Original Research Article

Evolution of the average temperature of the interior atmosphere of a habitable cell made of foamed concrete in Burkina Faso

ABSTRACT

Aims: This work consists in making a study of the thermal behavior of a habitat designed with foamed concrete (FC) in order to evaluate its thermal performance for the improvement of its thermal comfort and to compare its average internal temperature with those of other materials.
Study Design: A calculation model developed under the COMSOL Multiphysics 5.3a software was used to simulate the thermal behavior of a foamed concrete habitat. The meteorological data used are those of Ouagadougou in the month of April (hottest month in Burkina Faso).
Methodology: The temperatures of each side of the walls were determined. Moreover, the study of the influence of the thickness of the walls on the average internal temperature made it possible to determine an optimal thickness. Then, the thermal phase shift, the thermal amplitude reduction and the damping factor were carried out.
Results: The results obtained in the weather conditions of April in Ouagadougou, lead to an average internal temperature of the building of about 304 K, for a wall thickness of 17.5 cm. There is a thermal phase shift of 8 hours, and a reduction in thermal amplitude of 9°C or a damping factor of 8.6%. The maximum average internal temperature of the foamed concrete was compared with those of the cement block, the CEB, the adobe, the CLB which present respectively 311 K; 309.2K; 309K; 308.5K.
Conclusion: A building constructed with foamed concrete has a low average internal temperature compared to cinderblock, CEB, adobe and CLB. Thus, this material makes it possible to provide more thermal comfort and can be used for the construction of habitats with good energy efficiency.

Keywords: Foamed concrete, simulation, Comsol multiphysics, temperature, thermal phase shift.

1. INTRODUCTION

It is important to carry out actions (research for thermal comfort) in the building sector, because an analysis of sectors responsible for most of the energy consumption highlights the residential and tertiary sectors. Indeed, buildings account for about 40% of the world's total primary energy consumption and contribute significantly to global energy consumption [1] [2]. Buildings are spaces that play an essential role in the economy and society in general, but do not necessarily provide thermal comfort and good indoor air quality [3] [4]. A building is a structure intended to serve as shelter or habitat and to protect people and property from external weather conditions. To reduce greenhouse gas emissions, houses must be adapted to the climate context in order to significantly reduce their energy consumption. The ever-growing international interest in the energy efficiency of buildings has led to numerous scientific and industrial works of improving masonry elements in order to meet current energy saving requirements [5]. The energy performance of a building is often linked to the thermal performance of its envelope[6]. The energy situation in emerging and island countries such as Burkina Faso is becoming increasingly worrying as the demand for electrical energy continues to grow, while the means of production remain limited and the intensive use of air conditioning during the hot season aggravates the problems [7]. In Burkina Faso, statistics of 2006 show that 69.4% of dwellings have walls built of adobe (banco) and 13.8% of the walls are made of cement cinder blocks. 42.6% of hollow agglomeration masonry constructions predominate in urban areas [8]. The most frequent temperature distribution is between 24°C and 38°C in Ouagadougou. The hottest months are distinguished by temperatures above 38°C. These temperatures reach their highest levels in March, April and October and their lowest in December, January and February [9]. Studies carried out by Boureima Kaboré et al 2017 [10] showed that the hottest month in Ouagadougou is April. The Cinder block is one of the most used building materials in urban areas in Burkina Faso because of its good mechanical strength and durability. But this latter has a low thermal inertia that leads to the use of expensive and energy-consuming air conditioning equipment. Thus, it is essential to find materials which can reduce energy consumption in the building. For a compromise between thermal and mechanical properties, it is necessary to explore other suitable environmentally friendly materials. A foamed concrete was recently developed by Professor Blanchard, in Burkina Faso, and measurements of its mechanical and thermal properties have been carried out [11]. The simulation of the average internal temperature of a habitable cell made of foamed concrete as the main construction material of the envelopes, is part of this dynamic.

2. MATERIAL AND METHODS

2.1 Description of the building

2.1.1 Physical description of the habitable envelope

In this study, the physical model is a dwelling of individual house type (Figure 1), composed of a single room with 4 facades, including a door, a window and the roof. The geometry of the room for this simulation, is a square having for dimensions: Length (L = 4 m), width (l = 4 m) and a height of (h = 3 m). The construction is located on a surface of 16 m^2. The slab walls and slab roof are built with foamed concrete having the following characteristics: density of 930 kg/m^3, thermal conductivity of 0.2 W/m.K and Mass heat capacity 1780.09 J/kg.K.
The building has two openings, one of which is a door to the north face and a window to the south face.

