

Advancements in Phase Change Materials for Nearly Zero Energy Building Design: A Review

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ABSTRACT

Nearly Zero Energy Building (NZEB) leverage passive architectural design and active energy-saving technologies to create comfortable indoor environments while minimising energy use. This study aims to explore the utilisation of Phase Change Materials (PCM) to enhance the thermal inertia of building envelopes, reduce indoor temperature fluctuations, and decrease the capacity requirements of heating and cooling systems. The methodology involves a comprehensive review of the categorisation and properties of PCM, examining their integration with solar, air, and other renewable energy sources. The findings indicate that phase change materials applications in walls, windows, roofs, and floors can significantly enhance thermal inertia, reduce indoor temperature fluctuations, and improve energy efficiency. Additionally, incorporating nanoparticles such as Al_2O_3 , TiO_2 , and ZnO into PCM has been shown to enhance thermal conductivity, further optimising heat storage performance. The use of PCM presents an efficient and sustainable strategy for improving the energy performance of NZEBs. This study provides a valuable reference for the study and design of nearly zero energy buildings, emphasising sustainability and energy efficiency.

INTRODUCTION

As the demand for comfort in work and living spaces increases, buildings have become a major contributor to overall energy consumption (Harputulugil & de Wilde, 2021). According to European Union statistics, building energy consumption accounts for 40% of overall society energy consumption, while building Carbon Dioxide (CO_2) emissions account for more than 40% of total emissions (Economidou et al., 2020). In comparison to industrialised nations with comparable climatic conditions, buildings for housing in China use 2-3 times more energy per unit area (Guo et al., 2021). According to the Ministry of Housing and Urban-Rural Development, 95% of buildings in China are classed as high-energy-consuming, suggesting a

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considerable opportunity for using it for energy savings (Chen et al., 2022). As a result of this, there is an increasing focus on reducing energy use in buildings, which has led to the ongoing development and implementation of several energy-saving strategies for buildings (Hafez et al., 2023). To address this issue, the European Union introduced NZEB in the Energy Performance of Buildings Directive (EPBD), requiring all new buildings to comply with NZEB standards by the end of 2020 (Kurnitski, 2013). In January 2019, the GB/T 51350-2019 “Technical Standard for Nearly Zero-Energy Buildings” was released by Ministry of Housing and Urban-Rural Development of China (Deng et al., 2023). This standard aims to decrease the energy required for heating, cooling, and lighting in buildings by using passive building design techniques. It also emphasises the use of efficient energy equipment and systems, along with renewable energy sources, to create a comfortable indoor environment with minimal energy consumption (Li et al., 2018). Passive building design involves optimising the orientation, including thermal mass materials, using shading devices, promoting natural ventilation, and implementing other measures to optimise the usage of renewable energy sources (Muzhanje et al., 2022). PCM use temperature differences in natural environments to facilitate phase change processes for the absorption and release of heat. Renewable energy sources, such as solar energy, can be regulated, distributed, and utilised efficiently to reduce the energy consumption of buildings. Passive building energy-saving materials, such as PCM, are highly promising (Yang et al., 2021).

THERMAL SYSTEM OF A NEAR-ZERO ENERGY CONSUMPTION BUILDING

Every building is capable of acquiring, consuming, and storing energy. This is accomplished through the envelope, which provides an external thermal exchange (Elder, 2020). The integration of thermal resistance, PCM technology, and renewable energy sources to achieve near-zero energy consumption in buildings used in Figure 1 which adapted from Soares et al. (2013). The structure highlights the relationship between indoor load and demand, heat transfer mechanisms, and the role of exterior-protected construction in enhancing thermal comfort while minimising energy consumption.

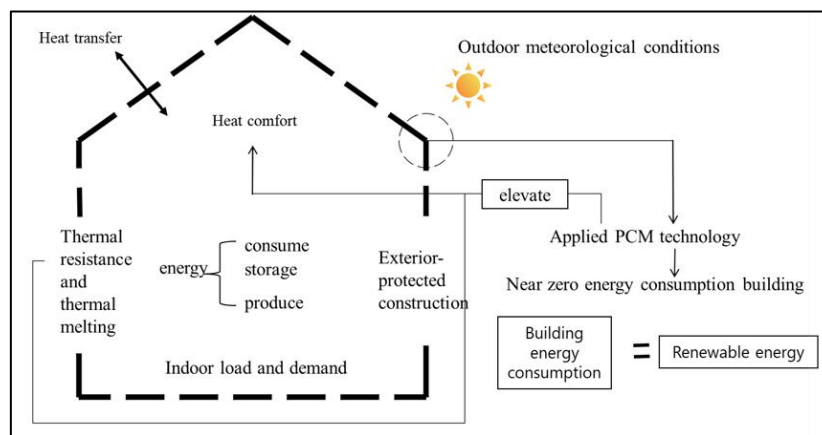


Fig. 1. Thermal Systems for Nearly Zero Energy Buildings

Source: Soares et al. (2013)

