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Numerical Investigation on the Energy Consumption of Buildings in Bangladesh by Incorporating Expanded Polystyrene Insulation on the Walls and Roof

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ABSTRACT

Urbanization, industry, and population growth raise energy consumption. Building construction and energy usage will rise with population expansion. Most buildings gain/loss heat through windows, ceilings, floors, and walls. This section covers roof and wall heat loss. Reducing the energy consumption of buildings could preserve energy savings. Energy uses include industrial, household, transportation, and agricultural. Heat losses in the building envelope result in energy loss. Insulators are essential for energy conservation. This work uses hollow concrete blocks and reinforced cement concrete (RCC) made of stone chips for walls and roof materials to identify effective insulation for building envelopes in Bangladesh. Commonly available and low-cost insulation Expanded polystyrene (EPS) is used to insulate the envelopes. The thermal resistance of the envelopes with EPS insulation was measured using an experimental technique. A model building's heat transfer and energy utilization are calculated using DesignBuilder software for Khulna's meteorological data. This program uses EnergyPlus as an energy simulation engine. The envelope U-value is calculated with and without EPS using Hukseflux sensors. In this research, hollow concrete block walls have 0.14 m^2.K/W and stone chip blocks have 0.17 m^2.K/W heat resistance. However, plywood-coated EPS insulators have approximately 2 m^2.K/W thermal resistance. Insulation saves 96.47% of the energy used for heating in the winter and 56.13% of the energy used for cooling in the summer. So, the addition of EPS insulation in the model building may reduce 56.57% of the energy consumption required for heating and cooling.

Keywords: Energy consumption, Resistance, EPS, Heat transfer, Envelope.

1. Introduction

Energy is utilized in various settings, including agriculture, transportation, households, and industries. Buildings consume a significant amount of energy. The energy needs are increasing due to industrialization, urbanization, and population growth. Building development and energy consumption will increase due to population expansion. Most buildings lose/gain heat through windows, ceilings, floors, and outside walls. The air releases heat from the body. This also includes heat loss/gain from the walls and the roof. Insulation, orientation, and type will all help to prevent heat loss through the building envelope. When choosing thermal insulation, factors include durability, cost, compressive strength, water vapor absorption/transmission, fire resistance, ease of use, and thermal conductivity [1]. Insulation between buildings is necessary for energy efficiency. Insulation of the building envelope is an inexpensive advantage. Inexpensive insulation might be utilized by builders and developers working within a limited budget. It may be required for initiatives that aim to save money. Several marketplaces offer insulation at a lower cost. Having those available makes it possible for builders to use them. Insulation at a low cost does not violate any building code criteria. By utilizing these items, construction companies are able to conserve energy and maintain their safety. When fuel costs are high, it makes sense to save energy. Bangladesh is experiencing fast industrialization, urbanization, and population increase, all contributing to the country's electrical issues. Both blackouts and load shedding may be reduced by energy saving. Most of Bangladesh's oil and LNG come from outside the country [2]. Efficiency lowers energy use and imports, which results in increased energy security. Traditional building materials don't provide enough thermal insulation, so extra insulation materials like solid boards, particles, and sandwiches are often added to different construction parts [3].

Berardi et al. [4] demonstrated that the relationship between temperature and conductivity is nearly linear for the preponderance of materials. This is accurate for certain petrochemical insulating materials, such as extruded polystyrene, and inorganic fiber insulations, such as rock wool and fiberglass, demonstrating diminished heat conductivity at lower temperatures. Certain materials, such as polyisocyanurate, which is present in molded foam insulations, exhibit non-linear relationships between temperature and conductivity. Using COMSOL Multiphysics software, Ayed et al. [5] analyzed a heat transfer to simulate the variation of the inner temperature of a hollow brick that is EPS insulated. This could be accomplished by inserting EPS into the facade coating mortar or through the voids of the brick. Expanded polystyrene allows for improved thermal insulation in the materials used in construction. Numerical research has identified practical techniques for incorporating EPS into hollow bricks. The effectiveness of EPS in construction materials was evaluated numerically, and the results

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demonstrated that hollow bricks containing EPS had much better thermal performance.