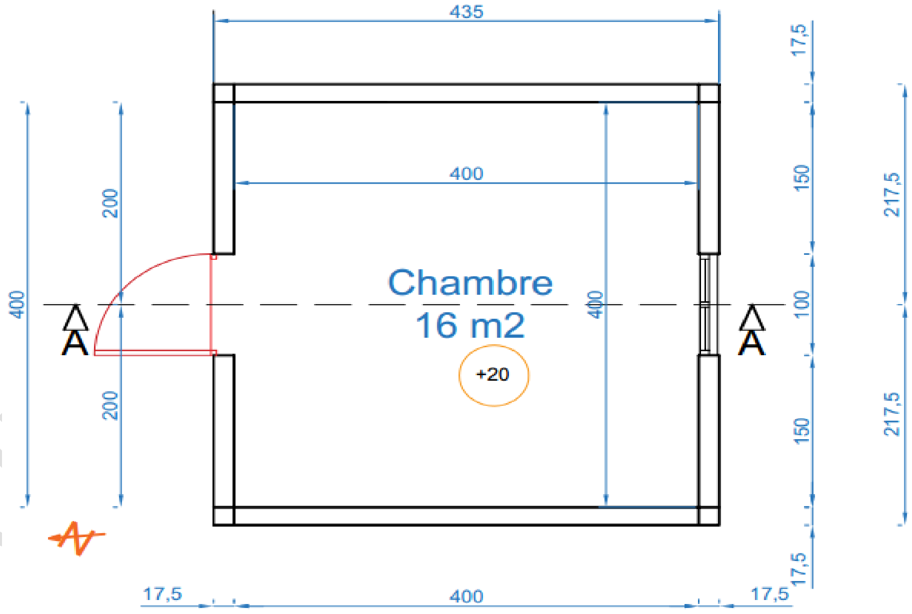


Figure 1: Building level plan

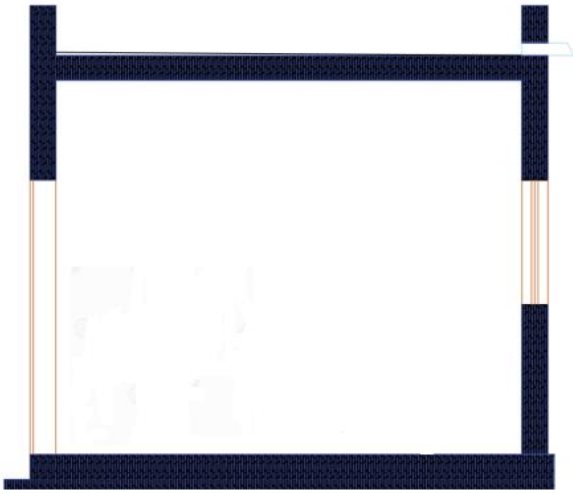


Figure 2: Elevation view or transverse cutting plane

2.1.2. Orientation of the building to be simulated

The geometry of the model was implemented in the COMSOL Multiphysics 5.3a software in 3 dimensions. The main face of the building, where the door is located, faces north.
The geometric model is created in two steps in most finite element calculation of code preprocessors:

- First, we represent the geometry of the studied structure
- In a second step, we carry out the generation of a mesh well adapted to the numerical calculation scheme chosen.

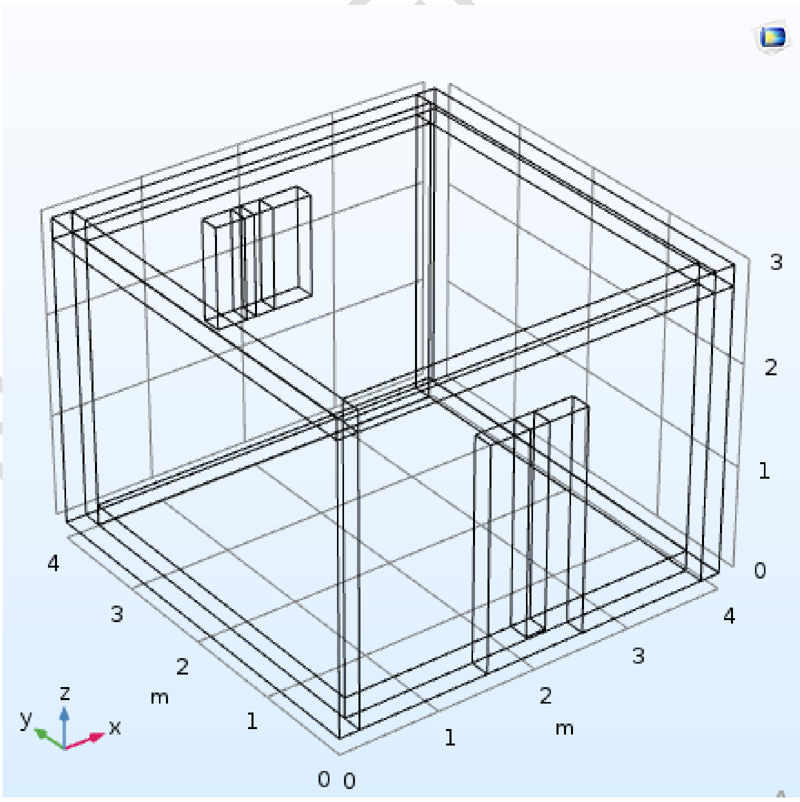


Figure 3: Building design model obtained with COMSOL Multiphysics 5.3a

Burkina Faso is a country that has a hot and dry climate. The reference month is April (the hottest month). We chose Ouagadougou as our reference city. In addition, April 15 is considered to be the hottest day of the year [12]. We chose this month for the simulation of our model.
A preliminary study was made by determining the heat flows exchanged by each wall and the roof of the building.

