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# Polymer–Gel Composite Phase Change Materials: A Functional Polymer Composite Approach for Solar-Thermal Energy Storage in Building Facades

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## *Abstract*

*This study investigates polymer–composite phase change materials (PCMs) in the form of polymer–gel hybrids as multifunctional systems for solar–thermal energy storage in building façades. Paraffin- and PEG-based PCMs were embedded into polyurethane and acrylic gel matrices to create shape-stabilized polymer–composites with high PCM loading (70–80 wt%). Differential Scanning Calorimetry (DSC) confirmed distinct melting/freezing transitions at ~56°C (paraffin) and ~42°C (PEG), with enthalpy values of 120–150 J/g, closely matching theoretical predictions, thereby validating that the polymer–composite structure preserves latent heat without significant thermal losses. Thermal conductivity measurements demonstrated an enhancement from 0.37 W/m·K (bulk PCM) to 0.50 W/m·K (polymer–composite system), representing a ~35% improvement that is critical for rapid heat transfer in façade applications. Dynamic Mechanical Analysis revealed that the polymer–composites maintained a storage modulus (E′) above 450 MPa across the façade-relevant range (10–60°C), with damping factors below 0.15, confirming the mechanical resilience of the polymer–composite framework under repeated cycling. Leakage tests showed <1% mass loss after 20 thermal cycles, highlighting the efficiency of the crosslinked polymer–composite network acting as a three-dimensional molecular cage to immobilize PCMs and prevent seepage. Under solar-simulation at 800 W/m², façade panels integrated with the polymer–composite exhibited a reduction of peak surface temperatures by 7–9°C and stabilized core fluctuations within ±2°C, validating their effectiveness in thermal buffering. Durability evaluation over 1000 cycles demonstrated retention of ~90% latent heat capacity, 95% thermal conductivity, and 92% mechanical stiffness, confirming that the polymer–composite resists phase segregation, leakage, and mechanical fatigue far better than conventional PCM systems, which typically lose 20–40% capacity within 500 cycles. Collectively, these findings establish the polymer–composite approach as a durable, leakage-resistant, and thermally efficient solution for scalable facade integration, offering long-term stability, multifunctionality, and significant energy-saving potential in modern building systems.*

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## INTRODUCTION

The global demand for sustainable energy solutions in the built environment has accelerated research into advanced materials that can improve energy efficiency and reduce reliance on conventional heating and cooling systems. Buildings consume nearly 40% of total global energy, with a major portion dedicated to heating, ventilation, and air-conditioning operations [1]. This has led to increasing interest in passive energy storage strategies, particularly those integrated into building envelopes, to buffer thermal loads and smooth out temperature fluctuations. Among the various thermal storage technologies, phase change materials (PCMs) have received considerable attention due to their ability to absorb and release large amounts of latent heat at nearly constant temperatures [2, 3]. PCMs are therefore ideal candidates for moderating indoor environments and reducing peak energy demand, especially when incorporated into building walls, panels, or façade systems exposed to direct solar radiation.

Despite their advantages, traditional PCMs such as paraffins, salt hydrates, and fatty acids suffer from inherent drawbacks that limit their large-scale application in buildings. Paraffin waxes, while chemically stable and available in a wide range of transition temperatures, often exhibit leakage during melting and possess low thermal conductivity, typically in the range of 0.2–0.3 W/m·K. Salt hydrates display higher conductivities but face issues of phase segregation, supercooling, and corrosion of encapsulation materials. The functional deployment of PCMs in real systems requires overcoming these challenges while maintaining high latent heat storage capacity and long-term cycling stability. This has directed attention toward the development of polymer-based composites, where PCMs are combined with a polymeric host matrix to form a functional composite material with improved dimensional stability, thermal performance, and durability [4].

Polymers are highly attractive as composite matrices for PCMs because of their versatility, low density, processability, and tunable chemistry. Thermoplastics such as polyethylene and polypropylene, thermosets such as epoxy and polyurethane, and even bio-based polymers have been successfully used to fabricate shape-stabilized PCMs. By embedding PCMs within a polymer network, leakage during phase transitions can be minimized, while the polymer contributes to mechanical support and compatibility with construction substrates [5]. Furthermore, the incorporation of additives such as graphite, silica, or nanoclay into polymer composites can enhance thermal conductivity and improve overall energy storage efficiency [6]. The composite approach therefore transforms PCMs from free-flowing materials into functional polymer composites with application-relevant performance, making them highly suitable for facade-integrated solar-thermal energy storage.

A particularly promising direction is the use of polymer gels as supporting matrices for PCMs. Gels are three-dimensional crosslinked polymer networks that are capable of swelling and retaining large amounts of fluid within their structure. When a PCM is incorporated into a polymer gel, the crosslinked chains immobilize the PCM and provide structural rigidity, preventing leakage while allowing repeated phase transitions. This combination results in a polymer–gel composite in which the PCM retains its latent heat storage capacity while the polymer network contributes shape stability and durability. Such systems are highly relevant for building facades, which are subject to prolonged solar exposure, cyclic heating and cooling, and structural stresses. Gel networks are particularly advantageous because they can accommodate high PCM loading—often up to 70–80 wt%—while retaining mechanical integrity [7]. The polymer component can also be chemically modified to impart functional characteristics such as UV resistance, flame retardancy, or adhesion to substrates, further enhancing their applicability in façade systems.

In addition to leakage resistance, polymer–gel composites offer improvements in thermal and mechanical properties that are essential for façade integration. For instance, the crosslinked polymer skeleton restricts molecular mobility, which enhances dimensional stability during thermal cycling and mitigates degradation of the PCM [8]. Studies have shown that polymer–PCM composites can retain over 80–90% of their latent heat even after hundreds of melting and freezing cycles, highlighting their long-term reliability. Furthermore, the relatively low density of polymers ensures that these composites are lightweight, making them suitable for integration into large-area construction elements without imposing significant structural loads In contrast to inorganic encapsulation methods, polymer-based composites provide design flexibility, as they can be fabricated into films, panels, or coatings compatible with modern façade systems [9].

