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Operative Temperature Variance and Life Cycle Assessment Impacts of Wall Construction Materials

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ABSTRACT

The overdependence on concrete in the construction industry in sub-Saharan African countries limits the potential use of sustainable materials in the construction of buildings. Hollow Concrete Block (HCB), the industry's most widely used wall material, contributes to excessive carbon emissions and environmental degradation. Moreso, constructions that employ HCBs, specifically in Nigeria, severely threaten the indoor comfort levels in Naturally Ventilated Spaces NVSs. This study relies on quantitative data to analyse the impact of alternative wall materials in a case building in northern Nigeria. Mud bricks (MB) and Timber/brick (TB) were compared with the existing concrete (CW) case building. The study uses Meteonorm 8 and Climate Consultant 6.0 for EPW file generation. At the same time, dynamic thermal simulation and comparative experiments for thermal comfort and carbon emissions were conducted using DesignBuilder V6 and OneClick Lifecycle assessment tools, respectively. Modelled and simulated under NVS conditions using ASHRAE's PMV model, the result of the study suggests that the MB alternative, although with an intermediate U-value of 0.318 W/m^2k, accounts for the best indoor comfort temperature annually. While the CW building accounts for 41.31% of hours above the comfort temperature of 28^0C, the TB and MB alternatives account for 29.99% and 27.37% of hours, respectively. Furthermore, the MB alternative is the most environmentally friendly material with 510 $KgCO_2/m^2$ emissions, a value 26% less than the CW building with an embodied carbon benchmark of 690 $KgCO_2/m^2$ during the building's life cycle stages. The author suggests that mud construction's thermal properties and Global Warming Impact (GWI) make it a better alternative to concrete and timber buildings in the tropics.

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1. Introduction

The Intergovernmental Panel on Climate Change, IPCC, warns that global temperature is increasing and has called for sustainable means and practices for mitigating climate change effects. The impact of climate change is felt in all regions across the globe, with the most significant change due to anthropogenic activities (IPCC, 2021). Buildings generally account for the largest share of global greenhouse emissions. These emissions raise serious concerns, especially in developing African countries that are very vulnerable to the catastrophic effects of a changing climate (Czechowski, 2020). Several countries are adopting different techniques to adapt to the changing climate, such as retrofitting the existing housing stocks (Kristl et al., 2020), improving energy efficiency in buildings (Ramos Ruiz & Olloqui del Olmo, 2022) and improving the "blue-green" landscape (Croce, 2020). In sub-Saharan Africa, extreme temperatures are experienced year-round. As buildings become more efficient in the operational phase, the material, manufacturing, and construction stages (embodied carbon phases) increasingly become the primary carbon hotspot (D'Amico et al., 2021). With a changing climate, the existing construction methods and material fabrics are unlikely to withstand the predicted extreme weather conditions in the next century. Several studies have predicted a high risk of overheating in future buildings in future climate scenarios, as modelled under different representative concentration pathways (Croce, 2020; Dodoo, 2020).

Nigeria is a growing economy with a high rate of urbanisation. The growth rate is expected to be more than double its current figure by 2055, according to (Macrotrends, 2022). This increase in population will amount to more housing needs that will result in a dramatic increase in heat stress and a higher energy demand for cooling in the future (Jenkins et al., 2015; Mahmoud & Ragab, 2021). One of the ways to improve the energy efficiency of both new and existing buildings is by using sustainable building fabrics with low global warming impact. Indoor temperature of naturally ventilated spaces is largely influenced by outdoor conditions. When the building fabric components are not adequately insulated, it results in uncomfortable hours indoors (Alegbe, 2022). One of the challenges with construction in Nigeria, especially in the building envelope, is the need for insulation and excessive use of concrete products known for high greenhouse gas emissions. However, other known sustainable materials like timber, brick, bamboo, and mud are readily available, but their use in the Nigerian construction industry is not fully harnessed. As asserted by (Agboola & Zango, 2014), incorporating indigenous materials into the building systems could enhance the traditional comfort principles of tropical buildings.

Furthermore, Nigeria's annual CO_2 emission in 2020 was 130.18 million tons, about a 39.5 % increase from 78.82 million tons recorded in 2000 (Hannah Ritchie et al., 2020). The 2030 emission targets set by Nigeria's Nationally Determined Contribution (NDC) do not seem to be in tandem with the reality of a geometric increase in Nigeria's carbon emission as it does not yet include lifestyle-based mitigation strategies like reduced material consumption (Salem et al., 2021). Governments of a developing country like Nigeria need to understand the extent of vulnerability to climate change impact. They must employ adaptive measures in the most threatened sectors, especially the built environment industry, which accounts for the largest share of GHG emissions (Huq et al., 2006). Therefore, this study experiments on the GWI and thermal comfort levels of locally sourced materials against the widely used concrete blocks employed in residential building constructions. An existing concrete block building in northern Nigeria was identified for this study. Thermal simulations were conducted on the existing building by replacing the wall fabrics with timber, brick, and mud in distinctive design combinations. The lifecycle assessment of these material alternatives was also calculated for 50 years to evaluate their global warming impacts. The results presented and discussed in section 5 of this research suggest the opportunity to attain thermal comfort and a reduced environmental impact through a conscious choice of construction materials.

2. Literature/Theoretical Underpinning

The primary focus of the construction of buildings is to provide a durable system that can protect all occupants and furniture in the building from the deteriorating effect of weather and other influential factors (Akande & Adebamowo, 2010). The building fabric which forms the building's enclosure plays a vital role in reducing capital and operational costs, improving energy efficiency and reducing carbon emissions when considered first in building design, using an approach called "fabric first" (DesigningBuildings, 2021). In furtherance, the changing trend in the design of buildings globally necessitates the importance of passive and low-carbon design strategies to achieve thermo-environmental balance in a hot-dry climate (Akande, 2010).

As purported by (A.C. Van Der Linden et al., 2002), one of the defining features of a building's performance is its indoor thermal condition. It is expected that this condition should optimally support the activities of the people and provide a good atmosphere for the furniture within the building. Additionally, (Iso, 2005) defined "thermal comfort" as the condition of the mind that feels relaxed with the thermal environment. This condition of the mind is affected by several factors, with temperature acting as the most common indicator or determinant (HSE, 2022). With reference to (Gorse et al., 2020), adaptive comfort temperature focuses on a temperature range within which most of the occupants in a building feel thermally comfortable. While indoor comfort levels depend on various parameters, including one's perception of an environment, its actual measurement, as suggested by (Akande & Adebamowo, 2010; Özdamar Seitablaiev & Umaroğulları, 2018), ideally captures three parameters: air temperature, relative humidity, and air velocity. In Nigeria, a tropical climate with a monthly mean external temperature of around 26^{o}C (MOP, 2016) suggests that 90% of occupants in Nigerian buildings would feel comfortable with temperatures up to 28^{o}C, as defined in the adaptive comfort chat in figure 1. This comfort temperature is tantamount to results presented by other literature, including that of (Siti Handjarinto & Veronica I, 1998), (Ogbonna & Harris, 2008) and (Jegede & Taki, 2021), who agree that most people feel comfortable between 25^{o}C and 28^{o}C.