The building envelope contains heat resistance and heat capacity causes a delay in the movement of heat between interior and outdoor environments. However, PCM could alter the thermal resistance of the building envelope. The heating capacity of a building may influence its performance by regulating the rate at which heat is transferred. The internal energy balance minimises energy usage in heating and air conditioning systems. Abdalla & Amin (2023) conducted a study on the impact of load on phase change

materials in cold buildings during the summer. The cooling capability of rooms utilising phase change materials during summer is much lower than that of normal rooms, while maintaining a constant internal temperature. Applying phase change material technology to building energy saving is an effective and sustainable approach (Navarro et al., 2016).

It may facilitate the attainment of NZEB criteria for structures. Hence, in the process of designing buildings with minimal energy consumption, it is crucial to maximise the use of renewable energy and phase change material technology. Additionally, the selection of suitable phase change material and implementation of energy-saving measures play a significant role. PCM may be used in NZEB using passive or active approaches. Passive applications refer to the use of PCM to counteract or harness external disturbances, resulting in the reduction of interior thermal loads or improvement of indoor comfort.

The use of phase change materials in near-zero energy structures may be categorised into two distinct types: passive and active. Passive application is the use of phase change materials to resist or harness external interference, with the aim of reducing interior heat load or enhancing indoor comfort. An example of this is the use of phase change walls to delay the peak of heat transfer between the indoor and outside environments. An active application refers to the use of phase change materials in building environment equipment to decrease energy consumption. This includes phase change ventilation (Faraj et al., 2020), air conditioning and heat pumps (Muzhanje et al., 2022), solar radiant heating (Hassan et al., 2022), heat recovery devices (Tyagi et al., 2021), and other similar technologies. Hence, this article mostly discusses the passive use of phase change materials in NZEB.

CLASSIFICATION OF PHASE CHANGE MATERIALS (PCM)

PCM may be categorised based on several physical features, such as solid-liquid, solid-gas, liquid-gas, and solid-solid materials. In the domain of NZEB, materials that are in a solid-liquid or solid-solid state are primarily used (Kim & Yu, 2018), as seen in Figure 2. PCM may be classified into organic and inorganic compounds based on their chemical characteristics. PCM may be categorised into mixed and embedded varieties based on how they are used with construction materials.

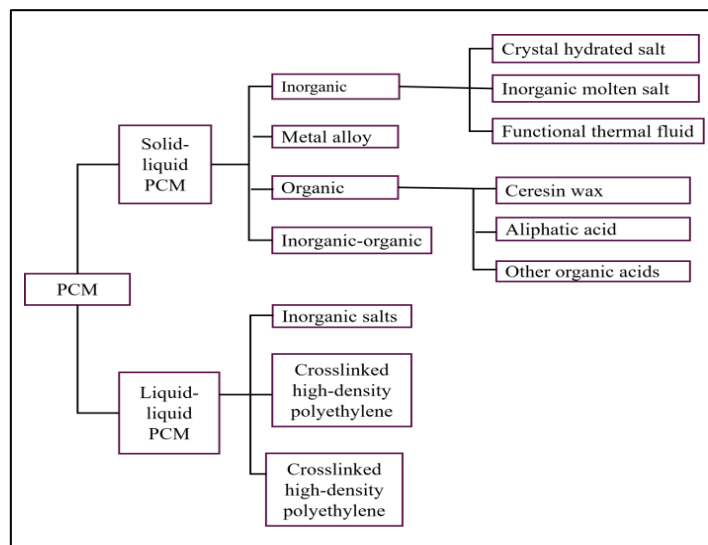


Fig. 2. Classification of Phase Change Materials in NZEB

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Despite the existence of several kinds of PCM, routinely used PCM still face significant challenges (Socaciu, 2012), including Organic PCM have a low thermal conductivity and an extremely low phase change enthalpy per unit volume. Additionally, experience substantial fluctuations in volume before and after undergoing a phase shift. Hydrated inorganic salts have poor nucleation properties, require a large degree of super cooling, are prone to phase separation, and are highly corrosive. And the thermo physical properties of eutectic mixtures are unclear and lack necessary data, and some lipid-based eutectic mixtures have a strong odour.

