the phase change materials commonly called PCM.

The incorporation of PCM, in the different construction elements, is done by different methods which are the direct incorporation of the PCM, the impregnation of the construction material, the incorporation of capsules filled with MCP in the construction elements, etc. [2]. Their use for air conditioning and heating in buildings shows that the temperature peaks in a room equipped with PCMs can be reduced by 3 to 4°C, thus the energy consumption linked to air conditioning drops by 30 % [2].

Many numerical and experimental studies have been carried out in recent years by Anfas Mukram [3], Esam Alawadhi [4], Souci Youcef [5], Amine Laaouatni [6], Mohamed Lachheb [7], N. Soares [8], Sandra Cunha [9], in order to evaluate the potential of resorting to the integration of a PCM in bricks, walls and/or building envelopes and to increase its thermal inertia to improve its energy performance.

The objective of this present work is to compare the heat transfer in a hollow block with or without PCM, BTC, BLT and adobe. This will be done by studying the evolution of temperature when they are subjected to a weather-dependent outdoor temperature.

2. DESCRIPTION OF THE PHYSICAL PROBLEM

The physical model studied is based on a hollow cement block that we have schematized in Fig. 1 and 2. It is a hollow block of dimensions $0,4 \times 0,2 \times 0,15m$. It consists of two parallelepipedic cavities whose geometric characteristics are: height, width and length are respectively $0,36m \times 0,2m \times 0,1m$. The PCM used in this study is encapsulated and then inserted into the cavities of the hollow block.

Table 1 below presents the thermophysical properties of the PCM and hollow block used in the simulation.

Fig. 3 represents the geometry of the physical problem on the COMSOL software. The exterior faces of the block are exposed to a temperature T_{ex} (t); those of the interior walls are maintained at a constant temperature.

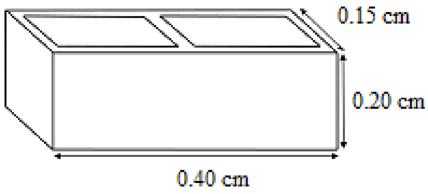

Fig. 1. Hollow brick in concrete block without PCM

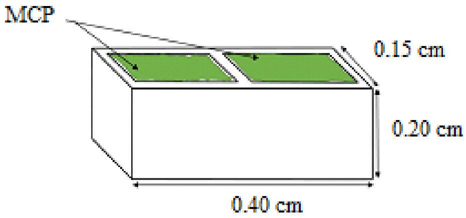

Fig. 2. Cinder block hollow brick containing PCM

Table 1. Thermo-physical properties of the materials used for the study [10-12]

	T_f (K)	$L_f\ (J/kg)$	$k\ (W/m/K)$	$\rho\ (kg/m^3)$	$Cp\ (J/kg/K)$
Paraffin RT27	300.15	179000	0.24 (solide) 0.15 (liquide)	870 (solide) 760 (liquide)	2400 (solide) 1800 (liquide)
Hydrated salt	302.9	187000	1.09 (solide) 0.53 (liquide)	1710 (solide) 1530 (liquide)	1400 (solide) 2200 (liquide)
Hollow cinder block	-	-	0.785	1050	1275

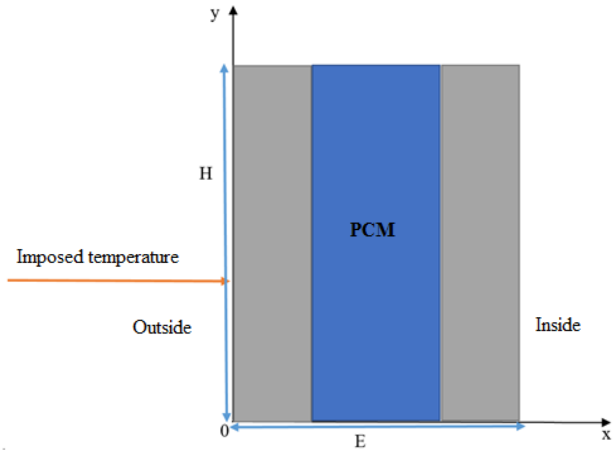

Fig. 3. Physical model of the block

3. MATHEMATICAL MODEL

3.1 Simplifying Assumptions

The simplifying assumptions of the problem are as follows:

