

The Impact of Phase Change Materials on the Thermal Insulation Properties of Building Structures in Regions with Extreme Temperature Fluctuations

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Abstract: The article examines the effect of the use of phase-shifting materials on the thermal insulation properties of building structures under conditions of extreme temperature fluctuations. Their physicochemical characteristics, such as high specific heat of the phase transition and thermal stability, are analyzed, which makes them effective in regions with extreme daily and seasonal temperature differences. Various ways of integrating this material into building structures such as walls, roofs and ceilings are being investigated, as well as their impact on reducing the need for heating and cooling. Special attention is paid to the economic aspects of implementing phase-shifting materials, including their cost, payback period and long-term benefits for energy efficiency of buildings.

Keywords: Phase change materials, thermal insulation, building structures, temperature fluctuations, energy efficiency.

I. Introduction

The construction sector currently experiences higher demands for energy-efficient buildings, precipitated by environmental issues and the desire to lower costs of operation. Today's building sector has more requirements for energy-efficient buildings driven by environmental degradation and reducing the cost of operations. Among the most promising ways is one that uses the use of phase change materials (PCM), which can hold and release thermal energy at their phase change temperature. These are capable of providing passive temperature change control indoor, thus enhancing the thermal insulation capacity of building fabrics.

In areas where there are tremendous temperature gradients, traditional building materials are plagued with problems including reduced thermal performance, increased degradation, and increased heating and cooling system costs. By regulating the room temperature, PCM can alleviate the problems, and as such it is most useful in areas where there are very large diurnal and annual temperature gradients. The above reasons emphasize the importance of conducting research on the impact of PCM on the thermal insulation ability of building structures. The aim of this study is to analyze the efficacy of using PCM in construction, particularly for regions that experience intense temperature changes.

II. Phase Change Materials: Properties and Operating Principles

Substances that are able to retain and release a high amount of thermal energy during a phase change are known as PCM from solid to liquid most commonly. Their fundamental physicochemical characteristics are a high latent heat of phase transition, enabling the absorption or release of high heats with minimal temperature change. These materials possess extremely good thermal stability in that they can be melted and solidified numerous times without significant loss of their properties. Another important advantage of PCM is that when undergoing phase change, their volume change is extremely small, such that it reduces the mechanical load on the building structures upon which they are cast. The phase transition temperature range of these materials can be tuned to desired applications, either equipment, construction, or refrigerator systems. PCM is also generally compatible with most building materials such as concrete, gypsum, and polymers and can be easily incorporated without significant modifications.

The functionality of PCM is based on the phase transition that occurs in response to environmental temperature changes (fig. 1).

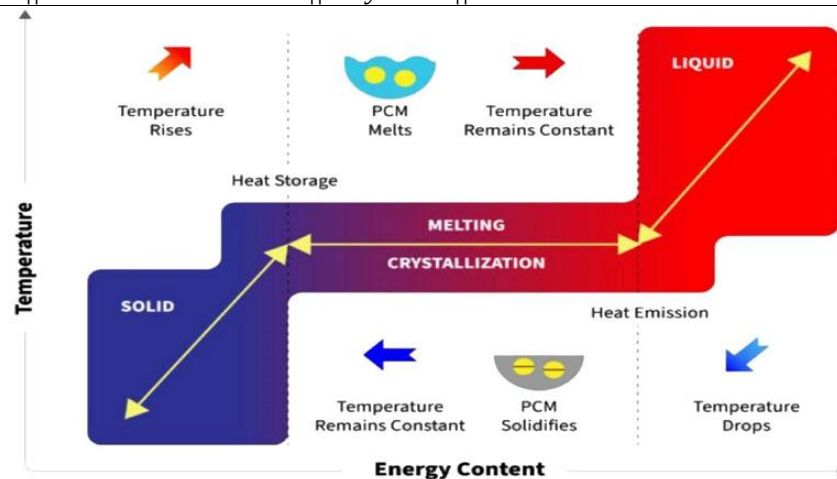


Fig. 1: Mechanism PCM

When heated to their melting point, PCM absorb substantial thermal energy, converting it into latent heat. This procedure maintains the temperature of a building or building component constant, preventing overheating. Conversely, if the temperature drops below the material's crystallization point, the absorbed heat is released to the environment, reducing heat loss when the temperature cools down [1].

The phase transformation, both crystallization and melting, allows PCM to act as thermal buffers. In the following stage of melting, energy from the external environment in the form of entering thermal energy is used to alter the phase of the material so that there is not a sudden transition in temperature of the system. In crystallization, latent heat stored in the material from melting is released to the environment, managing interior temperatures even during severe drops in external temperatures. This tends to reduce the burden on heating and cooling systems, making them energy efficient. In addition, PCM serve to extend the service life of building materials through the reduction of thermal stresses. As such, they represent an innovative technology for managing thermal flows in buildings, particularly those located in regions of extreme temperature variations.

III. Thermal Insulation Properties of Building Structures

The traditional insulation materials such as mineral wool board, polystyrene foam, polyurethane, and extruded polystyrene panels find extensive application in the building sector for building energy efficiency. Economy, low thermal conductivity, and relatively low cost rule them. However, their performance is generally limited by numerous factors, particularly at extreme levels of temperature changes. The key to their limitation is their low capability to withstand temperature changes. For instance, under the conditions of extreme overheating or cooling, these materials quickly lose their insulating properties [2]. Traditional insulation materials are most suitably used in stationary temperature regimes, and there is a great decrease in their effectiveness in the situation of frequent temperature alteration, which is especially inconvenient under areas of extreme climate conditions. These products also break down and age through exposure to environmental factors of humidity, physical stress, and exposure to ultraviolet light.

