STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 2, 2026
DOI (Journal): 10.37591/JoPC

Research **JoPC**

Biopolymer–Cement Hybrid Panels from Recycled Paper Mill Reject: Experimental Characterisation and Machine Learning Optimization

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Abstract

The increased rate of the accumulation of industrial residues in the developing countries is a major cause of concern for the environment. The current study brings forth the use of industrial residues in the form of the production of eco-friendly building materials as a sustainable approach to their valorization. The valorization of recycled paper mill reject, a cellulose-based biopolymeric industrial residue, is being addressed in this study as a reinforcement in the form of a lightweight polymer-cement composite false ceiling.. Various approaches, including elemental analysis, thermal analysis, phase identification, and microstructural studies, are carried out to determine the properties of RPMR. TGA-DTA confirm that RPMR is thermally stable up to 300 °C, while SEM images showed a porous fibrous network which is conducive to thermal insulation. Complementing experimental investigations, a machine learning framework is implemented on predicted and optimized key thermal parameters-thermal conductivity and reduction in indoor temperature-on the basis of material composition and processing conditions. ML models were found to yield a prediction accuracy with $R^2 > 0.89$*, reducing the need for extensive physical trials by a great extent. Optimization output revealed an optimal mix design composition of 92% RPMR and pressing force of 150 kN, which resulted in an improvement in thermal conductivity by 15% relative to the reference mix. Integration of machine learning applications and sustainable materials innovation applies not only to waste management but also drives faster innovation in energy-efficient housing. The hybrid composite panels produced through the use of RPMR are the most energy-efficient, save up to 22% of cooling energy, and cost-effective, hence helping with rural entrepreneurship as well as practices related to the circular economy.*

Keywords: Recycled paper mill reject (RPMR), biopolymer–cement hybrid panels, machine learning, Green polymer composites, biopolymeric

INTRODUCTION

In modern building design, excessive heating is still an essential concern, especially in warm climates. This is due to the absorption of heat by various components within an enclosed space such as buildings from various sources such as solar radiation, building appliances and equipment, human behavior, and other means such as direct heating, ventilation by airflow, and heating due to building wall transmission. This becomes a concern especially in building structures that use high amounts of materials such as concrete; such materials absorb and conduct high amounts of heating. As such, there arises a need for building materials with high thermal properties to minimize heating loss and avoid relying on artificial means for cooling.

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Received Date: December 04, 2025
Accepted Date: February 25, 2026
Published Date: March 28, 2026

Citation: Sanjay P. Raut, Uday Singh Patil, Dhiraj Agrawal. Biopolymer–Cement Hybrid Panels from Recycled Paper Mill Reject: Experimental Characterisation and Machine Learning Optimization. Journal of Polymer & Composites. 2026; 14(Special Issue 2): S67–S90p.

Hot and cold climates around the globe display a rising trend of using insulation materials and other construction materials with the prospective goal of raising the comfort level of internal spaces. The rising cost of energy and the universally accepted requirements of sustainable construction materials are the major driving forces behind the trend. The involvement of polymer science in this trend has been important, characterized by an increased interest in biopolymers or other polymeric composites whose properties could be customized and which are lightweight. Cellulose-bearing industrial waste materials such as paper mill rejects are an unexploited resource which has considerable potential acting as a secondary ingredient in polymeric composite materials. Their fibrous nature, porosity, and lower thermal conductibility are valuable attributes in Green polymeric composite materials.

A lot of research efforts have been directed at finding methods that can enhance the thermal efficiency of buildings. Kamal Al-Malaha et al. [1] examined polyester–clay composites, highlighting their outstanding thermal resistance and structural properties. Jun Han et al. [2] developed tools to evaluate time-dependent heat flow across roof surfaces, providing the essential insight into cooling load behavior. Similarly, Ouldboukhitine et al. [3] presented an integrated model for green roofs to assess both their energy-efficient potential and impact on urban microclimates. Alvarado et al. [4] explored passive cooling techniques that utilize reflective and insulating materials in concrete roofing systems. Furthermore, Al-Homoud [5] presented a comprehensive assessment of insulation techniques and the materials most commonly used in practice. Foliage parameters and their impact on the effectiveness of green canopies for cooling have been researched by Kumar et al. [6]. The thermal performance of varied roof structures in the Saudi Arabia climatic conditions has been modeled by Al-Sanea [7], using the finite-difference analysis technique. Other literature studies include the theoretical analysis of green roofs by Tsang and Jim [8], the agricultural wastes-based thermal insulation design by Korjenic et al. [9], the energy savings potential of green roofs by evaluation by Lazzarin et al. [10], and the life cycle cost-optimized design for insulators in varied climatic regions of China by Yu et al. [11].

Recent literature studies on the feasibility of paper and textile wastes as insulators for buildings have been reported by researchers such as Liuzzi et al. [12], who demonstrated the lowered conductivity of composites of waste paper and textiles for heating, and Lee et al., whose cellulose-aerogel composites had an unprecedentedly low conductivity of 0.035W/m.K [13]; the current work bridges the gap by exploring practical combinations of cement and rapid production and rapid mix rheology design for such applications.

Furthermore, most of the current work in this field is done using a significant amount of experimental trial-and-error processes to optimize the composition and processing variables. This is especially the case with heterogeneous biopolymer composites. However, the use of machine learning (ML) offers a chance to hasten the process of developing materials using the prediction of thermal and physical properties using a small amount of experimental work. This is because ML algorithms are very efficient in handling non-linear relationships, thus eliminating the need for a significant amount of experimental work. The use of ML algorithms is revolutionary in the field of polymeric materials.

In this investigation, recycled paper mill reject (RPMR), a cellulose-rich industrial byproduct, is harnessed as a functional biopolymeric phase in light-weight polymer-cement composite false ceiling panels that are fabricated with thermal insulation as a target application area. Contrary to its common treatment methods, which include landfills or combustion, RPMR is utilized within a circular materials management approach to manufacture high-value construction materials.