- heat transfer is two-dimensional (2D) and transient;
- the thermo-physical properties (thermal conductivity, density and specific heat) of the wall are constant;
- the thermo-physical properties of PCM are constant and homogeneous but may be different in the liquid and solid phases;
- the effect of the natural convection of the liquid PCM is not taken into account because it is insignificant when the temperature difference between the liquid and solid phase is small;
- convection and radiation within the materials are negligible;
  the materials used are homogeneous and isotropic.

3.2 Mathematical Equations of Thermal Exchanges

Considering the hypotheses mentioned, the equation that describes the phenomenon is written as follows:

$$\rho Cp \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (1)$$

The thermophysical properties ρ , Cp and k respectively, density, specific heat and thermal conductivity depend on the materials constituting the field, namely the hollow cement block and the PCM.

In order to integrate the liquid and solid phase properties as well as the latent heat of fusion, an apparent property is used for phase change materials. The expressions describing the thermo-physical properties of PCM are:

$$\rho_{PCM} = \theta.\rho_s + (1-\theta)\rho_l \qquad (2)$$

$$k_{PCM} = \theta.k_s + (1-\theta)k_l \qquad (3)$$

$$Cp_{PCM} = \frac{1}{\rho_{PCM}}\left(\theta.\rho_s Cp_s + (1-\theta)\rho_l Cp_l\right) + L_f \frac{\partial \alpha_m}{\partial T} \qquad (4)$$

α_m represents the mass fraction of the solid phase in the PCM. It is given by the following equation:

$$\alpha_m = \frac{1}{2}\frac{(1-\theta)\rho_l - \theta\rho_s}{\theta\rho_s + (1-\theta)\rho_l} \qquad (5)$$

3.3 Boundary and Initial Conditions

- **Initial conditions**

Initially $(t = 0)$, we consider that the PCM and the brick are at ambient temperature $T_{amb} \prec T_f$ (melting temperature).

$0 \prec x \prec E$ and $0 \prec y \prec H$;

$$T(x, y, 0) = Tamb \qquad (6)$$

- **Boundary conditions**

- Outer wall

At the moment $t > 0$, a temperature is imposed on the external face:

$x = 0$ and $0 \prec y \prec H$; $T=T_{ex}(t)$ (7)

with :

$$T_{ex}(t) = A_0 + B.\cos(\omega.t) + C.\sin(\omega.t) \qquad (8)$$

- Internal wall

At the moment $t > 0$, the outer wall is maintained at a constant temperature:

$x = E$ and $0 \prec y \prec H$; $T_{pi} = T$ (9)

*Block/MCP and block/wall interface

At the cinder block/PCM interface, we assume that there is a continuity of heat flow.

- Concrete block / PCM interface:

$$k_{mcp}\frac{\partial T_{mcp}}{\partial n} = -k_m \frac{\partial T_m}{\partial n} \qquad (10)$$

- PCM / concrete block interface:

$$k_m \frac{\partial T_m}{\partial n} = -k_{mcp}\frac{\partial T_{mcp}}{\partial n} \qquad (11)$$

With « n » the normal to the surface of the cavity filled by PCM.

* Horizontal walls of the cinder block:

The boundary conditions for the horizontal walls are formulated as follows:

For $y = 0$; $0 \le x \le e$, we have :

$$\left.\frac{\partial T}{\partial y}\right)_{x,0} = 0 \qquad (12)$$

$y = H$; $0 \le x \le e$, we have : $\left.\frac{\partial T}{\partial y}\right)_{x,H} = 0$ (13)

4. RESULTS AND DISCUSSION

Numerical simulations were performed using COMSOL Multiphysics software. The simulation time is 24h with a constant time step of 0.1h (6 minutes). The geometries of the bricks, the physical properties of the materials used as well as the initial and boundary conditions were defined in the software. An extra fine quadratic mesh was adopted with 4788 elements. The convergence criterion is $1,2.10^{-4}$.

