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Original Research

Assessment of Thermal Behavior of Model House Built with Sustainable Bricks

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ABSTRACT

This study evaluates the thermal behavior and economic feasibility of prototype houses constructed with sustainable bricks developed from textile effluent sludge (TES). Two 1 m³ model houses were built, one using TES–cement bricks and the other using fly ash bricks (FAB). Their indoor thermal performance was monitored under real outdoor conditions. TES bricks were fabricated with 24% cement, 51% TES, and 25% quarry dust, yielding compressive strength of 4.2 MPa, density of 990 kg/m³, and thermal conductivity of 0.36–0.89 W/mK, 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 thermal lag effect. Cost analysis showed TES bricks to be ~36% cheaper per unit and ~35% lower in overall construction cost compared to 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.

1. INTRODUCTION

The global construction industry is undergoing a paradigm shift in the direction of 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. Since building accounts for a huge percentage of energy consumption around the world, building materials selection plays an important part in enhancing energy efficiency and reducing carbon footprints. In recent years, alternative masonry materials, including fly ash bricks and cementitious composites incorporating industrial waste, have gained prominence.

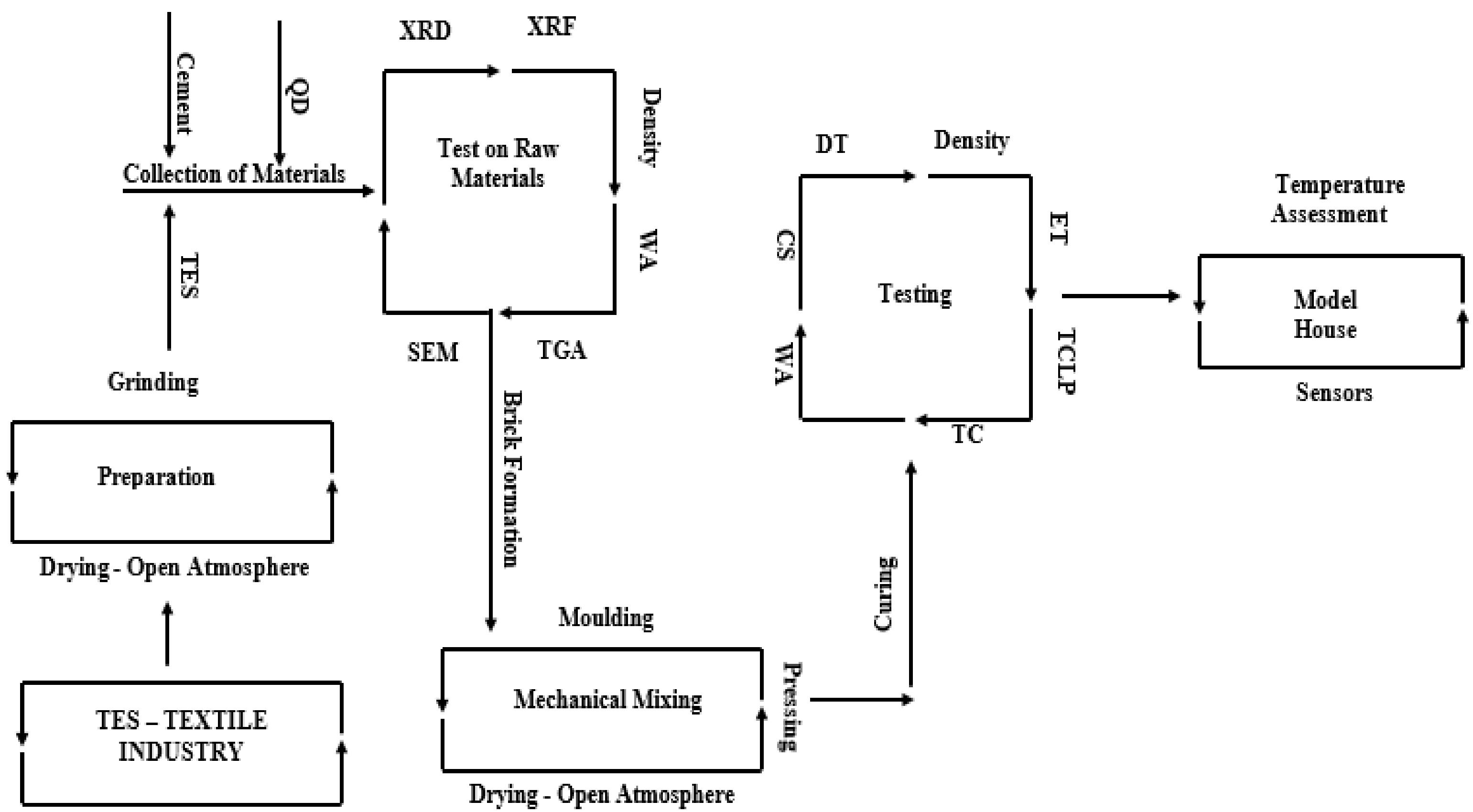
One of the most significant building materials is brick. Due to the rise in demand, there is a shortage of construction material and this increases the cost of the material. Industries are releasing various types of industrial waste whose disposal is found to be difficult and hazardous, with chemical effects not only on the environment but also on human health. The increasing global population drives a rising demand for goods and construction materials. Therefore, the utilization of industrial waste offers a feasible method of fulfilling these demands in a sustainable manner. Various studies have investigated the incorporation of different waste materials into construction components (Meshram, 2021; Padole, 2019; Asati, 2020; Raut, 2022; Muthupriya, 2025). (Zoubeir , 2012) investigated the thermal resistance of load-bearing perforated fired-clay brickwork. (Gomez, October 2016) gave a comprehensive overview of research on the thermal characteristics of bricks made from a variety of waste materials. This shows that the use of eco-friendly, low-cost, and lightweight building materials can be utilized for construction (Raut, 2011) Hence in the current investigation, the textile effluent sludge (TES) (Patil, 2021) served as an alternate substitute for brick material to reduce the use of fly ash, and cement while manufacturing the bricks. Sludge from the textile industry is a suitable constituent to make a new brick. Using sludge as a constituent of brick is useful to the environment and also fulfills the demand of the construction industry. TES is a waste product of the textile industry; it must be appropriately disposed of to avoid harming the environment or humans. If proper disposal techniques are not used, this sludge has more 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 out of textile effluent sludge. (Balasubramanian J, 2006) reused the textile effluent treatment plant sludge in developing various construction materials, viz., clay bricks, blocks, paver blocks, etc.

