Experimental Investigation and Numerical Validation on the Energy-Saving Performance of a Passive PCM Floor for a Real Scale Building

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Abstract

Phase change material (PCM) can store heat at a constant temperature, which is beneficial to reduce building energy consumption. Herein, we fabricated a PCM board that can store 98–102 J/g heat at 26 °C. The PCM boards were paved as the floor in the real-scale office to reduce power for temperature regulation, which led to the reduced energy consumption of 18.8% and 19.7% in winter and summer, respectively. A numerical model is validated by experimental data to evaluate long-term performance. The experiment and simulation results both demonstrate the high-performance PCM floor for effective reduction in electricity consumption of heating and cooling.

Keywords: phase change materials; thermal energy storage; building energy-saving; numerical simulation

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1. Introduction

Climate change has been a globally recognized challenge since the last century. Substantial evidence proves that the influence of human activity is responsible for the abnormal temperature fluctuation.^[1] Since energy consumption has an important impact on greenhouse gas emission, the community is urged to reconsider the energy-consuming approach.^[2–3] The building section accounts for about 46% of the final energy consumption in China, in which a large portion of the energy is used for operating temperature control systems.^[4] Thus, it will be more economical and environmentally friendly to develop buildings that can resist temperature change. Phase change

materials (PCMs) can absorb and release a large amount of heat in a certain temperature range during the phase transition process.^[5–6] When incorporated into the building envelope, PCMs can receive extra heat from the environment and release the stored latent heat when the ambient temperature drops, thus mitigating the room temperature change. Various experimental and numerical strategies are developed to combine PCMs with building envelopes.^[7–10]

Nevertheless, the leakage issue is the long-standing bottleneck for the practical building applications of PCMs. In this regard, macro-size container, microencapsulation or form-stable composition is the alternative method to hold PCMs in position.^[11–17] PCMs can be stored in macro-sized balls, tubes or plates.^[18–19] Zhou et al. tested the thermal performance of PCM bags in a radiant floor heating system in the basement.^[20] The results showed that PCM can provide longer and more stable heat discharge compared with sand in experiment and simulation. Navarro et al. fabricated the active slab consisted of concrete elements with channels filled with PCM tubes, which was coupled to a solar air collector for providing heat energy in a cubicle.^[21] The experimental results demonstrated

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that the system displayed effective energy-savings compared to conventional heating systems. Microencapsulation is another versatile method to incorporate PCMs into the building envelope, which provides a capsule that contains PCMs within polymer or inorganic shells that are more compatible with building materials.^[22-23] Bao et al. developed PCM cement composites consisting of microencapsulated PCM, nano-silica and carbon fiber for applications in passive solar buildings.^[24] The room model test exhibited the ability of the composite cement to effectively regulate the indoor room temperature. Jaworski et al. incorporated microencapsulated PCMs in ceiling panels, which were then integrated into a ventilation system to manipulate the temperature of air supply.^[25] The experimental results confirmed the effective control of indoor temperature by PCM units, while PCMs did not undergo the full phase transition process. A numerical simulation was further developed to obtain the ideal distribution and thickness of PCM capsules that could improve the efficiency. Cao et al. combined microencapsulated PCM into geopolymers concrete walls and numerically investigated the impact of climate conditions.^[26] The results showed that the wall orientation and the season could significantly affect the building energy efficiency. Form-stable PCM composites consist of PCMs and the supporting materials, which are usually polymers or porous materials. Compared with microencapsulation, the form-stable method is simpler and more economic because this method can effectively achieve large-scale production.^[27-30] Abden et al. developed form-stable PCM by incorporating PCM into diatomite, which was then integrated into the gypsum board ceiling for building energy conservation.^[31] The energy-saving performance and economic feasibility of the composites board were confirmed by the experimental results evaluated in a small-scale test chamber. Ye et al. fabricated $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ /expanded graphite composite panel and tested its properties in an artificial climate chamber.^[32] The PCM panel can effectively reduce the temperature difference according to the experimental results, which showed a good agreement with the alongside established numerical model. The model was further used to analyze the ideal thickness of panel.

