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Assessment of Thermal Behavior of a Model House Built with Sustainable Bricks

Uday Singh Patil† and S. P. Raut
Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, Maharashtra, India
†Corresponding author: Uday Singh Patil; patil.udaysingh4@gmail.com

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ABSTRACT

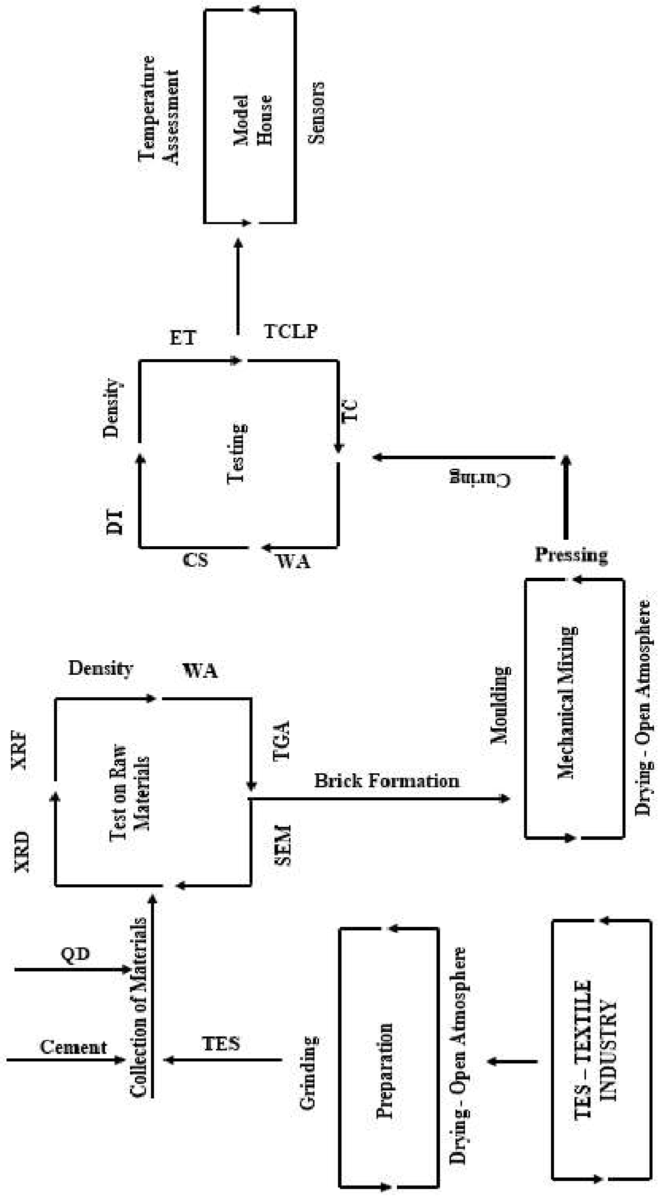
This study evaluated the thermal behavior and economic feasibility of prototype houses constructed using sustainable bricks developed from textile effluent sludge (TES). Two 1 m^3 model houses were built, one using TES–cement bricks and the other using fly ash bricks (FAB). The indoor thermal performance of the plants was monitored under real outdoor conditions. TES bricks were fabricated with 24% cement, 51% TES, and 25% quarry dust, yielding a compressive strength of 4.2 MPa, density of 990 $kg.m^{-3}$, and thermal conductivity of 0.36-0.89 $W.mK^{-1}$, all within Indian Standard requirements. Thermal monitoring revealed that TES brick houses maintained indoor temperatures 2-3°C lower than FAB houses during peak hours, confirming superior thermal resistance and a lag effect. Cost analysis showed that TES bricks were ~36% cheaper per unit and ~35% lower in overall construction cost than FAB. These findings demonstrate that TES bricks provide adequate mechanical strength, enhanced thermal insulation, and significant economic benefits, making them a sustainable alternative to conventional masonry in hot climatic regions for energy-efficient buildings.

INTRODUCTION

The global construction industry is undergoing a paradigm shift toward sustainable building practices driven by the imperative to mitigate environmental degradation and reduce energy requirements. Among the major areas of interest is the use of green building materials, which have not only ecological advantages but also economic and thermal performance benefits. Because buildings account for a significant percentage of energy consumption worldwide, the selection of building materials plays an important role in enhancing energy efficiency and reducing carbon footprints. In recent years, alternative masonry materials, including fly ash bricks and cementitious composites that incorporate industrial waste, have gained prominence.

Bricks are one of the most significant building materials. Due to the rise in demand, there is a shortage of construction materials, which increases the cost of the material. Industries release various types of industrial waste whose disposal is difficult and hazardous, with chemical effects not only on the environment but also on human health. The increasing global population drives the rising demand for goods and construction materials. Therefore, the utilization of industrial waste offers a feasible method for fulfilling these demands sustainably. Various studies have investigated the incorporation of different waste materials into construction components (Meshram 2021, Padole & Agrawal 2019, Raut & Patil 2022, Muthupriya & Arulraj 2025). Zoubeir (2012) investigated the thermal resistance of load-bearing perforated fired-clay brickwork. Gomez (2016) provided a comprehensive overview of research on the thermal characteristics of bricks made from various waste materials. This shows that eco-friendly, low-cost, and lightweight building materials can be used for construction (Raut &

Sedmake 2011). Hence, in the current investigation, textile effluent sludge (TES) (Patil & Raut 2021) was used as an alternative substitute for brick material to reduce the use of fly ash and cement during brick manufacturing. Sludge from the textile industry is a suitable constituent for making new bricks. Using sludge as a constituent of bricks is beneficial to the environment and fulfills the demand of the construction industry. TES is a waste product of the textile industry and must be disposed of appropriately to avoid harming the environment or humans. If proper disposal techniques are not used, this sludge can have detrimental consequences in a variety of ways. To address this challenge, numerous researchers have investigated the incorporation of sludge in the fabrication of sustainable construction materials. Palanisamy (2011) made bricks from textile effluent sludge. Balasubramanian & Sabumon (2006) reused textile effluent treatment plant sludge to develop various construction materials, such as clay bricks, blocks, and paver blocks.



QD – Quarry Dust, XRD: X-ray diffraction, XRF: X-ray fluorescence, SEM: Scanning electron microscopy, TGA: Thermogravimetric analysis, CS: Compressive Strength, WA: Water Absorption, ET-Efflorescence test, TCLP- Leaching Test, TC- Thermal Conductivity

Fig. 1: Process of Model House Construction.