Various categories of PCM include distinct benefits and drawbacks. Hence, scientists amalgamate organic and inorganic substances to enhance the thermal characteristics of phase transition materials by including nano-inorganic additives. This is a highly debated subject in the development of novel phase transition materials (Pritom et al., 2024). Utilizing phase change materials in the envelope structure of nearly zero energy buildings is a passive technique for conserving building energy. This technology enhances the thermal inertia of the building envelope structure, leading to a reduction in interior temperature variations and ultimately improving the comfort of living spaces (Suresh et al., 2022). Phase change materials have the potential to be used to walls, windows, roofs, and floors (Shah et al., 2022). Table 1 displays the recently released phase change materials from various producers in the building material industry. By manipulating the proportions of phase change materials and conventional construction materials, it is possible to create building materials that are ideal for various types of buildings and climates. Table 1 reveals that acrylic acid and paraffin are the predominant phase change materials, whereas phase change gypsum board stands out as the prevailing choice for construction materials.

Table 1. Phase-Change Building Materials Introduced by Different Manufacturers

Manu- facturer	PCM for building	Type of phase transition material and quality scores	Phase- transition tempera- ture (°C)	Latent heat (kJ/Kg)	Specific heat (kJ/kg.°C)	Thermal conductivity (W/m.K)	Size (cm)	Area quality (Kg/m ²)
A	Plywall (Ceiling + Wall)	Acrylic Acid	23, 25	110	1.16	0.27	50x 100x 2.5	23
B	Gypsum Wallboard	Acrylic Acid, 30%	23	110	1.20	0.23	125x 200x 1.2	11
C	Clay Plaster Wall Panels	Acrylic Acid, 20%	26	132	-	-	62x 125x 2.2	15
D	Ceiling; Plafond	Acrylic Acid, 25%	23	82	-	-	60x 60x 2.5	25
E	Wall, Ceiling	Paraffin, 60%	21.7	70	2.50	0.18 (solid), 0.14 (liquid)	100x 120x 0.5	4.5
F	Walls, Ceiling, Floor	Fatty Acid Esters, 100%	23, 25, 27	165~200	2.10	0.20	40x 120x 1.5	2.7
G	Ceiling, Wall Panels	Acroleic Acid	22	25.9	2.01	0.88	60x 60x 2.5	25
H	Ceiling, Wall Panels	Acroleic Acid	23, 26	110	1.20	-	120x 240x 1.2	10.2

Source: Authors (2025)

PHASE CHANGE MATERIALS IN NEARLY ZERO ENERGY BUILDINGS

Phase change materials are used in NZEB to both significantly decrease building energy usage and enhance the thermal comfort of the buildings. Ahangari & Maerefat, (2019) used the phase change materials in the walls, floors, ceilings, and other enclosure structures of the experimental room. This resulted in a reduction in heating energy consumption by 17.5% and 10.4% in dry and semi-arid climatic conditions, respectively. Furthermore, the level of satisfaction with interior thermal comfort rose from 63% to 75% in the semi-arid region and from 73% to 93% in the dry climate. As a result, PCM are being more and more recommended for use in low-energy or almost zero-energy structures. Table 2 displays notable research discoveries on PCM in buildings world-wide in recent years. Phase Change Materials are clearly transitioning from basic ornamental elements to a wide range of masonry materials. The following sections will present the current advancements in the study of Phase Change Materials used in various building envelope components.

