Phase Change Materials (PCM) in the Building Envelope: State of the Art.

Abstract:

Faced with the increasing energy demand linked to air conditioning in hot and humid climate countries, phase change materials (PCM) represent a promising passive solution to improve the thermal performance of the building envelope. This article presents a structured review in six parts. First, the physicochemical mechanisms governing the storage and release of energy by latent heat are explained. A multi-criteria classification of PCMs is then proposed, according to their chemical composition, microstructure and phase transition temperature. Selection factors such as thermal, physical and chemical properties are analyzed in order to identify the determining criteria for effective integration. The article then examines the different methods of integrating PCMs into building components such as vertical walls, ceilings, floors and glazing, drawing on documented experimental results showing significant reductions in interior peak temperatures and thermal oscillations. The impacts on load-bearing materials are also assessed: although the incorporation of micro-encapsulated PCMs improves thermal inertia, it leads to a degradation of mechanical properties and a significant increase in porosity, proportional to the incorporation rate. Finally, environmental and economic assessments reveal that bio-sourced PCMs have a significantly lower carbon footprint than conventional paraffins, while profitability remains strongly dependent on the climatic context and the type of application. This review aims to provide a documented basis to guide future work on adapting PCMs to the constructive and climatic specificities of West Africa.

Key words:Phase Change Materials (PCM); Building envelope; Thermal energy storage; Thermal inertia; Micro-encapsulation; Thermal comfort; Hot and humid climate; Life cycle analysis;Mechanicalstrength; Energy efficiency

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1. INTRODUCTION

The building sector accounts for approximately 40 % of global energy consumption and 15 % of direct CO_2 emissions [1]. This trend is accentuated in tropical and humid climate regions, where high temperatures and intense solar radiation generate particularly significant air conditioning needs [2]. In this context, improving the thermal inertia of the building envelope through passive means constitutes a strategic lever. PCMs offer a latent energy storage capacity 5 to 14 times greater than that of conventional materials at equal volume [2], making them particularly suitable for integration into walls, floors, ceilings and glazing.

The operating principle of PCMs is based on their ability to absorb and release large amounts of energy during their transition between solid and liquid states, at a nearly constant temperature [3]. This mechanism is governed by precise physicochemical parameters — enthalpy of fusion, transition temperature, thermal conductivity, vapor pressure and volumetric change — whose mastery directly conditions the efficiency and durability of the system [4]. During melting, volumetric expansion can damage containment enclosures and composite matrices [5].

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The diversity of available PCMs — organic, inorganic or bio-sourced — requires a rigorous classification according to chemical composition, microstructure and transition temperature range. Chemical compatibility with load-bearing materials is an essential criterion in this regard: mortars and concretes containing PCMs can reduce heating and cooling needs by 10 to 50 % depending on the simulated season [6], but their incorporation raises important structural questions, notably a reduction in compressive strength documented by Šavija et al. [7]. From an environmental standpoint, bio-sourced PCMs have a significantly lower carbon footprint than conventional paraffins [8], although economic profitability remains strongly dependent on the climatic context.

This is the objective set by the present article, proposing a systematic review covering successively the physicochemical mechanisms of PCMs, their classification, their selection criteria, their methods of integration into building components, their impacts on load-bearing materials, as well as their environmental and economic assessments.

2. PCM Operation: Physicochemical Mechanisms

The fundamental principle of phase change materials (PCM) is based on the exploitation of the phase transition enthalpy (generally solid–liquid) for thermal energy storage [9], [10]. Unlike sensible heat storage, latent heat storage allows the absorption or release of a high energy density within a restricted temperature range, close to the transition temperature [11].

