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Article

Exploring the Impact of Rice Husk Ash Masonry Blocks on Building Energy Performance

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Abstract: Operational building energy consumption accounts for 55% of global energy consumption. Most of this is attributed to residential buildings, as they make up the largest building type when compared to the total building stock worldwide. As the building envelope is a major contributor to building energy performance, especially the external walls, its optimisation is therefore imperative to reduce energy consumption and carbon emissions. This study set out to assess the effects of waste material additions to external walls and their effect on building energy performance. This research aimed to critically investigate the effect of rice husk ash (RHA) masonry blocks on building energy performance when compared to conventional masonry blocks in tropical climates. A mix of methods, including experimental investigation and simulation studies, were employed for this study. Three variations of RHA block samples were created for this investigation: RHA 5%, RHA 10%, and RHA 15%. Using prototype buildings from the study context, the building simulation results helped quantify the impact on building energy performance from the reuse of rice waste. The largest improvement to the building fabric was recorded with the RHA15% blocks, which resulted in a 9.9% and 11.3% reduction in solar heat gains through the external walls for the selected bungalow and duplex/storey building, respectively. This resulted in a 6.55% and 4.2% reduction in cooling loads and a 4.1% and 2.8% reduction in carbon emissions, respectively, for the bungalow and duplex/storey building. The findings of this research will prove valuable to householders, researchers, architects, and policymakers in their decision-making processes. The findings will also be useful in introducing new methods that can be adopted for similar studies, bridging the knowledge gap while promoting a circular economy through the reuse of landfilled waste.

Keywords: rice husk ash; cement-based masonry blocks; building envelope; building energy performance; sustainability; waste; EnergyPlus simulations; carbon emissions

Citation: Onyenokporo, N.C.; Taki, A.; Montalvo, L.Z.; Oyinlola, M.A. Exploring the Impact of Rice Husk Ash Masonry Blocks on Building Energy Performance. *Buildings* **2024**, *14*, 1290. https://doi.org/10.3390/buildings14051290

Academic Editor: Adrian Pitts

Received: 13 March 2024
Revised: 16 April 2024
Accepted: 26 April 2024
Published: 2 May 2024

1. Introduction

Paris et al. [1] report that approximately 4 billion tonnes of cement were produced in 2014. In 2021, this increased to 4.4 billion tonnes, and this figure is predicted to reach 5 billion tonnes by 2030 [2,3]. The excessive production and utilisation of cement is responsible for 5–7% of anthropogenic greenhouse gases produced annually and is currently considered unsustainable owing to its negative impacts on the environment, especially regarding climate change and its effects [4–6]. Furthermore, the International Energy Agency (IEA) [7] reports that there needs to be a 4% yearly decline in cement production up to 2030 to reduce these emissions and achieve net zero carbon emissions by 2050. Research has shown that the use of supplementary cementitious materials is a viable solution for reducing the amount of cement produced and used in the building industry [1,5,8].

Additionally, about 2.01 billion tonnes of solid waste are generated annually from manufacturing processes, industries, and construction, and this is predicted to increase to about 3.4 billion tonnes by 2050 [9]. Aprianti et al. [8] estimate that by 2050, the world's population will rise to 9 billion, which will lead to an increased demand for energy, food, housing, and clothing. This has prompted increased research into the effectiveness and availability of pozzolanic waste materials that can partially replace cement as these wastes remain in the environment, unused, and more waste is produced with continuous population growth. The use of waste materials in construction is currently growing in research globally [10–12]. Reusing these wastes in construction is encouraged, as it will reduce the amount of raw materials used and significantly reduce landfill waste. When combined with cement, waste materials such as supplementary cementitious materials (SCMs) have also been reported to improve some of the physical properties of cement-based materials where they are used. Several studies have been conducted on the use of SCMs originating from industrial wastes [13–18], agricultural wastes [19–25], and other general or natural wastes like plastics and glass [26–31]. However, research is growing regarding the reuse of agricultural wastes for construction purposes. This is because agricultural wastes typically release carbon dioxide during calcination, which is offset by the carbon dioxide absorbed by the plants throughout their lifecycle [32], thus making them a more sustainable alternative to other SCMs.

Rice husk ash, derived from rice husks, has been selected for this study due to the large quantities being produced in tropical countries and their ability to combine with hydrated cement to form compounds possessing cementing properties. Additionally, as many of these countries are fast developing, there will be an increase in population, economic development, and urbanisation, which will result in increased construction needs and higher energy demands in the years to come [12,33]. Rice is considered a staple food in most tropical countries and is grown multiple times a year, with worldwide production increasing from 650 million tonnes in 2010 to about 787 million tonnes in 2021 [1,34]. The resulting waste from rice production, rice husks, from which rice husk ash (RHA) is derived, make up 20–23% of harvested rice, are typically dumped in landfills during rice production, and have no economic value [35–37].

In addition to rising global cement consumption and waste production, there is a corresponding increase in global energy consumption. Due to the continuous depletion of finite natural resources as a result of growing population and urbanisation, in addition to excessive waste production, global energy consumption, which stands at 176,431 Twh, is predicted to increase to 197,000 Twh by 2030, with carbon emissions also rising to 40.4 billion tonnes by 2030 [38,39]. Furthermore, pursuing new energy sources to cater to increasing global energy consumption will further contribute to environmental degradation and the reduction of resources [40]. With operational building energy consumption contributing to 55% of global energy consumption [41], prioritising building performance and developing energy-efficient buildings, starting with the optimisation of the building envelope, remains crucial. The indoor thermal environment is actively controlled through the use of heating, ventilation, and air conditioning (HVAC) systems to regulate the temperature and overall climate. Although these systems ensure the thermal comfort of occupants, they can significantly impact building energy consumption and costs for households. According to Xie et al. [42], there is a growing increase in the use of energy to improve occupant well-being and indoor thermal comfort, which creates a need to improve the energy efficiency of buildings.

Globally, several solutions have been proposed to address this issue, such as policy change and implementation, the adoption of renewable energy systems, and the use of phase-change materials [43]. However, in most developing countries, where the majority of their population is in the low-income group, applying these strategies to address energy consumption remains a challenge [29,42]. More people are concerned about the upfront costs of buildings, and little consideration is given to building performance, which leads to many householders experiencing thermal discomfort within their homes [44,45]. Ochedi and Taki [44] explain that the major factors influencing energy usage in buildings are the building envelope and materials, occupant behaviour, climate, building design, artificial lighting and ventilation systems, and appliances. Furthermore, according to Oyekan and

Kamiyo [46] and Danso [47], the materials chosen to construct buildings have an impact on the amount of energy they consume and their cost. Research is currently advancing to include more solutions to address building energy performance, starting at the building envelope level [42]. Building envelope typically refers to building walls, windows, roofs, etc., based on their function and location. The building envelope is responsible for heat loss or gain from or into a building. The thermal transmittance of building elements can be used to compare the heat loss or gain through the building fabric from different building elements, such as the roof, windows, or walls [48,49]. Various researchers [48,49], report that the ratio of heat loss from the building envelope is 35–40% for external walls, 13–25% for ceilings, floors, and roofs, and 25–47% for windows and doors. Building elements with high thermal transmittance coefficients typically result in high heat gains or losses and high energy consumption for building occupants. In tropical climates, this heat gain usually results in the use of mechanical cooling systems to improve occupants' thermal comfort, thereby increasing building energy consumption [45,50]. According to Harish and Kumar [51], optimising the building envelope design can reduce building energy consumption by up to 20–50%. Controlling the heat gain or loss from the building envelope is therefore crucial to improving the energy efficiency of buildings.

Alqahtani et al. [52] explain that sustainable materials are being sought after to minimise the embodied and operational energy costs of buildings and reduce their associated carbon footprint. Masonry units serve as primary construction materials for external walls in many countries, and the energy efficiency of a building can be significantly improved by adopting masonry units that have better mechanical and thermal properties [53]. Previous research has reported that the use of rice husk ash (RHA) for the sustainable production of cement-based masonry units increases the strength with longer curing periods, reduces the density due to RHA having a lower specific gravity than cement, and reduces the thermal conductivity of the final product where it is incorporated [54–59], although there is an increase in water demand. However, studies have reported that the water absorption of these masonry blocks is below the maximum of 15% stipulated by ASTM C90-09 for medium-weight concrete masonry units [25]. Ferraro and Nanni [58] investigated the effects of using RHA blended with cement to produce mortar. They observed that using up to 15% off-white RHA to partially replace cement resulted in a 19% decrease in the thermal conductivity of mortar samples. The study also noted a 15% increase in compressive strength, a 9% increase in tensile strength, and a 1% reduction in water absorption after 28 days of curing. Likewise, Carig et al. [54] produced hollow concrete masonry units in their study using 5–15% rice husk ash to partially replace cement. They observed similar or lower values of water absorption using 5–15% RHA replacement when compared to the control sample. They also achieved up to a 43% increase in compressive strength, although this started to decrease after 10% RHA was introduced. Similar to Ferraro and Nanni [58], they reported up to a 13% reduction in the thermal conductivity of the RHA masonry block samples. Likewise, Onyenokporo et al. [55], who employed an experimental study to investigate the effect of rice husk ash on the thermal properties of cement-based masonry blocks, also observed a reduction of up to 17% in the thermal conductivity of the samples using 15% RHA replacement by weight of cement. In their study, Selvaranjan et al. [57] replaced river sand with rice husk ash at varying replacement values of 10–50% by weight of sand. They found that compressive strength decreased with increasing replacement values, but samples with up to 30% RHA still met the minimum required value for mortar after 28 days. Additionally, thermal conductivity decreased up to 67% with controlled-burnt RHA and up to 73% with open-burnt RHA. Selvaranjan et al. [57] explain that there is an increased number of pores in mortars containing RHA, which trap air and improve the overall thermal insulation of samples. Moreover, this reduction in thermal conductivity has a positive impact on the building envelope in terms of building energy consumption to address heat gains or losses.

Although current research shows the effect of rice husk ash additions on the thermal properties of cement-based masonry units, there is a dearth of literature properly quantifying the effects of these RHA masonry blocks on building energy performance when used as a building material for external walls. As the external walls constitute a major part of the building envelope, it has major implications for the overall energy performance of buildings and the resulting carbon emissions. So far, only Hitawala and Jain [60] have conducted energy performance analysis of a prototype building using rice husk ash for the building envelope. They combined rice husk ash insulation (88.28 wt% rice husk ash (RHA), 9.29 wt% of bentonite, and 2.41 wt% of exfoliated graphite) and rice straw ash blocks (60% paddy straw, 28% fuel ash, and 12% binder) for comparative analysis with burnt clay brick masonry wall assembly. They recorded a 22% reduction in energy performance index and a 48% reduction in embodied carbon emissions using the external wall and roof incorporating rice husk ash.

Due to the dearth of literature quantifying the effects of these RHA masonry blocks on building energy performance, this paper, therefore, contributes to the existing body of knowledge within the field. This study critically investigates the effect of rice husk ash masonry blocks on building energy performance when used as a walling material. Through the use of EnergyPlus interface in DesignBuilder v7 to carry out a simulation study, a prototype building from the context was selected to quantify this impact. The computer simulation allowed for a comparative analysis of the prototype building(s) using the RHA masonry blocks and conventional cement masonry blocks to evaluate the effects of rice husk ash on overall building performance in terms of heat gains through the walls, energy consumption for cooling, occupants' thermal comfort, and carbon emissions.

