Current Application Status of Phase Change Energy Storage in Building Energy Efficiency

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Abstract: Phase change materials (PCMs), as efficient latent heat storage media, demonstrate significant application potential in the field of building energy efficiency. This paper systematically reviews the research progress and application status of PCMs in building energy efficiency through a systematic literature review based on databases such as Web of Science, focusing on recent studies related to building phase change energy storage, PCM preparation, and building cases utilizing PCMs. A multi-scale inductive and logical synthesis was applied to the retrieved literature to summarize technical patterns, research hotspots, and key limitations at the material, component, and system levels. In-depth case studies of typical engineering projects across different climate zones and building types were conducted for comparative analysis, aiming to comprehensively reveal the overall performance of PCM-integrated buildings under various climatic conditions. Firstly, PCMs are categorized into organic, inorganic, and eutectic materials based on their chemical composition, with their thermophysical properties, optimization strategies, and suitability for different building components critically analyzed. Secondly, mainstream encapsulation technologies-macro-encapsulation, microencapsulation, and shape-stabilization encapsulation-are examined, highlighting their roles in mitigating leakage, enhancing thermal conductivity, and improving cycling stability. Key experimental findings, such as the reduction of indoor temperature peaks by 4.1°C using microencapsulated paraffin and the achievement of 0.247 W/m·K thermal conductivity in expanded perlite/PEG composites, are discussed to substantiate performance claims. Subsequently, the integration methods, thermal performance, and energy-saving effects of PCMs in building envelope components (walls, roofs, floors, windows) are elaborated, supported by empirical data from various climatic zones. For instance, in tropical climates, PCMs reduced annual heat gain by 21–23%, while in Mediterranean regions, cooling loads decreased by 7.5–9.5% and heating loads by 55–61.6%. Finally, current research challenges regarding long-term stability, thermal conductivity optimization, cost, and simulation-experiment discrepancies are identified. Future directions are prospected from the perspectives of material design, encapsulation techniques, system integration, and engineering demonstration. This paper aims to provide a systematic and data-supported reference for further research and application of PCMs in building energy efficiency.

Keywords: Phase Change Material; Building Thermal Management; Thermal Energy Storage; Passive Energy Storage

1. Introduction

Against the dual backdrop of an increasingly severe global energy crisis and escalating climate change challenges, building energy consumption has become a key component of total societal energy consumption, with its proportion continuously rising. This not only intensifies the contradiction between energy supply and demand but also constitutes a major source of carbon emissions. In hot summer climate zones, building cooling loads remain persistently high. Conversely, in cold winter and severe cold climate zones, building heating loads remain consistently elevated. Consequently, thermal management energy consumption represents a core operational cost and a primary source of carbon emissions in buildings. In this context, developing and scaling up the application of efficient passive energy-saving technologies to reduce building cooling and heating loads at the source has become a crucial pathway for promoting the achievement of the "carbon peak and carbon neutrality" strategic goals in the construction sector. It is also an inevitable choice for implementing the concept of green and low-carbon development.

Phase Change Materials (PCMs), as highly efficient latent heat storage media, offer an innovative solution for building energy efficiency by leveraging their unique capability to "absorb-store-release" latent heat within their phase transition temperature range. Integrating PCMs into building envelopes or thermal energy storage systems enables efficient absorption and storage of excess heat transferred indoors or from outdoors during the daytime. This delays the occurrence and reduces the peak of indoor temperatures, thereby significantly lowering air conditioning loads. At night, stored heat is released through the phase change process, facilitating energy recycling and stable indoor temperature regulation. This "peak shaving and valley filling" operational mechanism not only promotes the transition of buildings from a "high-energy-consumption extensive" mode to a "low-energy-consumption refined" one but also synergizes with the power grid for load regulation, alleviating temporal imbalances in energy supply and demand. It holds dual value for both building energy efficiency and energy system optimization.

This paper focuses on the core mechanisms, material development, encapsulation technologies, and integrated applications of phase change energy storage technology in building energy efficiency. By systematically reviewing domestic and international research, it analyzes the application status and bottlenecks of PCMs in different climatic zones, and summarizes technological breakthrough directions in material modification, encapsulation optimization, and system integration. The aim is to provide a theoretical basis and practical reference for the scaled-up and cost-effective application of this technology. This study will further clarify the development potential and technical pathways of phase change energy storage in the field of building energy efficiency, holding significant theoretical importance and engineering application value for promoting the upgrade of building energy-saving technologies, improving energy utilization efficiency, and contributing to the realization of the "dual carbon" goals.

2. Phase Change Materials Applied in the Building Sector

There are various classification methods for Phase Change Materials (PCMs), such as by phase transition type or phase change temperature. However, in the field of building energy efficiency, the most prevalent classification is based on chemical composition. According to this, PCMs are generally categorized into three main types: organic, inorganic, and eutectic PCMs. It should be noted that this classification is not entirely rigid, and overlaps between material types can occur in practical applications.

2.1 Organic Phase Change Materials

The chemical composition of organic PCMs primarily includes paraffin waxes, polyethylene glycol (PEG), and fatty acids, among others. Organic PCMs are the most widely used type. They offer advantages such as suitable phase change temperatures, stable chemical properties, non-toxicity, non-corrosiveness or low corrosiveness, and relatively weak supercooling. Their main disadvantages are susceptibility to leakage during the phase change process and relatively low thermal conductivity, typically around 0.2 W/m·K [1].

