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Enhancing Thermal Performance of Hollow Bricks with Wheat Straw

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One method for reducing a building's carbon footprint is to use bio-based construction materials capable of passively adjusting thermal performance. Extensive construction using cement hollow blocks creates energy concerns due to their inherent low thermal insulation. This study explores the potential of wheat straw, a readily available agricultural residue, as a sustainable insulation material for these blocks. Straw, a common agricultural byproduct, is being studied for its potential as a new type of insulation. Four test walls were constructed: one with no insulation and three with varying compacted wheat straw densities. Heat flow measurements revealed significant reductions (82.80–38.95%) in insulated walls compared with the non-insulated wall, highlighting the effectiveness of wheat straw insulation. Further analysis confirmed improved thermal performance with decreasing U-value (heat transfer rate) and increasing R-value (thermal resistance) in insulated walls. Notably, the highest compaction density (82.80% energy saving potential) demonstrated the greatest significant improvement. These findings suggest that wheat straw presents a promising, eco-friendly solution for enhancing the thermal insulation of cement hollow blocks, potentially leading to significant energy savings and environmental benefits in the construction sector.

Keywords: wheat straw, thermal resistance, hollow brick, construction material.

Introduction

The escalating energy demands of buildings pose a formidable challenge, calling for innovative solutions. Passive thermal management strategies, such as enhanced building envelope insulation, are emerging as crucial tools for sustainable building design. The ever-increasing global energy demands pose significant challenges, including resource depletion, environmental degradation, amplified greenhouse gas emissions, and disruptive ecological crisis. Minimizing energy consumption is paramount to address these problems. The Global Status Report for Buildings and Construction reported that the buildings and construction sector is a significant contributor to global climate change, accounting for 21% of global greenhouse gas emissions. In 2022, this sector consumed 34% of global energy demand and emitted 37% of energy and process-related CO_2 emissions (Platt et al., 2020; Walker et al., 2020).

Furthermore, renovation and building-related tasks are criticized for their resource-intensive nature, consuming significant amounts of energy and materials, degrading environment and generating substantial waste. India is not an exception, facing severe environmental challenges, particularly regarding air and water pollution. Notably, the energy consumption of their building sector reportedly outpaces the worldwide average. The Bureau of Energy Efficiency of Government of India has reported that India's rapidly growing building sector, consuming over 30% of the nation's electricity, demands urgent energy optimization (BEE, n.d.). With a significant portion of future building stock yet to be constructed, there is a pressing need to minimize energy consumption in both new and existing buildings.

India is the third-largest global emitter of CO_2, despite low per capita CO_2 emissions. The carbon intensity of its power sector in particular is well above the global average. Additionally, particulate matter emissions are a major factor in air pollution, which has emerged as one of India's most sensitive social and environmental issues. In 2019, there were well over one million premature deaths related to ambient and household air pollution. Improving the insulation properties of buildings is one of the key strategies employed to reduce energy consumption for air conditioning, cooling, and heating (Rabbat et al., 2022; Ramukevicius et al., 2021). High-performance thermal materials for insulation serve an essential contribution in achieving improved energy savings. Building materials significantly impact global efforts towards energy conservation and environmental protection by performing exceptionally well during the operation phase. Eco-friendly buildings incorporate various systems and construction materials characterized by their natural origin, renewability, accessibility, and health benefits. Utilizing locally available natural and renewable resources like agricultural residues in construction offers numerous advantages (Rojas et al., 2020; Koh and Kraniotis, 2020a, 2021b). Their simulation results indicate that incorporating an air chamber within the straw module is the most effective strategy for reducing heat transfer. This finding supports the use of straw as sustainable building material, especially in rural areas, promoting innovative and environmentally friendly construction solutions.

However, the issue of inappropriate agricultural waste disposal remains pervasive. Fortunately, a readily available solution lies in fiber-rich agricultural waste, a material already extensively employed in global construction. Prevalently burned, this waste represents a lost opportunity (Scrucca et al., 2020; Thomson et al., 2021). The Food and Agriculture Organization estimates that in 2017 alone the burning of wheat and rice paddy residues amounted to a staggering 92 Mt and 87.5 Mt, respectively. India, for instance, generated an average of 521 Mt of agricultural residue annually, with rice and wheat contributing 121 Mt and 114 Mt, respectively. The use of straw in construction extends far back into prehistory. Straw fibers served as a vital reinforcement material for mud and clay in structures dating back to the pre-Harappan era (before 3500 BCE) of the Indus Valley civilization (Tlaiji et al., 2022a; Tlaiji et al., 2022b).

