Original Research Article

Improving the habitat energy efficiency and thermal comfort through the design of walls in compressed earth block of agricultural and biopolymer residues.

Abstract

The building's design phase must be integrated as a part of building energy behaviour approach, in order to better identify the material adapted to the climatic context. This paper studies eco-materials building energy and hydrothermal behaviour by numerical method to contribute to the energy efficiency practice in the rural construction. The envelop wall material studies are CSEB of fonio straw and shea butter cake, cement blocks and cut laterite blocks and the building design were modelled in DesignBuilder interface. The thermal comfort and total amount of energy required for building cooling was calculated by means of dynamic modelling using EnergyPlus software. The simulation were run according to the meteorological parameters of Ouagadougou city. The results show that the habitat discomfort hour's number and its cooling energy loads are respectively reduced by an average rate of 10.60% and 93.86% with wall in CSEB of fonio straw coated by composite shea butter cake and earth material, compared to envelope walls in cement or cut laterite blocks. In terms of indoor environment, the effect of this envelope wall in compressed earth material in fonio straw and shea butter cake, makes it possible to maintain an average internal temperature and indoor operating temperature respectively at 28.64°C and 25.82°C. The average indoor temperature peaks damping is achieve to 6.54°C (i.e. 22.83%). It is thus noted that local building eco-materials are an efficient contribution to sustainable habitats construction in hot region.

Keywords: ***Modelling and Simulation, Eco-materials, Thermal comfort, Energy efficiency, Habitats, Hot region***

1. Introduction

The impact of the built environment on the climate and the earth's resources is very important, since the construction industry is the largest user of materials and energy in the world [1]. The increase in energy consumption in building design and construction and the issues related to environmental protection have steered many current researchers toward examining the ways to reduce total CO2 emissions, which resulted in the development of various measures to increase energy efficiency [2]. The Positive Energy Building is announced as the contribution of the construction sector to the solution of the major problems facing humanity at the beginning of the 21st century: global warming, depletion of fossil energy resources, scarcity of raw materials, and the finiteness of our world in general [3].

Local materials based on earth and natural resources are gradually giving way to concrete and its derivatives, which are now the most widely used building materials in the construction industry in Burkina Faso. Various considerations contribute to this and lead to an increase in the cost of construction and operation of buildings. Indeed, the unsuitability of these imported materials with the climate leads to an increase in energy needs over the entire life cycle. Sustainable development is becoming increasingly important in the construction sector. Therefore, building techniques that reduce environmental impacts by minimizing industrial processes and using locally available materials, such as earth, are receiving a new impetus [4].

A study on materials used in the building industry provides a basis for construction projects, but this must be done in relation to local conditions so that all parameters are examined for optimal use. In Burkina Faso, the materials used in the current construction such as concrete, cement block, are characterized by poor thermal properties with regard to solar radiation in hot region. Instead of local materials based on natural soil or stabilised with industrial, forestry and agricultural by-products [5], [6], [7].

This study is part of this dynamic and its focuses on the use of local build materials in dry tropical climate such as that of Burkina Faso. Building constructed with local material present nowadays interest in perspective of sustainable development [8] , as they are better adapted to local climate. The implementation of wall in adobe or CSEB is an alternative a sustainable construction [9].Indeed, the physical properties of local materials interact with each other and integrate other variables such as cultural construction practices and traditional technologies (knowledge and expertise) to form a coherent construction set for humans, environment and climate. Because maintaining the balance between the human body and its environment is one of the main requirements for health, safety and comfort [10]. And the current development challenge is based on responsible energy consumption. For a building to be comfortable, it must meet several requirements, including technical requirements. The temperature and humidity present in the building can cause energy consumption, degradation of building materials, and a feeling of discomfort for humans [11]. The study of building envelope material is important because [12] the wall thermal performance influences on habitat thermal comfort and energy consumption.

The nature of the building materials is a significant factor, whether natural or composite. To achieve sustainable and green technology in construction, more alternative methods were produced to replace the conventional construction materials which lack concern on elements of sustainability especially on humans, economics, and the environment [13]. According to [5], Nere pod stabilisation saves on 20 to 43% energy depending on the mixing rate compared to laterite and the decrement factor and the time lag are better when the wall thickness increases. It's in this context that this research, we highlight the compare the influence of wall in CSEB with fonio straw and shea butter cake, cement blocks, cut laterite blocks, on the habitat thermal behaviour. Thus, it's planned to design a housing model to determine whether thermal comfort is achieved; that by varying building walls material and their thermo physical properties.

2. Materials and Methods

2.1 Modelling and Simulation Frameworks

The numerical study consists to the modelling of a building used for socio-economic housing in Ouagadougou in Burkina Faso and the simulation of its energy and hygrothermal behaviour. Indeed, It's subject of wall influence according to the type of construction material used. This influence will be establish through the thermal parameters obtained such as temperature, relative humidity and the necessary energy quantity to maintain habitat thermal comfort. The period considered for this study is the month of April, which is the hottest month in the dry tropical climate zone. This study is completely numerical and we have established a conceptual framework for a descriptive study of our working methodology based on [14]. The Figure 1 shows our methodology main areas that will be described in the following paragraph.