Textile effluent sludge (TES), a byproduct of the textile industry, is a promising raw material for sustainable brick production, offering a potential solution for waste management and resource conservation. Integrating TES into brick manufacturing aligns with the principles of the circular economy and sustainable development by valorizing waste streams into functional construction materials. Solid waste management and the use of environmentally friendly insulating materials are becoming increasingly important.

The present study introduces a novel approach to evaluating textile effluent sludge (TES) as a sustainable construction material by moving beyond laboratory-scale investigations to the development of prototype houses tested under real outdoor climatic conditions. Unlike earlier studies that were largely restricted to material characterization or small-scale brick testing, this study provides practical insights into the thermal behavior of TES masonry under actual service environments, complemented by an economic analysis comparing TES bricks with conventional alternatives. The optimized mix proportions selected for the prototype construction ensured adequate mechanical strength while enhancing thermal insulation, thereby demonstrating both technical feasibility and cost-effectiveness. By integrating real-condition thermal assessment, economic evaluation, and material optimization, this study establishes a comprehensive contribution that advances beyond prior literature and positions TES bricks as an environmentally responsible and economically viable option for sustainable building construction.

MATERIALS AND METHODS

The strategy for developing sustainable bricks and prototypes is illustrated in Fig. 1. The main ingredients for brick development were: Ordinary Portland cement (Grade 53), TES samples (Fig. 2) identified and collected from the textile industry, MIDC Butibori, Nagpur, and Quarry dust from MIDC Butibori, Nagpur. Wet sludge from the textile industry is stored and dried in the open air for 10 to 15 days (Patil 2021). The dried sample was then crushed and pulverized in the laboratory to convert the lump mass into fine particles. To determine the properties of the TES, various tests were performed, as presented in Table 1.

Fig. 2: Open-air drying of wet sludge.

Table 1: Tests performed on the TES sample.

Sr.No.	Type of Tests	Name of Tests
1.	Chemical Test	X-ray fluorescence (XRF)
2.	Mineralogical Test	X-ray diffraction (XRD)
3.	Thermal stability test	Thermogravimetric Analysis (TGA)
4.	Morphological test	Scanning Electron Microscope (SEM)
5.	Physical Test	Specific gravity
		Density
		Sieve analysis

The quantities of raw materials for the different mixes of cement, sludge, and quarry dust were calculated, as detailed in Table 2. The components were manually blended with a predetermined volume of water until a uniform consistency was achieved. The water content was controlled between 8 and 10 percent by the weight of the dry mix to produce a semi-dry mixture. Bricks incorporating sludge were fabricated using varying cement (6–24%) and sludge (50–70%) ratios, with a fixed quarry dust content of 25% and dimensions of 230 × 150 × 100 mm. Fig. 3 illustrates the final TES-incorporated brick. These bricks were then sun-dried for approximately 15 days. Several tests were conducted on sun-dried textile sludge-incorporated bricks (Table 2). Similar tests were performed on commercially available burnt clay bricks (BCB) and fly ash bricks (FAB) for comparison purposes. The mixture with 24% cement, 51% TES, and 25% quarry dust was identified as the optimum composition, and the best combination of bricks was then used to develop the prototype model house of size 1 m × 1 m × 1 m. For comparison, similar prototypes were developed using the FAB. The thermal performance of both prototypes was assessed daily using temperature-measuring instruments and sensors.

Development of Prototypes

The experimental small-scale model houses were constructed with dimensions of 1 m in height, width, and length. Each model included a door measuring 0.3 × 0.7 m on the east-facing wall and three windows, each sized 0.3 × 0.3 m, positioned on the remaining walls. The cumulative area

Fig. 3: Manufacture of Bricks.

Table 2: Compositions for the development of bricks and various tests performed on them.

Sr. No.	Raw materials [wt%]			Tests Performed
	Cement	TES	QD	
1.	6	69	25	Compressive Strength Test - (IS 3495, 1992) Water Absorption Test - (IS 3495, 1992) Efflorescence Test - (IS 3495, 1992) Density Test - (IS:2185(Part I), 1979) Leaching Test - TCLP Presence of Chloride And Sulfate in the Brick – (ASTM C1218 (n.d)) Spectrophotometer Test – (IS 3025, 1986 (BIS 1986)) Effect of Carbonation - Phenolphthalein test Thermal Conductivity - Lee's disc
2.	9	66	25	
3.	12	63	25	
4.	15	60	25	
5.	18	57	25	
6.	21	54	25	
7.	24	51	25	

Fig. 4: Model house built for the analysis of Models M1 and M2.

of the openings, excluding the door, amounted to 0.27 m², complying with the SP: 7-2005 guidelines stipulated in the National Building Code of India (SP: 7 2005 (BIS 2005)). The wall thicknesses of models M-1 and M-2 were set to 125 mm. Fig. 4 depicts two different model houses, one using TES-cement bricks (M-1) and the other using FAB bricks (M-2). Bricks with dimensions of 19 cm × 9 cm × 9 cm were used to construct the prototype employing TES bricks. Brickwork was performed using a stretcher bond (1:4 mortar). A 10 mm thick plaster was used with 1:4 mortar for both internal and external plaster. For the construction of the prototype using FAB, a FAB of a similar size to FAB is used. The roof was made of a 3 mm-thick green sheet. The model houses were constructed on the terrace of the Civil Engineering Department, YCCE Campus, Nagpur, India, in a shadow-free location. To evaluate the thermal performance of the model houses, both ambient and indoor temperatures were recorded systematically. Given the critical importance of the internal temperature, micro-level thermal analysis was conducted for all model units, except in the rainy season. Data logger sensors were used to record the thermal parameters of the site hourly. In each model house, they were placed in the center and on the inside surface of the walls (Indoor Space Temperature Guidelines 2011). The sensors were positioned at the center of the indoor space at a height of 0.5 m from the floor level, and on the mid-height of the interior wall surface, approximately 0.25 m from the adjacent wall, and oriented perpendicular to the wall face. The internal temperature values were obtained in a confined, climate-controlled environment. Owing to the absence of clear sky conditions during the rainy season, ambient temperature measurements remained consistently within the thermal comfort range and were, consequently, excluded from the thermal performance analysis.

