Quantifying the effect of roof insulation on indoor comfort and cooling loads in Nigerian residences

Henry Odiri Igugu[1], Jacques Laubscher[1]
[1] Department of Architecture and Industrial Design, Tshwane University of Technology.
Staatsartillerie Road, Pretoria 0001, South Africa

Abstract

Nigerian urban residences largely depend on energy-intensive mechanical techniques to achieve a temperate indoor climate. Mechanical devices are powered with electricity from fossil-fuelled power stations. However, roof insulation as an effective passive measure of lowering indoor cooling loads is not standard construction practice in Nigeria. This study assesses the efficiency of using Extruded Polystyrene (XPS), Glass wool and Spray Polyurethane Foam (SPF) roof insulation materials to reduce annual cooling loads while maintaining optimum indoor thermal conditions. Using the Lagos metropolis as a case study, the dynamic simulations indicate improved comfort levels with cooling load reductions of approximately 7%-8% under an annual average outside dry-bulb temperature of 27.4°C and an ASHRAE recommended indoor temperature setpoint of 22°C. Furthermore, the results suggest an optimum roof insulation R-value range of 2.5 m^2K/W to 3.0 m^2K/W. Including insulation as part of the roof construction could alleviate the challenge of increased energy consumption in Nigeria's rapidly growing residential building population while reducing GHG and Carbon emissions during its operational lifetime.

Keywords: *Indoor thermal comfort; cooling loads; residential buildings, building energy simulation, Nigeria*

Key Innovations

- The study quantifies the performance of specific insulation materials to reduce the cooling loads in the Nigerian residential sector using simulations to develop the current energy codes and to demonstrate the need for improvements.

Practical Implications

Global South countries with recently developed energy codes may consider including simulation parameters for their contexts. Simulation practitioners can also consider international best practices as a baseline while ensuring contextual parameter specifications are included to accommodate local preferences and conditions.

Introduction

Globally, the energy sector contributes to approximately 70% of greenhouse gas (GHG) emissions (Friedrich et al., 2017, Bauer et al., 2018, International Energy Agency (IEA), 2018). The sectoral analysis of the energy sector highlights that buildings account for 30%-40% of global energy consumption (Rashid and Yusoff, 2015, Cao et al., 2016, Saghafi and Teshnizi, 2011). Furthermore, approximately 85% of building energy consumption occurs during the operational phase (Anderson et al., 2015). This energy is often used to provide comfortable indoor conditions with varying needs across building typologies.

Nigeria's residential sector is projected to account for nearly 60% of the country's energy consumption between 2013 and 2030 (Ezennaya et al., 2014, Olaniyan et al., 2018). In tropical regions such as Nigeria, cooling is a vital requirement to achieve optimum indoor thermal conditions in buildings (Ferrucci et al., 2017, Dominković et al., 2018). Indoor cooling can be provided using mechanical or passive means. However, in Nigeria, air conditioners are the preferred mechanical technique to attain optimum indoor thermal conditions. This practice accounts for 30%-75% of a residence's energy consumption (Onyenokporo and Ochedi, 2019, Ogbonnaya, 2019). In 2020, 52% of the Nigerian population of more than 200 million people lived in urban areas (World Bank, 2022). In the Nigerian urban residential sector, several studies indicate the extent to which mechanical ventilation systems are used to attain indoor thermal comfort (Akande, 2010, Adebamowo et al., 2013, Eludoyin and Adelekan, 2013). Given the projected population growth from approximately 209 million in 2020 to 400 million by 2050 and an urban population ratio of 53% (Schneider, 2022), the expected urban residential energy consumption could increase by up to 100% (Dioha and Kumar, 2020). Furthermore, Nigeria's reliance on fossil fuels as a primary energy source will result in higher GHG and Carbon emissions (Ebhota and Tabakov, 2018, Sulaiman and Abdul-Rahim, 2018). Therefore, optimising residential energy consumption should be a priority to achieve built environment sustainability in Nigeria.

