Improving the thermal comfort in hot region through the design of walls made of compressed earth blocks: an experimental investigation

Césaire Hema [a, b, *], Adamah Messan [a], Abdou Lawane [a], Doma Soro [a], Philbert Nshimiyimana [a, c], Geoffrey van Moeseke [b]

[a] *Laboratoire Eco-Matériaux et Habitat Durable (LEMHaD), Institut 2iE, Rue de la science 01 BP 594 Ouagadougou, Burkina Faso*

[b] *Architecture et Climat, Université catholique de Louvain (UCLouvain), Place du Levant 1, 1348 Louvain-la-Neuve, Belgium*

[c] *Urban and Environmental Engineering (UEE), Université de Liège (ULiege), Allée de la Découverte, 9, 4000 Liège, Belgium*

Abstract

There is growing need for new buildings to support the urbanization and demographic boom in developing countries. These buildings should be environmentally friendly, economically accessible and, most importantly, thermally efficient. The latter aspect is particularly important when dealing with naturally ventilated buildings in hot-dry regions. For this purpose, the thermal design of walls based on compressed earth blocks (CEB) need to be studied in order to achieve optimal use of this material. The present study aimed at experimentally analysing the ~~indoor~~ thermal performance of a test building which has three different design (wall layers) of external wall and two scenario of ventilation. Thermal sensors was used on the test building in order to determine the indoor and outdoor air temperature as well as the surface temperature of the walls. The results show that the location of wall layers influences the indoor climate. When CEBs layer is placed inside, it leads to the highest reduction of the indoor temperature fluctuations. When CEBs layer is placed outside, it presents the best opportunity to prevent overheating in building spaces mainly occupied at night. Regardless of the wall design, nocturnal ventilation is the most suitable strategy which leads to improving the indoor climate compared to continuous ventilation. It is highlighted that the occupancy pattern of the buildings' spaces as well as the addition of the insulation layer to the CEBs walls are important factor to consider for the design of external walls.

Keywords: compressed earth block, hot-dry climate, nocturnal ventilation, thermal comfort, wall design.

[*] Corresponding author.
Email: cesaire.hema@2ie-edu.org, cesaire.hema@gmail.com (Césaire Hema)

1. Introduction

The thermal comfort of buildings is one of the most important requirements that building designers must address in order to ensure the quality of the indoor environment, given that it impacts the productivity as well as the health of users [1, 2]. The achievement of thermal comfort of buildings in developing countries may be a tall order to fill due to the limited access to required products, extreme environmental conditions and limited financial capacity. Although the residential buildings represents up to 60-70% of total energy consumption at global scale, in developing countries, especially in sub-Saharan Africa, the energy consumption related to the operation of buildings is very low [3]. Indeed, the energy in built environment, in this part of the world, is mainly used for primary needs such as lighting instead of controlling the indoor thermal environment. In sub-Saharan African countries, having hot dry climate, the mitigation of indoor climate is based on vernacular and local architectural techniques such as eaves, blinds, high thermal inertia of materials and nocturnal ventilation of the buildings. These techniques, known as bioclimatic design principles, allow to reduce the heat transfer from the outside to indoor environment [4, 5]. The bioclimatic architectural options combines at the same times the environmental protection using local materials and the appropriate design of the building by considering climatic constraints. Therefore, the optimal design of building walls should help improve the thermal comfort especially since there are no standards relating to the thermal regulation of building materials in these countries. Considering the limited economic capacity of the population, a suitable wall should use low-cost materials such as compressed earth blocks (CEBs).

Earlier in the 60's, Givoni [6] theorized the building design principles in hot regions, noting that traditional architecture used heavyweight materials and thick exteriors walls and roofs to damp the temperature fluctuations at a level close to the average external temperature. The use of high thermal mass of external walls is an effective method to prevent overheating, thanks to its capacity to store heat, especially in buildings with a recurrent use pattern [7]. It has been particularly shown that the high thermal mass of external wall is effective for improving the indoor climate of buildings in Burkina Faso [5, 8].

Moreover, providing the walls with a thermal insulation layer can allow to improve the thermal comfort of the occupants of the building and also reduce the energy demand for cooling [9]. In fact, in hot climate, the wall should not be homogeneous but be made of several layers having different thermal properties [10]. Therefore it raises the question about the appropriate location of different layers in wall, i.e. thermal mass layer and thermal insulation layer. Givoni [6] stated that if a heavyweight layer is provided with an external layer of an efficient insulating material, the heat flow during the day from external to internal environment is restricted by the insulation and only a small proportion of the potential heat is absorbed in the element. Al-Sanea *et al*.[11] reached the same conclusions. In climatic conditions where the heat is transmitted to the interior space (heat gain) as well as outside the space (heat loss), placing high thermal mass layer inside and insulation layer outside provides more damping of load fluctuation and smaller peak load of the inner surface heat flow. Eben Saleh [12] investigated the effect of insulation material on the thermal performance of building in hot-dry climate and showed that better performance was achieved by locating the insulation layer on the outer side of the building envelope. Under the climatic condition of Turkey, Meral Ozel [13] investigated the effect of insulation location on the heat transfer characteristics of building and showed that wall with outside insulation gives the smallest fluctuation. Through a review of the literature on thermal inertia, Verbeke and Audenaert [14] concluded that in most buildings and climates, higher amounts of thermal mass at the inner side appears to be beneficial with regard to improving the thermal comfort.

However, depending on the parameters such as the occupant behaviour or air conditioning mode, other studies showed that the reverse construction system, i.e. placing the thermal mass layer outside and insulation layer inside provides better thermal performance. Bojic and Loveday [15] studied the impact of wall layers location. The authors performed a thermal simulation on a box with fixed wall thickness and U-value of 0.142 $W.m^{-2}.K^{-1}$. They showed that a wall with thermal insulation at the inner side can reduce

energy consumption by up to 40% in case of intermittent heating. On the basis of thermal simulation analysis, Kolaitis *et al.* [16] compared the impact of the location of thermal insulation, i.e. external or internal insulation, on the energy efficiency of residential buildings in warm climate. Two scenarios were considered: passive occupant behaviour (no movable shadings and closed window) and active occupant behaviour (movable shadings and night ventilation). They showed that the cooling energy demand of the building with internal thermal insulation is lower than that of the building with external thermal insulation in the passive behaviour scenario. On the contrary, the external thermal insulation performed better than internal thermal insulation in the active behaviour scenario. Tsilingiris [17] investigated the effect of spatial location of heat capacity and thermal resistance layers of walls exposed to harmonically time-varying conditions. The author showed that locating the thermal resistance inside leads to the suppression of room temperature swing. Al-Sanea *et al.* [18] recommended the insulation layer inside for spaces with intermittent cooling system. In another study [19], the authors state that the energy consumption in building is practically unaltered with regard to the location of insulation layer. A particular attention should be given to the high thermal mass walls coupled with a thermal resistance in order to take advantage of the cool climate at night in naturally ventilated buildings.