Building materials are among the most crucial considerations when it comes to energy conservation and environmental preservation. Natural, renewable, widely accessible, and healthful systems and building materials are used in the development of environmentally friendly structures. There are several benefits to ecology and human health when natural and renewable resources, including agricultural leftovers, are used locally as construction materials (Li et al., 2020). Prior research has provided evidence of the use of a variety of environmentally friendly substances for structural thermal insulation. Additionally, according to records, the thermal conductivity values of various agricultural leftovers, such maize husk and wheat straw, range from 0.046 to 0.047 W/mK. These values are comparable to those of several artificial insulations, such as mineral wool (0.040 to 0.045 W/mK), extruded expanded polystyrene (0.037 W/mK), molded expanded polystyrene (0.037 to 0.055 W/mK), and polyester (0.035 W/mK) (Walker et al., 2020).

Wheat straw is one of the most widely used agricultural wastes. It is an inexpensive, readily available natural product that is frequently burned in open fields as a yearly event that increases emissions of carbon monoxide, carbon dioxide, and nitrogen oxide. Straws have a long history of usage in construction as insulation because of their low density, porous structure, and better heat-insulating qualities (Yang et al., 2021; Abanomi, 2021).

A comparative study was conducted by Ahmadi et al. (2020) to assess the potential energy-saving benefits of wheat straw insulation in fired clay hollow bricks. Their findings revealed a substantial reduction in heat transfer through the straw-filled walls. Specifically, straw filled walls exhibited heat flow reductions of 41.23%, 30.45%, and 69.24%, respectively, compared with the normal wall.

The high silica content of straw prevents it from decomposing, and its long fibers make it useful for building homes. Furthermore, the geographic distribution of natural resources affects their availability, which is a significant factor in determining the mix of building materials and natural insulation used in structures (Marques et al., 2020). Previous studies have investigated the use of agricultural waste-filled hollow bricks as an effective insulation strategy. By incorporating these materials into hollow brick structures, Xie et al. (2022) have observed significant reductions in overall heat transfer coefficients. For instance, studies have shown that filling hollow bricks with rice straw can reduce the heat transfer coefficient by up to 32.7%, leading to improved thermal performance and energy efficiency (Xie et al., 2022).

Previous studies have explored diverse natural and renewable materials for building demonstrating their superior performance compared with conventional materials. The potential of incorporating straw bale insulation within cement hollow bricks as a building material, particularly its impact on reducing building energy consumption, remains largely unexplored.

This study focuses on investigating the potential of wheat straw as a sustainable thermal insulation material by filling concrete hollow bricks with varying compaction densities. The thermal conductivity and resistance of filled bricks will be evaluated to assess their effectiveness. Additionally, the potential environmental benefits associated with building insulation, such as fuel savings, cost reductions in energy, and pollution mitigations, are determined. This research contributes to the development of sustainable construction practices by promoting the utilization of natural, renewable materials for enhanced building energy efficiency.

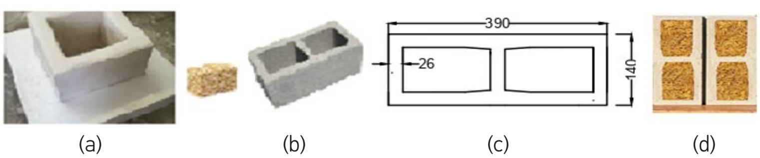
Methodology and Experimentation

To determine the influence of compacted wheat straw density on thermal conductivity, a test rig was constructed with four identical external side walls as shown in *Fig. 1*. These walls were built from cement hollow bricks detailed in *Table 1*, which presents the specifications of four walls (W1, W2, W3) filled with compacted wheat straw at varying densities and one control wall (W4) comprised of empty hollow bricks with no straw. Each brick measured 390 mm x 140 mm x 140 mm and contained two internal chambers measuring 88 mm x 78 mm x 110 mm.