The Lagos metropolis in Nigeria was selected as a case study because it characterises the typical challenge of increasing residential energy consumption. Lagos represents 0.4% (3577 km^2) of Nigeria's land area but accounts for more than 10% (20 million people) of the nation's population (Adewuya and Oladipo, 2020, Mogaji, 2020). In addition, Hoornweg and Pope (2017) projected Lagos' population by 2100 to be between 61 million and 100 million residents, making it possibly the largest city globally (Olowe, 2021). This potential increase further exacerbates the energy consumption challenge in the residential sector. Onyenokporo and Ochedi (2019) argued that up to 99% of current residents in Lagos depend on some form of mechanical ventilation to achieve a comfortable indoor climate. Applying passive techniques to achieve the desired indoor conditions could reduce the reliance on air conditioners and the resulting energy consumption. Thus, there is significant potential for implementing passive solutions such as roof insulation.

Various researchers have evaluated the impact of different passive techniques on the indoor comfort of buildings in Nigeria and the reduction of energy requirements for cooling. Akande (2010) investigated the influences of building orientation, building materials and natural ventilation on occupant comfort and cooling loads. Inusa and Alibaba (2017) explored passive design using bioclimatic analysis, improved window glazing, shading and evaporative cooling. The influence of tree shading on thermal conditions in buildings in Nigeria has also been investigated (Morakinyo et al., 2016). Other studies which assessed various passive strategies to improve thermal comfort and reduce cooling loads include (Ojo and Lawal, 2011, Amasuomo et al., 2017, Oluwafeyikemi and Julie, 2015). However, the use of roof insulation is not common practice in Nigeria, and the impact of various types of roof insulation materials on indoor comfort and cooling roads has not been effectively quantified in the Nigerian context (Adaji et al., 2019, Kwag et al., 2019).

To address the need for passive measures, the Nigerian National Building Energy Efficiency Code (BEEC) recommends a minimum R-value of 1.25 m^2K/W for roof insulation (Federal Ministry of Power Works and Housing (Housing Sector), 2017). However, Solid Green Consulting (2017) suggested a minimum R-value of 1.25 m^2K/W is low compared to similar energy efficiency codes and needs to be increased to 2.5 m^2K/W. This highlights a knowledge gap on the efficacy of roof insulation (and its corresponding R-values) in the Nigerian built environment. This study seeks to address the identified gap by evaluating the impact of three different roof insulation materials on indoor comfort levels and resulting cooling loads in urban residential buildings using dynamic simulations.

Methods

After establishing the typical architectural design, building geometry, zoning and material specifications used in urban residential buildings, data was imported to the commercially available DesignBuilder software to model and quantify its performance. Historical weather data and the hourly weather data from Meteonorm software for Lagos were used to determine the predicted performance of the selected three insulation materials in reducing the cooling loads.

Building geometry

To address the housing needs of Lagos residents, housing developers increasingly develop multi-storey family apartment blocks. Currently, it is the predominant housing typology. The typical residential design used in the study is the result of overlaying and combining the typical floor plans used in the studies by Solid Green Consulting (2017), Ezema et al. (2015), Babalola et al. (2019) and Ilesanmi (2012).

Ezema et al. (2015) used nine government-managed public housing estates in Lagos, examining 10182 residences to identify the typical plan configuration and housing typology, as shown in Figure 1 (redrawn by authors). The focus of the study by Solid Green Consulting (2017) was to develop the first edition of Nigeria's BEEC. At the same time, Solid Green Consulting (2017) defined the typical residential floor plan, as shown in Figure 2 (redrawn by authors). This standard plan is supported by the floor plans and designs of real-world residential buildings in varying locations across Nigeria, as identified by Ochedi and Taki (2022) and Emmanuel et al. (2020).

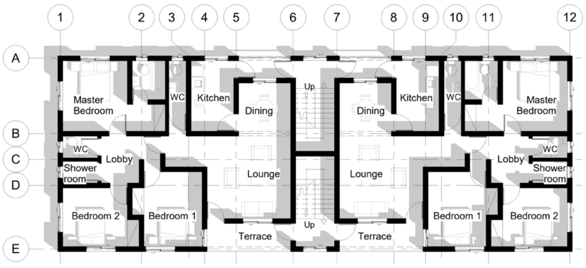

Figure 1: Typical floor plan of the residential typology, adapted from Ezema et al. (2015).

