Exploring the Sustainable Role of Phase Change Energy Storage Materials in Construction Engineering

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Abstract. With the development of the global economy, the carbon emission and energy utilization in the construction sector are facing great challenges. Phase change energy storage materials, as a new sustainable material, have a huge development market in low-carbon energy saving. This paper explores the potential of phase change energy storage materials in the field of construction. Through the detailed analysis of the characteristics of different types of phase change material (PCM) and their specific application cases on walls and roofs, the important role of PCM in improving building energy efficiency, improving indoor comfort and reducing carbon emission is revealed. However, the long-term stability, preparation cost and applicability of PCMs in different climatic conditions still need to be further studied and perfected. In the future, with the continuous development of technology and in-depth research, the wide application of phase change energy storage materials in the construction field will provide important support for the development of sustainable buildings, thus promoting the development of the construction industry in the direction of more environmental protection and energy saving.

Keywords: Phase change materials; energy storage; building; construction.

1. Introduction

With the continuous development of the global economy and the continuous growth of population, the construction industry not only meets people's housing and work needs, but also bears the increasingly serious pressure of energy consumption and environmental impact. The International Energy Agency (IEA) has reported that the construction industry is the main sector of energy consumption and carbon emissions, accounting for approximately 40% of global energy consumption. By the end of 2024, the energy consumption of the global construction industry is expected to increase by about 30%, and the market size of green buildings will also grow to $1.5 trillion. Therefore, finding and implementing sustainable development technologies and strategies, accelerating the development of green and sustainable buildings to reduce energy consumption and environmental impact in construction projects, has become one of the important tasks in the field of construction engineering and carbon neutrality today [1]. In this context, phase change energy storage materials, as a new type of material, have received widespread attention and research.

Phase change materials are a class of energy storage materials that store and release energy through physical phase shifts at a particular temperature. Phase change energy storage materials are materials that store and release energy by physically undergoing phase changes at particular temperatures [2]. By using phase change energy storage materials, buildings can more efficiently utilize energy, reduce dependence on traditional energy, thereby reducing carbon emissions and environmental pollution, and promoting the transformation of the construction industry towards sustainable development. Phase change material (PCM) has been listed as a national level research and development and utilization sequence in China. Therefore, phase change energy storage materials are considered a potential solution that can promote the construction industry to move towards sustainable development.

This paper aims to explore the sustainable role of phase change energy storage materials in construction projects, including their energy storage efficiency, indoor comfort improvement, and carbon emission reduction. Through the in-depth analysis of typical materials in phase change energy storage materials, it aims to provide theoretical and practical support for promoting their wide application in the field of construction engineering, and provide reference and reference for future research and engineering practice.

2. Classification of PCMs

At present, there are three main types of energy storage materials, namely: sensible thermal energy storage materials, phase change energy storage materials, and chemical energy storage materials. Among them, phase change energy storage materials are the most widely used, generally including main storage agents, phase change point adjusters, anti-overflow agents, anti-phase separation agents, and phase change promoters [3].

There are many different ways to classify PCMs. PCMs can be categorized into solid-gas PCMs, solid PCMs, liquid-gas PCMs, and solid-liquid PCMs based on the form of matter prior to and during the phase transition. According to their chemical composition, PCMs can be divided into inorganic PCMs, organic PCMs and composite PCMs. Among them, inorganic PCMs include crystalline hydrate salts (with poor reversibility), molten salts, metal alloys and other inorganic substances [4, 5] Organic PCMs include paraffin, carboxylic acids, esters, polyols and other organic compounds. Mixed PCMs are mixtures of organic and inorganic blended PCMs. This article lists some of the different types of substances in Table 1. A variety of PCMs can be mixed to obtain a suitable phase change temperature. Among them, the energy storage materials used in buildings are usually solid-liquid PCMs and solid-solid PCMs [6].

Table 1. Common Phase Change Energy Storage Materials for Insulation Walls [3-5].