2. Materials and Methods

2.1. Experimental Investigation of Rice Husk Ash and Masonry Blocks Production

A visual representation of the processes involved in the experimental investigation for this study is provided in Figure 1. The first step involved the collection of the rice husk from the context area and grinding it. Rice husks were obtained from a major rice mill located in Abakaliki, Nigeria. These husks were then calcinated in a controlled environment for 3 h at 600 °C to obtain rice husk ash [58,61].

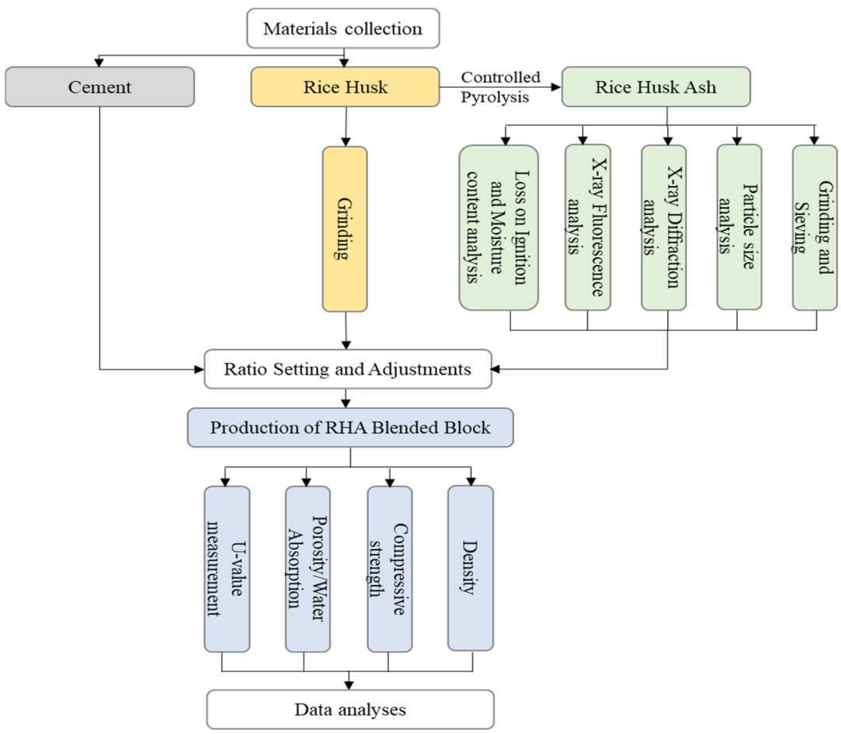


Figure 1. Experimental flow diagram used to develop the RHA masonry blocks [Authors].

The ash was then ground further to reduce the particle size to 45 µm, similar to that of cement, as stipulated by ASTM C618-19 [62]. The smaller particle size was adopted as it increases the solubility of the ash and encourages pozzolanic reactions. The chemical composition of the ash was examined using an X-ray diffractometer (XRD) and X-ray fluorescence (XRF) to determine the oxide contents and crystallinity. The particle size analysis, moisture content, and loss on ignition (LOI) of the rice husk ash were also determined. The XRD scan in Figure 2 revealed that a significant portion of the RHA sample is amorphous, as can be seen from the broad hump between 15 and 35°2θ [58]. The results of the XRF analysis in Table 1 show the total amount of silica (SiO_2), Alumina (Al_2O_3) and Ferrite (Fe_2O_3) in the RHA sample to be 85.74%, which is higher than the 70% minimum stipulated by ASTM C618-19 [62]. The loss on ignition (LOI) and moisture content were also less than the maximum stipulated values by ASTM C618-19.

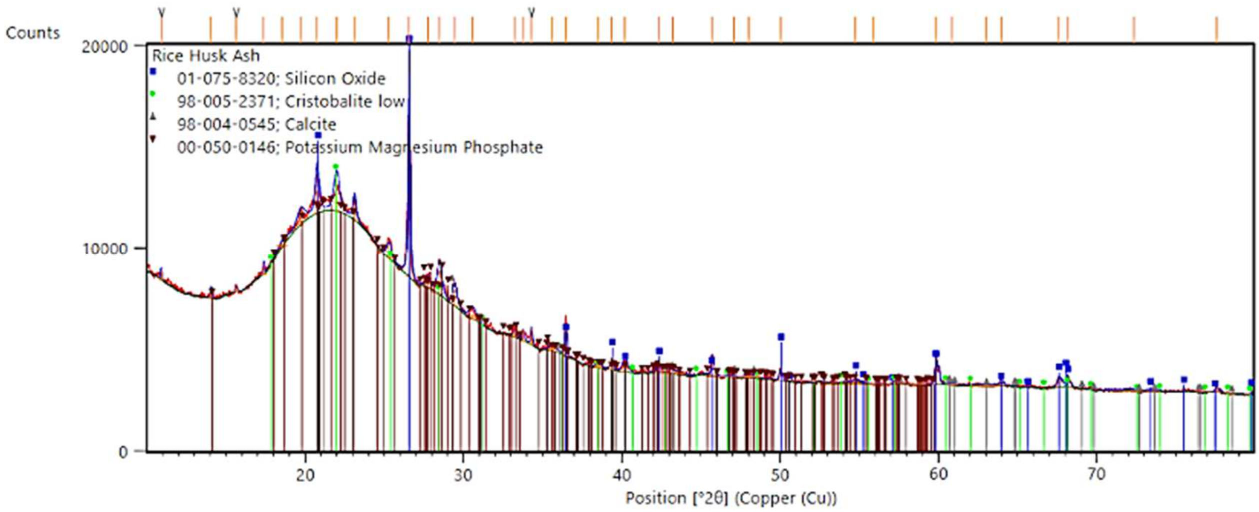


Figure 2. XRD graph of RHA sample [Authors].

Table 1. Chemical composition of RHA sample used in this study.

Parameter	SiO_2	Al_2O_3	Fe_2O_3	Cr_2O_3	MnO	TiO_2	P_2O_5	CaO	MgO	K_2O	Na_2O	SO_3
Composition %	83.83	0.75	1.16	<0.003	0.226	0.124	6.215	0.82	2.75	2.42	<0.06	0.22
$SiO_2 + Al_2O_3 + Fe_2O_3$			85.74%	Loss on Ignition (LOI)			1.32%	Moisture content at 105 °C				2.03%

Subsequently, the rice husk ash masonry blocks were produced in accordance with the National Building Code [63] and Nigerian Industrial Standards [64] and partially replaced with varied amounts of rice husk ash between 5 and 15%. The dimensions of the solid block samples were 300 × 150 × 113 mm (Figure 3).

Figure 3. Visual summary of RHA masonry block production [Authors].

The hardened masonry block samples were tested to determine their density, compressive strength, water absorption, porosity, and thermal transmittance (U-value). For each test, two to three samples of each replacement type were chosen to obtain representative averages, whose results were then compared. Full details of this experimental investigation can be found in Onyenokporo, Taki and Zapata Montalvo [25] and Onyenokporo et al. [55].

2.2. Study Context and Description of Selected Case Studies

Abuja, the Federal Capital Territory (FCT) of Nigeria, has been chosen for this study because of its economic importance and because it has the highest infrastructural development in Nigeria [65]. The Federal Capital Development Authority (FCDA) [66] reports that it is located between latitudes 9°03′ and 9°07′ N and longitudes 7°26′ and 7°39′ E in the north-central region of Nigeria, with a land area of 8000 km^2. Abuja has savanna grassland vegetation like the rest of northern Nigeria and a tropical wet and dry climate [67]. According to the Köppen–Geiger classification, Abuja belongs to the tropical wet-and-dry climate. With moderate weather conditions all year round, Abuja is known to experience dusty haze and intense heat/cold during the harmattan period. Relative humidity is high in the rainy season (Figure 4), which runs from March to October and peaks in September. However, the dry season, according to FCDA [66], runs from late October into early March. Abuja has a 32 °C daily average temperature year-round [67]. It is generally warm or hot most days. Figure 2 shows March as the hottest month, with a maximum temperature of up to 37.4 °C [68]. With January being the driest month, annual precipitation is about 999.9 mm.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Temperature (°C)	28.9	30.6	31.5	30.4	28.3	26.1	24.8	24.3	24.9	25.9	27.9	28.7
Min. Temperature (°C)	22.8	24.5	25.6	25.7	24.7	23.1	22.2	21.9	22	22.4	22.6	22.8
Max. Temperature (°C)	35.4	36.	37.4	35.6	32.5	29.7	28.2	27.6	28.8	30.3	33.6	35.1
Precipitation (mm)	1	3	12	44	103	159	228	296	270	127	9	1
Humidity (%)	23	26	35	54	69	79	83	85	84	80	50	26
Rainy days (d)	0	1	2	5	11	15	20	20	19	14	1	0
Avg. Sun hours (hours)	10.4	10.4	10.2	8.8	6.6	4.8	4.7	4.2	5.1	6.8	9.9	10.3

Figure 4. Average temperature in Abuja, Nigeria; derived from (Climate-data, 2022) [68]. The intensity of the colours depict the level of intensity of each parameter.

Abuja is one of the most populated cities in Nigeria, having a population of 3.65 million and a population growth rate of 5.42% [69], having grown by 1,210,338 since 2015. Abuja has an average household size of 6.05 people [70]. More than 50% of the households can be considered moderate-income households, while about 45% are categorised as poor or very poor-income households. Although it is one of the major cities in Nigeria, it has almost equal levels of both poverty and wealth. In addition, only about 69.5% of these households have access to electricity out of the total population of Abuja [70]. Due to the level of income, most homes have to rely on the national grid for power supply, which is reportedly supplied for only an average of 6–8 h daily. This forces households that can afford it to rely on off-grid power generators for additional electricity supply.

According to the Nigerian Bureau of Statistics [70], the majority of the houses in Abuja are built using either cement or concrete blocks (78.9%), 14.5% are built using mud or compressed earth, 6.4% are built with bricks, and the rest are built with other materials (e.g., metal sheets). Compared to other major cities in Nigeria where most areas have been built up, such as Lagos or Port Harcourt, Abuja is a planned city and is still developing. Even as it is, the Federal Capital Territory Administration (FCTA) reported that Abuja has a housing deficit of about 1.7 million houses [71]. Having a higher opportunity for infrastructural development in Nigeria, it is therefore a good case study for where the outcome of this research study can be applied to address the effects of urbanisation and slum proliferation and encourage affordable housing and sustainable communities.

For this study, one bungalow and one duplex house were selected from the context area (Abuja, Nigeria) to serve as prototypes for the simulation study. The two house types have been selected because they are identified as the two most common building typologies in the selected context. Case Study 1 is a four-bedroom detached bungalow located in Kuje, Abuja. Kuje is considered to be a developing neighbourhood and has several informal settlements [72]. It is a privately owned building and consists of four ensuite bedrooms, a kitchen, a dining room, and a living room, as seen in Figure 5 below. The building has a total floor area of 164.4 m^2. The external walls are made with 225 mm hollow concrete blocks plastered on both sides with 20 mm cement–sand render. The walls are not painted. The floor is made of concrete and layered with ceramic floor tiles on the inside. The house comprises single-glazed windows without any local shading to fend off direct solar radiation, as seen in Figure 6, except from the roof eaves. In addition, the building has an uninsulated pitched roof finished with aluminium roofing sheets.