RESULTS AND DISCUSSION

Chemical, Morphological, Thermal, and Physical Properties of TES

The XRF test results showed a higher SiO_2 concentration, indicating the possibility of pozzolanic properties. This study also assessed the concentrations of heavy metals such as Cu, Pb, Co, and Cr in textile effluent sludge (TES), which are commonly associated with dye residues in textile waste. The detected levels were comparatively lower. The lower concentration of heavy metals in TES was also confirmed by SEM coupled with EDS. According to the BIS regulations, the combined proportion of SiO_2 and CaO in OPC should not be less than 50%. In this study, the TES samples met this requirement, exhibiting a CaO + SiO_2 value of 74.55% (Table 3). Consequently, instead of relegating sludge to landfills, its potential for reuse and recycling can be explored through the application of suitable technological interventions. The pH of the sludge was 9.13, indicating that it was alkaline.

The morphological properties of the TES sample are depicted in the SEM image (Fig. 5). Particles of all forms and sizes have been discovered in the environment. The particles ranged in size from 12 to 50µm. Fine pores were also observed in the sludge particles, indicating that they were lighter. Some particles exhibited flaky and porous structures, which may have enhanced the specific surface area. This texture is beneficial for applications such as adsorption, cementitious materials, and composite

Table 3: Chemical profiling of Textile Effluent Sludge (TES).

Composition	Percentage [%]
CaO	16.719
Fe_2O_3	11.059
SiO_2	57.829
SO_3	-
TiO_2	0.995
K_2O	1.827
Cr_2O_3	0.05
MnO	0.158
CuO	0.206
ZnO	0.149
V_2O_5	0.044
SrO	0.037
NiO	0.011
ZrO_2	0.018
Al_2O_3	10.843
As_2O_3	0.026
MoO_3	0.018
Br	0.005
Y_2O_3	0.004

bricks, as it may improve bonding with the binders or matrices. XRD pattern (Fig. 6) shows the crystalline nature of TES, with quartz (SiO_2), hematite (Fe_2O_3), and calcite ($CaCO_3$) as the major crystalline phases.

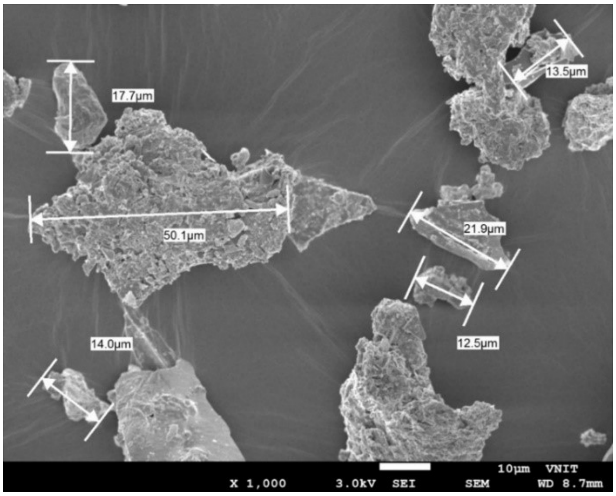


Fig. 5: SEM image of textile effluent sludge.

The TGA curve (Fig. 7) indicated an initial weight loss below 150°C due to moisture evaporation, followed by major decomposition events between 150°C and 700°C, associated with the degradation of organic matter and carbonates. An overall weight loss of approximately 40–50% was observed, leaving a stable inorganic residue at temperatures beyond 700°C. The corresponding DTA peaks confirmed the endothermic moisture loss and exothermic combustion of organics. These results suggest that textile sludge contains significant mineral content and exhibits thermal stability in the residual ash, making it a promising additive in

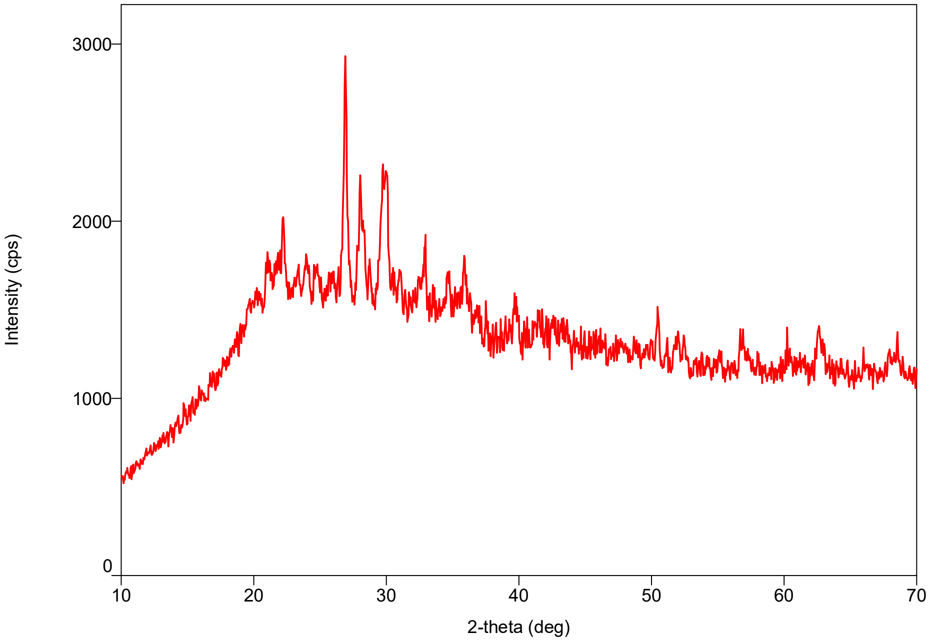


Fig. 6: XRD pattern of textile effluent sludge.

sustainable construction materials, such as bricks or cement composites.

Table 4 presents the physical properties of the cement, TES, and Quarry dust. The specific gravity of the sludge sample is lower compared to other raw materials that may further produce lighter building bricks. Sieve analysis results revealed that the majority of sludge particles were retained on the 75 µm sieve, indicating the presence of constituents with a broad particle size distribution.

Physicomechanical and Thermal Properties Of Developed TES Bricks

Table 5 presents the physico-mechanical and thermal characteristics of the bricks. For each mix, three bricks were tested for compressive strength, water absorption, and other physical properties to ensure the reliability of the results, and the average values were considered.

The effect of the textile effluent sludge on the brick was inversely proportional to its density. The density of the manufactured bricks was 40% and 41% lower than that of BCB and FAB, respectively. Thus, it can be inferred that when TES is utilized as a building material, the resulting unit weight of the brick is significantly lowered.

