Scientific Research Publishing

Journal of Minerals and Materials Characterization and Engineering, 2024, 12, 1-16
https://www.scirp.org/journal/jmmce
ISSN Online: 2327-4085
ISSN Print: 2327-4077

Optimisation of Thermal Comfort of Building in a Hot and Dry Tropical Climate: A Comparative Approach between Compressed Earth/Concrete Block Envelopes

Arnaud Louis Sountong-Noma Ouedraogo*, Césaire Hema, Sjoerd Moustapha N'guiro, Philbert Nshimiyimana, Adamah Messan

Laboratoire Eco-Matériaux et Habitat Durable (LEMHaD), Institut International de l'Ingénierie de l'eau et de l'environnement (Institut 2iE), Rue de la science 01 BP 594 Ouagadougou, Burkina Faso

Email: *louis.ouedraogo@2ie-edu.org

How to cite this paper: Ouedraogo, A.L.S.-N., Hema, C., N'guiro, S.M., Nshimiyimana, P. and Messan, A. (2024) Optimisation of Thermal Comfort of Building in a Hot and Dry Tropical Climate: A Comparative Approach between Compressed Earth/Concrete Block Envelopes. *Journal of Minerals and Materials Characterization and Engineering*, **12**, 1-16.
https://doi.org/10.4236/jmmce.2024.121001

Received: December 13, 2023
Accepted: January 26, 2024
Published: January 29, 2024

Abstract

Compressed earth blocks (CEB) are an alternative to cement blocks in the construction of wall masonry. However, the optimal architectural construction methods for adequate thermal comfort for occupants in hot and arid environments are not mastered. This article evaluates the influence of architectural and constructive modes of buildings made of CEB walls and concrete block walls, to optimize and compare their thermal comfort in the hot and dry tropical climate of Ouagadougou, Burkina Faso. Two identical pilot buildings whose envelopes are made of CEB and concrete blocks were monitored for this study. The thermal models of the pilot buildings were implemented in the SketchUp software using an extension of EnergyPlus. The models were empirically validated after calibration against measured thermal data from the buildings. The models were used to do a parametric analysis for optimization of the thermal performances by simulating plaster coatings on the exterior of walls, airtight openings and natural ventilation depending on external weather conditions. The results show that the CEB building displays 7016 hours of discomfort, equivalent to 80.1% of the time, and the concrete building displays 6948 hours of discomfort, equivalent to 79.3% of the time. The optimization by modifications reduced the discomfort to 2918 and 3125 hours respectively; *i.e.* equivalent to only 33.3% for the CEB building and 35.7% for the concrete building. More study should evaluate thermal optimizations in buildings in real time of usage such as residential buildings commonly used by the local middle class. The use of CEB as a construction material and passive means of improving thermal comfort is a suitable ecological and economical option to replace cementitious material.

Keywords

Compressed Earth Blocks, Hot and Dry Climate, Thermal Comfort, Architectural Optimization of Thermal Models, Cement Blocks, Empirical Validation

1. Introduction

West Africa is experiencing large growth in urban cities. The 2014 forecasts predicted a population increase of 50% in 2020 and 66% in 2050 [1]. Burkina Faso, a West African country, has a deficit in natural resources and is in an extreme, arid and tropical climate depending on the season. However, the country faces a hot and dry climate with maximum temperatures of nearly 40˚C in 2015 [2] and remains constantly growing [3]. It then becomes essential to be able to offer local residents affordable, healthy and thermally comfortable housing, and adapted to increasingly severe climatic conditions [4] [5].

Cementitious materials are very popular today in Burkina in construction, due to their good suitability to strict regulations regarding construction materials. However, the energy and ecological issues linked to this material are pushing the search for new alternatives. In fact, 4 billion tons of cement are produced worldwide with an annual growth of 4% [4]. This intensive production would be responsible for emissions of 45.45 billion tons of CO_2 globally in scenario 3 of shared socio-economic pathways [6]. In addition, the cement manufacturing process requires high energy consumption due to the calcination of the clinker at 1400˚C - 1450˚C and its grinding.

Earthen materials such as compressed earth blocks (CEB) have been the subject of many studies in recent decades as a suitable alternative to cementitious materials. These studies focused on the social perception of these materials [7], their potential to meet construction standards [8], their thermo-physical properties [9] and their durability [4] [10]. Despite the various advantages of the CEB compared to cementitious materials and the current improvement in the manufacturing, the conditions for improving the thermal comfort of CEB housing, based on the architectural effects of buildings and natural ventilation systems, are still to be assessed.

In addition, Burkina Faso has abundant resources of laterite [4] which can be used for the production of CEB. Therefore, this would contribute not only to making the economy prosper through job creation; but also, to mitigating the climate variability. Indeed, Burkina is very vulnerable to the impacts of climate change. The effects of climate change on temperatures and rainfall risk exacerbating climate vulnerability across West Africa [11]. Most CEB buildings in the Sahel environment are built while retaining the typical architectural plans of concrete block buildings, which are often unsuitable.

This article proposes as an overall objective, a relevant correction of these defects by evaluating the thermal behavior with various architectural modifications while highlighting the advantages of the BTC material compared to concrete blocks.

2. Methodology

2.1. Validation of Study Building Models

2.1.1. Study Context

In Burkina Faso, earth construction represents 53.4% of all wall masonries [12]. In rural areas, 70% of the households live in traditional earth buildings [4]. However, this material (adobe or banco) is subject to durability problems, CEB are being considered as a suitable alternative. In urban areas, cement-based materials are the most used for wall constructions, representing approximately 52% of cement block constructions compared to only 28% of those in earth blocks [13]. The choice of CEB is guided by the fact that they are deemed more ecological than concrete blocks or concrete [13]. CEB are produced from raw earth presenting certain physical and geotechnical characteristics, mixed with water and statically compressed to a pressure of approximately 10 bars. These CEB are very often stabilized with cement or lime as well as by-product materials to improve their physical, thermal, mechanical and durability characteristics, thus achieving the required standards [14] maintaining the Integrity of the Specifications.