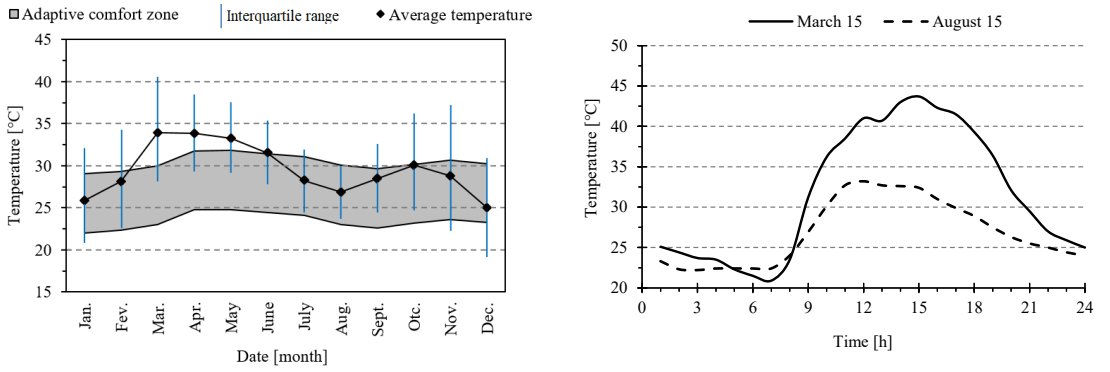
In summary, it can be noticed that there is a growing interest in determining the appropriate locations of the thermal layers in walls. However, the previous studies were carried out on thermal simulations or theoretical investigations and essentially were concerned with conditioned buildings, with the particular interest of saving the operating energy. The dependence between various parameters, the dynamic interactions between external walls and the environmental context introduces gap between thermal simulation and real case [20, 21]. Therefore, there is a need for more experimental studies to investigate the relative position of thermal mass and insulation layers in building walls, especially in buildings without air conditioning systems in hot-dry regions. The present study aims at analysing and comparing, at real-scale, the thermal performance of external walls in order to improve thermal comfort and prevent overheating in residential buildings. A particular attention is given to the definition of design solutions for future affordable and low-carbon buildings in developing countries such as Burkina Faso.

2. Methodology

Firstly, the climatic information of Burkina Faso is presented. Secondly, the wall materials are determined based on the global and local context. Thirdly, the experimental building as well as measuring equipment and measured parameters are described. Fourthly, the investigated wall designs are presented. Then, the mode of indoor air change applied to the building are presented. Finally, the parameters related to the assessment of overheating are introduced.

2.1. Climatic information

Burkina Faso is divided into three different climatic regions: the northern desert region, the central sudano-sahelian and the southern savannah region with monthly average temperature ranging between 22.6 °C and 35.5 °C [22]. Ouagadougou, the study area, is located in the central sudano-sahelian region. It has a monthly average temperature ranging between 25 °C and 34 °C and the average relative humidity which ranges between 14 % and 58 %, except during the rainy season where it can reach 80 %. Fig 1 (a) shows the evolution of the exterior air temperature. It also shows the thermal comfort zone according to the adaptive theory [23]. It is clear that the overheating in buildings is the most concerning given that there is almost no risk of discomfort due to the low temperature. The typical profile of daily temperature is shown in Fig. 1 (b) for two days, one in the hottest month of March and another during the rainy month of August. The high thermal amplitude between the day and night allows to consider nocturnal ventilation as strategy to improve the indoor climate.



(a) (b)

Fig. 1. Evolution of the exterior air temperature in Ouagadougou at (a) an annual scale and (b) a daily scale (TMY2)

2.2. Material of interest

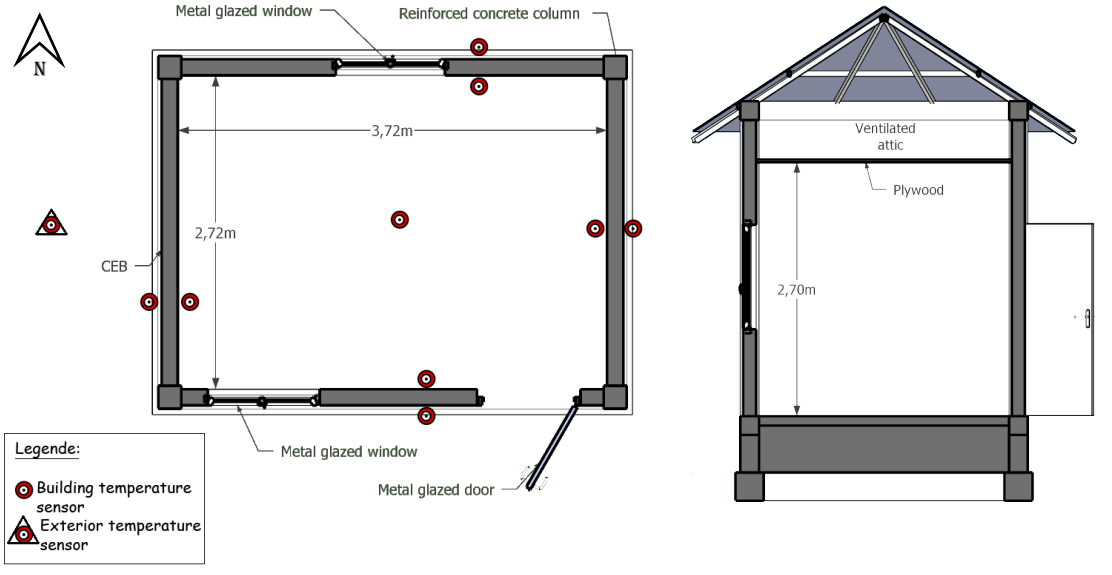
The building materials have an impact on greenhouse gases emissions through the operating and embodied energy of buildings. It is possible to reduce the CO_2 emissions up to 30% in the construction phase, through a careful selection of low environmental impact materials such as local material [24]. In regard to the local context, the available materials used for wall construction in Burkina Faso are mainly hollow concrete blocks, laterite building stones and stabilized compressed earth blocks (CEBs) [25]. It is shown that the hollow concrete blocks and stone blocks have higher embodied energy than stabilized soil blocks [26]. CEBs are strong alternatives to the classical materials used in urban zone of Burkina Faso, in sense that they are cheaper, reduce the energy required for construction and the embodied impacts of earth building are almost half of Portland cement building [7, 27, 28]. Furthermore CEBs fulfil the thermal mass function of wall which leads to the reduction of the operating energy of buildings [29]. From these advantages, CEBs were considered for the thermal mass layer in the current study. The insulation material used is glass wool given the limited market. It is the only commercial and ready-to-use insulation material for construction in the local context.

2.3. Test building and measured parameters

The experimental study was conducted on a pilot building located at “Institut 2iE”, Ouagadougou, Burkina Faso. The building consists of a single room of approximately 10 m². The openings of the building consist of two windows and one door, both made of metallic and glazed system. The two windows are on opposite façades oriented on S-N direction. From the outside to the inside of the building, the roofing system consist of aluminium metal sheet of 35/100 mm thick, a naturally ventilated attic and a ceiling made of plywood 3 mm thick. The building does not have internal heat sources and was not occupied during the experimentation. Although the dimensions of the pilot building are not representative of urban constructions, it seems to be a good compromise between experimental investigation and real-scale houses. Similar test cells were used by other authors to deal with indoor climate mitigation [5, 30, 31].