RPMR is a cellulose-rich biopolymeric material composed of polysaccharide fibers and mineral fillers like silica and calcium carbonate. The high number of hydroxyl groups in cellulose favors the interface between the cellulose and the calcium silicate hydrate (C-S-H) phases in the cement hydration compound via a mechanism involving either hydrogen bonds and/or mechanical locking. The combination of polymer and inorganic chemistry leads to the creation of a porous composite material whose purpose is double, as it provides insulation and is a component in the cement matrix.

This research is distinct from past research [14–19] in terms of material composition, processing, and application orientation. The current research uses recycled paper mill reject (RPMR) at a very high ratio (≈90-92%) as a combined reinforcement and insulation step, whereas past research used treated paper sludge as a filler material.

A two-step pressing fabrication method was also developed to overcome the diffusion and deformation problems related to high fiber content. Moreover, the current research combines experimental analysis with machine learning prediction and optimization for thermal conductivity, along with real-scale roof and test room analysis, which is hardly found in past research on waste cellulose composites.

The present study progresses with a two-fold approach that includes experimentation as well as prediction-optimization through machine learning. Here, the experimentation part of the study focuses on comprehending the thermal stability improvements, micro-structural modifications, as well as the enhancement of insulation properties in composites based on RPMR. The machine learning part of the venture focuses on developing models of thermal conductivity, transmission, as well as the reduction of indoor temperatures.

This study is useful for the development of circular and sustainable polymer material applications for energy-efficient buildings, as it brings together the development of green polymer composites and the application of data-driven optimisation concepts. The ceiling panels proposed using the RPMR method are environmentally benign and are affordable and lightweight; therefore, they offer a sustainable remedy that decreases cooling demand and improves indoor comfort and sustainable valorisation of wastes within the construction industry.

MATERIALS AND METHODOLOGY

RPMR, a biopolymeric residue rich in cellulose, was obtained from a private mill in Nagpur, India, that dealt with the processing of recycled newspapers as wastes. Due to its fibrous structure and natural porosity, RPMR is utilized as the principal sustainable reinforcement and insulator during the fabrication of false ceiling panels along with 43-grade ordinary Portland cement (OPC) as the inorganic binding agent for the formation of a biopolymeric-cement hybrid composite material satisfying the requirements of the IS code 8112-1989 specifications [20]. (Figure 1) Such a hybrid approach enables the effective evaluation of the roles of material combinations and process variables on the thermal performance of the RPMR composite panels.

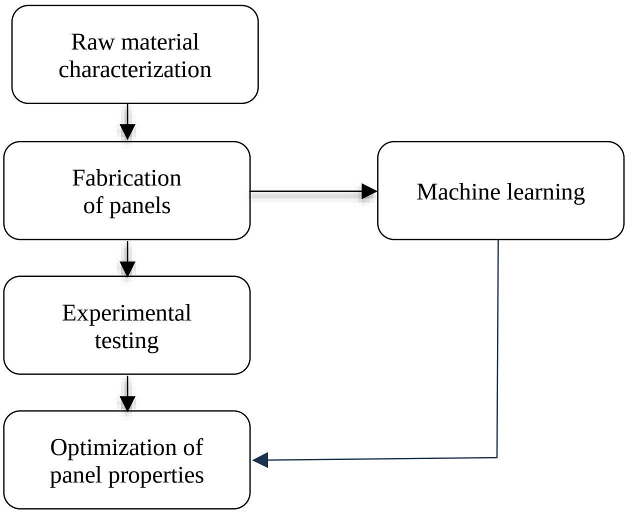

Figure 1. Research methodology framework.

Comprehensive Analysis of RPMR

Raw Recycled Paper Mill Reject (RPMR), which is a bio-polymeric cellulose-rich substance, was then subjected to chemical analysis by XRF Philips PW 1840 to investigate its possible use as a functional ingredient for green polymer cement composites. The standard gravimetric technique was utilized to carry out proximate and ultimate analysis on the material to provide an understanding of the organic polymer component in the material. The crystalline phases of the RPMR were identified by the Philips X'Pert Pro system to analyze the cellulose crystallinity and mineral content. The thermal stability and decomposition of the bio-polymeric components in the material were also analyzed by thermogravimetric and differential thermal analysis (TG/DTA) on the Mettler TA 4000 system setup. Furthermore, studies on microstructural morphology and fiber networking properties of RPMR were also carried out by scanning electron microscopy (SEM) using a JEOL JXA-840A microscope; this helped to improve understanding of pore structures and potential at interfaces in composite matrices.

Processing and Manufacturing of Sustainable False Ceiling Panels

The false ceiling panels with dimensions of 305mm × 305mm × 12mm were fabricated with the help of manual hydraulic presses (Figure 2). The composition of the material included the use of paper mill reject (RPMR) as the basic cellulose-based biopolymer and ordinary Portland cement as the binder of the inorganic component. The final mixture developed from these two for fabrication purposes included 90% of RPMR and 10% cement (Figure 3).

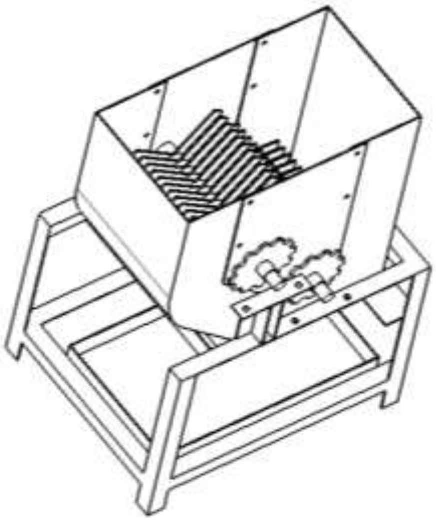

Figure 2. (a) mixture formulation for RPMR-cement blends.