A thermal insulator made of jute was developed by Samanta et al. [6]. Compared to glass wool and nitrile rubber, the insulation provided by four needle-punched jute felt folds with a 500 g/m2 density was substantially superior to 341 m^2 K/kW. For the purpose of thermal insulation, four-fold jute felt was 18.1 mm thinner than glass wool (25.0 mm), rock wool (50 mm), and polyurethane sheet (23.1 mm). The most significant drawback of jute insulation is its transitivity. It is a brief life. The frequency and cost of repairs are both high. Multiple researchers have examined using insulation to measure energy usage in cold and hot climates. Several studies have found that adding insulation to building envelopes benefits both climates. However, Bangladeshi climatic conditions have yet to be studied for EPS insulation. EPS is lightweight yet durable. Unlike other materials, EPS can resist moisture absorption, which prevents the loss of its insulating properties in humid environments. Because of its adaptability, gaps, and thermal bridges that could impair the effectiveness of insulation can be minimized by precision design and installation. Besides that, some drawbacks are associated with EPS, an artificial plastic foam substance. If not adequately managed, non-biodegradable EPS causes long-term waste and microplastic contamination. It recycles poorly due to contamination and processing issues. Despite its advantages, we should consider sustainable disposal and alternative materials to minimize environmental impact. Based on Bangladesh's climate, this study examines the energy usage of insulation-enhanced buildings hourly, daily, monthly and annually.

2. Methodology

The specific aims of this study encouraged the use of insulation to generate and obtain adequate solutions for enhancing the energy performance of the evaluated building. Furthermore, all processes were interconnected, and there are 2 stages to assess energy consumption.

2.1. Experimental Measurement of Thermal Resistance

The thermal resistance of envelope samples was evaluated utilizing an experimental setup as shown in Fig. 1. The experimental setup consists of a wooden chamber placed in an air-conditioned room maintained at 25°C. The specimen of the building envelope was fixed on one side of the chamber, and the other sides were insulated. The inside of the chamber is maintained at a constant temperature of 44.5°C using a heater with a thermostat. This allows heat to flow through the test specimen from inside to outside of the chamber. A thermal resistance measurement sensor, TRYS01, was used to assess the thermal resistance of experimental materials, such as walls or roofs. Hukseflux's TRYS01 technology detects thermal resistance on-site with great precision. The measurement system is founded on ASTM C1155/C1046 and ISO 9869. The experimental structure will have sensors mounted on envelope samples to measure indoor and outdoor temperatures. Data loggers collected temperature and heat flux data. The data logger was connected to a laptop for monitoring. The basic formula for heat conduction (Fourier's Law) in steady-state, one-dimensional heat transfer is:

$$Q = kA\frac{\Delta T}{d} \tag{1}$$

Here, Q = heat transfer rate (W)
k = thermal conductivity of the material (W/mK)
A = Cross-sectional area of the material (m^2)
ΔT = temperature difference across the material (K)
d = thickness of the material (m)

The amount of heat transferred per unit area is known as heat flux (q),

$$q = \frac{Q}{A} \tag{2}$$

Rearranging for Q:

$$Q = q \cdot A \tag{3}$$

Now, substitute Q = q·A into the equation for thermal resistance R for a unit area,

$$\frac{R}{A} = \frac{\Delta T}{Q} \tag{4}$$

$$\Rightarrow R = \frac{\Delta T . A}{q . A}$$

$$\Rightarrow R = \frac{\Delta T}{q} \tag{5}$$

The thermal resistance is calculated using the Eq. (5),

$$R = \frac{\Delta T}{q} \qquad m^2 . \frac{K}{W}$$

Here, ΔT = temperature difference, K
q = Heat flux, W/m

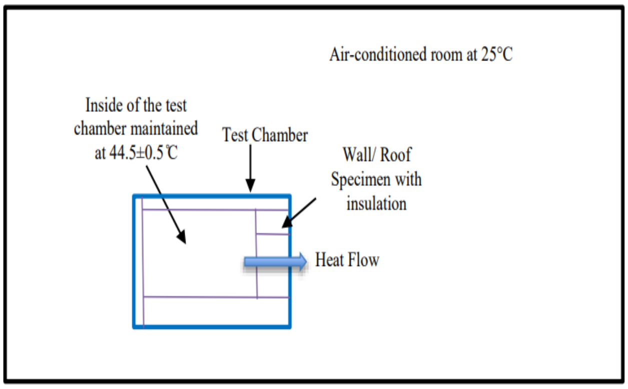

Fig. 1 Experimental set-up for the measurement of thermal resistance.

