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Comparative analysis of wall materials toward improved thermal comfort, reduced emission, and construction cost in tropical buildings.

Mark Alegbe

MSc Climate Resilience and Environmental Sustainability in Architecture, CRESTA, School of the Arts, University of Liverpool, UK, m.alegbe@liverpool.ac.uk, alegbemark@auchipoly.edu.ng

Abstract: Africa faces the greatest threat due to climate change. This research stems from the growing concerns for buildings in sub-Saharan Africa to respond to climate change issues by addressing the carbon emissions arising from using high embodied energy materials in building constructions. It investigates the use of timber and aerated brick as suitable replacements for concrete in the tropics for improved indoor comfort and reduced global warming impact (GWI). The investigation relies on Meteonorm and Climate Consultant for weather data collection, DesignBuilder for the case building simulations and One-Click LCA software for lifecycle assessment. The results show that the timber building has the least CO_2 emissions but with a significant threat of being very expensive. The timber/brick alternative accounts for the most improved operative temperature, while the concrete building has the highest emissions during the building's lifecycle but with the least impact in the maintenance and end-of-life stages.
Keywords: Thermal Comfort, Operative Temperature, Embodied Carbon, Lifecycle Assessment, Tropics

1. Introduction

It is known globally that buildings are responsible for more than 40% of energy use and one-third of greenhouse gas (GHG) emissions (Huovila et al., 2009). Many countries are adopting different approaches toward reducing global emissions and potential rising temperatures. One known solution to climate change mitigation is using low embodied energy materials to construct buildings (Ahmed et al., 2021). As opined by (Huovila et al., 2009), one of the significant messages of the Conference of Parties (COP) 15 that held in Kunming, China, is that failure to promote energy efficiency and low carbon alternatives in the design of new buildings or in retrofitting old ones will confine countries into the challenges that are related with poor performing buildings for decades.

The population growth rate, coupled with the pace of urbanisation in sub-Saharan African countries, and the low quality of buildings with a high energy consumption rate, force the reflection of low emissions phenomena to a potential increase in threats to the natural built environment. According to (Widera, 2021), these threats raise concerns about how buildings impact negatively on climate change. Like most in other parts of the continent, buildings in Nigeria are vast consumers of concrete and cement products; this trend cannot continue if the need to reduce greenhouse gas emissions is a priority. In a bid to foster solutions toward reducing these emissions in tropical buildings, the researcher attempts to replace some cement and concrete products with timber and bricks in a typical residential building in Nigeria. With available natural reserves in Nigeria, timber, a renewable and recyclable resource, could serve as a viable replacement for concrete in the construction of buildings.

Africa is the continent most vulnerable to the impacts of climate change. While the continent accounts for the smallest share of global greenhouse gas emissions with only 3.8%, in contrast to 23% in China, 19% in the United States, and 13% in the European Union, it faces the greatest threats due to changing climate (Czechowski, 2020, UN, 2006). More worrisome is that it is already experiencing an extreme temperature increase of approximately 0.7^{o}C across a greater fraction of the countries within it (UN, 2006). Nigeria is located approximately between latitudes 3^{o} 15' to 13^{o} 30'N and longitudes 2^{o} 59' to 15^{o} 00' E and shares boundaries with the Republic of Benin to the west, the Niger Republic to the north, Chad to the north-eastern corner and Cameroon to the east, as well as the Atlantic Ocean to the south. It has an approximate landmass of about 923,768 km^2 and a population of about 189 million in 2016 (FME, 2021). This population is predicted to be more than double its figure by 2050.

According to figures quoted by (Dunne, 2020), the country's annual greenhouse gas emissions were 506 metric tons of CO_2 equivalent ($MtCO_2e$) in 2015, with a proposed target of 442.5 $MtCO_2e$ by 2030 (Transparency, 2020). This target set by Nigeria's Nationally Determined Contribution (NDC) to the Paris Agreement is also in tandem with data compiled by the Potsdam Institute for Climate Impact Research (PIK). The figure presented by (Dunne, 2020) also includes emissions from land use change and forestry, which is roughly the same as the UK's total 2015 emissions.