We present the evolution of the temperature in the block and on its internal face according to the configuration: hollow block without PCM and with PCM.

4.1 Evolution of the Temperature within the Hollow Block with PCM or without PCM

Fig. 4 shows the evolution of the temperature within the hollow block with PCM or without PCM.

The curves in Fig. 4 show the variation in temperature within the hollow block with or without PCM and in the atmosphere as a function of time. The maximum temperature observed outside is 39.9°C. We also note that the maximum temperature reached in the hollow block is higher than in the hollow block with PCM. The maximum value is 36.918°C for the hollow block without PCM. On the other hand, it is 28.759°C for the hollow block containing RT27, i.e. a temperature difference between the hollow block without PCM and the hollow block containing the RT27 which is 8.159°C.

We will be interested in the thermal phase shift as well as the damping.

Table 2 presents the influence of the PCM on the phase shift and the damping of the temperatures.

In Table 2 represented above, it can be seen that the difference in terms of phase shift between the hollow block without PCM and that containing RT27 is 1h18min. This study shows that the integration of PCM in the recesses of the concrete blocks slows down the heat transfer through the concrete block.

4.2 Evolution of the Temperature at the Level of the Internal Wall

Fig. 5 shows the evolution of the temperature at the level of the internal wall of the hollow block with PCM or without PCM.

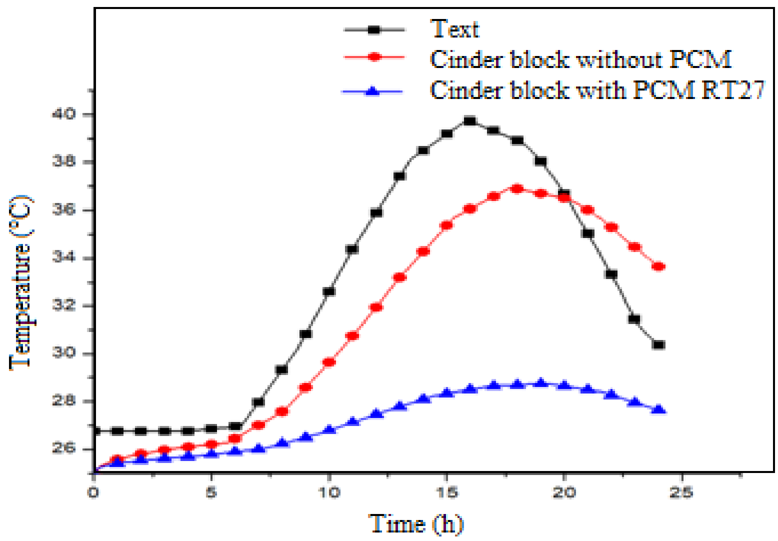

Fig. 4. Evolution of the temperature within the hollow block with or without PCM over time

Table 2. Influence of PCM on temperature phase shift and damping

Material	Damping	Phase shift
Cinder block without PCM	2.847°C	2h
Cinder block with PCM RT27	11.201°C	3h18min