Textile effluent sludge (TES), a byproduct of the textile industry, presents 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 components. Solid waste management and the use of environmentally friendly insulating materials are becoming increasingly significant.

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 works that were largely restricted to material characterization or small-scale brick testing, this research 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 prototype construction ensure 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, the 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.

2. METHODOLOGY

The strategy for developing sustainable bricks and prototypes is shown in Figure 1. The main ingredients for brick development were: Ordinary Portland cement (Grade 53), TES samples (Figure 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 is then crushed and pulverized in the laboratory to convert the lump mass to fine particles. To determine the properties of TES, various tests were performed as presented in Table 1.



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

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)
		Specific gravity
5	Physical Test	Density
		Sieve analysis

The quantities of raw materials for different mixes of cement, sludge, and quarry dust were calculated as detailed in Table 2. Subsequently, 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. Figure 3 illustrates the final TES-incorporated bricks. These bricks were then subjected to sun drying for approximately 15 days. Several tests were carried out 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. The mix 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 FAB. The thermal performance of both prototypes was assessed daily using a temperature-measuring instrument and sensors.

Fig. 3: Manufacture of Bricks

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

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) Spectrophotometer Test – (IS 3025, 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	

3. 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 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). The wall thickness for models M-1 and M-2 was set at 125 mm. Figure 4 depicts 2 different model houses, one using TES-cement bricks (M-1) and the other using FAB bricks (M-2). Bricks with dimensions of 19 x 9 x 9 cm were used to construct the prototype employing TES bricks. The brickwork was carried out with a stretcher bond (1:4 mortar). The 10mm thick plaster is used with 1:4 mortar for both internal plaster and external plaster. For the construction of the prototype using FAB, a similar size of FAB is used. The roof is 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 systematically recorded. Given the critical importance of internal temperature, micro-level thermal analysis was conducted for all model units, with the exception of the rainy season. The data logger sensors were used to record the site's thermal parameters hourly. In each of the model houses, they were put 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, oriented perpendicular to the wall face. Internal temperature values were taken 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.

Fig. 4: Model House Built for Analysis Model M1 and Model M2

4. RESULTS AND DISCUSSION

4.1. Chemical, Morphological, Thermal and Physical Properties of TES

The findings of the XRF test show a larger percentage of SiO_2 concentration, indicating the possibility of pozzolanic properties. The present investigation also assesses the concentrations of heavy metals such as Cu, Pb, Co, Cr, and others in textile effluent sludge (TES), which are commonly associated with dye residues in textile waste. The detected levels were found to be comparatively lower. The lower concentration of heavy metal in TES is also confirmed by the SEM test coupled with EDS. According to BIS regulations, the combined proportion of SiO_2 and CaO in OPC should not be less than 50%. In this study, TES samples met this requirement, exhibiting a $CaO + SiO_2$ value of 74.55% (Table 3). Consequently, instead of relegating the 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 determined to be 9.13, indicating that it is alkaline.

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

The morphological properties of a TES sample are depicted in the SEM image (Figure 5). Particles of all forms and sizes have been discovered. Particles ranged in size from 12 to 50µm. Fine pores were also found in the sludge particles, indicating that they are lighter in weight. Some particles show flaky and porous structures, which may enhance the specific surface area. This texture is beneficial for applications such as adsorption, cementitious materials, and composite bricks, as it may improve bonding with binders or matrices.

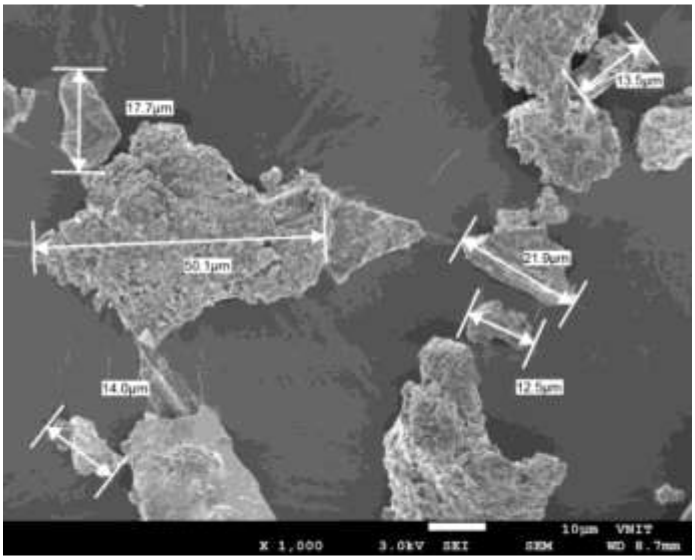


Fig. 5: SEM Image of Textile Effluent Sludge.

XRD spectrum (Figure 6) shows the crystalline nature of TES, having quartz (SiO_2), hematite (Fe_2O_3), and calcite ($CaCO_3$) as major crystalline phases.

