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Thermal Performance of Textile Reinforced Concrete Insulated Panels

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Abstract: The energy efficiency of construction materials plays a pivotal role in achieving sustainable building practices, where both embodied energy and operational performance define their lifecycle impact. This study presents an energy audit of Textile Reinforced Concrete Insulated Panels (TRCIPs), benchmarked against conventional concrete panels (CPs) and brick masonry walls. The thermal performance was evaluated through laboratory measurements of thermal conductivity using a TPS 2500S analyzer, with corresponding R-values and U-values computed to assess operational energy efficiency.

Results indicate that TRCIPs reduce thermal conductivity by 29% compared to CPs, achieving 26–35% higher thermal resistance. Economic appraisal demonstrates that although TRCIPs incur slightly higher initial costs, they achieve payback within 4–6 years under local tariff conditions and generate substantial lifecycle energy cost savings.

This integrated energy economic audit demonstrates that TRCIPs are energy smart, providing a replicable framework for evaluating sustainable walling systems. The results highlight TRCIPs as a viable next generation material for reducing building energy consumption and enhancing economic performance in construction.

Keywords: Energy Audit, Textile Reinforced Concrete, Thermal Performance, Insulated Panels, Sustainable building

I. INTRODUCTION

The building and construction industry is one of the largest global consumers of energy and natural resources, both during the production of materials and throughout the operational life of buildings. According to the International Energy Agency (IEA, 2023) [1], this sector accounts for nearly 36% of global final energy consumption and contributes approximately 40% of annual CO_2 emissions [2]. Such high embodied and operational energy demands make the sector a critical focus area for energy efficiency strategies and sustainable innovations [3].

Concrete remains the most widely used construction material, yet the energy intensity of Portland cement production has raised significant environmental concerns. Reducing the embodied energy of concrete through innovative material substitutions has thus become a pressing research priority.

Energy audits have emerged as effective tools for assessing the sustainability of construction materials and systems by quantifying both embodied energy (linked to material extraction, processing, and manufacturing) and operational energy (associated with thermal performance and building use) [4]. A comparative energy audit of different walling systems reported in literature are summarized in **Table 1**, highlights substantial differences in embodied and operational energy values [5] [6] [7] [8] [9]. Traditional brick masonry walls exhibit relatively high embodied energy due to the firing process of bricks, while concrete block walls demonstrate slightly lower energy intensity. Conventional reinforced concrete panels, despite their mechanical strength, remain highly energy intensive [10]. In contrast, expanded polystyrene-based sandwich panels offer much lower operational energy demands due to their excellent insulation but face criticism for their environmental footprint and recyclability [11].

Table 1: Energy Audit results for different walling system

Construction material	Typical thickness (inch)	Representative embodied energy (MJ/m²)	Operational energy / thermal remarks
Brick masonry (fired clay)	4–5	400–800 (single-leaf; higher for dense fired units)	Moderate thermal mass but poor insulation unless insulated; high EE due to firing energy.
Concrete block (hollow / solid)	6	200–600 (hollow blocks lower; solid / dense higher)	Moderate; hollow blocks + insulation reduces operational loads substantially.
Reinforced concrete panel (precast / cast-in-place)	4–6	600–1500 (varies with reinforcement content & thickness)	High thermal conductivity, relatively high operational cooling/heating unless insulated.
Precast sandwich panel (mineral/ EPS core)	4–6	200–600 (face + core dependent; EPS core lower EE but fossil-based)	Very low operational energy when high-quality insulation core used (EPS, PIR); trade-offs for recyclability.
EPS (Styrofoam) sandwich panel (typical façade)	4–5	150 – 350	Excellent insulation (low operational energy) but concerns over fire, VOCs and end-of-life recycling.

Recent advancements suggest that incorporating waste derived fibers, such as textile waste, not only improves ductility, crack resistance, and impact strength but also reduces density and thermal conductivity [12 [13]. These improvements directly influence the energy performance of concrete panels by lowering both embodied energy and operational energy requirements in buildings [14]. Previous research has largely concentrated on mechanical performance and durability of fiber-reinforced concrete [15]. However, while prior research has largely emphasized mechanical performance and durability of fiber reinforced concrete, sustainability assessments have predominantly focused on life-cycle analyses of conventional concrete [16]. Only limited studies have explicitly addressed the energy performance of textile fiber-reinforced systems, and even fewer have examined sandwich panels incorporating textile-based cores. Nonetheless, sandwich panels are well-recognized for their superior thermal insulation, enabling significant reductions in heating and cooling demands [17].