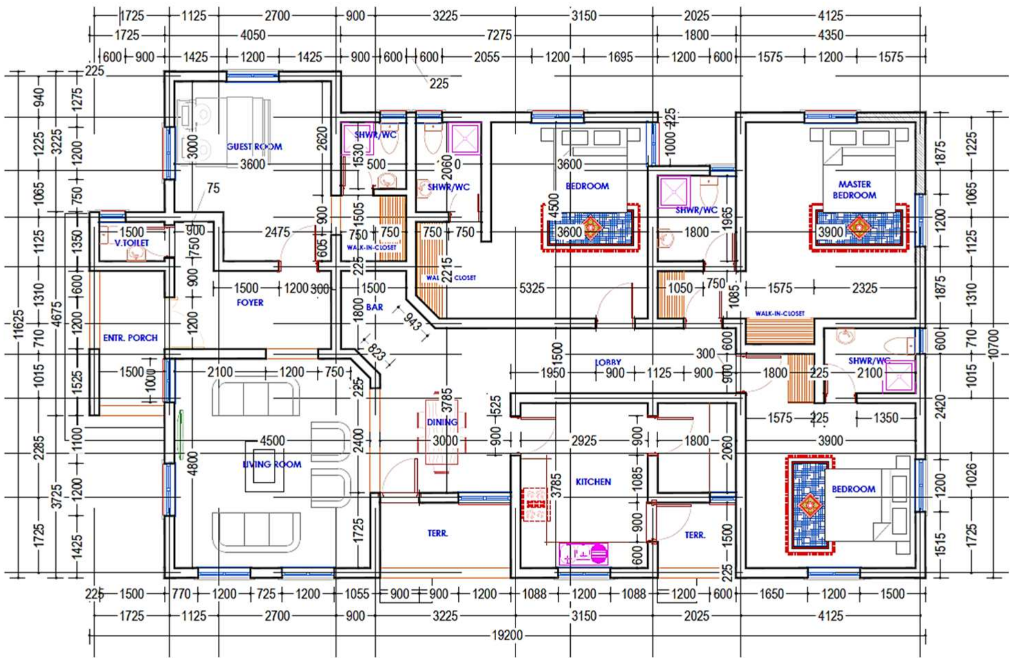
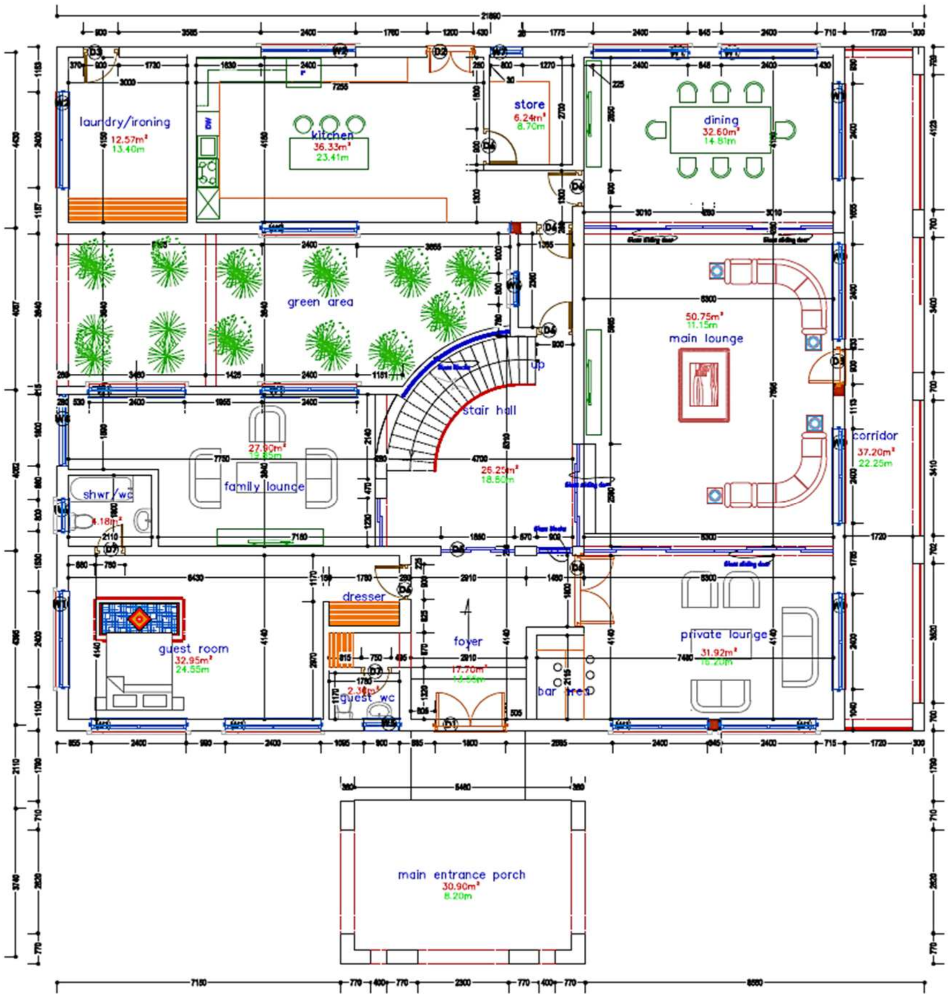


Figure 5. Floor plan of Bungalow [Authors].

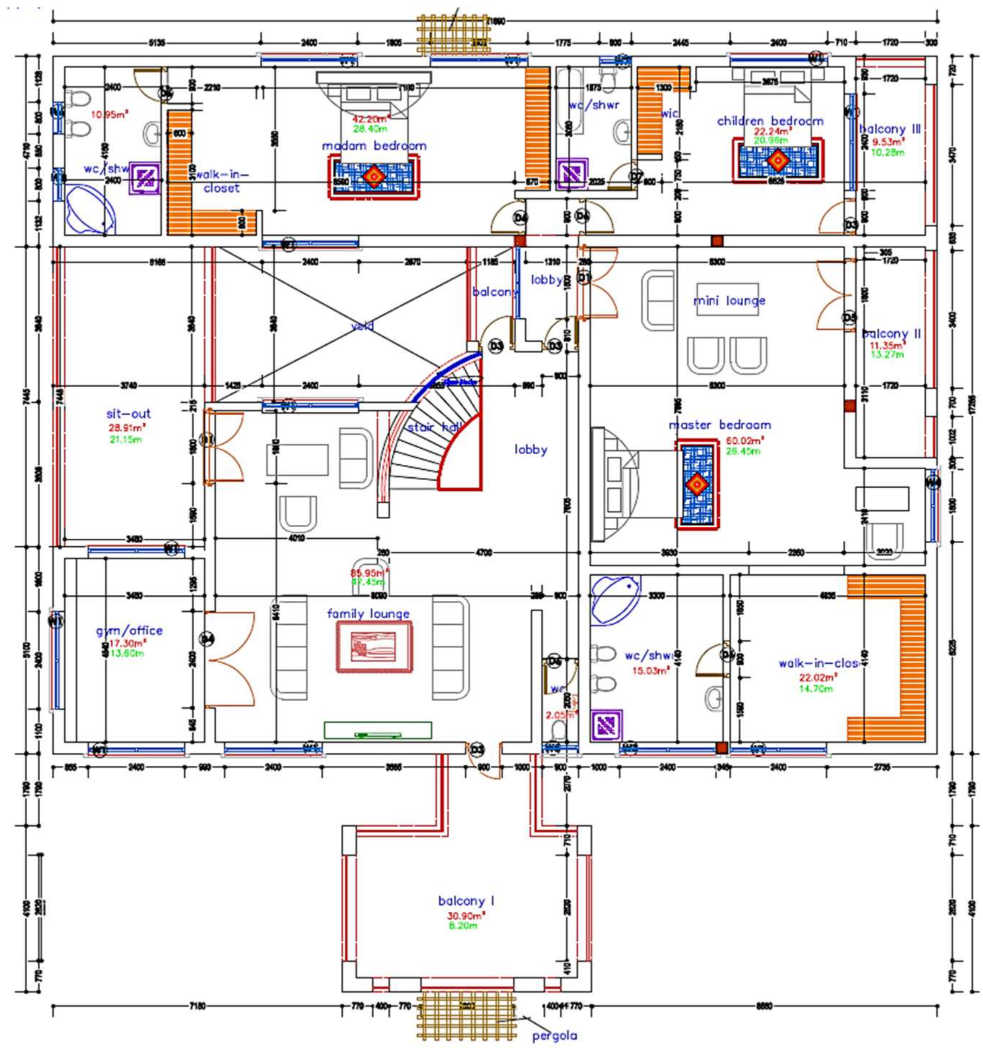
Figure 6. Photograph of the bungalow [Authors].

Case Study 2 is a detached, four-bedroom duplex house located in Jabi, Abuja. Jabi is located close to the city centre and is frequented by many residents for work or recreational activities. In contrast to Kuje, it is considered to be a more developed neighbourhood [72]. Similar to Case Study 1, the duplex house is also privately owned and consists of four ensuite bedrooms, a kitchen, a dining room, and several lounges, as seen in Figure 7a,b below. The building has a total floor area of 407.70 m^2. The external walls are also made with 225 mm hollow concrete blocks plastered on both sides with 20 mm cement-sand render. The floor is made of cast concrete and layered with ceramic floor tiles inside. Similar to the bungalow, the duplex house is comprised of single-glazed windows without any local shading to detract from direct solar radiation, although the glazing is tinted. The building also has an uninsulated pitched roof finished with aluminium roofing sheets and concrete parapet walls around the roof edge. The exterior of the building can be seen in Figure 8 below. The walls are painted a bright cream colour, which helps reduce solar heat gains through the walls.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. (**a**) Ground floor plan of duplex [Authors]. (**b**) First floor plan of Duplex [Authors].

Figure 8. Building exterior [Authors].

2.3. Building Energy Performance Simulation

Following the selection of suitable prototypes, a simulation study was performed to assess the effect on building energy performance of the use of RHA masonry blocks for residential buildings. The EnergyPlus simulation interface in DesignBuilder (version 7.0.2) was used for this purpose. It served to quantify the impact of using these masonry blocks as walling material for the external building envelope and, thus, the energy consumption and carbon emissions resulting from this. Two residential building prototypes were used as cases to represent the most popular building typologies in Nigeria.

To assess the thermal performance of the RHA masonry blocks, a simulation study was conducted in DesignBuilder software (version 7.0.2) using typical residential building prototypes in Nigeria (i.e., Case Studies 1 and 2). It is noteworthy to mention that the simulation study did not consider changes to building orientation, glazing type, lighting, or the use of renewables, as the focus of the simulation was to determine the effects on the thermal performance of the building envelope (external walls) using the measured U-values from the RHA blocks. The energy simulations were performed using the EnergyPlus simulation interface in DesignBuilder software (version 7.0.2). According to Ashraf et al. [73], EnergyPlus calculations are based on a heat balance technique that takes into account how building models interact with outdoor weather conditions to evaluate the various loads on an hourly basis. The use of EnergyPlus has been recommended by several researchers. According to Fumo, Mago and Luck [74], EnergyPlus is an accepted simulation programme for analysing building energy performance worldwide. EnergyPlus was selected for this research as it can be used to model lighting, heating, cooling, and ventilation, among other factors, in buildings. Simulations enable the in-depth evaluation of various design options to determine the best practice for a building.