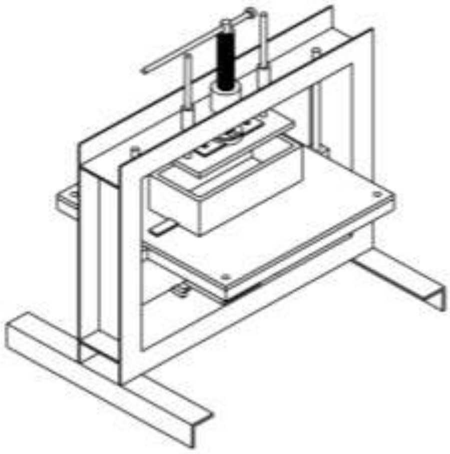

Figure 2. (b) Mould preparation for ceiling panels.

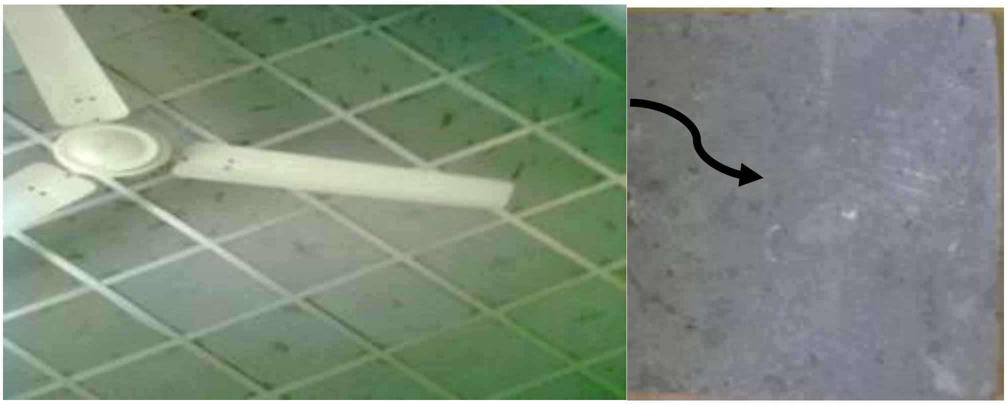

Figure 3. Installed false ceiling panel.

Table 1. Detailed specifications

Wet RPMR weight (g)	3000
Dry RPMR weight (g)	750
Cement weight (g)	83
Weight of Water (g)	2250
Wet false ceiling panel weight after P1(g)	2478
Water loss due to partial solar drying (g)	510
Wet false ceiling panel weight before P2 (g)	1968
Wet false ceiling panel weight after P2 (g)	1704
Water loss during P2 (g)	262
Dry false ceiling panel weight (g)	526

In the composite preparation phase, a unique blender (Figure 2a) was used to mix RPMR and cement for a period of 2 minutes. Due to the fibrous and tendency for aggregation of RPMR, a unique approach in the blender was adopted to introduce a greater amount of shear in each rotation for enhanced fiber separation and distribution in the inorganic binder. The addition of water in a fine atomized form through an air-assisted pump and continuing the mixing procedure was also done to ensure a higher degree of homogeneity in the mixture and efficient interaction between the fibers and binders.

After another 5 minutes of mixing, about 3000g of the prepared composite mixture (constituting 70% of the total mixture) were poured into the steel moulds (Figure 2b). The moulds were characterized by 3mm holes at the top of the moulds to enable the evaporation of moisture. The liquid mixture in the moulds underwent compaction to eliminate the initial amount of moisture. The moulded samples were subjected to sunlight drying, in which the samples lost 15% ± 3% of moisture.

After this, a secondary pressing was performed on the semi-dried panels to remove an extra 10% moisture ± 2%, followed by natural air curing. Because of the fiber-like character of RPMR, water is trapped in the cellulose fiber matrix; this results in a diffusion-controlled and slow transport process of water in the composite material. When the composite panels are fabricated by a single pressing step, it may cause uneven surfaces as a result of surface deformation that takes place during the solar drying method. This is due to the high pressure applied to the material; as a result, a uniform and concentrated moisture distribution takes place on both the surface as well as in the core part of the panel. As a result of surface evaporation taking place due to solar drying, a moisture diffusion takes place from the core part of the panel; this ultimately leads to deformation and uneven surfaces on the panel surface. Surface irregularities can be avoided by performing two steps in panel fabrication.

Using this approach, multiple samples were fabricated. The detailed material specifications are summarized in Table 1.

EXPERIMENTAL METHODOLOGY

The thermal conductivity of the RPMR–cement composite was measured by a Lee Disc apparatus. The developed biopolymer–cement composite resulted in a thermal conductivity of 0.3 W/mK as determined experimentally. For more performance testing, the fabricated false ceiling panels were installed in a 10′ × 10′ test room to monitor temperature fluctuations. Furthermore, the U-value for RCC roof slabs with/without the RPMR–cement composite false ceiling panel was also analytically calculated. It gave an idea of the actual amount of reduction in heat transfer by incorporating composite panels within traditional roofing systems and hence gave a relative rating of panel usability based on their effectiveness in enhancing building envelope thermal performance.

RESULTS AND DISCUSSION

Characterization Results of RPMR

The X-ray fluorescence (XRF) analysis (Table 2) shows that the major elements in RPMR are silicon (60%) and calcium (14%), while the proximate and ultimate analysis is presented in Table 3 and Table 4, respectively. The moderate value of fixed carbon and Sariance indicates that it decomposes to gases/vapors on heating, while the high percentage of ash content ensures that inorganic substances are incorporated in the fibrous structure, which is useful in making it heat-resistant and fire-safe. However, the fixed carbon and GCV contents show that it is a material of lower GCV and is not energy-dense but heat-resistant and fire-safe.