Paraffin wax is one of the most extensively used organic PCMs. Its phase change temperature (typically within the range of 18–28℃) aligns well with the human thermal comfort zone, and it possesses a high latent heat of fusion (approximately 200–240 J/g) [2]. However, its low thermal conductivity limits heat charge/discharge rates, and the leakage issue during solid-liquid phase transition must be addressed through encapsulation technologies. Consequently, the ultimate thermophysical properties of paraffin-based PCMs integrated into building components largely depend on the encapsulation process. For instance, Zhao et al. encapsulated paraffin using microencapsulation technology. The prepared PCM exhibited a latent heat value of 110.5 J/g. Although this is lower than that of pure paraffin, it successfully resolved the leakage problem and achieved functionality. When integrated into a building model, it reduced the peak indoor temperature on summer afternoons by 4.1℃. This clearly demonstrates that through effective encapsulation, paraffin PCMs can significantly mitigate indoor temperature fluctuations, improve thermal comfort, and possess energy-saving potential. The study also verified the material's good cycling stability after long-term outdoor testing [3].

The phase change temperature of polyethylene glycol (PEG)-based materials generally ranges from 45°C to 70°C [4]. Sun et al. developed a novel core-shell structure PCM (E-shell PCM) using expanded perlite (EP) to stabilize polyethylene glycol (PEG). The material itself had a latent heat value of 136.40 J/g. When this material was incorporated into a building composite at a 30% proportion, the composite's melting enthalpy and crystallization enthalpy reached 76.06 J/g and 74.61 J/g, respectively. In simulated building temperature control experiments, it effectively regulated indoor temperature, reduced temperature fluctuations, and enhanced environmental comfort. When added at a 20% proportion, the composite achieved a thermal conductivity of 0.247 W/m·K. Furthermore, the material exhibited good flame-retardant and smoke-suppression properties, broadening its application prospects in green buildings [5].

Fatty acid-based PCMs typically are not used as single compounds but are prepared as binary mixtures, such as capric acid-palmitic acid, capric acid-lauric acid, and lauric acid-stearic acid combinations. These materials are both organic PCMs and eutectic PCMs. Research progress on such materials will be discussed in the section on eutectic PCMs.

2.2 Inorganic Phase Change Materials

Inorganic PCMs mainly refer to salt hydrate PCMs. The phase change temperatures of salt hydrates often fall within the suitable range for building indoor environmental control (Common hydrated salt PCMs, such as $CaCl_2 \cdot 6H_2O$ and $Na_2SO_4 \cdot 10H_2O$, have phase change temperatures of approximately 29°C and 32°C, respectively.). They offer outstanding advantages such as high latent heat, relatively high thermal conductivity, low cost, and non-flammability, making them highly promising for thermal energy storage applications in building envelopes [2].

However, the practical building application of traditional salt hydrate PCMs has long been constrained by three inherent challenges: supercooling, phase separation, and potential corrosiveness.

Firstly, supercooling refers to the phenomenon where the material must be cooled below its theoretical freezing point to initiate crystallization and heat release. This can disrupt the thermal regulation rhythm of PCMs in buildings. If latent heat cannot be released promptly when indoor temperatures drop too low at night, the PCM loses its function of balancing room temperature. The fundamental approach to mitigating supercooling is promoting heterogeneous nucleation. Adding nucleating agents is currently the most direct and effective method [6]. For example, researchers from Tianjin University added a combination of 1.5 wt% nano γ-Al_2O_3 and 0.5 wt% $SrCl_2 \cdot 6H_2O$ as nucleating agents to a PCM, reducing the supercooling degree from 21.1°C to 0.41°C, almost eliminating the supercooling phenomenon [6].

Secondly, the phase separation problem affects the long-term cycling stability of PCMs. During repeated melting-solidification cycles of salt hydrates, density differences can lead to the separation of anhydrous salts and crystal water, resulting in the attenuation of phase change capacity. This makes it difficult for the energy-saving performance of PCMs in buildings to match the stable service life requirements of building components. Strategies to inhibit phase separation primarily focus on physical confinement and structural stabilization. The traditional method involves introducing thickening agents. Li et al. proposed a novel approach by introducing dextran sulfate sodium (DSS) to address phase separation. DSS does not rely on a thickening mechanism; instead, it inhibits the precipitation of PCM through electrostatic stabilization, significantly reducing phase separation [7].

Thirdly, some salt hydrates are corrosive. Chloride salts can corrode steel reinforcement and pipes, while sulfate salts can attack cementitious matrices. PCMs intended for building structures must consider corrosion prevention. The most effective strategy is also employing high-density encapsulation to minimize salt hydrate leakage. Liu et al., based on encapsulating disodium hydrogen phosphate dodecahydrate (DHPD) using melamine foam (MF) as a porous carrier, applied a UV-curable polyurethane acrylate (PUA) coating. The encapsulated PCM showed no leakage after heating at 60°C for 4 hours, with minimal mass loss (<0.1%), effectively preventing corrosion of building materials by the salt hydrate [8].