Greenhouse gas (GHG) emissions from buildings across Africa contribute to 3.8% of global emissions. Although this figure, compared to 23% GHG emissions from China alone and 19% from the US, appears minimal, its effect poses severe threats to the carbon emissions reduction target (UN, 2006). (Dunne, 2020) reported that in 2015, the annual GHG emissions of Nigeria were 506 metric tons of CO_2 equivalent ($MtCO_2e$) with a proposed target of 13% reduction by 2030 (Transparency, 2020). Also, In line with the Carbon Disclosure Project (CDP) Africa report of 2020, Lagos, the largest city in Nigeria and the most populous city in Africa, accounts for the most significant share of city-wide emissions in Africa (Figure 2).

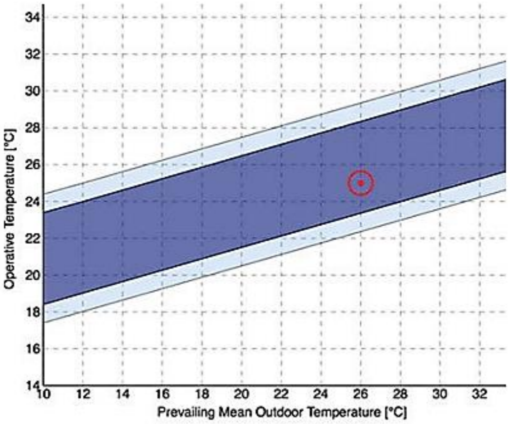


Figure 1 Adaptive Comfort Chart (MOP, 2016)

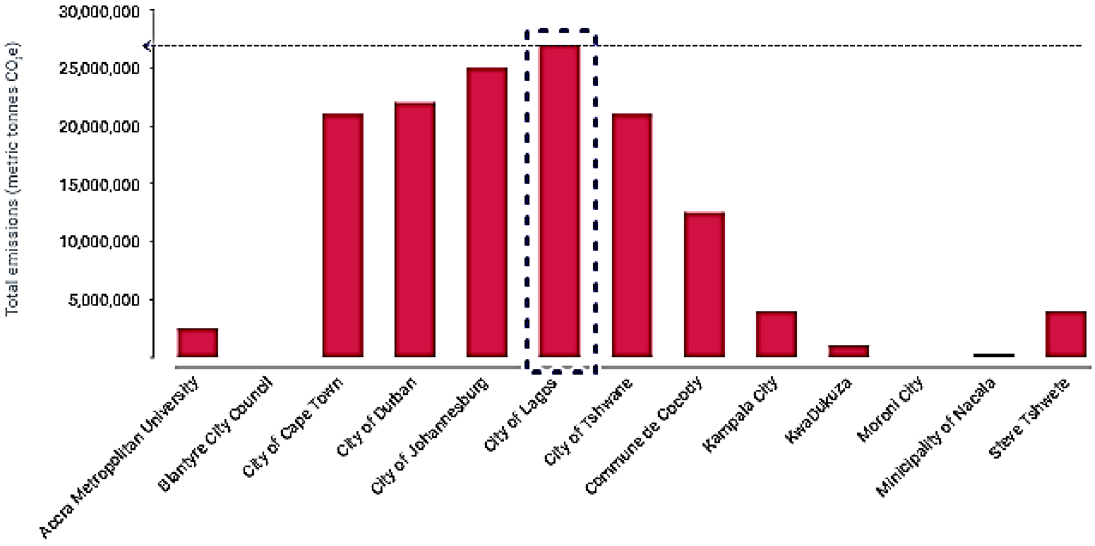


Figure 2 City-wide Emissions in Africa: Lagos Emphasised (Jegede & Taki, 2021)

These emissions from buildings relate to building materials processing and manufacturing, transportation to the site, installation and maintenance, and electricity generation from non-renewable technologies. Specifically, a large amount of these emissions is attributed to cities. According to (Alegbe, 2022; Gurupatham et al., 2021), electricity generation from fossil fuels has the most significant emissions amounting to about 92% of the total global warming impacts. Operational energy in a building's life cycle makes up the majority of energy consumption (Chang et al., 2019). These emissions from electricity can be reduced by considering natural and renewable systems for ventilation, cooling and or heating when needed. Also, mitigation opportunities exist through the efficient use of materials, by using less of the same material and by close substitution with a different but similar material in performance (D'Amico et al., 2021). The estimates provided by the International Energy Agency (IEA) show that cities account for more than 71% of energy-related emissions. This value is expected to escalate to 76% by 2030, making energy-related emissions the largest single source of GHGs (FME, 2021).

Previous research compared the performances of different building materials, using various analytical approaches to optimise indoor thermal comfort and decarbonise buildings. Most of the comparative studies conducted involved building materials like mass concrete, reinforced concrete, steel, clay bricks, compressed stabilised earth bricks (SEBs), HCBs, cross-laminated timber (CLT), and timber frames. The analysis done for embodied carbon emissions and environmental performance involved the life cycle cost and life cycle assessment methods. In addition, while the investigations drawn from this literature cut across tropical, temperate, and polar climates, they presented a similar approach regarding the investigation and computational methods.

To discuss further, (Ahlund, 2020) compared the embodied and operational environmental impact of a building in the temperate region of Sweden with concrete, wooden and cross-laminated timber frames. A multifamily residential building made of concrete was used as the base case study. His findings show that while the concrete building has the largest share of total embodied emissions, the wooden frame alternative has the least environmental impact, with 30% less embodied emissions. More so, (Broun & Menzies, 2011), using the LCA technique, compared the energy consumed and environmental impact of brick made from clay, hollow blocks from concrete and traditional timber frames as used for partitions in the temperate climate of the Uk. Findings from this work indicate that the timber wall has the least environmental impact of the three partitions, with clay brick having the most.

Also, (Gurupatham et al., 2021) compared and evaluated the environmental benefits of compressed stabilised earth bricks, burnt bricks, and cement sand blocks in Sri Lanka, a tropical climate. His findings, using the life cycle thinking approach, show that CSBs are the most efficient material, primarily when used without plaster, while cement sand blocks have the least eco-efficiency index. Cost comparison also indicates that using CSBs costs less for building projects than other materials. Similarly, the works of (Jayalath et al., 2020; Ryberg et al., 2021; Soust-Verdaguer et al., 2020; Zeitz et al., 2019) all presented similar views in analysing the environmental impacts of the use of timber and wood-based products against the likes of steel as investigated by (Zeitz et al., 2019) in the US, and reinforced concrete as analysed by (Jayalath et al., 2020) in Australia. The results presented by these works, though with different analytical approaches and research focus areas, show the degree to which the use of wood-based products, as against concrete and steel, lowers emission levels and improves the environmental performance of buildings globally.