Test pilot buildings have been widely used in the literature to characterize the thermal performance of building materials in quasi-real situations. The pilot buildings have previously been used to analyze the impact of thermal inertia, insulation, natural ventilation and thermal comfort [5] [15]. The main advantage of choosing a pilot buildings is to facilitate data collection in an efficient manner and reduce uncertainties due to building specifics [16]; an empirical validation approach as a quantitative methodology by comparing measured and simulated temperatures [4] [16]. The softwares such as GOOGLE SketchUp Pro 2021 and an extension developed by EnergyPlus, OpenStudio 1.3, were used to Predict theed temperatures and compare to experimental data describing the interior thermal conditions of the pilot building. During the experimental period, the test cell was in free-evolution mode, kept closed without human occupation.

2.1.2. Description of the Study Buildings

The buildings to be calibrated and virtually optimized are two pilot buildings of identical architecture; dimensions of 3.06 m wide; 4.06 m long and 4.33 m high. The platform is located at 12.46363˚ North and 1.55348˚ West with an altitude of 299 m. These buildings were built with materials commonly used in Burkina Faso by the middle class of the population, such as cement blocks and earth block of CEB for the wall masonry.

The walls of the first reference building are made of 15 cm thick cement block coated on both sides with 2.5 cm of cement mortar. The walls of the second test building are made of 14 cm thick CEB, stabilized with 8% cement, without additional coating on either side. For each building, the roof is made of 1.5 mm sheet metal. It is the most common type of roof in the locality due to its affordable cost and ease of implementation by local builders. The roof benefited from constant natural ventilation thanks to six openings of 10 cm in diameter on the main facades at attic level. The ceiling is made of 5 mm thick plywood and placed at 2.70 m from the floor. The floor slab is made of a 10 cm thick reinforced concrete. **Figure 1** shows the two pilot buildings pictures.

The thermal characteristics of the materials are summarized in **Table 1**. To ensure visual comfort, two identical windows were placed in the South and North walls respectively. Each window is made of a single 3 mm glass panel 1 m wide and 1.2 m high. From the existing EnergyPlus library, the construction properties of 3 mm single clear glass windows were used for the simulation. The door, 85 cm wide and 220 cm high, is made of metal in its lower part and has glazing identical to the windows in its upper part, fixed on the south side.

The pilot buildings were monitored in the period from September 2 to November 26 in 2017. The dry bulb temperatures of the envelope and the interior

(a) (b)

Figure 1. Experimental pilot buildings in cement block (a) and CEB (b) at the 2iE Kamboinsé/Ouagadougou.

Table 1. Initial values of thermal characteristics of construction materials of pilot buildings.

	Conductivity (W·m^{-1}·K^{-1})	Density (kgm^{-3})	Specific heat (J·kg^{-1}·K^{-1})	Emissivity (ε)	Solar Absorptivity (α)
CEB	1.02	1840	975	0.88	0.55
Cement blocks	0.80	1000	1000	0.90	0.60
Cement mortar	1.10	1700	1000	0.90	0.60
Concrete	1.40	2240	840	0.90	0.60
White painted plywood	0.15	500	1200	0.90	0.12
Sheet metal	45.28	7824	500	0.58	0.30

References: [5] [17] [18].

air were recorded using Delta OHM type HD32.3 equipment with three sensors positioned at 1.10 m above the ground as shown in **Figure 2**. This equipment is composed of a Pt 100 type probe (TP 3275) which measures the ambient temperature with a precision of 0.12˚C with a range of −20˚C to 85˚C, a type probe (AP 3203) which measures air speed and a third type probe (HP 3117R) which measures the wet bulb temperature and therefore the relative humidity.

The weather conditions of the building platform were monitored using a Vaisala system HydroMet MAWS100, which is suitable for harsh climatic conditions. This weather station is located approximately 100 m from the building platform. The global and diffuse solar irradiance on the horizontal plate was measured separately by two pyranometers mounted on a solar tracker. The outdoor air temperature and relative humidity sensors have been protected by a Vaisala DTR500 Series radiation shield. The data acquisition system used is the Vaisala Data Logger QML201C [4].

2.1.3. Development of Thermal Models of Buildings

The thermal model of the test buildings was implemented by Google SketchUp Pro 2021 software using an extension of the US Department of Energy of EnergyPlus software called OpenStudio. The version of the extension used in this study is OpenStudio 1.4.0 updated in 2021. EnergyPlus is one of the most advanced and widely used energy simulation programs. EnergyPlus provides, among other things, precise forecasts of temperature and thermal comfort [16]. Details of the data to be implemented, the calculation methods used in the EnergyPlus programs and the simulation with the OpenStudio extension are given by Ref. [19] [20].

Figure 2. Delta OHM type HD32.3 hygrothermal measuring equipment.

EnergyPlus provides three models for calculating air infiltration: Design Flow Rate, Effective Leakage Area and Flow Coefficient [4]. In this study, this infiltration will be evaluated using the Space Infiltration Design Flow Rate model [21].

Three statistical indicators were considered for the empirical validation of the thermal models. These are Normalized Bias Error (NMBE), Coefficient of Variation of Mean Square Error (CVRMSE) and Coefficient of Determination (R^2). These indicators have been proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14-2014 [22].