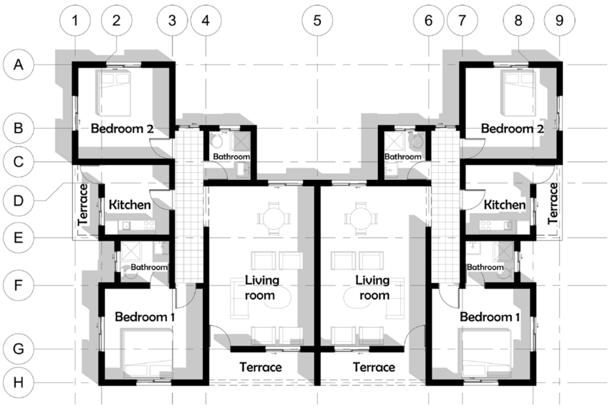

Figure 2: Typical floor plan of the residential typology, adapted from Solid Green Consulting (2017).

The impact of the roof on heat gain is most significant on the topmost floor of a multi-level building. The study uses a typical architectural design of the top floor of a multi-family apartment block. At the same time, the study is also applicable to single-storey residential buildings making the results relevant to the larger Lagos residential blend.

The layout used in the simulations is for the top floor of a 3-bedroom semi-detached residential design. It is representative of the Lagos residential context. The total roof area is 392 m^2 (including overhangs), with a total floor area of 231 m^2. The total floor area of the habitable rooms is 149.243 m^2.

Simulation zoning and design data

Following the development of the building geometry in DesignBuilder, the interior spaces were zoned by assigning the relevant activity templates, as shown in

Figure 3. Zones which typically do not have air conditioners, such as bathrooms, toilets, shower rooms and corridors, were excluded from the subsequent calculations. The simulations include the living rooms, dining rooms and bedrooms as habitable spaces.

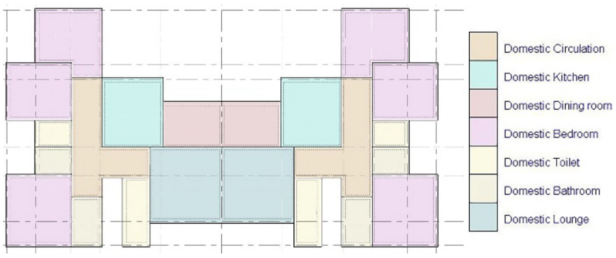

Figure 3: Internal zoning in DesignBuilder.

Table 1 highlights the data used for the dynamic simulations descriptive of the typical Nigerian built environment. Finally, hourly weather data were exported into *epw* format from Meteonorm software. Historical climate data from 2000 to 2009 from a Lagos/Ikeja weather station was used due to the absence of relevant weather data on the EnergyPlus database.

Table 1: Simulation data specifications in DesignBuilder.

Dataset	Element	Description
Construction	External walls	Concrete block wall, 225 mm, uninsulated, 13 mm dense plaster on both sides; R = 0.663, U = 1.508
	Roof	28-degree pitched 25 mm concrete roof tiles (without an underlay) and a 13 mm gypsum plasterboard ceiling. Average air gap of 1555 mm; R = 0.418, U = 2.393
	Internal partitions	Concrete block wall, 225 mm, uninsulated, 13 mm dense plaster on both sides; R = 0.663, U = 1.508
	Floors	Uninsulated, 11mm ceramic/porcelain tiles on 50 mm floor screed on 150 mm cast concrete; R = 0.473, U = 2.113
	Airtightness	Model infiltration, 1.00 ac/h
Glazing	Type	Single Clear 6 mm, SHGC = 0.819, U = 6.12
	Layout	Preferred height 1.20m,
	WWR	20% glazed
	Sill height	0.9 m
Lighting	NPD	3.40 W/m^2-100 lux
	Type	Suspended
HVAC	Type	Split, no fresh air
	Mechanical Ventilation	Min fresh air (Sum per person + per area)
	Cooling Fuel	Electricity from grid
	Cooling system CoP	1.80
	Min supply air temperature	12.00 degree Celsius
	Min supply air humidity ratio	0.008 g/g

WWR: Window-to-wall ratio; NPD: Normalised power density; CoP: Coefficient of performance; R: Thermal resistance in m^{2}K/W; U: Thermal transmittance in W/m^{2}K.

The U-values used in the study are typical for Nigerian residential construction. Table 2 compares the U-values of the floor, walls, and roof used in this paper against three contextualised studies to enhance the model's reliability. The U-values used in Solid Green Consulting (2017), Jegede and Taki (2022), and Ochedi and Taki (2022) are captured and presented as Study 1, Study 2, and Study 3, respectively. In addition, the case study location for each study is also included for added clarity.