The weather data for Abuja, Nigeria, used for the EnergyPlus simulations was obtained from White Box Technologies. White Box Technologies processes weather data for use in building energy simulations, and the weather files are provided in BINM format for DOE-2-based programmes, EPW format for EnergyPlus-based programmes, and other formats. The annual average site data can be seen below in Table 2.

Table 2. Annual average of site data for case study derived from weather data.

Site Data	
Outside Dry-Bulb temperature (°C)	29.60
Outside Dew-point temperature (°C)	20.13
Wind speed (m/s)	2.73
Wind direction (°)	180.25
Solar altitude (°)	0.10
Solar azimuth (°)	176.85
Atmospheric pressure (Pa) $\times 10^3$	97.34
Direct Normal solar (kWh)	362.56
Direct Horizontal solar (kWh)	1165.82

The layout of the bungalow and duplex house can be found in Figures 9 and 10, showing the typical annual sun path and all components of the case study buildings. The building specifications used for the simulation study in DesignBuilder can be seen in Table 3. The same templates were used for both the bungalow and duplex to input parameters for the occupant's activity, construction, glazing, lighting, HVAC, etc.

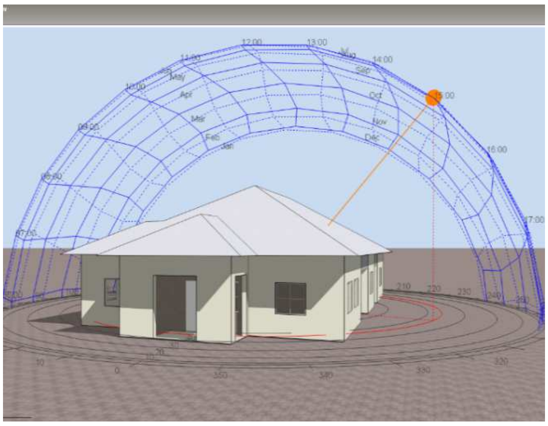


Figure 9. Model data and rendered view of the bungalow.

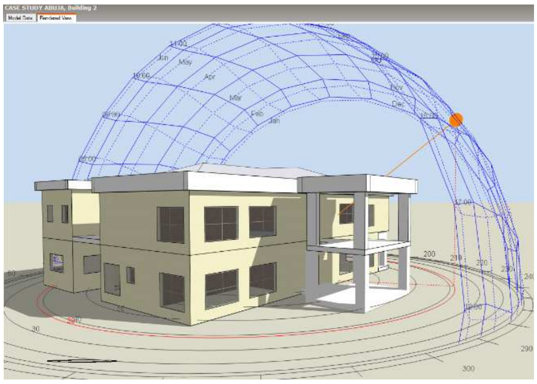


Figure 10. Model data and rendered view of the duplex/storey building.

Table 3. Building specification for simulation study in DesignBuilder.

Input Parameters	Bungalow	Duplex/Storey Building
Site Location	Abuja, Nigeria	Abuja, Nigeria
Longitude	9.08°	9.08°
Latitude	7.40°	7.40°
Building sector	Residential	Residential
Orientation	94°	17°
Floor height	3 m	3 m
Activity template	Common circulation areas; Domestic Lounge; Domestic Kitchen; Domestic Bedroom	Common circulation areas; Domestic Lounge; Domestic Kitchen; Domestic Bedroom
Occupied floor area	164.4 m^2	407.7 m^2
Occupancy density	0.02 people/m^2	0.02 people/m^2
External wall	* 150 mm solid concrete masonry block + 20 mm plaster both sides	* 150 mm solid concrete masonry block + 20 mm plaster both sides
Internal partitions	150 mm hollow masonry block + 15 mm plaster both sides	150 mm hollow masonry block + 15 mm plaster both sides
Roof	Uninsulated pitched roof comprising Aluminium sheets + wooden framework	Uninsulated pitched roof comprising Aluminium sheets + wooden framework
Ground floor	300 mm cast concrete + 50 mm cement screed	300 mm cast concrete + 50 mm cement screed

Table 3. *Cont.*

Input Parameters	Bungalow	Duplex/Storey Building
Internal Floor	150 mm cast concrete + 50 mm cement screed	150 mm cast concrete + 50 mm cement screed
Glazing template	Single glazing, clear, no shading	Single glazing, clear, no shading
Lighting template	Incandescent + lighting control	Incandescent + lighting control
HVAC Template	Natural ventilation- no heating/cooling	Natural ventilation- no heating/cooling
Outside air	2.5 ach	2.5 ach

* To compare with RHA masonry block samples.

The external walls tab, under the construction template, was the only value changed throughout the whole simulation after the typical values had been input in all the tabs of each template. For lighting, the authors have used incandescent light bulbs, as these are commonly used in many parts of Nigeria. Lighting control was added to simulate artificial lighting electricity usage only for hours without natural daylighting illuminance. The HVAC template was set to 'natural ventilation'—no heating or cooling. This was only changed to 'split unit cooling only' when the values for cooling energy consumption and CO_2 production needed to be quantified. The value for outside air change per hour was reduced by 50% due to the use of mosquito netting and steel security bars on the windows, which would reduce the flow of air into the living spaces [44].

The measured values for the thermal transmittance coefficient (U-values) from Onyenokporo et al. [55] were used for the simulation study to estimate the energy performance of the RHA blocks when used for the external walls. These were used to ascertain the effects on the external walls in terms of heat gains, energy consumption, CO_2 production, etc. Thermal conductivities for each sample were also calculated using measured U-values and a solid masonry block thickness of 150 mm. These can be found in Table 4 and Figure 11.

Table 4. Input values for external building walls derived from measured U-values (Onyenokporo et al., 2023) [55].

Sample	U-Values (W/m^2K)	Density (kg/m^3)	Thermal Conductivity (W/mK)	Thermal Resistance (m^2K/W)
RHA 0%	3.67	1799.02	0.55	0.27
RHA 5%	3.68	1784.51	0.55	0.27
RHA 10%	3.34	1735.29	0.50	0.30
RHA 15%	3.04	1784.31	0.46	0.33

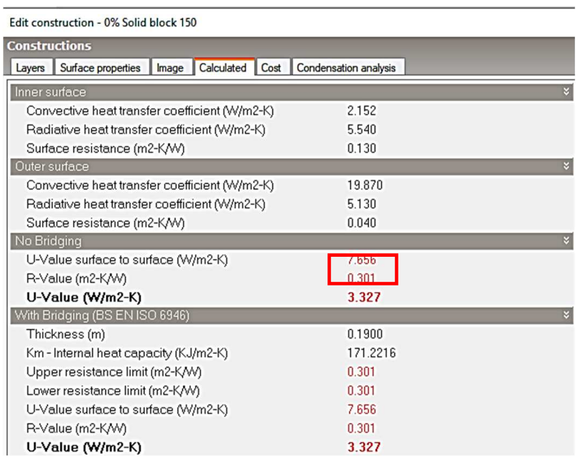


Figure 11. Final U-value of RHA 0% solid block with 20 mm cement-sand render.

With the addition of 20 mm of plaster to the inner and outer faces of the wall, the final U-value of the RHA0% block used as a control sample became 3.327 W/m^{2}K, as shown above. It is important to note that the exact parameters measured for RHA blocks (thickness and U-values) have been used for this simulation to depict an accurate quantification of the effects of these values on building energy performance.

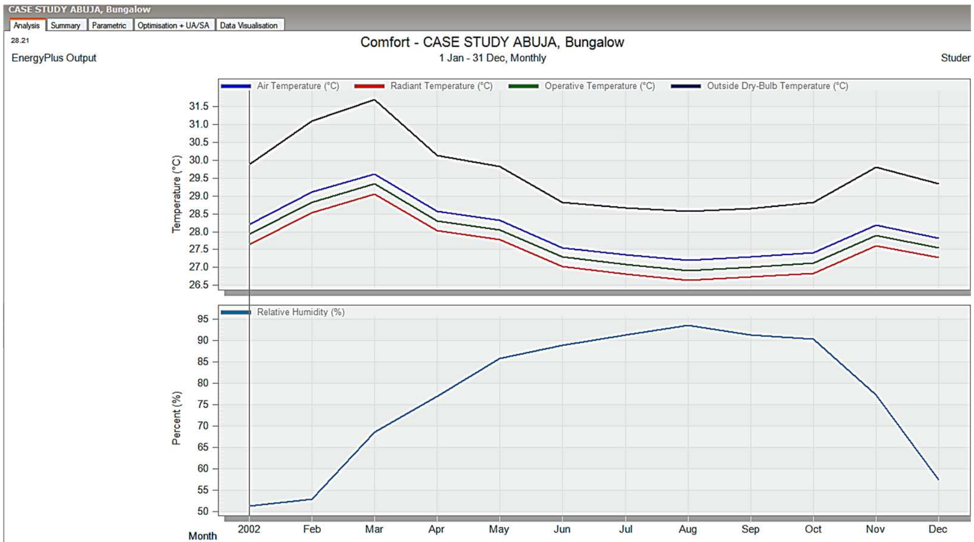
3. Results

The section details the results of the building simulation study. The results for the physical and thermal characterization of the RHA masonry blocks can be found in Onyenokporo, Taki and Zapata Montalvo [25] and Onyenokporo et al. [55].

3.1. Assessment of Building Energy Performance of Selected Buildings Using RHA Masonry Blocks for Walling

3.1.1. Case Study 1 (Bungalow)

Having input all the relevant data as mentioned above, the EnergyPlus simulation was run for a typical year, i.e., January to December. This was performed using the U-value for the RHA 0% block to represent the concrete masonry wall without any RHA additions. The monthly data for indoor temperature can be seen in Figure 12. Based on the input weather data, the highest air temperatures within the dwelling are observed between February and April, which is during the peak dry season when temperatures are higher. The lowest level is observed during the rainy season. The operative temperature, which is the average of the air and radiant temperatures within the building, reflects the actual temperatures obtained within the building and perceived by the building occupants with regard to comfort. Adebamowo [75] reports 28 °C as the neutral temperature for dwellings in hot-dry climates like Abuja, although Ogbonna and Harris [76] measurements for similar locations to this study report a neutral temperature of 26 °C. Nevertheless, the higher value of 28 °C is still exceeded in 4 out of 12 months (February–May).



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)	28.21	29.11	29.62	28.57	28.31	27.55	27.36	27.19	27.29	27.40	28.18	27.81
Radiant Temperature (°C)	27.64	28.54	29.05	28.02	27.78	27.02	26.82	26.63	26.73	26.84	27.61	27.27
Operative Temperature (°C)	27.93	28.83	29.34	28.30	28.05	27.29	27.09	26.91	27.01	27.12	27.89	27.54
Outside Dry-Bulb Temperature (°C)	29.88	31.10	31.71	30.13	29.83	28.82	28.67	28.58	28.64	28.82	29.82	29.34
Relative Humidity (%)	51.21	52.94	68.54	76.92	85.83	88.76	91.22	93.55	91.16	90.22	77.17	57.36

Figure 12. Graph showing occupant's comfort for the base case using RHA 0% masonry block wall.

The effect of the building envelope on the building performance is presented in Figure 13. The heat losses and gains through the building fabric can be seen in the heat balance graph. The focus is on the external wall heat gains, which are 18,108 kWh. This will serve as the typical value to provide a comparison for the RHA 5–15% blocks.