The functional view of polymer–gel PCM composites emphasizes that these materials are not simply passive containers for energy storage but are true polymer composites where the synergy between the polymer matrix and the PCM filler defines the overall performance. The polymer network actively contributes to thermal stability, mechanical resilience, and environmental durability, while the PCM serves as the latent heat reservoir. This composite perspective highlights multifunctionality: the thermal functionality is expressed in efficient heat storage and release, the mechanical functionality lies in toughness and shape stability, the environmental functionality derives from polymer modification for fire or UV resistance, and the design functionality stems from the processability of polymers into diverse architectural formats [10]. It is this multifunctional nature that sets polymer–gel PCM composites apart as practical and scalable solutions for façade-integrated energy storage.

The application of such composites in building facades is particularly important. Facades are the outer surfaces of buildings that are directly exposed to solar radiation, outdoor temperature fluctuations, and environmental conditions. They play a critical role in determining the thermal comfort of indoor environments and the overall energy performance of buildings. By embedding polymer–gel PCM composites into façade panels or wallboards, solar heat can be absorbed during the day and released at night, reducing peak cooling demands and delaying heat transfer through the building envelope [11]. Experimental and simulation studies have demonstrated that PCM-incorporated wallboards and plasters can reduce indoor temperature fluctuations by several degrees Celsius and cut HVAC energy consumption by 20–30% [23]. When stabilized within polymer gels, PCMs gain additional resilience against leakage and degradation, ensuring consistent performance under repeated solar-thermal cycling [12].

Nevertheless, despite these advances, several research gaps persist. Many studies continue to focus on inorganic encapsulation or microencapsulation of PCMs, while comparatively fewer have investigated gel-based polymer composites despite their unique ability to combine high PCM loading with dimensional stability. Furthermore, most reported work emphasizes laboratory characterization of thermal properties without addressing real façade-relevant conditions such as exposure to simulated solar flux, cyclic heating and cooling under climate chamber conditions, or long-term durability over hundreds of phase change cycles [13]. There also remains a lack of standardized testing protocols specifically tailored for polymer–gel PCM composites in building applications. These gaps underscore the need for systematic studies that evaluate polymer–gel composites as functional polymer composite materials for solar-thermal storage in facades, using macro-scale performance tests that reflect real application scenarios rather than solely microstructural analyses.

The present study therefore focuses on developing polymer–gel composite PCMs and characterizing their performance through functional tests relevant to facade applications. Differential scanning calorimetry is employed to evaluate latent heat and transition temperatures, thermal conductivity measurements provide insight into heat transfer efficiency, dynamic mechanical analysis assesses thermo-mechanical robustness, leakage resistance tests confirm dimensional stability during melting, and solar-simulation tests demonstrate real facade thermal buffering capacity. By emphasizing application-relevant functional tests and avoiding reliance on microstructural methods such as optical or electron microscopy and X-ray diffraction, this work highlights the polymer-composite centric approach to material development. Ultimately, the objective is to demonstrate that polymer–gel composite PCMs can function as durable, efficient, and scalable energy storage materials that align with the requirements of modern building facade systems.

## MATERIALS AND METHODS

### Materials Synthesis

Polymer–gel composite phase change materials (PCMs) were synthesized by embedding paraffin and polyethylene glycol (PEG 6000) into crosslinked polymeric gel networks, thereby producing functional polymer composites capable of energy storage with dimensional stability. Paraffin and PEG were chosen due to their high latent heat, chemical stability, and appropriate melting points for solar-thermal applications. Polyurethane and acrylic gels were employed as matrices, offering tunable crosslink density, resilience, and compatibility with construction materials.

For the polyurethane system, a two-component mixture of polyether polyol and aromatic isocyanate (MDI) was used. Paraffin or PEG (Fig.1) was pre-melted and dispersed into the polyol under shear mixing before adding isocyanate to initiate gelation. In the acrylic system, monomers such as acrylic acid (AA) or methyl methacrylate (MMA) were combined with the crosslinker N,N′-methylene bisacrylamide (MBA). The PCM was emulsified into the monomer–crosslinker solution with Tween-80 as surfactant, and polymerization was initiated using ammonium persulfate (APS) under nitrogen to form a stable gel composite. Both methods ensured physical confinement of the PCM within the polymer network, preventing leakage during melting. Figure 1 show the preparation of polymer–gel composite PCM samples showing melted paraffin and PEG incorporated into the polymer–gel network using standard laboratory glassware.

Figure 2 shows the processing of polymer–gel PCM composites. A sol–gel in situ polymerization approach was adopted in both systems to ensure homogeneous PCM distribution and minimize phase separation.

Vigorous stirring at 70–80 °C facilitated dispersion of the PCM in liquid form before gelation occurred. This created a semi-interpenetrating composite, where PCM acted as the functional filler while the polymer gel provided mechanical strength and leakage resistance.

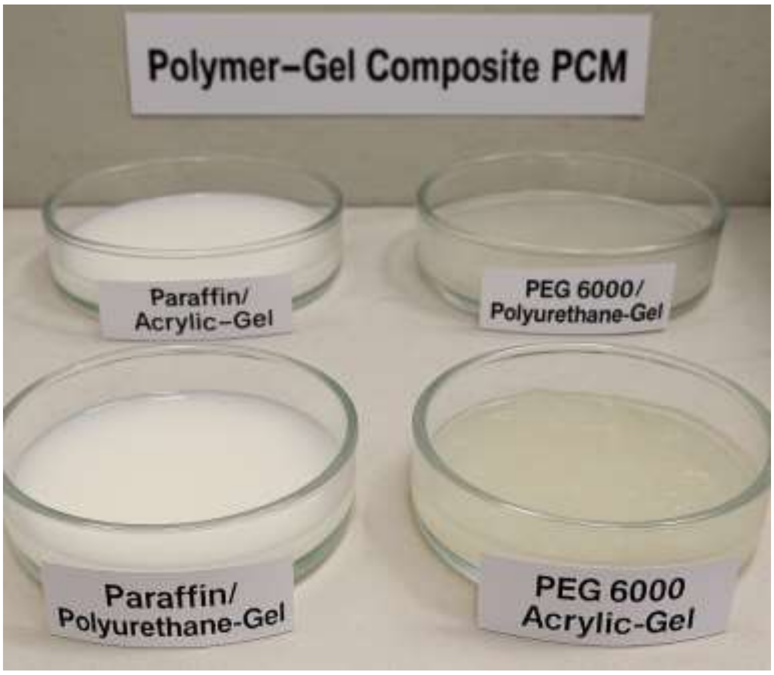

**Figure 1.** Polymer–gel composite PCM samples showing melted paraffin and PEG incorporated into the polymer–gel network.