In the tropical climate of Nigeria, an attempt was made by (Jegede & Taki, 2021) to analyse building performance by optimising the building envelope (roof, wall, and floors) using a combination of indigenous materials. According to the findings from his work, as against the existing concrete building, the optimised model (in DesignBuilder) made primarily with brick and timber resulted in about an 8% reduction in operative temperature. This attempt also increased the "thermal comfort months" (months with a mean operative temperature of 28^{0}C) from 3 to 9 months annually. The optimised model's emission and construction costs presented 32.31% and 41.81% reductions, respectively. Using indigenous material like mud for construction compared to concrete and HCBs proves to be an affordable and suitable alternative in the tropics due to its thermal properties (Olotuah & Taiwo, 2013). A recent study by (Alegbe, 2022) in the tropical climate of south-south Nigeria compared timber, timber/brick and concrete materials as external and internal wall fabrics in different design combinations. His study suggests that concrete walls, although with the least emissions in the maintenance (B2) and end-of-life (C1-C4) life cycle stages, account for the largest GWI. On the other hand, the timber alternative contributed to the most improved indoor comfort hours and reduced global emissions. The study, however, implies that the timber walls as the external fabric are the most expensive construction alternative.

These works of literature show that a study comparing timber and mud bricks, an indigenous material, with the widely used HCBs, especially their combined options or alternatives towards improving indoor thermal comfort and environmental impact, for use in the sub-Saharan African context is limited; hence, the need for this materials study in Nigeria.

2.1 Building Construction in Nigeria

Building construction in Nigeria is dependent on the concept of "total environment", which according to (Laryea, 2012) is "the sum total of the physical and cultural factors that exist in any locality". This is similar to views expressed by (Agboola & Zango, 2014), who imply that building systems, methods and patterns are associated with material availability, response to specific climates, local technology, and cultural belief systems. As (Costa, 1989) highlighted In his work, buildings in Nigeria emphasise socio-cultural factors, which are evident in most residential buildings' form. Sadly, these factors are considered more important than the impact of the designs and choice of materials on the environment. A significant part of the buildings built in the second half of the last century and the first decade of this century are characterised by massive consumption of natural resources and energy so that this unparalleled consumption that amounted to large waste generation, air and water pollution became the most considerable undesirable setback affecting the construction industry today (Concu, 2019; Thomas, 2020).

2.1.1 Concrete in Construction

Concrete has become a significant player in the construction industry, and its replacement in the climate of Nigeria appears to be a challenging task, even in the face of the challenge of global emissions reduction. This may be connected to a perceived cost increase or lack of technical expertise when alternative materials are considered, government policies and stakeholders' interests. All components of the building fabrics, including floors, walls, and roofs, have an element of concrete. This is one of the reasons why CO_2 emissions, with new buildings springing up, are on the increase. As (Marinković, 2013; Muneron et al., 2021) highlighted, the concrete industry is a heavy consumer of energy and natural resources due to the burning of fossil fuels during manufacturing. It was accentuated further that the production and use of concrete and its by-products have an enormous impact on the environment; therefore, the environmental assessment of concrete is of foremost importance in combating climate change.

2.1.2 Timber in Construction

The use of timber in the Nigerian CI is not gaining the much-needed acceptance for wall construction, even with huge reserves in the Tropical Rain Forest belt (Laryea, 2012) and numerous timber processing industries. This may be connected to industry policies, codes, and timber treatment to resist harsh weather conditions. Some of the disadvantages of using timber are exaggerated due to inadequate knowledge of its strength, durability and thermal performance (Temitope, 2019). Timber is predominantly used in constructing roof trusses, temporary sheds, and light storage houses. Although architects in Nigeria consider the use of timber very appropriate for the construction of buildings, in light of its low initial cost and aesthetic appeal, it faces one of the significant challenges of being exposed to weather and termite attack (Afolami et al., 2019). Treating timber to resist termites and external conditions like high humidity does not come cheap (Alegbe, 2022). More importantly, sustainability and carbon storage, according to (Brischke, 2019), are some of the major benefits of using timber as a renewable resource for constructing buildings. The longer timber is kept in use, the more carbon is stored, reducing climate and global warming impacts.

Additionally, (Concu, 2019) in his book acknowledged wood as a building material par excellence that has undergone extraordinary evolution in its technology and engineering. However, this domination has been retrogressed in sub-Saharan countries like Nigeria, where reinforced concrete and steel have monopolised the market. This is regardless of the numerous opportunities the use of timber presents to mitigate negative building environmental impacts, such as greenhouse gas emissions (Soust-Verdaguer et al., 2020).

3. Methodology

The overall objectives of this study involve

- collecting primary data through an all-inclusive review of relevant literature,
- identifying helpful case studies and
- using dynamic thermal simulation to perform the requisite experiment.

The literature presented in the preceding section were collected from online library resources, with a more significant percentage comprising journal articles. Conference proceedings, government documents, published theses and dissertations, and eBooks were also consulted. An evaluation of the identified case study is presented in the following section. Energy Plus Weather (EPW) files for the location were generated using Meteonorm 8 for use in Climate Consultant (CC) 6.0, while modelling, testing and simulations were conducted using DesignBuilder (DB) V6.0 software. One-Click LCA tool was used to calculate the building materials' carbon emissions and life cycle metrics.

The key approach of Meteonorm is the interpolation of long-term mean monthly values from meteorological stations. Ideally, measurement data can only be used within the vicinity of a weather station. Elsewhere, where no meteorological station is available, the data must be interpolated between stations within 10-30 km based on satellite imagery. CC uses annual 8760-hour EPW format climate data available for free to access thousands of weather stations worldwide via its website. The general objective of Climate Consultant is to show a graphical representation of the hourly data of the chosen location and to help visualise them using distinct and subtle patterns in a way that would otherwise be lost in tables and figures. Energy Plus, on the other hand, is a simulation programme for building energy used by professionals to model energy consumption for heating, cooling, ventilation, and lighting and is integrated with the CC software (Milne, 2021).

The study relies chiefly on DesignBuilder (v6.1.8.021) simulation software based on EnergyPlus 8.9 simulation algorithms for analysing building parameters, environmental impacts, alternative materials, and operational scenarios. It is used in this study to initially assess the implications of alternative walling materials on indoor thermal comfort, especially on operative temperature difference, using the same building case study and climate data. It is integral in generating a wide range of outputs and reports to help make a reasonable comparison of the performances of design or material alternatives.

The original plan for each case study was drafted in AutoCAD and imported into the software for accurate system boundary characterisation. Additionally, the software offers a virtual environment where building parameters are established, modelled, monitored, and evaluated. The ASHRAE adaptive comfort model in the software is the choice used to simulate the building models. This standard is preferred because it relies on Naturally Ventilated Spaces NVSs, which depend on outdoor climatic conditions. Therefore, with specific outdoor conditions based on generated climate data, the indoor comfort environment was monitored and reported for the different wall materials used. NVSs, peculiar to Nigeria’s tropical climate, allow for unconditioned zones in the building to respond to enveloping fabric and outdoor conditions only. This invariably serves as a model for accurately studying materials and their response to the natural environment.