Noteworthy, the reported test scenes for examining PCMs-combined building envelopes are all home-made chambers, whose sizes are much smaller than real buildings. Therefore, the performance tests in real-scale buildings are needed to evaluate the effectiveness of PCMs-combined building envelopes. In this work, we investigated the performance of the form-stable PCM board on energy-saving in real-scale office. The form-stable composite fabricated by organic PCM, expanded graphite (EG) and polymer was pressed into the rectangular board and paved as the floor in a commercial office. Another identical room without the PCM floor next to the test room was set up as the reference. The power consumed by temperature controlling systems was recorded and the temperature profiles of both rooms in different seasons were

compared. To further evaluate the long-term energy-saving performance of the PCM board, a numerical simulation validated by the experiment results was carried out.

2. Experimental section

2.1 Preparation of PCM board

The form-stable PCM board was fabricated by the melt blending method. The commercial PCM and EG at a mass ratio of 6:1 were mixed in a horizontal mixer at 60 °C for 30 minutes. 28 kg mixtures, 10 kg HDPE and 1 kg SEBS were then put into a planet stirrer at 150 °C and stirred for 120 minutes. The obtained black powder was pressed in a mold under 2 MPa for 30 minutes at room temperature. Finally, the as-prepared product was cut into rectangular brick sized 60 cm × 8 cm × 1 cm.

2.2 Performance characterization of the PCM board

The scanning electron microscopy (SEM, FEI Quanta 200F) was applied to observe the morphology of EG and PCM board. The enthalpy of the composite was measured using Differential scanning calorimetry (DSC) Setaram 131 Evo under Ar atmosphere with a temperature change rate of 5 °C/min. The thermal stability of the composite was characterized by the thermogravimetric analysis (TGA) SDT-Q600 from the TA company with a heating rate of 10 °C/min under N_2 gas flow.

2.3 Construction of the test room

The test room was set up in a commercial office, located on the fifth floor of Building No.7, Yard No.13, Cuihu Nanhuan Road, Haidian District, Beijing. To verify the energy-saving performance of the PCM board, we paved one layer of PCM boards as the floor in the room, named as the PCM room. And an identical reference room without the PCM board next to the PCM room was marked as reference room (REF room). A schematic illustration of the experimental set-up is shown in Fig. 1. The experiments with the same layout were carried out in two sets of rooms for winter and summer. The rooms for winter experiments had a dimension of 3.6 m (width) × 4.0 m (depth) × 2.7 m (height), which were equipped with an electric heater that worked to maintain the room temperature between 18 to 20 °C. The power of the heater is 1.8 kW. Another pair of rooms with a similar dimension of 3.7 m (width) × 4.7 m (depth) × 2.7 m (height) was prepared for summer. The air conditioner in the room kept the temperature between 24 to 26 °C. The power of the conditioner is also 1.8 kW. The temperature sensor was placed in the middle of the floor surface in each room to record the room temperature. To minimize the heat exchange with the environment, all the rooms were isolated from the environment by the 5 cm thick polystyrene board, except that the double-glazing glass was left in southern facet to through the sunlight.

Fig. 1 The experimental illustration. (a) the orientation of the rooms; (b) a 3D demonstration of the PCM room; (c) the PCM room and the REF room; (d) the PCM board was paved on the floor.

2.4 Numerical simulation

The yearly energy-saving performance of the PCM board can be evaluated more efficiently by numerical simulation. The model is based on the state-space method. In this method, the room is discretized and represented by several temperature nodes. Therefore, the dynamic thermal load of the room can be simulated by solving the equilibrium equation of the nodes. In our work, the numerical simulation is conducted in the Designer's Simulation Toolkit (DeST) software. The assumption of the simulation is given as followed:

- (1) The indoor temperature is considered homogeneous.
- (2) The construction materials of walls, roof, and floor are isotropic. And their thermal properties are constant.
- (3) To simplify the model, the room exchanges heat with the environment through the southern wall. And the other facets, including walls, roof and the boundary under the floor, are adiabatic.
- (4) The supercooling of the PCM is not considered.

The model of the room condition is depicted in Fig. 2. The governing equation for thermal conduction is:

$$c_p \rho \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

where T , ρ , c_p , and λ stand for temperature, density, specific heat, and thermal conductivity, respectively. In our model, the southern wall is considered isotropic. And the dimension of the wall thickness is much less than its length. Hence, thermal conduction can be regarded as a one-dimensional situation:

Fig. 2 The depiction of the room model.

$$c_p \rho \frac{\partial T}{\partial t} = \frac{\partial T}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right)$$