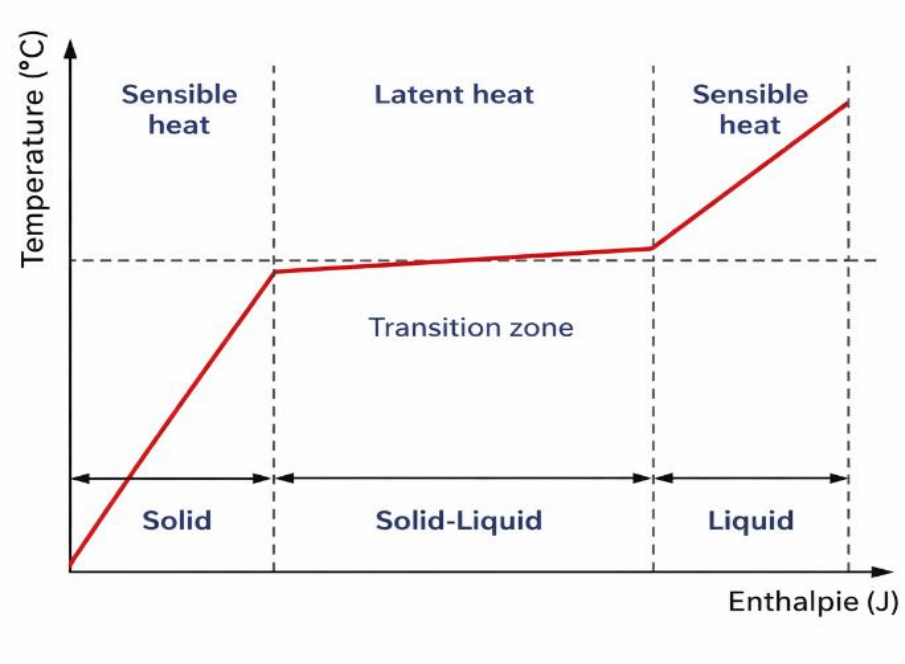

Figure 1 – Transition

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In the building envelope, this phenomenon generates a “buffer effect” which unfolds in two distinct phases:

2.1. Charging phase (daytime)

When solar radiation strikes the building envelope and the wall temperature reaches the melting point T_f of the PCM, the material begins to change state [9], [10]. The wall temperature then remains stable despite the continuous thermal input: the PCM acts as a “thermal sink” by intercepting the heat flux before it reaches the interior space [12]. This mechanism reduces interior temperature peaks and increases thermal phase shift, improving occupant comfort and reducing the air conditioning load [13], [14].

2.2. Discharging phase (nighttime)

When the outdoor temperature drops below T_f during the night, the PCM begins to solidify and releases the energy stored during the day [9], [10], [11]. For the system to be effective the following day, this heat must be evacuated to the outside, generally by natural night ventilation [14], [13]. This step is critical: if discharging is incomplete — night too warm — the PCM will begin the next cycle partially liquid, reducing its daytime absorption capacity [10].

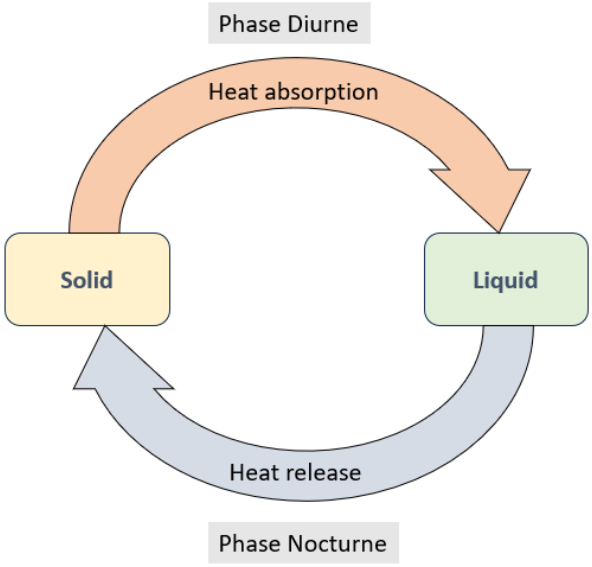

Figure 2 – Phase change states of Phase Change Materials throughout a day

3. Multi-Criteria Classification of PCMs

The selection and optimization of phase change materials (PCM) rely on multidimensional characterization according to their chemical nature, their phase transition temperature range and their microstructure, which defines the containment methods and structural stability within the building envelope.

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3.1. Chemical composition

Phase change materials are classified into three major chemical families: organic, inorganic and eutectic, each presenting specific thermodynamic behaviors.

3.1.1. Organic

Organic PCMs — paraffins and non-paraffinic compounds such as fatty acids and esters — store energy by breaking Van der Waals forces during the crystal–liquid transition [9], [13]. They are valued for their congruent melting, their thermal stability over thousands of cycles [11] and their chemical compatibility with cementitious matrices [14]. Their low thermal conductivity (0.15 to 0.25 W/m·K) constitutes their main limitation, to which is added a flammability risk requiring rigorous containment [13], [12].