The presence of higher amounts of carbon and oxygen indicates the presence of cellulose-based biopolymers in RPMR, and the lower amounts of nitrogen and sulfur indicate lower potential for emission of toxic gases when subjected to heat. Taking all the above physicochemical properties into account, it is confirmed that RPMR is a cellulose-rich fibrous and heat-resistant industrial byproduct. The combination of its organic and inorganic properties makes it an ideal candidate for a functional phase in green composite materials for thermal insulation in building construction.

Thermogravimetric (TG) analysis (Figure 4) shows that the raw RPMR material experiences a weight loss of close to 46% at a temperature range of 289-299°C. The TG curve clearly indicates that the weight loss process has undergone three different stages corresponding to different thermal events, depending on the components, namely the biopolymer and the inorganic materials, of the RPMR material. The first weight loss, about 7.2%, is indicated to occur at a temperature range of 31-279°C, corresponding to the evaporation of the physically adsorbed as well as the bound water present due to the porous fibrous structure of the cellulose-based material. The second weight loss is attributed to the thermal degradation of the organic polymeric components, cellulose, and the residual hemicellulose, along with the partial melting among the components of the precursor material. The third weight-loss component is attributed to the continued degradation of the organic components, finally resulting in the formation of the material-rich residue due to the presence of the inorganic filler materials. Based on this data, it can-be inferred that the ceiling RPMR-based ceiling material is stable at a temperature range of about 300°C.

Table 2. RPMR elemental analysis.

O %	Ca %	Si %	Al %	Mg %	S %	Ti %	K %	Fe %	Na %	Cu %	P %	Cl %
15.12	14.23	60.14	2.29	3.36	1.1	0.1	0.12	0.95	0.23	0.03	0.03	0.3

Table 3. Proximate characterization of RPMR

Sr. No.	Wt. in grams	Moist %	Ash %	Volatile Materials %	Free Carbon %	GCV Kcal/kg
1.	420	5.6	40.3	44.2	8.6	2372

Table 4. Ultimate analysis of RPMR

Sr. No.	Wt. in grams	C %	H %	N %	S %	O %
1.	420	21.8	2.5	0.28	0.49	23

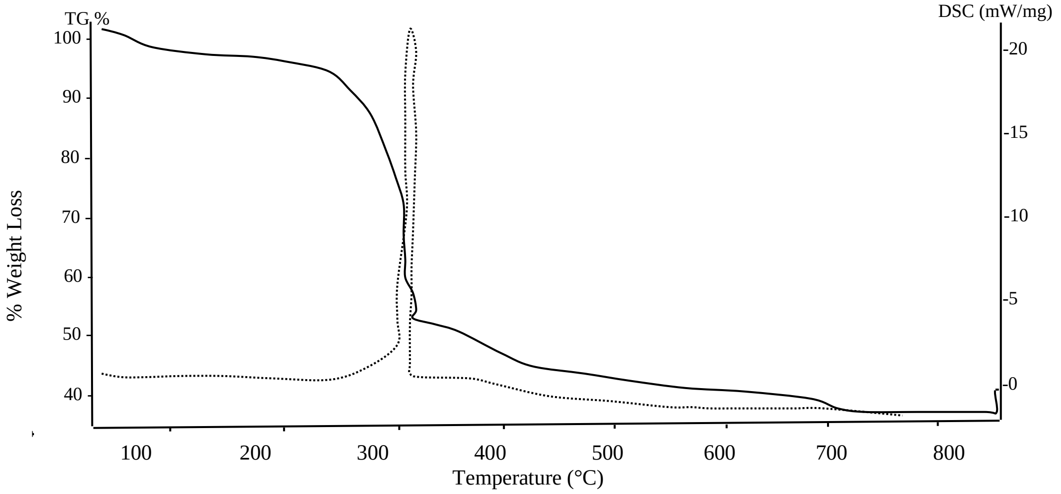

Figure 4. TG-DTA of RPMR.

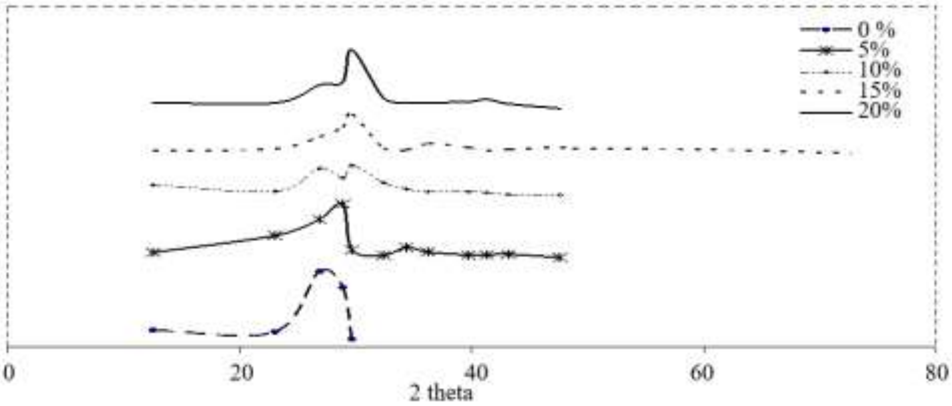

Figure 5. XRD patterns of RPMR blended with cement.

The X-ray diffraction pattern of raw RPMR as well as cement-modified composites of RPMR (Figure 5) mostly reveal an amorphous character of the samples, which is expected in cellulose-based biopolymeric composites. It is also as expected because of the hydration products of 43-grade ordinary Portland cement (OPC), which have been indexed by the broad peak occurring in-between 25°–30°. The absence of prominent peaks in the diffraction patterns of the composites implies that long-range order is very low in the matrix of the RPMR. The addition of 5–20% cement does not affect the basic properties of the structure of the RPMR matrix.