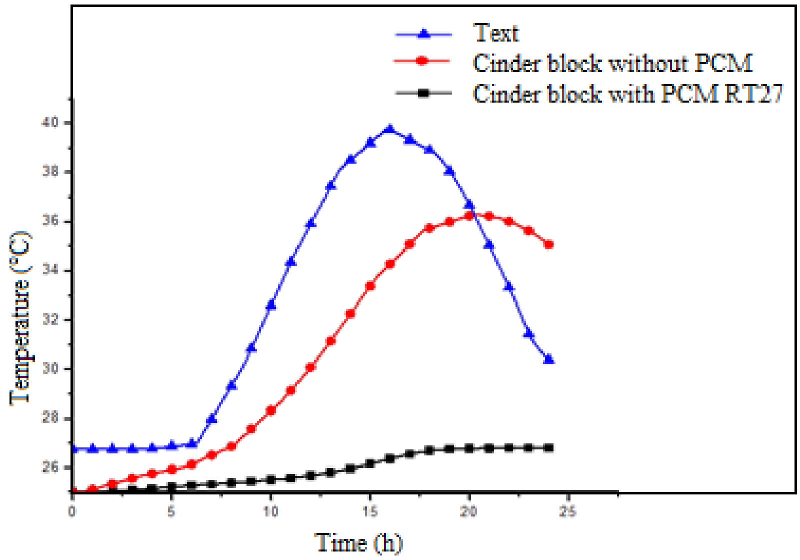

Fig. 5. Evolution of the temperature at the level of the internal wall

The curves in Fig. 5 show the variation in temperature at the level of the internal wall of the hollow block with or without PCM and in the atmosphere as a function of time. We find that the temperature of the inner wall of the hollow block containing RT27 is lower than that of the hollow block without PCM. For a period of 24 hours, it varies from 25°C to 37.3°C; reaches a maximum temperature of 37.33°C then decreases from 37.33°C to 35.5°C for the hollow block without PCM. For the hollow block containing RT27, the temperature changes from 25°C to 27°C for a period of 15 hours and then the oscillations are moderate and approach the melting temperature of PCM.

In Figs. 4 and 5, we observe that the temperature level reached by the hollow block with PCM is lower than the hollow block without the PCM. This is due to the large amount of heat absorbed during the melting of PCM as latent heat. This melting of the PCM helps to keep the temperature of the material constant and thus limiting the heat transmitted to the interior side.

It can also be explained by the effect of the thermal conductivity of the PCM which is low compared to that of the hollow cement block; which makes it more insulating by acting to slow down the phase change process, but this effect is weak compared to the effect of the latent heat of fusion.

This shows the effect of PCM in increasing the thermal inertia of the hollow cement block. So, for a good thermal insulation of the internal face, the use of a hollow block containing PCM is more advantageous than that of the hollow block without PCM.

4.3 Effect of the Paraffin Melting Temperature

In this part, we study the effect of the melting temperature of paraffin RT on the thermal behavior of concrete block. Indeed, the type of PCM is an important factor that influences the thermal performance of materials. The choice of melting temperature depends on the indoor temperature which varies from building to building and from season to season. The paraffins chosen have different latent heats and melting temperatures. Three paraffins, namely the RT21 $(T_f < T_{amb})$, the RT24 $(T_f = T_{amb})$ and the RT27 $(T_f > T_{amb})$ have been chosen [13].

a) Effect of the paraffin melting temperature on the evolution of the temperature within the concrete block

Fig. 6 shows the effect of paraffin melting temperature on the temperature evolution in the hollow block as a function of time.

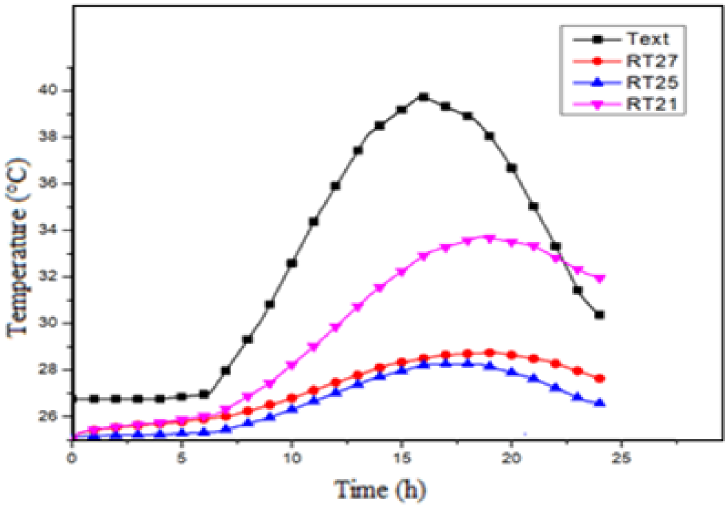

Fig. 6. Evolution of the temperature in the cinder block containing PCM over time

Table 3. Effect of melting temperature on temperature phase shift and damping

Material	Damping	Phase shift
RT21	6.033°C	2h42min
RT25	11.501°C	2h36min
RT27	11.201°C	3h18min

The curves in Fig. 6 show the variation in temperature within the hollow block containing RT21, RT27 and or RT25 and in the atmosphere as a function of time. The maximum amplitude reached for RT21 is 33.732°C (at 6:36 p.m.), that of RT25 is 28.264°C (at 6:30 p.m.) while for RT27 is 28.759°C (at 7:12 p.m.) while that reached by outdoor is 39.9°C. Note that the RT25 has a low amplitude compared to that of RT21 and RT27. This means that it absorbs more heat energy. Table 3 presents the influence of the melting temperature on damping and thermal phase shift.