3.1.2. Inorganic

Inorganic PCMs, essentially salt hydrates [16], offer a higher volumetric energy density and higher thermal conductivity (0.5 to 1.1 W/m·K), which improves their thermal reactivity. They are non-flammable but suffer from two critical phenomena — supercooling and incongruent melting — requiring the use of nucleating agents. Their corrosive nature with respect to metals requires special precautions during the design of building reinforcements [17].

3.1.3. Eutectics

Eutectics are binary or ternary mixtures whose mass proportion is adjusted to obtain a constant melting temperature, thus avoiding any risk of phase separation [18]. This property allows custom design of the transition temperature, ideal for targeting the thermal comfort range in humid tropical climates, generally between 25 and 28 °C [19].

Table 1 – Properties of certain Phase Change Materials

Category	Sub-family	Example	Tf (°C)	L (kJ/kg)	k (W/m·K)	ρ (kg/m³)	Study
Organic	Paraffins	n-Hexadecane	18–30	112–236	0.14–0.56	760–900	[13]
	Fatty acids	Lauric Acid	17–32	28–240	0.15–0.28	880–940	[13]
Inorganic	Hydrates	$CaCl_2 \cdot 6H_2O$	16–32	85–251	0.45–1.09	1400–1800	[13]
Eutectics	Mixtures	Capric/Lauric	18–25	140–160	0.15–0.25	~870	[13]

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3.2. Temperature

Phase change materials (PCM) are classified according to their phase transition temperature, which constitutes a determining parameter for their use in thermal energy storage systems [13].

Table 2 – Classification of PCMs according to temperature ranges and fields of application

PCM Type	Examples	Temperature (°C)	Fields of use	Studies
Low temperature	Ice, water-salt eutectics, alcohols	−35 to +5	Domestic and commercial refrigeration	[13]
Medium-low temperature	Fatty acids, paraffins, Glauber's salt	+5 to +40	Building heating and cooling (passive thermal comfort and interior thermal regulation)	[13]
Medium temperature	Vegetable waxes, salt hydrates, naphthalene	+40 to +80	Solar heating, domestic hot water production and cooling of electronic systems	[13]
High temperature	Nitrates/nitrites, metal alloys, molten salts	+80 to +300	Absorption cooling, waste heat recovery and electricity production	[13]