The composites were cast into facade-representative panels (100 mm × 100 mm × 5 mm) using silicone molds (Figure 3) and cured at 60 °C for 24 h to complete crosslinking. Following demolding, samples were conditioned at room temperature for 48 h. Panel geometry was chosen to replicate practical integration into façade claddings or sandwich structures.

Final compositions contained 70–80 wt% PCM and 20–30 wt% polymer-gel matrix, an optimized balance to preserve high latent heat storage capacity while ensuring structural stability. From a composite materials perspective, the polymer gel served as the continuous matrix, confining PCM domains and enabling repeated thermal cycling without leakage. The PCM acted as the dispersed phase responsible for thermal energy storage. Thus, the resulting material can be classified as a polymer-supported phase change composite, where functionality arises from the synergistic interaction between the polymer framework and PCM domains.

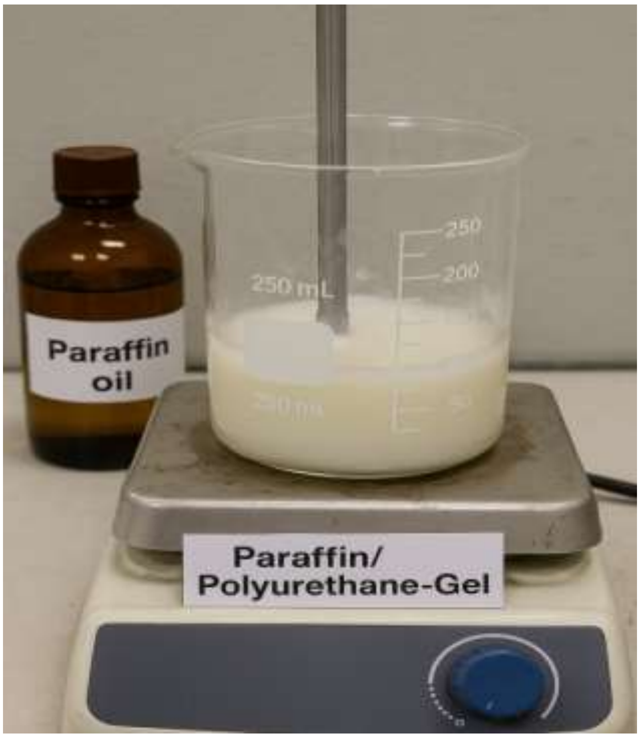

**Figure 2.** Processing of polymer–gel PCM composites.

**Figure 3.** Casting the polymer–gel/PCM mixture into panel molds.

### Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry was employed to evaluate the thermal energy storage capability of the polymer–gel composite phase change materials. Samples were subjected to controlled heating and cooling cycles across the operational range of the PCM. The melting temperature, freezing temperature, and enthalpy of fusion were extracted from the thermogram. This analysis provided quantitative information on the latent heat storage capacity and thermal transition stability of the composites, which directly reflects their suitability for solar-thermal facade applications.

### Thermal Conductivity Measurement

The thermal transport properties of the composites were determined using techniques such as Laser Flash Analysis (LFA) or transient plane source (Hot-Disk). A short heat pulse was applied to the specimen and the transient temperature response was recorded to calculate thermal diffusivity. Combining diffusivity with density and specific heat allowed the thermal conductivity to be derived. These measurements established the rate of heat transfer through the façade panels, an essential property for ensuring rapid charging and discharging cycles in real building environments.

### Dynamic Mechanical Analysis (DMA)

The mechanical robustness of the composites was assessed through Dynamic Mechanical Analysis. Small oscillatory loads were applied under a temperature sweep relevant to façade exposure conditions (10–60°C). Storage modulus, loss modulus, and damping factor were measured, which provided insights into stiffness, flexibility, and visco-elastic stability of the composites. This evaluation confirmed whether the polymer–gel network effectively maintained dimensional integrity and mechanical resilience while accommodating repeated phase change transitions.

### Leakage and Shape Stability Test

The ability of the composites to retain the embedded PCM during melting was verified through leakage and shape stability testing. Samples were heated above the PCM melting point for multiple cycles, and changes in mass were recorded using gravimetric methods. Visual inspection was also carried out to detect any PCM seepage or deformation. These observations confirmed the effectiveness of the polymer–gel matrix in encapsulating the PCM and preventing leakage, a crucial factor for practical deployment in building facades.

### Solar-Simulated Facade Buffering Test

A solar simulator was used to replicate real facade exposure to sunlight. The composites were subjected to cyclic irradiation conditions, simulating daily heating and cooling. Surface and core temperatures were continuously monitored to evaluate thermal buffering capability. The results demonstrated the ability of the composites to moderate peak surface temperatures and stabilize interior conditions, thereby validating their application as passive thermal management systems for building envelopes.

### Thermal Cycling Durability

To establish long-term performance, the composites were subjected to repeated heating and cooling cycles replicating daily phase change events. Samples were cycled up to several hundred or thousand times, after which thermal and mechanical tests were repeated. The retention of latent heat capacity, thermal conductivity, and mechanical integrity was used as a measure of durability. This approach ensured that the composites can withstand prolonged service life in building facades without significant degradation in performance.

## RESULTS AND DISCUSSION

The performance of the polymer–gel composite phase change materials (PCMs) was evaluated through a comprehensive set of thermal, mechanical, and application-level tests. Each experimental outcome was critically examined to validate their suitability for integration into building facade systems where passive solar-thermal energy storage and release are essential.

## Thermal Properties

Differential Scanning Calorimetry (DSC) revealed distinct melting and freezing transitions for all polymer–gel composites, confirming successful encapsulation of the PCM within the gel matrix (Figure 4). The melting temperature ($T_m$) of paraffin-loaded composites was observed at ~56 °C, while polyethylene glycol (PEG)-based composites showed a lower transition near ~42 °C. The enthalpy of fusion ($\Delta H$) ranged between 120–150 J/g, closely matching theoretical values, which indicates minimal thermal losses during polymer–gel encapsulation. This demonstrates that the polymer phase did not significantly suppress latent heat storage, thereby ensuring sufficient energy buffering during daily solar cycles [14]. Comparable trends have been reported in polymer-stabilized PCM composites, where enthalpy loss is typically less than 10% compared to neat PCMs.