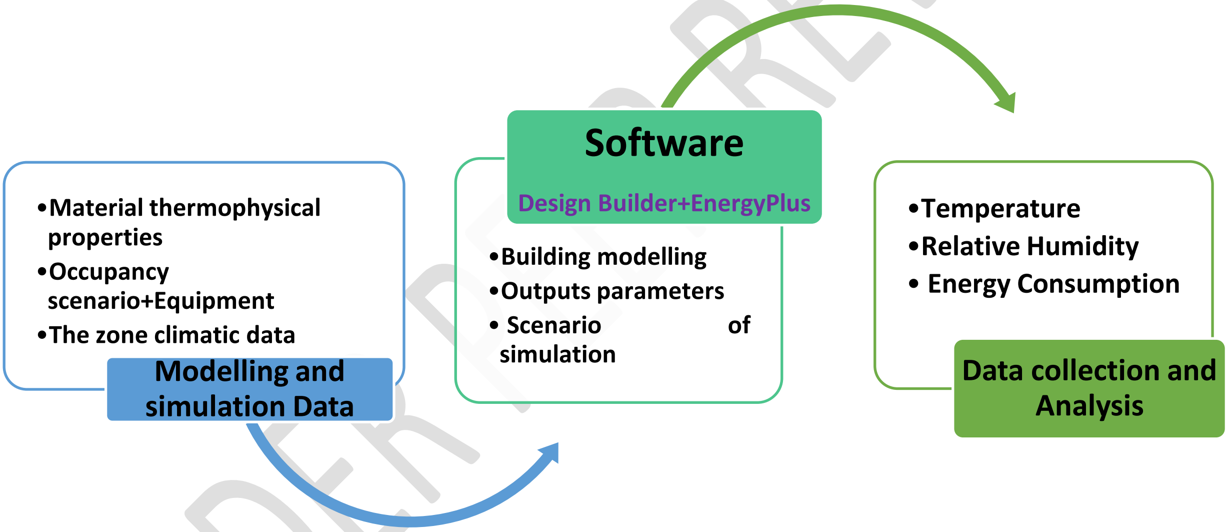

Figure 1: Study conceptual framework

2.2 Building description

Building constructed with local materials are nowadays of interest in the logic of sustainable development [8] . According to [15] the ultimate material efficiency aim is not to use lower materials quantity, but to reduce the impacts associated with their use. Our study aims at analysing walls constructed with local composite materials (earth + natural residues) impact on residential building thermal comfort and energy performances. In order to minimalize annual energy consumption, a shorter term objective is to design solids baselines on building envelope (wall, floors and roof) [16]. In search of energy efficiency, it's possible to investigate the choice of construction materials, building insulation, and the optimization of equipment operation. May the current development challenge be based on responsible energy consumption?

On an architectural level, the building to be assessed is common standard villa type F3 used in the city of Ouagadougou and characterized by a living area of 56.77m ² as designed in Figure 2. It is located northwest of the city and is subject to the conditions of a dry tropical climate and has six rooms including a common bathroom. For this purpose, the building will be considered in the climatic conditions of the area of Ouagadougou weather database file. The building description is shown in Figure 2 below:

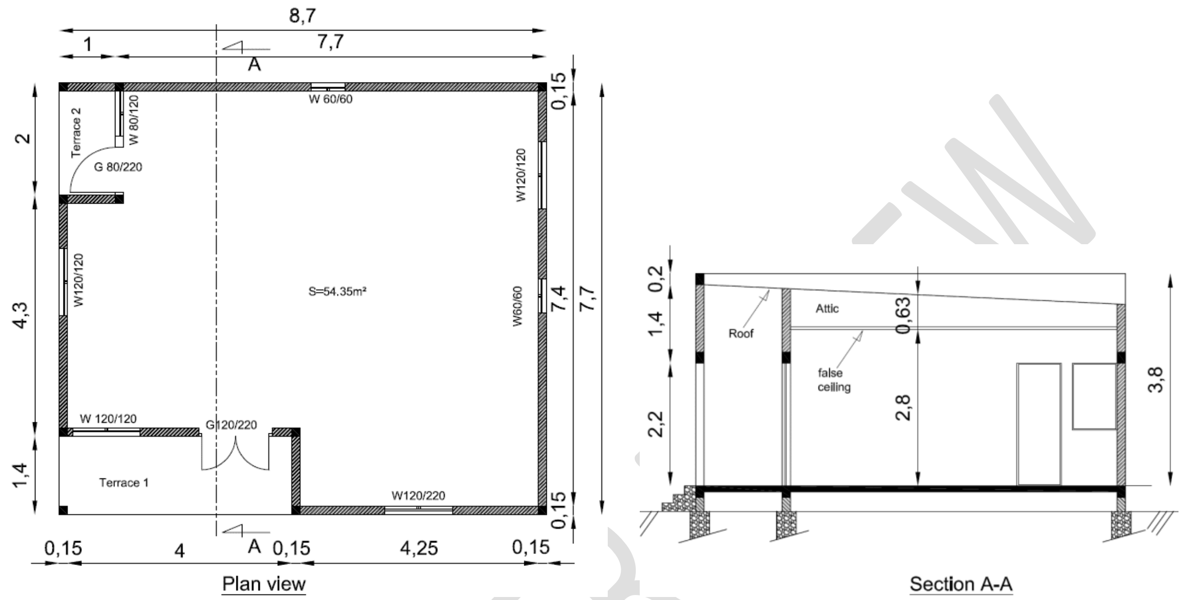

Figure 2: Building architectural plans

Table 1 presents building structural materials properties used in this study.