Furthermore, the study adopted the simple HVAC specifications approach in DesignBuilder, which uses ideal loads (DesignBuilder, 2022). The mechanical ventilation operating schedules were determined by the occupancy schedules per the included zones, as enumerated in Table 3.

Table 2: Comparing U-values in Nigeria's residential construction across contextualised studies.

Name	Floor	Walls	Roof	Location
Simulation	2.113	1.508	2.393	Lagos
Study 1	1.800	1.360	7.280	Abuja
Study 2	2.412	2.683	0.775	Abuja
Study 3	2.602	1.867	3.447	Lokoja

All values are in W/m^{2}K.

Table 3: HVAC operating schedules per zones.

Living rooms	Dining rooms	Bedrooms
Schedule: Compact, Dwell_Dom Lounge_Occ, Fraction, Through: 31 Dec, For: Weekdays Summer Design Day, Until: 16:00, 0, Until: 18:00, 0.5, Until: 22:00, 1, Until: 23:00, 0.66667, Until: 24:00, 0, For: Weekends, Until: 16:00, 0, Until: 18:00, 0.5, Until: 22:00, 1, Until: 23:00, 0.66667, Until: 24:00, 0, For: Holidays, Until: 16:00, 0, Until: 18:00, 0.5, Until: 22:00, 1,	Schedule: Compact, Dwell_Dom Dining_Occ, Fraction, Through: 31 Dec, For: Weekdays Summer Design Day, Until: 06:00, 0, Until: 07:00, 0.25, Until: 09:00, 1, Until: 10:00, 0.25, Until: 18:00, 0, Until: 19:00, 0.5, Until: 21:00, 1, Until: 22:00, 0.3, Until: 24:00, 0, For: Weekends, Until: 06:00, 0, Until: 07:00, 0.25, Until: 09:00, 1, Until: 10:00, 0.25, Until: 18:00, 0, Until: 19:00, 0.5, Until: 21:00, 1, Until: 22:00, 0.3,	Schedule: Compact, Dwell_Dom Bed_Occ, Fraction, Through: 31 Dec, For: Weekdays Summer Design Day, Until: 07:00, 1, Until: 08:00, 0.5, Until: 09:00, 0.25, Until: 22:00, 0, Until: 23:00, 0.25, Until: 24:00, 0.75, For: Weekends, Until: 07:00, 1, Until: 08:00, 0.5, Until: 09:00, 0.25, Until: 22:00, 0, Until: 23:00, 0.25, Until: 24:00, 0.75, For: Holidays, Until: 07:00, 1, Until: 08:00, 0.5, Until: 09:00, 0.25, Until: 22:00, 0,

Until: 23:00, 0.66667, Until: 24:00, 0, For: Winter Design Day All Other Days, Until: 24:00, 0;	Until: 24:00, 0, For: Holidays, Until: 06:00, 0, Until: 07:00, 0.25, Until: 09:00, 1, Until: 10:00, 0.25, Until: 18:00, 0, Until: 19:00, 0.5, Until: 21:00, 1, Until: 22:00, 0.3, Until: 24:00, 0, For: Winter Design Day All Other Days, Until: 24:00, 0;	Until: 23:00, 0.25, Until: 24:00, 0.75, For: Winter Design Day All Other Days, Until: 24:00, 0;

Material selection

The roof insulation materials to be included as part of the roof were selected based on the following criteria:

- An R-value not lower than 2.5 m^2k/W at a thickness of 100 mm, based on the recommendations by Solid Green Consulting (2017). The performance of the different roof insulation materials was evaluated at the same thickness to facilitate a suitable comparison.
- The difference in the material thermal conductivity (k-value), and
- The potential availability of insulation materials in Nigeria.

Table 4 shows the selected roof insulation materials tested in the simulations. The materials' thermal conductivity (k-values) is listed alongside its corresponding thermal resistance (R-value) at 100 mm depth. In addition, the specific heat capacity (SHC) and density for each material are also highlighted.

Table 4: Selected roof insulation materials.