A declining trend in compressive strength was observed with an increase in the proportion of textile effluent sludge (TES) in the mix. The strength reduction up to 29% is likely attributed to the finer particle size of TES and the presence of organic matter or trace contaminants, in contrast to the coarser and more stable cement particles. Despite this reduction, the compressive strength of the developed

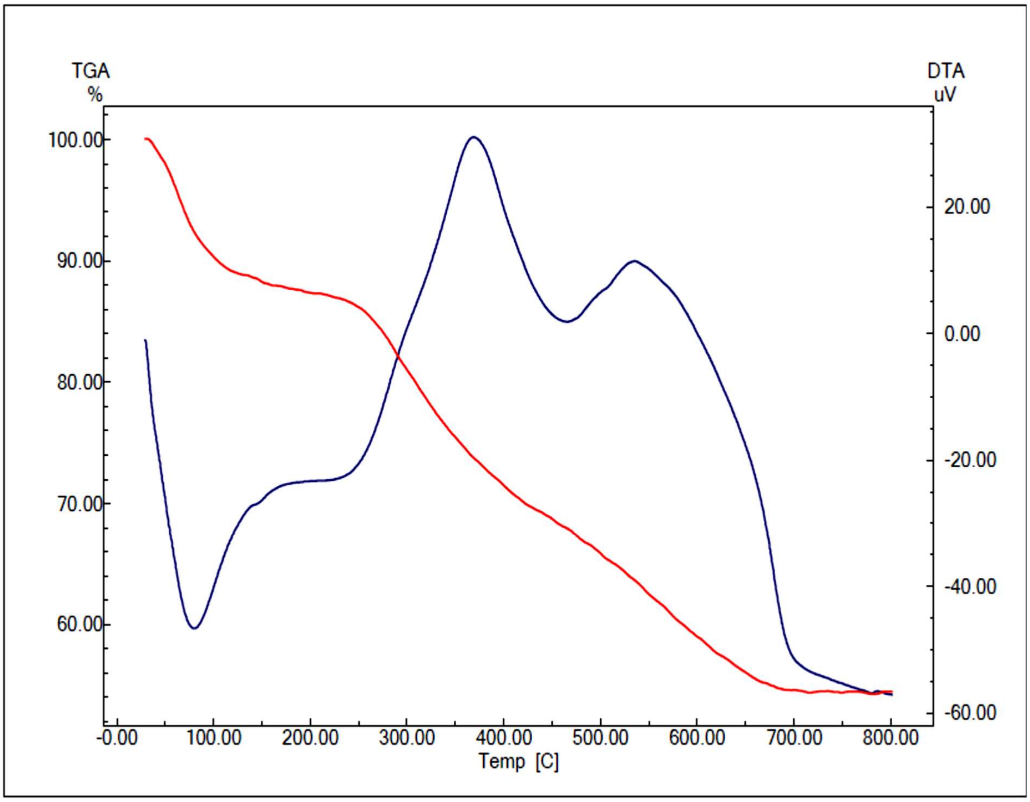


Fig. 7: TGA curve of textile effluent sludge.

Table 4: Outcomes of tests performed on TES, cement, and quarry dust.

Sr. No.	Tests Conducted	Test results		
		Textile effluent sludge [TES]	Cement	Quarry Dust
1.	Specific gravity	2.4	3.15	2.64
2.	Density [kg.m^{-3}]	936	1440	1650
3.	Water absorption [%]	24.3	-	10.6

Table 5: Findings of developed bricks.

Cement [%]	TES [%]	Quarry Dust [%]	Density [kg.m^3]	Density [kg.m^3] BCB	Density [kg.m^3]FAB	Compressive Strength [Mpa]	CS (MPa) BCB	CS [MPa] FAB	Water Absorption[%]	WA [%] BCB	WA [%] FAB	Thermal Conductivity [W.mK^{-1}]	TC BCB [W.mK^{--}]	TC FAB [W.mK^{-1}]	Efflorescence
24	51	25	990	1650	1700	4.2	4.3	5.8	16	27.1	18.4	0.89	1.24	1.10	NIL
21	54	25	910			4.0			18			0.81			NIL
18	57	25	880			3.7			20			0.64			NIL
15	60	25	844			3.6			25			0.58			NIL
12	63	25	835			3.3			28			0.43			NIL
9	66	25	826			3.1			29.5			0.38			NIL
6	69	25	810			3.0			31			0.36			NIL

bricks exceeded that of both BCB and FAB. A maximum strength of 4.2 N.mm^{-2} was recorded, surpassing the 4 N.mm^{-2} requirement for Grade D load-bearing units as per IS: 2185 (Part 1) (BIS 1979), and also exceeding the minimum threshold of 3.5 N.mm^{-2} specified for load-bearing bricks in IS: 1077 (BIS 1979). The values are also comparable to or, in some cases, higher than those reported for other sustainable bricks, including textile sludge–based bricks (Begum & Gobinath 2013, Rahman & Umar 2015) and bio-briquette ash bricks (Sakhare & Varma 2015).

For the water absorption test, an increasing trend with the percentage increase of textile effluent sludge in bricks was observed (Rahman & Umar 2015). The increased value of water absorption could be attributed to the porous texture of textile sludge particles (Begum & Gobinath 2013) and subsequently increased porosity of the bricks. The value is within the permitted limit of 20% for approximately 50% replacement, as indicated by IS 1077:1992 (BIS 1992). Furthermore, the water absorption values were lower than those of BCB and FAB. The water absorption values of the TES bricks were also lower than those reported for several other waste-based bricks in the literature (Raut & Patil 2022, Balasubramanian & Sabumon 2006).

IS 3495 Part-III: 1992 was used to measure efflorescence. Because there was no discernible efflorescence in any of the brick samples, they were labeled as 'NIL.'

Chloride and sulfate content analyses were performed on the TES-incorporated-brick specimens. The highest recorded chloride concentration was 0.085 kg.m^{-3}, which is significantly below the permissible limit of 3 kg.m^{-3} (IS 456 2000). With respect to SO▯, the total water-soluble sulfate content in the concrete mix must remain below 4% of the mass of the cementitious material, as per the permissible limits (Sakhare & Varma 2015). The concentration was 121.8 PPM. The chloride and sulfate concentrations in the bricks were found to be well within the maximum allowed limits (IS 456 2000 (BIS 2000)). A carbonation test was conducted to investigate the impact of atmospheric conditions on bricks. When the brick was exposed to the carbonation test, the surface color changed to pink, indicating that carbonation had occurred to a lesser extent (Shetty 2013).