According to (ASHRAE, 2013), the zone in which most people are comfortable is calculated using the Predicted Mean Vote model. This standard is specified to generate comfort conditions in CC that suit the simulation model objectives. In residential buildings, people adjust their clothing level to accommodate seasonal differences and feel comfortable in higher air velocities and so have a more comprehensive comfort range than in buildings with centralised HVAC systems. One of the critical factors in identifying the case studies used in this study is the reliability of climate data; thus, the location of the case study was first determined through Meteonorm to verify their proximity to weather stations.

3.1 Life cycle Assessment (LCA)

Life cycle assessment is a technique for investigating and evaluating the environmental impacts arising from the provision of a product or service (Reitinger, 2020). It is a method of considering the “cradle-to-gate” environmental consequences a material has during its entire life, from raw material extraction, through production, use, consumption and reuse or final disposal. The different life cycle modules of a building (Table 1) account for different amounts of environmental impacts (Ahlund, 2020). This study emphasises thermal performance and CO_2 emissions during the building’s life cycle, A1-C4, which according to (Hernandez et al., 2019), covers the period from when the construction raw materials are supplied to when the building is deconstructed or demolished.

3.2 Case Study- Building Typology

The study methodology requires computer modelling and simulation of an existing tropical residential dwelling unit located in northern Nigeria. It is crucial for the identified building to fit within the context of the chief material (concrete), which is to be substituted with timber, and mud brick in a combination of distinctive design alternatives and analysed for impact. Modern residential buildings in Nigeria are predominantly made of the components specified in the table 2 below; these components are identified within the case studies adopted for the study but with a focus on walling systems of the buildings only.

Table 1 Life cycle Modules (BSI, 2012)

Building Assessment Information				
Building Life Cycle Information				**Information Beyond the Building Life Cycle**
A1-3	**A4-5**	**B1-7**	**C1-4**	**D**
Product Stage	**Construction Process Stage**	**Use Stage**	**End of Life Stage**	**Benefits and Loads beyond the System Boundary**
A1: Raw material supply **A2: Transport** **A3: Manufacturing**	A4: Transport A5: Construction installation process	B1: Use B2: Maintenance B3: Repair B4: Replacement B5: Refurbishment B6: Operational Energy B7: Operational water	C1: De-construction C2: Transport C3: Waste processing C4: Disposal	Reuse Recovery Recycling potential

Table 2 Building Typology- Basic Building Components in Nigeria

Building Level	**Component**	**Type**	**Commonly used material**
Sub-Structure	Foundation	Strip	225mm concrete hollow blocks with cement and aggregate mix
Super-Structure	Wall	Internal	150mm concrete hollow blocks with cement screed plaster
		External	225mm concrete hollow blocks with cement screed plaster
	Floor	monolithic	Ceramic tiles finish with cement screed
	Doors	Solid core	Timber/Metal
	Windows	Sliding/casement	Aluminum/glass composite
	Ceiling	Non-suspended	PVC/Hardboard
	Roof	Pitched	Timber carcass and Aluminum roofing sheet

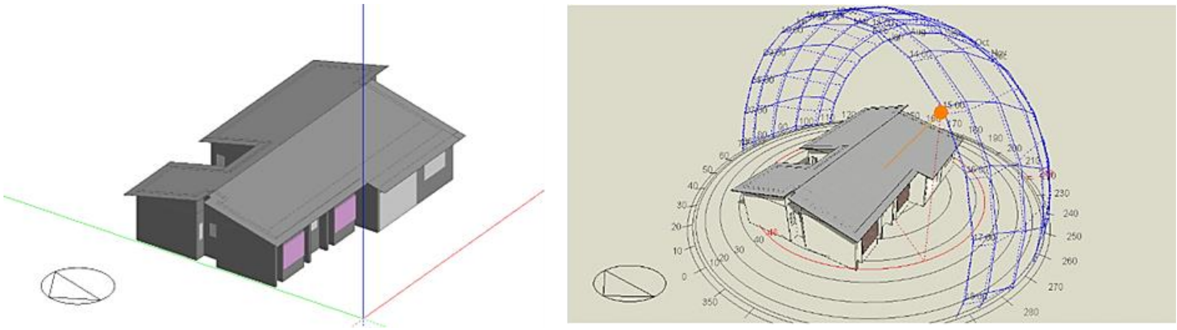


Figure 3 Case Building Model (Left), Building's Solar Path (Right) (DesignBuilder)

The case study building (Figure 3) adopted for this study is a residential bungalow belonging to a large polygamous family. It comprises five bedrooms, with only two of them ensuite, a livingroom, dining, a kitchen, and a storage room. A middle-aged businessperson owns it.

3.3 Site Location and Orientation

Case study two is in Kano, a city in northern Nigeria and the capital of Kano State. Kano City is the largest city in Nigeria after Lagos. Based on geographical coordinates collected from google maps, the building is sited within 11°58'06.4"N 8°33'51.5"E, with a tilt of 17^0 west from the North (Figure 4). Residential buildings bound it to the North and West, with some unoccupied plots to the East and South.

Figure 4 Kano Case Study Satellite Imagery (GoogleEarthPro)

3.4 Climate Classification / Justification

As extracted from DesignBuilder using imported Meteonorm EPW files, the climatic classification of the location according to ASHRAE climatic zone classification is 1B. Very hot temperatures and a dry atmosphere characterises this zone. Further to classifications by Koppen Geiger, and with reference to Figure 5A, the climate for this location is categorised as warm or hot semi-arid (BSh). The BSh climate, considered steppe, is an intermediate between the desert and humid climates and tends to have hot, sometimes extremely hot periods with very little precipitation. Also, a study by (Mobolade & Pourvahidi, 2020) identifies Kano city as a hot, dry climate according to the referenced map in Figure 5B.