Buildings in the tropics are exposed to high temperatures throughout the year, making the emphasis on design and construction of modern buildings more focused on providing a cooler indoor environment. A significant amount of savings can be achieved towards energy consumption and reduced emissions by carefully designing and appropriately planning energy-efficient measures and optimising the components of the overall building envelope (Chowdhury et al., 2016).

2. Aim and significance of the study

Towards reduced greenhouse gas emissions, energy consumption, and material cost of buildings, the predominant use of concrete blocks and concrete products as the chief wall construction materials in tropical buildings needs to be substituted with more suitable and environmentally friendly materials. This study suggests a suitable alternative to concrete by comparing the effects timber, brick, and concrete wall materials have on indoor thermal comfort, carbon emissions, and the construction costs of buildings in Nigeria.

2.1 Study objectives

I. To determine the performances of timber, brick, and concrete walls during the life cycle of a building to suggest a sustainable option for use in the tropics.
II. To compare the global warming impact of buildings with the wall materials
III. To compare the relative construction costs of using the materials as the building envelope in Nigeria.

3. Materials and methods

The overall study objectives of this research involve collecting data through a comprehensive review of relevant works of literature, identifying a case building and using applicable software to perform the requisite experiment. The wall materials compared in this study are concrete walls (CW), concrete external walls with timber partitions (CWT), timber walls (TW) and timber/brick external walls with timber partitions (TBT). 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 carried out using DesignBuilder (DB) V6.0

software. Furthermore, One-click Lifecycle Assessment software was used to assess the global warming impact of the buildings, while a take-off estimate using the Nigerian Institute of Quantity Surveying (NIQS) format was used to analyse the costs of the buildings. The ASHRAE adaptive comfort model is the standard used to simulate the building models. It is preferred because it relies on Naturally Ventilated Spaces NVSs, which depend on outdoor climatic conditions. According to (CIBSE, 2015), the adaptive comfort model is suitable for assessing the thermal environment of new or existing buildings with undersized systems or with neither cooling nor heating systems in place.

3.1 Case study

The building is situated in the ancient city of Benin, the capital and largest city in Edo state, Southern Nigeria. It is bounded by an access road, Eweka Lane to the south, and other residential buildings to the west and east. It lies within 6°21'30.0"N 5°37'59.0"E, with a tilt of 25^{0} west from the north. According to weather files collected from Meteonorm, this case study is identified under ASHRAE climatic zone 1A, considered Very hot and Humid.

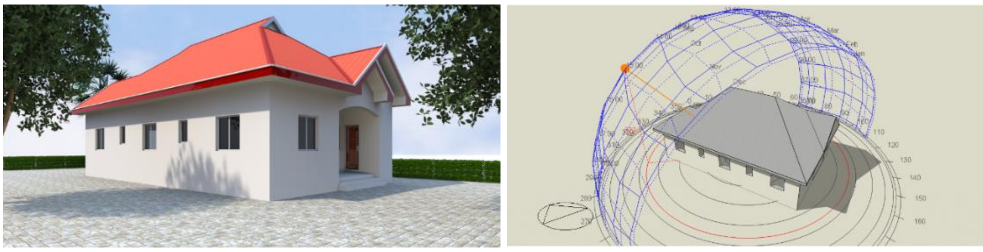

Figure 1. Case building model (Left)- Sketchup, Building's solar path (Right)- DesignBuilder

1.2 Climate data

Table 1. Weather data summary for Benin City. Source: Climate Consultant/Meteonorm.

Weather Data Summary				**Location: Benin City (Nigeria) Data Source: MN7 999 WMO Station Number Elevation: 72m**		
Months	**Dry Bulb Temp.** (ºC)	**Air Temp. 2m Gl.** (ºC)	**Rel. Hum.** (%)	**Global Hor. Rad.** (KWh/m²)	**Wind Speed** (m/s)	**Wind Direction** (Degrees)
January	27	27.2	63	152	1.6	220
February	28	27.9	69	130	1.8	190
March	30	27.6	76	163	2.0	190
April	28	26.9	80	165	1.8	210
May	28	26.3	80	162	1.5	210
June	26	25.3	84	142	1.6	200
July	26	24.8	84	144	1.9	210
August	25	24.6	88	142	2.0	220
September	25	24.8	88	148	1.6	180
October	26	25.5	86	161	1.3	220
November	27	26.4	86	160	1.3	200
December	27	26.8	70	152	1.4	230