Wheat straw compaction

To establish different compaction levels, first, wheat straw was loosely packed into the chambers of two identical cement hollow bricks, representing an uncompacted state. This initial loading aimed to simulate a minimal density scenario. Subsequently, the straw was reloaded into the chambers, this time subjected to maximum manual pressure, resulting in a maximum compaction state. This represented the highest achievable density within the given constraints. After each loading, the straw was carefully extracted, and its mass was measured for each chamber individually to account for potential variations. The mass of extracted

Fig. 1. *a – test chamber walls; b – straw bell and brick; c – hollow brick details; d – brick filled with straw*



straw from each chamber was measured individually, resulting in average masses of 37.7 g (uncompacted) and 94.37 g (maximum compaction). An intermediate compaction level of 65.5 g was established by averaging the previous measurements.

Brick preparation

Three distinct compaction levels (uncompacted, medium, and maximum) were achieved within the bricks by utilizing wheat straw masses of 37.7 g, 67.9 g, and 94.37 g, respectively. Corresponding straw densities within the chambers were calculated as 50 kg/m^3, 90 kg/m^3, and 125 kg/m^3 based on the known chamber volume.

Table 1. *Specifications of four walls of a test rig*

Sr. No	Cement brick wall with a high compaction straw (W1) wall	Cement brick wall with a moderate compaction straw wall (W2)	Cement brick wall with a low compaction straw wall (W3)	Cement brick wall with no straw wall (W4)
Straw density (kg/m^3)	125	90	50	–
Size of wall (mm)	780x560	780x560	780x560	780x560

Durability of straw blade insulation

Straw-based insulation, when properly installed and protected from excessive moisture, can offer long-term durability comparable to traditional materials like mineral wool or fiberglass. While traditional materials may have a longer lifespan under ideal conditions, straw-based insulation, when treated with appropriate fire retardants and moisture barriers, can provide decades of effective insulation.

Test rig construction

The test rig comprised 32 bricks bonded together using a sand-cement mortar. To minimize heat transfer, the corner cavities were filled with polystyrene, and the bottom and top were insulated with 15-cm thick polystyrene sheets. The final dimensions of the model were 780 mm x 560 mm x 560 mm (length, width, height), and it was maintained under controlled temperature conditions within a dedicated indoor environment.

Temperature measurement techniques

The tests were conducted inside the laboratory under three different heat input conditions (1000 W, 1500 W, 2000 W) after the system was normalized. A data logger thermometer (TM-531RH) equipped with thermal surface sensors was employed to record the internal (Ti) and external (Te) surface temperatures of the walls at 5-minute intervals for the duration of three hours. A distinct thermometer (TV-740) was utilized to gather data for calculating the U-value.

The tests were also conducted over a 15-day period (1/05/2023 to 15/05/2023) in an open environment to monitor variations in wall temperatures. A data logger thermometer with thermal surface sensors was used to record the internal (Ti) and external (Te) surface temperatures of the walls every 10 minutes.

Thermal transmission coefficient (U-value)

The U-value, measured in $W/m^2 \cdot K$, quantifies a wall's ability to resist heat transfer. This study employed a U-value meter (KIMO TM-210 U-kit) to assess heat loss during separate testing periods of three hours each. A wall with a lower U-value is believed to provide better insulation.

Thermal resistance (R-value)

Thermal resistance (R-value) is the reciprocal of U-value. It is expressed in $m^2 \cdot K/W$. It is determined via *Equation (1)*:

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

where R represents thermal resistance and U is the thermal transmittance ($W/m^2 \cdot K$).

Heat flux (q)

Heat flux (q), representing the thermal energy flow per unit area and time, was measured using four TM-947SD sensors and a separate TM-210 thermometer over three hours and three replications. *Equation (2)* was employed to calculate the overall heat flow through the walls, incorporating both internal and external surface temperatures.

$$q = U(Ti - Te) \tag{1}$$

Testing in an open environment without heaters

The test rig was located on the rooftop of a four-story structure at the Abhinav campus in Wadwadi, India. The studies were carried out between April and May, when the environment experienced hot conditions. The testing chamber was arranged per the geographical axes. The data were gathered over ten days in the entirely enclosed experiment chamber.