Name	**k-value (W/mK)**	**R-value (m^2K/W)**	**SHC (J/kgK)**	**Density (kg/m^3)**
Extruded polystyrene (XPS)	0.0340	2.94	1400.00	35.00
Glass wool insulation	0.0390	2.56	840.00	12.00
Spray polyurethane foam (SPF)	0.0227	4.40	6470.00	9.00

The parameters and data resulted in a baseline scenario for a Lagos residential building. To quantify the impact of the different roof insulation materials on cooling loads and comfort levels, the roof design data was modified to include each insulation material.

Results and discussions

Baseline scenario: Uninsulated roof

Figure 4 illustrates the baseline indoor thermal conditions relative to external temperatures. The total required system cooling loads (sensible cooling load + latent cooling load) to achieve the ASHRAE comfort scenario are also presented monthly for a representative year.

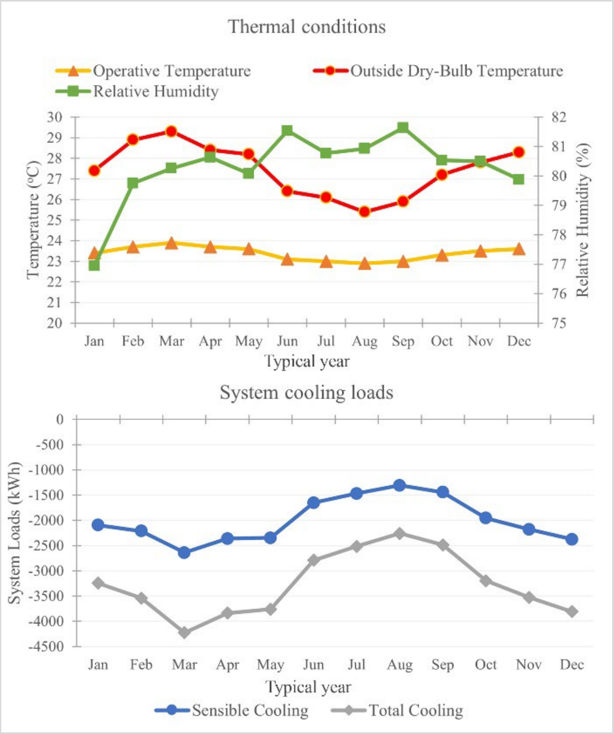

Figure 4: Indoor thermal conditions and total system cooling loads for the baseline scenario.

According to the output data, Lagos' annual average external dry-bulb temperature is 27.4ºC. However, external temperatures can rise to 34ºC (Adeniyi et al., 2018). The data further indicates that at an annual average indoor operative temperature of 23.4ºC and average relative humidity of 80.28%, indoor comfort can be achieved under the ASHRAE Standard 55-2004 comfort model. The peak and lowest operative temperatures were observed in March (23.9ºC) and August (22.9ºC), respectively. By cooling the indoor environment of the building under the ASHRAE comfort scenario, indoor comfort can be achieved for 6363 hours of 8760 hours in a year. This translates to a cooling load requirement of approximately 73%, as shown in the psychrometric chart in Figure 5.

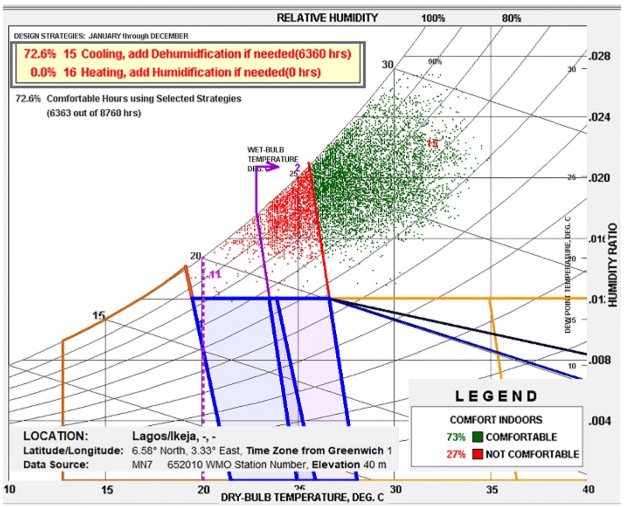

Figure 5: Psychrometric chart of Lagos from Climate Consultant using the imported weather file.