The climatic parameters were collected using thermal sensors placed inside the pilot building, on the walls and outside of the building. The measurements were recorded every hour. The values of the temperature of interior and exterior air were recorded using sensors type PT100 “TH of Waranet Solution”. They have an error margin of 0.12 °C for measurement recorded at 30.12 °C. The sensor for the measurements of exterior conditions was placed in an aerated box in order to protect it from the solar radiations. The interior sensor

was placed on a support in the middle of the building, 1.1 m high from the floor. The values of the temperature on the wall surfaces were recorded using sensors directly placed on the surface, and isolated from the influence of solar radiation or ambient air using glass wool. They are sensors type PT100 “TG of Waranet Solution”, which have an error margin of 0.36 °C (measurement recorded at 30.12 °C). Fig. 2 presents the positions of the sensors of temperature in the pilot experimental building.



(a) (b)

Fig. 2. Experimental building : (a) floor plan and (b) section plan

2.4. Wall configurations

Taking into account the available local materials, three designs of walls were implemented. (i) The double layer wall which has a thermal mass layer (i.e. CEB layer) placed on the inner side of the wall and the insulation layer (i.e. glass wool) outside, namely “CEB_{in}”. Throughout the present study, “CEB_{in}” was referred to as the wall or as the building related to this design. (ii) The double layer wall with the thermal layer placed on the outside and the insulation layer inside, namely “CEB_{out}”. The steady state thermal resistance of the two double layer walls is $R = 0.45\ m^2.K.W^{-1}$. A plywood layer was used as assembly and protection system for the insulation layer. (iii) The single layer wall made of 14 cm thick CEBs, namely “CEB”. This is the reference wall of the building. The steady state thermal resistance of the wall is $R = 0.31\ m^2.K.W^{-1}$. Table 1 shows the three designs of the wall. The designation “1” is related to the CEB layer, “2” to the insulation layer and “3” to the plywood used as protection of the insulation layer. Table 2 summarizes the thermal properties of the layers. Based on the building material and the colour (reddish brown, as it appears in table 1), it is assume that the solar absorptivity of the external surfaces of walls are quasi-similar and thus, the thermal response of the building is more controlled by the thermal properties of layers.

The dynamic thermal behaviour of the wall which affects considerably the thermal performance of buildings is associated with various physical and design parameters like the heat capacity, thermal resistance and also their space distribution with respect to the direction of the heat flow [17]. Considering one-directional heat transfer of a plane wall made of homogenous and isotropic *n*-layers, the heat transfer

177 matrix (Z) based on quadrupoles method allowed connecting the complex amplitudes of temperature ($\tilde{\theta}_i$)
178 and heat flow density ($\tilde{q}_i$) of both side of the wall as shown in equation (1) [32, 33].

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \times \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \times \ldots \times \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} \text{ and } \begin{bmatrix} \tilde{\theta}_2 \\ \tilde{q}_2 \end{bmatrix} = Z \cdot \begin{bmatrix} \tilde{\theta}_1 \\ \tilde{q}_1 \end{bmatrix} \quad (1)$$

179 Where, $\tilde{\theta}_1$ and $\tilde{q}_1$ are respectively the complex amplitudes of temperature and heat flow density of the inner
180 side, $\tilde{\theta}_2$ and $\tilde{q}_2$ respectively the complex amplitudes of temperature and heat flow density of the outer side,
181 A_i the element of heat transfer related to layer i, Z_{mn} the element of heat transfer matrix.

182 The relative position of layers (i.e. matrix $\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}$) in wall determine the values of heat transfer matrix
183 elements (Z_{mn}). Placing the thermal mass layer on the inner side of the wall, i.e. CEB_{in}, lead to a greater
184 internal areal heat capacity (k) than placing the thermal mass on the outside, i.e. CEB_{out}, given that the
185 values of Z_{11} and Z_{12} depends on the wall layering (equation (2)). Given that the periodic thermal
186 transmittance and the decrement factor are independent of the wall layering (not considering the surface
187 resistances), the relative position of layer result in the adjustment of the value of the internal areal heat
188 capacity.

$$k = \frac{T}{2\pi}\left|\frac{Z_{11} - 1}{Z_{12}}\right| \quad (2)$$

189 Where, T is the period of variation which is taken to be one day, i.e. 86400 s.

190 Ultimately, the indoor air temperature, θ_{in}, is linked to the interior surface temperature of the wall, θ_1. In
191 others words, the wall layering which influence the values of θ_1 also influence the indoor climate. The
192 energy balance of the test building is described through equation (3) [34].

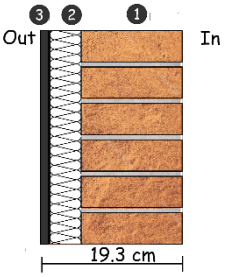
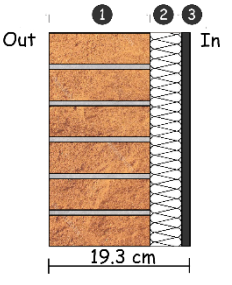
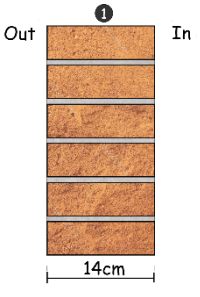
$$\rho \cdot c \cdot V \cdot \frac{d\theta_{in}}{dt} = \sum A \cdot \alpha(\theta_1 - \theta_{in}) + \dot{Q}_{sol} + n \cdot V \cdot \rho \cdot c\ (\theta_{ext} - \theta_{in}) \quad (3)$$

193 Where, ρ is the density of air [kg.m^{-3}], α the heat transfer coefficient [W.m^{-1}.K^{-1}], θ_{in} the indoor air
194 temperature [°C], θ_{ext} the exterior air temperature [°C], θ_1 the interior surface temperature, A the surface
195 area [m²], c the heat capacity of air [J.kg^{-1}.K^{-1}], n the air change per hour [h^{-1}], $\dot{Q}_{sol}$ the solar input which
196 leads directly to an increase of the air temperature or furniture [W], t the time [s], V the volume of the room.

197 The three wall designs were implemented for all the facades of the building. To switch from one wall design
198 to another (e.g. from CEB_{in} to CEB_{out}) the insulation layer is disassembled on the side on which it was
199 initially placed (i.e. outside) and reassembled on the opposite side (i.e. inside). Except the walls, all the
200 building components such as the roof and the floor were not insulated.

201

Table 1. Illustration of the investigated designs of wall.

Designation	Wall designs	Illustration of the building
CEB_{in} U-value = 0.66 $W.m^{-2}.K^{-1}$		
andCEB_{out} U-value = 0.66 $W.m^{-2}.K^{-1}$		
CEB U-value = 3.22 $W.m^{-2}.K^{-1}$		

202

Table 2. Thermal properties of layers [35-37].

N°	Materials	Density [$kg.m^{-3}$]	Specific heat [$J.kg^{-1}.K^{-1}$]	Thermal conductivity [$W.m^{-1}.K^{-1}$]	Thickness [m]
1	Compressed earth blocks	1900	1089	1.00	0.14
2	Glass wool	20	1030	0.042	0.05
3	Plywood	560	1500	0.13	0.003

203

204

2.5. Ventilation strategies

The passive design principles of the bioclimatic approach consider proper natural ventilation as an important parameter to improve the indoor thermal quality [3, 38, 39]. The nocturnal ventilation may improve the indoor climate of buildings in Ouagadougou given the high amplitude between the day and night temperatures (see section 2.1.). In addition to nocturnal ventilation two other strategies of air change (SAC) were investigated. The scenario named SAC0 is the base case in which the windows of the building are closed all day long. The potential air exchange between indoor and outdoor environment are only due to infiltration. This strategy allow to overcome, at some extent, the impact of wind and then compare the thermal performances of walls. For SAC1 scenario, the windows are closed during the day to avoid the exterior hot temperature and open during the night to take the advantage of mild temperature. For SAC2 scenario, the windows are fully open all the day long. A continuous air exchange occur between outdoor and indoor environment. Table 3 summarizes adopted strategies of air change as well as the period during which they were applied for each wall designs of the building.

