Using recycled materials as an approach to energy-efficient building: A residential building in North Egypt as a case study

Hatem Mahmoud
Sustainable Architecture Program, Egypt Japan University of Science and Technology

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Hatem Mahmoud[1]
[1]Sustainable Architecture Program, Egypt Japan University of Science and Technology, Alexandria, Egypt.
hatem.mahmoud@ejust.edu.eg

Abstract: *The building sector faces a pressing need to explore innovative solutions that mitigate resource depletion and reduce energy consumption. This study investigates the potential of integrating recycled materials into building construction as a sustainable approach to achieving energy-efficient buildings. It aims to assess the feasibility and effectiveness of incorporating construction recycled materials into building walls to enhance energy efficiency. The research will employ a multi-faceted methodology that combines laboratory experiments and computer simulations to quantify the benefits of tested recycled materials in comparison to traditional construction materials. The study revealed that the produced waste-based concrete blocks used as building envelope for a typical residential building could reduce the energy consumption for the heating and cooling loadings by 21.86% and 5.24% with satisfactory compressive strength and density to withstand loads. This study contributes to the growing body of knowledge aimed at fostering more environmentally responsible practices in the building sector.*

Keywords: Green concrete blocks; Wood and glass powder; Concrete additives, Thermal conductivity

1. INTRODUCTION

The global trend of urbanization and population growth has fueled infrastructure needs, and environmental pollution is becoming a major issue due to the increasing waste generation. The global waste crisis has become a matter of concern, posing threats to the environment. According to Sathiparan and De Zoysa [1], another factor contributing to environmental pollution is the uncontrolled exploitation of finite natural resources. In emerging economies like Egypt, the building sector has experienced recent expansion due to the number of construction activities, which has increased the need for various kinds of building materials. Ohemeng and Ekolu [2] acknowledged that the cost and other relevant aspects, such as the quality of the materials, strongly impact the construction of buildings in mitigating climate change. For buildings in Egypt, the stage of material fabrication is responsible for around 70% of the overall environmental impacts, while the stage of disposal is responsible for approximately 10% of these impacts [3].
Egypt, due to the increase in population, is faced with an increase in electricity demand, which has highlighted the importance of finding an innovative, affordable approach to improve the energy efficiency of a building envelope [4]. Buildings account for 60% of power use and contribute to 8% of CO_2 emissions in Egypt. The role of building materials in improving the energy efficiency of buildings cannot be downplayed. One of the most essential factors in determining the energy efficacy and overall sustainability of a building is its construction materials [5] [6]. How they are selected, designed, and applied can have a significant impact on a building's capacity to store and utilize energy efficiently.
The thermal conductivity and insulation properties of different building materials are some of the most significant ways in which building materials affect energy efficiency [7]. In recent years, utilizing recycled materials in construction stands out as an essential strategy for achieving energy efficiency and environmental responsibility [8]. The use of recycled materials in construction processes comes out as a critical practice among these.
Numerous research efforts have explored the potential of utilizing waste materials in the production of construction materials. For instance, Al-Jabri et al. [9] successfully produced lightweight concrete blocks by incorporating polystyrene beads, vermiculite, and cement kiln dust, resulting in reduced thermal conductivity. Lokeshwari and Jagadish [10] explored the utilization of granite fines waste in building blocks, demonstrating their compatibility as replacements for fine aggregates in comparison to conventional building materials. Ganjian et al. [11] and Yeo et al. [12] both investigated the use of various waste materials in the production of concrete paving blocks, with a focus on strength, durability, and environmental considerations. The incorporation of waste materials as aggregate replacements holds significant potential for developing eco-friendly concrete paving blocks in support of sustainable construction material development. Rosman et al. [13] employed concrete waste as a cement replacement in concrete blocks, optimizing their thermal and mechanical properties and achieving lower temperature results compared to the surrounding air. Sutcu et al. [14] utilized waste marble powder to manufacture charred clay bricks, reducing bulk density while meeting or exceeding strength standards and significantly decreasing thermal conductivity. Arumugam and Shaik [15] demonstrated the feasibility of designing environmentally friendly and energy-efficient building envelopes by using solid waste materials in mud bricks and assessing their thermal properties, with rice husk mud-brick walls and clay tile roofs providing the best outcomes. Boston-Osoteo et al. evaluated the rice husk ash and coconut shell ash as partial cement replacement for concrete hollow blocks production [16].
Despite the substantial utilization of waste materials in the production of construction materials, recent studies, such as those by Olofinnade et al. [17], and Solouki et al. [18], have predominantly focused on pavement concrete blocks, and often incorporating agricultural waste [19] [20] [21]. Similarly, studies on bricks, like Gavali et al.