The NMBE is a dimensionless index that estimates the average difference between measurements and simulations as looked in Equation (1). However, positive differences can compensate for negative ones and another indicator, CVRMSE, should be associated with it. The CVRMSE helps determine how well the model reflects the measured data (Equation (2)). The coefficient of determination R^2 can be used to deal with the quality of fit of a model in relation to the measured data (Equation (3)). In Equations (1), (2) and (3) m_i and s_i respectively represents the measured and simulated values for each occurrence *i*, $\bar{m}$ the average value of the measured data, *N* the number of points in the measurement/simulation interval.

$$\text{NMBE} = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N} m_i} \tag{1}$$

$$\text{CVRMSE} = \frac{\sqrt{\sum_{i=1}^{N}(m_i - s_i)/N}}{\bar{m}} \tag{2}$$

$$\text{R}^2 = 1 - \frac{\sum_{i=1}^{N}(m_i - S_i)^2}{\sum_{i=1}^{N}(m_i - \bar{m})^2} \tag{3}$$

Energy simulation models are considered calibrated if they meet the criteria defined by ASHRAE Guideline 14, namely NMBE < 0.10 and CVRMSE < 0.30 if the model is calibrated on an hourly basis or NMBE < 5% and CVRMSE < 15% on monthly basis [22]. Generally, to deal with prediction performance, the value of R^2 should never be less than 75%. Regarding the validation of indoor air quality, a value of $R^2 > 90\%$ is recommended. The slope of the regression line should be between 0.75 and 1.25 and the intercept less than 25% of the mean measurement [22].

2.2. Constructive and Architectural Improvements to the Thermal Comfort of Buildings

2.2.1. Climate Data

METEONORM data from station 703,950 (12˚22' North; 1˚32' West; 297 m above sea level) of Ouagadougou were used as typical annual data to take into account long-term climatic conditions.

According to ASHRAE standards 90.1 - 2004 and 90.2 - 2004 Climate zone, the climate is type "1B", a very hot and dry tropical climate. The country's hot season is March to May with a typical weekday period for study from April 19 to April 25. The cold season is from November to January with a typical week from November 12 to November 18.

2.2.2. Model Occupancy Calendar

Internal occupancy costs were limited to those linked to human activities. Table 2 presents the assumptions used for the construction of occupancy program. The adult occupants, with an average height of 1.73 m, a weight of 70 kg and the adult skin surface area is equal to the DuBois surface value: 1.8 m^2 [21].

2.2.3. Proposed Optimisations

Walls coated with plaster: plasterboard helps reduce the absorption of sunlight by the walls. Plaster has a solar absorptance of 0.07 [18], this will reduce the average temperature in the rooms. This modification is modeled by assigning a solar absorptance of 0.07 to the walls of the buildings. Quality doors and windows which are well sealed to reduce the air infiltration, as the internal humidity in buildings is a determining factor in thermal comfort and its control is crucial. However, the basic models show relatively high air infiltration which can be explained by the method of construction of the doors and windows of the test buildings. These openings have large gaps between the leaves and the frames. Better quality openings equipped with seals would drastically reduce air infiltration. The modification was modeled to reduce the air infiltration into the rooms. The Design Flow Rate infiltration model uses the Flow/Space calculation method with an average of 1 cm^3/s of air volume to simulate impermeability. Windows were opened according to an optimal schedule: to evacuate excess humidity, were modelled by momentary openings of the North and South windows of the buildings at a particularly chosen time of the day depending on the time of year. In OpenStudio, natural ventilation is modeled by Zone Equipment in a Thermal Zone called Wind and Stack with Open Area, in which the ventilation air flow is a function of wind speed and of the thermal effect of the chimney, as well as the area of the modeled opening [23].

The wind-driven ventilation rate (Q_W [m^3/s]) is given by Equation (4); with

Table 2. Occupancy schedule for pilot building models.

Time	People	Activity	Metabolic rate (W) [24]
6 am - 11 am	1	Seated, at rest	100
11 am - 1 pm	2	Standing, sedentary work	120
1 pm - 2 pm	1	sleeping	70
2 pm - 8 pm	1	Standing, sedentary work	120
8 pm - 10 pm	2	Seated, at rest	100
10 pm - 6 am	2	sleeping	70

C_W opening efficiency, $A_{opening}$ opening area [m^2], $F_{schedule}$ fractional planning of open area and $v$local wind speed [m/s]. The aperture effectiveness is calculated for each simulation time step based on the angle between the actual wind direction and the effective angle [degree] (a user-defined input) using Equation (5).

$$Q_W = C_W \cdot A_{opening} \cdot F_{schedule} \cdot v \tag{4}$$

$$C_W = 0.55 - \frac{|\text{Effective Angle} - \text{Wind Direction}|}{180} \cdot 0.25 \tag{5}$$

The ventilation rate driven by the stack effect (Q_S [m^3/s]) is given by Equation (6); with C_D the discharge coefficient for the opening, ΔH_{NPL} the height of the opening below the Neutral Pressure Level *NPL* [m], T_{zon} the dry zone air temperature [K], T_{odb} the local bulb temperature dryness of outside air [K]. The total natural ventilation rate for this model ($Q_{w,s}$) is calculated as the quadrature sum of the wind and stack components, given by Equation (7).

$$Q_s = C_D \cdot A_{op} \cdot F_{sche} \sqrt{2g\Delta H_{NPL} \frac{|T_{zon} - T_{odb}|}{T_{zon}}} \tag{6}$$

$$Q_{w,s} = \sqrt{Q_s^2 + Q_w^2} \tag{7}$$

2.3. Assessment of Thermal Comfort

The thermal models of the pilot buildings including the optimization proposals were subject to the evaluation of internal thermal comfort over the typical year using the tool for evaluating thermal comfort in natural ventilation in a climate hot and dry [5]. This tool is similar to the Givoni diagram, however it was adapted to describe thermal comfort in hot and dry regions of the sub-Saharan climate and specifically in three cities of Burkina Faso, including Ouagadougou. The graph of this tool is shown in **Figure 3**.