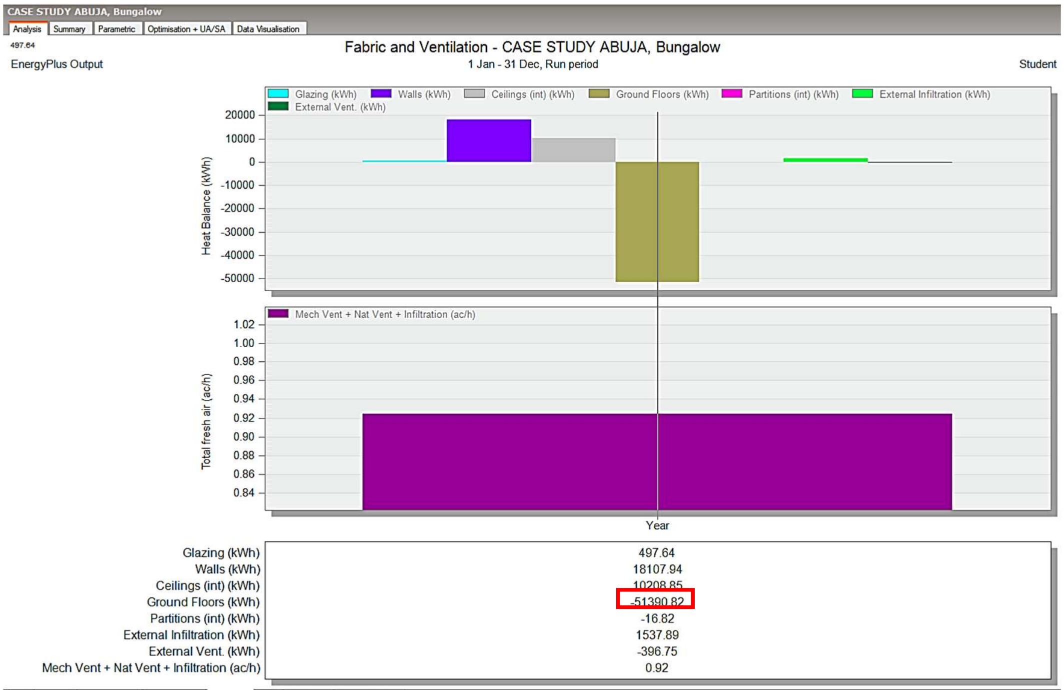


Figure 13. Graph showing fabric and ventilation heat gains for base case using RHA 0% block wall.

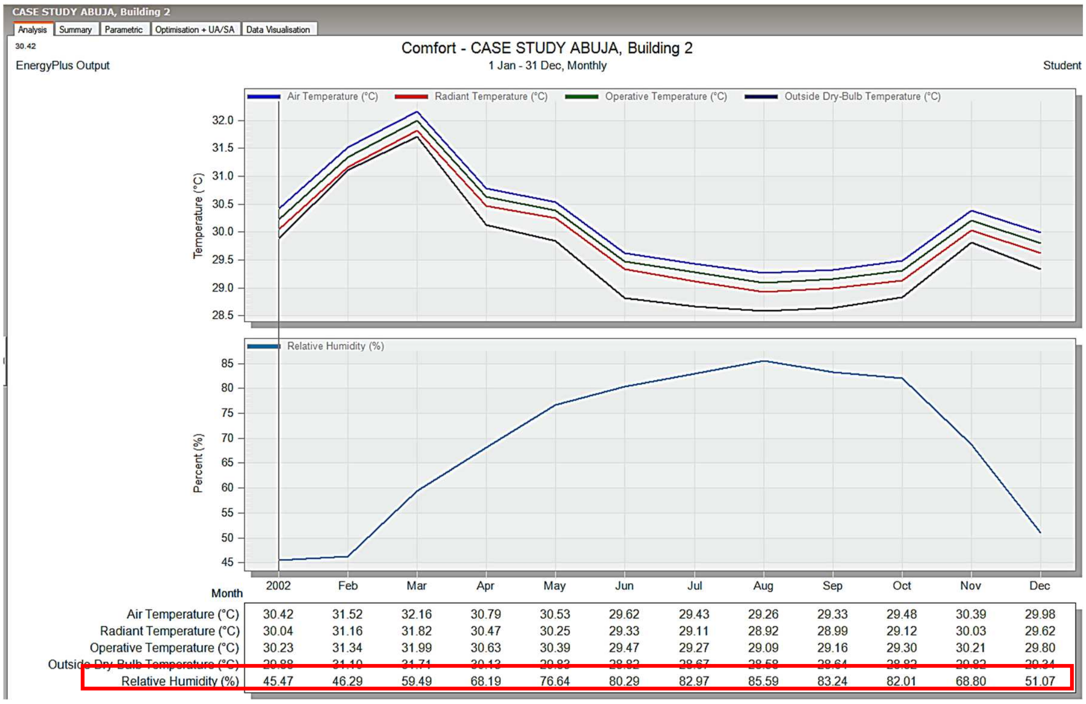
The external wall U-values for each case were adjusted using the measured U-values from Table 4. The effect of the various rice husk ash blocks on building operative temperature, external wall heat gains, cooling energy consumption, and CO_2 production can be seen in the values represented in Table 5**.**

Table 5. Annual simulation results for all block samples used for Case study 1.

RHA Wall	DB U-Values (W/m^2K)	Operative Temperature (°C)	Walls (kWh)	Cooling Load (kWh)	CO_2 Production (kg)
0%	3.327	27.77	18,108	16,842	16,311
5%	3.334	27.77	18,132	16,855	16,319
10%	3.050	27.67	17,179	16,263	15,960
15%	2.805	27.58	16,310	15,746	15,646
Percentage difference					
0%	control	0%	0%	0%	0%
5%	less	0%	0%	0%	0%
10%	less	0.4%	5.1%	3.4%	2.1%
15%	less	0.7%	9.9%	6.5%	4.1%

3.1.2. Case Study 2 (Duplex/Storey Building)

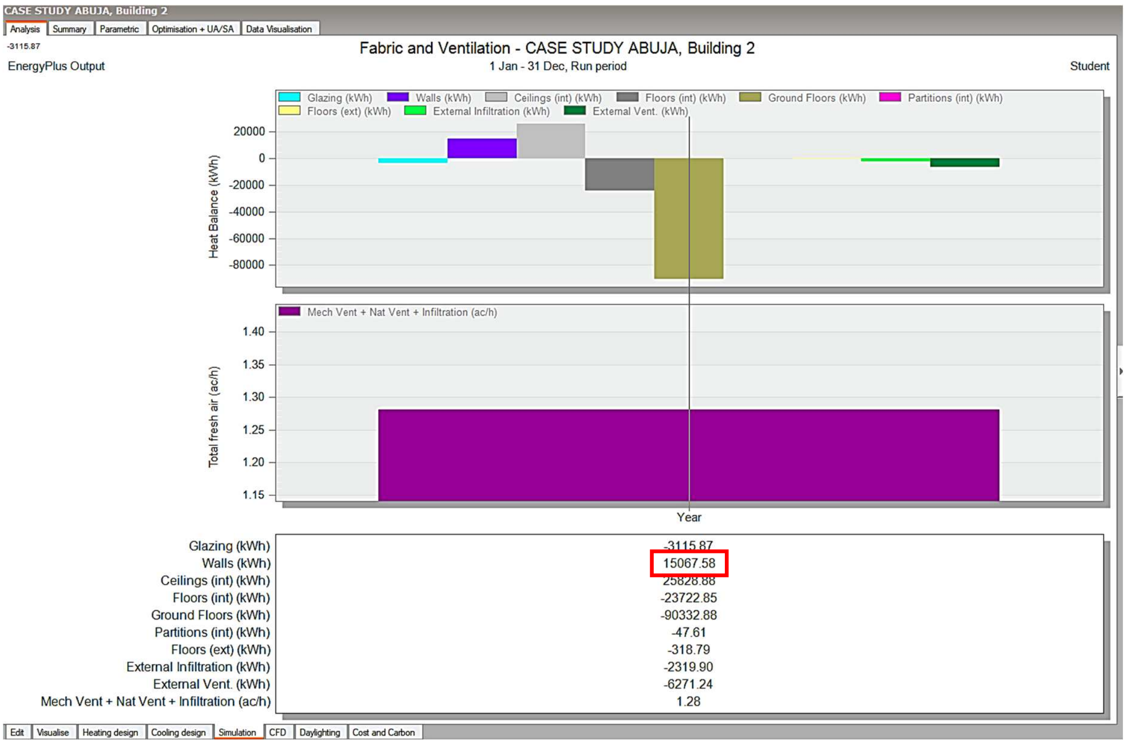
Similar to Case Study 1, the EnergyPlus simulation was run for a typical year, i.e., January to December, using input data values as mentioned above. The U-value for the RHA 0% block was also used to represent a conventional concrete masonry wall. The monthly data for building temperature can be seen in Figure 14. In contrast to the bungalow, the duplex house recorded much higher indoor temperatures. The highest air temperatures within the dwelling were observed in March, and the lowest were observed in August. Unlike the bungalow, which had only 4 out of 12 months of values exceeding the neutral temperature for a hot-dry climate, the indoor operative temperature values of the duplex for all 12 months exceeded the neutral temperature.



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)	30.42	31.52	32.16	30.79	30.53	29.62	29.43	29.26	29.33	29.48	30.39	29.98
Radiant Temperature (°C)	30.04	31.16	31.82	30.47	30.25	29.33	29.11	28.92	28.99	29.12	30.03	29.62
Operative Temperature (°C)	30.23	31.34	31.99	30.63	30.39	29.47	29.27	29.09	29.16	29.30	30.21	29.80
Relative Humidity (%)	45.47	46.29	59.49	68.19	76.64	80.29	82.97	85.59	83.24	82.01	68.80	51.07

Figure 14. Graph showing occupant's comfort for base case using RHA 0% block masonry wall.

The effect of the building envelope on building performance is displayed in Figure 15. The heat losses and gains through the building fabric can be seen in the heat balance graph. The external wall heat gains recorded were 15,068 kWh. This also serves as the typical value to provide a comparison for the RHA 5–15% blocks. Although the value for wall heat gains is slightly less than that of the bungalow, the heat gain through the roof/ceiling is observed to be twice as much due to the larger roof surface of the duplex.



	Year
Glazing (kWh)	-3115.87
Walls (kWh)	15067.58
Ceilings (int) (kWh)	25828.88
Floors (int) (kWh)	-23722.85
Ground Floors (kWh)	-90332.88
Partitions (int) (kWh)	-47.61
Floors (ext) (kWh)	-318.79
External Infiltration (kWh)	-2319.90
External Vent. (kWh)	-6271.24
Mech Vent + Nat Vent + Infiltration (ac/h)	1.28

Figure 15. Graph showing fabric and ventilation heat gains for the base case using RHA 0% block wall.

Similar to case study 1, the external wall U-value was adjusted using the measured U-values from Table 4. The effect of the various rice husk ash blocks on building operative temperature, external wall heat gains, cooling energy consumption, and CO_2 production can be seen in the values represented in Table 6.

Table 6. Annual simulation results for all block samples for Case study 2.