The boundary conditions are identified based on the real situation. All walls, including the roof and the floor, are regarded as adiabatic boundaries except the southern wall. Heat transfers into the room through the glazing system. Therefore, the boundary conditions are listed as followed:

$$\begin{cases} -k \frac{\partial T}{\partial x} \Big|_{x=l} = h_i (T_a - T) + q_r + \sum_j h r_j (T_j - T) \\ -k \frac{\partial T}{\partial x} \Big|_{x=0} = h_o (T_o - T) + q_{r,o} + h r_o (T_{env} - T) \end{cases}$$

where x is the dimension along the wall. When x equals 0 or l ,

the equation stands for the outer wall or inner wall situation. k is the thermal conductivity of the wall along the thickness. h_i and h_o are the convective heat-transfer coefficients of the inner-wall and outer-wall. T and T_a are the temperatures of the wall and the room temperature, and T_{env} represents the overall temperature of the surrounding surface. q_r and $q_{r,o}$ is the absorbed solar energy by the inner and outer wall. hr_j and hr_o are the long-length wave radiation heat-transfer coefficients from the inner walls and the surroundings.

The room temperature should satisfy the following equation:

$$c_{pa}\rho_a V_a \frac{dT_a}{d\tau} = \sum_{j=1}^n F_j h_i (T_j(\tau) - T_a(\tau)) + q_{hvac}$$

where $c_{pa}\rho_a V_a$ is the heat capacity of the ambient air. F stands for the area of the wall. q_{hvac} stands for the energy provided by the heating and air-conditioner system.

The intensity of the solar irradiation can be influenced by the weather and the air quality. The influence of air quality is given as the following equation:^[33]

$$Q = Q_0 [aS_1 + b \ln(D) + c] \exp\left(\frac{d \cdot AQI}{1000}\right)$$

In the model, we use clearness index k to measure the effect of weather and air quality index AQI for the air quality.^[34-35] The value of k is listed in Table 1.

Table 1. The clearness index k under different weather.

Weather	Overcast	Cloudy	Sunny
The clearness index k	$0 \leq k \leq 0.3$	$0.3 \leq k \leq 0.6$	$0.6 \leq k \leq 1$

3. Results and discussion

3.1 Analyses of the PCM board

The form-stable PCM board is shown in Fig. S1(Supporting information). The dark appearance of EG endows the composite with the ability to absorb sunlight into stored latent heat for coming use. Besides, the porosity of EG can effectively hold the melted PCM in position. From the SEM

images in Fig. S2 (Supporting information), the EG possesses the layer structure with the size of a few hundred micro-meter, while the PCM and polymeric supporter wrap onto the surface of the carbon sheet and form wrinkle cover in the composites. The surface tension drags the PCM from flowing away, thus the PCM board can stay form-stable even at high temperatures.

The thermal properties of the PCM board are identified by DSC and TGA tests, including the PCM board before and after use in room temperature regulation as shown in Fig. 3. The original PCM board can store 98-102 J/g heat at the melting temperature of 26 °C and release 93-97 J/g heat at the crystallization temperature of 25 °C. After usage, the heat capacity of the board is maintained as shown in the identical DSC pattern (Fig. 3(a)), indicating the stable heat storage capability that enables the PCM board to be used for long-term energy savings. The thermal stability of the PCM board was studied by heating it to 600 °C as shown in Fig. 3(b). The organic PCM and polymeric supporter decompose when the temperature reaches 160 °C and 400 °C, respectively. The TGA pattern illustrates that about 60 wt.% of the board is composed of PCM. After use, the thermogravimetric characteristics of the PCM board remain unchanged. The good thermal stability could be attributed to the structurally stable EG. After long-term use, its lamellar encapsulation can still hinder the leakage and decomposition of organic molecules and improve the thermal stability of the material. Therefore, the board can withstand days of the test.

3.2 Thermal performance of the test room in winter

3.2.1 The comparison between test room and reference room

The experiment in winter was carried out in February 2017. The comparison of the electricity consumption and experimental temperature record between PCM room and REF room is shown in Fig. 4 and Fig. 5(a), respectively. Then a simulation result based on the material properties was run in DeST and compared with the experimental results in Fig. 5(b) and Fig. S3 (Supporting information). In February, the average temperature in Beijing was between -2~9 °C. Therefore, the electric heater worked every day to keep the room temperature

Fig. 3 The thermal performance of the PCM boards. (a) the latent heat is evaluated by DSC; (b) the thermal stability evaluated by TGA.