Table 2. Studies on The Application of Phase Change Materials in Low-Energy Consumption Buildings

Reference	Location	Type of PCM	PCM's Temperature Range (°C)	Building Element	Type of Building Test
Wang et al. (2025)	Harbin Kunming et al. China	Organic PCM	18-28	Wall and roof	Office Building
Luo & Xu (2025)	Shanghai, China	Paraffin	15.2–20.7	Wall and roof	Hut Experiment
Helmi et al. (2025)	Beni-Suef, Egypt	Paraffin Wax	45-48	Trombe Wall	Test Room Experiment
Shih et al. (2024)	Chaoyang China	Wood-Plastic	28	Wood-Plastic	Small Test Room
Soleiman Dehkordi & Afrand (2022)	Iran	Plaster	20-24	Wall and roof	Test Cabinet
Khan et al. (2022)	Kingdom of Saudi Arabia	PCM-25 PCM-29	24–26, 28–30	Wall	Test Cabinet
Faraj et al. (2022)	Lebanon, France	Macro-encapsulated PCM (Coconut Oil & Paraffin Wax)	25-60	Underfloor	Experimental Test in Modular Prototypes
Bake et al. (2021)	United Kingdom	Plaster	-	Wall and roof	Small Test Room
Prajapati & Kandasubramanian (2020)	Mumbai, Maharashtra, India	High density polyethylene	42	Wall	Small Test Room
Fachinotti et al. (2020)	Sauce Viejo, Argentina and Frankfurt, Germany	Recycled brick aggregates	20-26	Wall	Test Cabinet

Source: Authors (2025)

Walls

PCM walls may be categorised as mixed PCM and embedded (fixed form) phase change walls based on the integration of PCM with building materials (Lamrani et al., 2021). The distinction lies in the uniform distribution of the phase change substance and the construction material. The hybrid phase change wall is a homogeneous blend of phase change material and conventional construction materials, categorised as either direct mixing or capsule type (Abdulmalik et al., 2023). One of the most advanced applications now being used is the incorporation of microencapsulated paraffin wax with concrete to create phase change wall (Al-Yasiri & Szabó, 2021). An embedded phase change wall involves the incorporation of phase change material into the gap inside or outside the construction material.

Microcapsule Phase Change Wall Test Cabinet

Another study examined the impact of gypsum board on the temperature conditions inside office buildings. Office buildings use light steel keel frameworks for their walls, including microcapsule phase change materials inside the gypsum panels. The microcapsules have an average diameter of 8 mm and are equally distributed throughout the gypsum crystals. The findings indicate that the use of this phase change wall decreases the duration in which the room temperature exceeds 28°C from 50 hours to 5 hours throughout the testing period. Furthermore, the thermal conditions of the room are notably enhanced (Schossig et al., 2005). Sá et al. (2012) incorporated a 25% acrylic phase change material into plaster mortar, resulting in a phase change plaster mortar with a latent heat of 25 kJ/kg, a phase change temperature range of 23-25°C, and a thermal conductivity of 0.3 W/(m·°C).

Embedded Phase Change Wall

In embedded phase change walls, there is a distinct macro-scale separation between construction materials and phase change materials, in contrast to the homogenous mixing process of capsule-type walls. Silva et al., (2012) developed a phase-change clay brick that was incorporated into a hollow clay brick after being enveloped with paraffin. The use of this phase-change clay brick in the test room resulted in a decrease of almost 5°C in indoor temperature during the summer, and a delay of 3 hours in the occurrence of the highest temperature. Another study used glass bricks as the shell material, filled them with PCM to make phase change glass brick blocks, and built solar passive houses with phase change blocks. By using a combination of experimental and numerical simulation methods to compare the thermal storage performance of three phase change materials: fatty acids, paraffin and salt water, and proposed a design method that combines phase change blocks with night ventilation to further reduce building energy consumption.

Ventilated Phase Change Material Wall

Approach is to include ventilation walls with PCM, creating a sort of phase change wall. This integration represents a mixture of active and passive measures in the construction of NZEB. This design enhances interior thermal comfort by including air ducts inside the walls and uses either natural or mechanical ventilation to optimise the natural or forced convection between the indoor air and the phase change material in the walls. Figure 3 illustrates that the wall is constructed using PCM, hollow bricks, solid bricks, and polystyrene boards, arranged in that order from the inside to the outside adapted from Facelli Sanchez & Mercado Hancoco, 2024. The study was used PCM to create active-passive ventilation walls. The numerical simulation, together with experimental verification, investigated the impact of varying phase change temperatures and latent heat on both the heat transfer efficiency of the wall and the minimal interior air temperature. The findings indicated that the most favorable temperature for phase change was 27.7°C, the lowest temperature inside during winter was 15°C, and the effectiveness of heat storage reached 86.7%.