SAC1 and SAC2 have been defined in relation to the local practices. In addition to providing nocturnal ventilation, SAC1 meets a safety need. In fact, the windows and doors of the houses remain closed in the absence of the occupants (gone to work) and open on their return. SAC2 is a scenario used in houses where there are permanent occupants. It is common in the African context to generally have at least one person present at home all times. The opening of the windows then responds to a need for lighting and dilution of pollutants and odors.

During the study, some sensors were damaged. The failure of a single sensor has an impact on the measurement period since the simultaneous acquisition of data from all sensors is required. The time period of the application of each strategy of air change was 11 days instead of 21 days initially projected.

Table 3. Strategies of air change: periods of applications of each scenario for each wall design

	CEB	CEBout	CEBin	Positions of window
SAC0	2020/01/22 - 2020/02/02	2019/09/02 - 2019/09/13	2019/04/08 - 2019/04/15 ; 2019/05/01 - 2019/05/03	Closed all day long
SAC1	2020/02/04 - 2020/02/16	2019/09/23 - 2019/10/03	2019/05/18 - 2019/05/27	Closed from 06h00 to 18h00, then open from 18h00 to 06h00
SAC2	2020/02/21 - 2020/03/02	2019/10/25 - 2019/11/04	2019/04/23 - 2019/04/28 ; 2019/05/09 - 2019/05/12	Open all the day long

2.6. Definition of wall performance parameters

The existing recommendation for the assessment of overheating in buildings includes criteria based on the fixed thresholds and the adaptive thermal comfort approach. The fixed thresholds criteria is based on data from controlled climate chamber studies and is mainly applicable to particular combinations of indoor thermal conditions, occupant metabolic rate and clothing insulation levels [40]. The adaptive thermal comfort criteria is based on a movable thresholds and suggest that occupant's thermal responses depend on the outdoor ambient temperatures. Its application requires data over a certain period (no few than seven days) which represents the external climate to which building occupants have become physiologically, behaviourally, and psychologically adapted [23].

Taking the above into consideration, the assessment of overheating in the present study was based on a fixed threshold. The limited time period of each experiment (i.e. 11 days) did not allow to consider the adaptive thermal comfort approach. However, taking into account the local hot climate and the free running ventilation of buildings, the threshold was assumed to be the average outdoor temperature. Indeed, the assessment of overheating based on the number of hours above the threshold of 26 or 28 °C is more appropriate for air-conditioned buildings [41].

The *relative operative temperature* (rT_{op}) was defined as the ratio of the indoor operative temperature to the average outdoor temperature. It is calculated using equation (4). The first term of equation (4) is the operative temperature calculated as prescribed by ASHRAE [23]. The second term is the overheating threshold. Therefore, $rT_{op} > 1$ suggests that the indoor operative temperature is greater than the mean temperature of exterior air, i.e. it is hotter inside the building than outside. Thus, it is assumed that the overheating of the indoor thermal ambiance occurs when $rT_{op} > 1$. By contrary, $rT_{op} < 1$ indicates that the indoor operative temperature is lower than the mean temperature of exterior air.

$$rT_{op} = \left(\frac{\overline{T}_{surf,int} + T_{air,int}}{2}\right) \cdot \frac{1}{\overline{T}_{out}} \quad (4)$$

With, $\overline{T}_{surf,int}$ [°C]: the hourly average of surface temperature of the four walls surrounding the indoor space; $T_{air,int}$ [°C]: the hourly temperature of indoor air; $\overline{T}_{out}$ [°C]: the average outdoor temperature over the study period (i.e. 11 days).

Based on the principle of decrement factor applied to walls, the *relative decrease in the variation of the interior operative temperature* (rVT_{op}) is defined and applied to thermal environment. The decrement factor is defined as the ratio of the periodic diurnal variation of indoor surface temperature to the periodic variation of outdoor surface temperature [42]. Similarly, rVT_{op} is the ratio of the periodic diurnal variation of operative temperature to the periodic variation of outdoor air temperature. rVT_{op} was used to address the ability of walls to resist the temperature fluctuation. It is calculated using equation (5). A low value of rVT_{op} (i.e. ≈ 0) indicates an important reduction of the fluctuation amplitude of indoor temperature, compared to the fluctuation of exterior temperature.

$$rVT_{op} = \frac{T_{op,max} - T_{op,min}}{T_{ext,max} - T_{ext,min}} \quad (5)$$

3. Results

3.1. Effect of wall design and strategy of ventilation on indoor temperatures

Fig. 3 shows the evolution of the indoor and outdoor air temperature for each design of wall and for each strategy of ventilation. The values of indoor temperature evolve similarly to the outdoor temperature, oscillating between a daily high and low peak. The results on building whose walls consist of CEB_{in} (Fig. 3 (a)) shows that the indoor temperature records more important fluctuations for scenarios SAC1 (12.5 °C) and SAC2 (14 °C) than SAC0 (8.5 °C). The latter records the most stable evolution of indoor temperature, also reaching lower fluctuations compared to the outdoor temperature. The peaks of indoor temperature remain lower than the outdoor peaks, regardless the strategy of air change. The evolutions of indoor temperature for scenarios SAC1 and SAC2 record similar minimum values as outdoor temperatures. Regarding the CEB_{out} building (Fig. 3 (b)), the fluctuations of indoor temperature remain lower for SAC0 (10.5 °C) than SAC1 (13.5 °C) and SAC2 (12.5 °C). However, the values of daily indoor temperature record quasi-similar maximum values (29.9-36.8 °C) as the outdoor temperature (28.4-38.4 °C), regardless

the strategy of air change. The solar radiation effect was more noticeable when the insulation layer was placed inside, as indicated by the maximum values of the indoor temperature which is higher than that recorded outside, for most days of SAC0. Regarding the CEB building (Fig. 3(c)), the results show that the maximum values of indoor temperature are similar or higher than the maximum values of outdoor temperature.