RHA Wall	DB U-Value (W/m^{2}K)	Operative Temperature (°C)	Walls (kWh)	Cooling Load (kWh)	CO_2 Production (kg)
0%	3.327	30.07	15,068	84,160	75,807
5%	3.334	30.07	15,089	84,211	75,838
10%	3.050	30.04	14,234	82,461	74,778
15%	2.805	30.01	13,359	80,665	73,690
Percentage difference					
0%	control	0%	0%	0%	0%
5%	less	0%	0%	0%	0%
10%	less	0.1%	5.5%	2.0%	1.4%
15%	less	0.2%	11.3%	4.2%	2.8%

3.2. Comparison of Building Energy Performance of Analysed Cases

3.2.1. Heat Gains through the External Walls

The annual external wall heat gains through the building fabric based on the four RHA wall types used for the simulation study for the bungalow are shown in Figure 16. The lowest value obtained for annual heat gains through the external walls was 16,309 kWh compared to the base case (RHA 0%), which was 18,108 kWh. This shows a significant reduction of 9.9% and was recorded from the use of the RHA 15% block wall. Likewise, the RHA 10% recorded a 5.1% reduction in annual external wall heat gains. No apparent difference was observed between the RHA 0% (base case) and the RHA 5% block wall, as shown in the graph below.

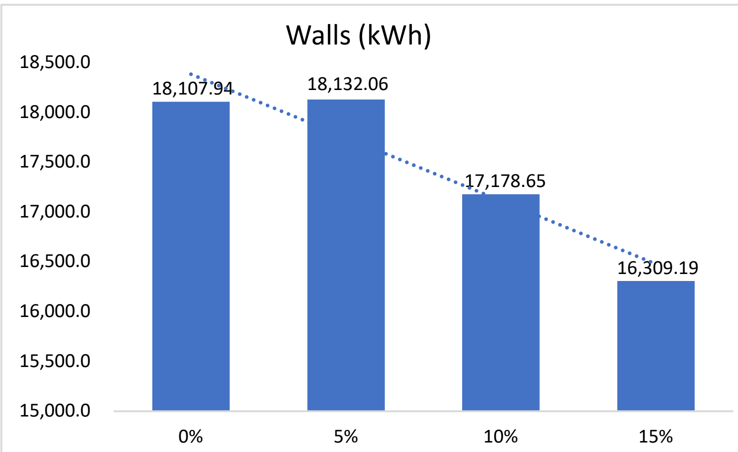


Figure 16. Graph showing annual external wall heat gains for all wall types.

The annual external wall heat gain recorded for the duplex house was 15,068 kWh using the base case (RHA 0%) wall. Compared to the bungalow, which recorded an annual external heat gain of 18,108 kWh, the duplex house has less heat gain through the walls. It is noteworthy to mention that since the duplex house has more windows and a larger roof surface area compared to the bungalow (Figure 8), a lot of the solar heat gains into the building can be attributed to these. From the simulation study, the solar heat gains through the external windows were 10,827 kWh for the bungalow and 44,332 kWh for the duplex, almost four times higher. This is also due to the little local shading provided by the roof eaves. Figure 15 also shows more heat gains to the duplex through the ceiling compared to the bungalow.

Nevertheless, based on the four wall types, the lowest value obtained for annual heat gains through the external walls of the duplex building was 13,359 kWh, as recorded by the RHA 15% block wall (Figure 17).

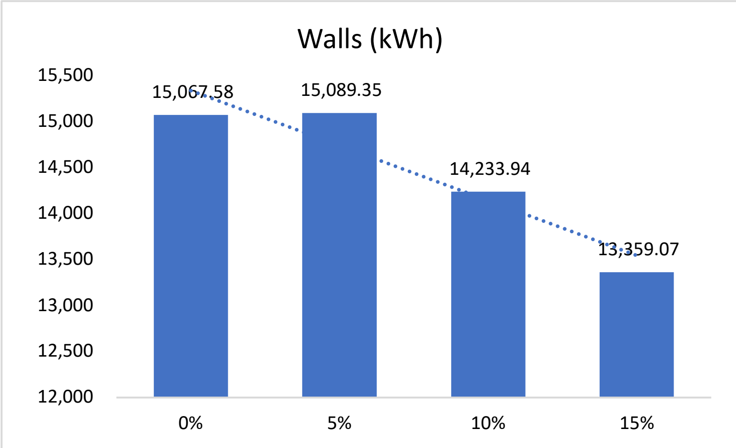


Figure 17. Graph showing annual external wall heat gains for all samples.

Applying the RHA 10% and 15% blocks resulted in a significant reduction of 5.5% and 11.3%, respectively, for the annual external wall heat gain into the building. However, as with Case Study 1, no apparent difference was observed between the RHA 0% (base case) and the RHA 5% block walls.

3.2.2. Occupant Comfort

For Case Study 1, in terms of building operative temperature, the lowest annual operative temperature recorded for all block wall types was 27.58 °C, which was observed when using the RHA 15% block wall. In terms of improving occupant comfort temperatures, the RHA 15% wall performed the best, followed by the RHA 10% block wall (Figure 18). Using the RHA 15% wall, the building's operative temperature was reduced by 0.7%. Likewise, the use of the RHA 10% wall resulted in a 0.4% building operative temperature decrease. In contrast, there was no significant difference between the operative temperatures for the RHA 0% (base case) and the RHA 5% block wall.

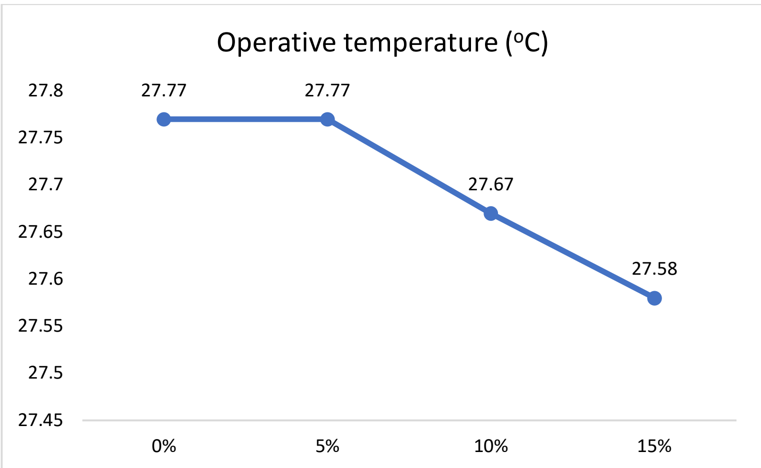


Figure 18. Graph showing annual operative temperatures for all wall types.

Case Study 2 (the duplex house), similar to the bungalow, recorded a decrease in annual building operative temperature. The lowest annual operative temperature recorded for all block wall types was 30.01 °C. This was observed when using the RHA 15% block wall, compared to the 30.07 °C recorded for the base case. Compared to the bungalow, the reduction in building annual operative temperature in the duplex house is not as substantial. In terms of improving occupant comfort, the RHA 15% wall performed the best, followed by the RHA 10% block wall (Figure 19), with a 0.2% and 0.1% reduction, respectively, in annual operative temperature. In contrast, there was no significant difference between the operative temperatures for the RHA 0% (base case) and the RHA 5% block wall.

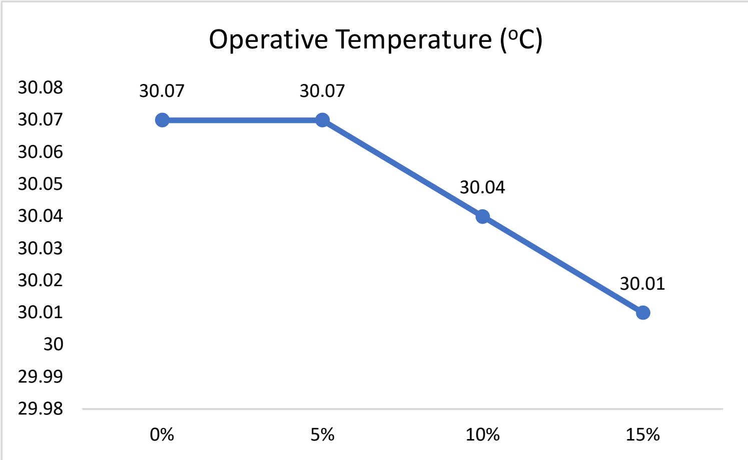


Figure 19. Graph showing annual occupant comfort for all samples.

3.2.3. Cooling Load/Energy Consumption

Following the improvements to the building envelope through the use of the RHA block walls, the resulting cooling energy consumption can be seen in Figure 20**.** This shows the decrease in annual energy consumption for cooling the building based on the four RHA wall types used for the simulation study.

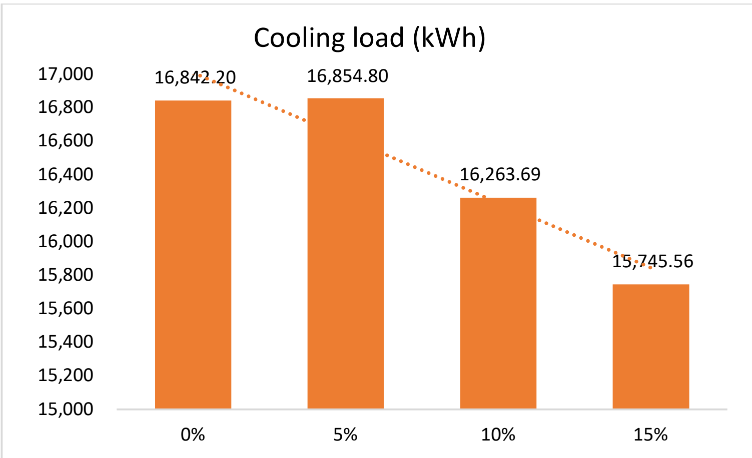


Figure 20. Graph showing annual cooling energy consumption for all samples.

For case study 1, the lowest value obtained for annual energy consumption for cooling was 15,746 kWh compared to the base case (RHA 0%), which was 16,842 kWh. Similar to the heat gains, this shows a significant reduction of 6.5% and was recorded using the RHA 15% block wall. In addition, using the RHA 10% block wall resulted in a 3.4% reduction in annual energy consumption for cooling. Nevertheless, no significant difference was observed between the RHA 0% (base case) and the RHA 5% block wall, as shown in the graph above.

Similar to the bungalow, in Case Study 2, following the improvements to the building envelope through the use of the RHA block walls, the resulting cooling energy consumption decreased. Based on the four RHA wall types used for the simulation study, the lowest value obtained for annual energy consumption for cooling was 80,665 kWh compared to the base case (RHA 0%), which was 84,160 kWh (Figure 21). This represents a significant reduction of 4.2% and was recorded using the RHA 15% block wall. In addition, using the RHA 10% block wall resulted in a 2.0% reduction in annual energy consumption for cooling. Just like the annual operative temperature, these values are not as high as those observed for the bungalow. Similarly, no significant difference was observed between the RHA 0% (base case) and the RHA 5% block wall, as shown in the graph above.

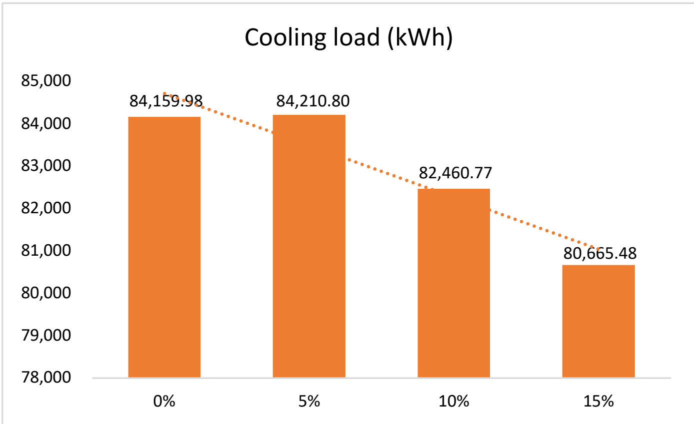


Figure 21. Graph showing annual cooling energy consumption for all samples.

