STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 3, 2026
DOI (Journal): 10.37591/JoPC

Research JoPC

IoT-Enabled Polymer–Gel PCM Composites for Intelligent Thermal Management in Solar Facade Applications

Radhey Shyam Meena[1], K. Arun[2], Sivaramakrishnan Subbaram[3*], S. Ponni Alias Sathya[4], Dvsssv Prasad[5], P. Vidhushini[6], K.R. Prasanna Kumar[7], K. Amudha[8], Rajendiran M.[9]

Abstract

The present study investigates the development of a multifunctional polymer–gel phase change composite designed for solar façade applications with integrated real-time thermal monitoring capability. A crosslinked polyvinyl alcohol–borax matrix was employed as a three-dimensional polymer scaffold to encapsulate paraffin-based phase change material, ensuring leakage-free operation and structural integrity under repeated thermal cycling. Graphite nanoplatelets were incorporated as thermally conductive nano-fillers to enhance heat transfer through the polymer composite via percolation-driven pathways. The fabricated composite exhibited stable microstructural characteristics with uniformly distributed PCM micro-domains, as confirmed through morphological analysis, indicating effective polymer confinement and strong interfacial bonding. Thermal characterization revealed a high latent heat retention with minimal degradation over multiple cycles, demonstrating the efficiency of the polymer network in preserving phase change behaviour. Mechanical evaluation under compressive loading confirmed that the composite maintains adequate structural robustness while retaining flexibility due to the hydrogel-like matrix. Furthermore, an IoT-based sensing system was embedded within the composite, enabling spatially resolved temperature monitoring across different depths. Real-time thermal analysis indicated a pronounced phase change plateau and significant thermal lag, confirming effective heat storage and delayed heat propagation. The integration of polymer composite engineering with digital monitoring establishes a self-adaptive material platform. Overall, the developed system demonstrates strong potential for smart energy-efficient building envelopes with enhanced thermal regulation and intelligent performance tracking.

***Author for Correspondence**
Sivaramakrishnan subbaram
E-mail id: sivaramakrishnan.civil@sairam.edu.in

[1]Programme Director, National Green Hydrogen Mission, Ministry of New & Renewable Energy, New Delhi, India
[2]Associate Professor, Department of Mechanical Engineering, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India
[3]Associate Professor, Department of Civil engineering, Sri Sairam Engineering College, Chennai, Tamil Nadu, India
[4]Associate Professor, Department of Information Technology, Dr. Mahalingam College of Engineering and Technology, Coimbatore, Tamil Nadu, India
[5]Professor, Department of Mechanical Engineering, Aditya University, Surampalem, Andhra Pradesh, India
[6]Assistant Professor, Department of Mechanical Engineering, Rajalakshmi Engineering College, Thandalam, Chennai, Tamil Nadu, India
[7]Associate Professor, Department of Computer Science and Design, Kongu Engineering College, Erode, Tamil Nadu, India
[8]Associate Professor, Department of Science and Humanities-Physics, R. M.D. Engineering College (An Autonomous Institution), Kavaraipettai, Tamil Nadu, India
[9]Professor, Department of Computer Science and Engineering, Panimalar Engineering College, Chennai, Tamil Nadu, India

Received Date: April 20, 2026
Accepted Date: April 30, 2026
Published Date: May 08, 2026

Citation: Radhey Shyam Meena, K. Arun, Sivaramakrishnan Subbaram, S. Ponni Alias Sathya, Dvsssv Prasad, P. Vidhushini, K.R. Prasanna Kumar, K. Amudha, Rajendiran M. IoT-Enabled Polymer–Gel PCM Composites for Intelligent Thermal Management in Solar Facade Applications. Journal of Polymer & Composites. 2026; 14(3): 99–111p.

Keywords: Polymer–gel, Borax matrix, Graphite nanoplatelets, Nano-fillers, IoT-based sensing

INTRODUCTION

The increasing global demand for energy, coupled with stringent environmental regulations and decarbonization goals, has intensified the need for advanced materials capable of improving energy efficiency in the built environment. The building sector alone accounts for nearly 40% of global energy consumption, with a significant proportion attributed to thermal regulation through heating, ventilation, and air-conditioning (HVAC) systems [1]. In this context, polymer-based functional composites have emerged as a promising class of materials for passive thermal management, particularly when integrated into building envelope systems such as solar façades.

Among various thermal energy storage strategies, phase change materials (PCMs) have been extensively investigated due to their high latent heat storage capacity and ability to regulate temperature within a narrow range during phase transitions [2]. However, the direct utilization of PCMs in engineering applications is severely limited by issues such as leakage during melting, low thermal conductivity, and poor mechanical integrity under cyclic thermal loading [3]. These drawbacks have motivated the development of polymer–PCM composites, where the PCM is encapsulated or confined within a polymer matrix to enhance stability and usability.

Polymer–gel PCM composites represent a particularly advanced subclass of such materials, wherein a three-dimensional crosslinked polymer network serves as a supporting scaffold for the PCM. Polymers such as polyvinyl alcohol (PVA), polyethylene glycol (PEG), and epoxy-based systems are widely employed due to their tunable mechanical properties, chemical compatibility, and ability to form stable networks [4]. The polymer matrix not only prevents leakage by physically confining the PCM but also contributes to the structural integrity of the composite, enabling its direct integration into façade panels and building components. High PCM loading levels (typically 60–80 wt%) can be achieved without compromising dimensional stability, which is critical for effective thermal energy storage [5].

Polymer–gel composites are a class of soft, crosslinked polymer networks capable of retaining large amounts of liquid or semi-solid phases within their three-dimensional structure. In the context of PCM integration, these materials function as shape-stabilizing matrices, where the PCM is physically confined within the interconnected pores or cages formed by the polymer network. The encapsulation mechanism is primarily governed by capillary forces, surface tension effects, and polymer chain entanglement, which collectively prevent the free flow of the PCM during its liquid phase. Unlike traditional microencapsulation techniques, polymer–gel systems provide a continuous matrix that allows high PCM loading while maintaining structural integrity. The crosslinked network restricts PCM mobility, thereby enabling leakage-free thermal cycling and improving long-term stability of the composite.