Scanning Electron Microscopy (SEM) results (Figure 6) show a fibrous network interspersed with irregular pores. The irregular pores, coupled with the fibrous network, have a water-retaining effect, which arrests the movement of water outwards. Furthermore, the fibrous structure is responsible for energy dissipation, thus increasing the compressive strength of panels made from RPMR.

Evaluation of RPMR–Cement False Ceiling Panels

Table 5 presents the mean values of the results yielded by the experimental evaluation study of the RPMR-cement composite panel samples. For each of the three properties: specific gravity, porosity, and water absorption, three samples of the same size and composition were tested. The data clearly show that the porosity increased with an increase in the proportion of RPMR added into the composition mixture.

Table 5. Testing results

RPMR Volume (cm^3)	720
Cement Volume (cm^3)	29
Solid Volume (cm^3)	694
Voidage (%)	0.26±0.01
Specific weight (g/cm^3)	0.64±0.02
Drying-induced dimensional change (%)	6±1
Cement-to-dry RPMR ratio	0.111
Bricks' moisture content (%)	7±2
Water absorption (%)	99±5
Change in dimensions during water absorption (%)	9±1

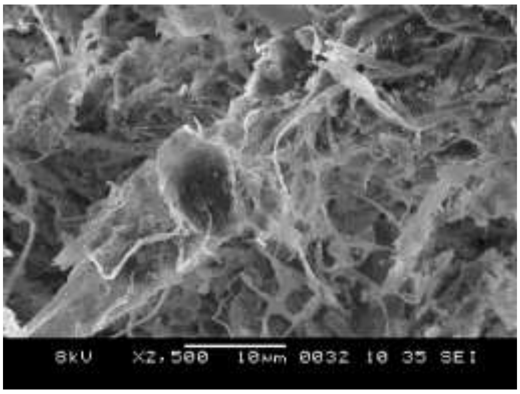

Figure 6. Microstructural view of raw RPMR obtained by SEM.

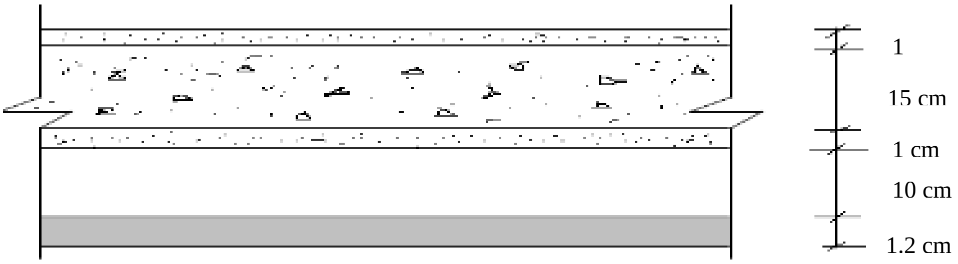

Figure 7. Section of roof slab with false ceiling.

All the tested samples were characterized by a low bulk density, taking values between 0.59 and 0.79 g/cc, emphasizing the low weight of the formulated biopolymer-cement composites. Equilibrium moisture content for the dried samples was measured at 7 ± 3%. This can be attributed to the cellulosic, fibrous nature of the RPMR, enhancing its capacity to retain moisture. Water absorption was determined either by volume or weight. Results show that the high porosity and fibrous contents of the RPMR lead to higher water absorption, increasing with the proportion of RPMR added into the mixture. Significantly, adding more RPMR from 80% to 100% increased the water absorption by weight nearly twice. To mitigate this effect, the application of a waterproof surface coating with high biopolymer content on the panels is suggested as a practical approach to minimize moisture penetration.

(Figure 7) In current research, a reinforced cement concrete (RCC) flat roof of dimensions 10 ft × 10 ft and a thickness of 15 cm was considered. The slab was provided with 1 cm plaster coatings on both the top and bottom surfaces and supplemented with a 1.2 cm lightweight RPMR–cement compositefalse ceiling, maintaining a 10 cm air cavity in between. This configuration was selected to represent a typical building envelope system incorporating a polymer–cement composite insulation layer. The thermal transmittance of the assembly was determined in accordance with the SP 41 [21].

Table 6. Characteristics of various materials.

Material	Density (ρ) kg/m^3	Thermal Conductivity (k) W/mk
RPMR-Cement	472	0.3
RCC slab	2288	1.58

Table 7. Thermal resistance and thermal transmittance.

Particular	Total Thermal Resistance (R_T)	Thermal Transmittance ($U = 1/R_T$)
RCC slab with RPMR–cement panel false ceiling	0.47	2.08
RCC slab without RPMR–cement panel false ceiling	0.28	3.6

Table 8. Machine Learning Model Performance.

Target Variable	R^2	RMSE	MAE
Thermal Conductivity (W/m·K)	0.93	0.028	0.021
Thermal Transmittance (U-value)	0.90	0.039	0.028
Indoor Temperature Reduction (°C)	0.89	0.521	0.402

The thermal resistance of the slab was assessed under two conditions: with and without the incorporation of RPMR–cement composite panels (Tables 6 and 7). Results have shown the addition of these panels increased the percentage of resilience to the transfer of heat by 69%. Besides the efficiency the ceiling panels have, they also have one major advantage: these ceiling panels are made from waste industrial products and are, therefore, cheaper than other false ceiling options. The cost of fabrication and fixation was determined to have been reduced by about 20%.