The heavy metal concentrations in the generated bricks were further tested using the TCLP method. The leachates of the samples were found to be within the Central Pollution Control Board threshold value. The results indicate that the developed bricks are safe and can be used for brick development.

Thermal Performance

The thermal conductivity of the fabricated bricks exhibited a downward trend with increasing TES proportions in the mix. (V. Sakhare 2015) Both the density and thermal conductivity of the TES-incorporated bricks decreased with increasing TES content, with a maximum observed reduction of up to 60%.

The use of wall materials with lower thermal conductivity is recommended by standards to save energy inside buildings (SP: 41,1987 (BIS 1987)). This can be accomplished using carefully selected materials, as proven in the current study. According to the standards for buildings, the comfort temperature range is 18–27°C. All models were subjected to external temperatures, and the temperature differences between the exterior and interior sides of the walls were recorded. Fig. 8 compares the internal temperature variations of two model houses constructed using different brick types, one with textile effluent sludge bricks (TES bricks) and the other with conventional fly ash bricks, over a 24-hour cycle. The model house constructed with TES bricks consistently maintained lower internal temperatures during peak daytime hours than the FAB model. This indicates the superior thermal insulation properties of TES. The temperature difference was most pronounced between 12:00 PM and 4:00 PM, where the TES brick model house showed a reduction of approximately 2–3°C relative to the fly ash brick house. This behavior can be attributed to the porous microstructure and potentially lower thermal conductivity of the TES bricks, which reduces heat transfer from the external environment. During the nighttime and early morning hours, both houses exhibited a convergence in temperature, suggesting that the thermal performance advantage of the TES bricks is particularly effective during periods of high solar radiation. These results demonstrate that TES bricks serve as a sustainable alternative to conventional bricks by recycling industrial waste and enhancing indoor thermal

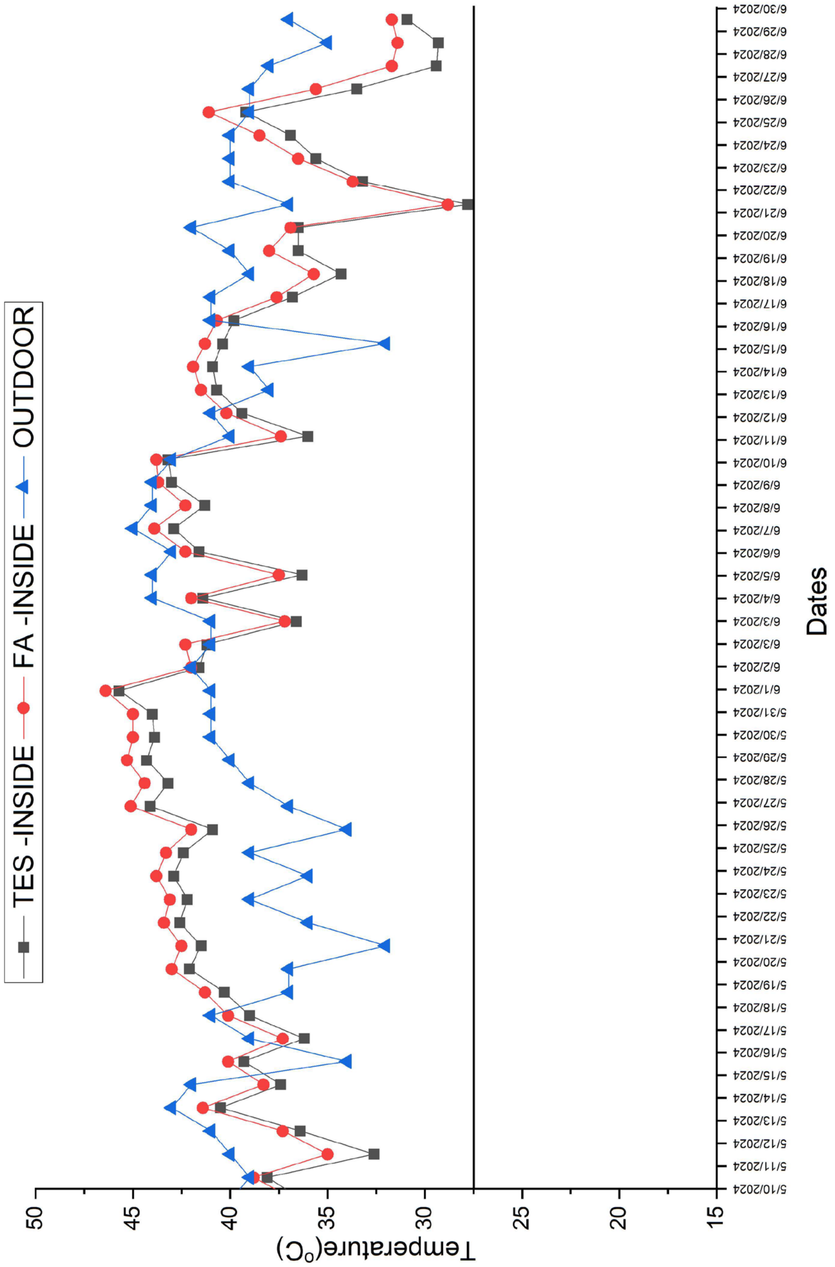


Fig. 8: Comparison of indoor temperatures of model house.

comfort, potentially reducing the need for active cooling in buildings.

Heat transfer analysis was conducted using standard equations (Cengel 2003), where daytime temperature differentials were applied through Equations (1–3) to estimate the conductive heat transfer rates, thermal resistance, and thermal transmittance of the south-facing wall assemblies across all model houses.

$$\text{Qcond}=\frac{\text{kA(T1}-\text{T2)}}{L} \quad ...(1)$$

$$\text{RT}=\frac{\text{l}(1-\text{n})}{\text{k}(1-\text{n})} \quad ...(2)$$

$$\text{U}=\frac{1}{R_T} \quad ...(3)$$

Where, Qcond - conduction heat transfer rate (W), k - thermal conductivity of the brick (0.356 W.mK^{-1}), A - wall area (1 m^2), T1 and T2 -temperature of outside and inside walls obtained from the sensor and thermal gun, respectively, L - thickness of the wall (0.19 m), RT - overall thermal resistance parameters ($\text{m}^2\text{K.W}^{-1}$), U-thermal transmittance ($\text{W.m}^{-2}\text{K}^{-1}$).