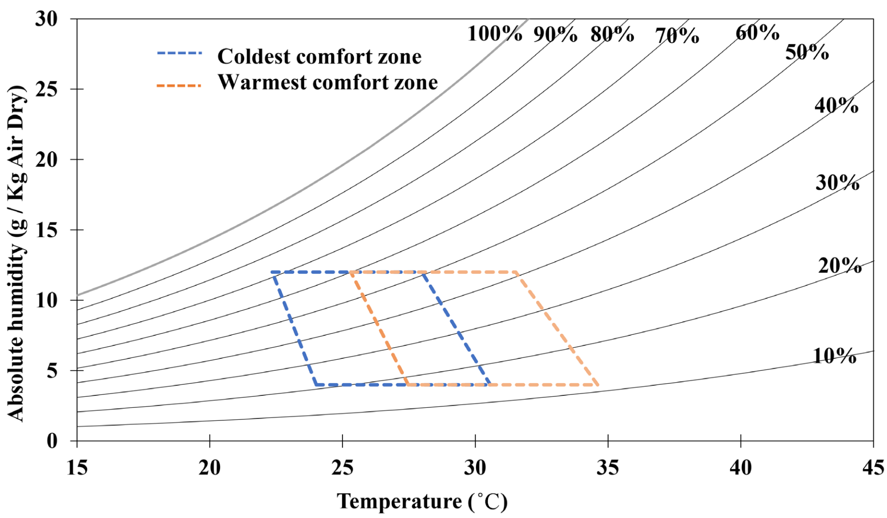

Figure 3. Delimitation of the thermal comfort zone in the city of Ouagadougou [5].

3. Results and Discussions

3.1. Abbreviations and Acronyms

The unmeasured and uncertain parameters necessary for the simulation are determined during modeling as being: the opening efficiency $A_{opening,i}$ of the attic openings which will simulate their method of construction (with mesh protection); The solar absorbances of the roof and the two types of walls without adding coating; the average air infiltration from the EnergyPlus Space Infiltration Design Flow Rate calculation model for the rooms of the two buildings. Table 3 shows the variation intervals of these parameters for our study as well as the retained values.

The simulation temperatures and relative humidity of the cells were calibrated and compared to the temperature and relative humidity from the measurements made for the typical period from November 12 to 18, 2017. The empirical validation criteria were verified and summarized in Table 4. The curves in Figure 4 and Figure 5 show the correspondence between the measured and simulated data.

3.2. Effects of Proposed Optimizations

The effects of the modifications are observed with the thermal comfort assessment tool; using the variant for the city of Ouagadougou [5]. The tool displays

Table 3. Validation values of uncertain parameters of pilot building.

	Parameters to calibrate	Variation interval [18]	Retained values
CEB pilot building	Opening efficiency (%)	0 - 100	90
	Solar absorption Roof (–)	0.12 - 0.41	0.15
	Solar absorption Wall (–)	0.50 - 0.70	0.58
	Room air infiltration (dm^3/s)	-	1.2
Cement block pilot building	Opening efficiency (%)	0 - 100	90
	Solar absorption Roof (–)	0.12 - 0.41	0.18
	Solar absorption Wall (–)	0.50 - 0.70	0.53
	Room air infiltration (dm^3/s)	-	1.2

Table 4. Verification of model validation criteria.

Type and part of pilot building	Temperature				Relative humidity		Validity criteria [22]
	Attic of CEB	Attic of cement block	Living space of CEB	Living space of cement block	Living space of CEB	Living space of cement block	
NMBE	0.003	0.030	0.005	0.009	0.096	0.084	<0.10
CVRMSE	0.068	0.040	0.018	0.015	0.132	0.126	<0.30
R^2	0.98	0.98	0.98	0.98	0.94	0.93	>0.90