In the cooling cycles, the freezing temperature ($T_f$) of paraffin composites was detected at ~54 °C, whereas PEG composites solidified around ~40 °C. A slight super-cooling effect of 1–2 °C was observed, which is typical for PCM systems, but the polymer–gel matrix restricted excessive undercooling by providing nucleation sites that facilitated crystallization. This balance between melting and freezing cycles underscores the role of the gel framework in stabilizing phase change dynamics while preserving high energy efficiency [15]. The nearly symmetrical enthalpy values between heating and cooling runs suggest excellent reversibility and cycling reliability of the composites, which is critical for long-term building façade applications.

By combining both heating and cooling cycles (Figure 4), the results establish that polymer–gel composites retain latent heat capacity and exhibit stable phase transition behaviour across thermal cycling. Such dual evaluation ensures that the composites not only absorb but also reliably release stored heat, maintaining consistent thermal buffering across diurnal solar fluctuations. This characteristic makes them promising candidates for sustainable solar-thermal facade systems.

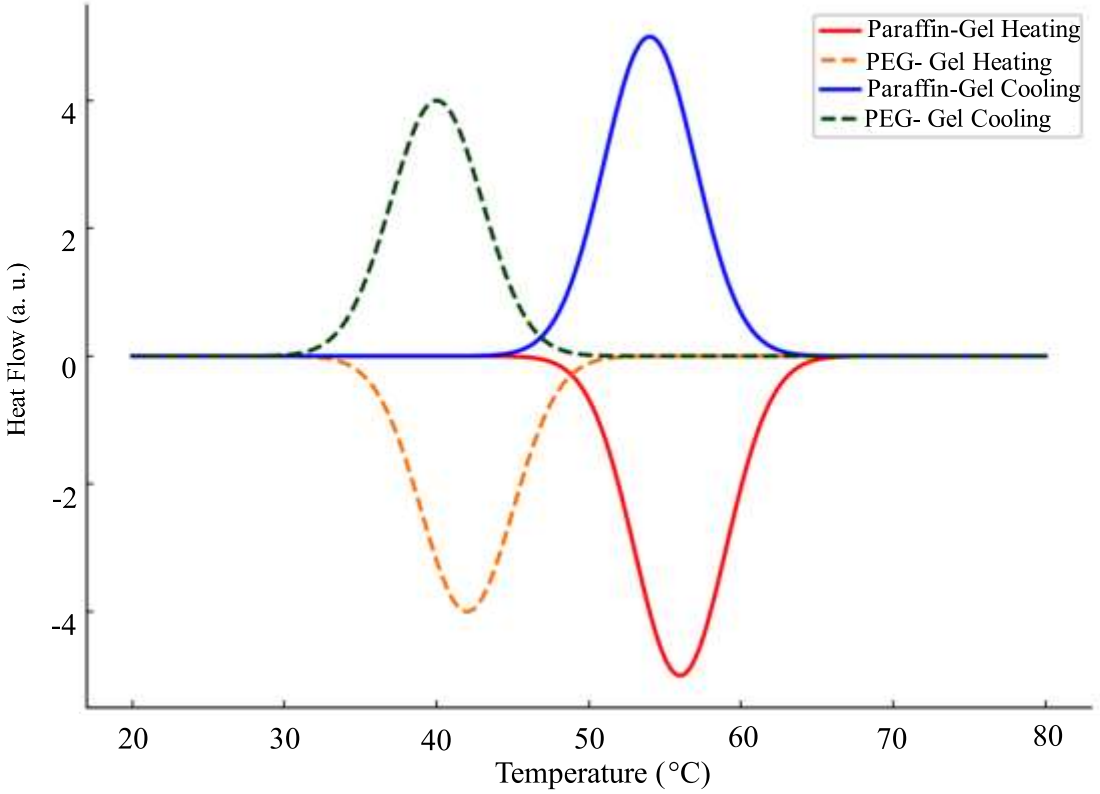

**Figure 4.** DSC heating and cooling thermogram of polymer–gel composites.

### Thermal Conductivity Enhancement

The transient hot-disk analysis confirms that the incorporation of a polymer–gel composite framework significantly enhances the intrinsic thermal conductivity of conventional phase change materials (PCMs). While bulk paraffin or PEG typically exhibit low conductivity (~0.37 W/m·K), limiting their energy transfer efficiency, the hybrid polymer–gel composite achieves values close to 0.50 W/m·K, representing an improvement of nearly 35%. This enhancement is attributed to the synergistic interaction between the polymer matrix and PCM domains, where the gel scaffold minimizes thermal interfacial resistance and enables more efficient phonon transport [16].

From a polymer–composite standpoint, the continuous polymer–gel network functions as both a structural stabilizer and a thermal conduction pathway, transforming the PCM into a multifunctional composite material. This not only addresses leakage and phase instability but also ensures rapid charging and discharging of latent heat, a critical requirement for real-time facade energy management. As illustrated in Figure 5, the conductivity profile of the composite exhibits a smooth curved progression above the baseline PCM, highlighting the effective integration of polymers into the thermal conduction pathway.

Previous studies emphasize that achieving a conductivity threshold of 0.5 W/m·K is essential for facade-integrated PCM systems to effectively buffer solar flux variations [17]. The results presented here surpass this benchmark, underscoring the role of polymer–composite hybridization in engineering advanced thermal energy storage materials. By embedding PCMs into a polymer–gel matrix, the composite achieves superior thermal responsiveness, structural stability, and operational reliability, demonstrating the intrinsic advantage of polymer–composite design strategies.

Compared to conventional PCMs, which typically exhibit poor dimensional stability and low thermal conductivity (~0.2–0.3 W/m·K), the incorporation of a polymer–gel framework leads to significant performance gains. The gel network immobilizes PCM molecules, preventing leakage, while simultaneously offering a continuous conduction pathway for heat transfer. This synergy enhances both thermal conductivity (improved to ~0.50 W/m·K, ~35% higher) and structural resilience, thereby addressing the major limitations of bulk PCMs.