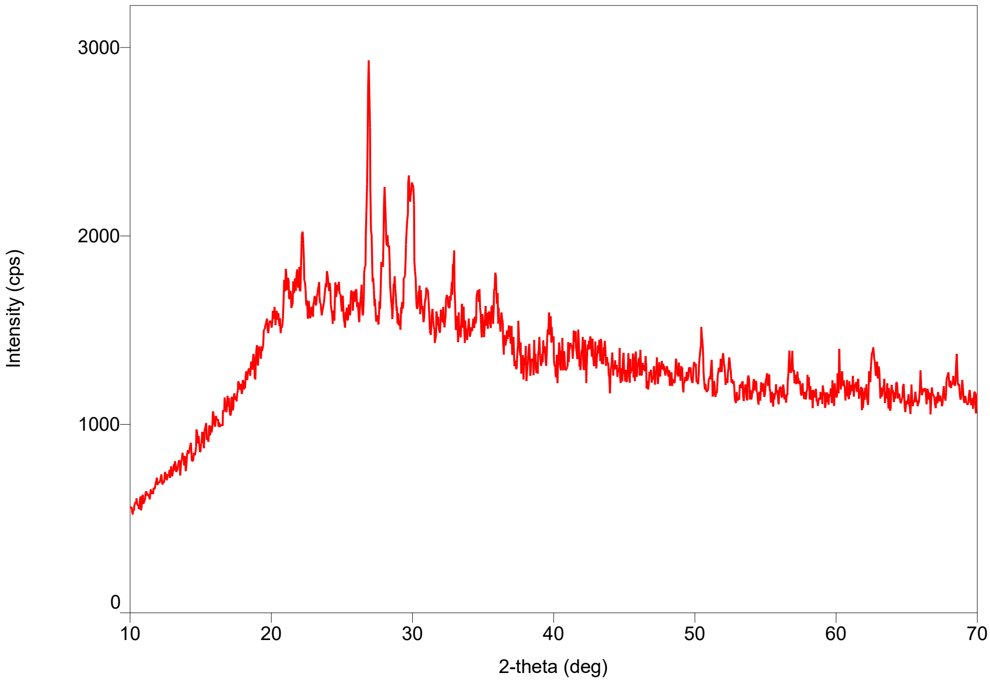


Fig. 6: XRD pattern of textile effluent sludge.

(Figure 7) The TGA curve 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 beyond 700°C. Corresponding DTA peaks confirmed endothermic moisture loss and exothermic combustion of organics. These results suggest that textile sludge contains significant mineral content and thermal stability in the residual ash, making it a promising additive in sustainable construction materials, such as bricks or cement composites.

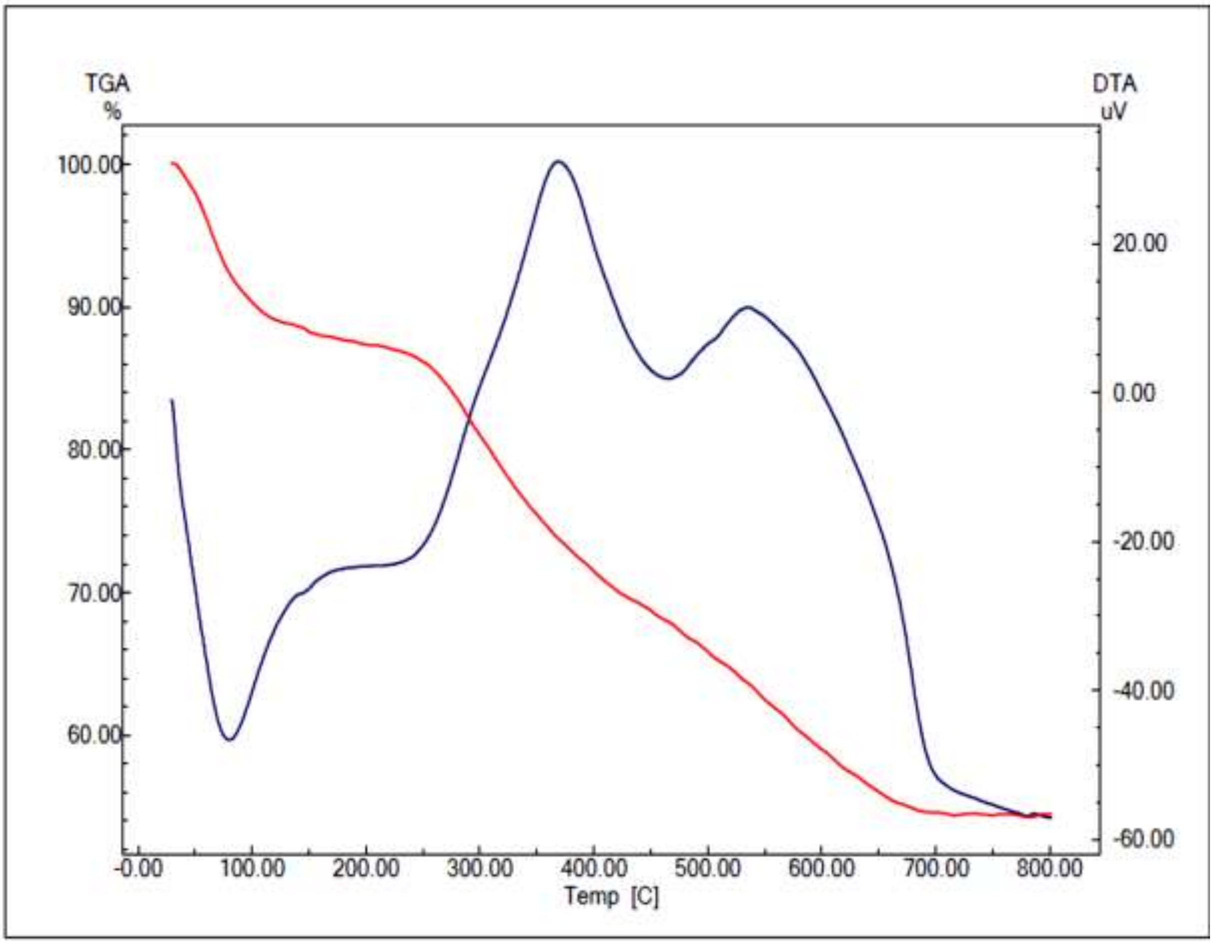


Fig. 7: TGA curve of textile effluent sludge.

Table 4 presents the physical properties of cement, TES, and Quarry dust. It can be seen that 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.