Table 1: Material thermo-physical properties ([14], [17]) RT2000 and IEPF 2002

N°	Material Description	λ (W/m. K)	Cp (kJ/kg. K)	ρ(kG/m3)	Thickness (cm)
1	Air gap(Attic)	0.192	1.00	1.218	62.5
2	Cement block	0,67	880	1250	15
3	Cut laterite block (BLT)	0.85	0.73	1850	15
4	CSEB -A13FF	0.504	1.967	1960	9
5	CSEB -A23FF	0.594	1.967	1904	9
6	Reinforced concrete paving	1.7	0.653	2400	10
7	Cement mortar (plaster)	0.87	1.05	2200	2.5
8	CEM-A13RL plaster	0.737	1.578	2008	2.5
9	False celling plaster	0.11	1.3	400	0.5
10	Floor tile	1.25	1.00	2000	0.7
11	Subfloor	1.21	1.00	1900	5
12	Single and clear glazing	0.96	0.837	2500	0.5
13	Isoplane door	0.12	2.51	593	2.5
14	Sheet metal	828	0.93	2700	0.07

The developed soil bricks can be used for affordable and sustainable housing construction across the world, particularly in developing countries [18], [19], [13]. In table 1, shows properties of common construction material and local's material such as the CSEB-A13FF, CSEB-A23FF and CEM-A13RL. These are local construction materials consisting by well define mixture of clay and agricultural residues and bio-polymer and whose thermo-physical and mechanical properties are characterized by [14]. This study will investigate the influence of these composite materials on the habitat thermal behaviour and compare them with cement block and cut laterite blocks (BLT) walls.

2.3 Choice and Description of the Simulation Tools

Building simulation software tools are mostly used by the building designers and engineers to explore various design alternatives under varying climatic conditions, internal gains, building envelope characteristics, building geometry, heating, ventilation and cooling (HVAC) system specifications, operation schedules, and control strategies, etc. [20] .

In perspective to reach this study objectives, the comparative approach is used by an analysing process based on dynamic energy simulation with Design Builder tool integrated to Energy+ calculation engine [21] available in Sustainable Building Design Lab of Liege University. The building energy and environmental performances and thermal comfort need reliable dynamic thermal simulation tools [22]. And the interface Design Builder/Energy+ allows us to perform dynamic simulations on the thermal and energy behaviour of buildings, as well as to obtain results on energy loads, indoor thermal environment and discomfort level. In fact, emergent energy and environmental questions related to buildings thermal comfort and indoor air quality require accurate knowledge of temperatures and air movements inside buildings [16] . For this purpose, the modelled building is considered as single thermal zone.

2.4 Simulations conditions

The simulation conditions considered the occupancy scenario, the installed equipment operation, the input data and thermal comfort physical parameters. Moreover the life cycle analyses showed the importance of operational phase in building energy balance in relation to construction and end-of life phases [23], [24].

In present study, the building energy and thermal dynamic simulation was done considering four (4) person occupancy scenario and split system for air conditioning equipment. The required thermal comfort conditions are indoor temperature between 26°C and 29°C and average relative humidity (HR) % of 50%.

A total of four types of walls envelope materials were studied. The description of building walls components is presented in Table 2 below:

Table 2 : Wall envelope and construction materials descriptions for case studied

Designation	Base case	Case 1	Case 2	Case 3
Wall	Cement mortar plaster+Cement block+Cement mortar plaster (=20cm)	BLT (17.5cm)	CEM-A13RL+CSEB-A13FF + CEM-A13RL (19cm)	CEM-A13RL+CSEB-A23FF + CEM-A13RL (19cm)
Roof	Sheet tile (7/10 mm)			
Windows	Single clear glazing and metallic frame (5mm) and size 120cm*120 cm et 60cm*60 cm			
False ceiling	Plaster false ceiling (5 cm)			
Ground	Reinforce concrete paving+ cement mortar+ floor tile(=15.7cm)			

The comparative study approach was chosen in order to evaluate the thermal and energy performance of the building constructed with walls in CSEB formulated by [14] at the Laboratory of Construction Materials of Liege University in relation to other conventional construction materials.

The walls thermal properties have both great influence on wall temperature distribution and on heat transfers from wall [21]. The walls nature level adaptation is particular interest in the solar radiation management, creating a barrier between the inside and outside of a room that modifies the thermal exchanges. The walls envelope materials component, their thickness, color, coating and thermo-physical properties are the main factors involved in their evaluation [10] . Three (03) types of building materials were selected: cement blocks and cut laterite blocks (BLT) commonly used and a CSEB composite material "earth + agricultural residues and biopolymer" and the study concerned four (04) case of walls envelope.

The characteristics of roof, openings and ground floor are kept identical for all studied cases. The only variation concerns the walls envelope, which by the construction materials used and the number of layers. The envelope material variants studied are described in Table 3 below.

Table 3 : Synthesis of wall variant layer modelled in Design Builder

Variant	Wall layer description			
	Outer layer	Main layer	Inner layer	Total thickness(cm)
Base case	Cement mortar	Cement blocks	Cement mortar	20
Case 1	-	Cut laterite block	Cement mortar	17.5
Case 2	CEM-A13RL Mortar	A13FF	CEM-A13RL Mortar	19
Case 3	CEM-A13RL Mortar	A23FF	CEM-A13RL Mortar	19

This study aims to contribute to local building materials valuation, given that no one can progress by ignoring the richness of its heritage. And by developing a scientific understanding of traditional know-how we can help to develop new architectural solutions inspired by tradition [10] . The simulation outputs collected are: the indoor discomfort hour's number, the air conditioning energy demand, the indoor and the average operating temperature for twelve months. To do compare result, on focusses of April month. Indeed, in this region, the most difficult periods are the maxima of April and June, when a supplement of artificial air conditioning is inevitable [25] and April is taken from the hot period when temperatures are high and humidity low [26].

3. Results

3.1 Indoor temperature evolution during hot period

Building thermal response depends on design, chosen construction materials and operating condition. This study focuses on wall construction materials influence of on indoor temperature evolution.

Below Figures 3 to 6 give modelled building interior temperatures evolution profile for each case of wall envelope studied.