Environmental considerations and energy savings

This study assessed the potential reduction in pollutants, energy savings, and cost savings associated with the investigated model. Equations (3) and (4) were used to calculate energy savings (S) and energy savings ratio (SR) based on the measured heat flow (q) through the insulated and non-insulated walls (W/m²). Additionally, equation (5) was employed to determine the total annual energy savings for a hypothetical building with a specified surface area (A).

$$S = q1 - qi \quad (3)$$

$$SR(\%) = [(q1 - qi)/q1]\ X\ 100 \quad (4)$$

$$S1 = AS \quad (5)$$

Cost savings

This analysis explored the potential cost savings associated with wheat straw insulation in cement hollow bricks, considering the entire energy chain from power generation to household consumption. Thermal power plants, the workhorses of electricity generation, have an inherent limitation. They typically convert only 30% to 40% of the energy from their fuel source (like coal or natural gas) into usable electricity. The remaining energy escapes as heat, highlighting the importance of efficiency. Electricity does not travel flawlessly from power plants to our homes. Transmission and distribution lines experience energy losses due to resistance and other factors, typically ranging from 8% to 15%. To account for both power plant inefficiencies and transmission/distribution losses, we considered the most conservative values: 30% efficiency for power plants and 8% loss during transmission/distribution. This combined efficiency translates to roughly 27.6%. A 1500 square feet typical house with a wall surface area of 1600 square feet through which energy exchange takes place was considered for estimation of cost savings.

Life cycle assessment

A life cycle assessment, or LCA, is a methodology used to assess how a process or product affects the environment at every stage of its life cycle, from the extraction of raw materials to the disposal of the product at the end of its useful life. Here, clay hollow bricks and cement bricks packed with straw were contrasted. For the life cycle assessment, straw filled hollow cement bricks were reviewed with clay fired hollow bricks. Agricultural straw-based insulation offers a lower 25-year life cycle cost (150 RMB/m²) compared with insulation derived from municipal and industrial solid waste, as well as traditional materials like XPS, EPS, PU, PF, perlite, rock wool, and glass wool (Zhao et al., 2022). To assess the environmental impact of clay versus cement brick walls (1 m x 1 m), a SIMAPRO life cycle analysis was conducted by (Raihan et al., 2023) across seven categories: climate change, ozone depletion, acidification, eutrophication, human toxicity, and photochemical oxidation. The analysis concluded that cement brick walls had a lower overall environmental impact.

1. *Raw material acquisition.* Clay bricks require energy-intensive processes and cause significant environmental damage. Straw-filled cement bricks use agricultural waste, consume less energy, and have a minimal environmental impact (Jonnala et al., 2024).
2. *Manufacturing process*. Clay brick production is energy-intensive, requiring water for mixing and curing, and causing air pollution. Straw-filled cement bricks are less energy-intensive, use less water, and have minimal emissions.
3. *Construction and use.* Clay bricks use traditional construction methods and may require energy-intensive heating and cooling systems. Straw-filled cement bricks use innovative techniques and offer excellent thermal insulation, reducing energy consumption.
4. *End-of-life.* Clay bricks can be recycled or reused but may end up in landfills. Straw-filled cement bricks are biodegradable, and the cement component can be recycled.

Applying wheat straw insulation on a larger scale

Scaling up wheat straw insulation involves addressing key challenges. Standardized installation practices, strict fire safety measures, and effective moisture and pest control are crucial. Compliance with building codes and reliable supply chains are essential. Cost-benefit analyses and public awareness campaigns can promote its adoption, ultimately contributing to a more sustainable and energy-efficient built environment. By addressing these challenges and promoting the benefits of straw-based insulation, it is possible to scale up its use in commercial and residential construction, contributing to a more sustainable and energy-efficient built environment.

Results and Discussion

Performance of straw for heat transfer

Figs. 2 to *5* show wall temperature variation for various tests. Across three test runs, the external temperature variance between walls W1, W2, W3 and W4 ranged from 4°C to 6°C. The heat transfer values for walls W1, W2, W3, and W4 during the tests were 1.419, 2.739, 5.016, and 8.217 W/m^2, respectively. Notably, W4 exhibited the highest thermal conductivity, while W1 demonstrated the lowest. This indicates that W1 offered the greatest resistance to the heat flow.