We observe in Table 3 that the damping is greater for the RT25 with a difference of 5.468°C between the RT25 and the RT21 and 0.3°C between the RT25 and RT27 but the thermal phase shift is higher for the RT27. The difference in terms of phase shift 36min between the RT27 and the RT21 while between the RT27 and the RT25 it is 42min.

b) Effect of the paraffin melting temperature on the evolution of the temperature of the inner wall of the cinder block

Fig. 7 shows the effect of the paraffin melting temperature on the evolution of the temperature in the hollow block over of time.

The curves in Fig. 7 show the variation in temperature at the level of the internal wall of the hollow block containing RT21, RT27 and or RT25 and in the atmosphere as a function of time. The maximum temperature observed outside is 39.9°C, while the maximum value is 31.882°C for the hollow block containing RT21; 25°C for the hollow block containing RT25 and for the hollow block containing RT27, it is 26.792°C. We note that the temperature of the internal wall of a hollow block containing RT25 remains constant during the simulation period, that of a hollow block containing RT27 increases and remains constant around its melting temperature while that of a hollow block containing RT21 is strongly believed.

These results show that the RT21 is not suitable for reducing the temperature of the inner wall of the hollow block because its temperature is high and quite close to that of a hollow block without PCM. The melting temperature of RT21 being low makes it quickly pass into the liquid phase despite its high latent heat of fusion. Therefore, the hollow block does not benefit from its high latent heat of fusion. For RT27, it has a high melting temperature than RT21 and RT25 but its latent heat of fusion (179kJ/kg) is lower than that of RT21 (190kJ/kg) and RT25 (230kJ/kg). Therefore, the amount of latent heat stored by this type of PCM is insignificant. On the other hand, when the RT25 is introduced, the fluctuation of the temperature of the internal wall of the concrete block is considerably reduced and remains constant. This is because the amount of latent heat stored by the RT25 is much greater to reduce the heat flow in the interior space of the hollow block.

4.4 Comparison of Temperature Profiles in Concrete Block for Different Types of PCM

We will study the thermal behavior of the hollow block for different types of PCM. The PCMs used are RT27 paraffin and hydrated salt. The thermo-physical properties are shown in Table 1. It is recalled that their melting temperatures are respectively 27° C. and 29.9° C.; the latent heat of fusion of 179 kJ/kg and 184 kJ/kg.

a) Evolution of the temperature within the concrete block for different types of PCM

Fig. 8 presents the evolution of the temperature in the cinder block over time.

The curves in Fig. 8 show the variation in temperature within the hollow cinder block containing RT27 and/or hydrated salt and in the atmosphere as a function of time. We observe that the maximum value is respectively 28.492°C; 31.885°C for the hollow block containing RT27 and hydrated salt with a temperature difference of 3.393°C between the hollow block, RT27 and hydrated salt, while the exterior has a maximum temperature of 39.9°C. The damping in relation to the outside temperature is 11.201°C for the RT27; 7.85°C for the hydrated salt and while the phase shift is respectively 3h18min and 3h24min with a difference of 6 min.

b) Evolution of the temperature at the level of the internal wall in the concrete block for different types of PCM

Fig. 9 presents the evolution of the temperature in the cinder block over time.

The curves in Fig. 9 show the variation in temperature at the level of the internal wall of the hollow block containing RT27 and/or hydrated salt and in the atmosphere as a function of time. It is observed that the maximum temperature reached is 26.792°C for the hollow block containing the RT27 and 30.82°C for the hollow block containing the hydrated salt while the maximum temperature reached at the level of the atmosphere is 39.9° vs. We note that the temperature level reached for the hollow block containing RT27 is lower than that reached for the hollow block containing hydrated salt; this is due to the thermal conductivity of the hydrated salt which is higher than that of RT27 paraffin.