Then, the measured R-value was used to calculate the thermal transmittance (U-value) using Eq. 6.

$$U = \frac{1}{R} \tag{6}$$

Expanded polystyrene (EPS) insulation is used to increase envelope thermal resistance. Use affordable, readily available materials to insulate walls and roofs to save energy. The envelope thickness and resistance determine energy savings. Table 1 shows thickness and resistance measurements for wall and roof samples. The thermal conductivity of EPS is typically between 0.030 and 0.040 W/m·K [7], and thermal resistance is 0.69 m^2K/W for 0.025m thickness [8].

The insulator is installed inside the wall and roof, as shown in Fig. 2(a,b), and then covered with plywood afterward.

Fig. 2(a) shows the cross-section of the wall structure. It consists of a hollow concrete block with a thickness of 102 millimeters as a wall material and a layer of expanded polystyrene (EPS) with a thickness of 25.4 millimeters as an insulating material. A cover made of 18mm plywood is used to preserve the interior design and EPS from any possible harm.

Table 1 Envelope and Insulation thickness with resistance.

Type	Thickness (mm)	Insulation Type	Insulation Thickness (mm)	Resistance ($m^2 K/W$)
Hollow Concrete Block wall	127	-	-	0.14[8]
Hollow Concrete Block wall with insulation	127	EPS + Plywood	25.4 + 18	2.06
Stone Chips RCC roof	106	-	-	0.17[8]
Stone Chips RCC roof with insulation	106	EPS + Plywood	25.4 + 18	2.91

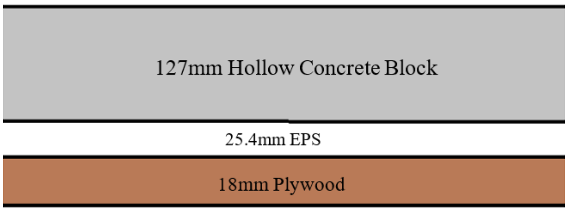

Fig. 2(a) Cross-section of insulated building Wall

Fig. 3(b) shows the cross-section of the roof. It consists of a Reinforced Cement Concrete (RCC) made of stone chips as a roof material with a thickness of 106 mm and a layer of EPS with a thickness of 25.4 mm as an insulating material. A layer of 18 mm plywood is used to avert damage to the EPS.

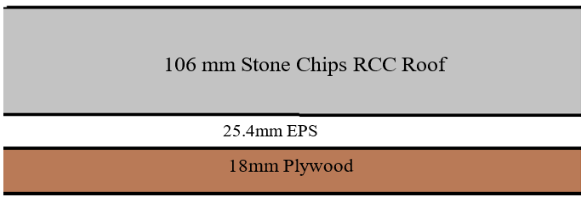

Fig. 2(b) Cross-section of insulated building roof

Ordinary Portland Cement (OPC) Concrete, Ready-Mix Concrete (RMC), and Fly Ash Concrete are the most frequently used concrete varieties in Bangladeshi construction. However, the thermal resistance of the envelopes of these concretes is not very efficient. Hossain [8] investigated some roof and wall samples. The research examined the thermal efficiency of burnt clay brick walls, 10 holes perforated brick walls, solid concrete block walls, hollow concrete block walls and, roof samples, brick chips roofs, stone chip roofs, hollow core roofs. The selection of hollow concrete block wall was based on its outstanding heat resistance and stone chips. RCC roof was chosen for its durability, lightweight, and appropriateness for residential use. Besides thermal resistance, these two samples will occupy less space in the room due to their slender thickness.