As observed in *Fig. 4*, wall W4 experienced the highest heat loss during Test 3, while W1 displayed the lowest during Test 3. This further emphasizes the superior thermal performance of W1. The slope of the exterior temperature curves in *Figs. 2*, *3*, *4*, 5 for the insulated walls (W1, W2, and W3) is consistently shallower compared with the non-insulated wall (W4). This reinforces the effectiveness of wheat straw insulation in reducing heat transfer through the walls. Furthermore, the shallower slope observed for W1 compared with W2 and W3 suggests that a higher degree of straw compaction translates to enhanced thermal performance. Wall W4, with an average U-value of 2.32 W/m$^2\cdot$ K and the R-value of 0.431 m$^2\cdot$ K/W, exhibited the highest heat loss and, consequently, the poorest thermal performance. Conversely, wall W1, with an average U-value of 0.41 W/m$^2\cdot$ K and the R-value of 2.43 m$^2\cdot$ K/W, demonstrated the lowest heat loss and, hence, the superior thermal performance. This signifies the positive correlation between straw compaction and thermal insulation efficiency.

Fig. 2. *Wall surface temperatures during test 1*

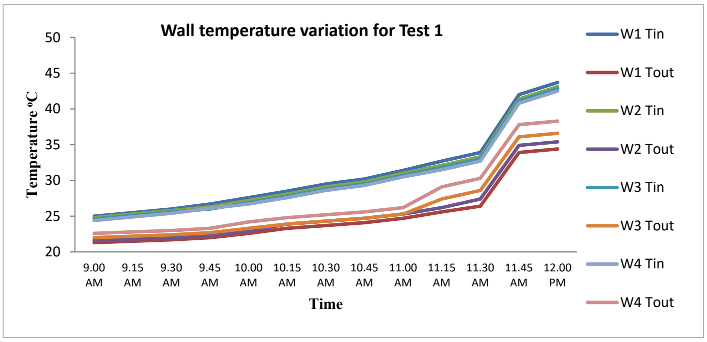


Fig. 3. *Wall surface temperatures during test 2*

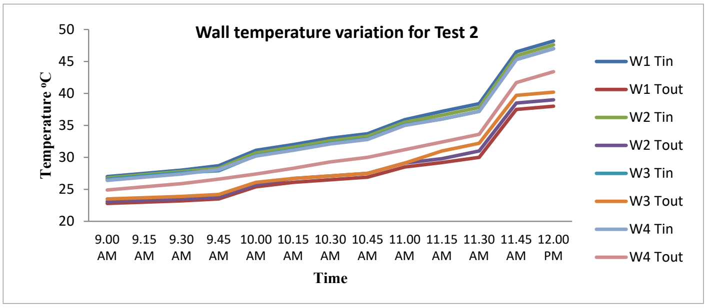


Fig. 4. *Wall surface temperatures during Test 3*

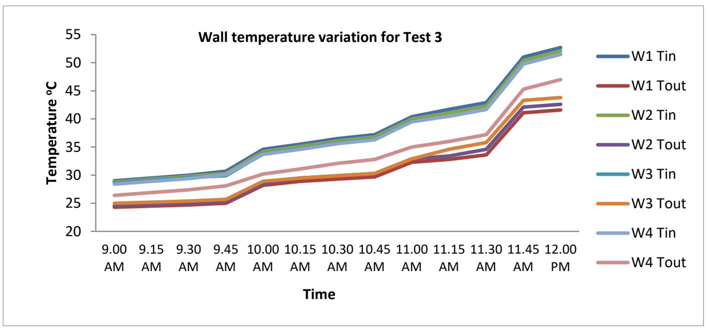
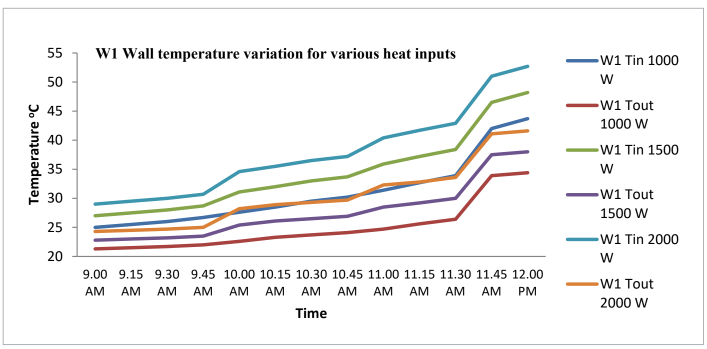