2.2 Determination of solar irradiation on each side

The different equations obtained below represent the modeling of solar irradiation on each side of the walls (walls), where the absolute value of the Fourier series is taken into account.

- **East Wall** (From 5:30 am to 3 pm)

$$P_{W1east} = abs\,[a_{0east} + a_{1east} * \cos(t * w_{east}) + b_{1east} * \sin(t * w_{east}) + a_{2east} * \cos(2 * t * w_{east}) + b_{2east} * \sin(2 * t * w_{east})] \quad (1)$$

- **West Wall** (From 9 am to 6 pm)

$$P_{W2\mathrm{West}} = abs\,[a_{0\mathrm{West}} + a_{1\mathrm{West}} * \cos(t * w_{\mathrm{West}}) + b_{1\mathrm{West}} * \sin(t * w_{\mathrm{West}}) + a_{2\mathrm{West}} * \cos(2 * t * w_{\mathrm{West}}) + b_{2\mathrm{West}} * \sin(2 * t * w_{\mathrm{West}})] \quad (2)$$

- **South Wall** (From 6 am to 6 pm)

$$P_{W3South} = abs\,[a_{0South} + a_{1South} * \cos(t * w_{South}) + b_{1South} * \sin(t * w_{South}) + a_{2South} * \cos(2 * t * w_{South}) + b_{2South} * \sin(2 * t * w_{South})] \quad (3)$$

- **North Wall** (From 6 am to 6 pm)

$$P_{W4North} = abs\,[a_{0North} + a_{1North} * \cos(t * w_{North}) + b_{1North} * \sin(t * w_{North}) + a_{2North} * \cos(2 * t * w_{North}) + b_{2North} * \sin(2 * t * w_{North})] \quad (4)$$

- **Horizontal** (From 6 am to 6 pm)

$$P_{W5horiz} = abs\,[a_{0horiz} + a_{1horiz} * \cos(t * w_{horiz}) + b_{1horiz} * \sin(t * w_{horiz}) + a_{2horiz} * \cos(2 * t * w_{horiz}) + b_{2horiz} * \sin(2 * t * w_{horiz})] \quad (5)$$

- **Room temperature** (From 0 am to 12 pm)

$$T_{room}(t) = a_0 + a_1 * \cos(t * w) + b_1 * \sin(t * w) \quad (6)$$

These equations of the above Fourier series are generalized by the equation of the radiation flux P_{wi} that arrives on each face.

$$P_{wface}(t) = a_{0,face} + \sum_{i=1}^{n} a_{i,face} \cos(iw_{face}t) + \sum_{i=1}^{n} b_{i,face} \sin(iw_{face}t) \quad (7)$$

2.3 Modelling heat transfer in the building

2.3.1 Heat transfer equations

The general equation for heat transfer is as follows [13][14][15]:

$$(\rho C_p)\frac{\partial T}{\partial t} + \rho C_p \mathrm{u}.(\nabla \mathrm{T}) = \nabla.(\lambda \nabla \mathrm{T}) + \mathrm{Q} \quad (8)$$

$$\mathrm{q} = -\lambda(\nabla.\nabla \mathrm{T}) \quad (9)$$

With ρ : Density of the fluid (kg/m^3), C_p : Mass heat capacity at constant fluid pressure (J/kg. K), ρC_p : Volumetric heat capacity at constant pressure (J/m^3.K), T : the ambient temperature (K), λ : Equivalent thermal conductivity of the medium, u : Fluid velocity field (m/s), Q: Possible heat source (W/m^3), q : Heat flow (W/m^3).

Study hypotheses:

- In this simplified model, considering the very low air speeds within the building we do not introduce a momentum equation;
- Small openings at the door and window lead to a low air change of about 0.1V/h; The medium considered is isotropic;
- Heat transfer by conduction is unidirectional in the walls;
- The temperature is uniform in a wall;
- The air used is homogeneous and transparent to radiation;
- The materials are assimilated to gray bodies;
- The thermo-physical properties of the materials are constant;
- It is assumed that at 0h, beginning of the simulation, all the walls of the envelope are at the same temperature of 303K;
- It is assumed that the volume of internal air is at homogeneous temperature at each step of time, throughout the occupied space; we make at each moment, the thermal balance of this volume of air taking into account all the heat fluxes that are transmitted to it by convection, radiation and infiltration.