4. Results

The comfort temperature in the tropics presented by different literature, including that of (Siti Handjarinto et al., 1998), (Ogbonna et al., 2008) and (Jegede et al., 2021) for naturally ventilated spaces agree that most people are comfortable between 25°C and 28°C. Additionally, (MOP, 2016) asserted that people feel comfortable within temperatures of up to 28°C. Table 2 shows the U-values, sizes, temperatures during the coldest and hottest months (highlighted in Table 1), and the costs of the walls studied.

The simulations carried out in this study show that the CW building performed the worst in terms of indoor comfort and carbon emissions compared to the TW and TBT alternatives. The high operative temperature recorded for the CW building could be due to a lack of insulation in the wall fabrics. The practice of not adequately insulating walls is prevalent in Nigeria. Insulation plays a significant role in controlling indoor temperature, as the more insulated a building fabric is, the less the U-value, and the slower heat is transferred (DesigningBuildings, 2022, Lymath, 2015). Furthermore, the TBT building contributes to the lowest indoor mean monthly operative temperature across the year (Figure 2) and the least percentage of uncomfortable hours (Table 3) in the indoor spaces. The U-value for the TBT external wall is 0.384 W/m²k which is 86% less than the CW external wall with a U-value of 2.765 W/m²k (Table 2).

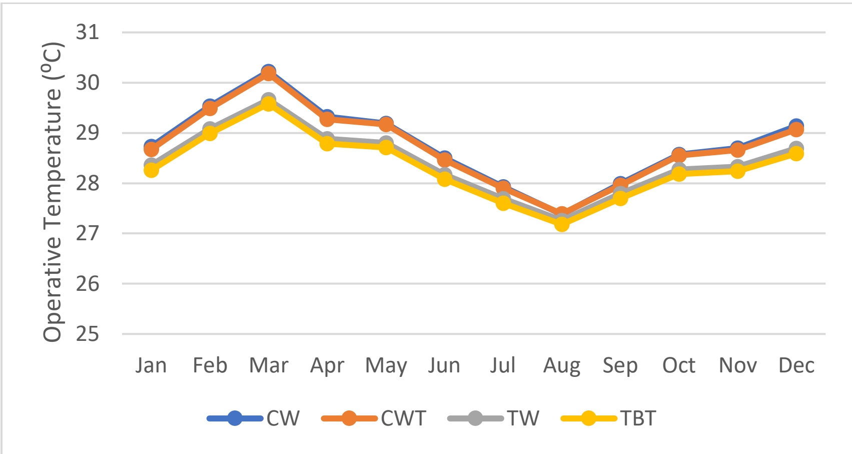

Figure 2. Mean monthly operative temperature.

Table 2. Buildings comparison- U-value, size, temperature, and cost.

	U-value (Interior) W/m²k	Size (mm)	U-value (Exterior) W/m²k	Size (mm)	Temp °C (March)	Temp °C (August)	Cost (₦) Walls Only
CW	2.579	200	2.765	300	30.22	27.38	1,638,000.00
CWT	0.337	150	2.765	300	30.18	27.39	3,043,000.00
TW	0.337	150	0.372	185	29.66	27.26	5,590,400.00
TBT	0.337	150	0.384	230	29.58	27.18	5,055,600.00

Table 3. Uncomfortable hours

	CW		CWT		TW		TBT	
	Hours at or above 28°C							
	Hours	%	Hours	%	Hours	%	Hours	%
B/rm 1 (NW)	5,856.50	66.86	5,661.00	64.62	4,455.00	50.86	4,286.50	48.93
B/rm 2 (W)	5,874.00	67.05	5,274.00	60.21	4,361.00	49.78	4,241.00	48.41
B/rm 3 (S)	6,266.00	71.53	5,821.50	66.46	4,579.00	52.27	4,425.50	50.52
L/room (E)	5,776.50	65.94	5,090.00	58.11	4,562.00	52.08	4,475.50	51.09

Additionally, the embodied carbon energy of the materials measured in the A1-A3 (materials) stage of the building's life cycle shows more carbon emissions for the CW building.