2.3 Eutectic Phase Change Materials

Single-component organic or inorganic PCMs often struggle to simultaneously meet the comprehensive requirements of building energy efficiency regarding phase change temperature, latent heat value, and cost. Therefore, researchers have begun combining two or more PCMs to form mixtures with a single eutectic point, known as eutectic PCMs.

Eutectic PCMs can be composites of organic PCMs with organic PCMs (such as the fatty acid-based PCMs mentioned earlier). The properties of these materials are fundamentally similar to those of organic PCMs. For example, researchers from Harbin Institute of Technology selected capric acid and polyethylene glycol for compounding. A 1:1 mass ratio was determined as the optimal eutectic composition, with a phase change temperature of 22.9°C and a latent heat value of 173.9 J/g. Intermolecular hydrogen bonding helped reduce supercooling. The material demonstrated good long-term reliability, maintaining stable performance and showing minimal corrosion after 200 thermal cycles. Economic and environmental benefit assessments indicated good potential for engineering applications and comprehensive energy-saving/carbon reduction value in building energy efficiency [9].

Eutectic PCMs can also be composites of inorganic PCMs with inorganic PCMs. Liu et al. from Shanghai University of Technology selected $Na_2HPO_4 \cdot 12H_2O$ and $Na_2SO_4 \cdot 10H_2O$ for compounding, determining an 80/20 mass ratio as optimal. This binary eutectic system had a phase change temperature of 28.1°C and an enthalpy of 229.1 J/g. Introducing 2% $Na_2SiO_3 \cdot 9H_2O$ as a nucleating agent optimized the supercooling degree to 3.25°C. After 50 thermal cycles, the enthalpy degradation was minimal (decreasing from 212.5 J/g to 209.1 J/g). Encapsulation with expanded perlite addressed leakage issues, laying the foundation for preparing PCM mortar components [10].

Furthermore, eutectic PCMs can be composites of organic and inorganic PCMs. A research team from Dalian University of Technology used methyl palmitate, $Na_2HPO_4 \cdot 12H_2O$, and $Na_2CO_3 \cdot 10H_2O$ as the base phase change components. Sodium carboxymethylcellulose(CMC-Na) served as an emulsifier and thickener, and silica aerogel was used as a porous carrier for encapsulation. They successfully prepared a novel organic-inorganic eutectic PCM. This material exhibited a phase change temperature of 22.9°C, a latent heat value of 174.1J/g, no supercooling issues, and good flame retardancy. Additionally, comparative experiments with a foam model demonstrated its promising performance for building thermal management [11].

3. Encapsulation of Phase Change Materials

The encapsulation of Phase Change Materials (PCMs) is a core step for their integration into building structures. Current mainstream encapsulation methods include macroencapsulation, microencapsulation, and porous carrier encapsulation.

3.1 Macro-Encapsulation

Macro-encapsulation involves encapsulating PCMs into containers at a millimeter scale or larger. The shape of these containers can be designed in various forms, such as spherical, tubular, or panel-shaped, according to practical needs. For example, tubular containers can be integrated into roof structures for PCMs, while macro-capsules can be placed within hollow bricks.

The advantages of macro-encapsulation are significant, including flexible selection of container shell shapes, relatively lower production difficulty and cost, and effective prevention of PCM leakage. However, it also presents some drawbacks, such as low specific surface area leading to lower heat transfer efficiency, the shell occupying space and adding mass, and non-uniform solidification/melting of the PCM within the shell.

The materials for macroencapsulation containers are mostly metal or plastic. Metals offer good thermal conductivity, but since inorganic PCMs are often corrosive to metals, metal containers are primarily used for encapsulating organic PCMs. Plastics can be used for encapsulation but have the disadvantage of poor thermal performance. Currently, macroencapsulation is the most widely used PCM encapsulation technology in practical applications [12].

Indian researchers utilized a cold forging process to create aluminum alloy containers, sealing an organic PCM with a phase change temperature of approximately 35°C to form macroencapsulation units. In hot climates, the roof unit integrated with PCM demonstrated clear advantages. Compared to a standard concrete roof, the peak temperature of the indoor surface was reduced by up to 7.2°C, with an average reduction of 4.8°C, and the overall thermal load was reduced by about 54%. Moreover, the aluminum encapsulation shell prevented leakage, and the PCM's phase change temperature remained stable after 1,000 thermal cycles [13].

Additionally, a Portuguese research team employed material extrusion 3D printing technology to fabricate macroencapsulation containers for PCMs. Through iterative parameter optimization, cylindrical PETG capsules achieved 0% PCM leakage after 35 thermal cycles; TPU capsules achieved 100% PCM retention on the first attempt, demonstrating the universality of the leak-proof design across different materials. This research systematically revealed the influence of printing parameters, geometric structure, and material selection on sealing performance, providing an effective solution for manufacturing customized and reliably sealed PCM containers [14].