For the simulation of heat transfers in walls, roofs and floors, the thermal conduction equation is used, it comes from:

$$(\rho C_p)\frac{\partial T}{\partial t} = \nabla.(\lambda \nabla T) + Q \quad (10)$$

$$\rho C_p \frac{\partial T}{\partial t} - \lambda \nabla^2 T = Q \quad (11)$$

By stating the hypothesis that the volume of internal air is at homogeneous temperature at each step of time, throughout the occupied space; we make at each moment, the thermal balance of this volume of air taking into account all the heat flows that are transmitted to it by convection and radiation.

$$m_{air}\rho_{air}C_P\frac{dT}{dt} + \int_S (n.q)\,dS = Q_v \quad (12)$$

With m_{air} : Air mass (kg), ρ_{air} : Density of air (kg/m^3), $\frac{dT}{dt}$:Total derivative, Q_v : Volume heat sources (W/m^3).

Boundary conditions

The different heat fluxes, convection and radiation, on the internal and external boundaries in equations (13), (14), (15) and (16) were considered. There is no internal heat production in our study model.

$$q = h_i(T_p - T_{int})\ au\ \partial\Omega_{int} \quad (13)$$

$$q = \varepsilon\,\sigma\,(T_{p,int}^4 - T_{int}^4)\ au\ \partial\Omega_{int} \quad (14)$$

$$q = h_e(T_e - T_p)\ au\ \partial\Omega_{ext} \quad (15)$$

$$q = \varepsilon\,\sigma\,(T_p^4 - T_{room}^4)\ au\ \partial\Omega_{ext} \quad (16)$$

With q: Heat flow, h: Heat transfer coefficient, T_p: Temperature at the limits, T_{int}: Internal temperature, T_e : External temperature, ε : Emissivity, σ : Stefan Boltzmann's constant, T_{room} : Ambient temperature.

2.3.2 Thermal phase shift and thermal damping in walls

Thermal phase shift is the time that separates the outer and inner temperature maxima. The damping or reduction of thermal amplitude is the difference in external and internal maximum temperatures.

The damping factor is obtained by comparing the internal maximum and minimum temperature difference to that obtained externally.

Thermal phase shift (in hours)

$$\emptyset = t_{max} - t_{min} \tag{17}$$

Damping or reduction of thermal amplitude (in degrees Celsius)

$$\alpha = T_{max,ext} - T_{max,int} \tag{18}$$

Depreciation factor (in percentage)

$$f = \frac{\Delta T_{int}}{\Delta T_{ext}} = \frac{T_{int\_max} - T_{int\_min}}{T_{ext\_max} - T_{extt\_min}} \tag{19}$$

With t_{max} : Maximum time in (h), t_{min} : Minimum time in (h), T_{max}: Maximum temperature in (K), T_{min}: Minimum temperature in (K).

3. RESULTS AND DISCUSSION

3.1 Building mesh

For numerical simulation, the meshes must adapt correctly to the geometry and have a sufficient number of elements to have accurate calculations.
The figure below shows the mesh chosen for the building in the Comsol software.