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

4.2. Physicomechanical and Thermal Properties Of Developed TES Bricks

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

Table 5: Findings of developed bricks

Cement (%)	TES (%)	Quarry Dust (%)	Density (kg/m³)	Density (kg/m³) BCB	Density (kg/m³) FAB	Compressive Strength (MPa)	CS (MPa) BCB	CS (MPa) FAB	Water Absorption (%)	WA (%) BCB	WA (%) FAB	Thermal Conductivity (W/mK)	TC BCB (W/mK)	TC FAB (W/mK)	Efflorescence
24	51	25	990			4.2			16			0.89			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	**1650**	**1700**	3.6	**4.3**	**5.8**	25	**27.1**	**18.4**	0.58	**1.24**	**1.10**	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

The effect of the presence of the textile effluent sludge in the brick was observed to be inversely proportional to density. The density of manufactured bricks is 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 will be significantly lowered.

A declining trend in compressive strength was observed with the increasing 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 bricks exceeded that of both BCB and FAB. A maximum strength of 4.2 N/mm² was recorded, surpassing the 4 N/mm² 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/mm² 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 percent increase of textile effluent sludge in bricks is observed. (Rahman A, 2015)The increased value of the water absorption could be attributed to the porous texture of textile sludge particles (Begum, 2013) and subsequently increased porosity of the bricks. The value is within the permitted limit of

20% for roughly 50% replacement, as indicated by IS 1077:1992. Furthermore, the water absorption values were also found to be lower than the BCB and FAB. The water absorption values of TES bricks are 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_3, the total water-soluble sulfate content in the concrete mix must remain below 4% of the cementitious material's mass, as per permissible limits (V. Sakhare, 2015). The concentration was found to be 121.8 PPM. The chloride and sulfate concentrations in the bricks are found to be well within the maximum allowed limits (IS 456, 2000). The carbonation test was used to investigate the impact of atmospheric conditions on the brick. When the brick was exposed to the carbonation test, the surface color changed to pink, indicating that carbonation had occurred to a lesser amount (Shetty, M.S., 2013).

The heavy metal concentration of the generated bricks was further tested using the TCLP method. The leachates of the samples were found to be within the Central Pollution Control Board's threshold value. As a result, it can be concluded that the developed bricks are safer and can be used for the development of bricks.

4.3. Thermal Performance

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

The use of lower thermal conductivity wall materials is recommended by standards to save energy inside buildings (SP: 41,1987). It could be accomplished with carefully selected materials, as proven in the current work. According to the standards for buildings, the comfort temperature range is 18 to 27°C. All models were subjected to external temperatures, and temperature differences on the exterior and interior sides of the walls were recorded. Figure 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. It is evident that the model house constructed with TES bricks consistently maintains lower internal temperatures during peak daytime hours compared to the FAB model. This indicates the superior thermal insulation properties of the TES bricks. The temperature difference is most pronounced between 12:00 PM and 4:00 PM, where the TES brick model house shows a reduction of approximately 2–3°C relative to the fly ash brick house. Such behavior can be attributed to the porous microstructure and potentially lower thermal conductivity of TES bricks, which reduces heat transfer from the external environment. During the nighttime and early morning hours, both houses exhibit a convergence in temperature, suggesting that the thermal performance advantage of TES bricks is particularly effective during periods of high solar radiation. These results demonstrate that TES bricks not only serve as a sustainable alternative to conventional bricks by recycling industrial waste but also enhance indoor thermal comfort, potentially reducing the need for active cooling in buildings.

The heat transfer analysis was carried out 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.

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

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

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

Where, Qcond - conduction heat transfer rate (W), k - thermal conductivity of the brick (0.356 W/mK), 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 (m^2K/W), U-thermal transmittance (W/m^2K)