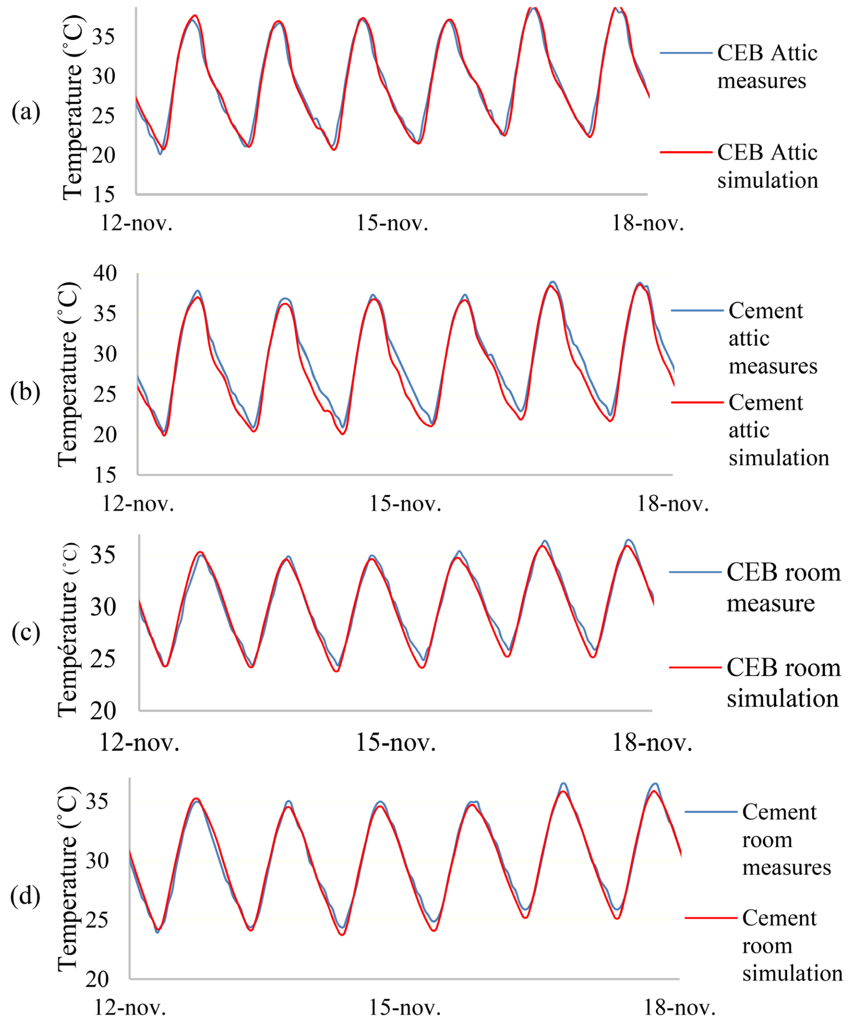

Figure 4. Superimposed profiles of the measured and predicted values of the attic temperature in CEB (a) and cement blocks (b), and of the room temperature in CEB (c) and in cement blocks (d) of the typical week.

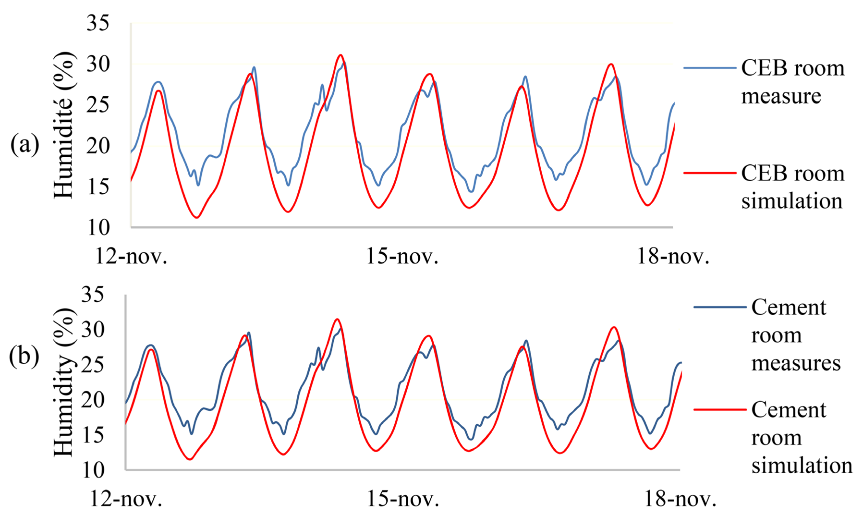

Figure 5. Superimposed profiles of the measured and predicted values of the relative humidity of the room in CEB (a) and cement blocks (b) of the typical week.

the 8760 hygrothermal sensation points of the typical year extracted from METEONORM which then correspond to the 8760 hours of the year, and each depends on the operating temperature and the relative humidity of the time considered in the room. The graph also shows the particular points that are included in the predefined comfort zone as well as the annual thermal comfort and discomfort percentage. Firstly, the thermal comfort of the pilot buildings was evaluated without any modification, the behavior of which can be observed in Figure 6, then optimization proposals were applied: as presented in Figure 7 which shows the improvement in thermal comfort due to a high concentration of sensation points in the comfort zone after the modifications in paragraph 2.2.3.

Figure 8 compares the evolution of temperature and relative humidity and discomfort level of the optimized models of the two buildings. The validated models, corresponding to the current construction method of the pilot buildings,