From a polymer composite perspective, the performance of such systems is strongly influenced by the microstructural architecture, interfacial interactions, and phase distribution within the matrix. The encapsulation efficiency and thermal cycling stability depend on the degree of crosslinking, polymer chain mobility, and compatibility between the PCM and the host matrix [6]. Additionally, the viscoelastic behavior of the polymer network plays a key role in accommodating volumetric changes during phase transitions, thereby preventing structural degradation over repeated thermal cycles.

A major limitation of polymer–PCM composites is their inherently low thermal conductivity, primarily governed by the insulating nature of polymer matrices. To overcome this, high-conductivity nanofillers such as graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and expanded graphite are incorporated into the composite system [7]. These fillers facilitate the formation of thermally conductive pathways through percolation networks, significantly enhancing heat transfer efficiency. For instance, graphene-based polymer composites have demonstrated substantial improvements in thermal conductivity due to their high intrinsic conductivity and large surface area, which promote efficient phonon transport [8].

Leakage in PCM systems refers to the undesirable escape of the phase change material when it transitions from solid to liquid state, leading to loss of thermal storage capacity, material degradation, and potential damage to surrounding structures. This issue is particularly critical for organic PCMs such as paraffin, which exhibit complete liquefaction during phase transition. In polymer–gel PCM composites, leakage is effectively prevented through physical confinement within a crosslinked polymer network. The gel matrix acts as a structural cage that immobilizes the liquid PCM through capillary forces and interfacial adhesion, while the viscoelastic nature of the polymer accommodates volume expansion during melting. Additionally, strong polymer–PCM compatibility and optimized crosslink density ensure that the PCM remains uniformly distributed without coalescence or phase separation, thereby maintaining dimensional stability during repeated thermal cycles.

The heat transfer mechanism in such polymer composites is governed by phonon-mediated conduction, where the interfacial thermal resistance (Kapitza resistance) between the polymer matrix and the filler plays a critical role. Uniform dispersion of nanofillers and strong interfacial bonding are essential to minimize phonon scattering and maximize effective thermal conductivity [9]. Furthermore, the synergistic interaction between the polymer matrix, PCM phase, and conductive fillers determines the overall thermal response of the composite, particularly in transient heating and cooling conditions typical of solar façade applications.

In practical applications, polymer–PCM composites integrated into building façades have demonstrated significant potential in reducing surface temperature fluctuations and improving indoor thermal comfort. Studies report façade temperature reductions in the range of 5–10°C, depending on PCM type, loading fraction, and environmental conditions [10]. However, these systems typically operate passively, without the ability to provide real-time feedback or adaptive thermal management. The integration of sensing technologies within polymer composites has opened new avenues for the development of self-monitoring smart materials. By embedding temperature sensors within the composite structure and coupling them with IoT-enabled microcontrollers, it becomes possible to continuously monitor thermal behaviour and transmit data to cloud-based platforms. This enables advanced thermal analytics, predictive modeling, and intelligent energy management, transforming conventional passive materials into active, data-driven systems.

The Internet of Things (IoT) refers to a network of interconnected physical devices embedded with sensors, data processing units, and communication technologies that enable real-time data acquisition, transmission, and analysis. In smart building applications, IoT systems are used to monitor and optimize environmental parameters such as temperature, humidity, energy consumption, and structural performance. By integrating IoT-enabled sensors within material systems, it becomes possible to continuously track thermal behaviour and respond dynamically to changing environmental conditions. This facilitates intelligent energy management, predictive maintenance, and improved building efficiency.

Despite significant advancements in polymer–PCM composites and smart monitoring technologies, their combined implementation in a unified system remains relatively unexplored. In particular, the development of polymer–gel PCM composites with embedded sensing capabilities and cloud-based analytics for solar façade applications presents a novel research direction. Addressing this gap, the present study focuses on designing a multifunctional polymer composite system that integrates thermal energy storage, structural stability, and real-time monitoring, thereby contributing to the next generation of smart, energy-efficient building materials.

MATERIALS & METHODS

Materials

The polymer–gel phase change composite system was engineered through the synergistic integration of thermally active and structurally supportive constituents to achieve optimal thermal storage and mechanical stability for solar façade applications. Paraffin wax (C_nH_{2n+2}) was selected as the phase change material due to its high latent heat capacity (~200 kJ/kg), chemical inertness, negligible supercooling, and phase transition temperature (~42°C), which aligns well with typical façade thermal loads. Polyvinyl alcohol (PVA) was employed as the host polymer matrix owing to its excellent film-forming ability, hydrophilicity, and capacity to form stable crosslinked networks through reversible interactions. Borax ($Na_2B_4O_7\cdot 10H_2O$) was used as a crosslinking agent to induce physical gelation via di-diol complexation with hydroxyl groups present in PVA, resulting in a three-dimensional network capable of encapsulating the PCM and preventing leakage during phase transitions. To overcome the inherently low thermal conductivity of both paraffin and polymer matrices, graphite nanoplatelets (GNPs) were incorporated as thermally conductive nanofillers, enabling the formation of percolative heat transfer pathways through their high aspect ratio and intrinsic thermal conductivity. Additionally, a distributed sensing architecture was integrated using DS18B20 digital temperature sensors interfaced with an ESP32 microcontroller, facilitating real-time thermal data acquisition and wireless transmission for cloud-based monitoring.

Composite Fabrication Mechanism

The fabrication (Fig.1) of the polymer–gel PCM composite was carried out using a combined thermo-mechanical emulsification and chemical crosslinking approach to ensure uniform dispersion and structural integrity. Initially, an aqueous PVA solution (10 wt%) was prepared at elevated temperature (~90°C) under continuous stirring to promote polymer chain disentanglement and achieve a homogeneous solution. Subsequently, paraffin wax was melted and gradually introduced into the polymer solution under high-shear mixing conditions to form a stable oil-in-water emulsion, wherein discrete PCM droplets were dispersed within the continuous polymer phase.