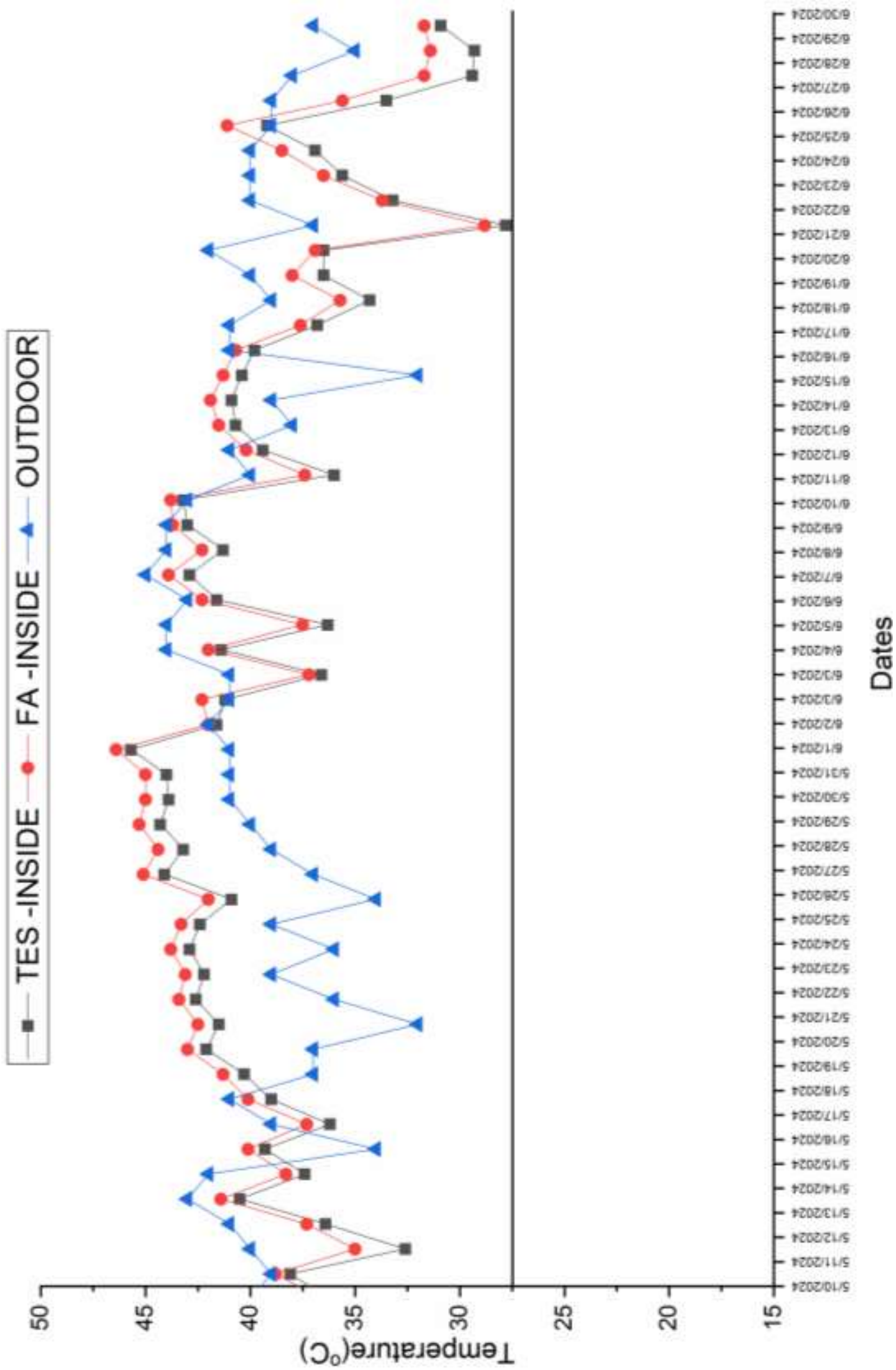


Fig. 8: Comparison of Indoor temperatures of model house

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

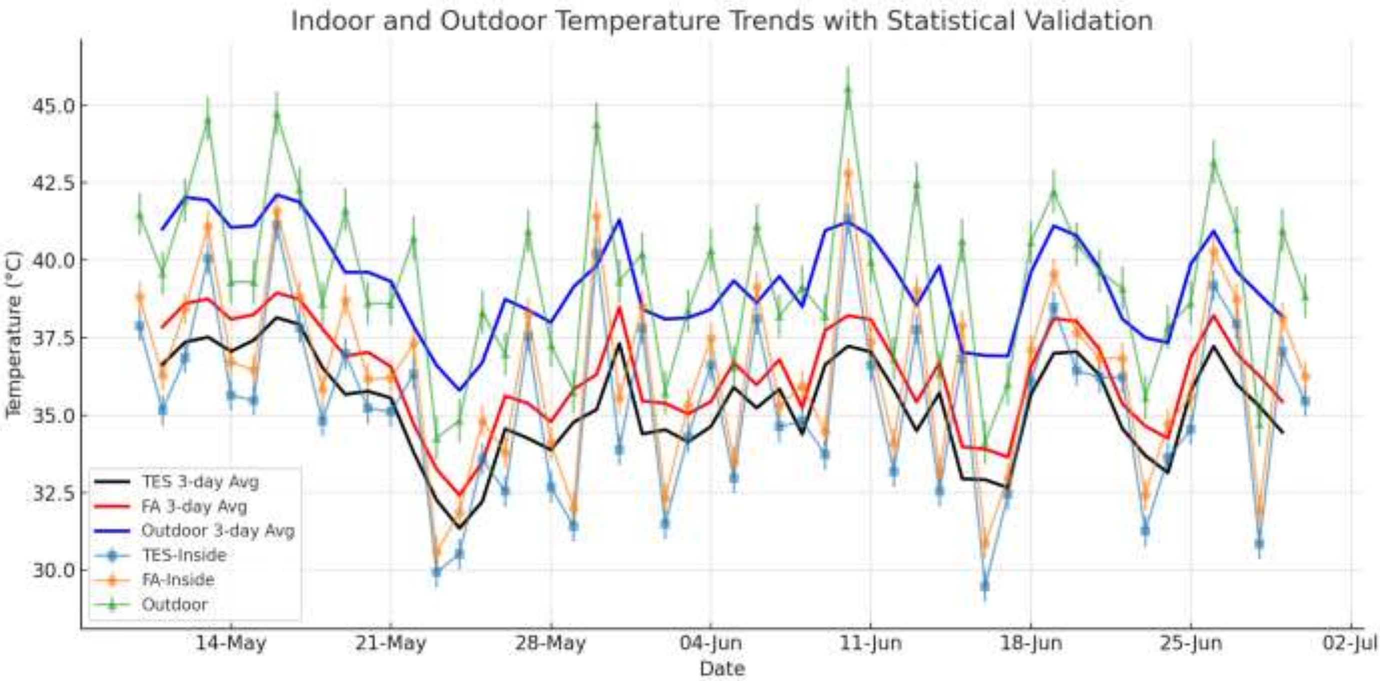


Fig. 9: Indoor and outdoor temperature trends with statistical validation

Figure 10 presents a comparative analysis of heat conduction through the M1 and M2 model houses. The measurements reflect the internal surface temperature over time, providing insight into the thermal conduction behavior of the materials. From the graph, it is evident that M1 consistently exhibits 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 lower thermal conductivity than fly ash bricks, effectively reducing the rate of heat transfer from the external environment to the interior. The subdued temperature rise 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 TES bricks. In contrast, M2 demonstrates a steeper rise in temperature and reaches higher internal surface temperatures more quickly, indicating greater heat conduction and reduced thermal resistance. This performance advantage of TES bricks implies potential energy savings in building cooling requirements.

