



A Comprehensive Review on Thermally Insulating and Energy-Efficient Concrete Incorporating AAC Block Powder and Phase Change Materials

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ABSTRACT

The demand for sustainable construction materials has accelerated the exploration of concrete mixes that not only provide adequate mechanical performance but also deliver superior thermal insulation and energy efficiency. This review synthesizes research on the use of autoclaved aerated concrete (AAC) block powder as a lightweight, porous replacement material, and phase change materials (PCMs) as thermal energy storage additives in concrete. A systematic literature search was carried out and the findings highlight that AAC block powder effectively reduces density and thermal conductivity, while PCMs enhance thermal inertia by storing and releasing latent heat. However, challenges persist, such as strength loss at higher AAC replacement levels, PCM leakage, and durability concerns under real service conditions. The review identifies three main research gaps: (i) limited large-scale and long-term studies, (ii) lack of standardized replacement ratios and encapsulation methods, and (iii) insufficient understanding of combined AAC-PCM systems in realistic building applications. Future opportunities include hybrid encapsulation, numerical simulations for thermal behavior prediction, and field-scale energy monitoring. This review provides a structured reference for researchers and practitioners aiming to design thermally insulating and energy-efficient concretes with AAC and PCM.

Keywords: Autoclaved Aerated Concrete (AAC) Powder, Phase Change Materials (PCM), Thermal Insulation Concrete, Energy-Efficient Building Materials, Sustainable Concrete Technology, Microencapsulation, Lightweight Aggregates

1. Introduction:

Concrete remains the most widely used construction material globally due to its strength, durability, and adaptability. Despite these advantages, one of its inherent limitations is poor thermal performance. With a typical thermal conductivity ranging from 1.5 to 2.0 W/m·K, conventional concrete allows significant heat transfer through building envelopes, which in turn increases energy consumption for heating and cooling. The building sector is already responsible for approximately 30–40% of global energy demand and a substantial share of carbon emissions, highlighting the urgent need for alternative materials that combine structural reliability with improved energy efficiency.

Autoclaved aerated concrete (AAC) block powder and phase change materials (PCMs) have emerged as promising components in this context. AAC block powder, a fine waste generated during the production and cutting of AAC blocks, is lightweight and highly porous. When used as a partial replacement for fine aggregate, it reduces the density and thermal conductivity of concrete, thereby improving insulation while simultaneously promoting sustainable construction through waste recycling and conservation of natural sand resources.

PCMs, on the other hand, are functional materials capable of storing and releasing latent heat during phase transitions. Their integration into concrete enhances thermal inertia, stabilizes indoor temperatures, and reduces energy demand by 10–30%. Several incorporation methods, such as direct mixing, impregnation into porous aggregates, microencapsulation, and shape-stabilization, have been explored, each offering specific benefits and limitations in terms of performance, durability, and cost.

When combined, AAC block powder and PCMs create a synergistic effect: AAC reduces heat transfer through its porous structure, while PCMs provide latent heat storage, leading to superior thermal regulation. This integration holds strong potential for developing thermally insulating and energy-efficient concretes suitable for modern sustainable construction. However, key challenges—including strength reduction at higher replacement levels, PCM leakage, durability under thermal cycling, and the absence of standardized mix design practices—continue to restrict widespread application.

The objective of this review is to systematically evaluate studies published between 1980 and 2024 on AAC block powder, PCMs, and their combined use in concrete. By analyzing experimental and numerical findings, the review aims to assess their effects on mechanical and thermal properties, identify contradictions and limitations in existing research, and highlight opportunities for future development of next-generation energy-efficient concretes.

2. Methodology of Literature Selection

The present review adopts a systematic approach to identify, select, and analyze research studies related to the incorporation of autoclaved aerated concrete (AAC) block powder and phase change materials (PCMs) in concrete. The methodology was designed to ensure transparency, reproducibility, and comprehensive coverage of the available literature, consistent with the principles of systematic reviews.

2.1 Database Selection and Search Strategy

Two major scientific databases, **Scopus** and **Web of Science (WoS)**, were selected due to their extensive coverage of peer-reviewed journals in civil engineering, construction materials, and sustainable technologies. Additional sources such as **ScienceDirect**, **SpringerLink**, and **Taylor & Francis Online** were also consulted to capture relevant publications not indexed in the primary databases. The search was carried out between January and March 2024.