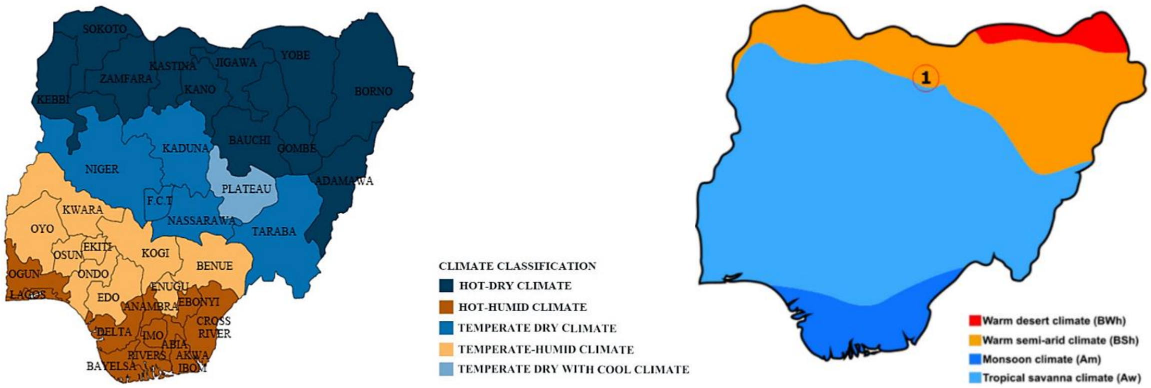


Figure 5 A- Bioclimatic Climate Classification (Left), B- Koppen Geiger Climate Classification (Right) of Nigeria- Kano in circle 1 *(Mobolade &Pourvahidi, 2020)*

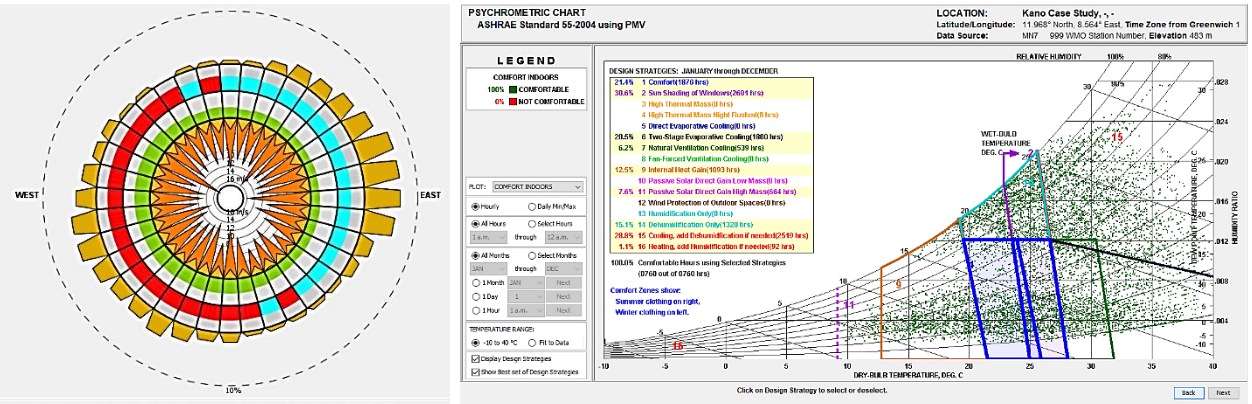
4. Results/Findings

4.1 Climate Data

The table below shows the climate data for the case building location. As recorded, the lowest dry bulb temperature occurs in January at 20⁰C. In April and May, two months after the lowest recorded temperature, extreme temperatures are experienced with as high as 31⁰C for outside dry bulb temperature. The air in this region is primarily dry, with humidity levels as low as 18% and recorded in March. Two wind directions are predominant in this region, north-easterly and south-westerly winds (Figure 6A), blowing strong at a maximum speed of 2.9m/s during the coldest month of January. The psychometric chart in Figure 6B displays a relationship between the recorded dry bulb temperature, relative humidity, and various parameters of supplied air.

Table 3 Weather Data for Study Location (Climate Consultant/Meteonorm)

Weather Data Summary			**Location: Kano (Nigeria)** **Data Source: MN7 999 WMO Station Number** **Elevation: 483m**		
Months	**Dry Bulb Temp.** (⁰C)	**Rel. Hum.** (%)	**Global Hor. Rad.** (KWh/m²)	**Wind Speed** (m/s)	**Wind Direction** (Degrees)
Jan.	20	27	159	2.9	80
Feb.	24	22	157	2.8	70
Mar.	28	18	196	2.7	80
Apr.	31	27	199	2.5	70
May	31	46	197	2.7	250
Jun.	28	65	189	2.8	240
Jul.	26	74	194	2.7	250
Aug.	25	79	176	2.3	270
Sep.	26	78	181	2.1	240
Oct.	27	54	183	2.1	90
Nov.	24	33	168	2.5	70
Dec.	21	30	151	2.8	70
🟦	Annual Lowest				
🟥	Annual Highest				



PSYCHROMETRIC CHART
ASHRAE Standard 55-2004 using PMV

LOCATION: Kano Case Study, -, -
Latitude/Longitude: 11.968° North, 8.564° East, Time Zone from Greenwich 1
Data Source: MN7 999 WMO Station Number, Elevation 483 m

DESIGN STRATEGIES: JANUARY through DECEMBER

21.4%	1 Comfort(1876 hrs)
30.6%	2 Sun Shading of Windows(2681 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
20.5%	6 Two-Stage Evaporative Cooling(1800 hrs)
6.2%	7 Natural Ventilation Cooling(539 hrs)
	8 Fan-Forced Ventilation Cooling(0 hrs)
12.5%	9 Internal Heat Gain(1093 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
7.6%	11 Passive Solar Direct Gain High Mass(664 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
	13 Humidification Only(0 hrs)
15.1%	14 Dehumidification Only(1320 hrs)
28.8%	15 Cooling, add Dehumidification if needed(2519 hrs)
1.1%	16 Heating, add Humidification if needed(92 hrs)

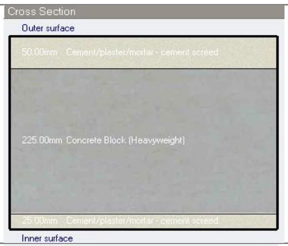
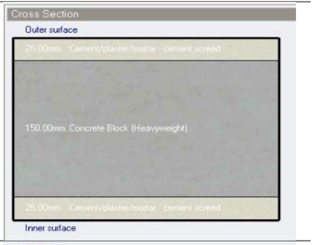
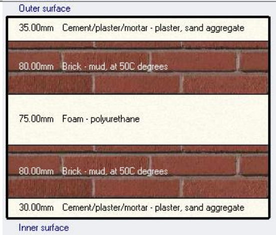
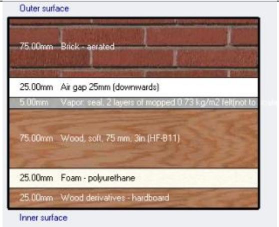
100.0% Comfortable Hours using Selected Strategies (8760 out of 8760 hrs)

Comfort Zones show:
Summer clothing on right,
Winter clothing on left.

Click on Design Strategy to select or deselect.