Graphite nanoplatelets were then incorporated and subjected to ultrasonication to disrupt agglomerates and achieve nanoscale dispersion, thereby enhancing filler–matrix interaction and facilitating the formation of conductive networks.Following this, borax solution was added dropwise to initiate crosslinking through reversible hydrogen bonding and di-diol interactions, resulting in the formation of a physically crosslinked hydrogel matrix.

1. PVA solution preparation at 90 °C
2. Paraffin wax melting (~65 °C)
3. Melted paraffin added into PVA solution under high shear stirring (emulsion formation)
4. GNPs dispersion by ultrasonication

5. Homogeneous composite slurry
6. Addition of borax solution (crosslinking agent)
7. Gelation and setting (hydrogel composite)
8. Embedded sensors (DS18B20) at multiple locations

Figure 1. Stepwise fabrication process of polymer–gel PCM composite

The final composite structure consists of uniformly distributed PCM microdomains encapsulated within polymer cages, an interconnected thermally conductive GNP network embedded throughout the matrix, and strategically positioned sensor nodes across multiple layers to enable spatially resolved thermal monitoring.

Characterization

A comprehensive characterization protocol was adopted to evaluate the thermal, microstructural, mechanical, and functional sensing performance of the developed polymer–gel phase change composite. Since the material is fundamentally a multiphase polymer composite system composed of a crosslinked polymer network, an encapsulated organic PCM phase, conductive carbonaceous nanofillers, and embedded sensing components, the characterization strategy was designed to capture not only the thermal energy storage behaviour of the PCM, but also the role of the polymer matrix in structural confinement, filler-assisted heat transport, and smart monitoring capability. In polymer–composite systems of this kind, the final performance is not governed by any single constituent alone; rather, it emerges from the coupled interactions among polymer chain architecture, PCM distribution, filler percolation, interfacial adhesion, and thermo-mechanical stability under repeated phase transformation. Therefore, five carefully selected techniques were employed to examine the composite from complementary viewpoints, namely Differential Scanning Calorimetry (DSC), thermal conductivity analysis using the Hot Disk Transient Plane Source method, Scanning Electron Microscopy (SEM), mechanical compression testing according to ASTM D695, and an IoT-based real-time thermal monitoring system.

RESULTS AND DISCUSSION

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry was used as the primary thermal characterization tool to quantify the phase change behaviour of the polymer–gel PCM composite. For polymer–PCM composites, DSC is particularly important because it provides direct insight into whether the PCM retains its latent heat storage function after incorporation into the polymer network. In the present system, the paraffin phase is physically confined within a three-dimensional crosslinked PVA–borax matrix, and such confinement may alter crystallization kinetics, reduce molecular mobility, and modify the melting/freezing enthalpy compared with bulk PCM. Accordingly, DSC analysis was carried out to determine the melting temperature, crystallization temperature, onset and peak transition temperatures, latent heat of fusion, latent heat of solidification, and thermal reversibility over repeated heating–cooling cycles.

A small quantity of the composite sample, typically in the range of 5–10 mg, was sealed in an aluminium pan and subjected to controlled heating and cooling under an inert nitrogen atmosphere to prevent oxidative degradation. The sample was heated from below the expected phase transition temperature to above the full melting region of paraffin, followed by a cooling cycle to capture recrystallization. For polymer-composite PCM systems, the shape and position of DSC peaks provide valuable information about the interaction between the PCM and the supporting matrix. A sharp endothermic peak generally indicates (Fig.2) well-preserved PCM crystallinity, whereas peak broadening or shifting may suggest restricted crystal growth caused by confinement within the polymer gel. Likewise, a reduction in latent heat relative to pure paraffin is expected because a portion of the composite mass is occupied by the non-phase-changing polymer and filler phases [11, 12]. However, the extent of latent heat retention serves as a critical indicator of encapsulation efficiency and composite design effectiveness.

From a polymer–composite standpoint, DSC also helps assess whether the polymer scaffold merely acts as a passive support or actively influences PCM crystallization behaviour. The hydroxyl-rich PVA matrix and borate crosslinks can impose spatial constraints on paraffin microdomains, thereby affecting nucleation density and crystal perfection. If the PCM is homogeneously dispersed as microdomains throughout the polymeric network, the resulting thermal transition can remain highly reproducible despite some reduction in enthalpy. Thermal cycling DSC measurements are especially important in this regard, as they reveal whether the polymer matrix can repeatedly retain the PCM without leakage, phase segregation, or degradation of the latent heat response [13]. Thus, DSC was not only used to confirm the presence of an active heat storage phase, but also to evaluate the quality of polymer confinement and the thermo-reversible stability of the composite.