Fig. 5. *Wall (W1) surface temperatures during three tests conducted*



Figs. 6 and *7* show wall temperature variation during open environmental testing. It can be observed that temperature variation is very high (16°C) for the non-insulated wall. Compared with the insulated wall, the non-insulated wall shows a smaller (6°C) temperature variation. This substantial difference in temperature variation underscores the effectiveness of the insulation material. The higher temperature fluctuation of the non-insulated wall implies a more robust thermal coupling with the external environment. In simpler terms, the non-insulated wall readily transmits heat, causing its internal temperature to closely track the ambient temperature changes. Conversely, the insulated wall demonstrates a more stable thermal profile. The insulation material acts as a thermal barrier, hindering the transfer of heat between the interior and exterior environments. This results in a more controlled and consistent temperature within the insulated wall assembly.

Fig. 8 illustrates the proportion of R-value for each wall across the three heat flow experiments. Wall W1, containing the densest straw compaction, consistently exhibited the highest R-value, indicating its superior ability to resist heat flow and contribute to an improved building envelope. The analysis of thermal properties underscores the significant impact of wheat straw compaction on the thermal performance of the investigated walls. Walls with higher compaction density exhibited lower thermal conductivity, heat flow, and U-value, while demonstrating a higher R-value. This leads to enhanced resistance to heat transfer and improved thermal insulation, ultimately leading to reduced energy consumption for building heating and cooling. Utilizing compacted wheat straw insulation in cement hollow bricks offers substantial environmental benefits by fostering improved energy efficiency and reducing greenhouse gas emissions, solidifying its position as a sustainable building material.

Compared with the uninsulated control wall (W4), wheat straw insulation in walls W1, W2, and W3 exhibited substantial reductions in heat flow. These reductions were 82.80%, 66.96%, and 35.74% for W1, W2, and W3, respectively. This translates to improved building energy efficiency by minimizing unwanted heat gain during summer and heat loss during winter. The U-value, a metric quantifying a wall's thermal transmittance, displayed significant reductions in W1, W2, and W3 walls compared with W4 (*Table 2*). Lower U-values indicate greater resistance to heat transfer, further enhancing building energy efficiency. The R-value, a metric representing thermal resistance, demonstrated a significant increase in W1, W2, and W3 walls compared with W4. These increases were 82.80%, 66.96%, and 35.74% for W1, W2, and W3, respectively. Higher R-values signify a greater ability to retain heat within the building, leading to reduced energy consumption for heating purposes. As evidenced, the construction industry can achieve significant reductions in fuel and energy consumption by adopting wheat straw insulation. This leads to lower operational costs and a diminished environmental footprint.

Fig. 6. *Wall surface temperature variation for 15 days during open environmental testing*

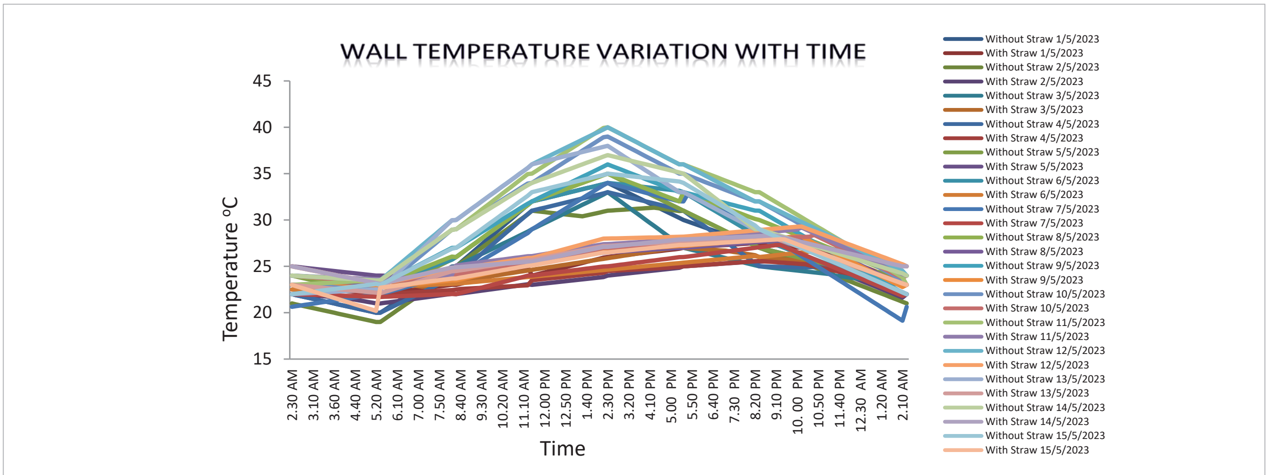


Fig. 7. *Wall surface temperature variation for one day during open environmental testing*