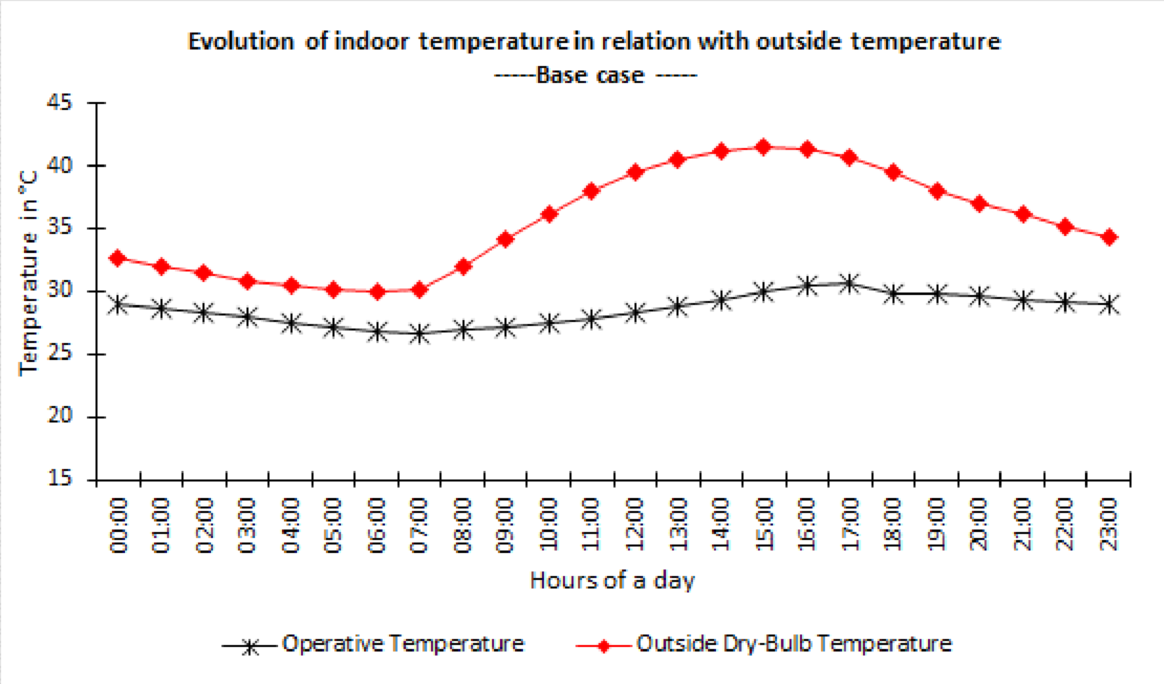

Figure 3: Indoor temperature evolution profiles in habitat with cement blocks wall (Base case)

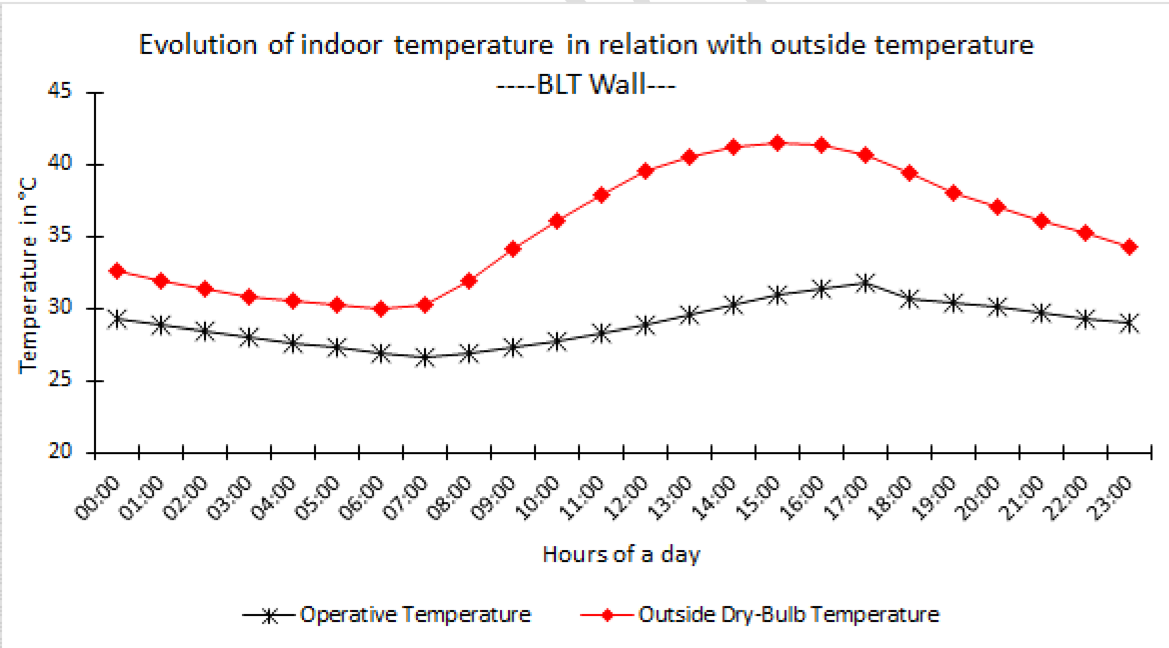

Figure 4: Indoor temperature evolution profiles in habitat with BLT Wall (case 1)