2.2. Simulation Procedure

The thermal performance of the experimental samples was analyzed numerically using the building energy simulation software Design Builder, which conducts parametric simulations with the help of the EnergyPlus program. The Building and Technology Programme of the Energy Efficiency and Renewable Energy Office supports Energy Plus, a US Department of Energy-developed, modular, and structured software program. It takes its foundation from the widely used BLAST and DOE-2.1 tools. EnergyPlus's integrated simulation includes simultaneous loads and systems, and accurate temperature and comfort predictions are possible. The program is famous for its ability to predict energy consumption, calculate loads, assess building performance, and maintain thermal and mass balances [9]. DesignBuilder, created by DesignBuilder Software Ltd. [10], is a user interface using the EnergyPlus engine for simulation [11]. Energy, carbon, lighting, comfort, load calculation, building performance, heat balance, and mass balancing of buildings are some of its many global applications [12]. Using a variety of fast and cost-effective analyses based on function and performance (such as the transfer function and the finite difference approach), DesignBuilder may evaluate many building designs.

To calculate the building's energy consumption, the geometry of a typical building was drawn, and opening data, HVAC system data, activity data, construction data, lighting data, and weather data were loaded into this software.

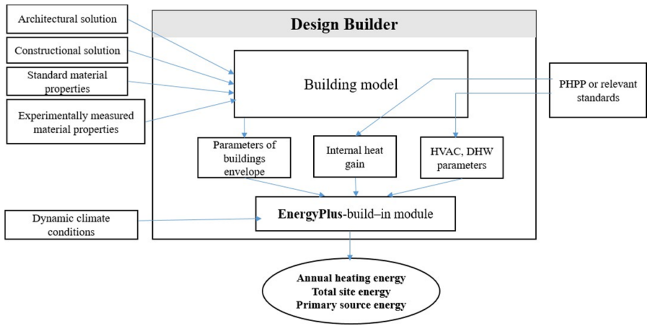

Fig. 3 DesignBuilder simulation flowchart [13].

EnergyPlus is a whole-building simulation tool. It enables modeling energy flows such as water use, lighting, ventilation, heating, cooling, and other energy fluxes. EnergyPlus is a standalone simulation program without an intuitive graphical user interface, so its integration into the Design Builder environment enables simulations to be carried out quickly and efficiently while defining the building model and input parameters, which were pre-calculated following a PHPP model. A flowchart of the DesignBuilder simulation procedure is shown in Fig. 3.

The location of Khulna has been chosen for this research. The Khulna weather file is collected from Climate.OneBuilding.org. To facilitate building simulations, this website provides climate data tailored to that purpose. Consequently, the data are published by several organizations and are known as Typical Meteorological Years (TMY). The Medical Center of Khulna University of Engineering & Technology (KUET) is selected as the model building for simulation. KUET Medical Center is located on the west side of campus. Walls, roofs, floors, doors, and windows determine heat transmission between interior and outdoor environments. The information on the building is given in Table 2. Simulation-based building energy analysis needs several parameters and building envelope data to avoid errors.

Table 2 Description of the building.

Characteristics	Description of the Building
Location	Khulna, Bangladesh
Floor area	1000.6 m^2, two elevations
Volume	3396.1 m^3
Ceiling height	3.5 m
Occupancy	0.0109 people/m^2

Alterations were made to the summer and winter HVAC schedules in order to operate the heating and cooling activity properly. Throughout both seasons, the temperature of 25 was maintained for thermal comfort.

Table 3 Heating Cooling Schedule

Season	Time of Day	HVAC
Summer	9 am to 5 pm (5 days of a week)	Cooling
Winter	9 am to 5 pm (5 days of a week)	Heating

3. Results and Discussion

The use of EPS increases thermal resistance. A hollow concrete block wall offers higher thermal resistance, so concrete walls are the material of choice when building in Bangladesh.

Fig.4 shows yearly heat transmission for insulated and non-insulated roofs. A positive value indicates that heat enters the room due to a temperature differential between the room and the outside surroundings. A negative value indicates that the room expels heat to the environment due to the room temperature exceeding that of the environment. Winter heat loss occurs from October to February and gains from March to September. The roof could present a distinct temperature gradient compared to the walls, notably due to solar gain on the roof during the day, especially in March, when the sun's angle begins to rise. During the morning or afternoon, the roof may collect solar radiation, resulting in an external air temperature at the roof that exceeds the inside temperature of the building. In this instance, thermal energy may transfer into the structure from the roof. When heat enters the building, the heat transfer value is often positive. Without insulation, December showed the highest heat loss of 2626 kWh. May has 6081 kWh more heat gain. Insulators reduce heat gain and loss from the roof by 79.04% annually. In addition, summer and winter heat transmission

The fluctuation is under +1100 kWh and -480 kWh, respectively, compared to +6000 kWh and -2600 kWh before insulation was installed. Insulation material reduces year-round heat transfer fluctuation.