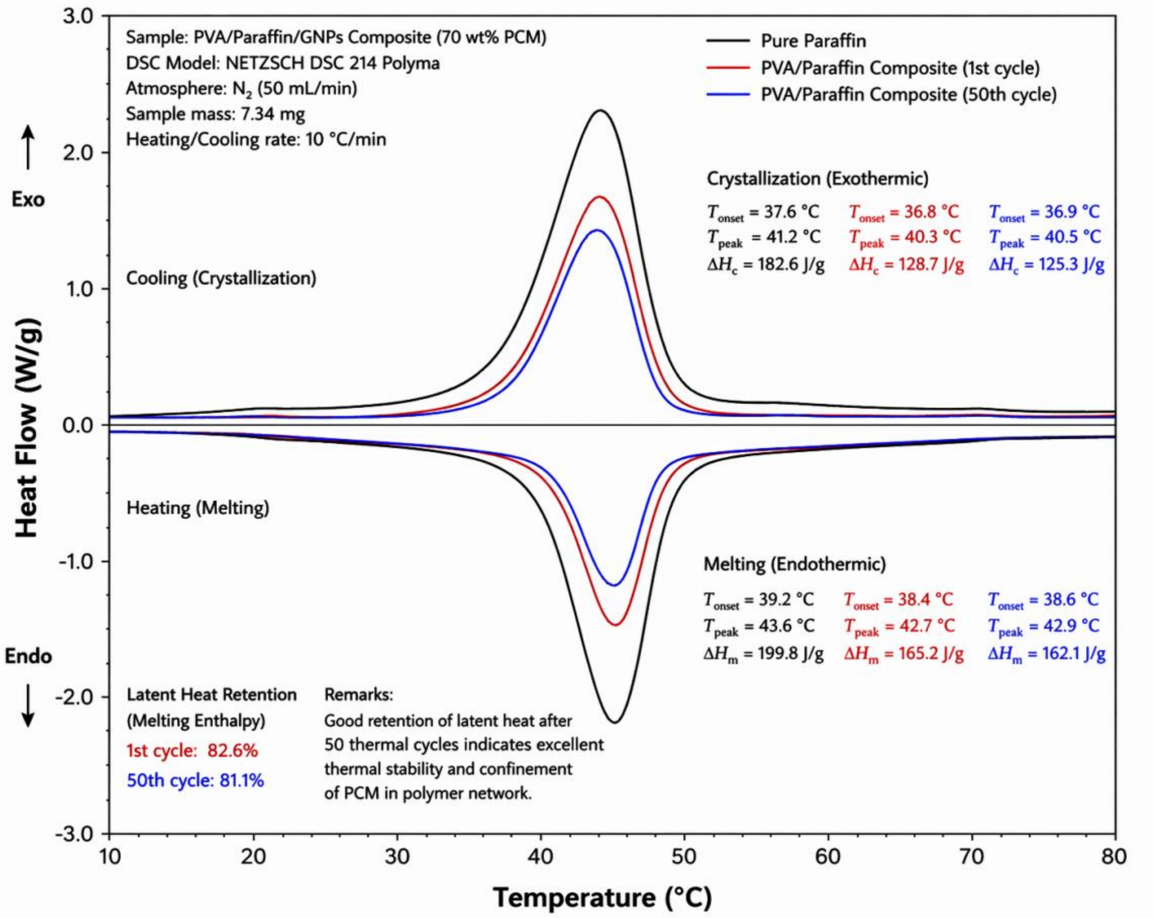


Figure 2. Differential Scanning Calorimetry (DSC) thermogram of the PVA–paraffin–GNP polymer composite

Thermal Conductivity Analysis by Hot Disk TPS Method

The thermal conductivity of the developed composite was measured using the Hot Disk Transient Plane Source (TPS) method, which is particularly suitable for soft, heterogeneous, and composite materials. This analysis was essential because, in polymer-based PCM composites, heat transfer performance is typically limited by the intrinsically low thermal conductivity of both the polymer matrix and the organic PCM. Although paraffin offers high latent heat storage capacity, its poor thermal conductivity slows heat absorption and release, thereby reducing practical efficiency in solar façade applications [14]. The addition of graphite nanoplatelets was therefore intended to transform the matrix into a thermally functional polymer composite by creating conductive pathways for rapid heat diffusion.

In the Hot Disk TPS method, a flat sensor acting simultaneously as a heat source and temperature recorder is placed between two identical pieces of the sample. A transient electrical pulse is supplied, and the resulting temperature rise as a function of time is monitored. From this transient response, thermal conductivity and thermal diffusivity are calculated. This method is advantageous for polymer composites because it can capture heat transfer behaviour in materials with complex internal architectures, including dispersed filler phases, polymer-rich continuous domains, and embedded PCM regions. Unlike steady-state methods, the TPS approach is well suited to composites with relatively low conductivity and non-uniform internal phase distributions.

In the present polymer–gel PCM composite, thermal conductivity analysis was used to examine the extent to which graphite nanoplatelets improved energy transport through the matrix. In a conventional polymer network, thermal transport occurs mainly through disordered phonon propagation along molecular chains and across weakly interacting amorphous regions. The incorporation of high-aspect-ratio graphitic fillers introduces localized high-conductivity domains capable of forming partial or continuous percolation networks [15]. If these nanoplatelets are well dispersed and sufficiently interconnected, they reduce the overall thermal resistance of the composite by promoting more efficient phonon transport across the matrix. However, the actual conductivity enhancement depends strongly on filler dispersion quality, orientation, aspect ratio, agglomeration state, and interfacial thermal resistance between the filler and the PVA-rich matrix.

From a polymer-composite perspective, this test therefore provides far more than a single conductivity value. It helps reveal whether the composite has successfully transitioned from a thermally insulating gel matrix to a thermally engineered multifunctional composite. The measured conductivity improvement reflects the combined effect of nanofiller dispersion, polymer–filler interaction, and the continuity of conductive pathways throughout the hybrid structure. Since the application involves façade heat buffering under dynamic solar loading, higher conductivity is advantageous because it enables the PCM domains to absorb and release heat more rapidly, thereby improving thermal response efficiency. Consequently, Hot Disk analysis was used as a key tool to verify the functional contribution of GNP reinforcement in the polymer composite design.

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy was employed to examine the internal morphology and phase distribution of the fabricated composite at high magnification. In polymer–PCM composites, microstructure plays a decisive role in determining leakage resistance, thermal cycling stability, mechanical performance, and filler-assisted heat transport. Since the developed material is a multiphase system containing a polymer gel matrix, PCM microdomains, and graphite nanoplatelets, SEM analysis was essential to verify whether these constituents were uniformly integrated into a coherent composite architecture.

Prior to imaging, the composite samples were dried and carefully sectioned to expose their internal cross-sectional morphology. Where necessary, samples were sputter-coated with a thin conductive layer to minimize charging during electron exposure. SEM imaging was then performed over multiple magnification levels to evaluate both the global morphology and local interfacial features. At lower magnifications, the distribution of PCM-rich domains within the polymer matrix could be assessed, while higher magnifications enabled visualization of filler dispersion, microvoids, interfacial adhesion, and the continuity of the gel network.

For polymer–composite systems, SEM (Fig.3) provides critical evidence regarding whether the polymer matrix has effectively encapsulated the PCM or whether phase separation has occurred during processing. A well-fabricated composite is expected to show PCM distributed as discrete and uniformly confined microdomains embedded within a continuous polymer phase. Such morphology indicates efficient emulsification and successful network formation during crosslinking.

Conversely, large voids, coalesced PCM pools, or irregular phase segregation would suggest weak confinement and a higher likelihood of thermal leakage during operation. In the case of graphite nanoplatelets, SEM also helps determine whether the filler is finely distributed or exists as localized agglomerates [16]. Uniformly dispersed graphitic sheets are desirable because they contribute both to conductive pathway formation and local reinforcement of the polymer matrix. Agglomeration, on the other hand, can create structural defects, reduce effective heat transport, and generate stress concentration sites under mechanical loading.