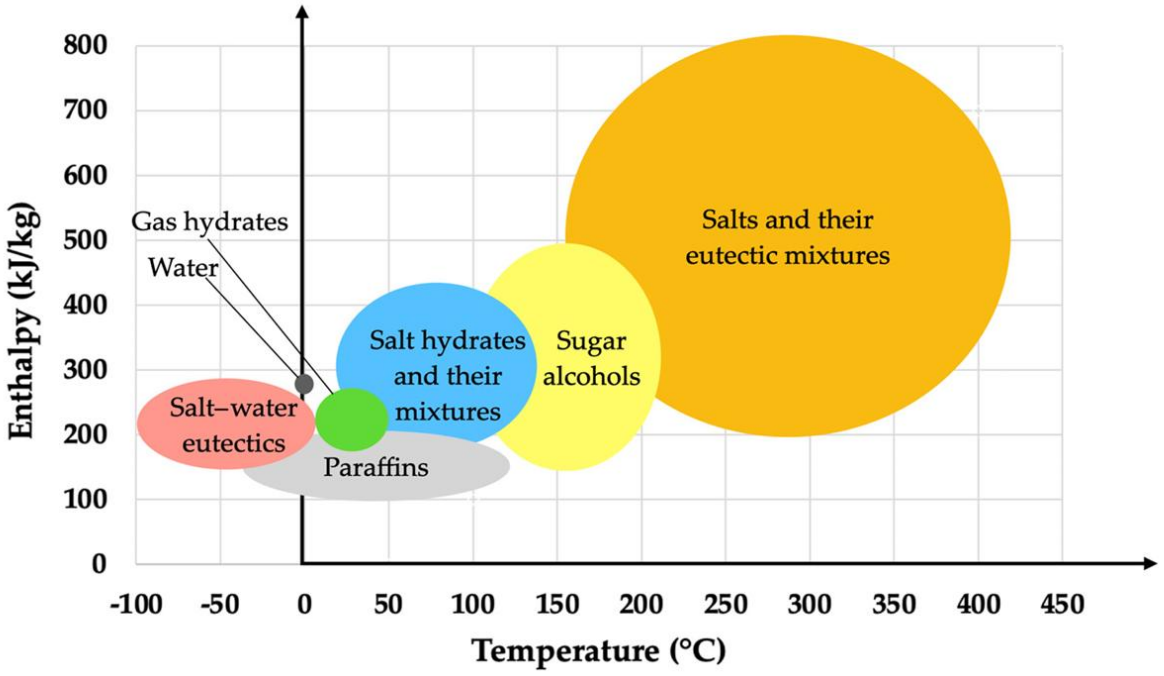

Figure 3 – Plot of working temperature vs. enthalpy of main existing PCMs [26]

3.3. Microstructure

The microstructure of PCMs determines their thermal performance, physical stability and method of integration into storage systems. Three approaches are distinguished.

3.3.1. Micro-encapsulation

This strategy is based on the synthesis of composite particles of the "core-shell" type where the PCM is encapsulated in a polymeric or inorganic membrane at the micrometric (1 to 1 000 µm) or nanometric scale. The very high mass-specific thermal exchange surface [20] promotes rapid charge and discharge rates, while the rigid shell prevents leaks in liquid phase and limits volumetric variations. This stability allows versatile integration into heat transfer fluids or construction materials.

3.3.2. Macro-encapsulation

Macro-encapsulation consists of isolating the PCM in macroscopic containers (> 1 mm) such as tubes, spheres or prefabricated panels [21]. This conditioning method protects the PCM against chemical interactions and facilitates integration into heat exchangers, but suffers from high internal thermal resistance due to the low surface-to-volume ratio. The insertion of reinforcing structures such as metal fins is often necessary [21].

3.3.3. Shape-stabilized

Shape-stabilized PCMs disperse and retain the active material in a porous matrix by capillarity and surface tension [10]. The interconnected network (expanded graphite, diatomite or cross-linked polymers) preserves the physical integrity of the composite even during complete melting at the microscopic scale. The use of porous carbon or metallic supports significantly increases the overall thermal conductivity of the composite [22].

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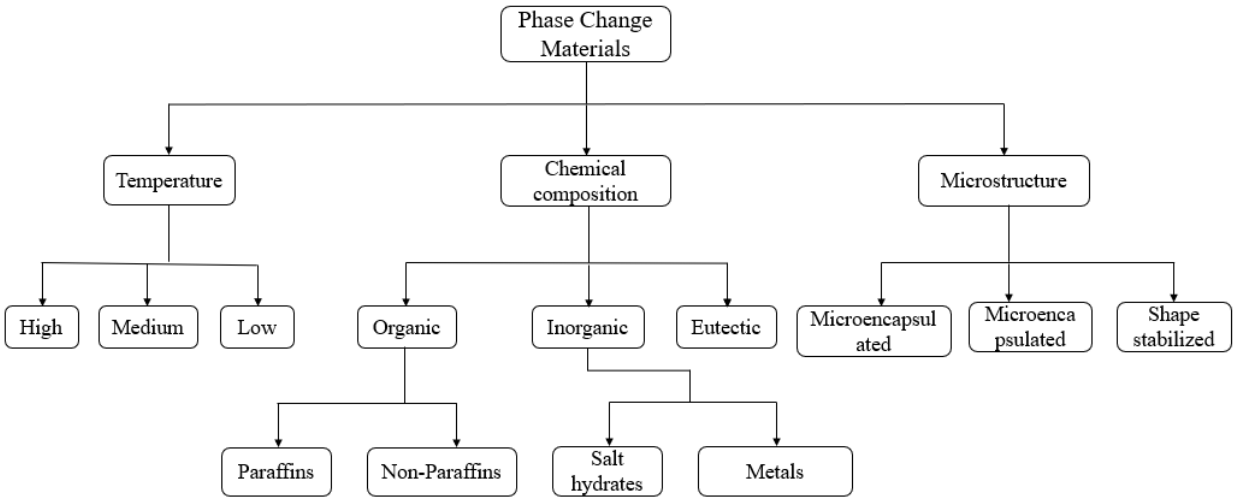

Figure 4 – Categorization of PCMs [13, 28]

4. Selection Parameters of PCMs for Buildings

The integration of phase change materials into the building envelope relies on a rigorous selection of thermal, physical and chemical parameters, ensuring effective and durable thermal regulation.