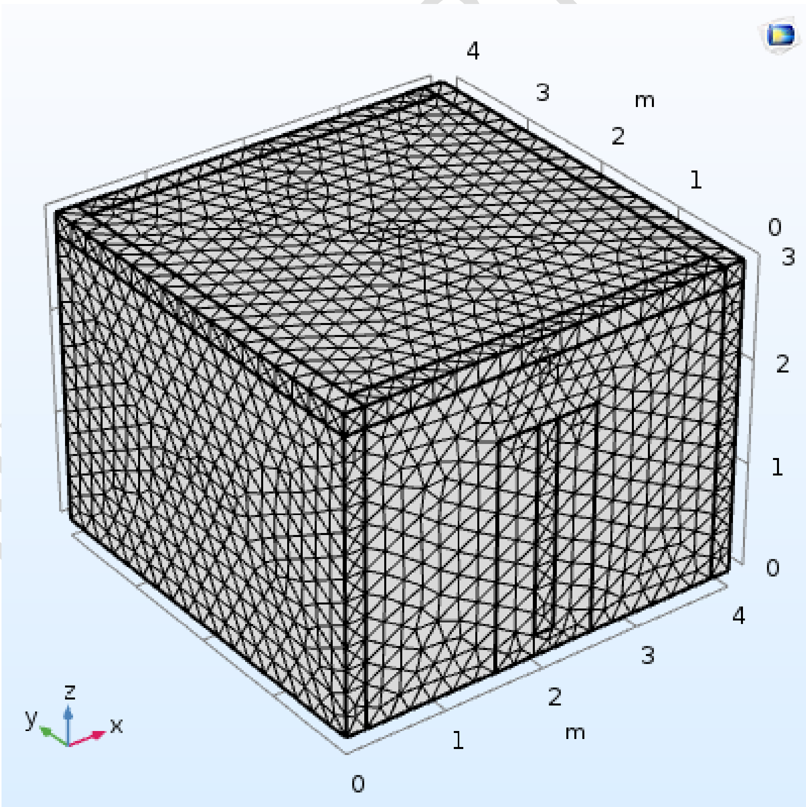


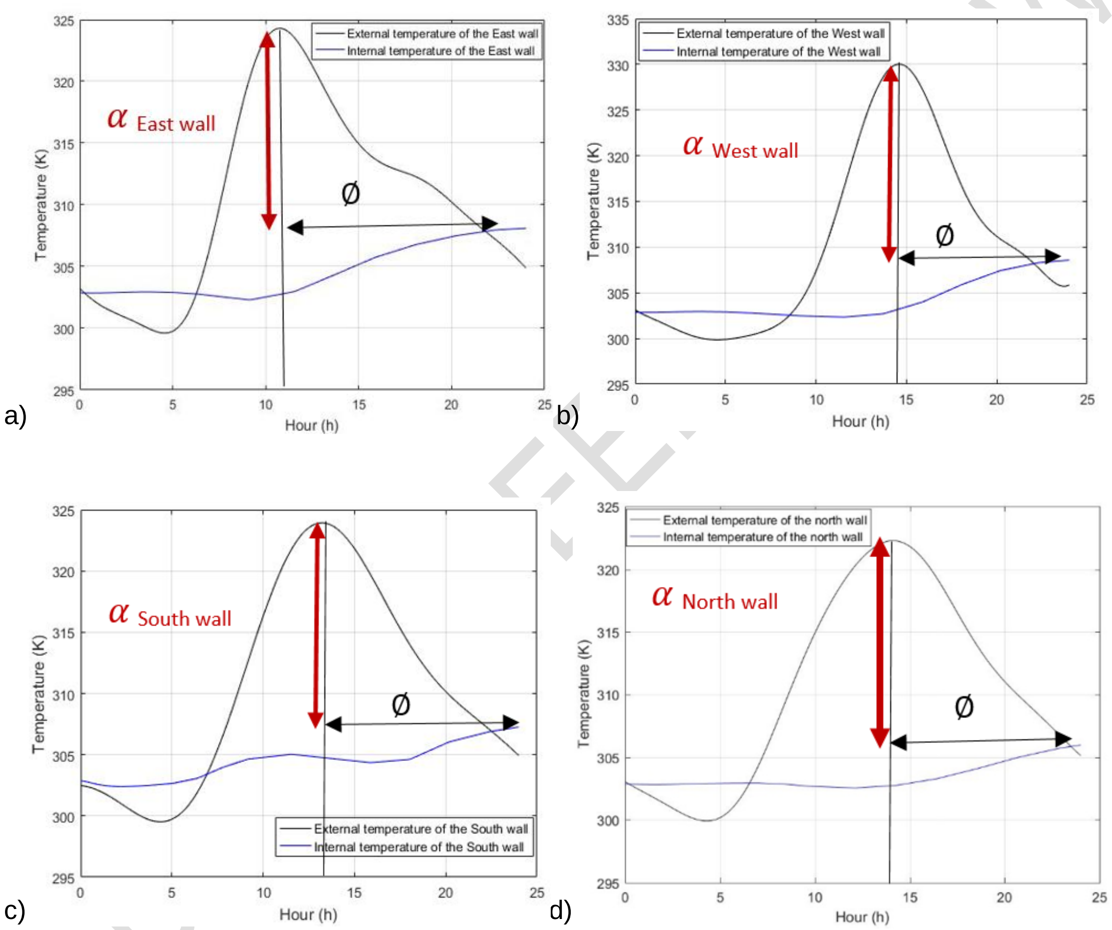
Figure 4: Geometry of the building mesh obtained

Figure 4 above shows the mesh geometry made in 3D. The system mesh is a structure of geometric elements that allows subdivisions of the surface to be represented using a set of polygons. The mesh of our model was built in the standard Model Builder interface of Comsol Multiphysics 5.3a software. The building was meshed using 861 points, 68896 degrees of freedom tetrahedral (DOF), 9154 triangles and 89 point elements. The finer the mesh, the smaller the gaps between simulation and reality. A finer mesh allows to have more precise results of the solutions of the equations.

3.2 Thermal behaviour of the foamed concrete building

3.2.1 Evolution of temperatures on each side of the walls

Figure 5 illustrates the thermal behaviour of the different faces of the walls and roof of the building. The East and West walls being more exposed to the sun during the day naturally have higher external temperatures than those of the North and South walls. This is how we placed the door on the north wall and the window on the south wall to avoid exposing the openings on the sunniest sides. The thermal inertia of walls plays an important role in the search for materials that contribute to the thermal comfort of buildings. Indeed, a strong thermal inertia shifts the maximum of the internal temperature to the hours when the outside temperature is the lowest.



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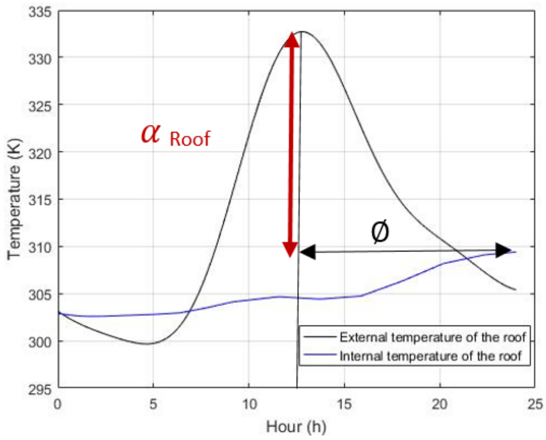

Figure 5: Evolution of temperatures of the inner and outer faces of walls, phase shift and thermal damping

Table (1) presents the results of the simulation of the phase shift, thermal damping and damping factor of the different faces of the walls and roof of the building.