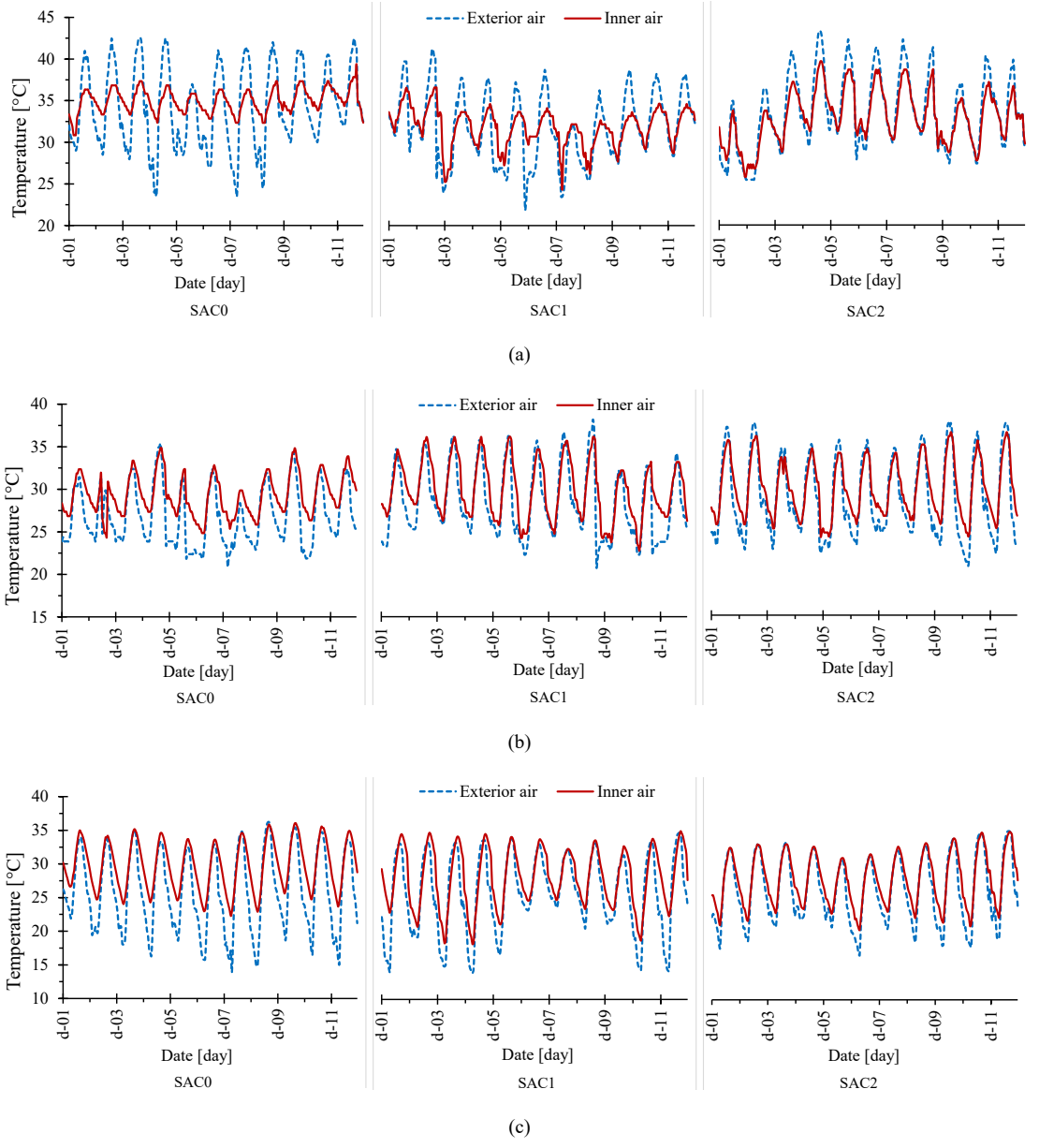
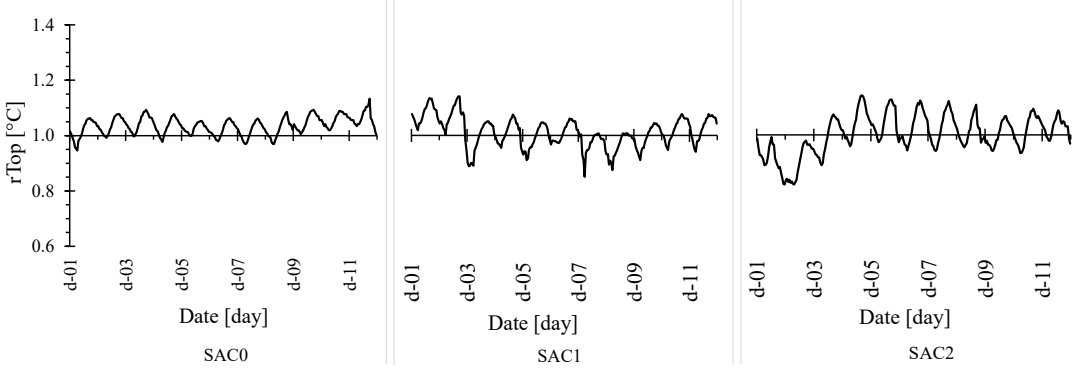


Fig. 3. Exterior and interior temperatures for the buildings made of (a) CEB_{in} (b) CEB_{out} and (c) CEB over the experimental time for different scenarios of air change.

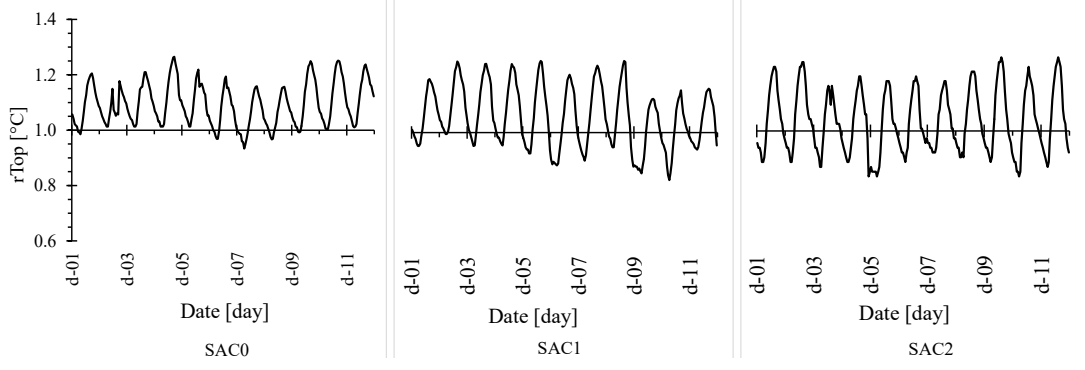
3.2. Effect of wall design and strategy of ventilation on relative parameters

Fig. 4 presents the evolution of relative operative temperature (rT_{op}) over time for different wall designs and scenarios of air change. For all wall designs, the evolution of rT_{op} under air change scenario SAC0 (i.e. no ventilation) is mostly above the threshold of 1, representing the overheating. It can be explained by the permeability of windows to solar radiation in the visible range, and their opacity to the radiation emitted by the surfaces at room temperature (infrared range) which result in greenhouse effect. The scenarios SAC1 (i.e. nocturnal ventilation) and SAC2 (continuous ventilation) allows a general decrease of the evolution of rT_{op} compared to SAC0. The lowest fluctuation of rT_{op} is provided by CEB_{in} building (0.19) as shown in Fig. 4 (a), while the highest is recorded for CEB building (0.32) in Fig. 4 (c). CEB building also records the highest and lowest peak of rT_{op} (1.36 and 0.74 respectively). The evolution of rT_{op} for CEB_{out} building (Fig. 4 (b)) always lays between both previous constructions systems.