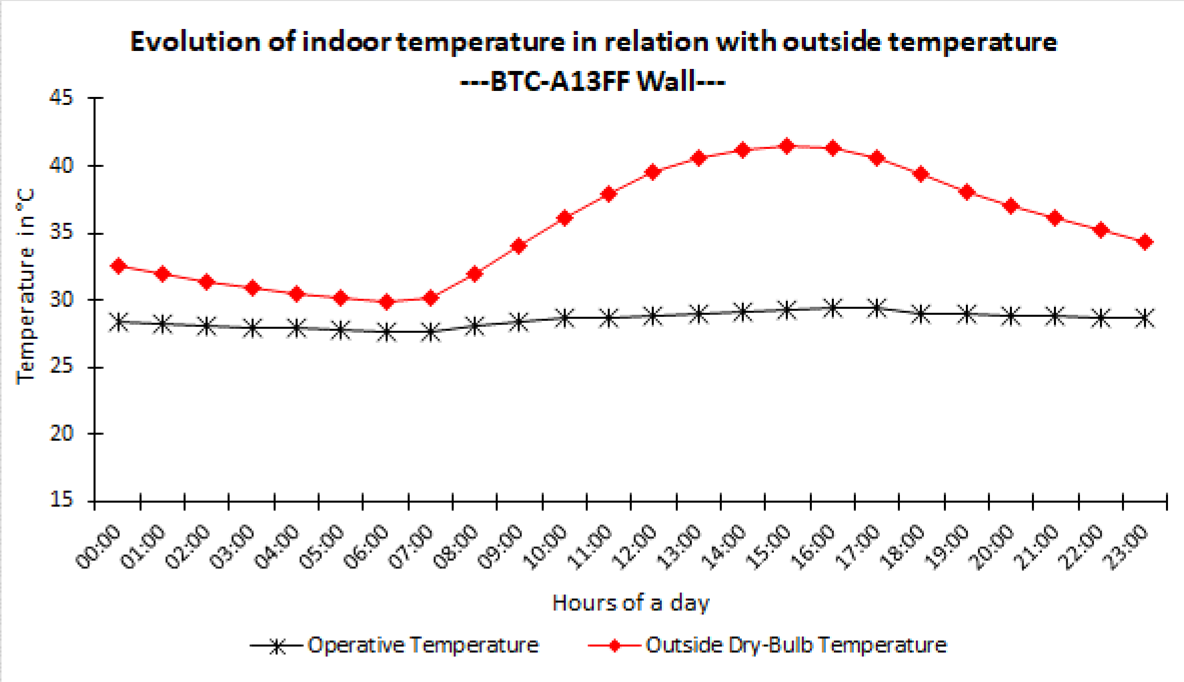

Figure 5: Indoor temperature evolution profiles in habitat with BTC-A13FF Wall (Case 2)

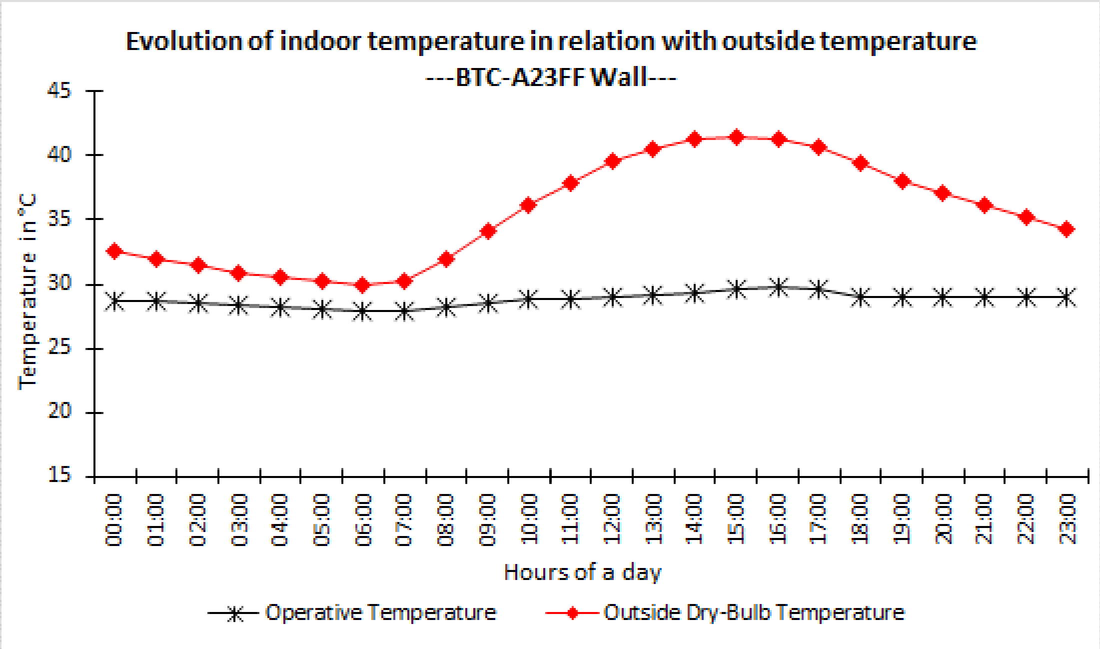

Figure 6: Indoor temperature evolution profiles in habitat with BTC-A23FF Wall (Case3)

Below Figures 7 and 8 present indoor temperature evolution in relation with ambient temperature respectively over a period of 10 days and 24 hours during April month.