The TW and TBT alternatives have the least emissions with 20,780.11 KgCO_2e and 24,275.08 KgCO_2e respectively. In the A4 (transportation) stage, emissions are again the most for the CW walls, with 1,643.60 KgCO_2e, three times more than the timber walls. However, the materials and configuration of the CWT, TW, and TBT alternatives show they have more emissions than the concrete walls during their B1-B5 (maintenance) stages. The B1-B5 and C1-C4 (end-of-life) stages see the CW building having advantages over other alternatives. When measured alone, the GWI of the walls (Figure 3) shows TW building accounts for the least emissions, followed by TBT, CWT and CW. The concrete walls have three times more emissions than the timber walls. As purported by (Brischke, 2019), timber is a sustainable material with the ability to store carbon for a very long time. This property accounts for one of the most significant advantages of timber over concrete. The TW has approximately 22,000 KgCO_2bio of carbon storage, more than twice the amount stored in the CWT option.

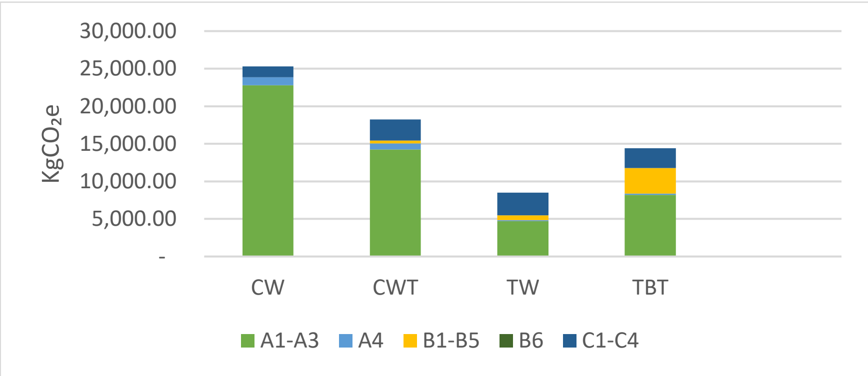

Figure 3. Lifecycle assessment- Global warming impacts of walls only

The operational energy accounts for the largest emissions in the entire life cycle of the buildings. This is due to electricity consumption during the 50-year period calculated for. Electricity alone generated from fossil fuels accounts for more than 92% of the total global warming emissions. As asserted by (Gurupatham et al., 2021), this electricity consumption is a burden in tropical countries that does not only impact the economy but also the climate.

Timber for external wall construction in Nigeria faces significant threats like weather and termite attack (Afolami et al., 2019). Preventing external timber walls from these threats makes construction very expensive. In this regard, TW building is the most expensive, while the CW building is the least expensive (Table 2).

5. Conclusion

The choice of materials for the building envelope has a potential impact on the embodied energy of the building and its GWI (Ximenes et al., 2013). This study compares indoor comfort, environmental impact in terms of carbon emissions, and comparative costs of using timber and brick in a combination of different design alternatives to replace concrete in residential buildings in Nigeria. In terms of operative temperature, the TBT building offers the best indoor comfort level. In the life cycle assessment, the TW building has the least emissions while the CW building has the most impact, making it the least sustainable building. The CW construction is the least expensive, while the TW option is the most expensive. The increased cost is mainly due to added insulation layer and weather-proofing timber finishings.

The author concludes that as a first step toward improving indoor comfort and reducing global emissions, the use of timber partitions or wood-based materials for retrofitting residential buildings is highly encouraged. For new builds, replacing conventional concrete with timber frames and brick cladding for weather protection can be a significant step towards mitigating the problems of climate change in buildings in the tropics. However, the author presents the following as recommended areas for further studies.

I. To investigate the comfort levels of buildings with proper orientation vis-à-vis the impact of these materials under naturally ventilated conditions.
II. To investigate the environmental impacts of the wall materials under HVAC conditions.
III. To compare mudbricks from mud, an available natural resource, and timber as external and internal wall fabrics respectively, in Nigeria's tropical climate.

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