in the comfortable range, which led to the linear increment of electricity consumption. As desired, the PCM room consumed less power than the REF room as shown in Fig. 4, and the calculation indicated that 18.8% of energy was saved by the PCM board. To figure out the working principle of the PCM board, the room temperatures of the PCM and REF rooms were recorded and the results of the first 6 days are presented in Fig. 5(a). As the sunlight heated the rooms, the temperatures in both rooms rise gradually, during which process the PCM board stored a part of the incoming heat as its latent heat and sensible heat in the PCM room, leading to the lower temperature compared with the REF room in the daytime. After sunset, the temperature of the REF room dropped quickly and the heater soon started to work. In comparison, the temperature in PCM room decrease at a slower speed since the PCM released its stored heat at the same time. When the temperature dropped to around 25 °C, the latent heat stored in the PCM board started discharging, which slowed down the temperature variation. The electric heater in the PCM room started working after midnight while the heater in the REF

Fig. 4 The comparison of electricity consumption between the REF room and the PCM room in February.

room had already worked for several hours, demonstrating that the PCM board helped shorten the working duration of the heater by latent heat discharge. Moreover, the temperature of the PCM room has a lower amplitude during nighttime compared with the REF room, which may owe to the sensible heat storage of the PCM board.

Fig. 5 (a) The comparison of the room temperatures in winter. **(b)** The comparison between the simulation and the experiment of the PCM room in winter.

3.2.2 Numerical simulation of the room temperature

We simulated the temperature of the PCM room and compared it with experimental results as depicted in Fig. 5(b). It can be seen that the simulated room temperature exceeds 20 °C during the daytime and the heater works during the night, which is consistent with the experiment. Nevertheless, during the daytime, the simulation result has a very smooth and symmetric curve while the experimental result curve is discrete and asymmetric. The difference could be attributed to the change of thermal conductivity in different phases, which are not taken into account in the simulation. As desired, the present simulation can reflect the temperature profile of the test rooms. The temperature profile of the whole winter and the energy efficiency was further calculated accordingly by using the same model. Heat supply in Beijing starts from November, 15th to March, 15th. The simulated room temperature during the 120 days is shown in Fig. S3

(Supporting information). It can be observed that the heater works frequently in January and February which are the coldest months in winter. The sunlight intensity is lower during these days, thus the PCM board receives less energy, leading to lower energy-saving efficiency. It can be concluded that the efficiency is greatly influenced by the average ambient temperature from the calculated energy saving ratio of each month. The PCM board saved more energy in December and March when the ambient temperature is relatively higher, while it received less energy and the stored heat is consumed faster due to the larger temperature gradient in January and February. Therefore, the energy-saving efficiency is dependent on the stored heat by the PCM board. Besides, weather and air quality can also affect the intensity of solar radiation, which will be further discussed in the next section.

3.2.3 The influence of weather and air condition in winter

Solar radiation is a crucial factor that influences the energy-

saving efficiency in winter since the solar heat is the sole source of the latent heat. The weather condition and air quality can directly determine the solar radiation, which in turn affect the energy-saving efficiency. In winter, poor weather conditions and air quality will reduce solar radiation intensity and affect the input heat. Therefore, the heat storage property of PCM board is not fully utilized, which will decrease the energy-saving efficiency. The influence between the air quality and energy-saving performance of PCMs-combined building envelopes was studied for the first time. The influence of the PCM board under different weather was studied and the corresponding temperature record is shown in Fig. 6(a). On cloudy days, the solar radiation received by the room is relatively small, and hence the increase in room temperature is

too low to reach the phase transition temperature. The PCM board absorbed part of the solar radiation through sensible heat while the latent heat did not work, which caused the negligible energy-saving performance. In the simulation, the energy-saving index decreases linearly with the lower clearness index k . The air condition can influence the energy-saving performance of the PCM board through a similar principle. We quantified the effect of air quality by using an equation to simulate the influence of air condition on solar intensity. As the result shown in Fig. 6(b), the energy-saving efficiency decreases as the air quality gets worse in both of the experiment and simulation results. It can be concluded that poor air quality is not only detrimental to human health but also consumes more energy.

Fig. 6 (a) The room temperature records under different weathers in winter. **(b)** The comparison between the simulation and the experiment of the PCM room in winter.