[22] and Akinyele et al. [23], have explored the integration of waste materials with limited emphasis on improving the thermal performance of building blocks. The exploration of the use of waste-based materials, especially in the context of building envelopes, is an area that warrants further investigation by researchers. It is crucial to note that studies of this kind have been noticeably scarce in developing countries like Egypt. Recognizing this research gap is of utmost importance.

Therefore, this study aimed to assess the thermal performance of concrete blocks produced from waste-based construction materials and predict their energy efficiency in comparison to traditional materials such as red or cement blocks. This study specifically considered the incorporation of silica fume, marble dust, wood, glass, and concrete aggregates as partial replacements for cement, sand, and gravel. The research focused on evaluating the impact of these waste materials on the density, thermal conductivity, and energy efficiency of the concrete blocks. Experimental testing was conducted on the produced concrete blocks to determine properties such as dry density, porosity, thermal conductivity, and resistance. The collected data from these tests served as input parameters in DesignBuilder software, enabling the assessment of the energy performance of the concrete blocks when utilized as a building envelope. This evaluation aimed to quantify the blocks' impact on a typical residential building located in Borg Al-Arab, Alexandria, Egypt. The goal of this research is to enhance the building envelope's efficiency using sustainable materials, aligning with the objectives of Sustainable Development Goal 7 (SDG7) for clean energy and SDG11 for sustainable cities.

2. DEVELOPMENT OF CONCRETE BLOCK SAMPLES

This section of the study sets down the comprehensive research process, encompassing the preparation and testing of concrete block specimens, as illustrated in Fig. 1.

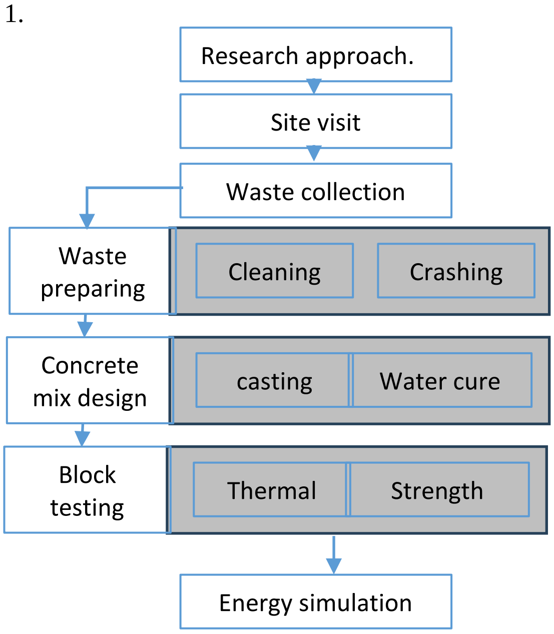

Fig. 1. The overall research process of the study.

2.1 Materials

The research involved conducting empirical casting of block samples within the laboratory, focusing on the measurement of their thermal conductivity and compressive strength properties. El-Borg Cement Type I was employed as the standard binding material, and river sand and gravel were used as natural aggregates. The particle size distribution of these aggregates ranged from 0.075 mm to 2.36 mm for sand and from 2 mm to 9.5 mm for gravel, as determined through sieve analysis. Five distinct waste materials were incorporated in this study, with four of them categorized as construction waste. These included marble dust, glass, wood, and old concrete aggregate obtained from the construction site at Egypt Japan University of Science and Technology (EJUST). The fifth waste material was upcycled silica fume. In the context of the study, marble dust and silica fume were employed as replacements for cement, while glass and wood were processed into fine aggregates for substitute sand. The gradation of these fine aggregates ranged from 0.06 mm to 3.45 mm. Additionally, the old concrete was crushed into coarse aggregates to replace gravel, and its particle size distribution ranged from 0.06 mm to 9.5 mm.