Figure 6 A- Wind Wheel (Left), B- Psychrometric Chart (Right) for Case Building Location (Climate Consultant)

Table 4 Wall parameters

Wall Type	U-Value External Wall (W/m²k)	Cross Section	U-Value Internal Wall (W/m²k)	Cross Section
CW	2.765	 Cross Section Outer surface 50.00mm Cement/plaster/mortar - cement screed 225.00mm Concrete Block (Heavyweight) 25.00mm Cement/plaster/mortar - cement screed Inner surface	2.579	 Cross Section Outer surface 25.00mm Cement/plaster/mortar - cement screed 150.00mm Concrete Block (Heavyweight) 25.00mm Cement/plaster/mortar - cement screed Inner surface
MB	0.318	 Outer surface 35.00mm Cement/plaster/mortar - plaster, sand aggregate 80.00mm Brick - mud, at 50C degrees 75.00mm Foam - polyurethane 80.00mm Brick - mud, at 50C degrees 30.00mm Cement/plaster/mortar - plaster, sand aggregate Inner surface	0.210	 Outer surface 25.00mm Wood derivatives - hardboard 50.00mm Foam - polyurethane 50.00mm Wood, soft, 50 mm, 2in (HF-B10) 50.00mm Foam - polyurethane 25.00mm Wood derivatives - hardboard Inner surface
TB	0.278	 Outer surface 75.00mm Brick - aerated 25.00mm Air gap 25mm (downwards) 5.00mm Vapor seal, 2 layers of mopped 0.73 kg/m2 felt(not to 75.00mm Wood, soft, 75 mm, 3in (HF-B11) 25.00mm Foam - polyurethane 25.00mm Wood derivatives - hardboard Inner surface	0.210	 Outer surface 25.00mm Wood derivatives - hardboard 50.00mm Foam - polyurethane 50.00mm Wood, soft, 50 mm, 2in (HF-B10) 50.00mm Foam - polyurethane 25.00mm Wood derivatives - hardboard Inner surface

5. Discussion

5.1 Thermal Comfort- Indoor Operative Temperature

Regarding the comfort temperature of 28⁰C, as purported by (MOP, 2016) for buildings in the tropics, the simulation carried out in this study shows that the mud brick (MB) alternative accounts for the most comfortable hours annually. On the other hand, the concrete wall (CW) case building contributes to the highest percentage of hours above the comfort temperature (Figure 7).

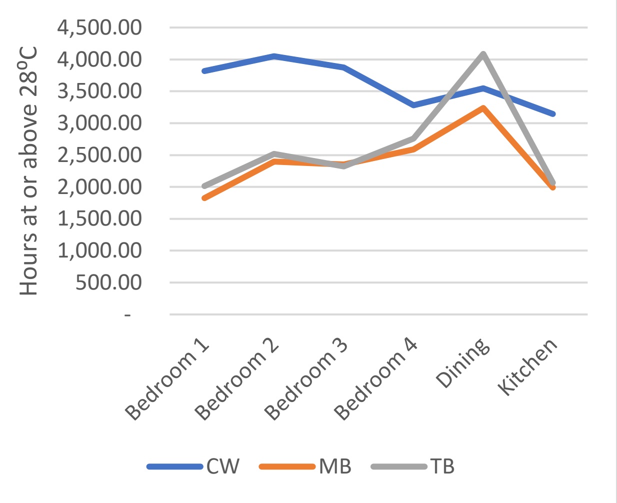


Figure 7 Hours above Comfort Temperature for the Wall Materials

According to (Datta & Mustafa, 2016), different building materials responds characteristically to different climate conditions due to their inherent properties. It is widely suggested that a material with a low U-value will provide better resistance to heat gain in the building; this is only in connection to the material properties. As presented in Table 4 above, the timber brick (TB) wall alternative has a u-value of approximately 13% less than the MB alternative but with a comparatively lesser performance regarding providing better living conditions. The MB's performance and its variation to the TB alternative, as suggested by (Datta & Mustafa, 2016), is likened to the embodied energy of the material components. While the U-value significantly reduces indoor temperature (DesigningBuildings, 2022), a lower U-value does not always imply a lower indoor temperature, as the heat transfer rate into the building depends on the thermophysical properties of the wall materials (Alegbe, 2022).

The orientation of a building, among other factors like glazing, fabric, wind speed and direction, and outdoor temperature, affects the amount of solar gain and indoor temperature in indoor spaces. These materials, subjected to the same indoor and outdoor conditions, show different levels of operative temperature. In the areas presented in Table 5 below, the CW building has the highest percentage of hours above the comfort temperature of 28⁰c, with 41.31%, while the MB and TB options have 27.37 and 29.99%, respectively. Additionally, the annual performance temperature variance of the materials (Figure 8) shows the consistency of the MB alternative over TB and CW. The improved indoor temperature of the mud brick building is further evidenced in spaces like the dining and bedroom 4, positioned along the west-east orientation and with more solar exposure.

In May, the hottest month, the TB building recorded the least operative temperature of 29.73⁰C, which is approximately 3% less than the recorded peak temperature for the concrete building. The annual mean performance of the material alternatives shows that the MB building offers the best indoor comfort in terms of hours above the comfort temperature. Simulations conducted under naturally ventilated spaces have indoor temperatures influenced by outdoor conditions.

Table 5 Comfort Hours for Building Wall Materials

		CW		**MB**		**TB**	
		Hours at or above 28⁰C					
Space	Orientation	Hours	%	Hours	%	Hours	%
Bedroom 1	N	3,820.00	43.61	1,824.50	20.83	2,014.00	22.99
Bedroom 2	W	4,049.50	46.23	2,395.00	27.34	2,520.00	28.77
Bedroom 3	SW	3,872.00	44.20	2,351.00	26.84	2,321.00	26.50
Bedroom 4	E	3,278.50	37.43	2,590.50	29.57	2,757.00	31.47
Dining	NE	3,549.00	40.51	3,237.50	36.96	4,086.50	46.65
Kitchen	NE	3,144.50	35.90	1,988.50	22.70	2,064.50	23.57

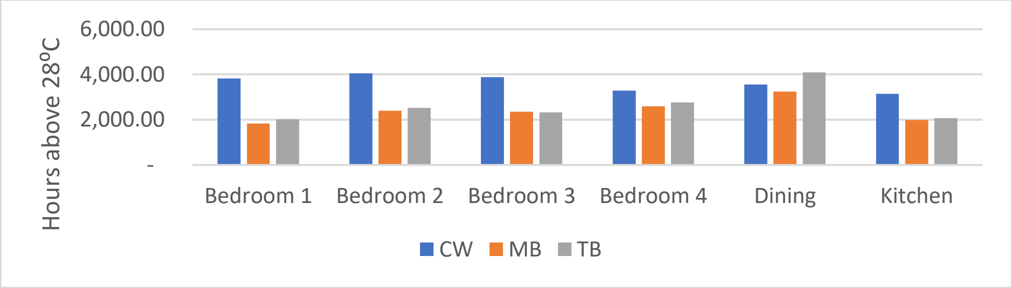


Figure 8 Annual Mean Performance Variance of Building Materials

One of the challenges posed by the alternative materials to concrete is that they offer low vapour resistance. Based on the glacier method analysis in the simulation model, when timber is introduced as the building fabric, the likelihood of mould growth on the surface results in increased humidity due to condensation. According to the dynamic simulation modelling, the interstitial condensation for the wall materials is calculated from the number of surfaces and thermal insulation properties of the walls. In this regard, the CW building offers the highest resistance to mould growth, while the timber brick, due to the presence of timber, a low vapour material, provides the least resistance to humidity (Figure 9).