Table 1: Summary of the results of the simulation of the thermal behaviour of the walls (walls)

Wall	East	West	South	North	Roof
Phase shift (h)	11.5	9	10.5	10	11
T_{ext} max (K)	324	330	324	322,5	332.5
T_{ext} min (K)	299	300	299	300	300
T_{int} max (K)	308	309	307.5	306.4	309.5
T_{int} min (K)	303	302.5	303	303	303
Damping or reduction of thermal amplitude ΔT (℃)	16	21	16.5	16,1	22.5
Depreciation or reduction factor (%)	20	22	18	15	22

Figure (5) shows a very important thermal phase shift and damping regardless of orientation. The thermal phase shift is always greater than 9 hours with a damping factor varying between 15% and 22% characterizing a good internal thermal stability.

3.2.2 Evolution of the average internal air temperature

Figure (6) shows the evolution of the average temperature inside the building for various wall thicknesses. The walls of the building are made of monolayer with foamed concrete bricks of density of 930 kg/m^3, mechanical strength of 3.4 MPa, thickness e equal to 17.5 cm without coating. The outer faces of the walls are subject to conditions of variable solar flux. In order to determine the thermal performance of foamed concrete, we simulate internal temperature variations as a function of envelope thickness.

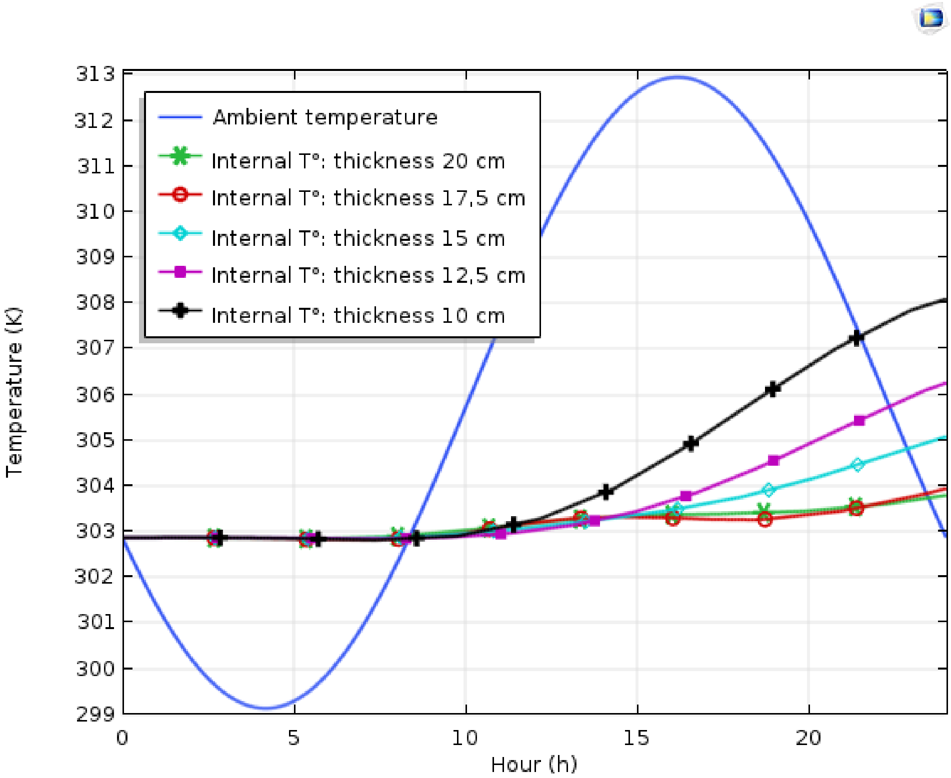

Figure 6: Average internal temperature of the building as a function of time of each wall thickness

In Figure (6), we present the variations in the average internal temperature of the building as a function of time for each thickness. A series of thicknesses (e=10cm, e=12.5cm, e=15cm, e=17.5cm and e=20cm) is tested to have an optimal thickness (maximum thermal insulation with minimum thickness) of the foamed concrete in the construction.
From 10:30 mn, the internal average temperature curves for the various envelope thicknesses grow faster. It is noted that for thicknesses greater than or equal to 17.5 cm, the average internal temperature of the building practically no longer varies; this is the optimal thickness.

3.2.3 Comparison of the average internal temperature of foamed concrete with other local materials

Table (2) below shows some thermal properties of local materials [16][17][18] that will be used as a comparison with foamed concrete.