Fig. 9 shows the indoor and outdoor temperature variations for the TES and FA model houses. The TES house consistently maintained temperatures 1–2°C lower than those of the FA house during peak summer, confirming its superior thermal resistance. The error bars and 3-day averages indicate that the differences were consistent across multiple days, demonstrating the improved thermal stability and passive cooling potential of the TES bricks.

Fig. 10 presents a comparative analysis of the heat conduction through the M1 and M2 model houses. These measurements reflect the internal surface temperature over time, providing insights into the thermal conduction behavior of the materials. From the graph, it is evident that M1 consistently exhibited lower internal surface temperatures than M2 during peak thermal loading periods, particularly between 11:00 AM and 4:00 PM. This indicates that TES bricks possess a lower thermal conductivity than fly ash bricks, effectively reducing the rate of heat transfer from the external environment to the interior. The subdued temperature increase in M1 suggests better thermal resistance, which helps maintain a more stable and cooler indoor environment during high ambient temperatures. The delayed peak temperature and quicker cooling trend after 4:00 PM in M1 further support the superior insulating performance of the TES bricks. In contrast, M2 demonstrated a steeper rise in temperature and reached higher internal surface temperatures more quickly, indicating greater heat conduction and reduced thermal resistance. This performance advantage of the TES bricks implies potential energy savings in building cooling requirements.

All the model wall assemblies were exposed to ambient outdoor conditions, and temperature fluctuations were monitored on both the exterior and interior wall surfaces. These measurements were taken during the day on May 30 2024, revealing that the highest surface temperature occurred on the south-facing wall of all model houses. Fig. 11 illustrates the temperature variation owing to heat conduction through the south-facing walls of the two model houses (M1 and M2). Given the south wall's direct exposure to intense solar radiation during the day, this section of the building serves as a critical indicator of thermal performance. The findings indicate that the internal surface temperature of the south wall of M1 was lower than that of M2 throughout

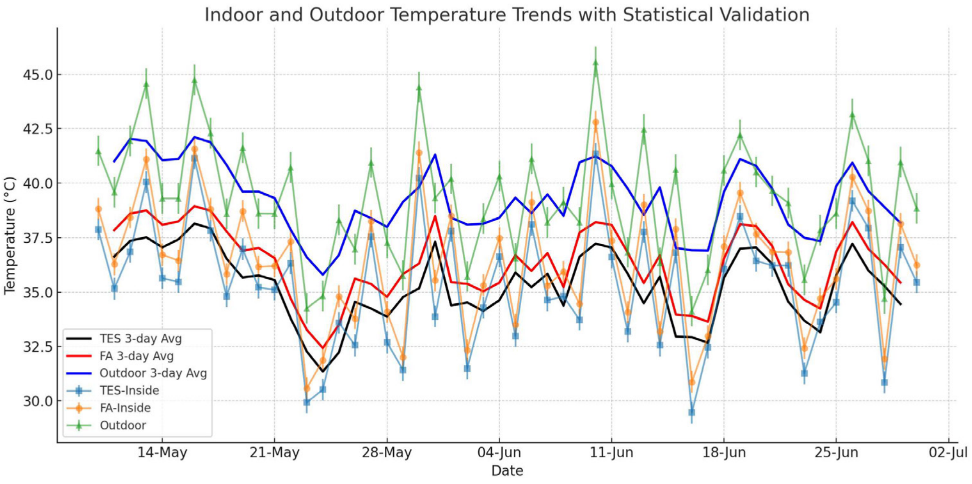


Fig. 9: Indoor and outdoor temperature trends with statistical validation.

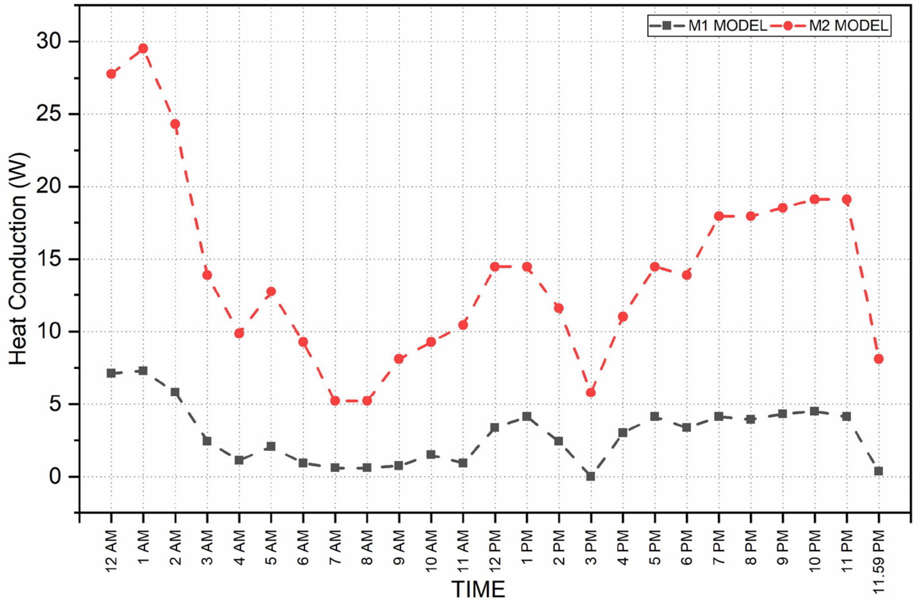


Fig. 10: Comparison of heat conduction in the M1 and M2 model houses.

the peak solar radiation time, especially from 11:00 AM to 4:00 PM. This indicates that the TES bricks have a greater resistance to heat flow, restricting the inward passage of thermal energy. The maximum temperature in M1 was lower and occurred later, exhibiting a thermal lag effect, which is a useful property for construction materials in warm climates. Conversely, the M2 wall experienced higher internal temperatures sooner, indicating a quicker heat conduction through the material. This implies reduced thermal inertia and greater thermal conductivity, exposing the interior to more external heat gains. Hence, the data confirms that TES bricks improve thermal comfort by controlling heat conduction, especially in south-exposed walls, which receive the most solar heating. This verifies the capacity of the TES bricks to minimize cooling loads in buildings, particularly in areas with high solar exposure.