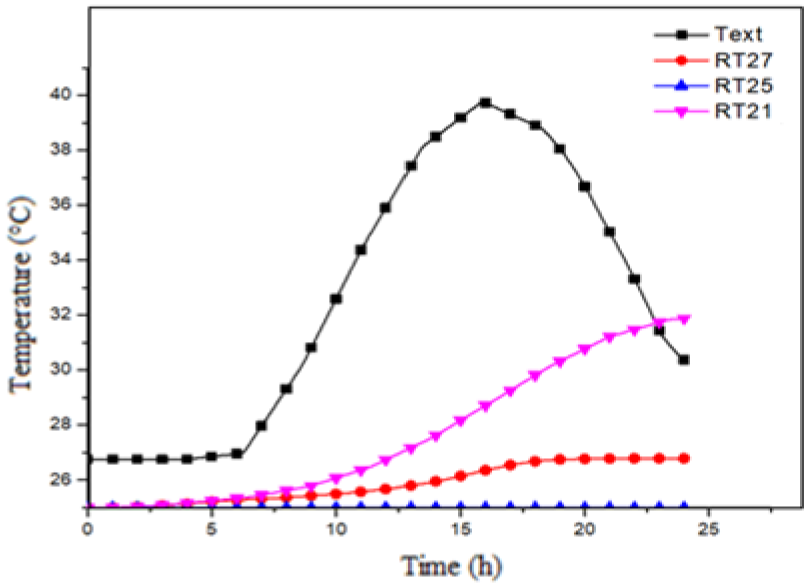

Fig. 7. Evolution of the temperature at the level of the internal wall over time

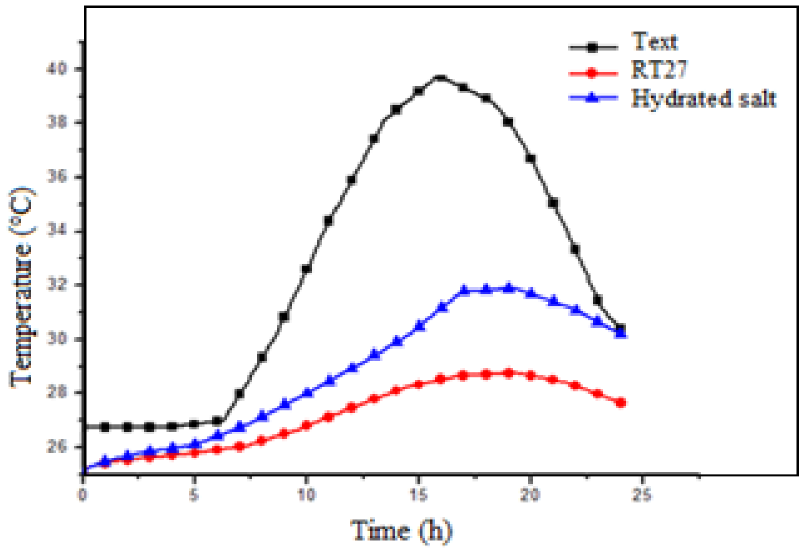

Fig. 8. Evolution of the temperature in the cinder block over time for different types of PCM