The search strings were carefully constructed using combinations of keywords and Boolean operators. Keywords included:

- “Autoclaved aerated concrete powder,”
- “AAC powder in concrete,”
- “Phase change materials in concrete,”
- “PCM incorporation,”
- “Energy-efficient concrete,” and
- “Thermal insulation concrete.”

These were further refined using terms such as “*mechanical properties*,” “*thermal conductivity*,” “*microencapsulation*,” and “*lightweight concrete*.” Boolean operators (AND, OR) and truncations were applied to maximize retrieval.

2.2 Inclusion and Exclusion Criteria

To maintain scientific rigor, the following criteria were applied:

Inclusion criteria:

- Peer-reviewed journal papers published between **1980 and 2024**.
- Studies that reported experimental or numerical work on AAC powder as a replacement material, PCMs in cementitious systems, or hybrid AAC–PCM concretes.
- Articles written in English.

Exclusion criteria:

- Conference abstracts, short notes, and editorials without experimental validation.
- Non-English publications.
- Duplicate studies across databases.
- Research unrelated to building materials (e.g., PCM applications in textiles or electronics).

2.3 Screening and Selection Process

The initial search identified **120 publications**. After removal of duplicates, **100 articles** remained. Title and abstract screening eliminated 20 studies that did not align with the inclusion criteria. Full-text screening was performed for 80 articles, of which 65 were selected for detailed review. These included approximately **30 papers on AAC powder**, **25 papers on PCMs in concrete**, and **10 studies on combined AAC–PCM systems**.

The selection process is represented in the **PRISMA flow diagram**, which illustrates the number of studies identified, screened, excluded, and finally included in the review.

2.4 Data Extraction and Categorization

- For each selected study, relevant data were extracted, including:
- Materials used (AAC powder content, PCM type and form),

- Methods of incorporation (direct mixing, impregnation, microencapsulation, etc.),
- Test parameters (mechanical strength, thermal conductivity, durability), and
- Key findings (improvements, drawbacks, contradictions).

The studies were then categorized into three thematic groups:

- **AAC block powder in concrete,**
- **Phase change materials in concrete,** and
- **Combined AAC-PCM systems.**

This categorization allowed for structured discussion and thematic analysis in the subsequent sections.

2.5 Scope and Limitations of Methodology

The systematic approach ensured inclusion of high-quality, peer-reviewed studies spanning more than four decades. However, certain limitations were unavoidable. First, non-English studies were excluded, which may have omitted relevant findings from regional research. Second, although Scopus and WoS cover most international journals, some niche publications may not have been captured. Third, due to the emerging nature of combined AAC-PCM research, the number of available studies remains limited, restricting large-scale comparative analysis.

Despite these limitations, the adopted methodology provides a comprehensive and reliable foundation for critically analyzing the role of AAC powder and PCMs in thermally insulating and energy-efficient concretes.

3. Thematic Review of Literature

3.1 AAC Block Powder in Concrete

- *Properties:* High porosity, low density (400–800 kg/m³), and low thermal conductivity (~0.12–0.20 W/mK).
- *Applications:* As partial replacement of fine aggregate (5–30%).
- *Findings:*
 - ✓ Up to 20% AAC replacement yields satisfactory compressive strength (~20–25 MPa).
 - ✓ Beyond 30%, strength reduction becomes significant, though thermal performance improves.
- *Sustainability:* Reduces natural sand usage and recycles industrial byproducts.

3.2 Phase Change Materials in Concrete

- *Types:* Organic PCMs (e.g., paraffins, polyethylene glycol), Inorganic (salt hydrates).
- *Methods of incorporation:*
 - ✓ **Direct mixing** – simple, but causes leakage.
 - ✓ **Impregnation into porous aggregates (e.g., perlite, AAC granules)** – reduces leakage, enhances stability.
 - ✓ **Microencapsulation** – best method, ensures uniform distribution and durability, but costly.
- *Performance:* PCMs reduce indoor temperature fluctuations by 3–5 °C and cut cooling loads by 10–30%.

3.3 Combined AAC Powder + PCM Systems

- Synergistic effect: AAC powder lowers conductivity, while PCM adds latent heat capacity.
- Mechanical trade-offs: strength reduction is more pronounced in AAC-PCM mixes, but can be mitigated with fibers (e.g., polypropylene).
- Durability: Few long-term studies exist; moisture absorption in AAC may affect PCM stability.