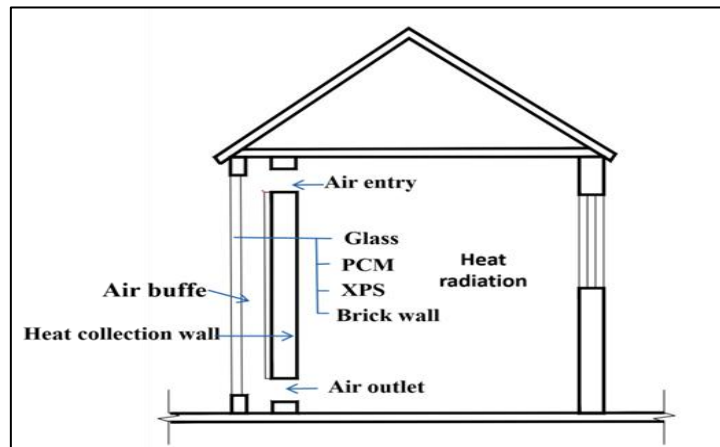


Fig. 3. Structure of Phase Change Material Ventilation Wall

Source: Facelli Sanchez & Mercado Hanco (2024)

Another research included the development of a ventilated phase change wall in a Mediterranean property. The study aimed to assess the impact of this wall on the internal temperature over the course of a year. The findings shown that the implementation of a ventilated phase change wall effectively delays the occurrence of the high wall temperature and contributes to the stabilisation of the indoor temperature (Stazi et al., 2012).

Windows

Windows are crucial elements of building envelopes, and they have a much higher heat transmission rate per unit area compared to walls. Consequently, researchers are constantly working on the development of PCM and architectures that are appropriate for windows. A study was conducted on hexahydrate calcium chloride was included as a phase change material into the interlayer of window glass. This resulted in a substantial increase in the thermal inertia of the window, leading to an effective reduction in heat transmission through the window. The experimental findings shown that phase change windows effectively maintained the inner surface temperature of the window at 25°C, even when the exterior temperature dropped to -15°C, while simultaneously ensuring that the internal temperature remained at a comfortable 21°C (Koláček, 2017). Another study established a model of phase change glass windows by adding paraffin to double-layered glass that has been combined with nanoparticles like Titanium Dioxide (TiO₂), Zinc Oxide (ZnO), and Aluminum Oxide (Al₂O₃). Figure 4 illustrates this model, adapted from Zhang et al. (2020). By looking at how this window system transfers heat and how nanoparticles affect the phase change material's ability to exchange heat. The findings showed that adding ZnO nanoparticles raised the inner surface temperature of the window by 0.89°C in the winter and 0.84°C in the transition season, respectively, while adding TiO₂ to the paraffin decreased the inner surface temperature of the window by 0.82°C in the summer.

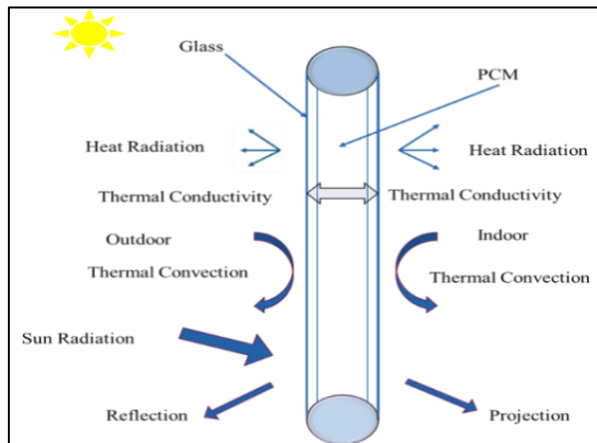


Fig. 4. Schematic Diagram of Composite Double Glass Window Structure of Nano-Phase Change Material

Source: Zhang et al. (2020)

Figure 5 shows a ventilated phase change material window that can operate in three different modes: overnight cooling, nightly ventilation, and daytime pre-cooling adapted from Hu & Heiselberg, (2018). A heat exchanger made of phase-change materials is installed in the bottom portion of the window. The phase change material in the heat exchanger loses heat to the outside cold air during overnight ventilation mode operation, lowering the temperature of the daytime fresh air provided to the room. A 10 mm thick phase change material might have a heat exchange efficiency of 89.85%, according to experimental data. Its heat absorption capability was 3.19 Megajoule (MJ), allowing it to collect heat for 3.9 hours during the day and release heat for 4-5 hours at night.