3.2 Microencapsulation

Microencapsulation (MEPCMs) involves encapsulating PCMs within microcapsules ranging in size from 1 mm to 1 μm. The core structure consists of a core made of PCM and a shell made of polymer or inorganic material. The core, composed of the PCM, is responsible for storing and releasing latent heat. The shell, forming a sealed protective layer around the PCM, prevents leakage and provides mechanical support. Shell materials can be categorized as: organic shells (e.g., melamine-formaldehyde resin (MF), polyurethane (PU), polystyrene (PS), polymethyl methacrylate (PMMA), known for good flexibility, ease of preparation, and high mechanical strength); inorganic shells (e.g., SiO_2, offering high thermal conductivity, flame retardancy, and stability); and hybrid/multi-layered shells (e.g., organic-inorganic composites or multi-layered structures incorporating metals or carbon materials to further enhance thermal conductivity, mechanical properties, or impart specific functionalities) [15].

This technology physically isolates the PCM from the external environment, effectively addressing issues such as leakage during phase change and reactions with the surroundings. The shell structure confines the PCM within microscopic spaces, preventing leakage even when the PCM melts, making it suitable for long-term cycling. It also significantly increases the specific surface area of the PCM, accelerating heat absorption and release, thereby improving the system's thermal response speed and heat exchange efficiency. Furthermore, it can limit phase separation of the PCM at the microscale, reducing performance degradation during cycling. However, the complex microencapsulation process results in higher production costs compared to traditional PCMs.

To optimize performance, researchers focus on improving the shell through material composites. For example, Zhang et al. investigated the effect of graphene oxide (GO) modification on melamine-urea-formaldehyde (MUF) shells for microcapsules with n-hexadecane as the core. The results showed that the thermal conductivity of the microcapsules increased significantly with higher GO content. Microcapsules containing 0.1 wt% GO exhibited an average latent heat of 217.2 J/g with an encapsulation efficiency of 95%; those with 0.3 wt% GO achieved the highest thermal conductivity coefficient of 0.1554 W/(m·K). This research provides preferred materials for MEPCM applications [16].

Addressing the issue of reduced mechanical performance when microencapsulated PCMs are combined with cementitious materials, a research team from the University of Alabama developed a novel organic-inorganic hybrid microcapsule shell composed of cenospheres and ethyl cellulose (EC). Using a solvent evaporation method, EC was coated onto industrial cenospheres to form a tight encapsulation, producing ECPCM microcapsules. This shell structure better preserved the mechanical properties of the composite; with a 20% dosage, the 28-day compressive strength of cement mortar decreased by only about 22.6%, a reduction significantly lower than that reported for most polymer-shell microcapsule systems in the literature [17].

3.3 Shape-Stabilization Encapsulation

shape-stabilization encapsulation involves impregnating PCMs into porous carriers, utilizing capillary forces, surface tension, etc., to achieve encapsulation. This method is a key technological pathway for addressing the core challenges faced by PCMs, particularly inorganic salt hydrates and some organic PCMs, in applications (such as liquid leakage, phase separation, poor thermal conductivity, and corrosiveness). It represents one of the most promising directions in recent research and application of building-integrated PCMs.

There are three primary processes for achieving encapsulation using porous carriers: direct impregnation, vacuum impregnation, and sol-gel method. The most basic and simplest process is direct impregnation, which relies primarily on the gravity, capillary action, and diffusion of the liquid phase change material (PCM) to spontaneously penetrate the pores of the porous carrier. However, the PCM loading capacity achieved through this process is relatively low and unevenly distributed. Currently, the most widely used and effective process in laboratory research and applications is the vacuum impregnation method. This method involves evacuating air from the internal voids of the porous carrier to create a negative pressure, thereby utilizing the ambient positive pressure to force the liquid PCM into the pores of the carrier. For instance, in the preparation of shape-stabilized composite PCM using $Na_2SO_4 \cdot 10H_2O$-$Na_2HPO_4 \cdot 12H_2O$/expanded perlite via porous carrier encapsulation, researchers from the University of Shanghai for Science and Technology employed the vacuum impregnation method. By evaluating three key indicators-adsorption efficiency, PCM adsorption capacity, and leakage resistance-the researchers selected expanded perlite with a particle size of 2–2.5 mm as the porous adsorbent material. This material achieved a PCM adsorption rate of up to 92%, with a mass loss rate of 1.97% after leakage testing[10]. The sol-gel method involves converting molecular-level liquid precursors into a nanoscale solid network (gel) through hydrolysis and condensation reactions, followed by post-treatment to obtain porous solid materials.

The selection of porous carriers is diverse, with common carrier materials including expanded perlite (EP), diatomite, expanded graphite, and synthetic organic porous materials. For example, Tian et al. utilized silica gel waste to prepare porous silica carriers, loaded them with capric acid–hexadecanol PCM, and enhanced thermal conductivity by incorporating expanded graphite (EG). The resulting shape-stabilized composite exhibited a latent heat of 105.6 J/g, and its thermal conductivity increased to 0.9513 W/(m·K) after EG addition. When incorporated into phase change mortar, the temperature regulation time within the range of 18–32℃ was extended by approximately 267.9% compared to ordinary mortar[18]. This study provides a novel approach for the conversion of waste resources and the development of high-efficiency building temperature-regulation materials.

In summary, phase change materials of different types and encapsulation technologies exhibit significant variations in phase change temperature, latent heat value, thermal conductivity, and other key properties. These performance characteristics directly determine their effectiveness in building energy efficiency applications. The key performance parameters and features of representative PCMs are summarized in Table 1.