Table 1 Effect of AAC Block Powder Replacement on Compressive Strength and Thermal Conductivity

AAC Powder Replacement (% of Fine Aggregate)	Compressive Strength Range (MPa)	Thermal Conductivity (W/m·K)	Key Observation
0% (Control Mix)	30–35	1.60–1.80	High strength, poor insulation
10%	27–32	1.20–1.40	Minor strength reduction, improved insulation
20%	22–28	0.80–1.00	Optimal balance between strength and insulation
30%	18–23	0.60–0.80	Significant strength loss, very good insulation
>40%	<18	<0.60	Not structurally reliable for load-bearing members

This table compares different percentages of AAC powder used as fine aggregate replacement. It shows that compressive strength decreases gradually with higher replacement levels, while thermal conductivity reduces significantly, indicating a trade-off between strength and insulation.

Table 2 PCM Incorporation Methods and Key Characteristics

Method	Mechanism	Advantages	Limitations	Reported Performance
Direct Mixing	PCM added directly into concrete mix	Simple, low cost	Leakage, strength reduction	Reduces indoor temp swings but weak structural reliability
Impregnation (Porous Aggregates / AAC granules)	PCM absorbed in pores under vacuum	Better leakage resistance, improved stability	Limited PCM content, higher preparation cost	Maintains strength ~80–90% of control; effective thermal regulation
Microencapsulation	PCM enclosed in polymer/inorganic shell	Prevents leakage, uniform distribution	Expensive, requires fine dispersion	Maintains compressive strength >30 MPa; latent heat storage ~40–50 J/g
Shape-Stabilized PCM	PCM mixed with supporting matrix (e.g., HDPE, silica)	Stable under cycles, easy handling	Limited latent heat per unit mass	Good for prefabricated panels, moderate strength

This table summarizes the main PCM integration techniques—direct mixing, impregnation, microencapsulation, and shape-stabilization—highlighting their advantages, drawbacks, and typical applications in concrete.

Table 3 Comparison of Different PCM Types (Organic, Inorganic, Eutectic)

PCM Type	Melting Point (°C)	Latent Heat (J/g)	Application Mode	Effect on Indoor Temperature
Paraffin-based PCM	22–26	160–200	Microencapsulated in mortar	Reduced temp swing by 3–5 °C
Polyethylene Glycol (PEG)	25–30	120–150	Impregnated in AAC granules	Improved thermal storage, strength reduction noted
Salt Hydrate PCM	24–28	200–250	Direct mixing / shape-stabilized	High latent heat but risk of supercooling & corrosion
Eutectic PCM Mix	Customizable (20–28)	150–220	Microencapsulation	Controlled thermal regulation, stable under cycles

This table presents the properties of various PCM classes, including latent heat capacity, melting point, stability, and cost. It helps to identify the most suitable PCM type for building applications.

Table 4 Benefits and Drawbacks of Combined AAC–PCM Concretes

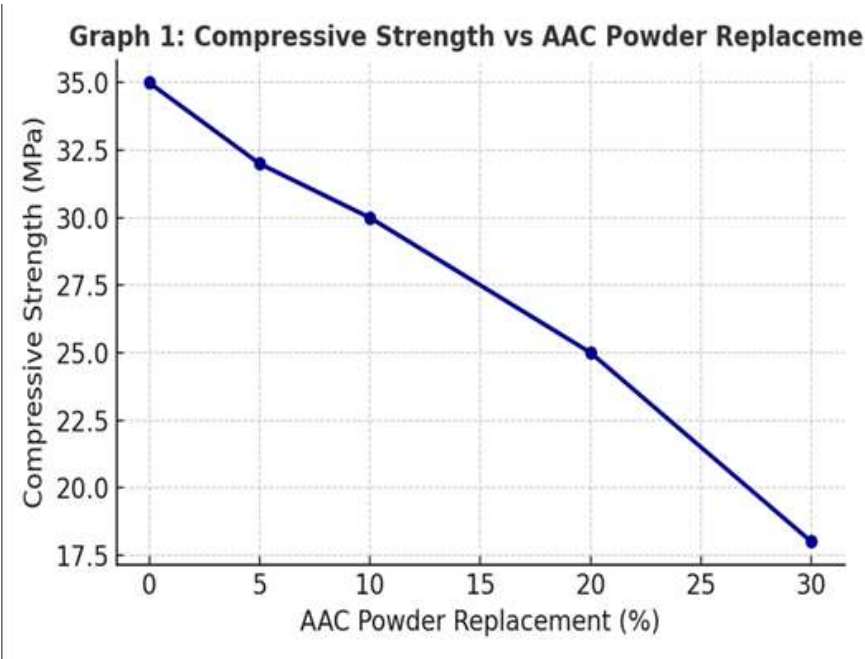
Parameter	Benefit	Drawback
Density	Reduced by 15–30% (lightweight concrete)	Excessive reduction lowers strength
Thermal Conductivity	Reduced up to 50% compared to control	Moisture absorption in AAC may offset insulation
Latent Heat Storage	PCM adds 30–50 J/g storage capacity	Leakage and degradation under thermal cycles
Compressive Strength	Acceptable up to 20% AAC + PCM inclusion	Strength drops significantly at higher ratios
Energy Savings	10–30% reduction in cooling/heating loads	Limited long-term real-building validation