3.2.4. Operational Carbon Emissions

The reduction in building annual energy consumption resulted in a proportional reduction in annual CO_2 production, as observed in Case Study 1. This can be seen in Figure 22, where the lowest value obtained for building annual CO_2 production was 15,646 kWh compared to the base case (RHA 0%), which was 16,311 kWh. Based on the four RHA wall types used for the simulation study, there was a significant reduction of 2.1% and 4.1% in building annual CO_2 production recorded using the RHA 10% block wall and the RHA 15% block wall, respectively. However, there was no major difference observed between the RHA 0% (base case) and the RHA 5% block wall, as shown in the graph below.

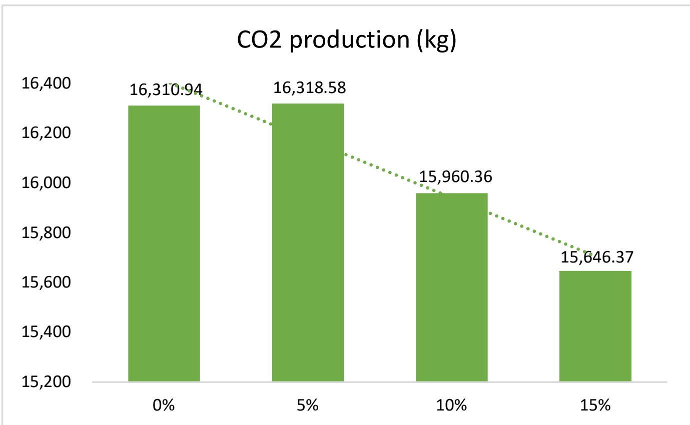


Figure 22. Graph showing annual building CO_2 production for all samples.

Figure 23 shows the improvements to building annual CO_2 production observed for Case Study 2. The lowest value obtained for building annual CO_2 production was 73,690 kWh compared to the base case (RHA 0%), which was 75,807 kWh. Based on the four RHA wall types used for the simulation study, there was a reduction of 1.4% and 2.8% in building annual CO_2 production recorded using the RHA 10% block wall and the RHA 15% block wall, respectively. Similar to the building's annual energy consumption, although significant, the values recorded are not as substantial as those recorded for the bungalow. Nevertheless, there was no key difference observed between the RHA 0% (base case) and the RHA 5% block wall.

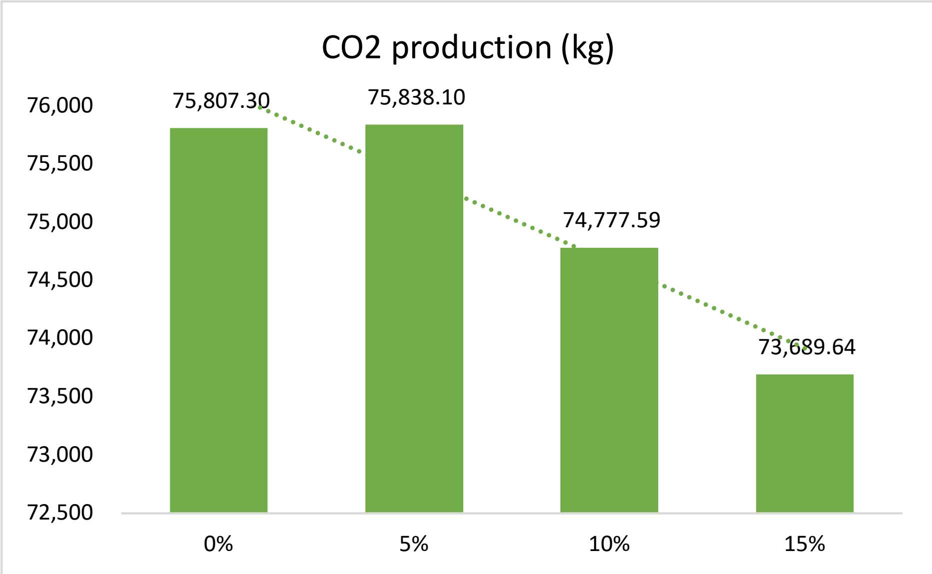


Figure 23. Graph showing annual building CO_2 production for all samples.

3.3. Comparison and Validation of Simulation Data

In order to improve the reliability of the simulation data obtained from DesignBuilder, the authors decided to compare the results to monitored daytime data for the study context using the existing literature. Adaji et al. [45,77] carried out an investigation on occupants' comfort and their responses for both dry and rainy seasons in Abuja, Nigeria. In their 2016 study, they used several buildings of low-to-middle-income households as their case study. During the dry season, which is the period between November and March, they took physical measurements from the 18th of March to the 18th of April 2015. Also, during the rainy season (between April and October), they conducted physical measurements from the 17th of June until the 12th of July 2015. Indoor air temperature and relative humidity were monitored for 24 h periods. For the dry season, they recorded a range of values between 28.4 and 36.8 °C for the living room and bedroom. For the rainy season, they recorded air temperature values between 24.3 and 35.9 °C for these living spaces.

Case Study 1 was used for this comparison as it is a bungalow similar to the buildings used by Adaji et al. [77]. In this study, using the same timeline of the dry season as the monitored data, the authors obtained average indoor air temperatures ranging from 28.22 to 31.58 °C for the living room and 27.22 to 31.17 °C for all bedrooms in the building. Similarly, for the rainy season, using the same timeline as the monitored data, the researcher obtained average indoor air temperatures ranging from 27.50 to 28.35 °C for the living room and 26.42 to 27.95 °C for the bedrooms. The information from DesignBuilder is attached in Appendix A. These results are in line with the range of average values provided by Adaji et al. [45,77].

4. Discussion

Based on previous studies using RHA for partial cement replacement, this study focused on quantifying the energy performance of the RHA masonry blocks, as the topic is still under-researched. In addition, previous studies had focused on the strength and other physical properties of the blended blocks, with not much thought given to the thermal properties that affect the building's energy performance after the blocks have been used for the construction of building walls.

It is noteworthy to mention that although the effect of the RHA blended blocks may not seem very significant in terms of operative temperature, cooling load, and carbon dioxide production, the effect was more significant for reducing the heat gains through the external walls, as these were the only parameters of the existing building adjusted in DesignBuilder. Based on the observation of the prototype buildings, it is evident that the houses were not built with passive design strategies such as solar shading and the use of greenery to reduce direct solar radiation into the buildings. This is also reported by Adaji et al. [45], who agree that mechanical cooling is used in most homes in Nigeria and other Sub-Saharan African countries to improve their thermal comfort. This is an unsustainable approach to achieving long-term thermal comfort in these houses because it is both costly and energy-intensive. Moreover, for a country like Nigeria, which is situated directly at the equator, the sun is directly overhead, especially in the daytime, resulting in high levels of solar heat gain through the building envelope. The incorporation of passive design strategies into the building can significantly improve its energy performance [50]. When these passive strategies are combined with the change to external walls, as demonstrated in this study, it will result in a more significant improvement to the overall building's energy performance.

Nigeria is a country with sporadic electricity supply, which is greatly augmented by off-grid power generators to run cooling mechanical equipment in a bid to improve indoor building temperature. With buildings and households recording huge amounts of energy consumption, especially with the use of electrical devices and cooling equipment, the importance of improving building energy performance cannot be overstated. The results of this study will go a long way towards reducing building energy consumption as well as carbon emissions from these activities. Coupled with the use of waste materials to reduce building costs, the improvement to the thermal performance of the building fabric will contribute to reducing both embodied energy and operational energy costs, making buildings more affordable to build and operate. Also, waste reuse and recycling contribute to the growth of a circular economy [53]. The potential of using this waste material in construction is therefore evident and would go a long way towards reducing global energy consumption. Although this study only focused on the external walls, the use of RHA can also be extended to include both internal walls and other cement-based components such as mortars, plasters, and concrete floors. The sheer impact of this will drastically result in a reduction in building energy consumption and carbon emissions.

Although the focus of the research was on the thermal properties of the RHA masonry blocks and their effect on building energy performance, the study also determined the physical properties of the RHA masonry blocks, such as density, compressive strength, and water absorption, as these are very important parameters to consider for building components, and this data is useful for their adoption as well as for use in further studies. Full details can be found in Onyenokporo, Taki, and Zapata Montalvo [25] and Onyenokporo et al. [55]. It is noteworthy to mention that one major limitation to the commercial adoption of rice husk ash as a partial replacement for cement is its slow early strength gain and increased water absorption when compared to conventional concrete masonry blocks. However, solutions to these have been provided in previous studies. Ettah et al. [56] recommend that adequate attention be given during the curing process and a chemical activator be used to improve the strength. Similarly, Trejo and Prasittisopin [78] explain that the water absorption of RHA block samples can be increased by reducing the particle size of the rice husk ash, either through mechanical grinding or the chemical alkali extraction method. Future work will therefore consider curing for longer periods than 28 days and also using a chemical activator or superplasticizer to improve the strength of RHA block samples. Further reduction in the RHA particle size to less than 45 µm, as used in this study, should also be considered. As recommended by Trejo and Prasittisopin [78], reducing the cellular, honeycomb-shaped structure may cause a decrease in water absorption properties, meaning that fresh concrete mixtures containing smaller RHA particles will have improved workability and lower water requirements compared to those containing larger RHA particles.

5. Conclusions

This study focused on the potential of using rice husk ash (RHA) masonry blocks for external building walls in tropical climates, using Abuja, Nigeria, as the study context. For the bungalow, using the RHA10% and RHA15% blocks reduced the heat gains through the external walls by 5.1% and 9.9%, respectively. This represents a reduction of about 3.4% and 6.5%, respectively, in terms of cooling load and a 2.1% and 4.1% reduction in carbon emissions. However, in terms of indoor operative temperature, the reduction was not very significant, with approximately a 1% reduction in the operative temperature using RHA15%. This was similarly observed for the duplex/storey building. Using the RHA10% and RHA15% blocks resulted in a reduction of heat gains through the external walls by 5.5% and 11.3%, respectively. This also translates to a reduction of about 2.0% and 4.2%, respectively, in terms of cooling load and a reduction of 1.4% and 2.8% in carbon emissions.

The findings from this study demonstrate the potential of using rice husk ash masonry blocks for external building walls in tropical climates, which can help improve building energy performance. The prospects of improving the building envelope through the use of RHA masonry blocks will contribute towards reducing the operational costs spent on cooling in most households, reducing carbon emissions from the process, and improving the thermal comfort of building occupants. An increase in population leads to an increase in energy demand as well as an increase in demand for and use of natural resources. The significance of the research outcomes cannot be overstated, as they provide evidence to justify the utilisation of these supplementary cementitious materials, like rice husk ash, for sustainable building construction. This research will prove useful in encouraging the adoption of this waste material, reducing landfilled waste, and encouraging a circular economy. It will also add to the existing knowledge on design strategies to minimise building energy consumption. The outcomes of this research will prove useful to householders, researchers, architects, and policymakers in their decision-making processes. In addition, this study will be beneficial in bridging the knowledge gap as well as introducing new methods that can be adopted for similar studies.