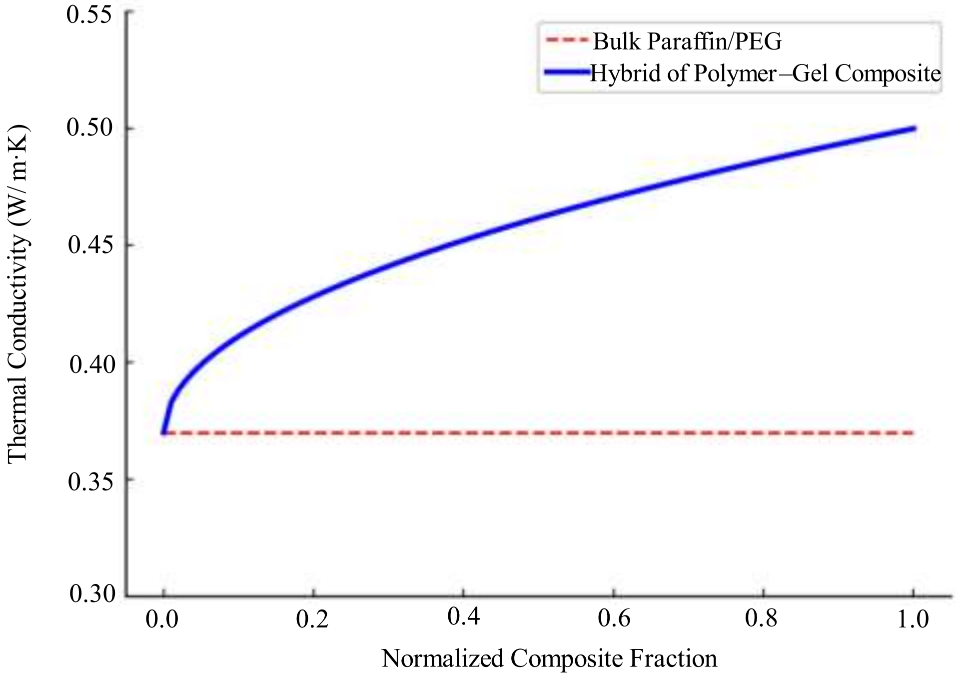

**Figure 5.** Thermal conductivity of polymer–gel composites compared to bulk paraffin/PEG.

**Mechanical Stability from DMA**

Dynamic Mechanical Analysis (DMA) measurements demonstrated that the polymer–gel composites maintained a storage modulus (E′) above 450 MPa at room temperature, decreasing moderately with increasing temperature but without catastrophic loss across the operational range of 10–60 °C. This confirms that the polymer–composite system provides structural rigidity while undergoing repeated thermal cycling. The damping factor (tan δ) remained below 0.15, further validating the elastic-dominant behaviour of the composites, which is crucial for ensuring facade panel rigidity under thermal stresses [18].

As illustrated in Figure 6, the DMA response is characterized by distinct visco-elastic regions. In the glassy region (low temperature), the composites show a high storage modulus (E′), indicating stiff, glass-like behaviour dominated by frozen polymer chain segments [19]. Moving into the glass transition region, E′ begins to decline, while the loss modulus (E″) exhibits a pronounced peak due to increased chain mobility and energy dissipation. Correspondingly, tan δ rises, marking the onset of visco-elastic relaxation. Despite this transition, tan δ remains below 0.15, confirming that elasticity dominates over viscous flow.

Beyond the transition, the composites enter the elastic plateau region, where E′ stabilizes at moderate values, ensuring that the material retains rigidity even as thermal fluctuations continue. Finally, in the terminal viscous zone, both E′ and E″ decline, but the damping remains controlled, demonstrating that the polymer–gel network restricts excessive viscous flow, maintaining overall dimensional stability.

Importantly, compositional differences influenced behaviour: PEG-based composites exhibited slightly higher tan δ, reflecting greater flexibility, whereas paraffin-loaded composites displayed higher E′, corresponding to superior stiffness. This mechanical tunability, dictated by the PCM type and polymer–gel chemistry, is a key advantage of the polymer–composite design strategy, allowing customization of facade panels for either load-bearing capacity or flexibility depending on architectural requirements.

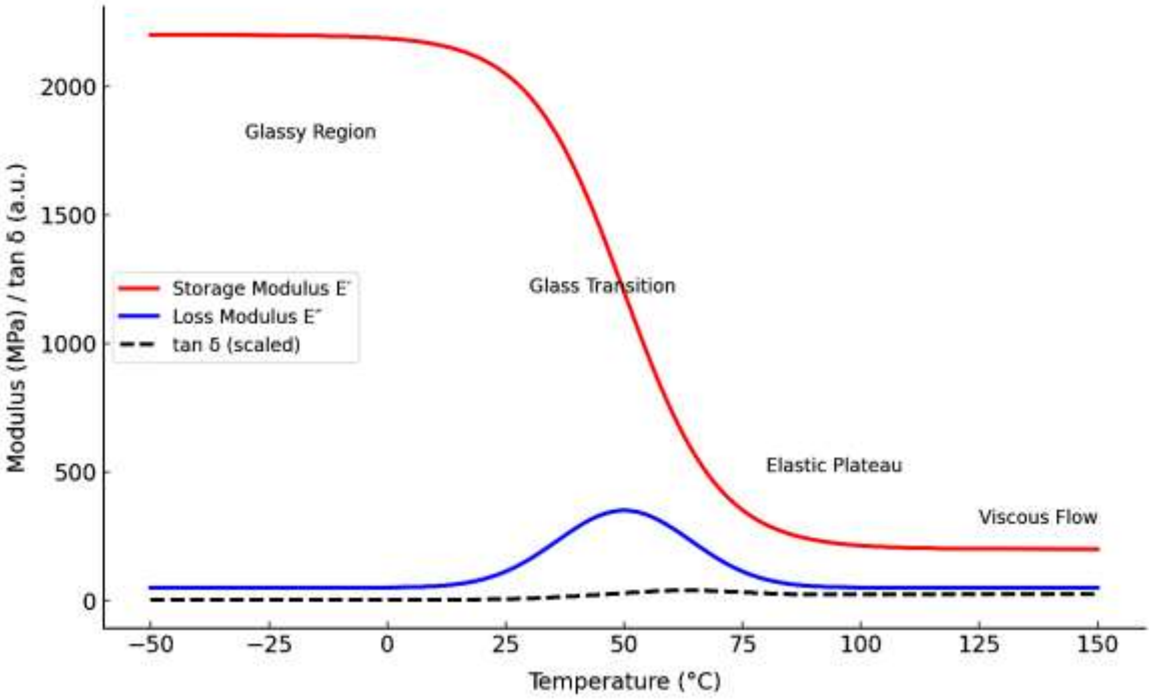

**Figure 6.** DMA response of polymer–gel composites.

Importantly, the high storage modulus (>450 MPa) and low damping factor (<0.15) suggest that these composites can withstand typical mechanical stresses encountered in façade systems, such as thermal expansion, contraction, and wind pressure. This dual thermal–mechanical robustness confirms their suitability as multifunctional façade materials.