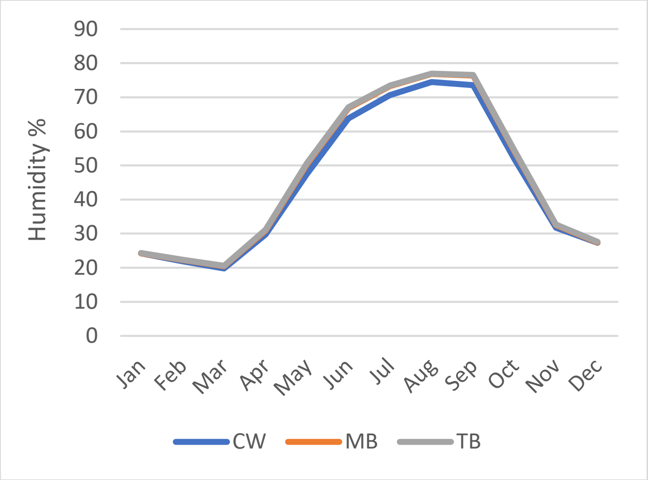


Figure 9 Humidity Levels- Interstitial Condensation of Wall Materials

August recorded the highest humidity level in this climate (Table 3). While all three material options provide a better indoor humidity level than the registered outdoor's, it is 74.47% for the CW, 76.83% for the MB building and 76.94% for the TB option. The concrete building shows better resistance to condensation and mould growth. As opined by (de Oliveira Fernandes et al.), a low-vapour resistant material increases the chances of condensation. This vapour condensation relationship between these materials and their impact on perceived thermal comfort calls for further investigation.

5.2 *Global Warming Impacts (GWI)*

The assessment of the materials' GWI on various life cycle stages shows different emission levels. This is expected as the materials embodied, and operational carbons vary. As stated by (Norton et al., 2021), one of the processes leading to GHG emissions from buildings is always connected to the "cradle-to-gate" life cycle stages of the material. The result of the LCA shows that the embodied carbon benchmark of the as-built CW building is 690 KgCO₂e/m² in class F, the MB building is in class D with 510 KgCO₂e/m², while the TB building is in class D with 542 KgCO₂e/m² of emissions (Table 6). While the embodied emission levels of the TB and MB alternatives are within the same benchmark, the MB building has approximately 6% less than the TB and about 26% less than the as-built CW building.

Table 6 Carbon Benchmark and Global Warming Life Cycle Stages of Wall Materials

Wall Type	**Global Warming Life Cycle Stages (KgCO₂e)**					**Carbon Benchmark**	
	A1-A3	A4	B1-B5	B6	C1-C4	KgCO₂e/m²	Class
CW	92,506.99	3,859.96	5,442.19	1,010,408.80	5,667.68	690	F
MB	65,751.68	1,595.62	11,639.77	1,010,408.80	6,410.53	510	D
TB	62,900.27	1,075.59	22,264.82	1,051,059.81	8,139.44	542	D

Electricity (B6) which contributes to the highest emissions in the entire life cycle of the buildings, accounts for more than 90% of the total emissions (Table 6 and Figure 10A). Outside electricity, the MB building contributes 21% less emissions than the as-built concrete building, while the TB alternative contributes approximately 12% fewer emissions than the CW building (Figure 10B). More so, the total emissions in the life cycle stages for the CW building is 1,117,885.62 KgCO₂e; the MB building accounts for 2% less, while the TB building accounts for 2.4% more.

The results of the study by (Alegbe, 2022) show the timber/brick alternative as the relatively best substitute for concrete. A combination of timber and brick on the exterior contributes to a lower indoor temperature when compared to only timber and concrete fabrics. However, the introduction of mud bricks as an exterior wall element in this study shows a better performance than the TB. This implies the thermal performance and environmental friendliness of mud over other sustainable wall materials.

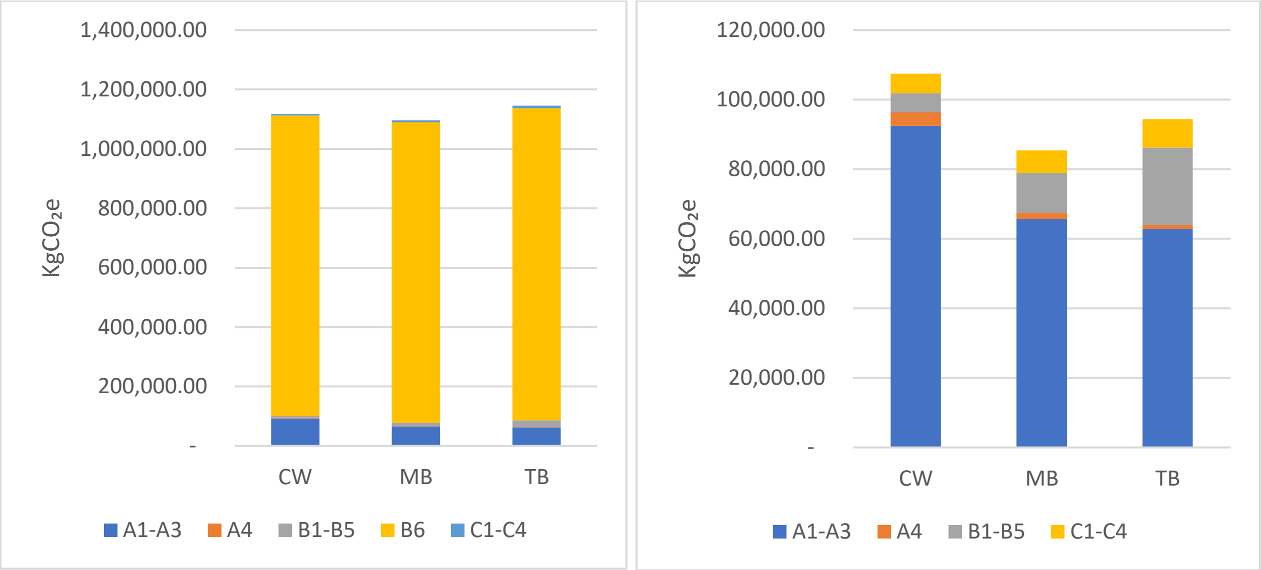


Figure 10 A- GWI of Buildings with Electricity (Left), B- GWI of Buildings without Electricity (Right)

The advantage of the as-built building lies in the maintenance and end-of-life stages. The TB alternative has the most significant benefits of fewer emissions in the material (A1-A3) and transportation (A4) stages (Table 6). The overall assessment of the buildings puts the MB alternative as the most suitable in terms of global warming potentials. The most significant embodied emissions of a building are in areas that contain steel and cement (Norton et al., 2021); this include foundations, floor slab and other structural components. Additionally, (Wesonga et al., 2021) emphasised the importance of analysing wall elements, as they form an integral part of the building's embodied energy. The life cycle impact of the wall systems alone, without other building elements was analysed and presented in table 7 below.