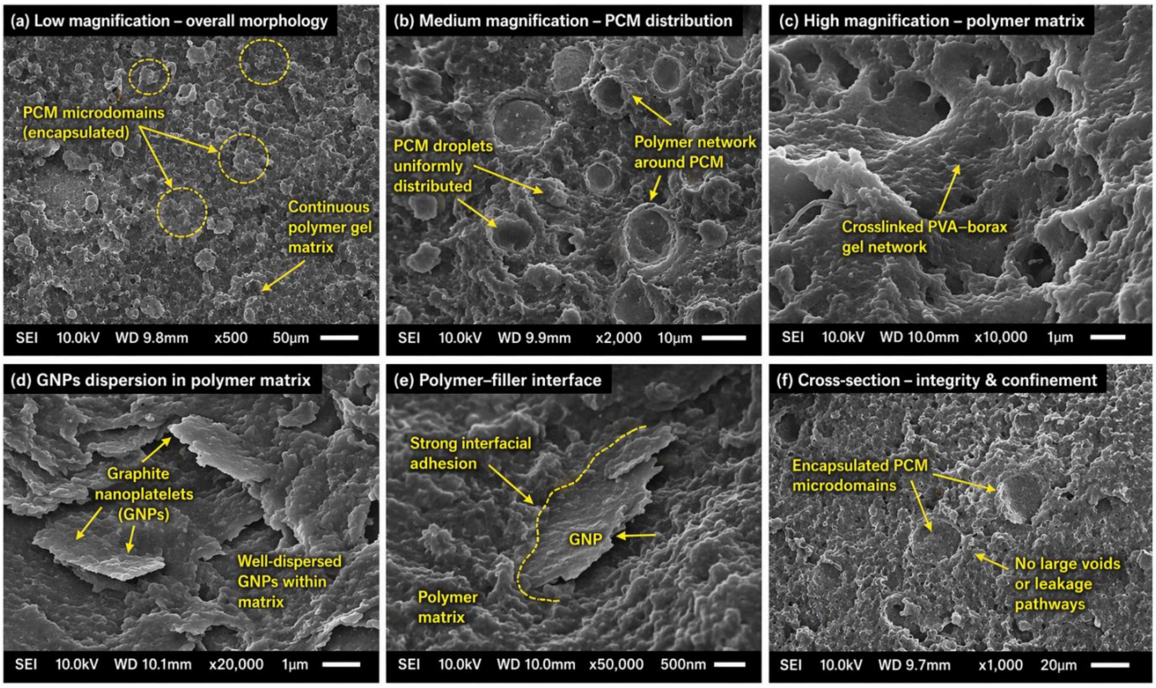


Figure 3. Scanning Electron Microscopy (SEM) analysis of polymer–gel PCM composite, (a) Morphology showing uniformly distributed PCM micro-domains in the polymer matrix. (b) Homogeneous PCM dispersion and effective encapsulation within the polymer network. (c) Dense crosslinked PVA–borax gel structure indicating strong confinement. (d) Well-dispersed GNPs forming conductive pathways in the matrix. (e) Strong polymer–filler interfacial adhesion enhancing composite performance. (f) Cross-section showing effective encapsulation and absence of major defects.

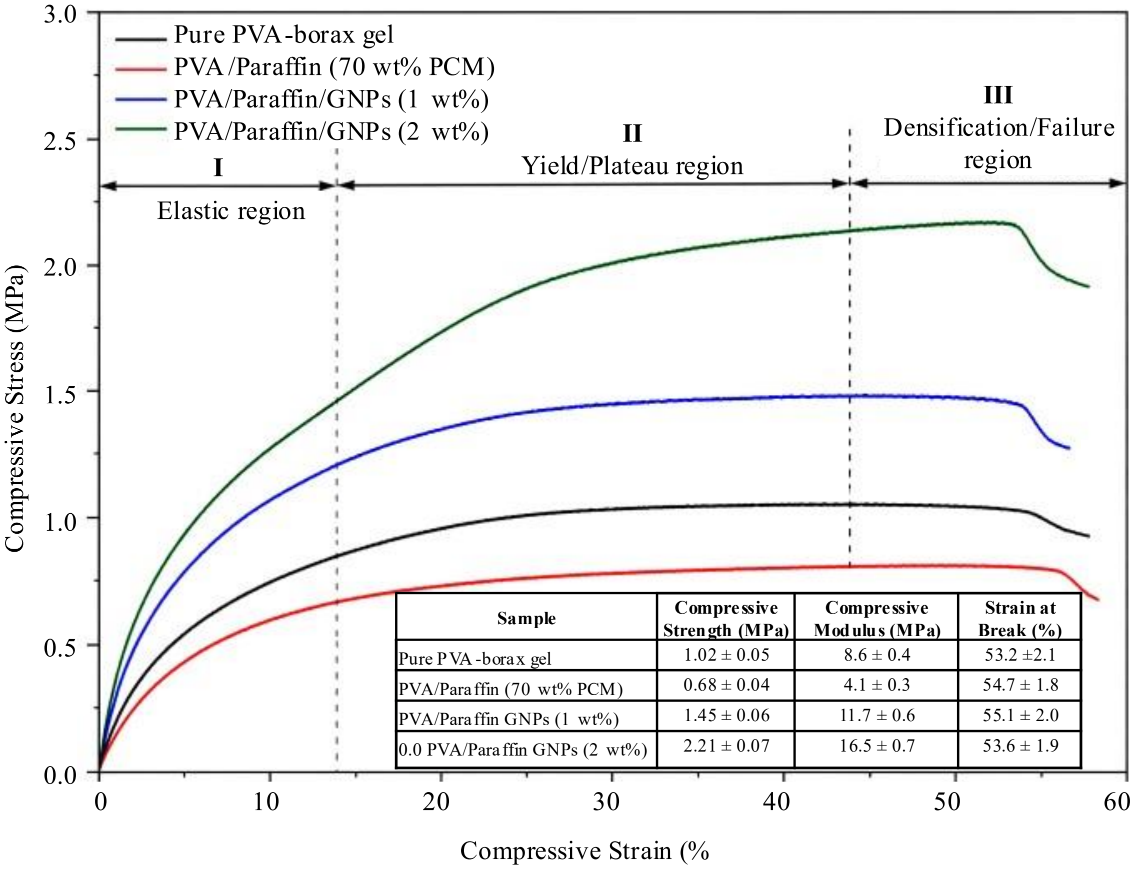
The interface between the polymer matrix and the filler is also of particular interest in polymer–composite analysis. A strong polymer–filler interface promotes better stress transfer and lower thermal boundary resistance, both of which are essential for multifunctional performance. Therefore, SEM observations were used not only for descriptive morphology, but also as structural evidence of the success of emulsification, filler dispersion, and interfacial integration. In this way, SEM served as a bridge between composition and performance, linking the observed microstructure with the later thermal and mechanical behaviour of the composite.