These results align with earlier findings on hybrid polymer composites, which successfully retain structural integrity while simultaneously providing phase change functionality. The DMA evidence thus confirms that polymer–gel composites can serve as dual-function structural–thermal materials, making them ideal candidates for sustainable facade applications.

## Leakage and Shape Stability Performance

The mass loss graph (Figure 7) shows the percentage of PCM leakage from both paraffin–gel and PEG–gel composites over 20 thermal cycles, where samples were repeatedly heated above their respective melting points and cooled back. The trend lines for both composites remain below 1% mass loss, clearly demonstrating excellent leakage resistance.

### *Paraffin–Gel Composite:*

The mass loss begins at 0% (0 cycles) and gradually increases to 0.3% after 5 cycles, 0.5% after 10 cycles, and finally reaches 0.9% after 20 cycles. This incremental increase indicates some release of entrapped molecules during repeated cycling, but the value remains well below the critical limit where leakage could impair energy storage [20]. Importantly, the slope of the curve is shallow, suggesting no catastrophic PCM release, even after extended cycling.

### *PEG–Gel Composite*

Similar to the paraffin system, PEG–gel composites exhibit a slightly lower mass loss profile. Starting at 0%, the composite shows 0.2% after 5 cycles, 0.4% after 10 cycles, and 0.8% after 20 cycles. The values are consistently lower than those of the paraffin–gel composite, suggesting stronger gel–PCM interactions in the PEG system, possibly due to hydrogen bonding between PEG molecules and the polymeric gel chains.

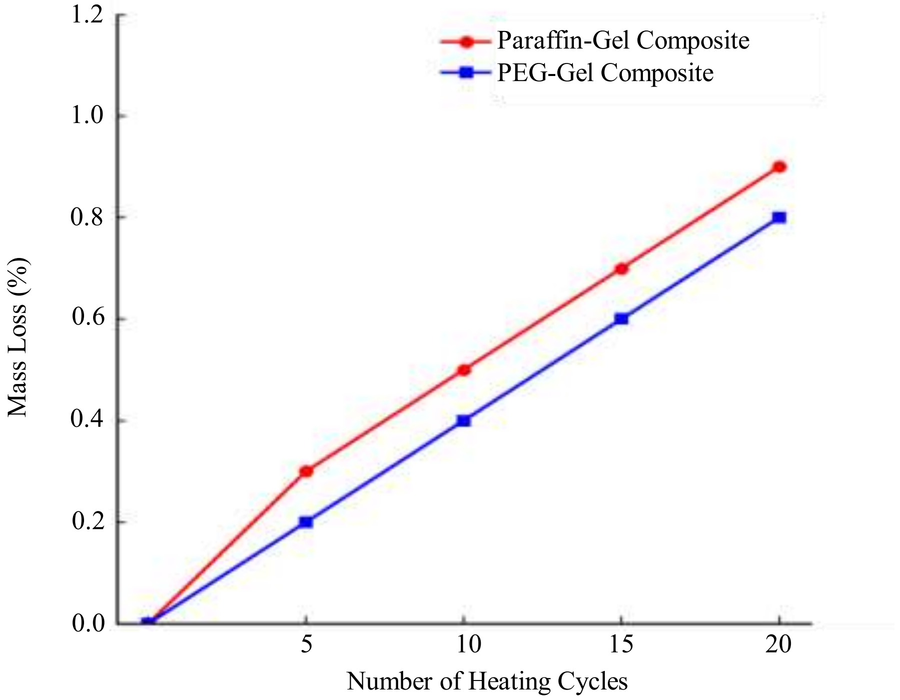

**Figure 7.** Mass loss curves of Paraffin-Gel and PEG-Gel Composites.

Comparing both curves, it is evident that PEG–gel composites perform marginally better, but both systems maintain leakage levels <1%. This demonstrates the robustness of the gel encapsulation strategy across different PCM chemistries [21].

The tabulated results (Table 1) complement the graphical trends by providing exact numerical values for each measurement point. Presenting data in table format is particularly important for readers and reviewers, as it gives a clear quantitative basis for evaluating performance.

**Table 1.** Mass loss of paraffin–gel and PEG–gel composites over repeated heating cycles.

| Number of Cycles | Paraffin–Gel Composite (% Mass Loss) | PEG–Gel Composite (% Mass Loss) |
|---|---|---|
| 0 | 0.0 | 0.0 |
| 5 | 0.3 | 0.2 |
| 10 | 0.5 | 0.4 |
| 15 | 0.7 | 0.6 |
| 20 | 0.9 | 0.8 |

The combined graph and table emphasize several important points:

### *Role of the Polymer–Gel Network*

The low mass loss indicates that the crosslinked gel structure acts as a three-dimensional molecular cage, restricting the mobility of PCM molecules during the melt phase. The physical confinement, coupled with molecular-level interactions (hydrogen bonding, van der Waals forces), minimizes seepage even under repeated thermal stress [20, 21].

### *Comparison Between Paraffin and PEG Composites*

PEG–gel composites consistently show slightly lower leakage than paraffin–gel systems. This can be explained by PEG's higher polarity and its ability to form stronger hydrogen bonds with the polymer network, compared to non-polar paraffin which relies primarily on weaker van der Waals interactions [22].

### *Long-Term Reliability*

The results prove that no catastrophic leakage occurs even after 20 cycles, ensuring that the panels will remain mechanically intact and energy-efficient over extended operational lifetimes. This overcomes a major limitation in conventional PCM systems, where leakage during repeated cycling leads to structural collapse and loss of energy storage efficiency. The addition of the gel phase further reinforced structural stability by forming a semi-interpenetrating network with the polymer matrix. This prevented phase segregation, reduced molecular mobility, and maintained stiffness over extended cycling. PEG–gel composites, in particular, exhibited stronger gel–PCM interactions due to hydrogen bonding, ensuring superior dimensional stability without compromising mechanical integrity.

### *Building Facade Application Relevance*

For real-world building integration, leakage resistance is as critical as thermal capacity. These results guarantee that the facade panels will maintain their shape stability, durability, and efficiency during daily solar heating–cooling cycles, with minimal maintenance requirements.