Table 7 Global Warming Life Cycle Stages of Wall Components Only

Wall Type	**Global Warming Life Cycle Stages (KgCO$_2$e) Walls Only**				
	A1-A3	A4	B1-B5	B6	C1-C4
CW	57,885.90	3,060.61	-	-	4,298.41
MB	39,122.37	1,077.84	-	-	4,783.98
TB	36,324.30	558.32	10,678.40	-	6,513.70

The case building (CW) had only the wall fabric replaced while maintaining other elements of the building component. This wall impact analysis influences the overall carbon emission levels. The result shows that the CW has the most significant emissions, with 65,244.92 KgCO$_2$e of total carbon emissions (Figure 11). The MB alternative has 31% fewer emissions, while the TB alternative has 17% less emissions compared to the case building. In this regard, there are zero emissions for the CW and MB during the B1-B6. This is due to savings during the use stage for maintenance, repair, replacement, refurbishment, and operational energy.

The TB option, on the other hand, accounts for 10,678.40 KgCO$_2$e of emissions. This is connected to the material composition of the wall component; timber and brick, which will require maintenance and replacement during the building use. However, the biocarbon storage of the TB building makes it a good material for consideration in terms of the ability to preserve carbon. In this regard, the TB building has about 49,778.10 KgCO$_2$bio storage, while the MB alternative has only 16, 561.54 KgCO$_2$bio storage. In this climate, protecting timber from mould growth, though expensive, can serve as a way of reducing the carbon count in building (Alegbe, 2022), and with solutions that limit fire risks, it can be engineered to replace concrete and steel (Norton et al., 2021). The amount of carbon storage accounted for in the mud bricks alternative is owed to the timber partitions in the building. Concrete has no carbon storage ability; hence the case building has zero carbon storage for the wall component.

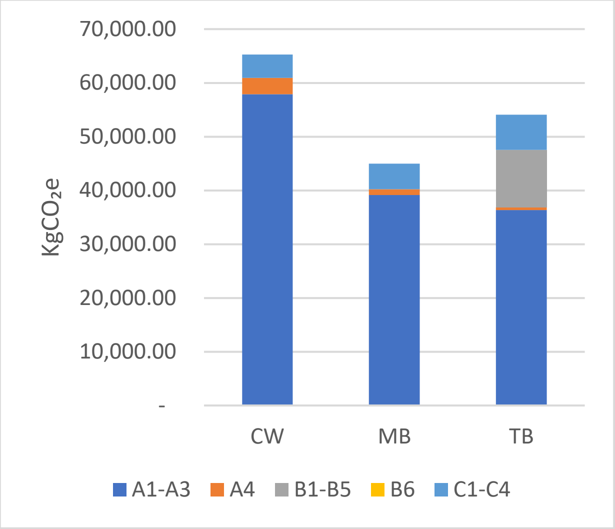


Figure 11 GWI of Walls

6. Conclusion

More than ever, the need to improve indoor thermal comfort and reduce emissions in tropical buildings, which rely significantly on natural means for ventilation, is necessary, given that rising temperatures are experienced globally, and non-renewable/non-recyclable natural resources are in depletion. Most buildings in Nigeria are not climate responsive, giving rise to occupants' discomfort and much energy for cooling (Akande & Adebamowo, 2010). Improving indoor comfort in tropical buildings should not be at the expense of overusing building materials, as emissions from non-green materials pose a severe threat to changing climate. (Norton et al., 2021) noted that reducing greenhouse gas emissions will involve reusing and recycling building materials. HCBs, the widely used wall materials in Nigeria accounts for a large percentage of emissions in the continent of Africa.

These emissions are primarily due to the extraction and processing of the raw materials and the transportation (A1-A4 LCA stages) to the site of the finished product for use (Alegbe, 2022). Buildings are hard to decarbonise as they consume a large and varied amount of natural resources (D'Amico et al., 2021), and studies show that using building materials with high recycling or reuse potential is considered one of the most productive ways of reducing the overall embodied energy impact of buildings (Chang et al., 2019). Overdependence on cement-based building materials negates the potential for recyclable and renewable materials to gain exigency in the Nigerian construction industry.

Thermal comfort, according to (Latha et al., 2015), "could be costly to handle if the choice of materials and construction techniques are not properly addressed". This study examines the potential for timber, aerated clay bricks and mud bricks to provide a better indoor comfort temperature and reduced emissions over the widely used concrete blocks. This research uses dynamic thermal simulation models and life cycle assessment techniques to determine the comfort levels and global warming impacts of concrete walls (CW), timber brick walls (TB) and mud brick walls (MB) in different design alternatives.

The results show that the MB building alternative performs better than the as-built CW building and the TB alternative regarding both operative temperature variance and overall global warming impacts. The MB alternative has 21% fewer emissions (without electricity generation) and 33.8% lesser hours above the comfort temperature compared to the concrete building. The poor performance of the CW option on indoor operative temperature is likened to limited or lack of insulation to address the heat balance between outdoor and indoor conditions. Manufacturing cement-based product amounts to excessive carbon emissions; hence, the case building is the least environmentally friendly one. Building material "greenness" is not only associated with its use in buildings but with its resource management, toxicity and environmental performance (de Castro et al., 2014). The TB wall alternative, comprising both timber and aerated clay bricks exterior, also has a better indoor comfort temperature and fewer emissions than the CW building. Due to its material component, the TB alternative accounts for the most significant emissions during the maintenance stage, but with a comparative advantage due to its carbon storage ability. The advantage of concrete regarding global warming life cycle stages is its low emissions at the maintenance and end-of-life stages.

The author, therefore, concludes that given the distinct advantages of mud bricks over timber, aerated clay bricks and concrete wall materials, in terms of providing lesser hours above the operative comfort temperature of 28^{0}C, environmental impact and de-construction potential, it is therefore recommended as the best alternative for use as external walling fabric in the tropical climate of Nigeria.

7. Future Research

This study does not clearly define the influence of the Interstitial condensation level of the materials on the operative temperature variance of the indoor spaces where they are used. The study focused on operative temperature, paying less attention to other factors like humidity and human factors like clothing level that affect thermal comfort. Therefore, further studies should be conducted on the humidity level of these materials when used for the specific building case study and location to ascertain their overall impact on indoor comfort.

Additionally, it is recommended that this study be conducted under "Fan-Simple HVAC" aeration as an alternative means of ventilation in tropical Nigeria. Since outdoor factors primarily affect indoor conditions in NVSs as modelled in this study, a similar investigation under a controlled environment could suggest a better indoor thermal environment.

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