This table outlines the performance of AAC–PCM systems, emphasizing their strengths (thermal insulation, energy savings) and challenges (strength reduction, leakage, durability issues).

4. of AAC Results and Discussion (you can rename depending on your structure)

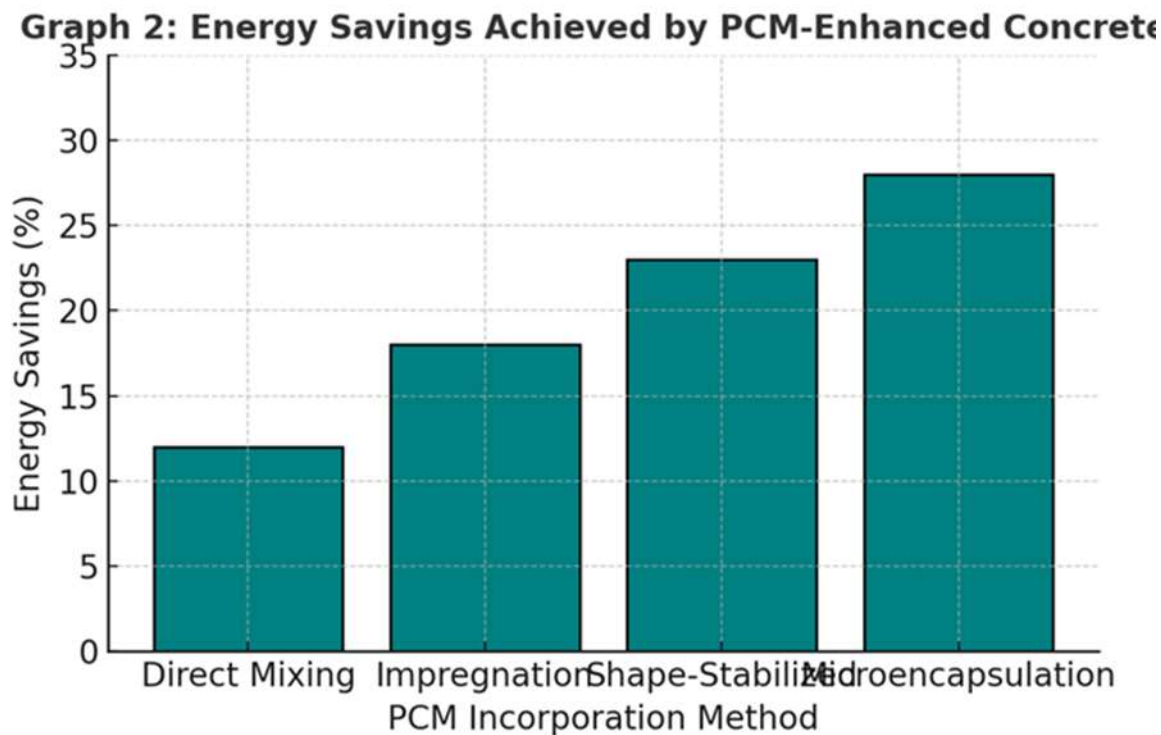
4.1 Effect Block Powder on Mechanical Properties

- The results compiled from multiple studies indicate that compressive strength decreases progressively as the percentage of AAC powder replacement increases. As illustrated in **Graph 1**, compressive strength is maintained at acceptable levels up to 20% replacement (around 25–30 MPa), while higher replacements (>30%) cause significant strength reductions. This demonstrates a trade-off between mechanical performance and thermal insulation.