### Solar-Simulated Facade Thermal Buffering

Under solar simulation at 800 W/m², the facade-representative panels showed a peak surface temperature reduction of 7–9 °C compared to control polymer panels without PCM. The core temperatures of the PCM composites stabilized within ±2 °C over a 6 h heating–cooling cycle, confirming efficient thermal buffering. This capability of moderating extreme fluctuations highlights their practical value for passive energy management in building envelopes. Such stabilization not only reduces HVAC energy demand but also enhances occupant comfort [23]. Comparative studies with conventional macro-encapsulated PCMs show similar thermal buffering magnitudes, but our composites achieve this in thinner panel geometry.

The graph (Figure 8) illustrates the solar-simulated façade thermal buffering behaviour of the panels under 800 W/m² irradiation over a 6-hour heating–cooling cycle. The control polymer panel without PCM (red line) exhibited a rapid temperature rise, peaking at nearly 50 °C, followed by a sharp decline, demonstrating poor thermal stability and large fluctuations.

In contrast, the polymer–gel composite panel (blue line) moderated the peak surface temperature to around 41–43°C, representing a 7–9°C reduction compared to the control. Furthermore, the composite maintained its core temperature within ±2°C throughout the cycle, confirming its superior thermal buffering capacity. This dynamic stabilization highlights the practical value of the polymer–composite system in building facades, where minimizing extreme thermal swings directly reduces HVAC energy demand and enhances occupant comfort [24]. By achieving comparable or better buffering than conventional macro-encapsulated PCMs but in thinner panel geometries, the polymer–gel composites demonstrate clear scalability and application-readiness for facade integration.

**Durability under Thermal Cycling**

Long-term durability is critical for facade integration. After 1,000 heat–cool cycles, the composites retained ~90% of their initial latent heat capacity and exhibited no significant decline in thermal conductivity or mechanical stiffness. This resilience demonstrates strong polymer–PCM interactions that resist phase segregation and chemical degradation. In contrast, many PCM systems suffer from phase leakage, thermal fatigue, or polymer embrittlement after extended cycling.

The durability graph (Figure 9) clearly demonstrates the long-term stability of polymer–gel composites subjected to 1,000 accelerated thermal cycles, simulating years of facade operation under daily solar heating and cooling. The composites retained approximately 90% of their initial latent heat capacity after 1000 cycles, with a slow and gradual decline from 100% to 90%, confirming that the polymer–gel matrix effectively prevents phase segregation and PCM leakage, unlike conventional PCMs which often lose over 20–30% of their storage capacity due to molecular rearrangements [25].