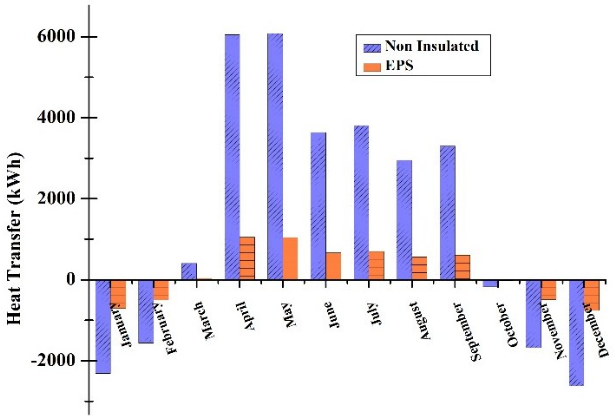

Fig.4 Heat transfer through insulated and non-insulated roofs in summer and winter.

Fig. 5 illustrates the annual heat transmission of insulated and non-insulated walls. October through February loses heat, and March through September gains it. Depending on location and time, the morning or evening temperature of the outside is colder than the inside temperature in March. Heat will escape via the walls if the outside temperature is lower than the inside. Insulation-free January heat loss is 2948.34 kWh. May had 8198.35 kWh of heat gain. An insulator reduced annual heat transmission by 69.61%, making the building less heat-conductive. After using the insulator material, summer and winter heat transfer fluctuations are now under +1900 kWh and -100 kWh, respectively, compared to +8100 kWh and -2945 kWh.

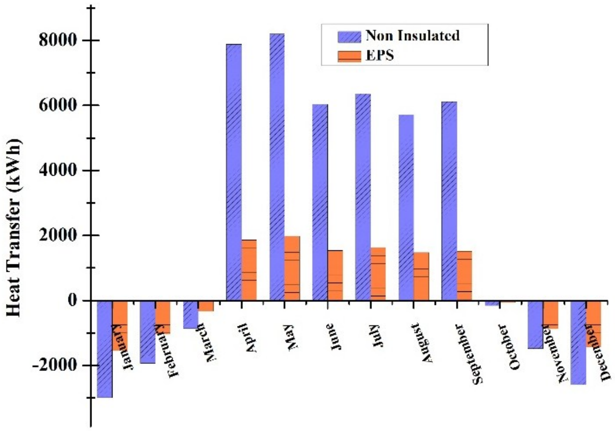

Fig. 5 Heat transfer through insulated and non-insulated walls in summer and winter.

Fig. 6 and 7 show heat transfer on a sunny May 12th summer day. Day-to-day fluctuations in heat transfer are quite small. Insulated envelopes decrease heat transfer into and out of the space, improving thermal stability. Fig. 6 indicates that heat transmission in a non-insulated envelope can reach +45 kWh in the afternoon and -2 kWh at night. Envelopes without insulation allow more heat to enter during the warmest portion of the day and exit during cooler hours.

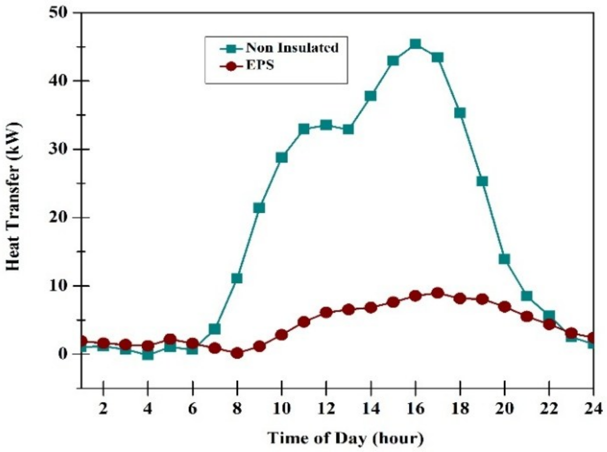

Fig.6 Heat transmission through the wall on a typical day in May

Heat entering through non-insulated envelopes increases between 6 AM and 6 PM, peaking at 15-16 in the afternoon when the outside temperature is likely maximum. After 6 PM, the heat transfer for non-insulated envelopes decreases and becomes negative, suggesting that they lose heat to the outside when the exterior temperature lowers.