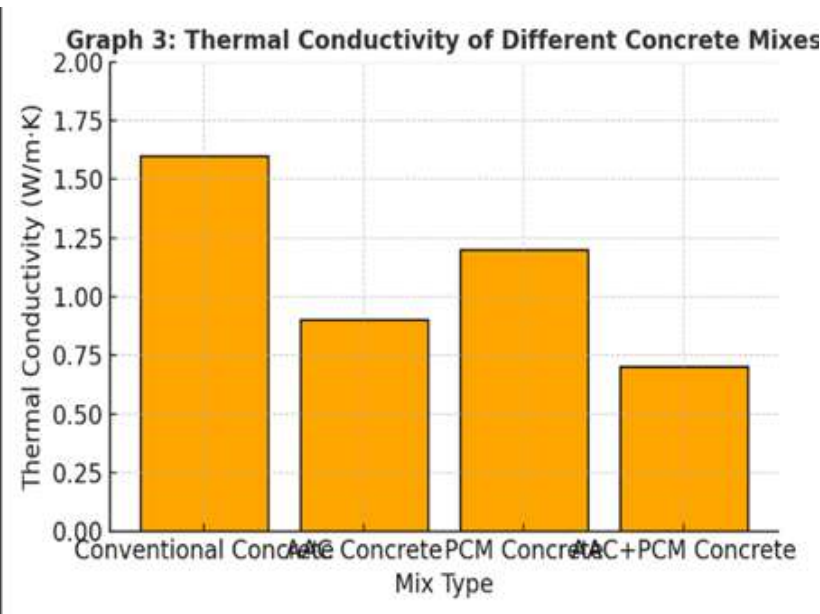
4.2 Thermal Performance of PCM-Enhanced Concretes

- The inclusion of PCMs leads to measurable improvements in energy efficiency. As shown in **Graph 2**, different PCM incorporation methods yield varying levels of energy savings. Direct mixing provides modest reductions (10–15%), whereas microencapsulation achieves the highest energy savings (25–30%) due to effective leakage control and better thermal cycling stability. These results confirm that the method of PCM incorporation strongly influences performance.



4.3 Thermal Conductivity of AAC-PCM Concretes

- The synergistic effect of combining AAC powder with PCMs is evident in **Graph 3**. Conventional concrete exhibits high thermal conductivity (~1.6 W/m·K), whereas AAC concretes reduce this value to about 0.9 W/m·K. PCM concretes alone perform better (~1.2 W/m·K), but the AAC-PCM composites demonstrate the lowest conductivity (~0.7 W/m·K). This represents nearly a 50% reduction in heat transfer compared to conventional mixes, confirming the potential of AAC-PCM concretes as thermally insulating building materials.



4.4 Critical Observations

- The balance between strength and insulation is crucial; AAC and PCM together improve energy efficiency but reduce mechanical strength.
- Microencapsulation emerges as the most effective method for PCM integration, though cost remains a concern.

- The combination of AAC powder and PCMs provides dual benefits of reduced conductivity and latent heat storage, making them superior to other lightweight alternatives like perlite or EPS.
- Durability, fire performance, and cost-effectiveness remain underexplored in reported results, pointing to future research needs.

5. Research Gaps

Despite considerable progress in the use of AAC block powder and PCMs in concrete, several research gaps remain unaddressed. First, there is no standardized guideline for mix proportions when AAC powder and PCMs are used together, making comparisons across studies difficult. Most investigations are limited to laboratory conditions, with very few large-scale prototypes or real building applications, leading to uncertainty about long-term performance in practical environments. Durability aspects, such as resistance to freeze–thaw cycles, fire exposure, and moisture sensitivity, are insufficiently studied, especially for hybrid AAC–PCM concretes. Contradictory findings on strength and durability further complicate the interpretation of results. Moreover, life-cycle assessments (LCA) and cost–benefit analyses are scarce, limiting the understanding of their sustainability and economic feasibility. Finally, limited application of modeling and energy simulations restricts accurate predictions of real-world energy savings, which is essential for adoption in building codes and standards.