Table 2: Thermal properties of local materials

Materials	Thermal conductivity λ (W/m.K)	Density ρ (kg/m^3)	Mass Capacity C_p (J/kg.K)
Carved Laterite Block (CLB)	0.469	1853	943
Adobe	0.556	1835	1417
Compressed Earth Block (CEB)	0.671	1960	1492
Hollow Cinder Block	0.833	1000	1000

Figure (7) below shows the comparison of the average internal temperatures of foamed concrete with other materials.

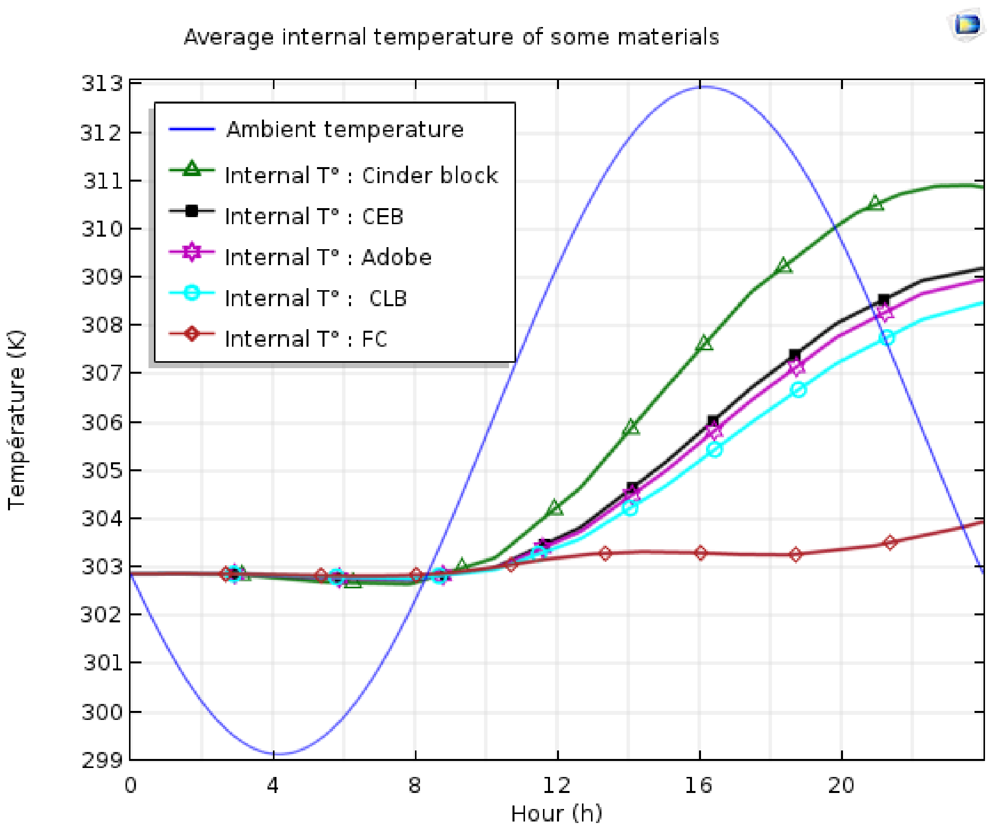

Figure 7: Comparison of the average internal temperature of the building according to materials (foamed concrete, CLB, CEB, Adobe and cinderblock)

Figure (7) shows the comparison of the internal average temperatures of some materials. These are cement cinderblock, CEB, adobe, CLB and foamed concrete. For a thickness of 17.5 cm, these materials have respectively maximum internal average temperatures of 311 K; 309.2 K; 309 K; 308.5 K and 304 K. We see a large temperature difference between foamed concrete and other materials ranging from 4.5°C to 7°C. Our results obtained with local materials are similar to those obtained by E. Malbila, [19] Fati Amadou, [20] and A. Compaoré [21]. The results of their work show that the average internal temperature of cement cinder block varies from 310.5 to 311.8 K; CEB from 308 to 311.65 K; Adobe 308.5 to 309 K; the CLB from 308 to 311.07 K. Thus, it is concluded that the foamed concrete studied is a very good insulator.