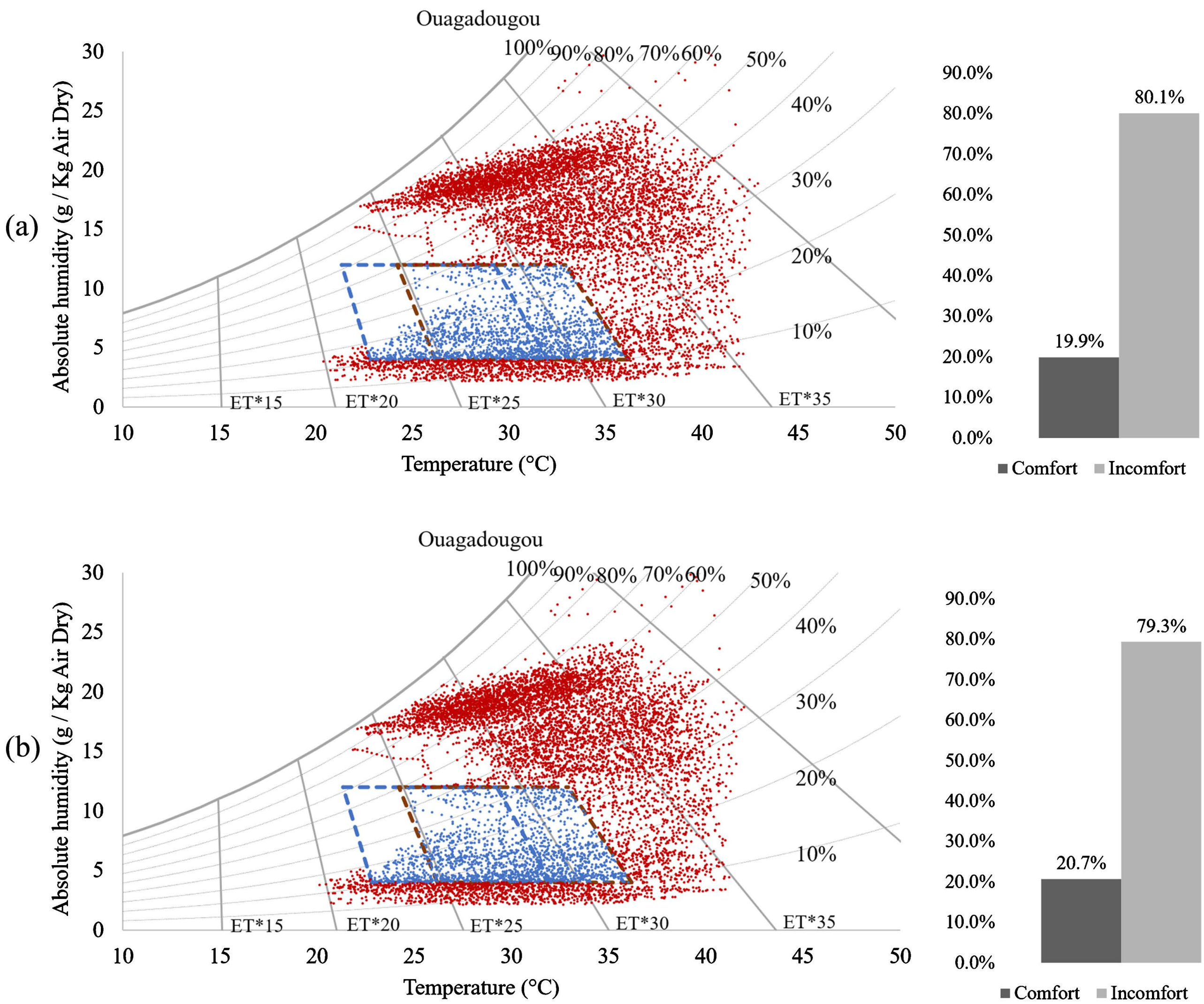

Figure 6. Graphical representation of the hygrothermal state and percentage of thermal comfort of the CEB building (a) and the cement block building (b) in calibrated condition.

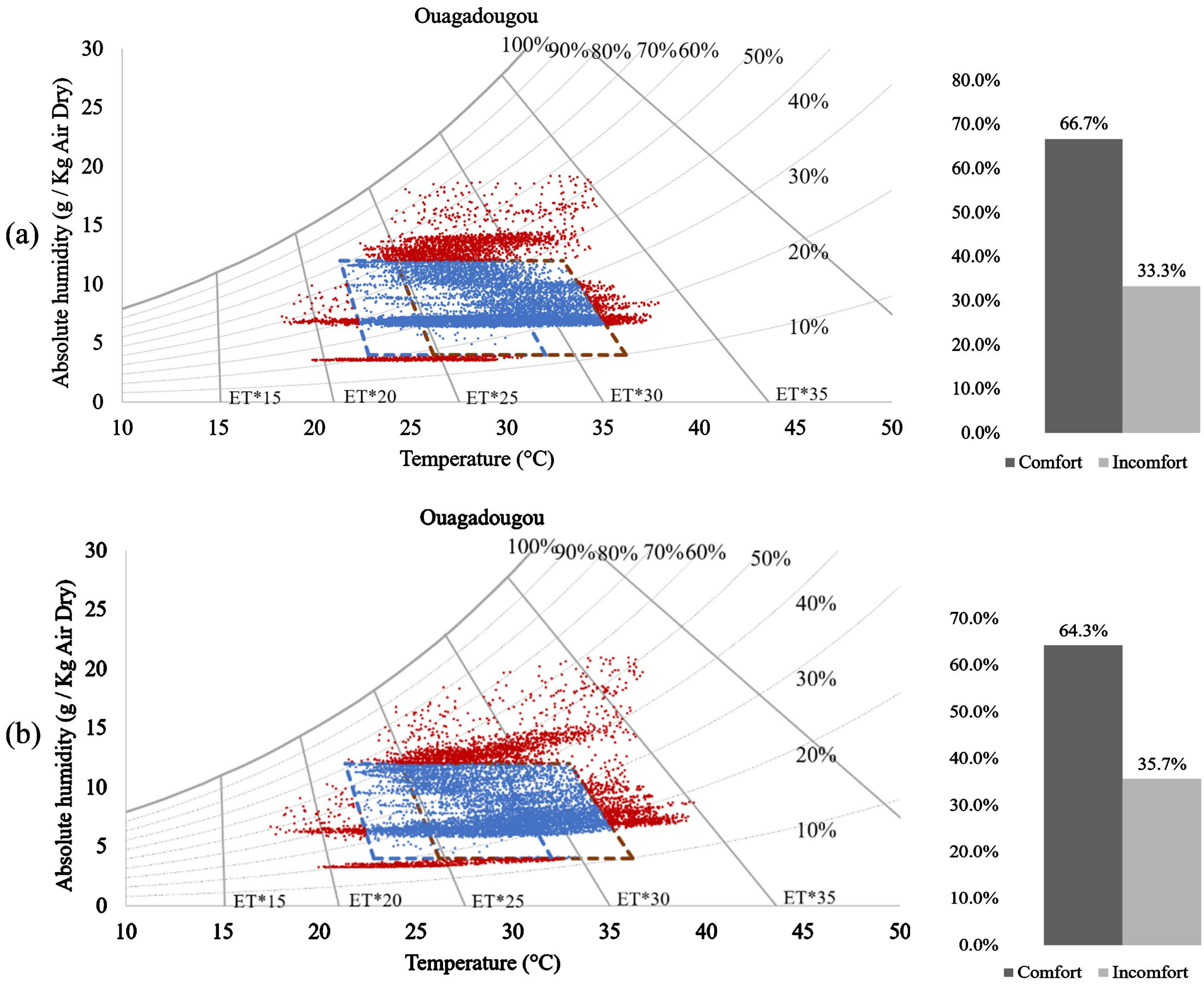

Figure 7. Graphical representation of the hygrothermal state and percentage of thermal comfort of the CEB building (a) and the cement block building (b) in optimized condition.