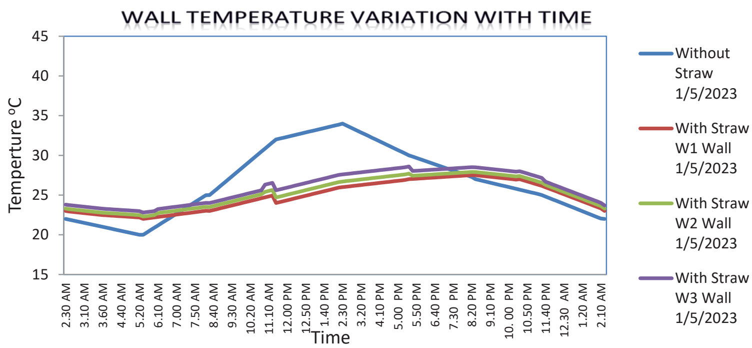


Fig. 8. *Analysis of the R-value of the walls in relation to the heat transfer for three tests*

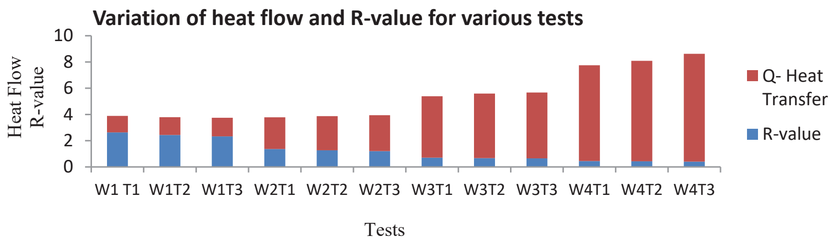


Table 2. *Measured U-value and the computed R-value for the walls*

Sr. No.	Wall type and test number	U-value $W/m^2 \cdot K$	R-value $m^2 \cdot K/W$	Q Watts	% Reduction in comparison with W4
1	W1T1	0.38	2.6316	1.254	82.81
2	W1T2	0.41	2.4390	1.353	82.33
3	W1T3	0.43	2.3256	1.419	82.73
4	W2T1	0.73	1.3699	2.409	66.97
5	W2T2	0.79	1.2658	2.607	65.95
6	W2T3	0.83	1.2048	2.739	66.67
7	W3T1	1.42	0.7042	4.686	35.75
8	W3T2	1.49	0.6711	4.917	35.789
9	W3T3	1.52	0.6579	5.016	38.96
10	W4T1	2.21	0.4525	7.293	0
11	W4T2	2.32	0.4310	7.656	0
12	W4T3	2.49	0.4016	8.217	0

Performance of straw for fuel and cost savings

Increasing the compaction density of wheat straw insulation significantly enhances its effectiveness in reducing thermal energy loss from the walls. This leads to improved building thermal performance and potential energy cost savings for heating and cooling. An effectiveness ratio (SR) was calculated for each insulated wall (W1, W2, and W3) across three test runs, comparing their performance to the non-insulated wall (W4). Wall W1 exhibited the highest energy savings with an average SR of 82.80%. Walls W2 and W3 demonstrated lower effectiveness, with SR values of 66.967% and 35.74%, respectively. The greater energy savings observed in W1 are attributed to its higher straw density and lower porosity. This results in reduced air gaps within the insulation, hindering heat transfer through the wall.

This section delves into the potential economic and environmental benefits of employing the various wheat straw configurations (W1, W2, and W3) in a prototypical building. The prototypical building is a residential structure with a 111.48 m^2 living space. To assess the cost-effectiveness and environmental impact, we estimated the energy, fuel, and cost savings associated with each wall type (W1, W2, and W3) within the prototype building. These estimations were based on the data gathered during the three test runs for the three different straw compaction densities.