Classification	PCM product/name (effective component)	Melting point range (°C)	Phase change latent heat (J · g-1)
Solid-liquid phase transition	Acrylic palmitic acid ester	**16-19**	**186**
	Paraffin RT20	**20-22**	**172**
	Dodecanol	**17.5-23.3**	**188.8**
	Glycerol	**17.9**	**198.7**
	Paraffin RT28	**28-30**	**173**
	Heptane	**18**	**214**
Solid-solid phase transition	Grafted polymers	**29.2-58**	**11.6-179.5**
	Blocking polymer	**65.2**	**138.7**
	Crosslinked polymers	**57.6-61.1**	**72.8-115.2**
	Organic compounds	**25.8-184.6**	**5.1-181.5**
	Organic metal class	**32.8-160.5**	**62.5-153.8**

2.1. Solid-liquid PCMs

When the temperature reaches its phase transition point, the substance undergoes a mutual phase transition from solid to liquid, accompanied by a large latent heat of phase transition [6]. Generally, it only involves changes in the state of the substance, and the volume change is relatively small. Solid liquid phase change energy storage materials mainly include organic, inorganic, and eutectic mixtures according to their chemical composition.

2.1.1. Organic PCMs

These types of materials are typically based on organic compounds, such as wax or polymers, which have a wide range of phase transition temperatures and can transition from solid to liquid at specific temperatures, but have poor chemical stability [7]. Organic PCMs are widely used in temperature control and thermal management fields, such as in temperature control systems for spacecraft, buildings, and comfortable clothing.

2.1.2. Inorganic PCMs

Inorganic PCMs are generally composed of inorganic compounds, such as metal alloys or inorganic salts, which undergo solid-liquid phase transitions at specific temperatures [8]. Inorganic phase change energy storage materials have good thermal conductivity and high latent heat, but they have high undercooling and are prone to corrosion of concrete. This type of material has important applications in energy storage, temperature control, and heat transfer, such as solar energy collection systems, energy-saving buildings, and temperature control equipment.

2.1.3. Eutectic mixed PCMs

Eutectic mixed PCMs are composed of two or more different components, which form a eutectic system through mixing. They have high latent heat and relatively fixed phase change temperature, but their application is limited and their cost is extremely high. This type of material design aims to optimize its phase transition temperature and thermal capacity to meet specific application requirements, such as thermal energy storage, temperature regulation, and sensor technology [4].

These solid-liquid PCMs have important applications in various fields, including energy storage, thermal management, temperature control, and environmental monitoring. Different types of PCMs have their own characteristics and advantages, and suitable materials can be selected according to specific needs.

2.2. Solid-solid Phase Transition Materials

Solid-solid phase change energy storage materials are materials that store and release energy between solid phases. Solid PCMs do not change their material state before and after the phase change, and their volume remains almost unchanged [5]. The principle is that the internal structure of the lattice undergoes changes and absorbs or releases heat energy [9]. Its advantages include low undercooling, non-toxicity, non-corrosion, and long service life. Due to the high phase transition temperature, it is difficult to obtain such materials that can be used in construction. It can be mainly divided into organic categories and organic metals.

2.2.1. Organic class

Organic solid phase change energy storage materials are usually based on organic compounds, such as waxes or organic polymers. These materials have a polymer chain structure and can store and release energy during phase transitions [10]. This type of material has high latent heat of phase change and adjustability, as well as characteristics such as lightweight, good plasticity, and customizability. It is suitable for temperature control and energy storage applications in fields such as temperature control, thermal comfort, spacecraft, and electronic devices [8].

2.2.2. Organic metals

Organic metal solid phase change energy storage materials refer to composite materials composed of organic compounds and metal ions. These materials typically have complex crystal structures and can store and release a large amount of energy during phase transitions [11]. Organic metal PCMs have excellent thermal stability and energy storage efficiency, and can be used in fields such as solar energy collection systems, thermal energy storage devices, and temperature control equipment.