4.1. Thermal Factors: Kinetics and Isothermal Regulation Capacity

4.1.1. Melting temperature (T^{φ}): Lever of passive activation

The melting temperature defines the phase transition window where the material absorbs or releases energy in a quasi-isothermal manner. For integration into the building envelope, T_f must be correlated to the human thermal neutrality zone, i.e. a target interval of 20 °C to 30 °C [22]. Outside this interval, the PCM cannot fulfil its dynamic thermal buffer function and behaves as a simple sensible thermal mass, whose energy density is significantly lower.

4.1.2. Latent heat of fusion (Lh): Energy density and compactness

The enthalpy of fusion determines the amount of energy stored per unit mass during the phase change, conditioning the building's capacity to absorb significant solar gains without increasing the ambient temperature. The required performance range is above 200 J/g for paraffin-based PCMs and 220 J/g for bio-sourced PCMs [6]. Insufficient latent heat imposes a disproportionate mass of PCM, leading to structural overloading of partitions.

4.1.3. Cycle stability: Guarantee of thermodynamic longevity

Given the average lifespan of a building, the PCM must withstand a minimum of 10 000 nycthemeral cycles without drift in its melting temperature or decrease in its storage capacity.

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Early degradation — often due to phase separation — progressively reduces the thermal buffer effect and leads to an increase in active cooling needs.

4.1.4. Thermal conductivity (k): Power and reactivity of the system

Thermal conductivity defines the rate at which heat penetrates the material to activate storage. An optimal value between 0.5 and 2 W/(m·K) is necessary to balance deep storage and insulation. Below 0.2 W/(m·K), only the surface of the material melts, drastically reducing the actually mobilized storage capacity [10]. Adequate conductivity also ensures complete nocturnal solidification, avoiding thermal saturation of the system [24].

4.2. Physical Factors: Structural Design and Climatic Resilience

4.2.1. Density (ρ): Optimization of storage volume

A range of 800 to 1 500 kg/m³ is preferred to maximize energy stored in a restricted volume [24]. At equal thermal capacity, a denser PCM occupies less space, reducing containment costs and facilitating architectural design [10].

4.2.2. Vapor pressure: Air quality and safety

Vapor pressure must remain negligible at the maximum service temperature in order to avoid any mass loss through volatilization, as well as risks of toxicity (VOC) and flammability [25]. According to the Clausius-Clapeyron relation, it grows exponentially with temperature:

$$ln(Pv) = -\frac{\Delta Hvap}{R} \cdot \frac{1}{T} + C$$

where P_v is the saturating vapor pressure, ΔH_{vap} the enthalpy of vaporization, R the universal gas constant (8 314 J·mol^{-1}·K^{-1}), T the absolute temperature and C a constant specific to each substance [25]. In micro-encapsulated systems, this increase in internal pressure can induce rupture of the polymeric shell.

4.2.3. Volume change (ΔV): Mechanical integrity of containment

The majority of PCMs undergo a volumetric expansion of 5 to 15 % during melting [26], described by the Clapeyron relation:

$$\frac{dP}{dT} = \frac{L}{T \cdot \Delta V}$$

In confined systems, this expansion generates internal pressures that can cause cracking of protective enclosures, while contraction during solidification can create air voids degrading heat transfer. Compensatory devices — porous matrices or free volumes — are therefore necessary.

4.2.4. Optical properties: Synergy with natural lighting

For glazing, the PCM must provide high transmittance in the visible spectrum (380–780 nm) while modulating the near infrared to limit interior overheating. The phase transition often induces a variation in opacity offering a passive thermal regulation mechanism [27].

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4.3. Chemical Factors: Material Integration and Fire Safety

4.3.1. Corrosion: Protection of structural components

The corrosion rate of the PCM with respect to its container must remain below 1 mg/cm²/year. Salt hydrates [28] attack metals by oxidation or pitting, compromising the long-term stability of walls. Although paraffins are chemically inert with respect to metals, their propensity to diffuse through certain polymers requires a systematic compatibility study with all materials in contact [29].