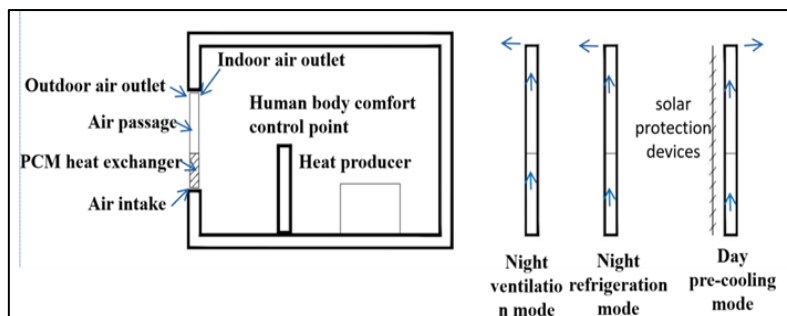


Fig. 5. Working Mode of Ventilated Phase Change Form

Source: Hu & Heiselberg (2018)

Roof

Roof materials are exposed to the elements and the sun, it can damage and leak. Thus, it is necessary to consider the composite phase change materials' photo stability and waterproofing. The waterproofing and thermal stability of polyurethane roofing materials were investigated by varying the wax content from 15% to 35%. The findings of a previous study showed that polyurethane materials with 25% wax content had the most favourable overall performance (Fang et al., 2019). A parallel study was conducted to create a roof material made of a combination of wood and plastic, which was infused with a substance called phase change material (specifically paraffin). The purpose of this development was to mitigate the urban heat island effect and lower the temperature of roofs. The research shown that the use of roof materials

including phase change material resulted in a reduction of the roof's surface temperature in all seasons, with an average drop of 4.9°C (Yang et al., 2019).

Flooring

In light of the lack of direct exposure to sun radiation, conventional flooring experiences little temperature differential and heat transmission. Consequently, phase change materials are often integrated with electric heating floors and solar heating systems. Solar heating systems, use phase change material to store solar radiation heat generated throughout the day in the flooring. During nighttime, as the interior temperature decreases, the PCM initiates the release of heat, thereby meeting the goal of heating. This process serves as a passive energy-saving method. Zhang & Xu (2019) developed a solar heating system that integrates phase change materials. The experimental findings demonstrated that the system could sustain interior temperatures over 20°C, even in external conditions when the temperature fell below -10°C. Unlike solar floor heating, electric floor heating is an active heating method that capitalises off-peak electricity prices to store thermal energy. The heating cables are energised during off-peak electricity periods at night. This process primarily heats the phase change material layer, causing it to dissolve and absorb heat, and provides heat to the interior space. In order to satisfy the room's heating requirements during the day, the PCM solidifies, and the heating cables are deactivated during non-off-peak electricity periods. This process releases the heat that has been stored during the night.