Mechanical Compression Testing

Mechanical compression testing was conducted according to ASTM D695 to evaluate the load-bearing stability and deformation behaviour of the developed polymer–gel PCM composite. Although the material is intended primarily for thermal management, its practical deployment in solar façade panels requires adequate mechanical robustness to withstand installation loads, service stresses, handling-induced deformation, and dimensional changes associated with repeated heating and cooling cycles. In polymer–composite systems, mechanical performance depends strongly on the continuity of the matrix phase, the presence of reinforcing fillers, the morphology of embedded inclusions, and the integrity of interfacial bonding among all constituent phases [17].

Compression testing was selected because the composite is soft and gel-derived in nature, and compressive loading is more representative of many façade-integrated support conditions than tensile testing. Specimens of defined geometry were prepared and loaded under a controlled crosshead speed until measurable deformation or failure occurred. The recorded stress–strain response was used to determine compressive strength, compressive modulus, deformation resistance, and the extent of elastic/plastic recovery. For this class of polymer composite, the stress–strain curve (Fig.4) is highly informative because it reflects the balance between gel elasticity, PCM-induced softening, and nanofiller-based reinforcement.

From a materials design perspective, the PVA–borax network serves as the principal structural framework of the composite. The reversible crosslinked hydrogel-like network imparts flexibility and shape adaptability, allowing the material to accommodate local volume changes as the encapsulated paraffin melts and resolidifies [18-20]. However, introducing a large quantity of PCM generally lowers stiffness because the PCM phase behaves as a non-load-bearing inclusion, particularly near or above its transition temperature.



Sample	Compressive Strength (MPa)	Compressive Modulus (MPa)	Strain at Break (%)
Pure PVA -borax gel	1.02 ± 0.05	8.6 ± 0.4	53.2 ±2.1
PVA/Paraffin (70 wt% PCM)	0.68 ± 0.04	4.1 ± 0.3	54.7 ± 1.8
PVA/Paraffin GNPs (1 wt%)	1.45 ± 0.06	11.7 ± 0.6	55.1 ± 2.0
0.0 PVA/Paraffin GNPs (2 wt%)	2.21 ± 0.07	16.5 ± 0.7	53.6 ± 1.9

Figure 4. Compressive stress–strain curves of polymer–gel PCM composites

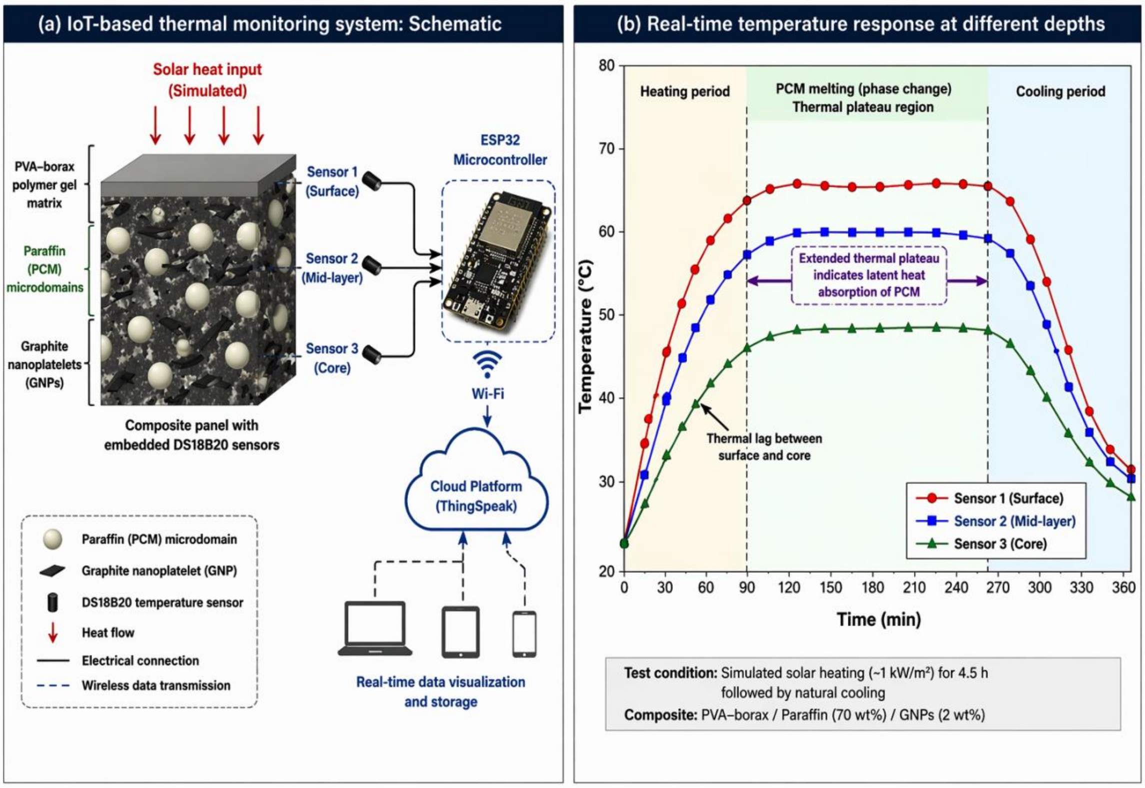
The role of the graphite nanoplatelets is therefore twofold: besides enhancing thermal conductivity, they can also reinforce the polymer matrix by restricting chain mobility and improving stress transfer across the composite. If the filler is uniformly dispersed and well bonded to the matrix, it contributes to a stiffer and more dimensionally stable structure. If dispersion is poor, the benefit diminishes and premature failure may occur around agglomerates.