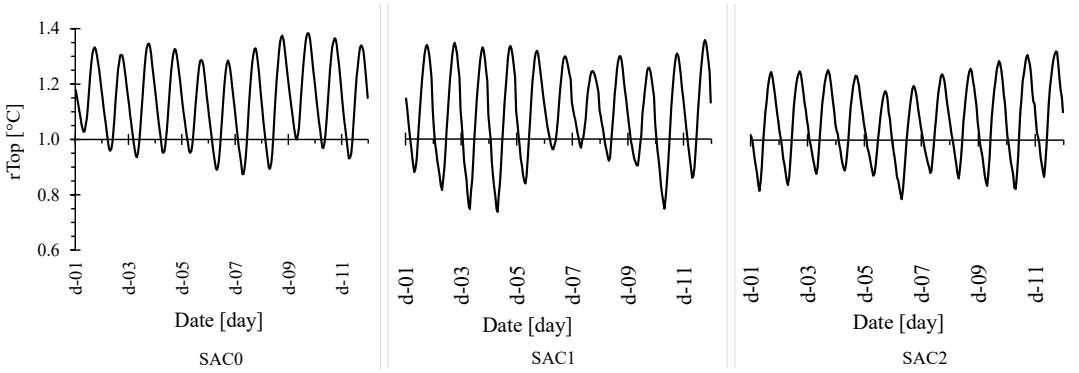
Fig. 5 shows the evolution of the relative decrease in the variation of the interior operative temperature (rVT_{op}) of the three wall designs for different scenarios of air change. The values of rVT_{op} for a defined type of wall design and scenario of air change should be quasi-constant (see equation 6). The fluctuations of rVT_{op} can be explained by the effect of other climatic variables such as the solar radiation and wind. However, the results shows that the CEB_{in} building presents lower values of rVT_{op} comparatively to CEB_{out} and CEB buildings, regardless of the ventilation strategy. The values of rVT_{op} for CEB_{in}, CEB_{out} and CEB buildings respectively lay between 0.17 and 0.60, 0.57 and 0.88 and 0.56 and 0.97. There is not a noticeable difference between the evolution of rVT_{op} for both CEB_{out} and CEB building with scenarios SAC0 and SAC2. However, with scenario SAC1, the evolution of rVT_{op} for CEB_{out} building is generally lower than that of CEB building.



(a)



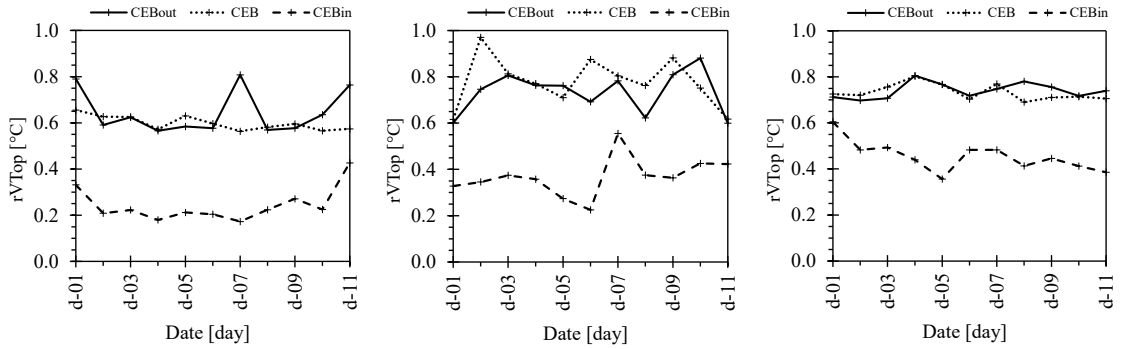
(b)



(c)

Fig. 4. Evolution of relative operative temperature under scenarios SAC0 SAC1 and SAC2 for (a) CEBin, (b) CEBout and (c) CEB building.

299



(a) (b) (c)

Fig. 5. Evolution of relative decrease in the variation of the interior operative temperature of CEB_{in}, CEB_{out} and CEB building for scenarios (a) SAC0, (b) SAC1 and (c) SAC2.

300 *3.3. Distribution of overheating*

301 Fig. 6 presents the distribution of indoor overheating as a function of the adopted ventilation strategy. For
302 the record, it is assumed that the overheating occurs when the value of rVT_{op} is greater than 1, i.e. the indoor
303 operative temperature is higher than the exterior air temperature. The values of $rVT_{op} > 1$ occurring in the
304 time period of 5am to 9pm are considered as "day time" overheating, while the $rVT_{op} > 1$ in the period of
305 9pm to 5am are considered as "night time" overheating. Therefore, Fig. 6 presents the distribution of the
306 overheating based on the previous results presented in Fig. 4, in the day or night time. The results generally
307 show that overheating in the day time contribute the most important fraction of the total overheating,
308 between 80 and 100 % depending on the wall design and ventilation strategy, towards the total overheating.
309 The scenario SAC0 (Fig. 6(a)) records the most important fraction of overheating in the night time, up to
310 21 %, compared to SAC1 and SAC2 (Fig. 6(a) and (b)). The wall design CEB_{out} leads to the almost
311 elimination of overheating in night time, while the CEB_{in} and CEB wall presents the lowest fraction of
312 overheating in the day time.

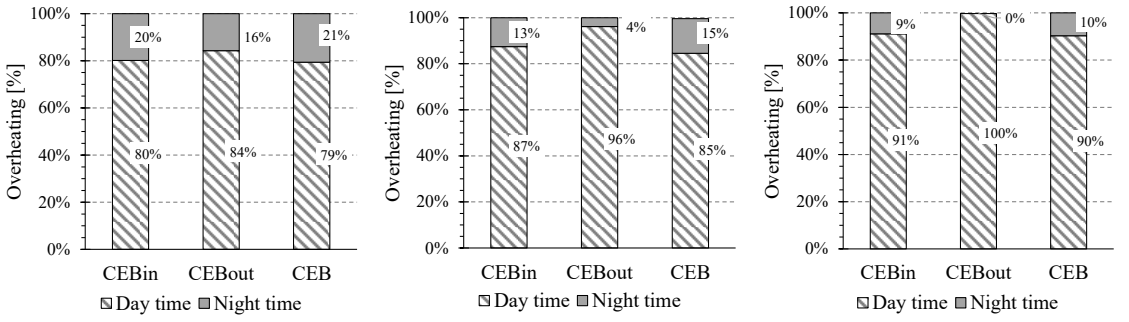


Fig. 6. Distribution of overheating as a function of the wall design for (a) SAC0, (b) SAC1 and (c) SAC2

3.4. Effect of wall design on surface temperatures

Fig. 7 presents the maximum and minimum values of temperature on the wall surfaces (external and internal) reached for each wall design oriented toward the East when applying SAC0 (see appendix A for the other orientations). It shows the gradients of temperature, between the internal and external surfaces, which are the driving force of the heat flow through the walls. The largest range of the variation of external temperature is observed for CEB_{in} (Fig. 7 (a)), related to the high fluctuation of outdoor temperature (Fig. 3 (a)) and solar radiation occurring during that period of measurement. These results also show that CEB_{in} has the highest ability to dampen the temperature. As far as the CEB_{out} and CEB walls are concerned (Fig. 7 (b and c)), the range of variation of external temperature is 12 °C, while the variation of the internal temperature is 6 °C. For the same thermal resistance R = 0.45 m².K/W, CEB_{in} provide the lowest fluctuation of internal temperature compared to CEB_{out}. This obviously shows that the relative position of layers in the wall is crucial.