Usage of PCM significantly improves building structures' thermal insulation standards, especially in areas with dramatic temperature fluctuations. Besides keeping the heat loss or overheat, they provide another level of thermal stabilizing by absorbing and releasing heat after the temperature fluctuates. They are also effectively integrated into traditional insulation materials to attain multilayer constructions with better thermal insulation performance [3].

One advantage of the combination of PCM with traditional materials is their ability to compensate for the weakness of existing insulation materials, i.e., lack of temperature control performance. In overheating, for example, PCM absorbs excess heat, preventing its accumulation, and in cooling, it releases stored heat, providing more indoor temperature stability conditions. This approach significantly enhances building energy efficiency, comfort living, and reduced operating costs.

IV. Application of PCM in Construction under Extreme Temperature Fluctuations

The introduction of PCM into various building structures ensures the improvement of their thermal insulation properties and the creation of thermostable conditions in the premises. One of the most common methods is their use in walls, roofs, and ceilings of buildings, where they can actively regulate temperature by absorbing and releasing heat during the phase transition (table 1).

Table 1: Applications of PCM in building structures [4, 5]

Structuralelements	The role of PCM in design	The effect of the application
Wall structures	Can be embedded in building blocks	They help to absorb excess heat during the day and release it at night, maintaining a stable temperature inside the room. This reduces the need for additional heating and cooling.
Roofs	They are used in roofing systems to stabilize temperature fluctuations.	They provide room cooling during the day and heating at night, effectively manage heat flows.
Overlaps	They are integrated into insulation materials for roofs and ceilings, as well as in combination with traditional thermal insulation materials.	Increases the efficiency of thermal insulation and improves the thermal stability of rooms, reducing dependence on heating and cooling systems.

According to the author, integrating PCM into various elements of building structures significantly enhances thermal insulation properties and creates stable temperature conditions. These materials, through their ability to regulate heat flows, not only optimize the energy efficiency of buildings but also reduce the operational burden on heating and cooling systems.

These conclusions are confirmed by practice, for example, in a study in Oak Ridge on the use of microcapsulated waxed PCM in combination with cellulose insulation showed that their addition to building materials significantly improves the thermal stability of buildings, reducing heat fluxes by 30% during peak heat hours. During these tests, the PCM not only reduced temperature fluctuations, but also shifted peak loads by several hours, which reduced the need for active cooling on hot days □ 6□ .

Also, a study was conducted using PCM in the walls and roofs of buildings, where improvements in energy efficiency were also noted. Their use in such structures has reduced heating and cooling needs, especially in climate conditions of wide temperature variation between day and night. They have been shown to be effective in considerably reducing energy consumption by improving general thermal stability of buildings under extreme conditions of temperature variation [7].

Thus, one of the most important advantages of using PCM is to improve thermal stability in buildings. These materials absorb excess heat during summer and release it gradually when ambient temperature falls. This minimizes sudden temperature fluctuations in buildings, providing a comfortable microclimate. The utilization of PCM also leads to a significant decrease in energy expenses for heating and cooling. Energy saving is 20% to 30% in areas that experience broad variations of temperature, as conventional materials are used. Upon installation, the temperature is managed effectively, reducing the heating equipment load during winter and air-conditioning system load during summer and hence saving electricity and running costs.

However, the economic efficiency of such solutions is not limited only to reducing energy costs. Although thermal insulation materials during the stage of current development and application may be more costly compared to traditional thermal insulation materials, application in construction displays incredible economic effectiveness in the long run [8]. Payback period depends on a variety of factors like climatic conditions, cost of energy and material utilized, and generally is 5 to 10 years based on the utilization rate of heating and cooling systems. The energy savings in those areas where the difference of winter and summer temperatures will significantly reduce the duration. In addition, it is responsible for the improvement of the strength of construction structures, decreasing heat deformations and the load of climatic equipment, consequently reducing maintenance and repair expenses.

Therefore, after the initial investment, inclusion of PCM in construction becomes a financially viable choice, especially in climatically hot regions with extreme temperature fluctuations, where the efficiency of such materials can actually reduce operation costs and maximize living comfort in buildings.

New application methods of PCM in extreme climates open new perspectives for increasing the energy efficiency and comfort of buildings. The development of multifunctional systems where PCM is used together with solar panels, ventilation systems, and heat exchangers can enhance energy efficiency drastically. The employment of «smart» walls or roofs that have the ability to control temperature using solar energy and phase transitions minimizes reliance on external energy sources. Both passive and active PCM systems, in which behavior of the material is employed to modulate temperature or supplement traditional heating and cooling systems, have the capability to offer high comfort and efficiency levels.

Besides, the introduction of PCM into new types of building materials, e.g., «smart» concrete mixtures or facade coatings enhancing thermal stability and insulation characteristics, can significantly increase building

resistance to extreme temperatures. New technologies are of significant promise for the development of more energy-efficient and convenient buildings in climatic regions with radical temperature fluctuations.

V. Conclusion

The application of PCM in buildings where there are high differences in temperature greatly influences the thermal insulation of buildings. Due to their ability to store and release heat while undergoing phase changes, PCM stabilizes indoor temperatures by reducing temperature fluctuation amplitudes and sustaining more comfortable indoor conditions. In areas with extreme seasonal and daily temperature variations, these materials reduce reliance on active heating and cooling systems, thus yielding lower energy costs and building energy efficiency. Even though higher in material and installation cost initially, long-term conservation of energy and greater thermal stability make PCM a cost-effective approach to building development in areas of extreme climatic conditions.

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