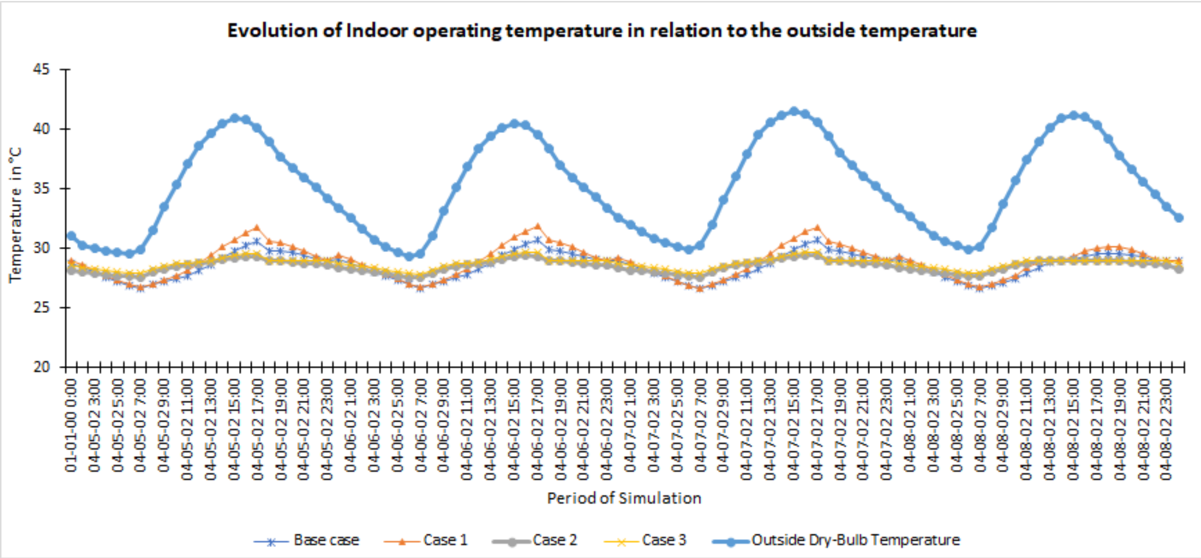

Figure 7: Comparison of Indoor temperature evolution in relation with external temperature for all wall cases studied (from 4-9th April)

Figure 7 present the comparison of indoor temperature evolution profiles for walls cases studied and in relation with ambient temperature over period of 10 days during April month of reference year in dry tropical climate condition.

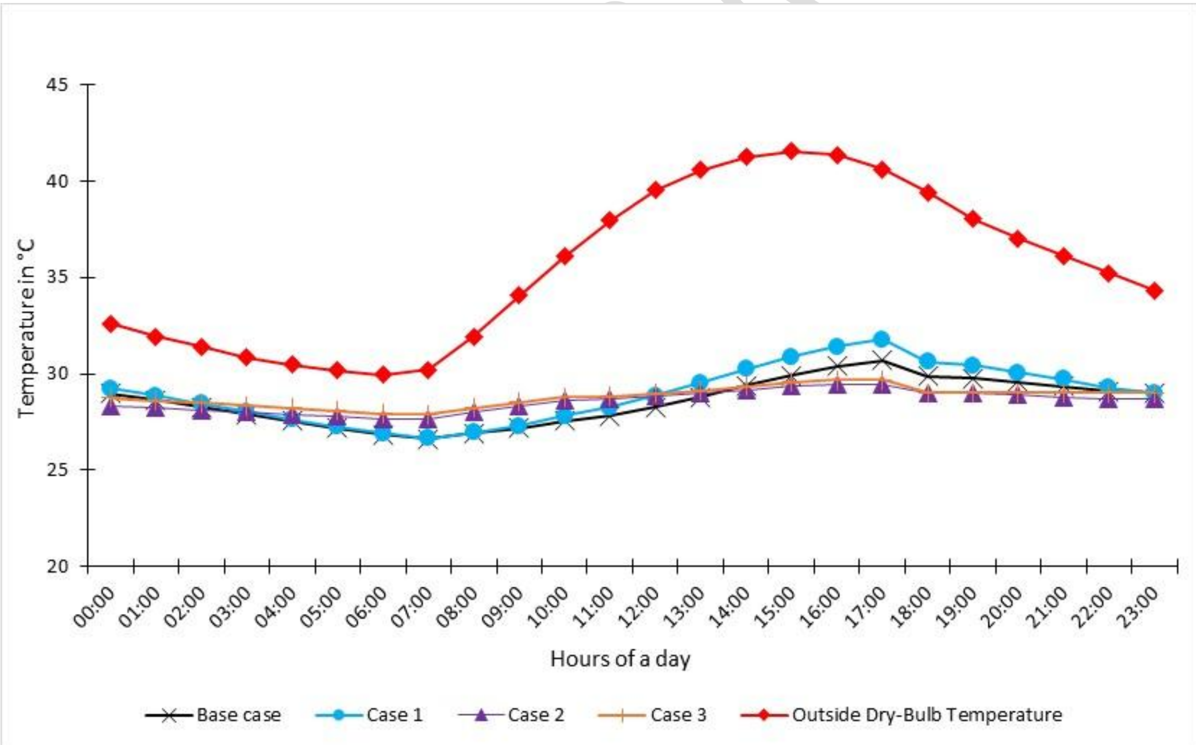

Figure 8: Indoor temperature evolution in relation with ambient temperature over period of 24 hours

Figure 8 present the comparison of indoor temperature evolution profiles for walls cases studied and in relation with ambient temperature over period of 24 hours during the day 7th April in dry tropical climate condition.

The curves on all figures describe identical indoor temperature evolution profiles whatever the type of building wall construction materials used. The average indoor temperature are between 28.52°C to 28.91°C and lower than ambient temperature. This indicate that all walls construction materials used allow for building indoor temperature peaks dumping during considered period, especially during heat period. Then, the average percentage of temperature dumping over the considered period are 23.28%, 21.67%, 23.32% and 22.35% respectively for base case, variants 1 to 3 studied.

3.2 Discomfort hours evaluation in building

Thermal comfort is a complex notion defined as the occupant satisfaction sense and which depends on several physical and physiologic parameters. For physical parameters, temperature and relative humidity are used to appreciate and evaluate the level of thermal comfort according to the climatic conditions. The simulation over the year allows to evaluate the number of thermal discomfort hours as shown in below Figure 9.