Table 5. Statistical values of hygrometric parameters of models without modification.

Type of pilot building	Temperature		Relative humidity	
	Average	Standard deviation	Average	Standard deviation
Living space CEB	32.08	4.37	40.54	22.90
Living space of cement block	31.62	4.24	40.42	22.40

displays, in the typical year, 7016 hours of discomfort equivalent to 80.1% discomfort for the CEB building, and 6948 hours of discomfort, or 79.3% discomfort for the cement block building. Table 5 shows the hygrothermal averages.

Following the modifications on the two models, the CEB building displays 2918 hours of discomfort, or 33.3%; while the cement block building displays 3125 hours of discomfort, or 35.7%. The CEB pilot building becomes slightly more comfortable than the cement block building and this is mainly due to the low

Table 6. Statistical values of hygrometric parameters of optimized models.

Type of pilot building	Temperature		Relative humidity	
	Average	Standard deviation	Average	Standard deviation
Living space CEB	28.67	3.54	35.44	14.09
Living space of cement block	29.18	3.93	33.71	13.71

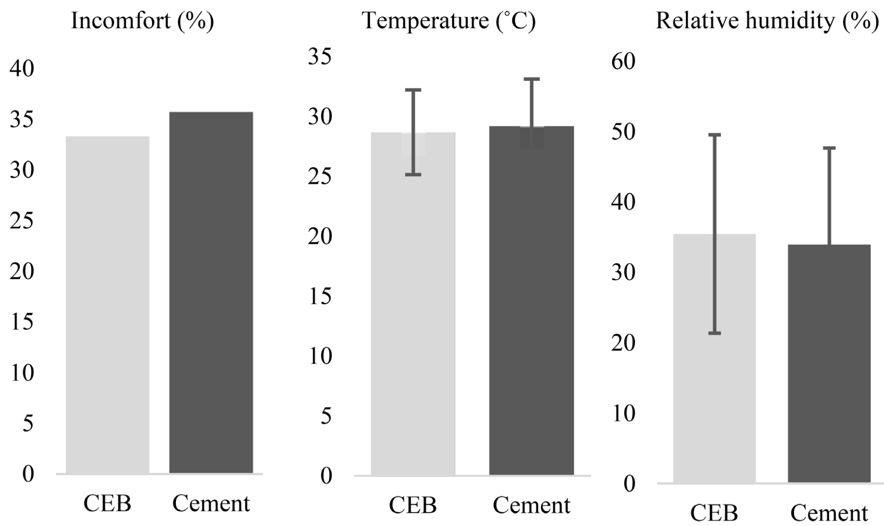

Figure 8. Comparison of the temperature and relative humidity and discomfort level of the optimized models of the two buildings.

temperature dispersion in the first. Indeed, as noted in **Table 6**, the standard deviation of the Operating Temperature variable is lower for the CEB building than that of cement blocks, 3.54 compared to 3.93; with the average temperatures relatively close to the neutral temperatures of the two extremes weather conditions in the year for the city of Ouagadougou which are 25.5 in January and 28.3 in April [5].

The discomfort levels of the pilot buildings decreased by more than half after the proposed optimizations and are 33.3% for the CEB building and 35.7% for the cement block building. However, the CEB building is more comfortable than its cement block counterpart, this is due to the high thermal inertia of the CEB material compared to the composite section of the cement block wall. Indeed, the thermal inertia of the material attenuates temperature variability, resulting in better thermal performance [5] [13] [25].

4. Conclusions and Perspective

This study focused on the determination and evaluation of improvements in the thermal comfort of single-room buildings commonly used as housing in Burkina Faso, based on two pilot buildings. The approach consisted of empirical validation of the thermal model of the pilote building to guarantee the accuracy of the thermal model of buildings through EnergyPlus software. The two pilot buildings of the study, located in the city of Ouagadougou, were modeled and calibrated with SketchUp and its OpenStudio extension developed by EnergyPlus, then validated by checking the approximation criteria of Guideline 14 of ASHRAE; based on hygrothermal data measured on site. Constructive and architectural modifications to optimize thermal comfort were then proposed and applied to the validated models.

The results showed that the proposed optimization, namely a plaster coating on the exterior side of the walls, good sealing of doors and windows and natural ventilation programmed according to the weather conditions, made it possible to reduce the level of discomfort from 80.1% to 33.3% in the CEB building and from 79.3% to 35.7% for the cement block building. The optimized building in CEB has better comfort than that in cement blocks. Therefore, it can be confirmed that CEB can be used as an alternative material to cement block. In addition, the above-mentioned constructive and architectural modifications are an excellent solution to mitigating the thermal discomfort, reducing it by more than half compared to the current method of construction. However, future studies will have to focus on the social aspect regarding the acceptance of the local population to stay in such accommodation as well as their capacity to use it.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] UN-HABITAT (2014) L'Etat des ville africaines : Réinventer la transition urbaine.