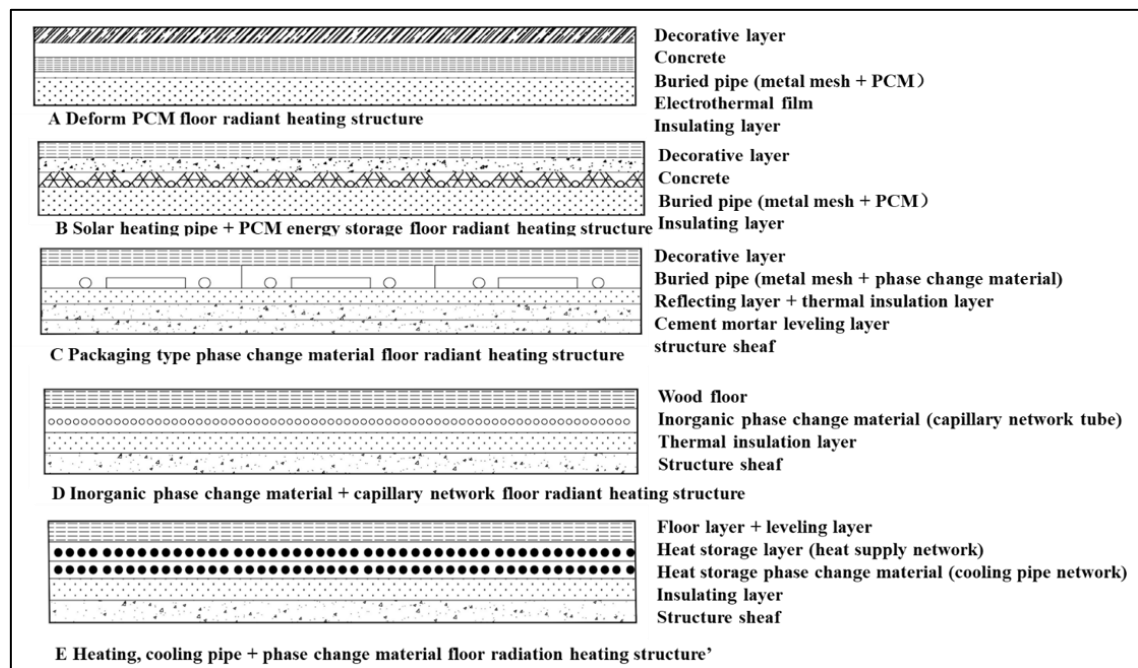


Fig. 6. Heating Floor Structures with Different Structural Forms and Phase Change Material Types

Source: Authors (2025)

Xing et al. (2018) performed a study on floor panels that used fatty acid eutectic mixtures as phase transition materials. The findings revealed that the phase transition temperature of the eutectic mixture of fatty acids varied between 20°C and 30°C. This temperature range allows for a consistent heating process, with 8 hours of heat storage during the night and 16 hours of heat release during the day. At present, there is an abundance of research focused on phase change material flooring, which encompasses a wide range

of structural designs. Figure 6 depicts schematic diagrams showcasing various structural shapes and kinds of phase change materials used in radiant floor heating systems adapted from Plytaria et al. (2018). In addition, phase change material flooring may be used with heat pump heating technology. As an example, Muzhanje et al. (2022) devised and simulated three distinct solar-assisted heat pump floor heating systems for buildings of 100 m² in size. The PCM is positioned between the floor and the heating system, and the researchers considered several conditions, such as different collecting areas of the floor, kinds of collectors and thickness of the insulating layer. The findings revealed that the inclusion of a phase change material layer in the floor heating system resulted in a reduction of the thermal load by roughly 40%.

CONCLUSION

The use of Phase Change Materials (PCM) in practically zero-energy structures has several benefits. Firstly, it improves the ability of building envelope structures to retain heat, which decreases the temperature difference between the envelope and indoor air. This leads to lower indoor temperatures and less variation in temperature, resulting in reduced heating and cooling needs for the building and improved thermal comfort. Furthermore, it enables more efficient harnessing of renewable energy sources like solar energy and air energy, hence decreasing the energy consumption of buildings. This article has presented a comprehensive review of frequently used PCM and has examined the current advancements in their implementation in domestic and international contexts, namely in walls, windows, roofs, and floors. Where acrylic acid and paraffin are the most commonly used PCM Acrylic acid exhibits good compatibility with materials like cement and gypsum, often mixed homogeneously to form microencapsulated PCM, whereas paraffin, with its poor compatibility with conventional building materials, is frequently used as embedded phase change materials. In addition, when developing and using PCM, consideration must be given to their thermal properties, phase change kinetics, chemical properties, economic viability, and environmental performance. In addition to parameters such as phase change temperature, latent heat, thermal conductivity, and degree of undercooling, stability and waterproofing of PCM must also be taken into account. Composite PCM can be developed by leveraging the advantages of organic PCM, such as consistent PCM, and inorganic phase change materials, such as high thermal conductivity, large latent heat, and minimal density changes. Improvements in the performance of phase change materials can be achieved by incorporating nanoparticles or additives like Al₂O₃, TiO₂, and ZnO. This paper also discusses the application of phase change materials in NZEB, which is not limited to passive energy-saving technologies." Phase change materials can also be integrated into active facilities like floor heating and heat pump systems, reducing equipment energy consumption and improving the thermal comfort of building environments. Future research should focus on the long-term durability of PCM-integrated materials in real-world applications and explore their potential integration with smart building technologies for dynamic thermal regulation and optimised energy efficiency.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Suqi Wang was responsible for the conceptual framework, literature review, original draft preparation, and visualization of the study. Emma Marinie Ahmad Zawawi provided supervision, guided the methodology, and contributed to the critical revision of the manuscript. Qi Jie Kwong contributed to technical validation, offered resource support, and participated in manuscript review and refinement. Yihan Wu assisted in data organization, literature retrieval, and manuscript formatting in accordance with journal standards. Congxiang Tian supported internal review, managed references, and performed language proofreading to ensure clarity and coherence.

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