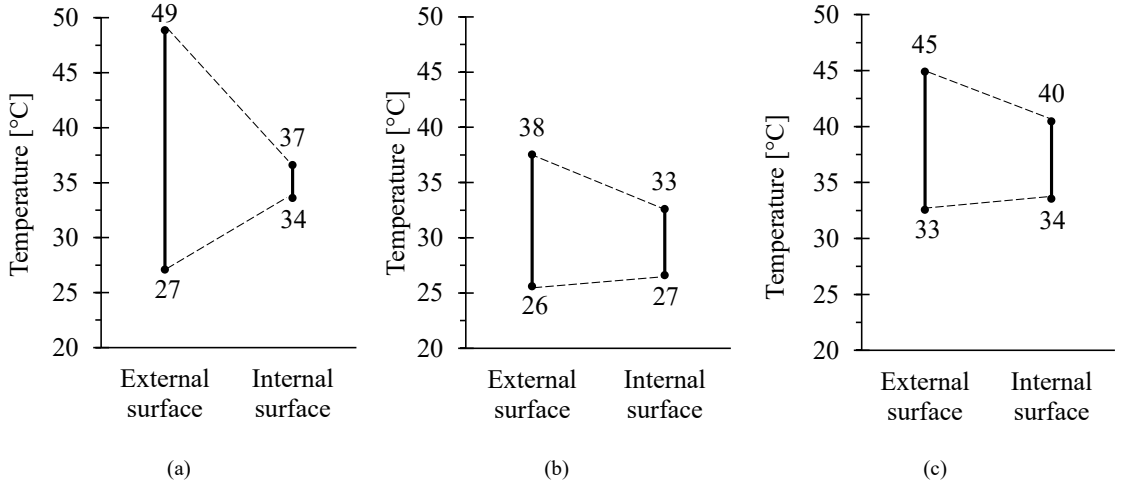


Fig. 7. Temperature range of the external and internal surface of Eastern walls under scenario SAC0 for (a) CEB_{in}, (b) CEB_{out} and (c) CEB

4. Discussion

The objective of the present study was to assess the potential of the design of wall based on compressed earth blocks to mitigate and prevent overheating in naturally ventilated building with regard to the different strategies of ventilation. The novelty of the study lies in the relative location of the CEBs layer in double layer wall of naturally ventilated building in hot-dry region, especially in Burkina Faso. The study also investigated the effects of the adopted scenario of ventilation on the indoor climate. The evolutions of indoor temperature are strongly influenced by the design of the exterior walls and outdoor temperature as well as the strategy of ventilation, as shown by Fig. 3. The CEB layer placed inside (CEB_{in}) leads to the appreciable damp of the fluctuations of indoor temperatures comparative to the inverse construction system, i.e. when the CEB layer is placed outside (CEB_{out}). The nocturnal and continuous ventilation (SAC1 and SAC2) are appropriate strategy at night for all the three wall design, leading to reducing the indoor temperature as low as the mild exterior temperature. This is more explicit in Fig. 4, where the rT_{op} frequently crossed the threshold of 1, indicating the reduction of overheating. However, the levels of overheating reached for each design of wall are not evenly distributed between the day and the night time. The night discomfort is almost non-existent in CEB_{out} building, while it occurs up to 21 % for the CEB_{in} and CEB building (Fig. 6). The best mitigation of the impact of outdoor climate on indoor temperatures is obtained when the CEBs layer is placed on the inside (Fig 5 and 7). This briefly shows that it is interesting to add an insulation layer to CEBs walls in naturally ventilated building in hot-dry regions and the relative positions of layers are crucial.

The present analysis compares three designs of walls on their ability to improve the indoor environment and prevent the overheating of residential buildings. The CEBs walls provided with additional thermal resistance layer act as thermal shield which results in less heat transmission compared to single layer CEBs wall. One of the concerns with the use of insulation material in non-conditioned building is the risk to increase the overheating. In fact, the increase of the wall thermal resistance may result in trapping the heat from the indoor environment and therefore leads to high temperatures. However, the results from the current study shows that double layer walls contribute to preventing the overheating if provided with proper ventilation and suitable location of the layer in walls. When the thermal mass layer is placed inside (CEB_{in}), it allows to absorb and store the heat from the indoor air during the day, while the resistive layer outside curbs the heat flow (through the wall) from the solar radiation and exterior air. The values of indoor temperature are generally similar to the mean exterior temperature. The result about the position of the thermal mass layer is similar to that reported by other authors [6, 7, 11-13]. However, it is highlighted herein that the CEB_{in} is particularly suitable for the rooms mainly occupied during the day time (5 a.m. to 9 p.m.), while the CEB_{out} should be considered for the rooms occupied at night (9p.m. to 5a.m.) in order to deal with the thermal comfort. When the insulation layer is placed inside (CEB_{out}), it prevents the heat absorbed by the thermal mass during the day from being released into the indoor environment at night. Therefore, if provided with nocturnal or continuous ventilation, CEB_{out} allows the mild temperature of the air to be instantly available for the thermal sensation of occupants instead of cooling the thermal mass layer. When considering the CEB_{in} wall, the heat to be removed from the thermal mass is mainly directed towards the interior environment due to the thermal resistance placed on the outside. Therefore, the potential for improving the thermal comfort provided by nocturnal ventilation is reduced as the mild outdoor temperatures are also used to cool the thermal mass. These results regarding the design of the walls as a function of the periods of occupancy have been highlighted in the literature through thermal simulation [43, 44]. The present study provides additional trends on the importance of occupancy pattern of the buildings spaces when it comes to dealing with the improvement of the thermal comfort. The occupancy profile must be taken into account during the design of external walls.

Given the hot climate, the limited financial capacity of households and the cost of energy in Burkina Faso, the occupants of modest homes will find acceptable the indoor climate during the day when the indoor temperatures are less than those outside. At night, the target is to have the indoor temperatures similar to those outside. The optimal design of the wall must meet the indoor climate requirements during the day and at night. Since the thermal behaviour of the investigated wall cannot simultaneously fulfil the two requirements, a distinction has to be made between the optimal wall for the spaces occupied during the day (i.e. CEB_{in}) and that for the spaces occupied at night (i.e. CEB_{out}).

The analysis of the local context of the building sector established the CEBs as a promising material for the construction of affordable houses in urban zone of the country [25]. Various studies have also reported the suitability of local materials for the improvement of the physio-mechanical and hygro-thermal performances of CEBs for structural and efficient applications in contemporary construction [35, 45-49]. Regarding the capacity of earth-based houses to improve the indoor thermal environment, the research studies have to be conducted to complete the characterization of the materials.

One of the limitations of the present study was not to be able to control the discharge rate of natural ventilation and to measure the solar radiation. In fact, the wind speed and direction as well as the solar radiation are among the parameters that affect the indoor climate of naturally ventilated building. Therefore, the discussions were limited to the effects of ventilation for each type of wall design, and did not compare the effects among different wall designs. Another limitation of the study was the limited number of test buildings for parallel monitoring of the thermal parameters. The outdoor climate changed between successive monitoring. This had an impact on recorded parameters related to the indoor climate. However, it is believed that the parameters in section 2.6 allowed to mitigate the influence of the variations of outdoor climate. Future studies could also carry out the monitoring of the test building over the extended period of time; this would improve the completeness of data.

Nevertheless the present study highlights the interest of coupling the earthen material, which has a high thermal capacity, with an insulation layer in naturally ventilated buildings in hot-dry regions. The holistic approach, which take into account the real variability of the climate, allowed to go beyond theoretical and simulation studies which are limited to ideal climates.

5. Conclusions

The passive design techniques of houses, including the mode of ventilation, occupant interactions with the building and design of the wall can contribute significantly to reducing the impact of buildings on the environment and improve the thermal comfort. However, in developing countries such as Burkina Faso, the design and dynamism of buildings are based on local materials and on vernacular habits. Due to globalization and the country being open to the international market, one of the challenges is to assess the opportunity offered by materials such as insulation on the improvement of the indoor climate of naturally ventilated buildings.