[2] Bambara, D., Compaoré, H. and Bilgo, A. (2018) Évolution des températures au Burkina Faso entre 1956 et 2015: Cas de Ouagadougou et de Ouahigouya. *Physio-Géo*, **12**, 23-41. https://doi.org/10.4000/physio-geo.5688

[3] Osaulenko, O.H. and Kobylynska, T.V. (2021) Climate Change Statistics: European Experience and National Assessment. *Statistics of Ukraine*, **92**, 4-15. https://doi.org/10.31767/su.1(92)2021.01.01

[4] Neya, I., Yamegueu, D., Messan, A., Coulibaly, Y., Ouedraogo, A.L.S.N. and Ayite, Y.M.X.D. (2023) Effect of Cement and Geopolymer Stabilization on the Thermal Comfort: Case Study of an Earthen Building in Burkina Faso. *International Journal of Building Pathology and Adaptation*. https://doi.org/10.1108/IJBPA-05-2022-0069

[5] Ouedraogo, A.L.S.N., Messan, A., Yamegueu, D. and Coulibaly, Y. (2022) A Model for Thermal Comfort Assessment of Naturally Ventilated Housing in the Hot and Dry Tropical Climate. *International Journal of Building Pathology and Adaptation*, **40**, 183-201. https://doi.org/10.1108/IJBPA-02-2021-0011

[6] Zhang, C.Y., Han, R., Yu, B. and Wei, Y.M. (2018) Accounting Process-Related CO_2 Emissions from Global Cement Production under Shared Socioeconomic Pathways. *Journal of Cleaner Production*, **184**, 451-465. https://doi.org/10.1016/j.jclepro.2018.02.284

[7] Zoungrana, O., Messan, A., Nshimiyimana, P. and Pirotte, G. (2021) The Paradox around the Social Representations of Compressed Earth Block Building Material in Burkina Faso: The Material for the Poor or the Luxury Material? *Open Journal of Social Sciences*, **9**, 50-65. https://orbi.uliege.be/handle/2268/256349

https://doi.org/10.4236/jss.2021.91004

[8] Goodhew, S., Boutouil, M., Streiff, F., Le Guern, M., Carfrae, J. and Fox, M. (2021) Improving the Thermal Performance of Earthen Walls to Satisfy Current Building Regulations. *Energy and Buildings*, **240**, Article ID: 110873. https://doi.org/10.1016/j.enbuild.2021.110873

[9] Azil, A., *et al.* (2022) Earth Construction: Field Variabilities and Laboratory Reproducibility. *Construction and Building Materials*, **314**, Article ID: 125591. https://doi.org/10.1016/j.conbuildmat.2021.125591

[10] Nshimiyimana, P., Fagel, N., Messan, A., Wetshondo, D.O. and Courard, L. (2020) Physico-Chemical and Mineralogical Characterization of Clay Materials Suitable for Production of Stabilized Compressed Earth Blocks. *Construction and Building Materials*, **241**, Article ID: 118097. https://doi.org/10.1016/j.conbuildmat.2020.118097

[11] UN-HABITAT (2010) L'état des villes Africaines: Réinventer la transition urbaine, Nairobi, Kenya.

[12] INSD (2020) Cinquième Recensement Général de la Population et de l'Habitation du Burkina Faso/Résultats Préliminaires. Institut National de la Statistique et de la Démographie.

[13] Moussa, S.H., Nshimiyimana, P., Hema, C., Zoungrana, O., Messan, A. and Courard, L. (2019) Comparative Study of Thermal Comfort Induced from Masonry Made of Stabilized Compressed Earth Block vs Conventional Cementitious Material. *Journal of Minerals and Materials Characterization and Engineering*, **7**, 385-403. https://doi.org/10.4236/jmmce.2019.76026

[14] Nouemssi, G.A., Ntamack, G.E., Mbozo'O, M.N. and Djeumako, B. (2023) Thermal Properties of Earth Bricks Stabilised with Cement and Sawdust Residue Using the Asymmetrical Hot-Plane Method. *Open Journal of Applied Sciences*, **13**, 1910-1934. https://doi.org/10.4236/ojapps.2023.1311151

[15] Neya, I., Yamegueu, D., Coulibaly, Y., Messan, A. and Ouedraogo, A.L.S.N. (2021) Impact of Insulation and Wall Thickness in Compressed Earth Buildings in Hot and Dry Tropical Regions. *Journal of Building Engineering*, **33**, Article ID: 101612. https://doi.org/10.1016/j.jobe.2020.101612

[16] Goldwasser, D., Ball, B.L., Farthing, A.D., Frank, S.M. and Im, P. (2018) Advances in Calibration of Building Energy Models to Time Series Data. National Renewable Energy Laboratory (NREL), Golden.

[17] Kaboré, M. (2015) Enjeux de la simulation pour l'étude des performances énergétiques des bâtiments en Afrique sub-saharienne. Ph.D. Thesis, Université Grenoble Alpes, Grenoble.

[18] Marchetto, L. and Clement, M. (2023) Guide de l'éco-construction. https://www.econologie.com/telecharger-guide-eco-construction/

[19] Hale, E., *et al.* (2014) Cloud-Based Model Calibration Using Open Studio. National Renewable Energy Laboratory (NREL), Golden.

[20] Al-Zubaydi, A.Y. (2013) Building Models Design and Energy Simulation with Google Sketchup and Openstudio. *Journal of Advanced Science and Engineering Research*, **3**, 318-333.

[21] (2013) ASHRAE 55, ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook: Fundamentals. ASHRAE, Atlanta.

[22] ASHRAE (2014) Measurement of Energy, Demand, and Water Savings. ASHRAE

Guideline.

[23] Figueiroa, V. and Torres, J.P.N. (2022) Simulation of a Small Smart Greenhouse. *Designs*, **6**, Article 106. https://doi.org/10.3390/designs6060106

[24] Auliciems, A. and Szokolay, S.V. (2007) Passive and Low Energy Architecture International. Design Tools and Techniques, Department of Architecture, The University of Queensland Brisbane.

[25] Hema, C., Nshimiyimana, P., Messan, A., Lawane, A. and Van Moeseke, G. (2022) Reducing Overheating Risk in Naturally Ventilated Houses through the Design of Compressed Earth Blocks Walls in Hot Dry Climate. *International Journal of Building Pathology and Adaptation*. https://doi.org/10.1108/IJBPA-12-2021-0160