The data indicates that a total cooling load of 39191.5 kWh/year is needed to achieve the ASHRAE comfort levels. Peak cooling loads were similarly observed in March (4226.3 kWh), while the lowest loads occurred in August (2258.5 kWh). When comparing the outside dry-bulb temperatures with the cooling loads, March and August were noted to have the highest and lowest external temperatures at 29.3ºC and 25.4ºC, respectively. Therefore, an external temperature range of 3.9ºC resulted in a cooling load range of 1967.8 kWh. The impacts of the different roof insulation materials on the total cooling load required to achieve the ASHRAE comfort levels are further discussed.

Insulated roof: Extruded polystyrene (XPS)

Figure 6 shows the thermal conditions and resulting cooling loads for the building with extruded polystyrene as roof insulation for the duration simulated. The data is reported monthly for the typical calendar year, from January to December. In addition, the cooling temperature setpoint in DesignBuilder remained constant at 22ºC.

The results indicated that at the same external average temperatures, the annual average operative temperature was 23.3ºC. A slight increase in relative humidity of 0.71% from the baseline scenario was observed, resulting in a yearly average of 80.99%. Similarly, March showed the maximum indoor operative temperature of 23.5ºC, decreasing to its lowest value in August at 22.8ºC.

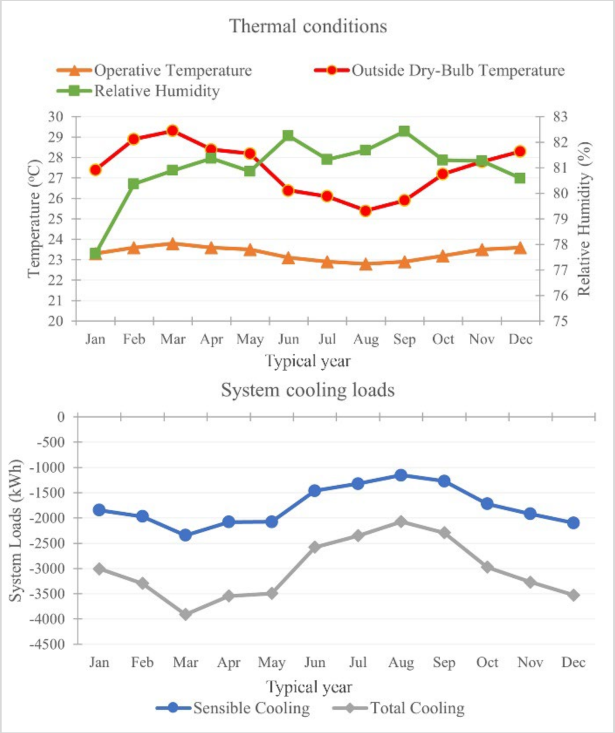

Figure 6: Indoor thermal conditions and total system cooling loads for XPS insulation.

The data further indicated that the resulting total cooling load was 36311.4 kWh/year to achieve the ASHRAE comfort level. This represents a 2880.1 kWh/year reduction compared to the baseline scenario. Peak cooling loads were observed in March at 3910.5 kWh, resulting in a decrease of 315.8 kWh with an XPS-insulated roof. August showed the lowest recorded total cooling load of 2072.5 kWh, a reduction of 186 kWh from the baseline. The data shows that at a cooling temperature setpoint of 22ºC, the use of XPS roof insulation decreased energy consumption for cooling loads annually by 7.35%.

Insulated roof: Glass wool insulation

The thermal conditions for the building with glass wool material as roof insulation and the resulting system loads required for cooling are presented in Figure 7. Similarly, data is indicated for the entire year on a monthly report basis from January through December.

This simulation was carried out to observe the cooling loads of the building when using 100 mm of glass wool as roof insulation at a cooling temperature setpoint of 22ºC. Similar annual average operative temperatures of 23.3ºC at a relative humidity of 82.32% were achieved. Furthermore, the peak and lowest operative temperatures were consistent with previous simulation outputs, with March, at 23.8ºC, and August at 22.8ºC, respectively.