5. INTEGRATION OF PCMS INTO BUILDING COMPONENTS

5.1. Integration into vertical walls and interior partitions

The integration of PCMs into vertical walls aims to increase the thermal inertia of the building by transforming structural elements into latent energy reservoirs. In addition to plasterboard panels, PCMs can fill the cavities of hollow bricks [22] or be incorporated into the concrete matrix in the form of impregnated aggregates [30]. Three incorporation modes predominate: direct impregnation by capillarity, macro-encapsulation and micro-encapsulation. The total thermal load (Q) absorbed by these walls is calculated by cumulating sensible and latent heat:

$$Q = m \times [Cp,s(Tm - T1) + L + Cp,l(T2 - Tm)]$$

where m is the mass of the PCM, $C_{p,s}$ and $C_{p,l}$ the thermal capacities in solid and liquid states, L the latent heat, and T_1, T_2, T_m the initial, final and melting temperatures.

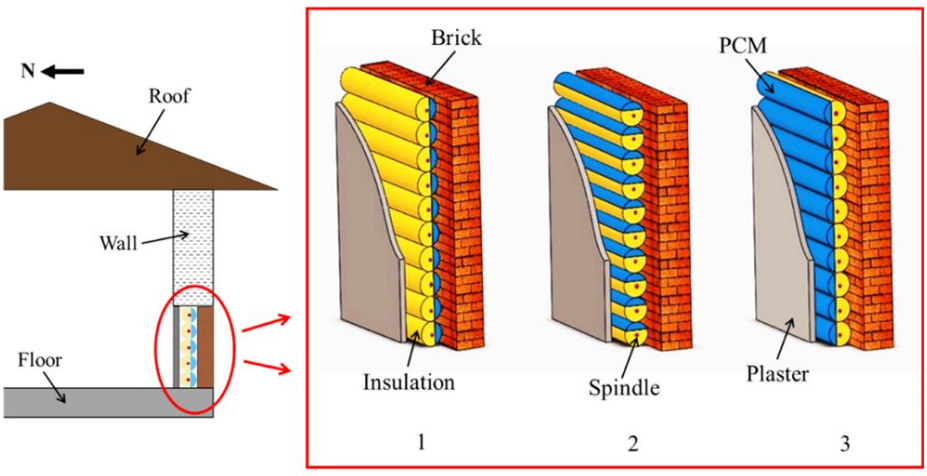

Figure 5 – Image of PCM integrated in the wall panel [35]

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5.2. Active ceilings and thermal stratification regulation

In a passive cooling ceiling, the heated interior air rises by natural convection towards the false ceiling [31]. The PCM layer captures this sensible heat and, by melting, maintains the ceiling surface at a cool and constant temperature. At night, ventilation — natural or mechanical — releases this thermal stock and re-solidifies the material. The choice of T_f is paramount to ensure this cyclical operation. Honeycomb aluminium panels or high thermal conductivity matrices are often recommended to compensate for the naturally low conductivity of PCMs and accelerate charge and discharge kinetics [24].

5.3. Floors

Floors are particularly conducive to PCM integration as they receive direct solar radiation and can store 5 to 14 times more energy per unit volume than conventional thermal mass, with a melting temperature generally chosen between 22 and 26 °C [32]. As early as 2006, experiments on PCM floors in passive solar buildings showed an average interior temperature approximately 2 °C higher with a significantly reduced thermal amplitude [33]. More recent tests have demonstrated a reduction of nearly 10 °C in peak interior air temperature [34].

5.4. Glazing

The integration of PCMs into the layer of a double or triple glazing allows the absorption by latent heat of the majority of solar infrared radiation while allowing visible light to pass through for natural lighting. Glass blocks filled with paraffin in the liquid state can achieve up to 90 % light transmission, compared to only 5 to 19 % in the solid state, giving the glazing adaptive behavior according to solar irradiation [6]. A PCM glazing prototype monitored over six months under real conditions confirmed the control of interior surface temperatures and the improvement of thermal comfort. The main challenge remains the choice of melting temperature: an unsuitable T_f can cause interior overheating or obstruct the view to the outside.

6. Impact on Structures: Physical, Chemical and Mechanical Properties

The incorporation of phase change materials into cementitious matrices improves the thermal performance of construction elements, but simultaneously induces significant modifications of their physical, chemical and mechanical properties, whose magnitude is proportional to the incorporation rate, as summarized in the table below.