Textile Reinforced Concrete Insulated Panels (TRCIPs), as examined in this study, are designed to balance structural performance with reduced embodied energy and improved operational efficiency. This research presents a comprehensive operational energy audit of TRCIPs and benchmarks their performance against conventional walling systems. The findings are expected to contribute toward reducing overall building energy demand and economy.

II. METHODOLOGY

The methodology adopted in this research study encompasses material collection, fabrication of insulated panels, energy auditing procedures, and evaluation techniques to assess the energy performance of Textile Reinforced Concrete Insulated Panels (TRCIPs) in accordance with established international standards. An experimental procedures and analytical modeling, was employed to evaluate the operational energy demand of TRCIPs, with comparative benchmarking against conventional concrete panels (CPs).

The study was conducted in the following stages:

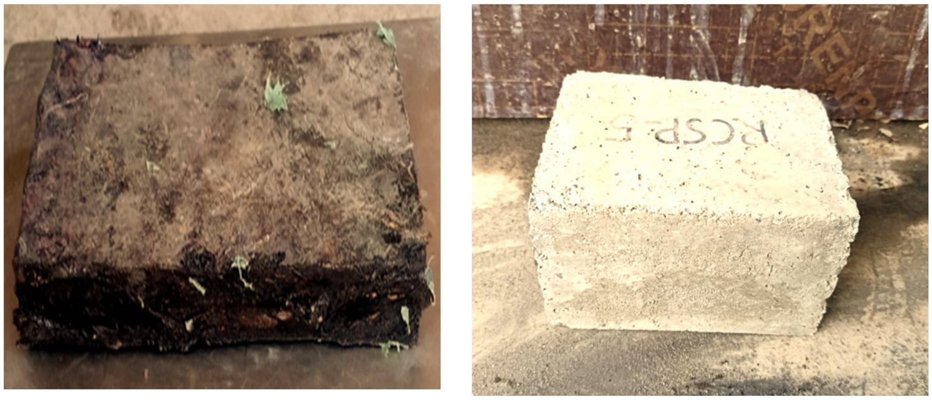
1) Fabrication of Panels
2) Experimental Testing
3) Operational Energy Evaluation (Thermal Performance Analysis)

A. Panel Fabrication

The fabrication of reference CPs and TRCIPs was carried out following the design and construction configuration established in a previous experimental study by Wajid Ali, which focused on the seismic capacity assessment of precast panels [18]

The CPs were produced using normal concrete with a mix ratio of 1:2:4 (cement: sand: coarse aggregate). A prefabricated cage of 16-gauge steel wire mesh (1″ × 1″ spacing) was placed within the concrete to provide reinforcement and improve crack resistance.

For the TRCIPs, the fabrication process involved preparing a 1-inch-thick textile fibers core as illustrated in **Figure 1 (a)**, which was sandwiched between concrete wythes as shown in **Figure 1 (b)** according to the design configuration established in a previous experimental study [18].



a B

Figure 1: (a) Textile Fibers Core (b) Textile Reinforced Concrete Insulated Panel

B. Experimental Testing

The thermal insulation performance of both types of panels was evaluated indirectly through measurement of thermal conductivity using Thermal Constants Analyzer (TCA) in accordance with ISO 22007-2 at UET Peshawar as illustrated in **Figure 2**. The sensor consists of a flat, double-spiral element (hot-disk) that functions simultaneously as a heat source and a temperature sensor. The top and bottom faces of the panels were surface-leveled to ensure uniform contact with the TPS sensor. A flat TPS sensor was placed at the mid-plane between two identical insulated panel specimens. The specimens were carefully aligned and clamped to ensure full surface contact without air gaps. The sensor was supplied with a transient electrical current to generate heat. The corresponding temperature rise was continuously recorded by the thermal analyzer. Measurements were conducted under controlled laboratory conditions (25 ± 2 °C).