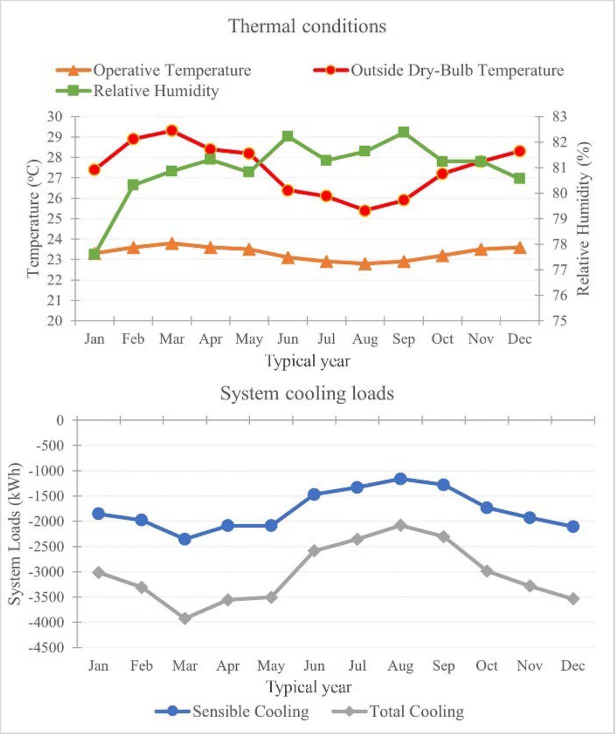

Figure 7: Indoor thermal conditions and total system cooling loads for glass wool insulation.

The system loads data depicted that the total cooling load required was 36436.1 kWh/year to achieve the ASHRAE comfort levels. This represents a decrease of 2755.4 kWh annually compared to the uninsulated roof. Peak cooling loads were noted in March at 3923.3 kWh, while the lowest logged total cooling load of 2081.6 kWh occurred in August. The data shows that at an ASHRAE-defined cooling temperature setpoint of 22ºC, glass wool roof insulation resulted in an annual 7.03% decrease in energy consumption.

Insulated roof: Spray Polyurethane Foam (SPF)

The thermal conditions of the building with SPF as roof insulation are shown in Figure 8, including the total system cooling loads required to attain the optimum conditions. The data is indicated for a typical annual period (1 Jan – 31 Dec) and reported monthly.

This simulation aimed to ascertain the cooling loads of the building when 100 mm of SPF material was used as roof insulation at a set cooling temperature of 22°C. The results depict that indoor operative temperatures and the relative humidity achieved were consistent with other roof insulation materials, at 23.3°C and 82.36%, respectively. March and August remained the months recording the highest and lowest indoor operative temperatures at 23.8°C and 22.8°C, respectively.

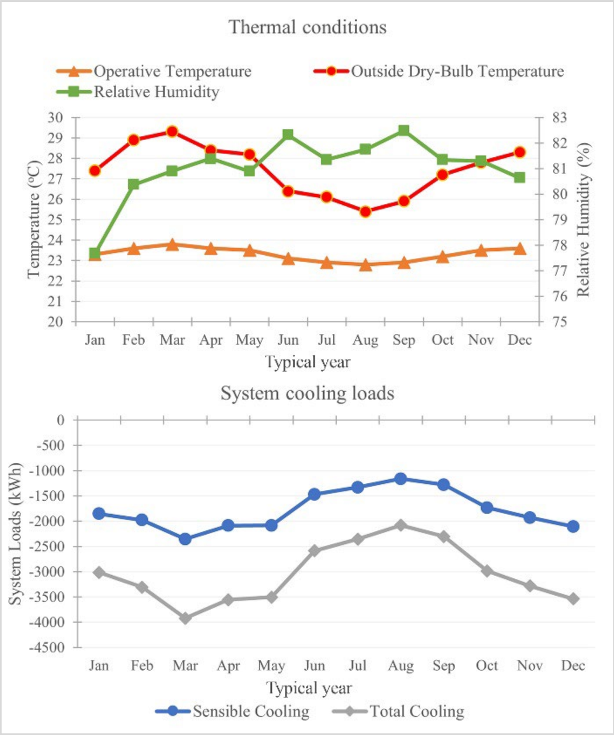

Figure 8: Indoor thermal conditions and total system cooling loads for SPF insulation.