Table 1. Performance Parameters and Characteristics of Different Types of Phase Change Materials

Material Name	Phase Change temperature (℃)	Latent Heat ($J \cdot g^{-1}$)	Thermal Conductivity (W/ m·K)	Characteristics	References
Paraffin@gelatinized flour phase change microcapsule	15.7	110.5	-	encapsulation efficiency 66.7%	[3]
Expanded perlite/polyethylene glycol composite PCM	16.1	136.4	0.247	flame retardancy and smoke suppression	[5]
$CaCl_2 \cdot 6H_2O$/Expanded Perlite/Nano-γ-Al_2O_3 composite form-stable PCM	27.17	138.22	1.480	The supercooling degree decreased to 0.41 °C	[6]
$Na_2SO_4 \cdot 10H_2O$/expanded graphite / dextran sulfate sodium / borax	-	166.6	4.5±0.5	The cost ranges from 18.13 to 116.31/kWh	[7]
The MXene-modified melamine foam shape-stabilized composite phase change material based on disodium hydrogen phosphate dodecahydrate (DHPD)	36.05	224.43	0.195	The incorporation of MXene significantly enhances the photothermal conversion efficiency	[8]
Decanoic acid / Polyethylene glycol	22.9	173.9	0.2025	The cost is 34.5 CNY/kg	[9]

$Na_2HPO_4\cdot 12H_2O$/ $Na_2SO_4\cdot 10H_2O$/ Expanded Perlite/ $Na_2SiO_3\cdot 9H_2O$	24.85	156.7	-	The adsorption rate reaches 92%	[10]
Methyl palmitate/ $Na_2HPO_4\cdot 12H_2O$/$Na_2CO_3\cdot 10H_2O$/ SiO_2 aerogel/ Sodium carboxymethyl cellulose	22.9	174.1	-	Possess fire-resistant propertie	[11]
Graphene oxide-modified melamine urea-formaldehyde@n-hexadecane phase change microcapsules	25	210.5	0.1554	The encapsulation efficiency reaches 93%	[16]
n-octadecane/ cenosphere / ethyl cellulose	29.98	77.8	-	Suitable for structural components with mechanical performance requirements.	[17]
Decanoic acid / Cetyl alcohol / Porous silica / Expanded graphite	26	88.1	0.9513	Utilizing silicone waste to reduce costs and pollution	[18]
Decanoic acid / Cetyl alcohol / Porous silica	18.2	105.6	0.3650	Utilizing silicone waste to reduce costs and pollution	[18]

4. Phase Change Materials in Building Envelopes

Based on the integration location, the application of phase change materials in buildings can be categorized into different scenarios such as walls, roofs, floors, and windows.

4.1 Walls

As the core component of the building envelope, integrating Phase Change Materials (PCMs) into walls to enhance their thermal regulation and energy-saving performance has become an important research direction. Depending on the wall construction system and integration methods, current research primarily follows two main technical pathways: first, incorporating PCMs into the bulk matrix of cast-in-place concrete; second, placing PCMs into the cavities of prefabricated hollow bricks or blocks.

The integration of PCMs into concrete walls focuses on the composite of PCMs with the matrix material, aiming to develop novel composites that possess both good mechanical properties and high thermal inertia. This typically requires careful evaluation of the impact of PCMs on the mechanical performance of concrete. A representative study is the novel energy-saving concrete developed by an Australian research team: using recycled concrete aggregate (RCA) as a porous carrier to encapsulate PCM via an impregnation process, followed by CO_2 curing treatment. This technology not only enhanced encapsulation stability but also significantly increased the material's compressive strength to 48.7 MPa, a 47.1% improvement compared to ordinary recycled concrete. Regarding thermal performance, applying this material in the building envelope can reduce the peak indoor temperature by 5.0°C. Simulations indicated that it could achieve an average annual energy consumption reduction of 37.1% in buildings across multiple climate zones, demonstrating a synergy between mechanical enhancement and energy-saving [19].

The pathway for PCM integration in hollow bricks/blocks focuses on placing encapsulated PCMs into the cavities of prefabricated components. The technical core lies in optimizing the encapsulation form and the placement position within the cavity to maximize the thermal buffering effect. Research mainly involves two integration methods: one is the placement of macro-encapsulated aluminum capsules. For instance, Abbas et al. placed paraffin encapsulated in aluminum capsules into brick cavities. Experiments measured a reduction of 4.7°C in the peak inner surface temperature of the PCM-integrated wall and a 23.84% decrease in the fluctuation amplitude of indoor air temperature [20]. The other method is direct filling with microencapsulated PCM. Some studies directly filled commercial microencapsulated PCM into pre-set holes in cement bricks. Experimental results showed that integrating PCM at the center of the brick yielded the best effect, with the peak temperature of the inner wall reduced by up to 8.91°C [21].

In summary, current research indicates that integrating PCMs into concrete systems faces the core challenge of reconciling thermal functionality requirements with mechanical performance assurance through material and process innovations (e.g., porous carrier design, CO_2 curing technology). In hollow block systems, the key technology involves optimizing the PCM encapsulation form (aluminum encapsulation, capsule encapsulation, etc.) and its spatial configuration within the cavity (e.g., placing PCM closer to the exterior wall side in hot climates) to fully utilize its latent heat storage and temperature regulation functions. Both technical pathways have significantly improved wall thermal performance, providing effective solutions for building energy efficiency and indoor thermal comfort enhancement. Future research could further focus on the long-term reliability, cost-effectiveness of different integration technologies, and their synergistic design within composite wall systems.