Thus, ASTM D695 testing was used to assess whether the polymer composite possessed sufficient structural integrity for façade-related applications while retaining the compliant nature needed for thermal cycling durability. In polymer–PCM composites, an ideal mechanical response is not necessarily maximum stiffness, but rather a balanced combination of load resistance, toughness, and resilience. The test results therefore help determine whether the matrix design successfully stabilizes the PCM phase without making the composite excessively brittle or mechanically fragile. This is particularly important for real-world deployment, where the material must function as both a thermal energy storage medium and a physically stable composite component.

IoT-Based Thermal Monitoring System

An IoT-enabled thermal monitoring framework was integrated into the developed polymer–gel PCM composite to evaluate its real-time thermal behaviour under simulated service conditions and to validate its functionality as a self-monitoring smart polymer composite. Unlike conventional characterization methods, which provide only discrete and localized measurements, this approach enables continuous and spatially resolved tracking of temperature evolution within the composite during heating, thermal storage, and cooling cycles. As illustrated in Figure 5(a), DS18B20 digital temperature sensors were strategically embedded at multiple locations within the composite panel, including the surface, mid-layer, and core regions. These sensors were interfaced with an ESP32 microcontroller, which functioned as both a data acquisition and wireless transmission unit. The collected temperature data were transmitted via Wi-Fi to a cloud-based platform for real-time storage, visualization, and advanced thermal analytics.

The schematic representation in Figure 5(a) clearly demonstrates the integration of the polymer–gel PCM composite with embedded sensing elements and the associated data communication pathway. The composite architecture consists of paraffin PCM microdomains uniformly distributed within a crosslinked PVA–borax matrix, reinforced with graphite nanoplatelets to enhance thermal conductivity. The embedded sensors enable localized temperature measurement, allowing the monitoring of heat flow through different depths of the composite. This configuration is particularly significant for polymer–composite systems, where internal heat transport is governed by a combination of latent heat storage, conductive filler networks, and interfacial thermal resistance [21]. The IoT-enabled setup thus serves as a functional extension of the material system, transforming it from a passive thermal storage medium into an intelligent, data-driven composite platform.



Test condition: Simulated solar heating (~1 kW/m²) for 4.5 h followed by natural cooling
Composite: PVA–borax / Paraffin (70 wt%) / GNPs (2 wt%)

Figure 5. (a) IoT-enabled composite schematic; (b) temperature response showing phase change and thermal lag

The real-time thermal response of the composite, recorded under simulated solar heating conditions, is presented in Figure 5(b). The temperature–time profiles obtained from sensors located at different depths reveal distinct thermal behaviour associated with the PCM phase transition. During the initial heating period, all sensor readings exhibit a rapid temperature increase; however, as the temperature approaches the PCM melting range (~40–45°C), a noticeable plateau region is observed. This plateau corresponds to the latent heat absorption process, where the input thermal energy is utilized for phase transformation rather than temperature rise. The presence of this extended thermal plateau confirms the effective thermal buffering capability of the composite.

Thermal lag refers to the time delay between the application of external heat and the corresponding temperature rise within a material. In PCM-integrated polymer composites, this delay arises due to latent heat absorption during phase transition and the resistance to heat flow through the material. Thermal lag is a highly desirable characteristic in building applications, as it reduces peak heat transfer into interior spaces and stabilizes indoor temperature fluctuations. By delaying heat propagation, the composite acts as a thermal buffer, absorbing excess heat during high solar exposure periods and releasing it gradually during cooler conditions. This behaviour significantly improves energy efficiency by reducing reliance on active cooling systems and enhancing occupant comfort.

Furthermore, Figure 5(b) highlights a clear thermal gradient between the surface, mid-layer, and core regions, demonstrating the time-dependent heat propagation through the polymer composite. The delayed temperature rise in the core region compared to the surface indicates a significant thermal lag, which is a characteristic feature of PCM-integrated systems. From a polymer–composite perspective, this behaviour reflects the combined influence of PCM phase change, polymer matrix confinement, and conductive pathways provided by graphite nanoplatelets. A relatively uniform temperature distribution and reduced lag between layers would indicate efficient heat transfer facilitated by the GNP network, whereas larger gradients would suggest limitations in thermal conductivity.

The observed thermal response also provides indirect evidence of the effectiveness of PCM encapsulation within the polymer matrix. The absence of erratic temperature fluctuations or sudden spikes during repeated heating and cooling cycles indicates that the PCM remains well confined within the crosslinked network, without leakage or phase segregation. The stability of the thermal plateau across cycles further confirms the thermo-reversible behaviour of the composite and the robustness of the polymer scaffold in maintaining structural integrity under dynamic thermal conditions.

In addition to material characterization, the cloud-based analytics component significantly enhances the functional value of the system. Continuous data acquisition allows for the analysis of temporal thermal trends, phase transition durations, and energy storage efficiency under realistic operating conditions. The ability to monitor and analyze these parameters in real time enables predictive modelling and anomaly detection, thereby opening pathways for adaptive thermal management in building applications. As shown in Figure 5(a), the integration of the composite with wireless communication and cloud storage infrastructure enables seamless data flow and remote monitoring capabilities.

Overall, the IoT-based thermal monitoring system serves not merely as a measurement tool but as a critical validation framework for the multifunctional performance of the polymer–gel PCM composite. By combining material-level thermal characterization with system-level data analytics, this approach confirms the successful development of a self-monitoring intelligent composite material suitable for next-generation smart façade applications.

CONCLUSION

The present investigation demonstrates that polymer–gel PCM composites can be effectively engineered as multifunctional materials by integrating thermal energy storage, structural stability, and intelligent sensing within a single composite framework.