2.2 Block sample fabrication

The concrete ingredients were proportioned by weight according to the specifications outlined in Table 1. A 20-litre universal mixer was employed for a mixing duration of 5 minutes to ensure the homogeneous blending of the raw materials. Subsequently, rectangular steel molds with dimensions of 25 x 13 cm and a height of 6.5 cm were utilized to cast the concrete block samples. The prepared mixture was placed into the molds in three layers, with each layer being hand-compacted to eliminate air voids. Afterwards, the samples were demolded once they had achieved sufficient hardening, typically after 24 hours, and subsequently subjected to a water-curing process for 28 days. The mix samples (CB-1, CB-2, CB-3, and CB-4) incorporated the waste materials as a composite mixture to replace the conventional raw materials. These mix designs were based on trial mixtures, which aimed to attain the requisite level of compressive strength development. The chosen percentage replacements were validated based on prior research to ensure their suitability for concrete formulations.

Table 1. Mix proportions of block samples (SF: Silica fume, MD: Marble Dust, FW: Fine wood, FG: Fine Glass, CA: Concrete Aggregate).

Mix codes	Water (kg)	Cementitious ingredients (kg)		
		PC	SF	MD
CB-RF		3.34	-	-
CB-1		2.5		0.5
CB-2	1.28	2.34	0.33	0.67
CB-3		2.5		0.5
CB-4		2.34		0.67

Mix codes	Aggregates (kg)					
	Sand	FW	FG	CA	Gravel	Crushed
CB-RF	4.76	-	-	-	4.03	
CB-1	3.58	0.24	0.95	1.01	3.02	
CB-2	3.09	0.48	1.19	1.21	2.82	
CB-3	3.58	0.24	0.95	1.01	-	3.02
CB-4	3.09	0.48	1.19	1.21	-	2.82

2.3 Testing

The selection of building materials plays a crucial role in the construction's temperature control strategy. Therefore, the thermal conductivity and resistance are determined using the Heat Flow Meter-100, a widely employed method known for its simplicity, speed, and applicability to a wide range of materials (See Fig. 2). The Heat Flow Meter-100 apparatus boasts excellent precision and calibration within the expected heat flow range. It utilizes specimens traceable to an absolute measurement method and originating from a recognized national standards laboratory.

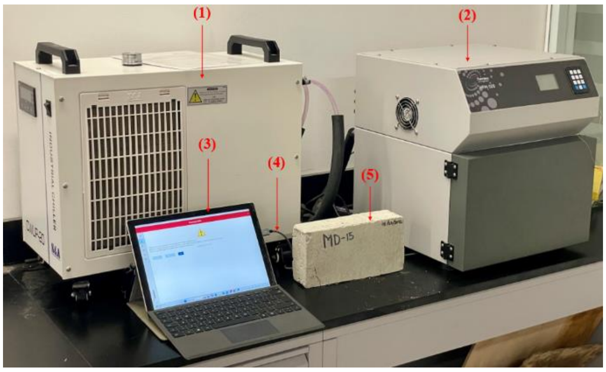

Fig. 2. Photograph of thermal testing set up in the laboratory. (1) Temperature device; (2) HFM-100 device; (3) HFM-100 Windows software; (4) USB cable from HFM-100 to computer device; (5) Concrete block sample ready for testing.

This device establishes steady-state, one-dimensional heat flux through a test specimen positioned between two parallel plates at constant but different temperatures, following the principles outlined in ASTM C518-10. The mathematical calculation for the Heat Flow Meter-100 is straight forward. Through appropriate calibration of the heat flux transducers with standards and the measurement of plate temperatures and separation, Fourier's law of heat conduction is applied to calculate thermal conductivity and resistance, Calibration is a prerequisite before conducting tests, and it must be performed for every desired test temperature. The test specimens, sized at 0.25 m x 0.13 m with a thickness of 0.065 mm, were used. These samples were retained in molds for 24 hours and then subjected to a 28-day water-curing process. To ensure consistent moisture and ambient conditions, all samples were allowed to air dry for 24 hours prior to testing, as thermal conductivity is influenced by material density, moisture content, and ambient temperature.

Heat was applied through the lower plate to the sample and received at the upper plate, with a preset temperature difference of 20 °C. Subsequently, the representative thermal conductivity value, based on the application of heat area, sample thickness, temperature difference, and power for generating the temperature difference, was obtained at 28 days following ISO 8302 guarded hot plate procedures.