4.2 Roof Structures

As the building envelope component receiving the strongest solar radiation heat gain, integrating PCMs into roofs plays a crucial role in suppressing building cooling loads at the source. Studies generally confirm that its energy-saving and carbon reduction potential surpasses that of walls [6], making it a key focus area for PCM application. Current research centers on two core issues: thermal performance optimization and overcoming heat dissipation bottlenecks.

Regarding performance optimization, parametric studies for climates like the Mediterranean suggest an optimal PCM layer thickness of about 15 mm, with aluminum tube and triangular aluminum shell encapsulation showing better performance in latent heat utilization and thermal stability, respectively [22]. In terms of structural form, dome structures in hot-arid climates can leverage the chimney effect to enhance ventilation, with PCM integration achieving about 1°C greater temperature reduction compared to flat roofs [23]. However, the inherent issue of slow nighttime heat release in PCMs limits their latent heat utilization and full-day regulation effectiveness.

To address this bottleneck, the coupled system of PCM with passive/active cooling technologies has emerged as a cutting-edge research direction. A representative work is the delignified wood-based PCM-solar reflective coating (SRC) roof proposed by Yang et al.: Through chemical delignification, a wood carrier with high porosity was obtained, increasing the PCM loading capacity to 182.02 kg/m³. Additionally, a multi-layer structure of "SRC coating - PCM/wood layer - thermal insulation layer" was adopted, forming a synergistic mechanism of "daytime SRC reflection + PCM heat storage, and nighttime SRC radiation-driven PCM solidification". Measurements demonstrated that this system could achieve a peak surface temperature drop of 7.4°C on the exterior surface and a 24-hour average cooling load reduction rate of 156.9%, significantly overcoming the heat dissipation limitations of PCM-only roofs. This study not only validates the feasibility of an integrated materials-structure-function design but also provides a key paradigm for the development of intelligent thermal regulation roof systems adaptable to different climates [24].

4.3 Floors

Integrating PCMs into floors is often aimed at addressing the "energy storage and precise regulation" challenges in radiant floor applications. Integration methods include direct compounding of PCMs with floor finishing materials and compounding PCMs with the construction layers of radiant floor systems.

In the pathway of compounding with floor finishing materials, a South Korean research team vacuum-impregnated n-heptadecane and n-octadecane PCMs into three types of flooring: engineered, composite, and solid wood, significantly improving the materials' thermal performance. Experiments showed PCMs effectively filled wood pores, increasing floor thermal conductivity and endowing them with excellent thermal energy storage and release capabilities. Among them, n-heptadecane-impregnated engineered flooring achieved a latent heat of 33.98 J/g, and n-octadecane-impregnated solid wood flooring reached 76.94 J/g. Simulation tests confirmed this PCM flooring could stabilize indoor temperature more effectively and enhance comfort, providing a viable flooring solution for energy-efficient buildings [25].

In the pathway of integrating PCMs into the construction layers of radiant floor systems, Liu et al. from the University of Shanghai for Science and Technology developed a novel phase change mortar. This mortar can reduce indoor temperature fluctuations, maintain comfortable temperatures, achieve "peak shaving and valley filling" of heat, and reduce heating energy consumption [10]. Researcher Wang et al. further compared three PCM integration modes: stratified, embedded, and encapsulated. Results showed that with the same PCM quantity, the encapsulated mode (PCM wrapping the heating pipe) offered the best comprehensive performance: its floor surface temperature fluctuation decreased by 65.64% compared to the PCM-free baseline, average heat flux decreased by 8.93%, and it could maintain surface temperature within the comfortable range of 19–29°C. This is mainly attributed to the increased contact area between PCM and the heat source in this structure, improving latent heat utilization, despite its relatively slower thermal response [26]. In cold regions, winter heating is the primary demand, but summer cooling also affects occupant comfort and building energy consumption. Ju et al. demonstrated that an active PCM radiant floor system designed for winter heating in cold-climate buildings could also operate efficiently in summer when coupled with horizontal ground heat exchanger direct cooling and intelligent anti-condensation control strategies. Such systems enable "one system, two functions," maintaining indoor thermal comfort (PMV) within the excellent range of -0.2 to 0.5 during the cooling season, and achieving significant reductions of 83.1% in energy consumption and 83% in operational costs compared to conventional systems [27].

4.4 Windows

Windows, as the thermally weak point in the building envelope allowing easy solar heat gain transmission indoors, are another key focus for PCM application.

The traditional method of integrating PCMs into windows involves filling window cavities with materials like paraffin. For example, Iraqi researchers filled the cavity of a double-glazed window with paraffin (PCM) replacing the air gap. Experiments showed the PCM window significantly improved indoor temperature regulation: effectively blocking outdoor heat during the day, reducing indoor temperature by over 10%; exhibiting excellent performance in thermal resistance, heat storage, and delaying heat transfer, capable of suppressing indoor temperature peaks under short-term strong sunlight, delaying peak thermal loads under prolonged sunlight, thereby enhancing thermal comfort and reducing air conditioning cooling loads [28].