Figure 2: Thermal Conductivity Test Set up connecting with TCA

C. Data Acquisition and Analysis

The thermal conductivity was calculated directly by the TPS 2500S software, based on the transient response of the sensor. Multiple readings were recorded to ensure repeatability, and the mean value was reported. After obtaining the value of thermal conductivity, thermal resistance (R-value) for both types of panels were computed using equation:

$$R = \frac{t}{k}$$

where t is the specimen thickness (m) and k is thermal conductivity (W/m·K).

Thermal conductivity serves as a key parameter for quantifying the insulation efficiency of the TRCIPs compared to conventional CPs. Lower thermal conductivity indicates reduced heat transfer, which directly translates into lower cooling and heating energy demand in buildings. The measured k values were further incorporated into the energy performance evaluation to estimate potential energy savings and cost benefits associated with the use of TRCIPs in building envelopes.

III. RESULTS ANALYSIS AND DISCUSSION

The primary objective of this study was to conduct an energy audit by evaluating the thermal performance of TRCIPs in comparison with conventional CPs. The focus was to determine how effectively TRCIPs reduce heat transfer, thereby improving insulation efficiency and contributing to sustainable construction practices. To achieve this, thermal conductivity tests were performed using the TPS 2500S analyzer under steady state laboratory conditions. The obtained thermal conductivity values and calculated thermal resistance values are summarized in Table 2, which highlights the comparative performance of the different panel types.

Table 2: Thermal Conductivity result from Thermal Constant Analyzer TPS 2500S

Specimen Type	Thickness (in)		Thermal Conductivity, k (BTU/hr·ft·°F)	R-value (hr·ft²·°F/BTU)
Textile Block	1"		0.248	0.34
TRCIP	3"		0.746	0.34
CP	3"		1.011	0.25

The results clearly demonstrate that the textile waste as a core material significantly reduced the thermal conductivity of the TRCIP compared to the conventional CP. The textile waste block itself exhibited the lowest conductivity, which confirms its suitability as an insulating material. From the results of R-values, it is indicted that TRCIPs provide 35% higher thermal resistance than conventional CPs of the same thickness, thus improving building envelope insulation.

A. *Cooling Energy Savings*

Over an annual cooling period of approximately 120 days, this translates into 15–20% reduction in HVAC electricity demand, depending on climatic zone.

B. *Economic Benefits*

The economic benefits were estimated by linking energy savings with electricity cost. Assuming:
Average electricity tariff is PKR 45/kWh (domestic slab, 2025 rates),
Cooling load reduction is 20%,
Average residential cooling energy use is 2000 kWh/year,
then annual savings approximately equal to PKR 18,000/year per household.
Thus, households adopting TRCIPs in wall construction can save approximately 18,000 PKR annually in electricity costs. Over a 20-year building life cycle, this translates into PKR 360,000 savings, excluding tariff escalation.

IV. CONCLUSIONS

This study evaluated the thermal insulation performance of TRCIPs against conventional CPs using the TPS 2500S analyzer. The findings clearly establish the superior thermal efficiency of TRCIPs, driven by the incorporation of textile waste as a lightweight insulating core material. The findings of the research study are concluded as:

1) The TRCIP exhibited 29.2% lower thermal conductivity than conventional CPs, confirming the potential use of textile waste as a sustainable insulating core.
2) Based on an average household consumption of 2000 kWh/year for cooling, TRCIPs enable savings of approximately PKR 18,000 annually, equivalent to PKR 360,000 over a 20-year building life cycle.
3) In addition to lowering the panel’s weight, the integration of textile waste cores into TRCIPs contributes to sustainability by reducing embodied energy, reusing textile waste, and enhancing thermal efficiency, making them suitable for sustainable construction applications.

These results demonstrate that TRCIPs are not only technically viable but also economically advantageous for sustainable construction applications.

V. RECOMMENDATIONS

1) TRCIPs shall be promoted as an alternative to conventional panels for residential and commercial buildings, particularly in regions with high cooling loads.
2) Building energy codes in Pakistan shall include guidelines for the use of low conductivity, waste-based composites such as TRCIPs to encourage adoption.
3) Future studies should focus on long term durability testing, fire resistance, and mechanical strength optimization of TRCIPs to ensure compliance with structural and safety standards.
4) A full environmental life cycle assessment of TRCIPs, including embodied energy and carbon footprint, is recommended to quantify their sustainability benefits.
5) Subsidies or tax incentives may be introduced to encourage builders and households to adopt TRCIPs, enhancing energy security and reducing national electricity demand.

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