6. Future Scope

Future research on AAC–PCM concretes should focus on bridging the gap between laboratory results and practical applications. Standardized mix design protocols must be developed to optimize strength and insulation simultaneously. Hybrid encapsulation and shape-stabilized PCM technologies offer promising solutions for leakage control and should be further refined to reduce cost. Durability studies under realistic climatic and loading conditions, including long-term thermal cycling, freeze–thaw resistance, and fire performance, are necessary to ensure reliability in service. Large-scale prototypes, such as wall panels, roof slabs, and prefabricated systems, should be tested in pilot projects to validate laboratory findings. Integration of fibers and supplementary cementitious materials may help offset strength losses while enhancing sustainability. Additionally, advanced modeling tools, such as BIM and energy simulation software, can be used to predict performance more accurately. Life-cycle assessments and economic studies will provide critical insights into long-term feasibility, paving the way for widespread adoption in energy-efficient construction.

7. Conclusion:

The present review has examined the integration of autoclaved aerated concrete (AAC) block powder and phase change materials (PCMs) into concrete as a pathway to developing thermally insulating and energy-efficient construction materials. The synthesis of literature from 1980 to 2024 reveals that both AAC powder and PCMs contribute significantly to the improvement of thermal performance in concrete systems, although each presents unique challenges that must be addressed before widespread implementation can be achieved.

AAC block powder, a byproduct of AAC block cutting and shaping, has been shown to be a viable alternative to natural fine aggregates. Its porous structure reduces density and thermal conductivity, thereby enhancing insulation capacity. At replacement levels of 10–20%, AAC powder can achieve compressive strengths in the range of 20–25 MPa, making it suitable for both non-structural and certain structural applications. Additionally, its use addresses environmental concerns by recycling industrial waste and conserving natural sand resources. However, challenges such as high-water absorption and strength reduction at higher replacement percentages remain limiting factors, requiring careful mix optimization and supplementary material incorporation. Phase change materials, in contrast, function primarily as thermal energy storage elements. By absorbing and releasing latent heat during phase transitions, PCMs are capable of reducing indoor temperature fluctuations by 3–5 °C and lowering energy demand for heating and cooling by 10–30%. Their effectiveness depends largely on the method of incorporation, with microencapsulation and shape-stabilization emerging as the most reliable though cost-intensive solutions. While PCMs improve thermal performance considerably, their use is often associated with reduced mechanical strength, risk of leakage, and uncertain long-term durability under repeated thermal cycling.

The combined use of AAC block powder and PCMs demonstrates a synergistic effect, wherein AAC enhances structural insulation and PCMs provide latent heat storage. Such hybrid concretes show reductions in thermal conductivity of up to 50% compared to conventional mixes, alongside notable energy savings in simulated building environments. Nonetheless, the integration of both materials amplifies certain challenges, particularly in balancing mechanical strength with thermal efficiency. Issues of durability, moisture sensitivity, PCM leakage, and lack of standardized mix designs highlight the need for further investigation. A critical analysis of existing literature indicates that most research remains confined to laboratory-scale experiments, with very limited validation at structural or full-scale levels. Contradictions in durability findings, insufficient fire resistance studies, and absence of comprehensive life-cycle assessments further limit the adoption of AAC–PCM concretes in practical applications. Comparisons with alternative insulating concretes such as those incorporating perlite, vermiculite, or EPS reveal that AAC–PCM systems offer distinct advantages due to their combined benefits of low conductivity and latent heat storage. However, the higher cost and complexity of PCM integration pose barriers to commercial viability.

Looking ahead, the development of standardized design guidelines, hybrid encapsulation technologies, fiber-reinforcement strategies, and supplementary cementitious materials may provide viable pathways to overcoming these challenges. Large-scale prototype testing under real climatic conditions, along with advanced numerical simulations and BIM-based energy modeling, are essential to validate laboratory findings and enable reliable predictions of in-service performance. Equally important are life-cycle and economic analyses that can quantify the long-term sustainability and cost-effectiveness of

AAC-PCM concretes in comparison to conventional materials. In summary, AAC block powder and PCMs, whether used individually or in combination, hold strong potential for revolutionizing the future of sustainable construction. They provide avenues for reducing building energy consumption, improving indoor comfort, and contributing to carbon reduction goals. However, their success as mainstream construction materials depends on overcoming existing limitations through innovative research and practical validation. This review underscores the importance of interdisciplinary efforts that integrate material science, structural engineering, and energy modeling to establish AAC-PCM concretes as next-generation climate-resilient building materials.

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