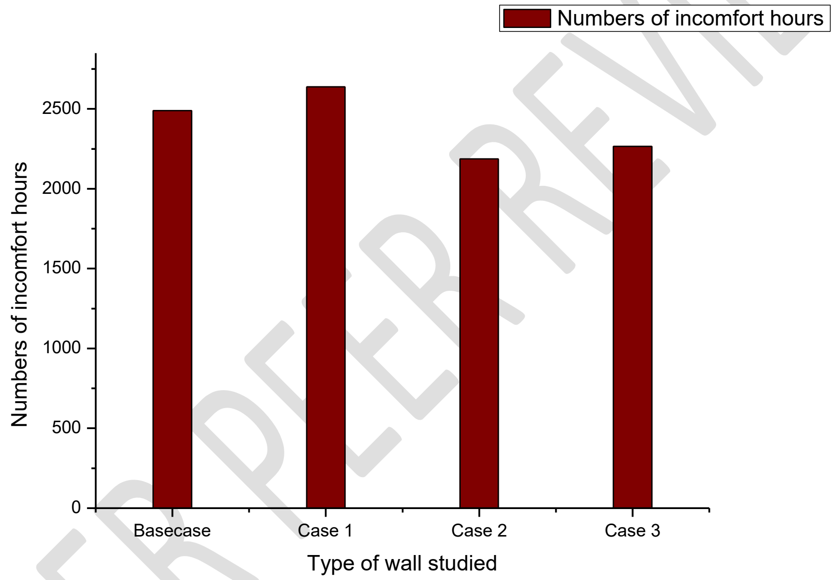

Figure 9: Building indoor discomfort hours in relation with wall construction materials

Figure 9 shows the number of buildings indoor discomfort hours as a function of the type of envelope wall. From this graph and depending on the wall construction material, the number of building thermal discomfort hours is higher when the envelope wall construction materials is cement blocks (Base case) or cut laterite blocks(Case 1) than Compressed stabilized earth blocks(Case 2 and 3).

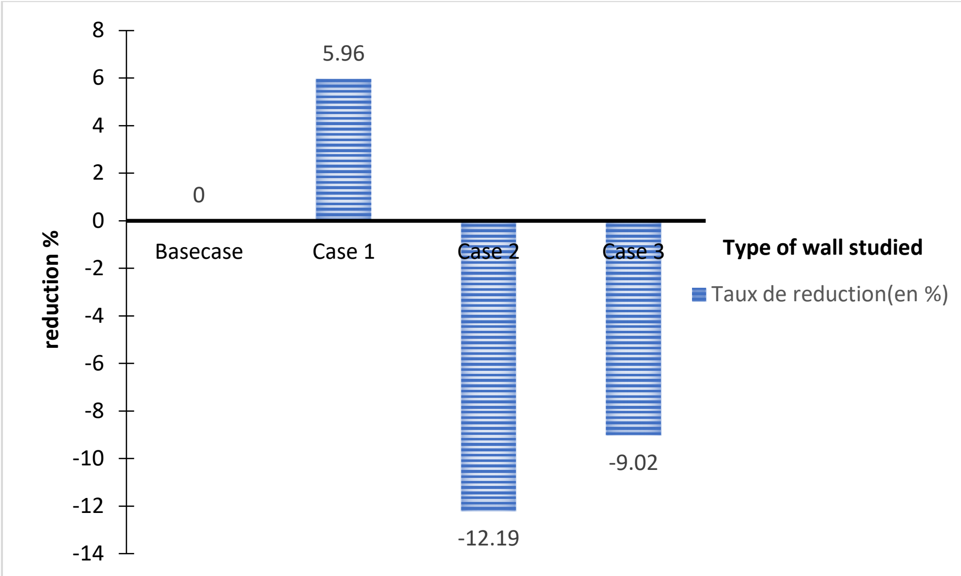

Figure 10: Building indoor discomfort hours decrease rate in relation with wall construction material

Figure 10 present the building indoor discomfort hours decrease rate in the four case studied. As shown in Figure 10, the discomfort hour's number is lower for walls built with CSEB-A13FF and CSEB-23FF and coated with composite earth material (CEM-A13RL). These wall types permit to reduce discomfort hours from 9.02% to 12.19% compared to cement block wall.

3.3 Cooling energy requirement in building

Figure 11 present the building air conditioning (AC) quantity requirement graph in the four case of wall construction materials studied.

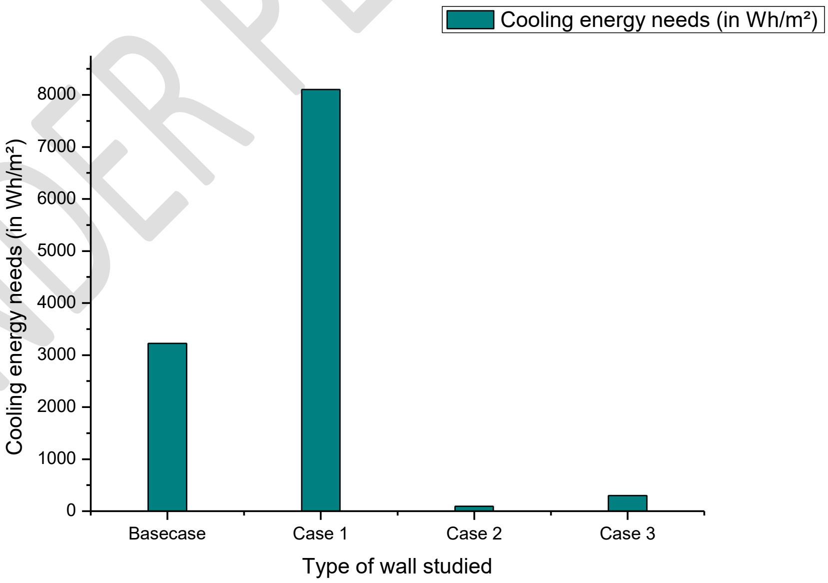

Figure 11: Building cooling energy needs in relation with wall construction materials

As shown in Figure 11 graph, the building cooling energy demand is lower in the case 2 and 3 which walls are built with CSEB-A13FF and CSEB-23FF and coated with composite earth material (CEM-A13RL). The cooling energy needs are estimated at 94.95wh/m², 300.51Wh/m², 3223.12Wh/m² and 8104.56Wh/m² respectively for case 2, 3, and base case and case 1.