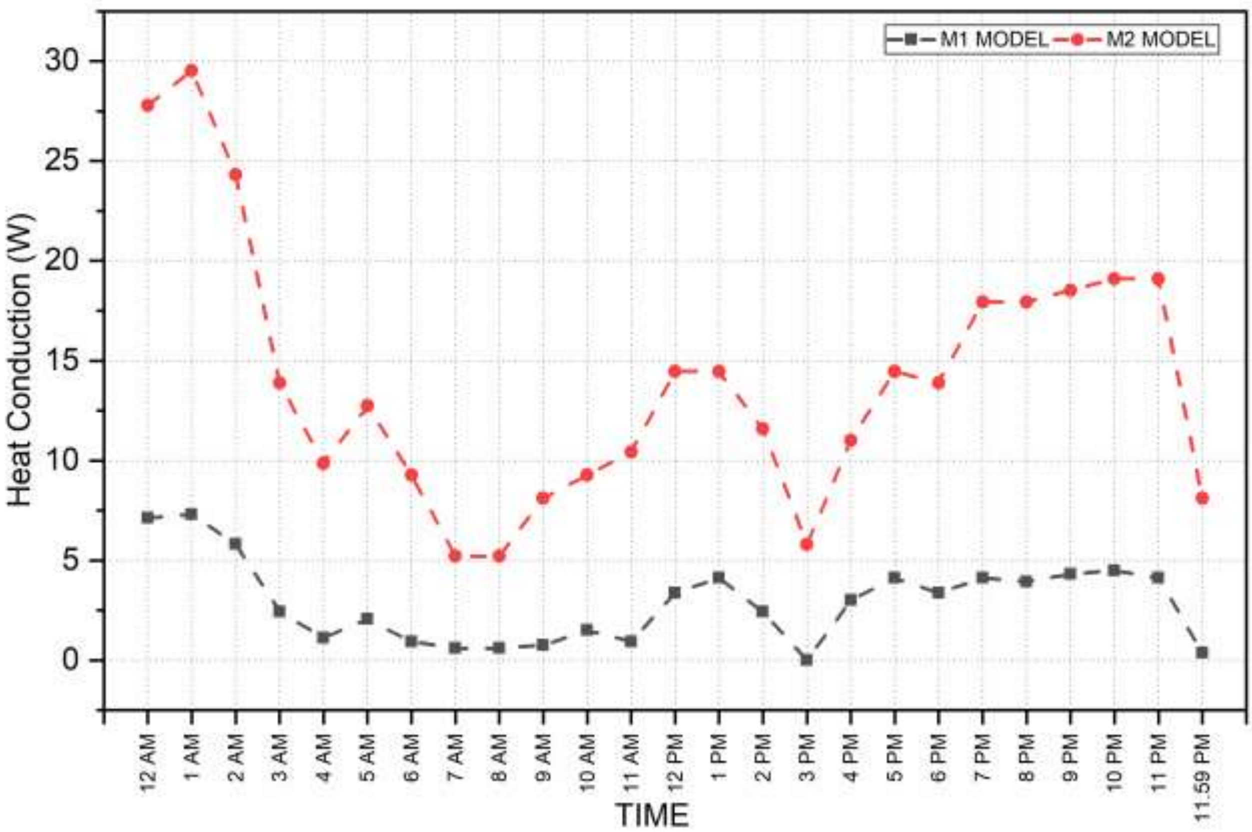


Fig. 10: Comparison of the heat conduction of the M1 and M2 model houses.

All 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 the model houses. Figure 11 illustrates the temperature variation due to heat conduction through the south-facing wall of 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 evidently indicate that the internal surface temperature of the south wall of M1 is lower than that of M2 throughout peak solar radiation time, especially from 11:00 AM to 4:00 PM. This indicates that TES bricks have greater resistance to heat flow, restricting the inward passage of thermal energy. The maximum temperature in M1 is lower and later, exhibiting a thermal lag effect—a useful property for construction materials in warm climates. Conversely, the M2 wall experiences higher internal temperatures sooner, indicating quicker heat conduction through the material. This implies reduced thermal inertia and greater thermal conductivity, exposing the interior to more outside heat gains. Hence, the data confirms that TES bricks improve thermal comfort by controlling heat conduction, especially in south-exposed walls, the ones that receive most solar heating. This verifies the capacity of TES bricks in minimizing cooling loads in buildings, particularly in areas of high solar exposure.

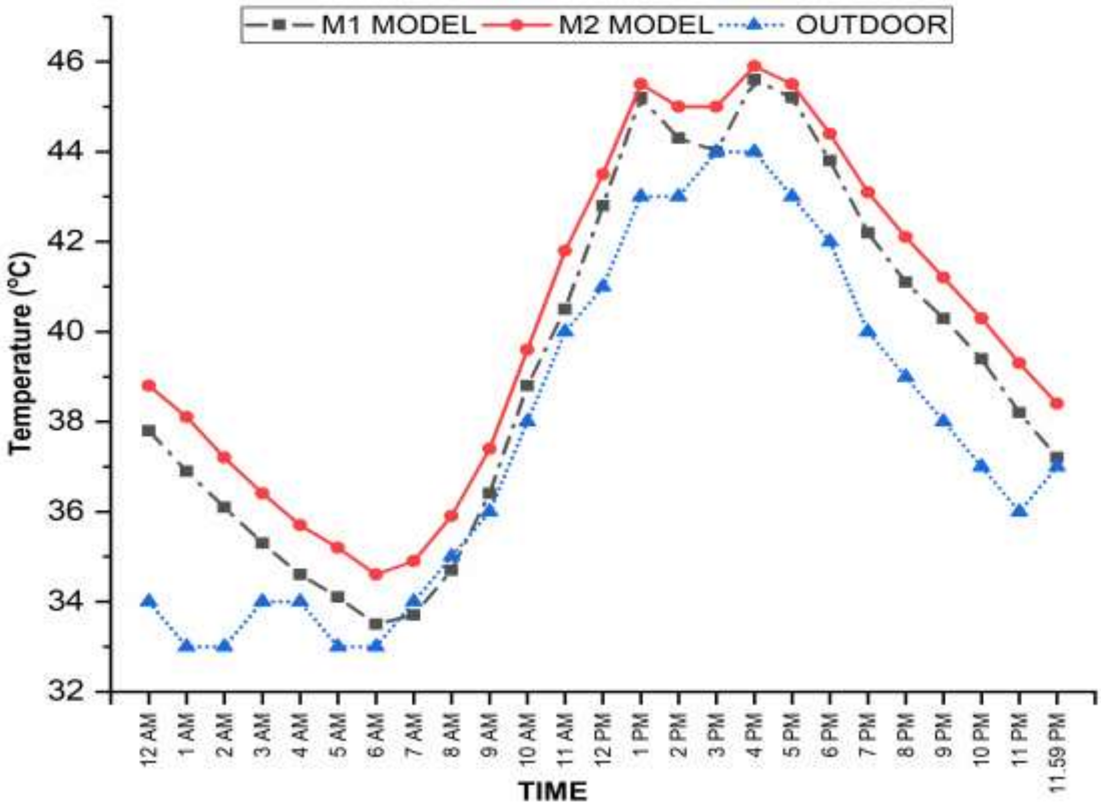


Fig. 11: Temperature variation in the south wall of model houses (M1 and M2).