These solid phase change energy storage materials have important application prospects in renewable energy utilization, energy conservation and emission reduction, and thermal management, providing important technical support for future sustainable development. However, there are also significant issues such as undercooling, phase separation, volume change during phase change, corrosion of containers, and liquid phase leakage that cannot be ignored.

2.2.3. Liquid-gas PCMs and solid-gas PCMs

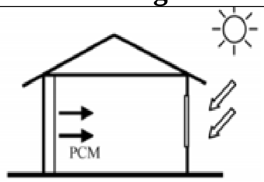
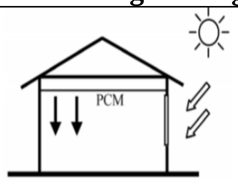
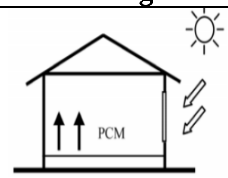
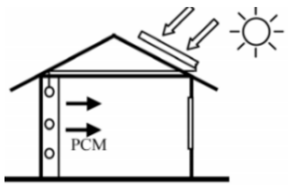
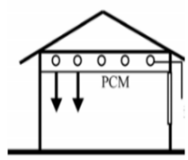
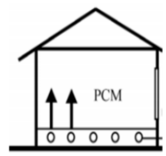
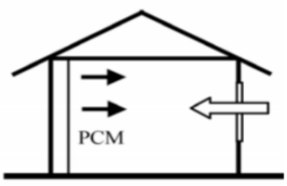
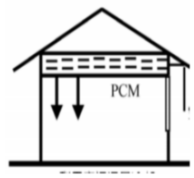
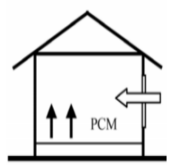
Liquid-gas PCMs and solid-gas PCMs absorb or release other energy during the phase change process, and their volume changes are relatively large. The stability and robustness required for building structures are not met, and the volume changes of these PCMs may cause deformation or damage to the building materials. Therefore, in the selection of building materials, priority is usually given to materials with stable volume and good durability to ensure the long-term stability and safety of the building structure. Therefore, it is difficult to apply it to the field of building energy conservation.

3. The Application of PCMs in the Field of Architecture

PCMs can be applied in structures such as walls, roofs, and floors in the field of architecture to achieve heat storage and insulation functions. PCMs also have good thermal insulation performance. They can reduce the conduction of heat in structures such as walls, roofs, and floors, providing better insulation effects. This insulation performance can maintain indoor warmth in winter and block the entry of high temperatures from the outside in summer, thereby improving indoor comfort [3]. The combination of PCMs and building materials will provide innovative solutions for building energy conservation. By utilizing the high thermal storage density and phase change characteristics of PCMs, thermal storage and insulation functions can be achieved, energy consumption and carbon emissions can be reduced, and indoor comfort can be improved [4]. In the future, PCMs have broad application prospects in the field of construction and are expected to become a common practice, contributing to sustainable building development.

3.1. Roof

Table 2. Application forms of PCM in building [1].

Phase	Phase change wall	Phase change ceiling	Phase change floor
Passive solar heating	 **Utilize solar radiant energy during the day**	 **Utilize solar radiant energy during the day**	 **Utilize solar radiant energy during the day**
Active heating	 Utilize solar heat collection system for hot water heating	 Use cheap electric energy heat pump for heating at night	 Utilize cheap electric energy for floor heating at night
Cool down at night	 Use night ventilation to cool	 Use night ventilation to cool	 Use night ventilation to cool