In regions requiring consideration of daylighting, traditional opaque PCMs are no longer the research focus. Transparent PCMs-particularly hydrogels-have become a new core direction. U.S. researchers encapsulated sodium sulfate decahydrate (SSD) within a polyacrylamide-acrylic acid copolymer hydrogel matrix, developing a shape-stable, highly transparent composite material. With 70 wt% SSD solution, this material exhibited a melting enthalpy of 133.3 J/g, good cycling stability, a visible light transmittance of 90%, and could achieve a 30-minute delay in thermal load transfer, demonstrating significant potential for building thermal regulation and grid peak-shaving [29]. To further increase the response speed and UV resistance of PCM windows, Wang et al. constructed a composite hydrogel smart window based on HPMC. Utilizing the Hofmeister effect by adding sodium sulfate, the response time was shortened from 150 seconds to 30 seconds. Simultaneously, incorporated polydopamine nanoparticles endowed the window with excellent UV resistance while maintaining high visible light transmittance (66.9%). The final integrated smart window achieved a 10.2°C indoor temperature reduction, demonstrating rapid response, durability, and efficient all-day optical and thermal regulation capabilities [30].

5. Validating the Energy-Saving Potential of PCM-Integrated Buildings Under Multiple Climatic Conditions

5.1 Tropical Regions

In tropical regions characterized by year-round high temperatures, the primary goal of building energy efficiency research is to mitigate extreme cooling loads. Utilizing their high latent heat capacity to act as a "thermal buffer" within the building envelope, Phase Change Materials (PCMs) present an effective technological pathway to address this challenge. Research indicates that their application effectiveness is closely related to specific climate subtypes and system design.

In tropical rainforest climate zones with high temperature and humidity, such as Singapore, PCMs are primarily used to suppress heat gain caused by intense and sustained solar radiation.

Numerical simulation studies demonstrate that using PCMs in tropical rainforest climates can effectively reduce annual building heat gain by 21% to 23%, with application on external wall surfaces proving more advantageous than on internal surfaces [31].

In extreme hot and arid tropical desert climates, such as Kuwait, the significant diurnal temperature range creates ideal conditions for PCM charge-discharge cycles. Experimental results from Kuwait show that in passive mode, PCMs can effectively lower daytime indoor temperatures by up to 5.75°C and help maintain indoor temperatures at night, raising them by up to 2.75°C. In active mode, with air conditioning maintaining a constant 20°C, the energy consumption of a PCM-integrated test room was lower than that of a baseline room, achieving energy savings of 26.8% in late March and an overall 15.9% in April [32].

Similarly, in Haikou, China, which experiences a tropical monsoon climate, optimization research on Double-Layer Shape-stabilized PCM Wallboards (DLSPCW) also demonstrates significant energy-saving effects. Haikou has long, hot summers with prominent cooling energy consumption. Numerical simulations and energy consumption analysis revealed that using a double-layer PCM structure with phase change temperatures of 31.5°C (PCM-A) and 22°C (PCM-C), each 50 mm thick, could achieve energy savings of 18,816.62 kWh during the summer cooling period (April to October), representing a saving rate of 38.26%. Indoor temperature fluctuations were also significantly reduced [33]. This further illustrates that in tropical climates, rational selection of phase change temperatures and optimization of PCM layer thickness can effectively enhance the thermal insulation performance of building envelopes and reduce air conditioning loads.

In summary, in tropical regions, whether confronting high humidity and heat or extreme aridity and heat, PCMs demonstrate clear potential for reducing building heat gain, mitigating temperature fluctuations, and decreasing air conditioning energy consumption. The key to maximizing their efficacy lies in the precise matching of phase change temperature to the climate subtype, optimized placement within the building envelope (e.g., external wall integration), and targeted system configurations (e.g., employing double-layer structures with gradient temperatures).

5.2 Mediterranean Region

The Mediterranean climate, characterized by its distinct seasonal pattern of "hot, dry summers and mild, wet winters," creates a unique building thermal environment. Buildings must simultaneously address strong cooling demands in summer and non-negligible heating demands in winter. The core rationale for applying PCMs in this climate zone lies in utilizing their latent heat for spatio-temporal energy regulation-absorbing and storing excess indoor heat in summer and releasing stored heat to supplement heating in winter, thereby effectively mitigating indoor temperature fluctuations and improving thermal comfort.

Research from Lebanon found that PCMs with phase change temperatures between 21°C and 24°C performed best, helping to absorb excess heat in summer and release stored heat in winter, thus stabilizing indoor temperatures. Simulation results indicated that buildings with PCMs integrated into roofs and walls could reduce cooling loads by 7.5% to 9.5% and heating loads by 55% to 61.6%. The annual energy saving rate ranged from 11% to 13.4% [34]. Another study focusing on the Bizerte region of Tunisia found that PCM with a 21°C phase change temperature was most effective. This study also emphasized the impact of integration location, noting that deploying PCMs closer to the indoor side maximized their effectiveness. Under this strategy, cooling energy consumption could be reduced by 14.7%, with an optimal energy saving rate of 26.77% [35].