Figure 12 illustrates the internal temperature fluctuation of model houses during a normal summer day and reveals the thermal performance of the respective materials during hot weather conditions. The record indicates that M1 has lower internal surface temperatures than M2 throughout the day, especially from 10:00 AM to 5:00 PM when solar radiation and ambient temperature reach their peak. This indicates the excellent thermal insulation properties of TES bricks, which significantly delay heat flow into the building interior. Significantly, the temperature increase in M1 is slower and postponed, indicating thermal lag, where the heat is transferred gradually through the walls, thus minimizing indoor heat gain at peak hours of the day. This postponement and suppression of peak temperature are important for enhancing thermal comfort in warm climates and minimizing the energy requirements of cooling systems. On the other hand, the model house M2 using FAB experiences a steeper and earlier increase in internal temperature with higher peak values. This shows greater thermal conductivity and lower heat resistance, thereby being 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.

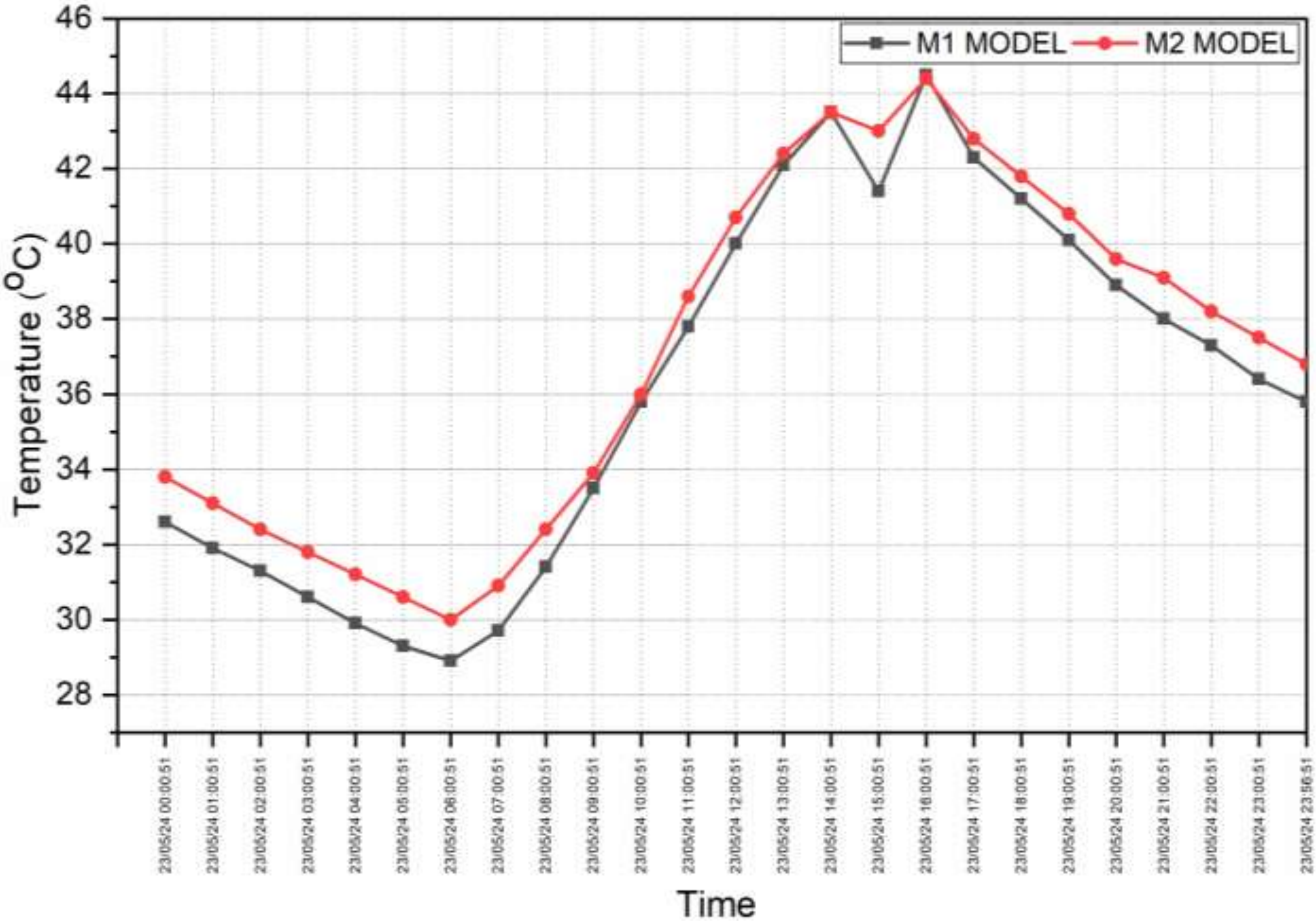


Fig. 12: Internal temperature variation of model houses M1 and M2 on a typical summer day.

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

$$Top = \frac{(Tmr + Tin)}{2} \quad .. (4)$$

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

$$Tmr = T1A1 + T2A2 + \ldots\ldots\ldots + \frac{TNAN}{(A1+A2+\cdots+AN)} \quad .. (5)$$

where TN = surface temperature of surface N; AN = area of the surface.