Table 3 summarizes the projected savings. Wall W1 (highest compaction) consistently exhibited the greatest energy savings across all three tests, solidifying its position as the most energy-efficient option. A typical 111.48 m^2 single store carpet area house had a 148.64 m^2 wall surface area through which energy interaction takes place from the surroundings. The energy savings from insulated Wall 1 were 6.798 x 148.64 = 1.0104 kw, and the cost of energy was approximately Rs. 4 per kWh. Wall W1 emerged as the leader with the highest average fuel savings. Based on the average energy saving capacity and the total building area, an estimated annual energy savings of 3777.67 could be expected for the prototype building.

Performance of straw for pollutants reduction

This section explores the potential of wheat straw insulation in reducing pollutant emissions associated with building energy consumption. As highlighted by research, modern society faces significant environmental challenges linked to energy use. This leads to increased greenhouse gas emissions contributing to climate change. Coal, a common source of power production, significantly contributes to greenhouse gas emissions and air pollution. *Table 4* (Ebrahimi and Keshavarz, 2015) illustrates the emission rates of the three main pollutants per unit of energy generated by burning coal. Notably, CO_2 emissions are the highest, followed by NOx and CO.

Table 4. *Greenhouse gas emissions of CO, CO_2, and NO_x per unit of energy generated by burning coal (Ebrahimi and Keshavarz, 2015)*

Greenhouse gases	CO	CO_2	NOx
Emissions (g/kWh)	0.9	900	6

The experiment demonstrates the reduction in CO, CO_2, and NOx emissions proportional to the fuel and energy savings achieved in the prototype building with insulated walls (W1, W2, and W3). The findings suggest that utilizing wall W1 (highest compaction) could potentially reduce CO, CO_2, and NOx emissions by nearly double compared with walls W1 and W2.

The 1.0104 kW energy savings achieved by the insulating wall will reduce greenhouse gas emissions by 0.9 g of CO, 909 g of CO_2, and 6.06 g of NOx. These results indicate that wheat straw insulation, particularly with a higher compaction density, can contribute to environmental improvements by lowering energy consumption and, consequently, reducing greenhouse gas and air pollutant emissions. This aligns with sustainable building practices aiming to minimize the environmental impact.

Table 3. *Energy, fuel and cost savings for the assumed sample house*

Sr. No	Wall type and test number	Energy savings (S) (W/m^2)	Energy saving ratio (SR) W	Cost saving for 111.48 m^2 house (Rs/year)	Cost saving for 139.4 m^2 house (Dollars/year)
1	W1 T1	6.039	82.81	15110.71	177.33
2	W1T2	6.303	82.33	14895.87	174.81
3	W1T3	6.798	82.73	14752.64	173.13
4	W2T1	4.884	66.97	12604.2	147.92
5	W2T2	5.049	65.95	12174.51	142.88
6	W2T3	5.478	66.67	11888.05	139.51
7	W3T1	2.607	35.75	7662.778	89.93
8	W3T2	2.739	35.78	7161.475	84.04
9	W3T3	3.201	38.96	6946.631	81.52

Conclusions

This study investigated the effectiveness of wheat straw as an insulating material for cement hollow bricks. The findings strongly support the use of compacted wheat straw for sustainable building practices. The study identified several advantages of using wheat straw insulation detailed below.

Enhanced thermal performance: Compared with non-insulated walls, wheat straw insulation, especially with higher compaction, significantly improved thermal performance. This results in reduced heat transfer and increased energy efficiency within buildings.

Energy savings and cost reduction: The improved thermal performance of highly compacted wheat straw (W1) led to substantial energy savings in the modeled building, potentially resulting in annual cost savings of up to \$177.33 Rs. 15110.71 for a typical 111.48 m^2 house.

Environmental advantages: By lowering energy consumption, wheat straw insulation contributes to reduced greenhouse gas emissions and decreased air pollution, aligning with sustainable building principles. This research supports the use of compacted wheat straw as a sustainable and environmentally friendly building material. It offers significant benefits in terms of improved thermal performance, reduced energy consumption, and minimized environmental impact. Encouraging its widespread adoption in the construction sector holds immense potential for contributing to a more sustainable future.

Further studies should focus on investigating the long-term durability and performance of straw-filled hollow blocks, considering factors such as aging, moisture ingress, and pest infestation. In addition, a comprehensive assessment of the material's mechanical properties, including compressive and shear strength, as well as its seismic performance, are essential.

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