Table 3 – Impact of the incorporation of PCMs on the properties of cementitious materials

Category	Property	Impact	Study

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Category	Property	Impact	Study
Physical	Density and porosity	The addition of micro-encapsulated PCMs increases internal porosity (reduces density) and weakens the interfacial transition zone, constituting the main cause of degradation of the composite material.	[7]
	Workability	The addition of PCMs increases the demand for water and superplasticizer, due to the large specific surface area of the microcapsules and the chemical adsorption of water by the hydroxyl and amine groups of their shell.	[35, 36]
	Thermal conductivity	The incorporation of micro-encapsulated PCMs progressively and proportionally reduces the thermal conductivity of the composite with dosage — each 1% increment of PCM leading to a decrease of approximately 9% in conductivity — thus improving the overall thermal insulation of the element while slowing heat exchanges within the material.	[37]
Chemical	Cement hydration	During cement hydration, PCMs act as a thermal buffer by absorbing the heat released by exothermic reactions, thereby reducing differential thermal gradients responsible for early micro-cracking — without detectable chemical alteration of the cementitious matrix. However, their presence delays hydration kinetics, resulting in a reduction in mechanical strengths at early ages.	[38]
Mechanical	Compressive strength	The compressive strength of cement pastes decreases by 31.2%, 44.5% and 54.8% for PCM volumetric incorporation rates of 10%, 20% and 30% respectively, measured at 28 days.	[7]

7. Environmental and Economic Analyses

7.1. Health analysis

The integration of PCMs in buildings raises health concerns related to volatile organic compound (VOC) emissions [4]. Certain organic PCMs (paraffins, fatty acids) as well as their encapsulation systems can release volatile substances during repeated phase change cycles, including compounds such as formaldehyde or benzene [5], presenting risks ranging from short-term irritation to toxic or carcinogenic effects in the long term [6]. The use of PCMs in buildings must

therefore incorporate a rigorous assessment of their impact on indoor air quality, favoring low-emission materials and safe encapsulation solutions [13].

7.2. Environmental analysis

Conventional paraffin-based PCMs generate a significant carbon footprint over their entire life cycle [8]. In contrast, bio-sourced PCMs present carbon footprints 14 to 18.5 % lower than those of petroleum-derived PCMs, according to life cycle analyses [39]. Applications in technical heating or cooling systems can present an environmental payback period of less than two years [40], while structural integration remains penalized by the embodied impacts linked to PCM manufacturing and containment.

7.3. Economic analysis

The integration of PCMs in buildings involves high initial costs, with energy savings during operation generally insufficient to compensate for the increase in life cycle cost linked to construction and dismantling [40]. PCM applications could nevertheless become viable if energy prices increase significantly or if the cost of PCMs decreases by approximately 40 %. Profitability depends strongly on the climatic context: promising in cold to temperate climates, it remains very limited in hot and humid climates, where the return on investment period can exceed 20 years [8].

8. CONCLUSION

This article has presented a systematic review of the integration of phase change materials into the building envelope, from fundamental physicochemical mechanisms to environmental and economic assessments.

On the thermal level, PCMs constitute an effective passive solution thanks to their latent energy storage capacity 5 to 14 times greater than that of conventional materials, with significant reductions in interior temperature oscillations confirmed in walls, ceilings, floors and glazing. Their effectiveness remains nonetheless conditioned by the rigorous choice of melting temperature, particularly critical in tropical and humid climates where the risk of incomplete cycling constitutes a major operational limitation. From a selection standpoint, each PCM family presents specific constraints — low conductivity and flammability for paraffins, corrosion and segregation for salt hydrates — with chemical compatibility with load-bearing materials remaining an essential criterion. From a structural standpoint, incorporation into cementitious matrices generates cumulative negative effects: reduction in compressive strength reaching 54.8 % at 30 % incorporation, increased porosity and delayed hydration kinetics, imposing rigorous optimization of formulations.

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From environmental and economic standpoints, bio-sourced PCMs present the most favorable carbon footprint, while profitability remains dependent on the climatic context, with a payback period ranging from less than one year in cold climates to nearly 20 years in hot climates. Future research should focus on the development of PCMs with melting temperatures adapted to tropical conditions, the improvement of their thermal conductivity, their durability under repeated cycles in humid environments and the reduction of their cost through locally available raw materials.

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