The compressive strength resistance was determined after 28 days of curing using a compressive test machine with a capacity of 3,000 KN. as shown in Fig. 3.

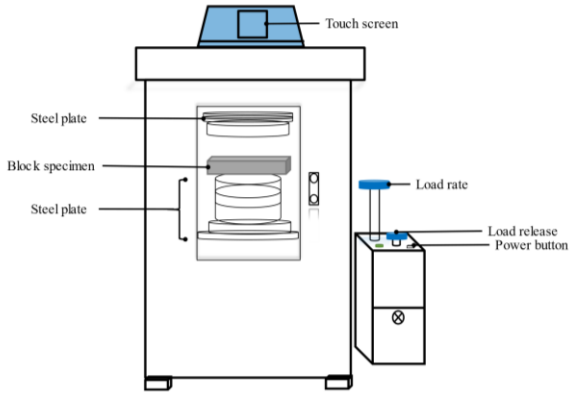

Fig. 3. Schematic view of compression test.

2.4 Properties of the developed concrete block samples

Table 2 shows the thermo-physical and mechanical properties of the concrete block samples. The findings related to compressive strength indicate that CB-RF exhibits the highest strength at 46.70 MPa, with CB-1, CB-2, CB-4, and CB-3 following in descending order. Noteworthy is the decreasing trend in compressive strengths for CB-1, CB-2, CB-3, and CB-4, reflected in their respective values of 32.70 MPa, 21.35 MPa, 13.75 MPa, and 15.05 MPa. This trend aligns with the initial analysis, highlighting the critical role of aggregate selection. Density, a crucial parameter influencing both thermal and structural properties in construction materials, reveals that CB-RF boasts the highest density at 2183 kg/m³, with CB-3, CB-1, CB-4, and CB-2 following suit. The observed pattern suggests that incorporating crushed marble aggregates into CB-2 and CB-4 may decrease overall density, likely due to the lower weight of crushed marble than gravel. Thermal conductivity values offer valuable insights into the insulation qualities of concrete mixtures. CB-RF records the highest thermal conductivity at 1.655 W/m·K, while CB-2 exhibits the lowest at 0.723 W/m·K. This implies that integrating pulverized marble as an aggregate in CB-2 concrete enhances its insulation characteristics. Conversely, CB-1, CB-3, and CB-4 show intermediate thermal conductivity values determined by their aggregates. Thermal resistance values underscore the concrete mixtures' insulation capacity. In contrast to CB-2 (0.077 m²·K/W), CB-RF exhibits a comparatively reduced thermal resistance of 0.040 m²·K/W despite its notable compressive strength. This inconsistency highlights the intricate correlation between thermal resistance and compressive strength, indicating that increased compressive strength does not necessarily equate to improved thermal insulation.

The use of fine wood positively affects the reduction of conductivity. Conversely, crushed aggregate increases conductivity and reduces strength. Therefore, replacing gravel with crushed aggregate poses a challenge and requires further investigation to improve its performance. The correlation between thermal conductivity, thermal resistance, compressive strength, and density highlights the importance of considering various properties in the concrete design when evaluating these block samples for use in a building envelope. The findings related to compressive strength suggest that these blocks exhibit satisfactory strength, a crucial characteristic for loadbearing elements like block walls. The lower density can be advantageous for weight reduction, potentially supporting sustainable construction practices [24]. The thermal conductivity values provide insights into the insulation qualities of the blocks. The improved thermal properties values may be advantageous since thermal conductivity and resistance are a priority for the building envelope [7]. This indicates a trade-off between thermal insulation and structural strength, emphasizing the necessity for a systematic approach to block selection. The suitability of these block samples for a block wall building envelope ultimately depends on the specific requirements and priorities of the construction project.

Table 2. Thermo-physical and mechanical properties of the concrete block samples.