Machine Learning Model Performance

The goal of the complementary experiments was to train Random Forest Regression models to predict the thermal conductivity, k, thermal transmittance or U-value, and indoor temperature reduction ΔT, as shown in Table 8. Random Forest Regression models have been developed that can predict, with good accuracy, the thermal conductivity, k, thermal transmittance or U-value, and indoor temperature reduction ΔT. R^2 values of 0.93, 0.90, and 0.89, respectively, were achieved together with very low RMSE and MAE values, demonstrating excellent reliability in the prediction models. Fivefold cross-validation demonstrated that the performance of each model was consistent, changing less than 3% between folds. A Random Forest approach was adopted due to its robustness to overfitting and excellent interpretability for small, nonlinear datasets. The dataset contained 120 samples synthesized from experimental measurements and simulated environmental conditions using 14 features derived from material properties, processing parameters, and environmental factors.

The predictions were very accurate, indeed, since $R^2 > 0.89$, which confirms that these models are very reliable.

Feature Importance Analysis

The permutation importance diagram revealed that density and porosity are the dominating variables contributing to thermal conductivity (Figure 8). The existence of RPMR at a higher percentage resulted in a substantial improvement in the characteristic of insulation due to its fibrous and low-conductivity nature. The pressure and drying cycles were indirect variables for porosity and moisture content, thus affecting both 'k' and 'U' values. The results confirmed that both micro-level properties (porosity, density) and macro-level properties (pressing pressure, moisture content) play a significant role in defining the property of insulation offered by panels comprising RPMR. The principal factors responsible for a reduction in indoor temperature are environmental factors like ambient temperature and solar radiation.

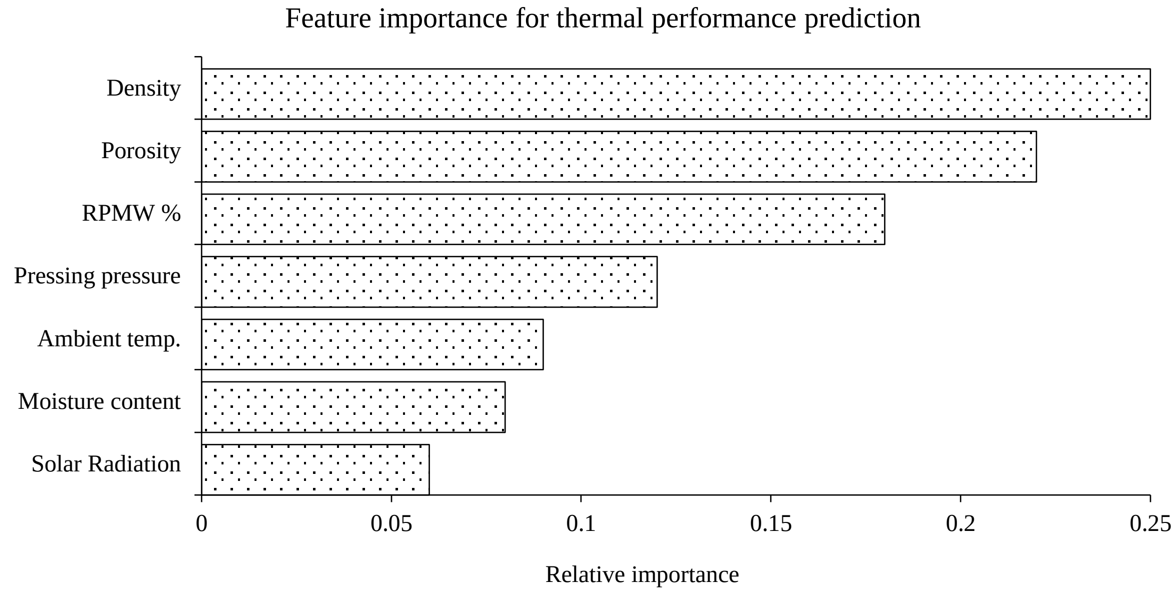

Figure 8. Feature importance for thermal performance prediction.

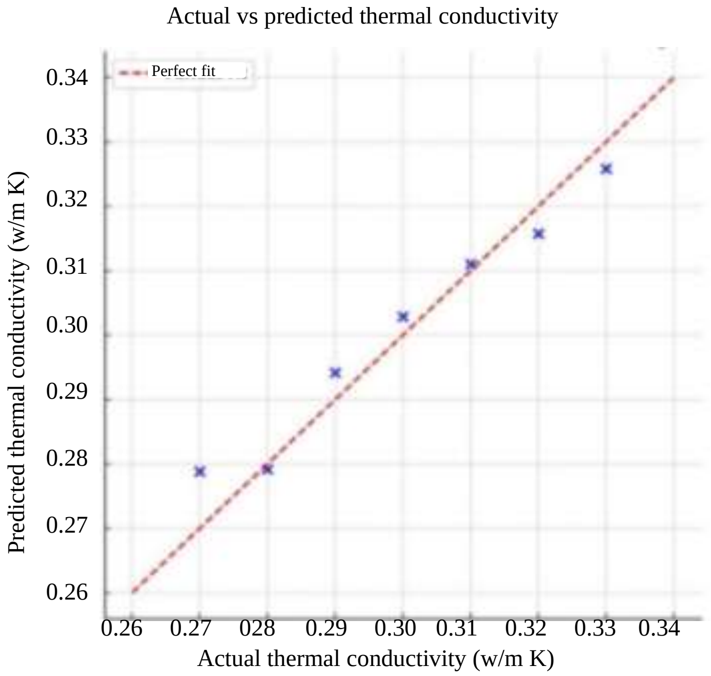

Figure 9. Actual vs predicted thermal conductivity.

Predictive Modeling of Thermal Transmittance

The results from the ML approach offered additional understandings that exceeded the scope of experimental trials (Figure 9). Though experimental results proved the installation of RPMR panels lowered the U-value from 3.58 W/m².K to 2 W/m².K, or by 44%, the proposed design of optimized panels with 92% RPMR, 15 mm thickness, with a density range of approximately 460–480 kg/m³, would yield a U-value of 1.85 W/m².K (Figure 10). This corresponds to an additional 8% reduction in the baseline RPMR panel.