4. Results discussion

4.1 Summary of Main findings

The building thermal and energy behavior were studied in two stages by modelling the habitat on Design Builder and then the simulation of different cases of envelope wall by integrating Energy Plus. The simulation outputs collected are: the indoor discomfort hour's number, the air conditioning energy demand, the indoor and the average operating temperature. Table 4 summarize the values obtained for each envelope wall variant studied.

Table 4: Synthesis of energy and thermal simulation results

Variant	Discomfort hour's number		Cooling energy needs		T_{opm}
	(in hour)	Decrease %	(in Wh/m²)	Decrease %	(in °C)
Base case	2490	-	3223.12	-	25.95
Case 1	2638.50	+5.96	8104.56	+151.45	26.25
Case 2	2186.50	-12. 19	94.95	-97.05	25.71
Case 3	2265.50	-09.02	300.51	-90.67	25.92

Table 4 shows that operative temperature (25.71°C-25.95°C), cooling energy needs (94.95 - 300.51 Wh/m²) and the discomfort hour's number (2186.50-2265.50 hours) are lower in building walls modelled with CSEB than cement or cut laterite blocks walls. Therefore, on the basis of these three selected criteria, the Building thermal and energy behavior is better with walls variants 2 and 3. By keeping habitat other constant parameters, we noticed that the envelope construction materials choice is important in building energy and thermal comfort performance search.

The analysis of the results indicates an average reduction of 10.60% of discomfort hours and 93.86% in thermal loads with an average operating temperature between 25.71°C and 25.92°C when using CSEB to fonio straw with coatings of CEM with 3% Shea butter residue. Moreover, the indoor temperatures are between 28.52°C and 28.91°C (Figures 7 and 8), i.e. an average difference of 0.16°C to 0.39°C from variant 3 to the base case. These operating and indoor temperatures are below those of the building constructed either in cement or cut laterite blocks. This performance of building stabilized soil material was observed by [27] who find that the thermal performance coefficients Ubat and G are lower in earthen constructions (adobe, BTC, BLT) than in modern constructions (cement block). However, the results obtained can be reinforced by complementary options in terms of roof type, building orientation and openings.

This local eco-materials option permit therefore in line with the objective to meet of having internal temperatures with the Ouagadougou building thermal comfort zone (26-30°C), obtained by [28] through the use of insulation materials such as cotton and straw coupled with BLT giving temperatures between 28.7°C to 30.5°C for cotton, and 29.8°C to 31°C for straw.

Thus, the present study results increase the scientific knowledge on CSEB with natural local resources and their potential impacts on buildings thermal and energetic performance. This could contribute to Burkina Faso and other UEMOA (West African Economic and Monetary Union) country government for the integration political of building energy efficiency requirements code in their area [29]. Indeed, building with earth materials have many advantages, such us its availability and required thermo-physicals and thermal properties in habitat construction, cost reduce and environmental impacts reduce by minimizing industrial processes [4].

4.2 Strength and limitations

We studied the wall envelope influence on building thermal and energetic global behavior. The study results show that earth material improved with fonio straw and Shea butter residues contribute to a better thermal comfort et reduce energy consumption in habitat. It appears that:

- the walls in Compressed earth blocks stabilised with fonio straw (CSEB-A13FF or CSEB-A23FF) and coated by composite shea butter cake and earth material (CEM-A13RL formulated by [14] offer good average interior and operating temperatures;
- the number of discomfort hours and the energy requirements for air conditioning are reduced;
- the choice of the type of envelope construction materials is very decisive in the search of the thermal comfort achievement;

These results contribute to the valuation of local building materials in hot region but this study remains in numerical study by simulation case and does not take into account:

- recent meteorological data of the study area ;
- separately the building different pieces.

4.3 Implication on Practice and Research

The results obtained show that the building industry can rely on the use of local building materials to address the duality of thermal comfort and energy consumption search in hot region context. For example, sustainability guidelines for energy and carbon emissions suggest that we need to halve our energy use from 2000 to 2050 [30] [31]. In this context, it's important and essential to reduce building operating and construction materials production energy used.

In terms of research prospects, we will be interested in:

- In-situ instrumentation of habitat built with wall envelope in Compressed earth blocks stabilised with fonio straw (CSEB-A13FF or CSEB-A23FF) and coated by composite shea butter cake and earth material (CEM-A13RL) ;
- CSEB-A13FF/CSEB-A23 and CEM-A13RL adhesion characterization when used for composite wall envelope. The presence of the rendering is important and its hold on the wall structure must be perfect. For the rehabilitation of old houses, the coating of aerogel-based rendering considerably reduces energy consumption [32].

– In-situ CEM-A13RL coating durability and repellency characterization on existing building in adverse weather conditions.

5. Conclusion

The best way for the construction industry is to explore the use of natural and industrial secondary resources to provide new materials for green construction. This paper presents the results of wall in local materials influence on habitat behaviour by numerical study. The result indicate that wall in Compressed earth blocks stabilized with agricultural residues (fonio straw) and bio-polymer (Shea butter cake or residue) give the habitat advantageous thermal comfort and energy consumption compared to wall in cement and cut laterite blocks . Indeed, by using this wall in local composite material, the habitat indoor temperature remains within the limits prescribed for dry tropical climates thermal comfort, with a significant reduction of discomfort hour's number and air conditioning energy requirements. Then, the compressed stabilized earth blocks of fonio straw and shea butter cake present an environmentally sustainable alternative that avoids the use of energy intensive during habitat life cycle. This study highlight the influence of local eco-materials on housing thermal behaviour and its contribution to habitat energy efficiency.

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