Fig. 12 illustrates the internal temperature fluctuations of the model houses during a normal summer day and reveals the thermal performance of the respective materials during hot weather conditions. The records indicate that M1 had

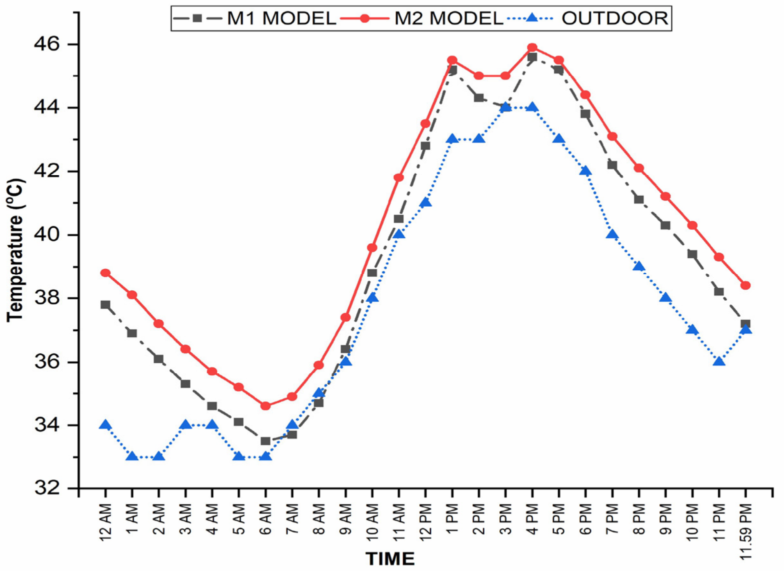


Fig. 11: Temperature variations in the south walls of the model houses (M1 and M2).

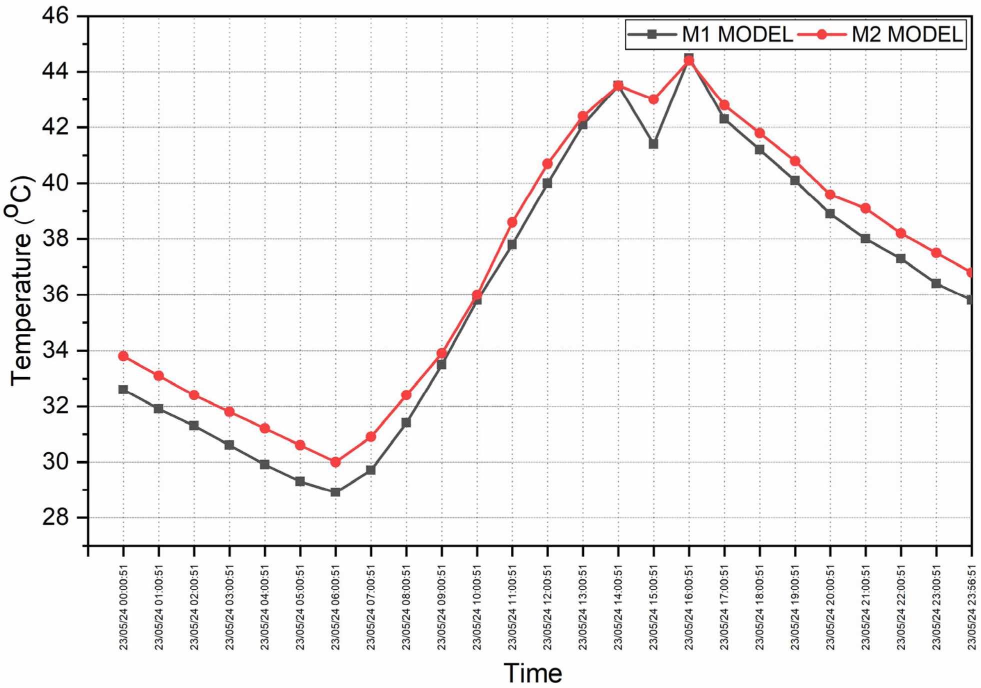


Fig. 12: Internal temperature variations in model houses M1 and M2 on a typical summer day.

lower internal surface temperatures than M2 throughout the day, especially from 10:00 AM to 5:00 PM, when solar radiation and ambient temperature reached their peak. This indicates the excellent thermal insulation properties of the TES bricks, which significantly delayed the heat flow into the building interior. The temperature increase in M1 was slower and postponed, indicating a thermal lag, where the heat was transferred gradually through the walls, thus minimizing indoor heat gain at the peak hours of the day. This postponement and suppression of the peak temperature are important for enhancing thermal comfort in warm climates and minimizing the energy requirements of cooling systems. By contrast, model house M2, which used FAB, experienced a steeper and earlier increase in internal temperature with higher peak values. This indicates greater thermal conductivity and lower heat resistance, making it less effective in protecting against external heat. All these facts prove that TES bricks make a notable contribution to the passive thermal control of buildings, especially under conditions of high summer temperatures.

The inner surface temperatures of the model houses were recorded hourly between 10:00 a.m. and 5:00 p.m. during May and June 2024 to facilitate the calculation of the operative temperature. These measurements were then used to compute the operative temperature for all three models using Equation (4) (Soleimani-Mohseni 2006).

$$\text{Top} = \frac{(Tmr + Tin)}{2} \qquad \ldots(4)$$

where Top = operative temperature, Tin = indoor air temperature, and Tmr = mean radiant temperature. The mean radiant temperature was estimated using Eq. (5)

$$= \mathrm{T1A1} + \mathrm{T2A2} + \ldots\ldots\ldots + \frac{TNAN}{(A1+A2+\cdots+AN)} \qquad \ldots(5)$$

where TN is the surface temperature of surface N, and AN is the area of the surface.

The overall trend of operative temperatures in the study showed a rising pattern (Fig. 13) throughout May, reaching its peak towards the end of May or early June, before declining in late June. This trend aligns with the typical seasonal progression observed during the early summer. When comparing M1 and M2, M1 consistently exhibited lower operative temperatures than M2 throughout May and June. This suggests that TES bricks offer better thermal insulation, effectively delaying heat transfer into the interior, thereby maintaining a cooler indoor environment. The peak operative temperature for M2 was likely observed in early June, possibly between June 1st and 5th, indicating higher heat retention and poorer thermal performance compared to M1. Although M1 also reached a peak, it occurred at a significantly lower temperature, demonstrating its superior thermal regulation. In terms of thermal comfort, the TES brick model (M1) remained closer to or within the thermal comfort range (typically 25–35°C) for a longer duration,

Table 6: Cost comparison of TES brick and FAB brick.