Block No.	Compressive Strength (MPa)	Density	Conductivity (w/m.k)	Resistance (w/m.k)
CB-RF	46.7	2183	1.65	0.040
CB-1	32.7	1733	0.79	0.066
CB-2	21.35	1654	0.72	0.077
CB-3	13.75	1756	1.00	0.065
CB-4	15.05	1684	0.86	0.078

3. CASE STUDY MODEL

3.1 Description of the building design

The building model under scrutiny in this study is a self-standing four-story residential Building in the New Borg Elarab city. The building has a total height of 15 meters. The residential building's layout consists of five floors (ground, first, second, third, and fourth) which encompasses four flats. Each flat includes a living area, a kitchen, two bedrooms, and a bathroom, as listed in Table 3 with the areas. The height of each flat is 3.00 m. It is noteworthy to mention that the layout and dimensions are consistent throughout each flat. Fig. 4. shows the floor plan design of the building model. The roof of the building is a reinforced flat concrete structure with parapet walls. For a comprehensive view, the floor plan, and three-dimensional visualizations of the analyzed building from various angles are presented in Fig. 5. The design of the building was executed using DesignBuilder software version 9.4.

Table 3. Rooms listed.

No.	Room type	Area (m^2)
01	Reception	31.415
02	Kitchen	6.667
03	Bathroom	5.970
04	Bathroom 1	14.427
05	Bathroom 2	11.186

Note: Consistent through all floors

3.2 Building model for dynamic simulation

The energy simulation calculations of the building model were carried out using Design Builder-Energy Plus, which is a complex simulation tool for modeling of heating, cooling, ventilation, or lighting of buildings. This software, recognized for its advanced and distinctive graphic user interface-based energy simulation capabilities, has been employed in numerous studies [25] [26] [27].

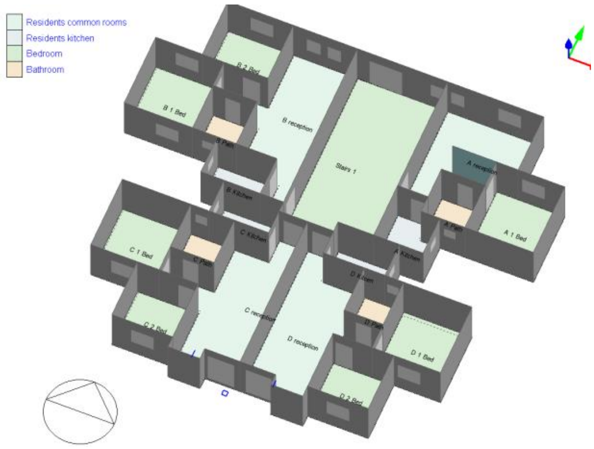

Fig. 4. Isometric Plan view of the residential building design.

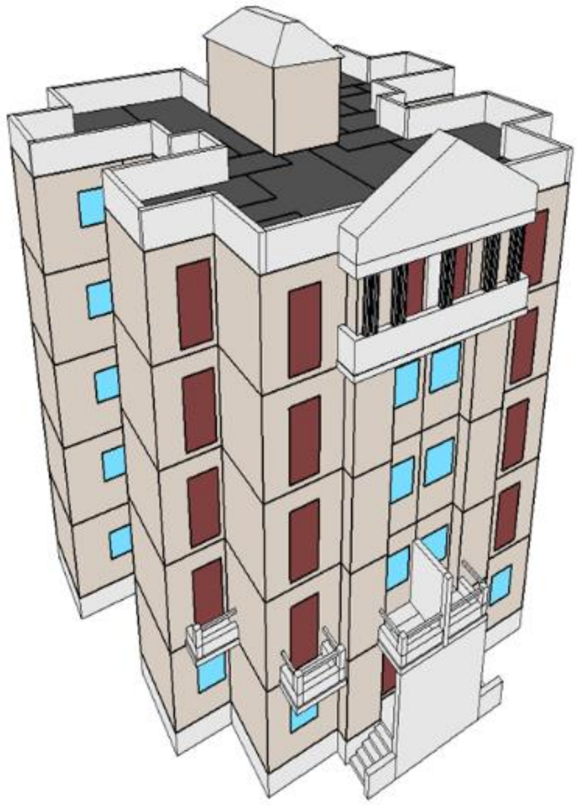

Fig. 5. Plan view and the perspective view of the residential student building design.