To more precisely address seasonal load differences, employing double-layer or multi-layer PCM systems with different melting temperatures is considered a promising solution. In such systems, the PCM layer with a lower melting temperature focuses on improving winter heating efficiency, while the layer with a higher melting temperature is dedicated to summer cooling savings. This functional partitioning has the potential to further enhance overall annual energy efficiency.

5.3 Severe Cold Winter Regions

In severe cold regions, the primary research objective is significantly reducing building heating energy consumption and costs. These areas experience long, extremely cold winters where heating demand dominates the annual building energy consumption.

Beijing Zhongxingneng Technology Co., Ltd., based on long-life, high-energy-density salt hydrate PCMs developed by a joint team from the Institute of Process Engineering, Chinese Academy of Sciences and the University of Science and Technology Beijing, established a "PCM Thermal Storage - Grid Valley Electricity" clean heating demonstration project at core venues for the Beijing Winter Olympics in Zhangjiakou. With a total heating area of 8,000 m² and a total power of 1.2 MW, this project addressed the challenge of heating and thermal storage for mountain buildings in extremely cold climates [36].

Beyond centralized thermal storage heating systems, the integrated application of PCMs within the building envelopes of residential structures in severe cold regions also shows significant potential. Research indicates that in typical severe cold cities like Harbin and Shenyang, applying a PCM mortar layer with a phase change temperature range of 21–26°C on the inner side of external walls can not only absorb and store indoor and solar heat gains during winter days but also continuously release heat at night, effectively mitigating indoor temperature fluctuations and reducing heating loads. Simulation data suggest that such PCM-integrated walls can achieve a heating energy saving rate of approximately 14.76% during winter in severe cold regions [37].

6. Challenges and Future Perspectives

6.1 Current Research Challenges and Bottlenecks

1) Long-Term Cycling Stability of Materials: Phase change materials (PCMs) may experience issues such as phase separation, severe supercooling, and degradation of thermophysical properties after undergoing numerous solid-liquid phase change cycles. While cycling stability tests are commonly conducted in research, they predominantly rely on accelerated thermal cycling tests with cycles numbering in the tens to hundreds. For real-world applications, the results from such accelerated tests may not adequately simulate the synergistic effects of all aging factors. The service life of PCMs in buildings should ideally match that of the buildings themselves. A lifespan of merely a few hundred cycles may be insufficient to meet this requirement.

2) Thermal Conductivity Issues: The academic community widely recognizes the issue of low thermal conductivity in PCMs, particularly organic ones. This characteristic significantly constrains the responsiveness and efficiency of PCM-integrated building components in dynamically regulating the indoor environment. Notably, research on the ideal thermal conductivity of PCMs for building applications remains insufficient. Specifically, there is a lack of systematic investigation into the optimal thermal conductivity ranges required to meet building thermal performance demands under different environmental conditions. Furthermore, in-depth studies on how to quantitatively assess the optimal thermal conductivity index for PCMs in specific application scenarios are scarce.

3) Cost Considerations: At present, the commercial-scale application of high-performance PCMs, which often involve complex encapsulation processes and exhibit excellent thermophysical properties, is significantly hindered by cost constraints. Their use remains largely confined to laboratory research and small-scale demonstration projects. Although Life Cycle Assessment (LCA) studies confirm that integrating such materials into building envelopes can reduce energy consumption, the payback period is lengthy. This deviates significantly from the typical 3-5 year return-on-investment expectation prevalent in the construction industry, posing a key barrier to their market adoption.

4) Discrepancy Between Simulated Performance and Measured Data: Existing research frequently relies on building energy simulation software (e.g., EnergyPlus, TRNSYS) to validate the effectiveness of PCM applications. There is a notable shortage of case studies involving actual, occupied buildings, leading to a gap between predicted and real-world performance.

6.2 Future Development Directions

1) Long-Term Cycling Stability: Develop more scientific full-cycle validation methodologies. Future research must move beyond accelerated tests involving only a few hundred cycles. It is crucial to establish long-term monitored databases, correlating and calibrating accelerated test results with multi-year performance tracking data from real environments. Accelerated thermal cycling tests should evolve to incorporate multi-factor coupled aging protocols (temperature-humidity, freeze-thaw, UV

exposure, etc.) to better simulate synergistic effects in real-world conditions.

2) Addressing Thermal Conductivity: Promote research towards application-driven design. Establish a clear mapping relationship between "application scenario" and "ideal thermal conductivity." Future studies need to systematically quantify the optimal thermal conductivity ranges for PCMs required to achieve specific thermal regulation objectives (e.g., peak load shaving, time lag) in different building components (e.g., external walls, roofs, floors) and across different climatic zones.

3) Cost Control: Future efforts should vigorously develop bio-based PCMs (Bio-PCMs). Leveraging biomass feedstocks like palmitic acid and other fatty acids offers advantages such as renewability, low cost, and environmental friendliness. Another promising avenue is the development of prefabricated building components with integrated PCMs to enable industrialized production, potentially reducing costs.

4) Bridging the Simulation-Measurement Gap: To enhance the practical guidance value of simulations, future research should follow this path: First, accurately obtain the true thermophysical properties of PCMs and composite components through experiments, enabling precise parametric characterization of their performance.

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