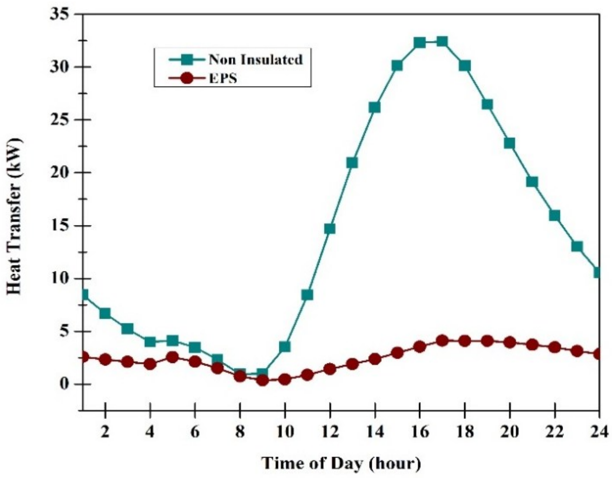

Fig. 7 Heat transmission through the roof on a typical day of May

Fig 8 and 9 show the heat transfer from the envelope occurring on December 28. This day is foggy. There is a large amount of heat loss from the inside to the outside during the early morning hours (e.g., 1-8 AM) when the heat transfer is strongly negative, with values reaching approximately -17.5 kWh. The natural convection current from a warmer inside to a cooler exterior makes this sound like a chilly day outside. The heat transfer through the uninsulated envelopes starts negative before 10 AM. It progressively turns positive between 10 AM and 5 PM, reaching a high of about +10 kWh at 2 PM. This change indicates that heat is entering the area, which increases the inside temperature as the day advances and the outside temperature rises. Once again, the heat transfer turns negative around 6 o'clock. The precipitous decrease in outside temperatures in the afternoon leads to heat escape from the building's interior through the uninsulated envelopes. Compared to the non-insulated envelope, the insulated one exhibits negligible heat loss in the early morning (slightly negative readings).

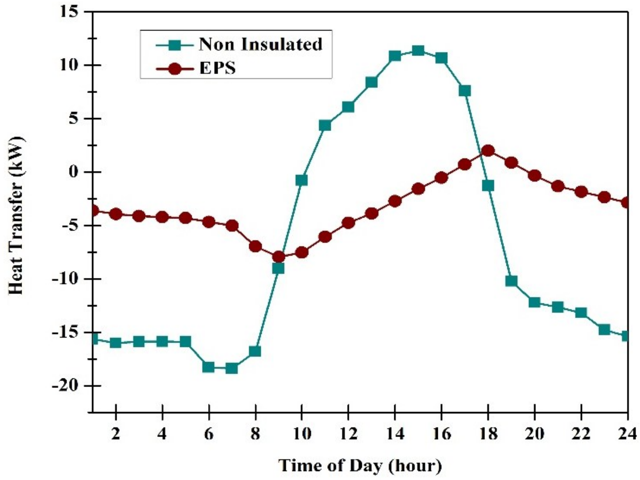

Fig. 8 Heat transmission through the wall on a typical day in December

The EPS-insulated envelopes exhibit significantly less heat uptake (positive values) during the day when external temperatures rise than the non-insulated envelope.