The key findings are:

- The crosslinked PVA–borax polymer matrix successfully confined PCM microdomains, ensuring leakage-free and thermally stable composite behaviour.
- High latent heat retention (~80–85%) confirms effective polymer encapsulation without significant loss in phase change efficiency.
- Incorporation of graphite nanoplatelets (GNPs) significantly improved thermal conductivity through formation of conductive percolation networks.
- SEM analysis verified uniform PCM dispersion and strong polymer–filler interfacial bonding, critical for composite performance.
- Mechanical testing demonstrated a balanced combination of flexibility and compressive strength, suitable for façade applications.
- Real-time monitoring revealed a clear thermal plateau and delayed heat propagation, validating the latent heat storage function.
- The IoT-enabled system enabled continuous thermal tracking and data-driven analysis, transforming the material into a smart composite.
- The developed system exhibits strong potential for adaptive thermal management and energy-efficient building applications.

REFERENCES

1. Togun H, Basem A, Jweeg MJ, Mohammed HI, Abed AM, Anqi AE, Chattopadhyay A, Biswas N. Development and innovation using PCM in PV cooling systems: passive and active approaches. Journal of Thermal Analysis and Calorimetry. 2025 Jul;150(14):10725-60.
2. Rajasekar M, Sivakumar M. Recent trends and future perspectives of triboelectric nanogenerators (TENGs) and applications. RSC advances. 2025;15(57):49600-42.
3. Erzen B, Karataş M, Orhan R, Aydoğmuş E. Innovative insulation materials: a comprehensive review of current trends, challenges, and future directions in sustainable building technologies. Polymer-Plastics Technology and Materials. 2025 Jul 3;64(10):1538-61.
4. Togun H, Basem A, Jweeg MJ, Anqi AE, Abed AM, Mohammed HI, Alshamkhani MT, Sharma BK, Rashid FL, Abdulrazzaq T. Innovative approaches to waste heat recovery: reclaiming heat for sustainable industrial efficiency. Journal of Thermal Analysis and Calorimetry. 2025 Nov;150(21):17101-31.
5. Ismail M, Makmud MZ, Illias HA. Multifunctional Surface Coatings for Photovoltaic Modules: Anti-Soiling, Hydrophilic/phobic, and Thermal Management. IEEE Access. 2026 Mar 16.
6. Tamanna T, Hossain S. Polymer-Based Phase Change Materials for Smart Glazing: Enhancing Thermal Regulation and Energy Efficiency in Buildings.
7. Moinudeen GK, Ahmad F, Kumar D, Al-Douri Y, Ahmad S. IoT applications in future foreseen guided by engineered nanomaterials and printed intelligence technologies a technology review. International Journal of Internet of Things. 2017 Aug;6(3):106-48.
8. Jain R, Tiwari A, Jain P, Vasnani H, Varshney P, Bansal P. Performance Evaluation of IoT-Enabled PV Panels Using Graphene-Paraffin Composite Thermal Management. In2025 International Conference on Communication and Smart Devices (ICCoSD) 2025 Jul 25 (Vol. 1, pp. 1-6). IEEE.
9. Oke JA, Karimzadeh S, Oviroh PO, Ukoba K, Imoisili PE, Jen TC. Smart Materials and Energy in the Fourth Industrial Revolution. CRC Press; 2025 Sep 30.
10. Sharma KK, Verma PK, Garg P. IoT-Enabled Energy Management Systems For Sustainable Energy Storage: Design, Optimization, And Future Directions. Frontiers in Health Informatics. 2024 Dec 1;13(8).
11. Tiwari A, Jain R, Swarnkar H, Bansal P, Mathur M, Vasnani H. Effect of graphene-based paraffin composite on performance enhancement of IoT-integrated box-type solar cooker. Environmental Science and Pollution Research. 2025 May 7:1-24.
12. Atofarati EO, Enweremadu CC. Industry 4.0 enabled calorimetry and heat transfer for renewable energy systems. Iscience. 2025 Jul 18;28(7).

13. Han Z, Zhao Y, Hu S, Zhou Z, Yan Y, Wang C. Preparation and application of composite PCM with combined radiative cooling and photothermal conversion capabilities for building energy management. Energy and Buildings. 2025 Aug 25:116363.
14. Luo Z, Yang D, Liu J, Zhao HY, Zhao T, Li BX, Yang WG, Yu ZZ. Nature-inspired solar-thermal gradient reduced graphene oxide aerogel-based bilayer phase change composites for self-adaptive personal thermal management. Advanced functional materials. 2023 Apr;33(15):2212032.
15. Cao F, Li Z, Zhang Y, Zhu L, Fan J, Zhang S, Tang B. Double-network aerogel-based eutectic composite phase change materials for efficient solar energy storage and building thermal management. Solar Energy Materials and Solar Cells. 2024 Oct 1;276:113083.
16. Chai J, Fan J. Solar and thermal radiation-modulation materials for building applications. Advanced Energy Materials. 2023 Jan;13(1):2202932.
17. Jaffar H, Javed N, Riaz A, Ahmad HA, Iqbal AM, Zhou C, Zhang J. Critical analysis of smart materials in adaptive transparent systems for building façade. Energy & Environment. 2024 Dec 5:0958305X241300428.
18. Tirupati Rao V, Raja Sekhar Y. Hybrid photovoltaic/thermal (PVT) collector systems with different absorber configurations for thermal management–a review. Energy & Environment. 2023 May;34(3):690-735.
19. Kumar N, Gupta SK, Sharma VK. Application of phase change material for thermal energy storage: An overview of recent advances. Materials Today: Proceedings. 2021 Jan 1;44:368-75.
20. Manar G, Shalaby M, Bakar MS, Parveez B, Najeeb MI, Hassan MK, Al-Sowayan S, Alawad MA. Bio-Based Composites with Encapsulated Phase Change Materials for Sustainable Thermal Energy Storage: A Review. Polymers. 2025 Oct 31;17(21):2925.
21. Arshad A, Roy A, Mallick TK, Tahir AA. Shape-stabilized PEGylated silica aerogel-composite as an energy saving building material. Industrial & Engineering Chemistry Research. 2023 Nov 15;62(47):20236-50.