Cost Component	TES Bricks [₹/brick]	FAB Bricks [₹/brick]
Raw materials	2.50	5.00
Cement binder	1.80	2.20
Processing/Manufacturing	1.20	1.80
Transportation	0.80	1.20
Labor	0.70	0.80
Total Cost/brick	**7.00**	**11.00**

particularly during the early and late parts of the period. In contrast, the Fly Ash brick model (M2) is likely to exceed comfortable temperature limits for a more extended period, especially from mid-May to early June.

The results from the prototype houses demonstrated that TES walls consistently reduced indoor temperatures compared to conventional alternatives under peak summer conditions. Although the experiments were conducted on 1 m³ models, the observed thermal resistance and lower U-values can be extrapolated to larger building envelopes. In

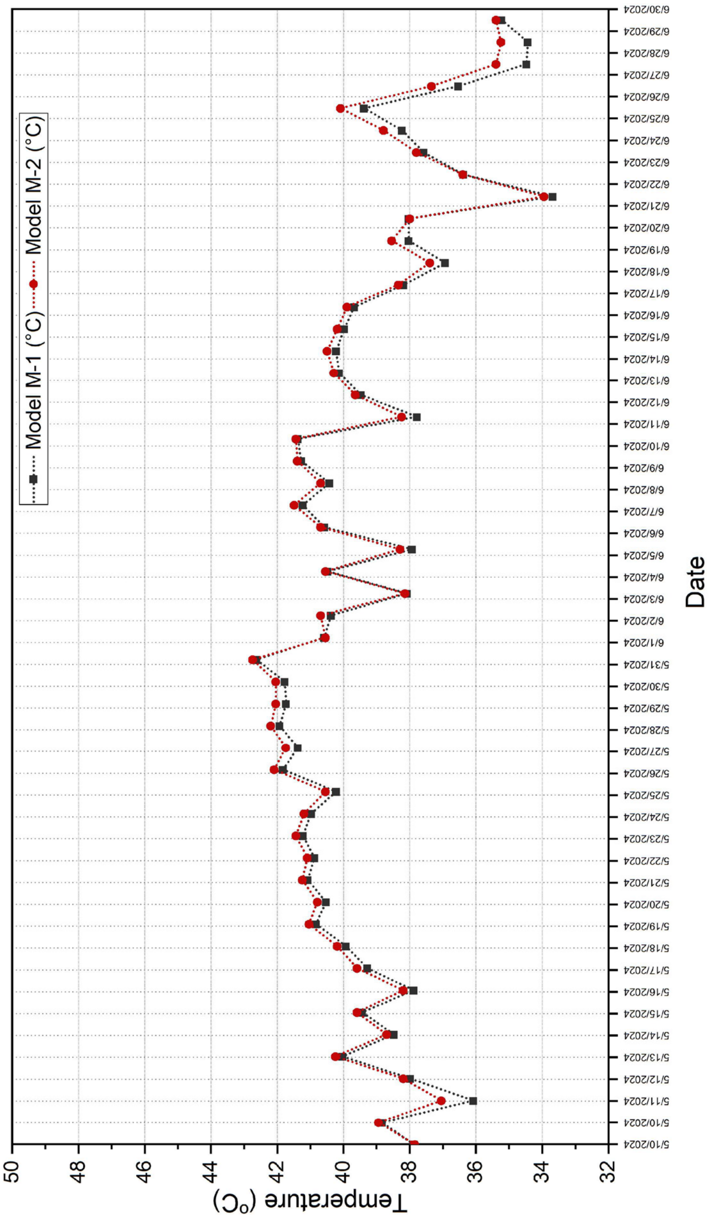


Fig. 13: Operative Temperature Profiles of Model House.

real-sized dwellings, this reduction in heat ingress translates to a significant passive cooling effect, lowering the need for mechanical ventilation or air conditioning during hot periods. For example, even a 1°C reduction in the average indoor temperature has been reported to decrease the cooling energy demand by 6–10% in residential buildings.

This analysis highlights the practical implication that TES bricks are more suitable for energy-efficient building construction in hot climates, as they help maintain lower operative temperatures, thereby potentially reducing the reliance on artificial cooling.

A cost analysis comparing TES bricks with fly ash bricks was conducted, revealing that the cost of TES bricks was approximately 36% lower than that of conventional bricks available in Central India (Table 6). The reduction in cost (~36%) is primarily attributed to the use of waste-derived raw materials, which substantially lowers material expenses and reduces processing energy. Transportation costs are also minimized because TES and quarry dust are locally sourced by-products. These savings outweigh the marginal differences in labor and cement usage. Additionally, the construction cost per square meter using TES bricks was 35% lower than that of conventional bricks.

CONCLUSIONS

This study illustrates the viability of textile effluent treatment sludge (TES) as a sustainable and thermally efficient material for brick manufacturing.

1. Incorporating TES within masonry units led to light bricks possessing sufficient compressive strength, low thermal conductivity, and good durability, thus complying with Indian Standards for load-bearing purposes.
2. The TES-cement bricks produced were found to have higher thermal insulation than commercially purchased fly ash bricks, as verified through sustained temperature measurements in model houses subjected to actual climatic conditions.
3. The prototype house built with TES bricks had lower internal temperatures at all times, especially during hours of intense solar radiation, owing to the thermal lag effect and lower heat gain, both of which are important for passive thermal comfort in hot weather.
4. Quantitative thermal analysis of the operational temperature and heat transfer rates also confirmed the higher thermal resistance of the TES brick walls.
5. The cost evaluation showed a high value for money, with the TES brick price and construction costs being approximately 30–35% lower than those of conventional practices.
6. From a practical perspective, the use of TES bricks can improve passive thermal comfort and reduce the energy demand for cooling, making them particularly suitable for hot climatic regions and cost-sensitive housing projects. The economic feasibility of producing bricks from locally available industrial waste supports large-scale adoption while simultaneously addressing the critical challenge of sludge disposal.
7. In terms of scalability, the performance demonstrated in small-scale model houses provides a strong basis for pilot applications in full-scale residential and institutional buildings in the future. Integration into government housing schemes and green building certifications can accelerate real-world deployment.
8. For future research, long-term durability studies, performance evaluations under varying climatic zones, and life-cycle environmental assessments are recommended. Further optimization of the mix proportions and exploration of hybrid blends with other waste materials may enhance the properties and broaden their applicability.

By aligning environmental sustainability with economic viability, TES bricks present a pathway to circular construction practices and resilient building infrastructure.

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