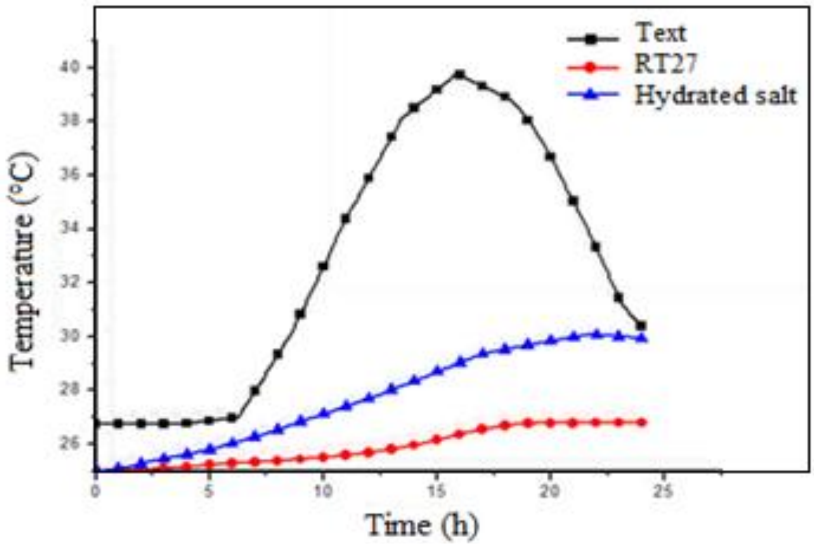

Fig. 9. Evolution of the temperature at the level of the internal wall of the concrete block over time for different types of PCM

4.5 Comparison of Temperature Profiles in Cinder Block Containing PCM and Local Building Materials

The previous study showed that the integration of PCM in the hollow cinder block reduces the heat flow in the interior space by providing effective thermal resistance to external stresses. However, in Burkina Faso, hollow cement blocks are not the only materials used for the construction of buildings. Authors such as Compaoré et al [1]; Malbila et al. [14] and Fati Amadou et al [11] have shown that hollow cement blocks are a material that should be avoided in the construction of habitats in the Sahelian zone. And yet these cinder blocks are widely used for most housing constructions in Burkina Faso. This is why in this part, we will compare the thermal performance of a hollow cinder block containing PCM (RT27) with other building materials such as adobe, BTC and BLC. The thermophysical properties of adobe, BTC and BLC are presented in Table 4.

Table 4. Thermophysical properties of adobe, BLT and BTC [1] [11]

	$k\left(W\ /\ m\ /\ K\right)$	$\rho\left(kg\ /\ m^{3}\right)$	$Cp\left(J\ /\ kg\ /\ K\right)$
Adobe	0.5	1305	1060
BLT	0.556	1075	1310
BTC	0.671	1960	1492

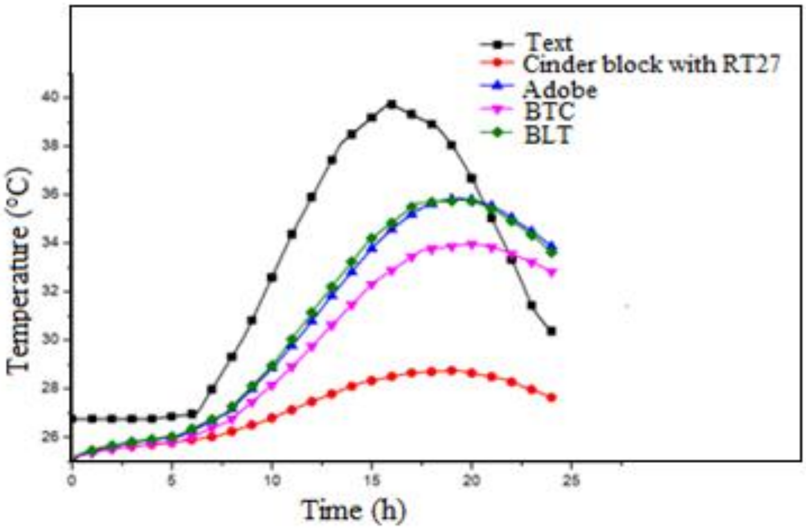

Fig. 10. Evolution of the temperature within the materials over time

a) Evolution of the temperature within the different materials

The following Fig. 10 shows the evolution of the temperature within the materials over time.

The curves in Fig. 10 show the variation in temperature within the hollow block containing RT27, BLT, BTC and/or adobe and in the atmosphere as a function of time. We respectively observe a maximum temperature of 35.84°C; 33.974°C and 35.794°C for Adobe, for BTC and BLT while that reached by the hollow block containing the PCM is 28.759°C. Note that the temperature level reached is lower for the hollow block containing the PCM.

The curve shows us a difference of 7.081°C; 7.035°C and 5.215°C respectively between the hollow block containing MCP and Adobe, the hollow block containing PCM and BLT and the hollow block containing PCM and BTC.