The present study aimed to improve the indoor comfort and prevent overheating through the design of external walls of naturally ventilated houses in hot regions. The compressed earth blocks, an improved local capacitive materials from the traditional practices, and glass wool, an industrial imported resistive material, were combined in order to assess their effect on the thermal behavior of the building. The experimental study carried out made it possible to evaluate the thermal performance of three types of wall designs and to experiment with two ventilation scenarios.

The comparative analysis showed the thermal advantages offered by the different walls. The building whose external walls are made of CEBs layer on the inside and insulation layer on the outside (CEB_{in}) provides the best opportunity to reduce the overheating during the day time. This design provides the lowest

fluctuation of internal surface temperatures of walls. The walls consist of CEBs layer on the outside and the insulation layer on the inside (CEB_{out}) are suitable for the building spaces mainly occupied during the night, when the building is provided with the free night ventilation. The interaction of the occupants with the houses in the local context mainly involves two scenarios of ventilation: the night ventilation and continuous ventilation. These scenarios allow to improve the indoor climate.

This study presents important advances for the resiliency of future constructions towards climatic conditions and the consumption of resources. Future investigations should focus on more environmentally friendly insulation materials than the glass wool used in the present study. Alternatively, the studies can be oriented toward the usage of local and plant fibers or residue of paper cellulose. This are general perspectives to preserve the environment and depletion of non-renewable resources and integrate the circular economy in the local construction techniques. The effect of solar radiation in the climate of Burkina Faso represents a significant fraction of heat gain in buildings. Therefore, it is necessary to conduct additional studies on the design of window shading devices as well as the design of the roof in order to further address the issue of improving the thermal comfort of houses. One of the weakness of CEBs is their sensitivity to water. Indeed, the resistance and durability of these blocks are affected by water absorption. Therefore, it is essential to carry out further studies with regard to increasing the water resistance of CEBs.

Acknowledgements

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Appendix A. Surface temperatures of external wall

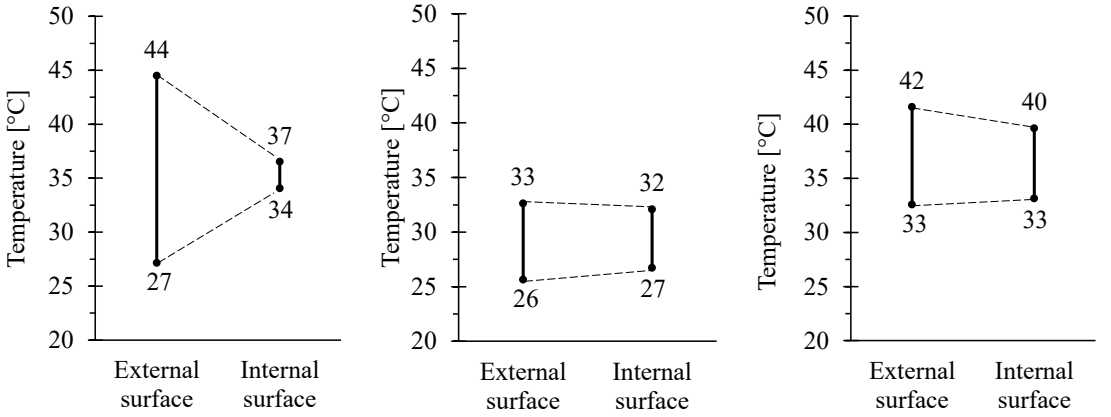


Fig. A1. Temperature range of the external and internal surface of Northern walls under SAC0 for (a) CEB_{in}, (b) CEB_{out} and (c) CEB

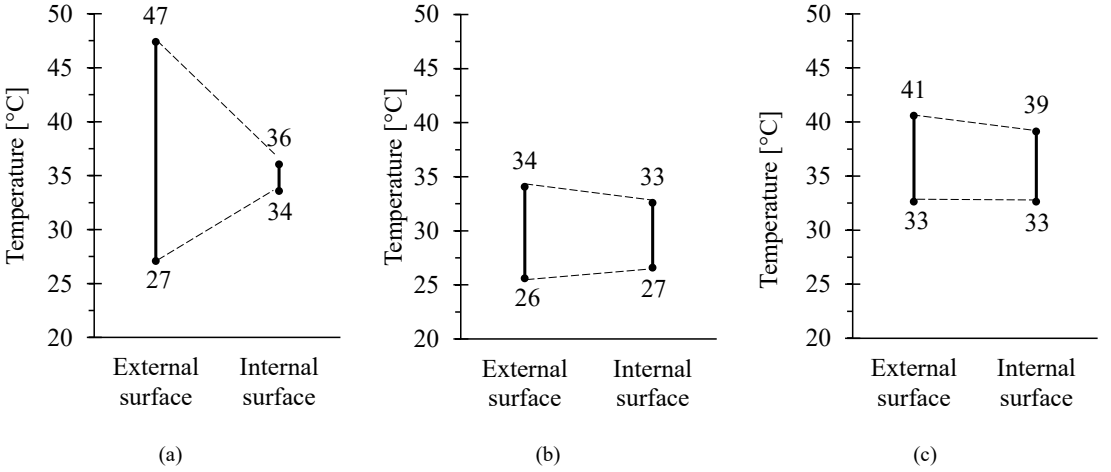


Fig. A2. Temperature range of the external and internal surface of Southern walls under SAC0 for (a) CEB_{in}, (b) CEB_{out} and (c) CEB

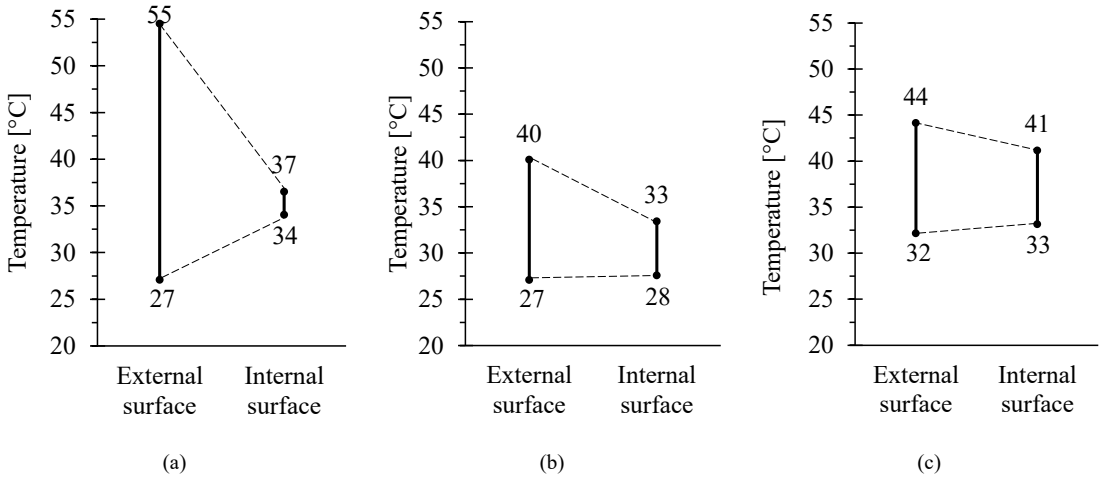


Fig. A3. Temperature range of the external and internal surface of Western walls under SAC0 for (a) CEB_{in}, (b) CEB_{out} and (c) CEB

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