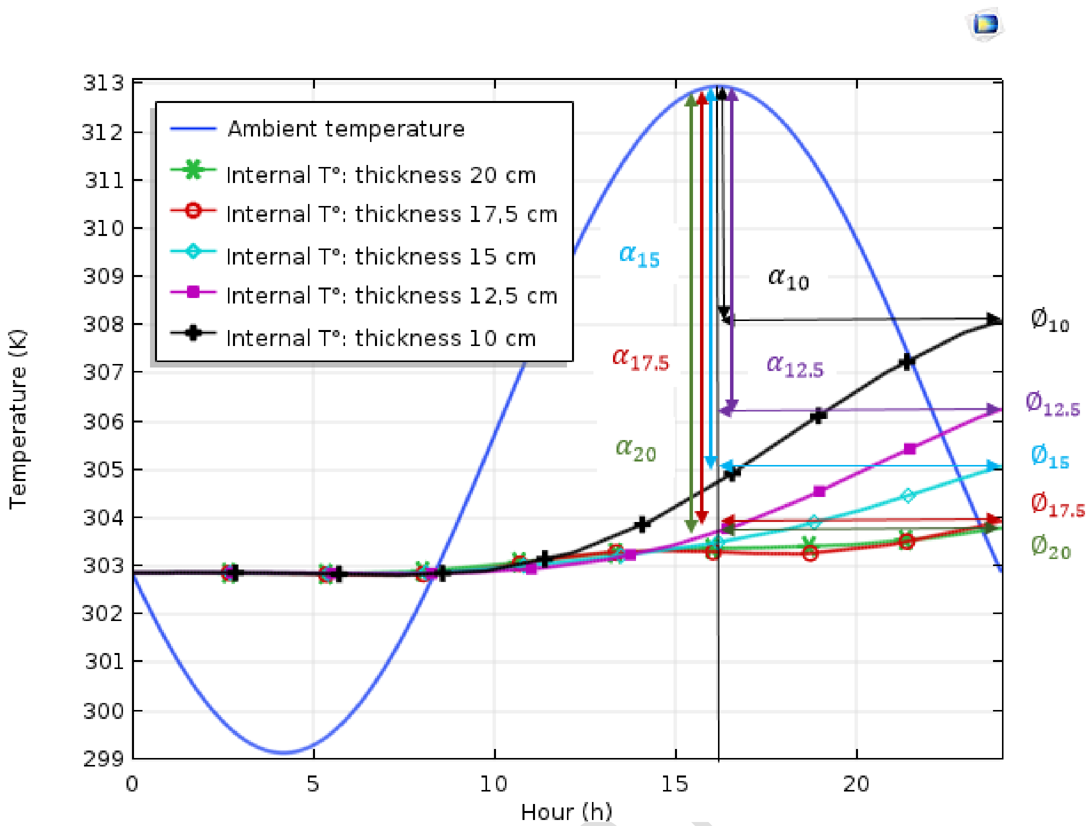

Figure 8: Determination of the phase shift and thermal damping of the internal building (foamed concrete)

During periods of high heat, the thermal phase shift of materials is very important for thermal comfort in habitats. A material that has a high thermal phase shift has a small variation in the interior temperature of the building. Figure 8 shows the evolution of the curves of the internal average temperature as a function of time for each thickness. The phase shift and thermal damping of the internal air in relation to the ambient environment were determined (see Figure 8).

Table 3: Phase Shift and Thermal Damping for a 24-Hour Period

Thickness	10 cm	12,5 cm	15 cm	17,5 cm	20 cm
Thermal phase shift	8	8	8	8	8
T_{ext} (K) max	313	313	313	313	313
T_{ext} (K) min	299	299	299	299	299
T_{int} (K) max	308,1	306,2	305	304	303,8
T_{int} (K) min	302,8	302,8	302,8	302,8	302,8
Damping or reduction of thermal amplitude ΔT (°C)	4,9	6,8	8	9	9,2
Depreciation or reduction factor (%)	37,9	24,3	15,7	8,6	7,1

The minimum value of the ambient temperature and the average internal temperature of each thickness is 302.8 K or (31 °C). For phase shifting, we have a minimum period of 16 hours up to a maximum period of 24 hours. For duration of 24 hours, the thermal phase shift remains almost equal. For a period of 24 hours, the thermal phase shift of the material obtained for each thickness is about 8 hours. The damping or reduction of thermal amplitude increases from 4.9 to 9.2 °C and the damping factor decreases from 37.9 to 7.1%. As the thickness of the wall increases, the damping factor decreases.
Amadou Fati 2021, [21] did similar work on cement cinderblock, CEB, adobe and CLB. The BLT appears to be the most efficient with a phase shift of 6 hours, an amplitude reduction of 5 ° C and a damping factor of 40.56% for a thickness of 20 cm, against respectively, 8h, 9.1 ° C and 7.1% for our foamed concrete with a thickness of 17.5 cm.
A low damping factor provides fewer internal temperature fluctuations [22]. We also notice that the lower the damping factor, the greater the thermal amplitude and phase shift. This good thermal inertia significantly reduces energy consumption. The material studied therefore has thermo-physical properties that are then an asset for obtaining thermal comfort in buildings in the Sahelian zone.

4. CONCLUSION

Our work consisted in simulating the thermal behavior of a habitat composed of a single room built with foamed concrete in order to compare its thermal performance with that of other materials used locally. The results show that from a thickness of at least 17.5 cm of the walls, the average internal temperature of the building practically no longer varies. The interior environment has a fairly low average internal temperature of 304 K and a thermal phase shift of 8 hours. The thermal amplitude damping is 9 °C with a damping factor of 8.6%. On the other hand, for cinderblock, CEB, adobe and CLB have average internal temperatures of 311 K, 309.2 K, 309 K, and 308.5 K respectively. Thus, foamed concrete, due to its highly insulating properties, makes it possible to strongly dampen temperature peaks while improving thermal comfort in the building.

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