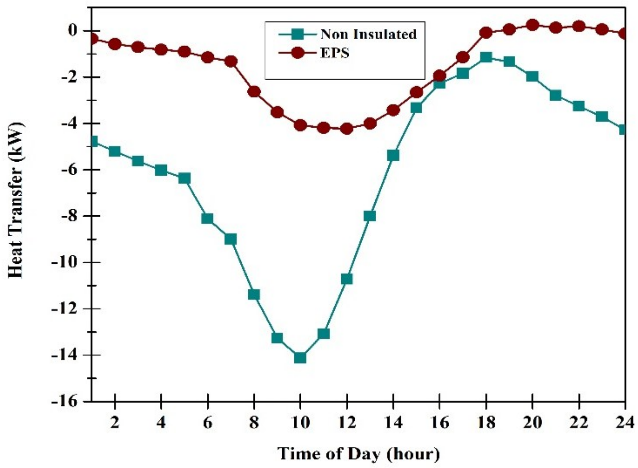

Fig. 9 Heat transmission through the roof on a typical day in December

In Fig. 10, heating energy usage decreases in non-insulated and EPS-insulated conditions in January, February, November, and December. This means these months' outdoor temperatures stay around 25°C, reducing heating needs. As temperatures climb from March to September, cooling becomes the main energy consumer. April to September are peak months for non-insulated building energy usage, frequently exceeding 7000 kWh. The high demand suggests thermal efficiency issues, requiring more energy to maintain 25°C indoor temperatures. EPS-insulated buildings use less energy during these months. EPS insulation reduces cooling demand by minimizing heat exchange with the outside. The outside temperature is frequently high in March and October, close to 25°C. These two months are regarded as the transitional period between summer and winter. There is no need for significant heating or cooling to reach a reasonable inside temperature because the outside climate is already favorable. Winter energy consumption for heating in the non-insulated envelope is 946.53 kWh, while its summer energy consumption for cooling is 86433.84 kWh. For the insulated envelope, the energy consumption during the winter is 33.44 kWh for heating and 37921.64 kWh for cooling. Insulation saves 96.47% of the energy used for heating in the winter and 56.13% of the energy used for cooling in the summer. With insulation, the energy consumption per unit floor area of the building is 40.91 kWh/m², while without EPS, it is 94.2 kWh/m². EPS insulation has the potential to reduce energy consumption for heating and cooling by as much as 56.57%. This significant savings highlights its effectiveness in enhancing energy efficiency.

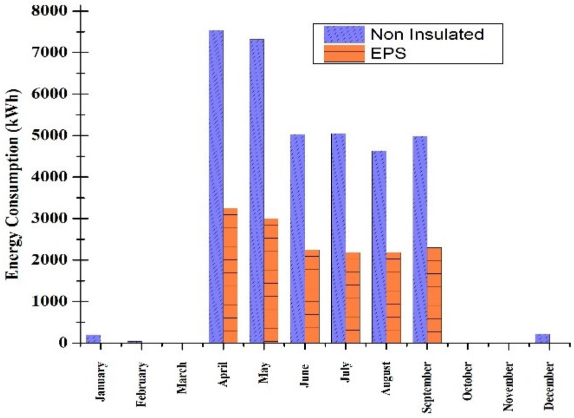

Fig. 10 Monthly energy consumption for heating and cooling

4. Conclusion

This study examines a hollow concrete wall and a stone-chip RCC roof, insulated with EPS, in Khulna, Bangladesh. This research aims to calculate the total energy consumption and heat transfer for these kinds of structures. Results show that using EPS significantly decreases heat transmission through building walls and roofs. When EPS is used in summer, the heat sent through the roof is reduced by 82.07%, and the amount transmitted through the wall is reduced by 75%. In contrast, the roof loses 69.19% during winter, while the wall experiences a drop of 47%. Insulation saves 96.47% of the energy used for heating in the winter and 56.13% of the energy used for cooling in the summer. The addition of EPS insulation in the building model may reduce energy consumption for heating and cooling by 56.57%. Because of this, EPS is a practical approach for lowering energy use at a low cost, which is an important economic consideration. Better inside temperature stability results from the EPS insulated wall's capacity to maintain relatively constant heat transmission, with few gains or losses.

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NOMENCLATURE

R : thermal resistance, m^2.K/W
ΔT : temperature difference, K
q : heat flux, W/m^2
U : thermal transmittance, W/m^2.K
Q : heat transfer rate, W
d : thickness of material, m
A : Cross-sectional area, m^2
k : thermal conductivity, W/m.k