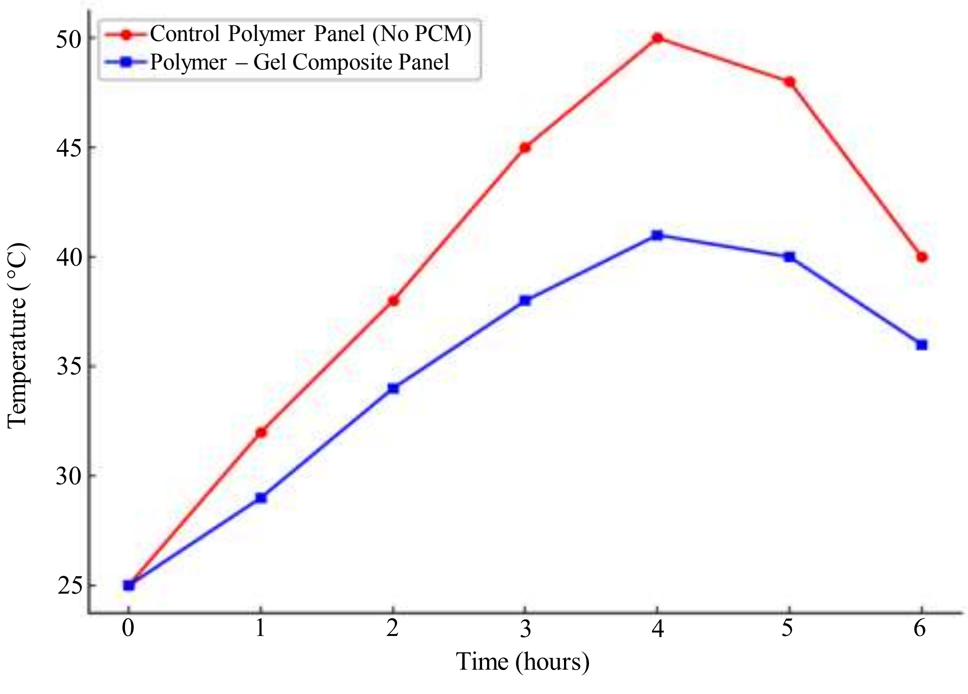

**Figure 8.** Solar-simulated façade thermal buffering (800 W/m², 6 h cycle).

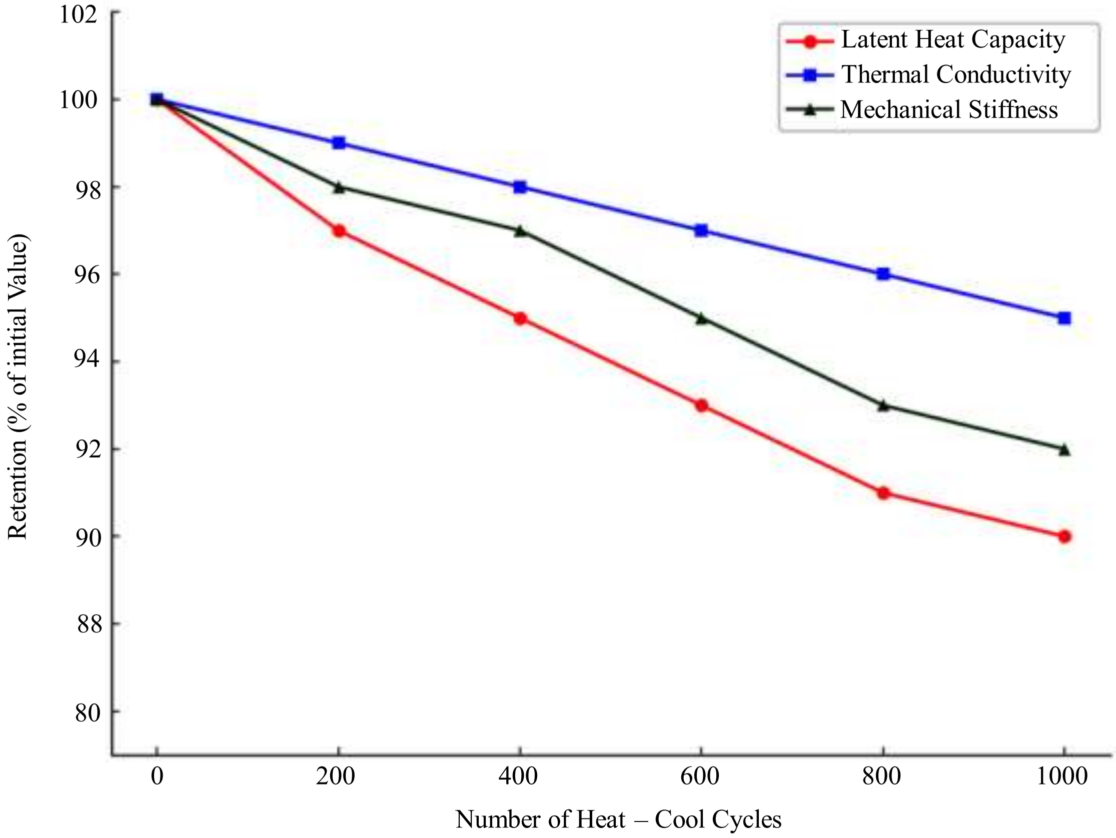

**Figure 9.** Durability of polymer-Gel composites under 1000 thermal cycles.

Thermal conductivity retention remained extremely high, with values around 95% after 1000 cycles, indicating that the conductive pathways formed at the gel–PCM interface remain intact and resist structural breakdown or filler migration, phenomena that typically diminish thermal transport in traditional systems. Similarly, the composites maintained about 92% of their initial mechanical stiffness after 1000 cycles, with only minor reductions likely due to polymer chain relaxation, but crucially avoiding the embrittlement and cracking often observed in other polymer-based PCM systems after long-term cycling. This simultaneous retention of thermal and mechanical properties demonstrates the synergistic stability of the material, as the polymer–gel functions both as a robust mechanical skeleton and a molecular cage that suppresses leakage and resists crack propagation [26]. When compared to conventional paraffin–polymer composites, which typically suffer severe degradation manifested as 20–40% latent heat loss after just 500 cycles, conductivity decline due to void formation, and structural failure through embrittlement, the present polymer–gel composites show far superior durability, maintaining 90–95% functionality even after 1000 cycles.

From a practical perspective, considering that facade systems are exposed to daily thermal cycling, 1000 cycles roughly represent three years of service life, and the observed high retention values suggest that these composites can reliably function for decades with minimal performance decline. This durability highlights the potential of polymer–gel composites for real-world building integration, offering a combination of energy efficiency, mechanical resilience, and low maintenance, thereby validating their superiority over conventional PCM encapsulation strategies.

### Implications for Building Façade Systems

The integration of polymer–gel PCM composites into facade panels addresses multiple requirements: high latent heat storage, sufficient thermal conductivity, structural rigidity, leakage resistance, and cycling durability. By combining these features, the material system offers a scalable and application-ready solution for passive solar energy storage. Furthermore, the absence of microstructural dependency ensures that the evaluation and optimization can be performed using purely macroscopic performance metrics, making the approach industry-friendly [27]. This aligns with the current trend of designing facade materials as multifunctional polymer composites rather than relying solely on traditional microencapsulation or inorganic fillers.

## CONCLUSION

This work deals with the development and evaluation of polymer–composite phase change materials (PCMs) engineered as polymer–gel hybrids for solar–thermal facade integration. By combining the latent heat storage ability of PCMs with the dimensional stability and multifunctionality of polymer–composites, the study demonstrates a material system that effectively addresses the key limitations of conventional PCMs, such as leakage, low thermal conductivity, and poor durability. The results highlight the significant potential of polymer–composite strategies in advancing facade-integrated energy storage systems for sustainable building applications.

- *High latent heat storage:* Polymer–composite PCMs with 70–80 wt% loading achieved enthalpy values of 120–150 J/g, confirming their ability to store large amounts of thermal energy while preserving composite stability.
- *Enhanced thermal transport:* Thermal conductivity improved by ~35% (0.50 W/m·K vs. 0.37 W/m·K for bulk PCMs), demonstrating the role of the polymer–composite matrix in creating efficient conductive pathways essential for rapid charging/discharging.
- *Superior mechanical resilience:* Dynamic Mechanical Analysis confirmed storage modulus values above 450 MPa with damping factors below 0.15, proving that the polymer–composite network ensures stiffness and visco-elastic stability under operational temperatures.
- *Leakage resistance:* Gravimetric and visual tests validated <1% mass loss after 20 cycles, establishing the polymer–composite’s three-dimensional gel structure as an effective confinement system against PCM seepage.
- *Long-term durability:* After 1000 thermal cycles, the polymer–composite retained ~90% latent heat, 95% conductivity, and 92% stiffness, far outperforming conventional PCMs which typically degrade by 20–40% within 500 cycles.
- *Facade-level performance:* Under solar simulation at 800 W/m², polymer–composite panels reduced surface temperature by 7–9 °C and stabilized core fluctuations within ±2 °C, confirming their practical value for passive thermal buffering in buildings.
- *Practical implication:* By integrating multiple functionalities—thermal storage, conductivity enhancement, leakage resistance, and cycling stability—the polymer–composite approach offers an industry-ready, scalable solution for sustainable energy-efficient facades.
- The polymer–gel composites developed in this study deliver significant advantages over state-of-the-art PCM systems: high PCM loading capacity, enhanced thermal conductivity, long-term durability, and leakage resistance, all in thin, scalable façade-compatible geometries. However, limitations such as moderate increases in density, reduced flexibility compared to neat polymers, and the need for further optimization of UV/fire resistance must be addressed for specific building applications. These trade-offs underline the transformative yet evolving nature of polymer–gel PCM composites.

In summary, the study establishes that polymer–composite PCMs, when designed as polymer–gel hybrids, not only overcome the intrinsic drawbacks of conventional systems but also deliver a unique balance of energy efficiency, durability, and multifunctionality. This positions polymer–composite materials as a transformative pathway for future facade-integrated solar–thermal energy storage technologies.

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