For the use of SPF material, the total cooling load required to achieve ASHRAE Standard 55-2004 comfort level using air conditioning was 35979.6 kWh/year. This data translates to a decrease of 3211.9 kWh/year compared to the baseline scenario of an uninsulated roof. The peak cooling loads were again observed in March at 3868.1 kWh. The lowest cooling loads were observed in August at 2056.0 kWh. The simulation output showed that at a cooling temperature setpoint of 22°C, using Spray Polyurethane Foam insulation reduced cooling loads annually by 8.20%.

Comparison of simulation outcomes

A summative comparison of the roof insulation materials with their respective average annual performances against the baseline is shown in Table 5. It highlights each material's resulting thermal resistance (R-value) and comfort levels. The material's key performance index (KPI) for energy use (in *kWh/m²/year*) is also stated. The formula used in calculating the KPI is stated as follows:

$$KPI = A_{ec} \div T_{fa} \qquad (1)$$

where KPI is the key performance index, A_{ec} is the annual energy consumption, and T_{fa} is the total floor area. The total floor area used in the calculations is the sum of the floor area of the habitable rooms, which is 149.243 m^2.

Table 5: Material and performance comparison.

Name	**R-value (m^2K/W)**	**Oper. Temp. (°C)**	**RH (%)**	**KPI kWh/m^2/year**
Baseline	N/A	23.4	80.28	262.60
XPS	2.94	23.3	80.99	243.30
Glass wool	2.56	23.3	82.32	244.14
SPF	4.40	23.3	82.36	241.08

As shown in Table 5, the SPF material demonstrates the highest performance of 241.08 kWh/m²/year compared to XPS and Glass wool. The XPS material performs closely at 243.30 kWh/m²/year, while the Glass wool material performs the least at 244.14 kWh/m²/year. The data further illustrates that for an R-value range of 1.84 m^2K/W between the best and least performing materials, the performance range is approximately 3.00 kWh/m²/year. This suggests that an increase in the R-values of the roof insulation material from approximately 2.5 m^2K/W to 3.0 m^2K/W does not correspondingly translate to significant energy performance improvements.

Conclusion

Optimising building energy consumption is a significant step in facilitating built environment sustainability and addressing climate change. Nigeria's reliance on mechanical ventilation systems to achieve indoor thermal comfort contributes to increased energy consumption. Projected population and economic growth will lead to an increase in square meters in Nigeria's residential sector. Using material as a passive design measure could reduce energy consumption in the Nigerian built environment.

Using dynamic simulations, this study aimed to quantify the impact of selected roof insulation materials as a passive measure on comfort levels and cooling loads in Lagos' urban residential buildings. Hourly weather data from Meteonorm were utilised in DesignBuilder to conduct an EnergyPlus simulation analysis. A baseline scenario was developed in DesignBuilder to quantify the initial cooling loads required for optimum indoor conditions. Further simulations assessed the effect of Extruded Polystyrene (XPS), Glass wool and Spray Polyurethane Foam (SPF) on the comfort levels and the required cooling loads in the baseline building.

Despite the significant range in R-values at a thickness of 100 mm, the resulting KPIs were closely valued. The study confirms that an R-value of 2.5 m^2K/W is more desirable and effective than the 1.25 m^2K/W recommended by Nigeria's energy regulations. However, R-values beyond 3.0 m^2K/W demonstrate diminishing improvements.

Cooling load reductions of approximately 7%-8% with improved comfort levels were achieved under the ASHRAE Standard 55-2004 recommendation of a 22°C temperature setpoint. Thus, the implications include a reduction in building operational costs and enhanced indoor conditions. Furthermore, this facilitates a decrease in GHG emissions and an increase in the sustainability of the residential sector in Nigeria.

Although this study only focused on the top floor of multi-story flats typology, the study's findings can potentially inform retrofits of the existing residential building stock in which single-storey buildings are well typified. The residential buildings' sustainability and energy efficiency could be improved by combining roof insulation with other passive techniques such as Low-emissivity glass, double-glazed windows, or wall insulation. Further studies can be done to assess the combined impact of these techniques.

International comfort models may not depict nor account for cultural preferences. Thus, testing these passive techniques under contextualised conditions is necessary. This could potentially show different and improved outcomes, and further studies are necessary. Also, further studies are required to investigate the performance of other roof insulation materials.

This study adopted a theoretical investigatory framework using a case study and simulations. While this could be addressed in the future, it points to an immediate need to create standardised simulation metrics for different microclimatic regions as a part of Nigeria's BEEC.

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