Table 5 above presents the influence of each type of material on damping and thermal phase shift.

We find that the damping is higher in the case of hollow block containing RT27 with relatively a little lower phase shift than BTC, BLT and adobe. This phase difference in terms of time between the hollow block containing the PCM and respectively the adobe, the BTC and the BLT is 06 min, 42 min and 24 min.

Table 5. Influence of each type of material on phase shift and thermal damping

	Damping	Phase shift
Cinder block containing RT27	11.201°C	3h18min
Adobe	3.925°C	3h24min
BTC	5.791°C	4h
BLT	3.971°C	3h42min

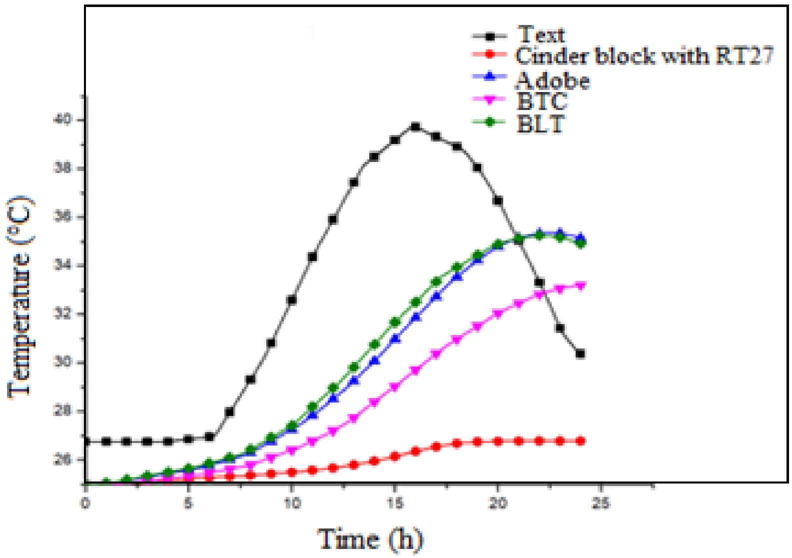

Fig. 11. Evolution of the temperature at the level of the internal wall over time

b) Evolution of the temperature at the level of the internal wall of the different materials

The following Fig. 11 shows the evolution of the temperature at the level of the internal wall over time.

The curves in Fig. 11 show the variation in temperature at the level of the internal wall of the hollow block containing RT27, BLT, BTC and/or Adobe and in the atmosphere as a function of time. Although the thermal phase shift is a little weak for the hollow block containing PCM, we observe that the temperature of the internal wall of the hollow block containing the PCM is lower than the BLT, BTC and Adobe. The maximum values observed are respectively 27°C; 35°C; 33.97°C and 35.79°C for the hollow block containing the RT27, for the Adobe, for the BTC and for the BLT, while that observed in the atmosphere is 39.9°C. This is explained by the fact that the PCM absorbs a large amount of heat in latent form coming from the outside.

5. CONCLUSION

In this work, we numerically simulated the thermal behavior of a hollow cinder block without PCM and a hollow cinder block containing PCM on the one hand and on the other hand a hollow cinder block containing PCM with other building materials (adobe, BTC and BLC). The Phase Change Material used in this study is RT27 paraffin and hydrated salt. The numerical simulation of the thermal behavior was carried out on the COMSOL Multiphysics software.

The results obtained show that the temperature of the internal wall of the hollow cinder block containing RT27 is lower than the others (hollow block without PCM, hollow block containing hydrated salt, adobe, BTC and BLC).

The numerical results obtained show that the temperature of the internal wall of a hollow block containing RT27 is lower than that of a hollow block without MCP, hollow block containing hydrated salt, BTC, BLT and adobe with respectively a temperature difference of 8.354°C; 3.39°C; 5.79°C; 3.97°C and 3.92°C and the difference in terms of phase shift is 1h18min, 6min, 24min, 42min and 6min for the hollow block containing RT27, the hollow block containing hydrated salt, BTC, BLT and l 'adobe.

Therefore, the integration of PCM in building materials increases their thermal inertia.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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