As shown in Table 2, when the sun shines on the roof of a building during the day, PCMs absorb solar energy heat and store it. This helps to reduce the transfer of heat from the roof to the interior, lowering the indoor temperature. At night or on cloudy days, when the outdoor temperature drops, PCMs begin to release stored heat, thereby playing a role in insulation, preventing indoor heat loss, and maintaining relatively stable indoor temperature [10]. At present, the phase change energy storage materials commonly used in roof insulation in construction projects are paraffin/fatty acids, expanded perlite, and expanded vermiculite. Paraffin/fatty acid PCMs have good thermal storage performance, as well as good thermal conductivity and high heat storage and release performance, making them the most suitable as building roof insulation materials. Although expanded perlite and expanded vermiculite have high melting points and good thermal conductivity, their thermal storage performance is relatively poor. Therefore, using expanded perlite and expanded vermiculite as roof insulation layers requires some special treatment [1]. The application of PCMs in rooftop buildings utilizes their characteristics of heat storage and release, effectively regulating indoor temperature, reducing the use of air conditioning or heating, thereby improving building energy efficiency and thermal comfort while saving energy and reducing carbon emissions.

3.2. Wall

At present, the PCMs widely used in walls are mainly polymers (such as paraffin) and concrete PCMs. However, different installation positions, orientations, and bonding forms can lead to different temperature control capabilities [6, 7].

According to Li Jie's research, PCMs are encapsulated in high-density polyethylene spherical shells in concrete, forming a PCM concrete layer [12]. the daily heat load variation rate through walls were studied when placing PCMs concrete layers at different locations in five typical climate zones of China [13, 14]. The results indicate that in order to fully utilize PCMs in summer, the phase change temperature is recommended to be between the outer surface temperature and the inner surface temperature. PCMs should be placed in the center of the wall in situations when the temperature of the outside and inner surfaces is higher than the phase change temperature. Winter PCMs should be positioned in accordance with the range of ambient temperature in order to be fully utilized. The sun's heat is enough to melt the PCMs when the outside temperature is higher than 30.8°C. It is recommended to install the PCM layer next to the inner surface of the wall to release more heat indoors. When the ambient air is warm enough, between 22.4°C and 30.8°C, solar energy can melt some PCMs. It is recommended to install a PCM layer next to the outer surface of the wall to absorb more solar energy. When the ambient temperature is below 22.4°C, solar energy cannot melt PCMs, and it is not recommended to install a PCM layer. The phase transition temperature should be between the outer surface temperature and the inner surface temperature when cooling conditions akin to those of summer are present [15]. The PCM layer should be positioned in the center of the wall in situations when the temperature of the outer and inner surfaces is higher than the phase transition temperature. When applying PCMs in situations akin to winter heating, caution should be used.

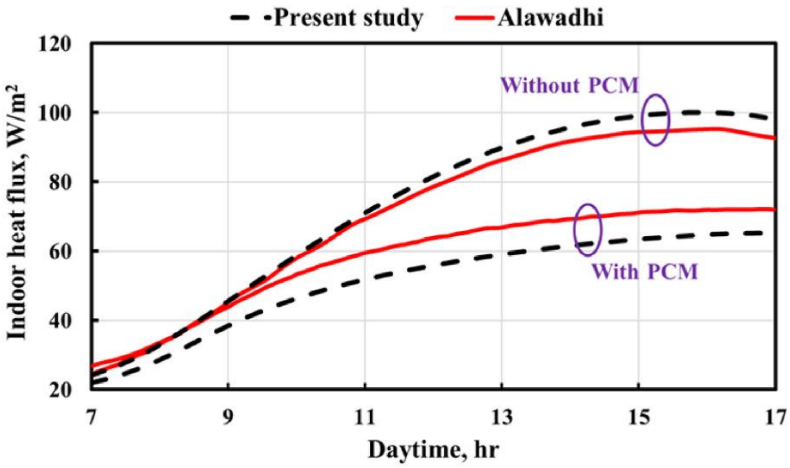


Fig 1. Verification of the interior heat flux model using Alawadhi's findings [16].