The overall trend of operative temperatures in the study shows a rising pattern (Figure 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 during early summer. When comparing M1 and M2, M1 consistently exhibits 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 and thus maintaining a cooler indoor environment. The peak operative temperature for M2 is likely observed in early June, possibly between June 1st and 5th, indicating higher heat retention and poorer thermal performance when compared to M1. Although M1 also reaches a peak, it occurs at a significantly lower temperature, demonstrating its superior thermal regulation. In terms of thermal comfort, the TES brick model (M1) remains closer to or within the thermal comfort range (typically 25–35°C) for a longer duration, 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 demonstrate that TES walls consistently reduced indoor temperatures compared to conventional alternatives under peak summer conditions. Although the experiments were carried out on 1 m^3 models, the observed thermal resistance and lower U-values can be extrapolated to larger building envelopes. In 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 average indoor temperature has been reported to decrease 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, 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, as well as reduced processing energy. Transportation costs are also minimized since 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% less than that of conventional bricks.

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**

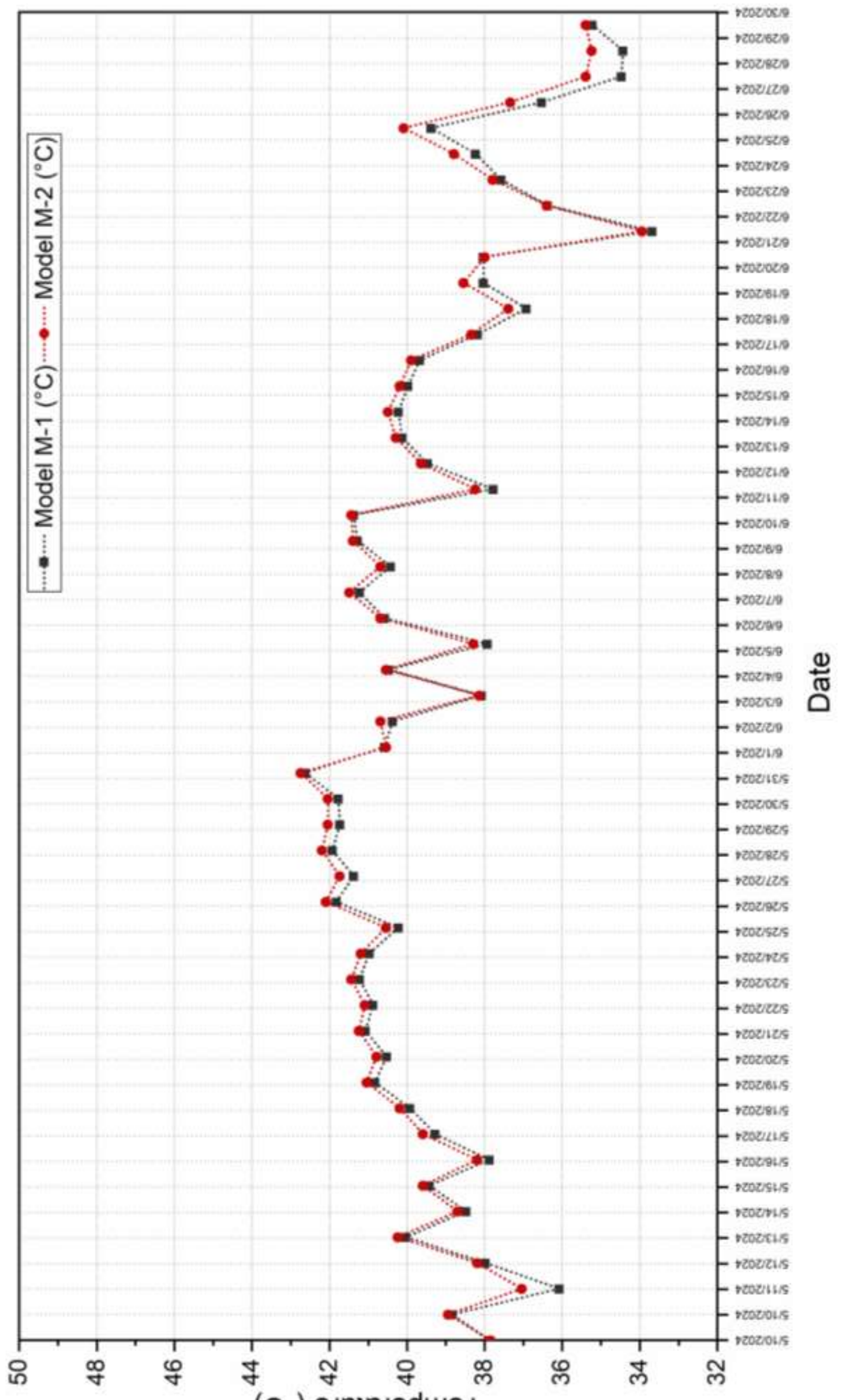


Fig. 13: Operative Temperature Profiles of Model House.

5. CONCLUSIONS

This research illustrates the viability of textile effluent treatment sludge (TES) as a sustainable and thermally efficient material for the manufacture of bricks.

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 market-purchased fly ash bricks, as verified through sustained temperature measurement 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—due to the thermal lag effect and lower heat gain, all important for passive thermal comfort in hot weather.

4. Quantitative thermal analysis, both operational temperature and heat transfer rates, also confirmed the higher thermal resistance of TES brick walls.

5. The cost evaluation showed high value for money, with TES brick price and construction costs being about 30–35% lower compared to conventional practices.

6. From a practical perspective, the use of TES bricks can improve passive thermal comfort and reduce 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 demonstrated performance in small-scale model houses provides a strong basis for pilot applications in full-scale residential and institutional buildings. Integration into government housing schemes and green building certifications could accelerate real-world deployment.

8. For future research, long-term durability studies, performance evaluation under varying climatic zones, and life-cycle environmental assessments are recommended. Further optimization of mix proportions and exploration of hybrid blends with other waste materials may also enhance properties and broaden applicability.

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

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