To demonstrate the potential benefits of using combined waste-based concrete blocks as an energy-efficient building envelope, five cases (Case 1-5) were simulated for comparative analysis. In Case 1, conventional concrete blocks without any waste materials were employed as the base case. Cases 2 to 5 involved the production of concrete blocks incorporating various waste ingredients. Construction details and specifications of the exterior walls in the building model were adjusted for each case, with experimental results serving as input parameters for the simulation process. The primary focus of the energy simulation was on the external walls of the building model, specifically examining heat transfer from the outside to the inside of the building. The simulation was performed for 12 months (from 1st January – 31st December), utilizing typical weather data available in EnergyPlus to estimate total energy consumption for heating and cooling. During the simulation process, essential settings were established, including the application of the energy code according to ENPER's internal energy code. The assumed location for the building was the city of Alexandria, Nouzha, Egypt.

Table 4. The climate information of Alexandria

City	Alexandria
Climate zone	Humid subtropical 2A
Latitude	31.20
Longitude	29.95
Elevation	7m
Extreme hot week starting	August 1
Extreme cold week starting	February 22

The building envelope consisted of four layers in all cases: the outermost layer (plaster) with a thickness of 0.001 m, a mortar layer measuring 0.02 m, concrete block layers of 0.065 m, and an innermost layer of 0.02 m. For each case, the general properties of the external block, including thermal conductivity, resistance, and density, were adjusted. Additionally, surface properties such as roughness were modified, considering variations from smooth to rough. The energy

y outputs considered during the simulation encompassed Surface Heat Transfer, Internal Gains, and Latent Loads. These factors were crucial in evaluating the overall energy performance of the building envelope and its impact on heating and cooling requirements. The simulation took 17 minutes on average to complete each case.

The following inputs (table 5) were used for the investigated blocks (CB-RF, CB-1 to CB-4). All samples thickness was 0.065 m.

Table 5. The input parameters used for energy simulation.

Case	Block	Density (kg/m^3)	Conductivity (W/m.k)	Resistance (m/W.k)
1	CB-RF	2183	1.655	0.04
2	CB-1	1733	0.793	0.066
3	CB-2	1654	0.723	0.077
4	CB-3	1756	1.001	0.065
5	CB-4	1684	0.859	0.078

4. RESULTS

The annual energy simulation outputs on the overall energy consumption of the modeled building were analyzed for comparison among the mentioned cases. Total annual readings were normalized per unit area of the external walls of the building. The overall energy consumption reflects the heating and cooling loads.

In Fig. 6, the typical concrete block without the inclusion of waste ingredients exhibits the highest energy consumption of about 114.89 kWh/m^2. Conversely, the cases with waste-based concrete blocks as the building envelope demonstrate slight reductions in the energy consumption of the walls (sum of heat gains to the zone from external wall inner surfaces). Case 2 to Case 5 shows energy consumption levels of 99.04 kWh/m^2, 96.61 kWh/m^2, 105.03 kWh/m^2, and 101.24 kWh/m^2, respectively. Case 3 achieves better energy consumption by saving 15.91% compared to the first case, which uses conventional building materials, closely followed by Case 2, which achieves energy savings of 13.80 kWh/m^2. Additionally, the results encompass heating electricity (total fuel consumption due to the operation of heat generators such as air conditioners) and cooling electricity (total chiller fuel consumption plus any fuel consumption due to DX cooling coils, air-cooled chiller condenser fans, and evaporative coolers) in relation to walls. Case 1, as illustrated in Fig. 7, exhibits the highest heating (57.68 kWh/m^2) and cooling loads (220.52 kWh/m^2) compared to the other cases. Case 3 registers the lowest heating electricity consumption at 45.07 kWh/m^2 and the lowest cooling electricity consumption at 208.96 kWh/m^2. Both Case 2 and Case 5 show relatively lower values for both heating and cooling electricity compared to Case 1, which records the highest values in both categories.

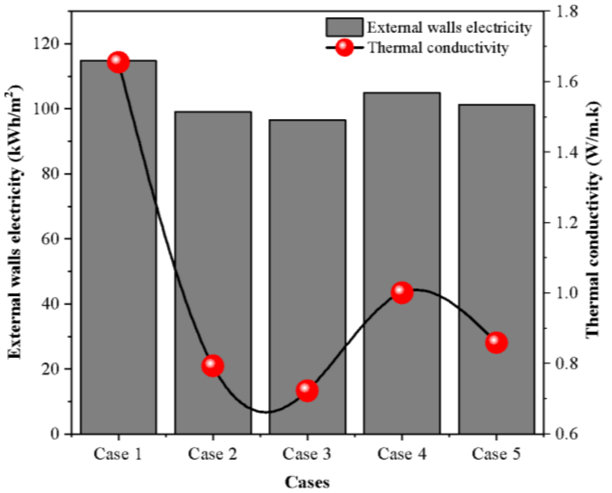

Fig. 6. Annual energy consumption of the simulation outputs.