Based on the weather conditions simulated by Montaser Mahmoud in Sharjah, the United Arab Emirates and five countries, the influences of different wall directions on PCMs efficiency were compared and analyzed [15]. The wall without PCM (60mm insulation) is used as the reference standard case, while the other three walls include an additional 10mm thick inner layer (insulation, PCM-31 and RT-41).

Their group examines heat flux and inner wall temperature while taking various surface orientations into account. Key meteorological factors that influence heat transfer through walls are also sun radiation, wind speed, and ambient temperature. It tested all walls in different directions to identify the impact of PCM and direction on energy consumption. As shown in Fig. 1, the effect of PCMs is more significant under the experimental conditions of Alawadhi. Meanwhile, investigations into the inner wall temperature indicate that using PCM, especially PCM-31, helps improve stability and reduce temperature fluctuations. PCM-31 exhibits the highest stability, with inner wall temperatures fluctuating between 26 °C and 27 °C in all orientations. Compared with the reference case without PCMs, the addition of PCMs resulted in a temperature reduction of more than 2 °C for the horizontal wall and the wall facing east.

With a peak reduction of 78.6%, PCM-31 had the best performance in indoor heat flux, although RT-41 also performed admirably. With walls that face east and horizontally, RT-41 performs well; nevertheless, its influence is minimal in other orientations. Since PCMs work best on walls facing east due to intense sun radiation and overlapping environmental temperatures, they are most beneficial when a sudden load jump occurs [16].

4. Conclusion

This paper mainly studies the application of PCMs in the field of architecture and draws the following main conclusions:

(1) PCMs can be divided into two categories: solid-liquid PCMs and solid-solid PCMs. Solid liquid PCMs store and release energy through the transition from solid to liquid, making them suitable for scenarios that require significant energy storage and release, such as temperature control and thermal management. In contrast, solid-phase transition materials store and release energy between solids, with higher energy storage density and more stable phase transition temperature, making them suitable for scenarios with high stability requirements, such as solar energy collection systems and energy-saving buildings. Organic PCMs and inorganic PCMs each have their own advantages. Organic PCMs have a wide range of phase change temperatures and good thermal conductivity, making them suitable for temperature control and thermal management fields; Inorganic PCMs have high energy storage density and stability, making them suitable for specific engineering scenarios. Solid phase transition materials can be divided into two categories: organic and organometallic, which have important application prospects, but there are also some challenges, such as undercooling, phase separation, and container corrosion.

(2) The application section further explores the specific applications of PCMs in the construction field, and cites relevant studies for verification. The application of phase change energy storage materials in the construction field is an important and diverse engineering practice. In terms of walls and roofs, most of the applications of PCMs are for heat storage and insulation, and according to the results of this paper, it is possible to achieve heat storage and insulation by embedding solid-liquid PCMs, such as paraffin wax or polymers, in the wall. These PCMs can absorb solar heat during the day and release the stored heat at night, thereby reducing indoor temperature fluctuations, improving indoor comfort while saving energy, reducing energy consumption and carbon emissions. In addition, different types of PCMs and layouts can be used to optimize the thermal insulation effect of the walls according to the characteristics of different wall orientations and climatic conditions in different regions.

(3) In terms of research shortcomings and prospects, this article points out that further research and improvement are needed for the long-term stability, cost, and environmental adaptability of PCMs. Especially, it is necessary to pay attention to the performance of PCMs under temperature changes, mechanical stress, and chemical corrosion, in order to improve their stability and extend their service life. In addition, the cost of PCMs is still relatively high, and it is necessary to find more

economical and practical preparation methods, and reduce costs through technological innovation and industrial promotion to promote their widespread application in construction engineering. Finally, according to the climate characteristics of different regions, it is necessary to develop PCMs and their application solutions suitable for different environments, in order to improve their applicability and popularity in the field of construction. Phase change energy storage materials have enormous potential in construction engineering, providing new solutions for energy conservation and environmental protection. However, in-depth research and practice are still needed in some specific application scenarios to promote its widespread application and development in the field of architecture.

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