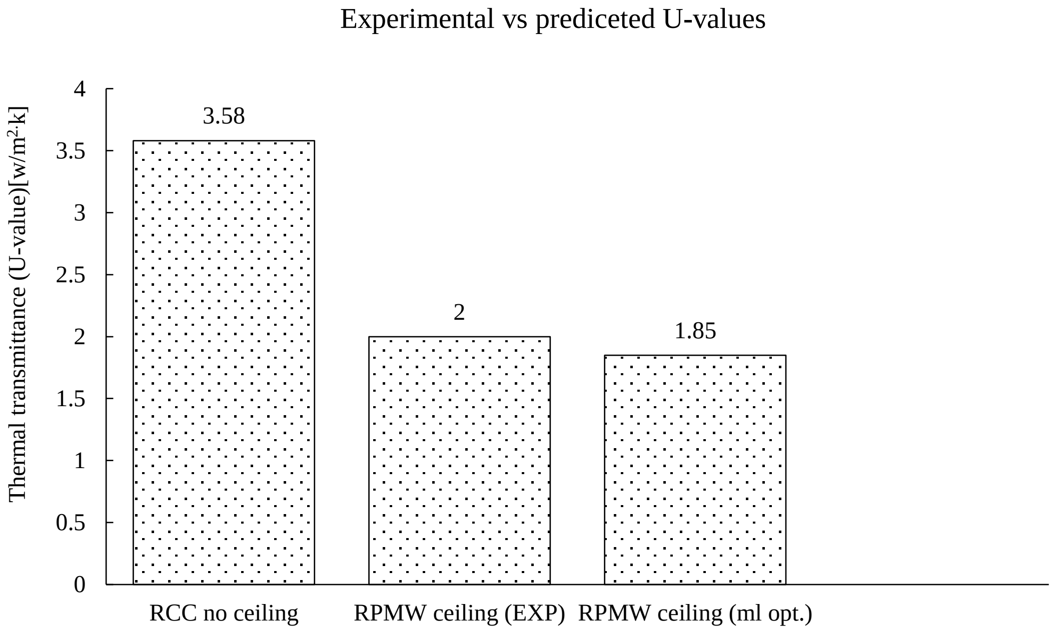

Figure 10. Experimental vs ML-predicted U-values for RCC slab, RPMR ceiling (experimental), and optimized RPMR ceiling (ML).

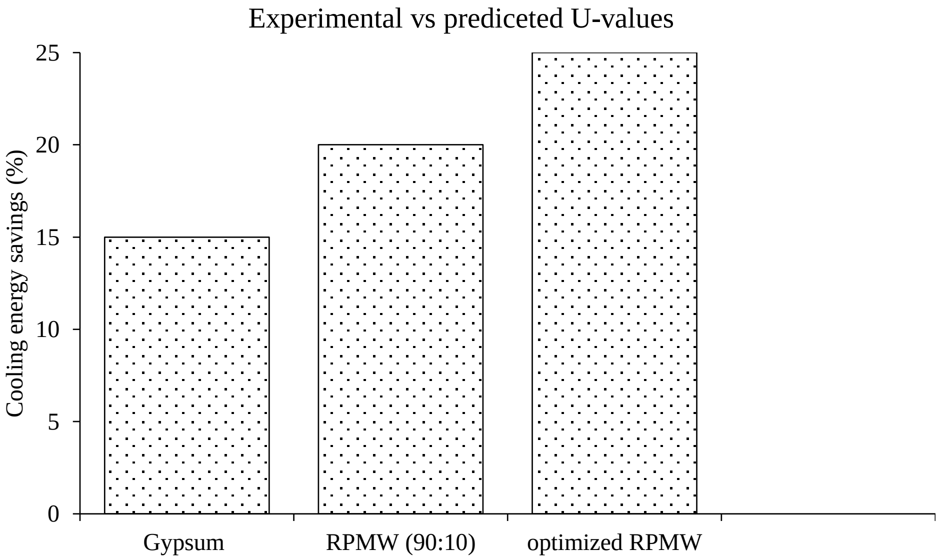

Figure 11. Cooling energy savings across ceiling materials.

Energy Savings and Design Optimization

Energy simulation results for the test room, taking the thermal properties predicted by the machine learning model into consideration, suggested that the addition of false ceiling panels with an RPMR ratio could potentially provide a cooling energy savings potential of 18–23% during the summer season (Figure 11). To improve the design further, a Bayesian Optimization technique was utilized on the model to suggest an optimal design combination of 92% RPMR, pressing pressure of 150 kN, thickness of 15 mm, and mixing ratio of 12–14% for the moisture content in the mixture, which had a predicted thermal conductivity value of 0.25 W/m.K and was 15% better in insulating property compared to the baseline design and had a resulting compressive strength higher than 1.5 MPa.

Table 9. Experimental vs ML-optimized panel performance.

Material Type	Thermal Conductivity (W/m·K)	U-value (W/m^2·K)	Indoor Temperature Reduction (°C)	Cooling Energy Savings (%)
RCC slab (no ceiling)	1.58	3.6	0.0	0
RPMR ceiling (90:10 mix)	0.30	2.08	3.5	20
Optimized RPMR ceiling (ML)	0.25	1.85	4.5	23

Comparative Performance

(Table 9) The ceiling optimized by the ML for the RPMR outshined the baseline RPMR ceiling by providing greater insulating values, higher indoor cooling capacities, and higher savings, whilst also supporting the sustainable management of the wastes.