The need for continued research in this field cannot be overemphasised, as it has the potential to foster the development of more energy-efficient construction materials. Additionally, the impact of this research will be further strengthened if an actual RHA masonry building is built. Producing a building prototype of an RHA building will help to strengthen the results obtained from the building simulation study and provide a real-life example of a rice husk ash masonry building. Furthermore, a post-occupancy survey can be conducted to gauge the influence on building energy performance and compare this to the simulation results. For future experiments as well as building simulation studies, it will be useful to consider using RHA in concrete, mortar, and plaster, as these are also major cement-based components of the external envelope. This will provide a bigger picture to demonstrate the effect of rice husk ash additions to the building envelope.

Author Contributions: Conceptualization, N.C.O., A.T. and L.Z.M.; Investigation and Data curation, N.C.O.; Formal analysis, N.C.O.; Funding acquisition, A.T.; Methodology, N.C.O. and A.T.; Resources, N.C.O. and M.A.O.; Writing—original draft, N.C.O.; Writing—review and editing, N.C.O., A.T., L.Z.M., and M.A.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the De Montfort University Highflyer Research Scholarship 2019—this research received no external funding.

Data Availability Statement: Data are contained within the article.

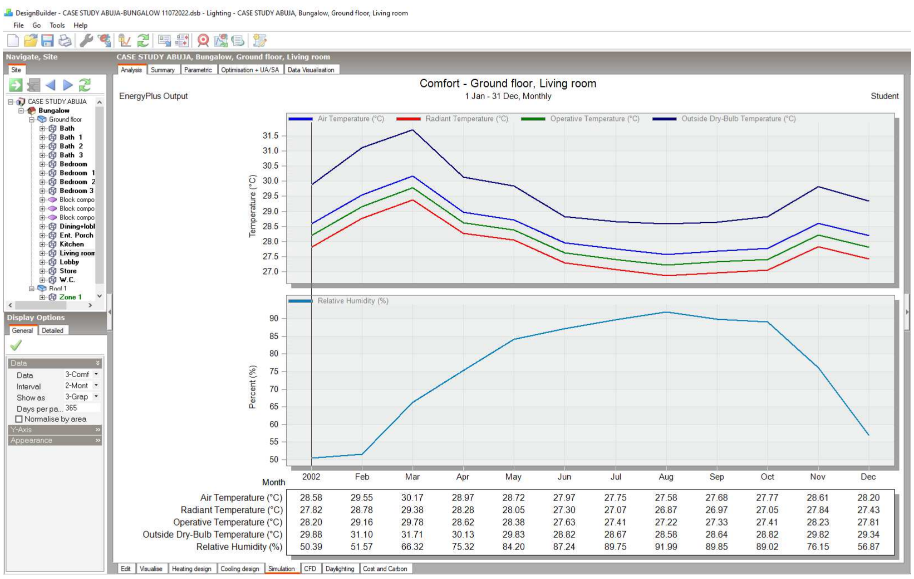
Acknowledgments: The authors acknowledge the Doctoral College at De Montfort University for funding this study. The authors also appreciate all the technical staff who provided support throughout this study.

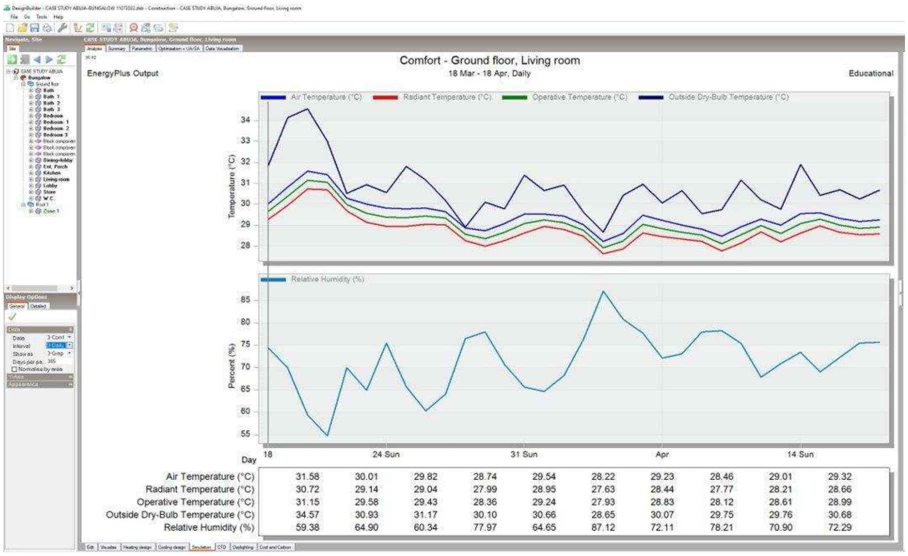
Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data in the writing of the manuscript; or in the decision to publish the results.

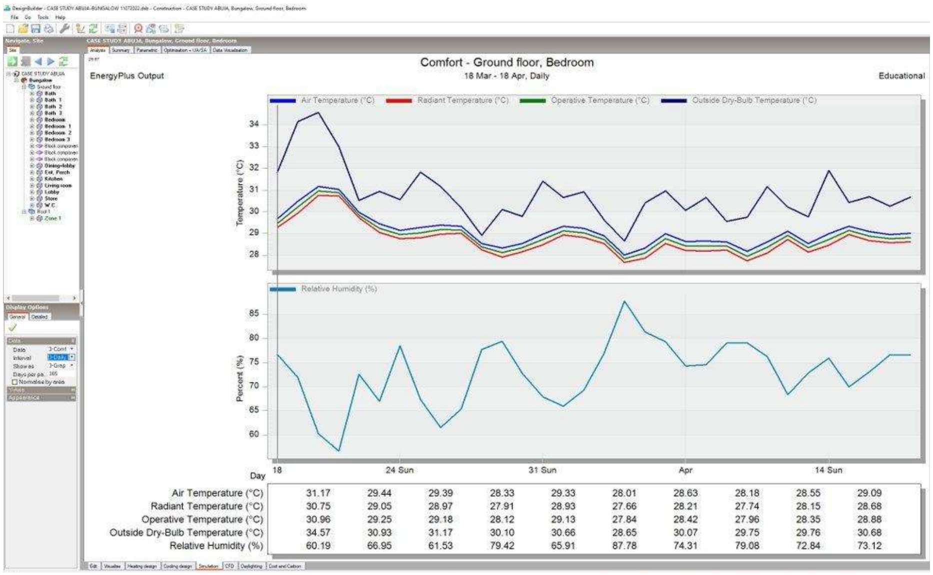
Abbreviations

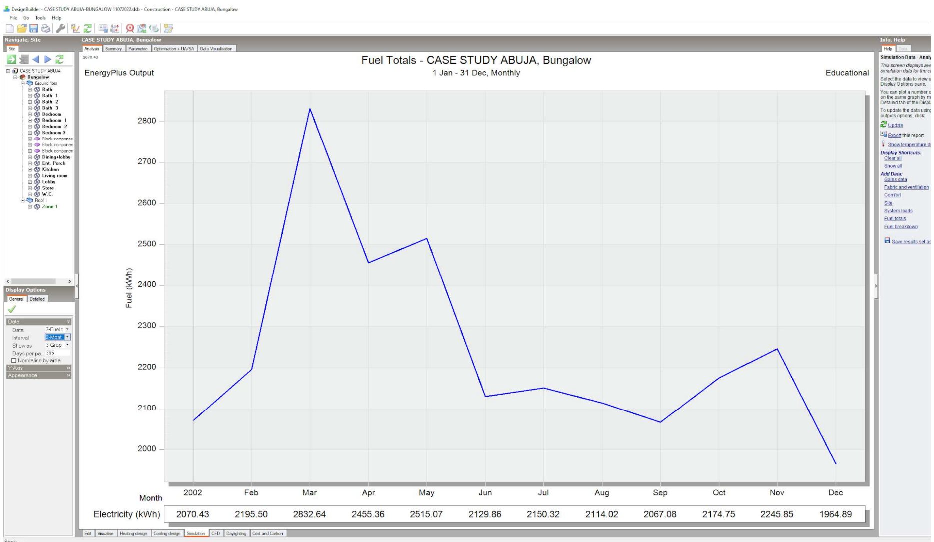
ach	Air changes per hour
ASTM	American Society for Testing and Materials
BINM	DOE2 weather file format
CO2	Carbon dioxide
EPW	EnergyPlus weather data file format
FAO	Food and Agricultural Organization of the United Nations
FCTA	Federal Capital Territory Administration
GHGs	Greenhouse gases
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
NIS	Nigerian Industrial Standard
RHA	Rice husk ash
SCMs	Supplementary Cementitious Materials
U (W/m^2 K)	U-value or Thermal transmittance coefficient

Appendix A Sample of Input Data for EnergyPlus Simulation




Comfort - Ground floor, Living room
18 Mar - 18 Apr, Daily
EnergyPlus Output
Educational
Air Temperature (°C)
Radiant Temperature (°C)
Operative Temperature (°C)
Outside Dry-Bulb Temperature (°C)
Temperature (°C)
Relative Humidity (%)
Percent (%)
Day
18
24 Sun
31 Sun
Apr
14 Sun
Air Temperature (°C) 31.58 30.01 29.82 28.74 29.54 28.22 29.23 28.46 29.01 29.32
Radiant Temperature (°C) 30.72 29.14 29.04 27.99 28.95 27.63 28.44 27.77 28.21 28.66
Operative Temperature (°C) 31.15 29.58 29.43 28.36 29.24 27.93 28.83 28.12 28.61 28.99
Outside Dry-Bulb Temperature (°C) 34.57 30.93 31.17 30.10 30.66 28.65 30.07 29.75 29.76 30.68
Relative Humidity (%) 59.38 64.90 60.34 77.97 64.65 87.12 72.11 78.21 70.90 72.29


Comfort - Ground floor, Bedroom
18 Mar - 18 Apr, Daily
EnergyPlus Output
Educational
Air Temperature (°C)
Radiant Temperature (°C)
Operative Temperature (°C)
Outside Dry-Bulb Temperature (°C)
Temperature (°C)
Relative Humidity (%)
Percent (%)
Day
18
24 Sun
31 Sun
Apr
14 Sun
Air Temperature (°C) 31.17 29.44 29.39 28.33 29.33 28.01 28.63 28.18 28.55 29.09
Radiant Temperature (°C) 30.75 29.05 28.97 27.91 28.93 27.66 28.21 27.74 28.15 28.68
Operative Temperature (°C) 30.96 29.25 29.18 28.12 29.13 27.84 28.42 27.96 28.35 28.88
Outside Dry-Bulb Temperature (°C) 34.57 30.93 31.17 30.10 30.66 28.65 30.07 29.75 29.76 30.68
Relative Humidity (%) 60.19 66.95 61.53 79.42 65.91 87.78 74.31 79.08 72.84 73.12


Fuel Totals - CASE STUDY ABUJA, Bungalow
1 Jan - 31 Dec, Monthly
EnergyPlus Output
Educational
Fuel (kWh)
Month
2002
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Electricity (kWh) 2070.43 2195.50 2832.64 2455.36 2515.07 2129.86 2150.32 2114.02 2067.08 2174.75 2245.85 1964.89

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