3.3 Thermal performance of the test room in summer

3.3.1 The comparison between test room and reference room

The experiment in summer is set up in another pair of rooms. As illustrated in Fig. 7, the electricity consumption in summer showed a similar trend with winter that the PCM room consumed less power than the REF room, and the calculation indicated that 19.7% of energy was saved by the PCM board in May. In order to explore the principle of energy saving in summer, the temperature profiles of a typical day in May, June, and July respectively were recorded as shown in Fig. 8. In summer, the phase change temperature of the PCM board is generally lower than the average temperature, thus the stored latent heat works as “cold” energy to modulate the temperature variation of the room. Intense fluctuation in the temperature profile represents the operating hours of the air conditioner. The working principle of the PCM board varies with the monthly average temperature. In May and June, the air conditioners worked from the early morning to late afternoon. Owing to the latent heat of the PCM board, when the solar radiation became weaker, the room temperature of the PCM room can be kept within the human comfort zone even if the air conditioner stopped working. Therefore, the working hours of the air conditioner were shortened, which reduced the power consumption significantly. In July,

however, the average ambient temperature was usually higher than 24 °C, leading the air conditioners in both rooms to keep working all day. In this case, the latent heat of the PCM board achieved energy savings by reducing the operating frequency of air conditioners. The reduction is not as prominent as shortening the working hours of the air conditioner; therefore, the energy-saving efficiency is lowest in July and highest in May which is also proven in the DeST simulation. Notably, the fluctuation amplitude of the PCM room was larger than

Fig. 7 The comparison of electricity consumption between the REF room and the PCM room in May.

Fig. 8 Room temperature records of typical days in summer. (a) May, (b) June, and (c) July.

that of the REF room, which could be attributed to the sensible heat storage of the PCM board. When the temperature changes, heat can be absorbed or released from the PCM board. During this time, the air conditioner will keep working, resulting in the reduced room temperature. The PCM board can also play the role of thermal isolation. Therefore, the lowest temperature was lower in the PCM room than the reference room.

3.3.2 The influence of weather and air condition in summer

In summer, the influence of solar irradiation is different from the winter. According to the National Oceanic and Atmospheric Administration database, 56% of the average ambient temperature is higher than 26 °C. As a result, the test rooms could receive heat from solar radiation as well as the environment heat, which causes that the energy efficiency doesn't decrease linearly with clearness index k . It is proven by the simulation and experiment that the energy saving is not

obviously relevant to the weather condition and the efficiency varies between 13–24% under different weathers. The temperature record of a cloudy day is shown in Fig. 9(a). The PCM board absorbed the heat from weak solar radiation and the environment to regulate the change in room temperature, during which the air conditioner in the PCM room worked less than the REF room. Furthermore, the simulation and experiment results of the effect of air conditions on energy-saving performance in summer are present in Fig. 9(b), which is similar to the effect of the weather condition. The numerical model is proven to be valid since the experiment result is consistent with the simulation. The efficiency varies in a small range under different AQI. In summer, the air conditioner needs to work all day for the high average temperature, and the latent heat buffering has been effective in the meantime. Therefore, the energy-saving effect is also kept at a similar level.

Fig. 9 (a) The room temperature record of a rainy day in May. (b) The calculated energy saving ratio of the PCM room under different air conditions in summer.

4. Conclusions

In this study, the PCM board was fabricated and paved as the floor in a real-scale office to reduce energy consumption for temperature regulation. The energy-saving performance of the PCM board was evaluated by both practical application and numerical simulation. In the experiment, the PCM floor effectively reduced the energy demand while maintaining indoor comfort in both summer and winter according to the recorded room temperature profiles. 18.8% and 19.7% of electricity consumption are reduced respectively in the two seasons. Long term investigation was carried out in the

numerical model, which indicates that the PCM board is less effective in the hottest and coldest days. Furthermore, the results reveal that the intensity of solar radiation which could be affected by the weather condition and the air quality has a stronger effect on energy-saving efficiency in winter than in summer. In conclusion, the fabricated PCM board can effectively reduce electricity demand of commercial office by latent heat storage. The stored energy can mitigate the indoor temperature fluctuation, thus shorten the working hours of the temperature control system. Our numerical simulation model is proven to be valid, which provides a convenient method to

study the performance of the PCM-based building envelope. As far as our knowledge, this is the first time that a PCM composite has been tested in real-scale commercial buildings, providing favorable evidence for the large-scale application of PCMs.

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Supporting Information

The Supporting Information is available free of charge on the Engineered Science Publisher website at DOI: [10.30919/esee8c380](https://doi.org/10.30919/esee8c380).

Additional experimental and theoretical details. Figures showing cyclic voltammograms, ex situ and operando XAS analysis, XRD and Raman analysis, binding and formation energies (PDF)

Conflict of interest

There are no conflicts to declare.

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