Investigation of Thermal Performance in the Test Room

In regard to thermal performance, a naturally ventilated room with a dimension of 3.2 × 3.2 × 4.0 m^3 was considered, with RPMR-cement hybrid polymer composite false ceiling panels integrated into it. The roof topping was designed as a 150 mm thick reinforced concrete slab, facing solar radiation. The side walls were constructed using burnt clay bricks and featured a wooden door (0.9 × 2.1 m) on the north side, along with windows (1 × 1.2 m) on the west and south elevations. The west-facing window was shaded by a 1.5 m wide porch, preventing direct solar ingress, while the eastern wall was bordered by adjoining rooms.

An unventilated air gap of 1 m was provided between the RCC slab and the installed RPMR–cement composite false ceiling (thermal conductance, Ca = 6.22 W/m^{2}K, as per SP: 41-1987). Surface temperatures of the roof were recorded from September to November 2024 to evaluate the heat transfer mitigation provided by the biopolymer-based panels. The study focused on determining the role of false ceiling panels in reducing heat influx and consequently lowering the need for cooling.

To determine thermal fluctuations, temperature recordings were measured at two locations: one underneath the RCC slab and the other at the back of the false ceiling. Using the area-under-curve methodology, the computed measurements on the RCC slab and false ceiling surfaces read 2781 sq. units and 2511 sq. units, respectively. It follows that the false ceiling has realized an average temperature drop of around 11% in comparison with the inner slab surface (Figure 12), therefore evidencing the efficiency of the lightweight biopolymeric composite in reducing heat influx and relaxing building cooling demand.

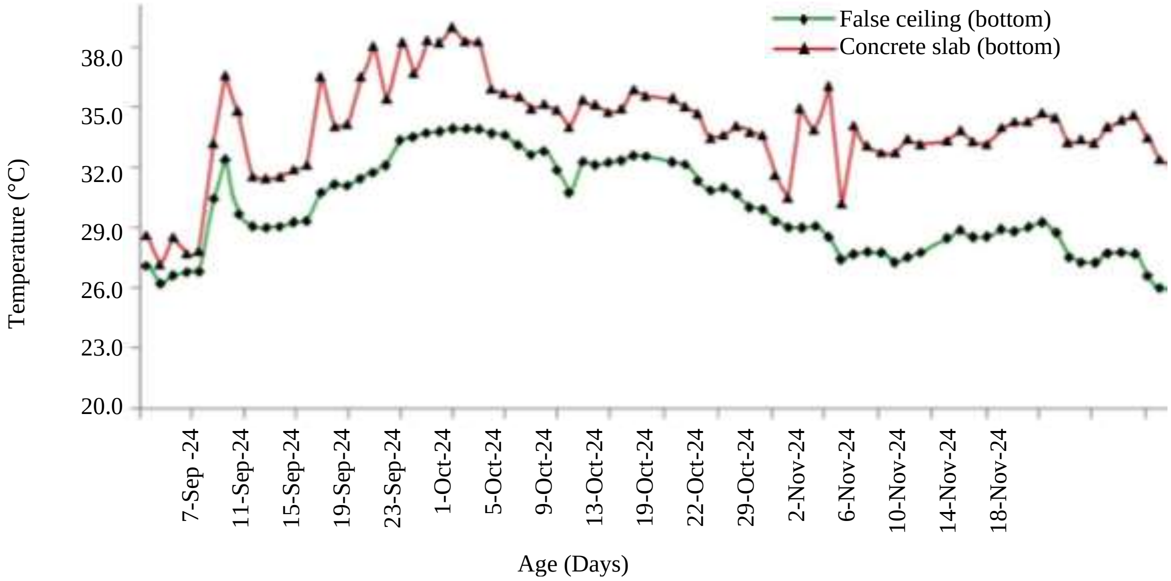

Figure 12. Comparison of roof surface temperatures.

CONCLUSIONS

The present study focuses on the development and performance evaluation of lightweight RPMR-cement hybrid polymer composite panels for sustainable thermal insulation applications. Based on the hybrid experimental and machine learning investigations, the following key conclusions are drawn:

1. Experimental characterization showed that the RPMR–cement panels are light-weight, with a density of ~472 kg/m³ and thermally efficient, with a thermal conductivity of 0.30 W/m.K.
2. Installation of RPMR false ceilings beneath RCC slabs lowered the U-value from 3.6 W/m².K to 2.08 W/m².K. It reflects a 44% gain in thermal resistance.
3. Test room monitoring showed an 11% reduction in indoor surface temperature compared to a bare RCC slab, demonstrating practical cooling benefits attributable to the biopolymer-based composite.
4. The panels are cost-effective, about 20% less during the manufacturing and installation process compared to conventional false ceiling options; therefore, they are suitable for scalable applications.
5. The machine learning model (Random Forest Regression) worked well and predicted the thermal conductivity, U-value, and decrease in indoor temperature accurately, thereby validating its use as a predictive tool. $R^2 > 0.89$.
6. The results of the analysis of the importance of the characteristics have disclosed that the key factors determining the thermal characteristics are the density, porosity, and RPMR content.
7. Optimization through ML suggested an ideal configuration (92% RPMR, 150 kN pressing pressure, 15 mm thickness, 12–14% moisture) that achieved a predicted thermal conductivity of 0.25 W/m.K and U-value of 1.85 W/m².K, offering an additional 8% improvement over experimental results.
8. The energy simulation analyses indicated the potential of cooling energy savings between 18% and 23% during the peak period, thus underlining the importance of employing RPMR false ceilings.
9. The hybrid experimental methodology, along with machine learning, reduces the need for laboratory work on a large scale and makes it easier to understand what matters in sustainable material design.

Thus, the RPMR-cement hybrid false ceiling panels offer a cost-effective, high-performance, and environmentally friendly solution toward advanced indoor thermal comfort, reduced HVAC energy demand, and circular economy practices through industrial waste utilization. This study demonstrates the potential of biopolymer-based composite materials combined with data-driven optimization for next-generation sustainable building applications.

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