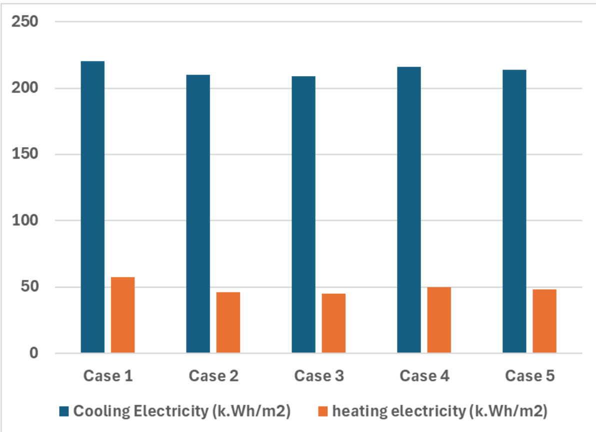

Fig. 7. Heating and cooling loads.

5. DISCUSSION

Choosing recyclable building materials is a crucial strategy for mitigating the effects of climate change and promoting energy-efficient buildings in resilient cities [28]. The inclusion of low-energy materials and those produced from recycled building waste in construction provides an opportunity for reducing overall energy consumption. The introduction of combined waste materials in our study demonstrates the potential for energy savings through the block wall, with a reduction of over 10%. This is accompanied by a decrease in heating and cooling electricity by 12.61 kWh/m2 and 11.56 kWh/m2, respectively.

Among the listed cases, Case 3 emerges as the most energy-efficient, boasting the lowest values for both heating and cooling electricity consumption. This case involves a concrete block with approximately 95% waste ingredients in its production, resulting in a reduction in dry density and thermal conductivity coupled with higher thermal resistance. The lowered energy consumption in waste-produced concrete blocks can be attributed to their thermophysical properties, particularly the low thermal conductivity. Materials with lower thermal conductivity can effectively reduce building energy consumption by influencing the heat and moisture transfer characteristics of building envelope materials [29].

The reduction in thermal conductivity, primarily through improved insulation, is a fundamental factor in decreasing energy consumption in buildings [30]. Using lightweight aggregates in concrete contributes to reducing thermal conductivity, thereby decreasing energy consumption for heating or cooling in buildings [31]. Additionally, enhancing the resistance to heat transfer in enclosing structures not only reduces transmission heat losses but also impacts the overall heat balance in residential buildings. This suggests that materials with good thermal insulation properties, combined with proper structural design, can lead to a reduction in energy consumption and an improved indoor environment.

6. CONCLUSION

This study delved into the potential of utilizing recycled waste materials as a strategy for energy-efficient construction. Initially, these recycled waste materials were incorporated as raw materials in the laboratory production of concrete blocks, and various dry properties—including density, compressive strength, thermal conductivity, and resistance—were meticulously measured. Subsequently, a case study was conducted, simulating a residential hostel facility to perform an energy simulation exercise using Design Builder to ascertain the energy consumption of these concrete block samples when employed as a building envelope. The study yielded the following conclusions.

The results highlight the significance of passive design strategies in enhancing sustainability, particularly when coupled with low-energy and cost materials. The incorporation of potential recycled materials as a viable option for energy-efficient buildings resulted in a notable reduction in wall electricity consumption, decreasing from 114.89 kWh/m2 to 96.61 kWh/m2, representing a 10% drop compared to the conventional design that utilizes typical concrete raw materials as a building envelope. Furthermore, heating and cooling electricity were reduced by 21.86% and 5.24%, respectively. The observed correlation between thermal conductivity and electricity consumption emphasizes that low thermal conductivity is associated with reduced electricity consumption and vice versa. Overall, this presents a significant benefit to occupants, allowing them to save on electricity costs and potentially reduce environmental impact. This will provide direction for more comprehensive studies to be conducted on the subject domain.

7. ACKNOWLEDGEMENT

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