WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.151000

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 3 2024

pp. 531 –544

Research paper

The building application of foam concrete combined with PCM in cold regions and its energy efficiency

Huifang Wang[1]

Abstract: Building performance in cold regions greatly affects the quality of people living in the building. With the further development of the construction industry, how to improve the energy efficiency of buildings in cold regions has become one of the key issues. The study introduces paraffin phase change capsules as aggregate components on the basis of foam concrete, and then designs a matching energy efficiency analysis method to regulate the concrete parameters, and finally tests the performance of the research method and conducts an application analysis. The experimental results show that in performance simulation testing, the internal surface temperature decreases to 288.2 K at the minimum when the external temperature is 0°C to 4°C. It shows that the research method can effectively analyze the building performance, and the analysis method can optimize the performance of the foam concrete materials proposed in the research, and obtain building materials with better thermal insulation performance than the existing conventional materials. Research can provide certain technical references for building energy conservation in cold regions.

Keywords: cold regions, foam concrete, paraffin phase change capsule, energy efficiency, heat transfer model

[1]MsC., Department of Architecture Engineering, Yangzhou Polytechnic Institute, Yangzhou, 225127, China, e-mail: wanghuifang8203@163.com, ORCID: 0009-0001-6699-7443

1. Introduction

With global energy constraints and the growing importance of environmental protection, the need for energy efficiency and sustainability in the building industry is becoming increasingly urgent. In cold regions, the insulation performance of buildings is crucial and has a significant impact on indoor comfort and energy consumption [1,2]. The commonly used thermal insulation materials for buildings in cold regions around the world mainly include traditional polystyrene board, polyurethane foam board, etc. These materials can provide insulation to a certain extent, but due to their high density and high thermal conductivity, they are difficult to meet the needs of modern buildings for lightweight and efficient energy consumption [3]. Current methods to improve the energy efficiency of buildings include smart appliance systems, efficient heating and ventilation design, etc. Most of these methods focus on the building after completion [4]. Foam concrete is a kind of lightweight porous material made of cement, foaming agent and water. Its unique microstructure gives foam concrete good thermal insulation performance, lightweight and high compressive strength. In cold regions, the application of foam concrete can effectively reduce the heat loss of buildings, reduce the energy consumption of heating systems, and achieve the goal of energy conservation and emission reduction. However, the current common foam concrete may form a thermal bridge in the construction process, affecting the insulation effect, and may also have structural stability problems. Foam concrete combined with Phase Change Material (PCM) as a new structural material, combines the lightness of foam concrete and the thermal energy storage property of phase change material, which can improve the thermal energy storage control [5]. Conducting energy-saving analysis can obtain the thermal insulation and energy-saving performance of materials, and then adjust material parameters to optimize performance [6]. Under this background, the research innovatively designed a building material based on foam concrete combined with PCM in cold regions, redesigned the energy saving analysis method of the material, and targeted optimization of the material with performance analysis. In order to provide more technical references for energy-saving design of buildings in cold regions through innovative building materials.

This research consists of four parts:

– the first part discusses and summarizes the current research results and applications related to building materials and foam concrete in cold regions,
– the second part focuses on the design of foam concrete combined with PCM materials and the supporting energy efficiency analysis methods
– the third part is a test and application analysis of the performance of the research methods,
– the last part is a summary and discussion of the whole paper.

2. Related works

Currently, the research methods for material strength in the construction industry are relatively mature, so it is necessary to design appropriate energy-saving analysis methods to select and study materials. Some scholars have conducted research on building materials or energy efficiency analysis methods for cold regions, and Zhang et al. have proposed a wall construction material using wood-plastic composite for the insulation of buildings in cold regions. The process will be one-structured wood walls for single and double frame construction. According to the findings, the method has good efficiency and can maintain the temperature of the building in cold regions [7]. Khan et al. proposed a method for concrete construction using phase change materials for the problem of the influence of building walls on energy efficiency. The outcomes of the trial indicate that it has strong energy efficiency [8]. Esbati et al. suggested a building way for the problem of energy efficiency of buildings in cold regions. The process applies the energy storage material in the building facade. The outcomes of the trial indicate that it built a building with good insulation capacity [9]. Xue et al. proposed an energy simulation model for the problem of controlling energy efficiency of buildings in low-temperature areas. The process is tested with the energy exchange of the building using the simulation multi-objective method. The outcomes of the trial indicate that it is beneficial to building energy efficiency analysis [10].

There are also some scholars who have conducted research on foam concrete. Lim et al. proposed a foam concrete material mixed with eggshell waste for the green sustainability of concrete. The results showed that the proposed method has good noise reduction capability [11]. Jhatial et al. proposed a foam concrete material using ternary binder for waste disposal of concrete. This process partially replaces palm oil fuel ash and eggshell powder by adding them to cement. The study's findings revealed that it can reduce the cost of concrete, which has a good ecological effect at the same time [12]. Na et al. proposed a foam concrete material using circulating fluidized bed boiler ash and desulfurization gypsum for the heavy metal ions in concrete. The findings suggested that the elution of heavy metal ions was significantly dropped [13]. Shi et al. proposed a foam concrete material incorporating wax spheres for the pore structure strength of concrete. The process was carried out to reduce the density of concrete. The findings revealed that it has better pore strength and the material is more stable [14]. Stolz et al. proposed a porous foam concrete material for the problem of thermal conductivity of concrete. The findings revealed that it provides good control of the thermal conductivity of the material [15].

To sum up, although foam concrete materials have been used in many aspects such as building noise reduction, ecological environment protection, etc., there are few studies on the use of foam concrete to improve building insulation and energy efficiency in cold regions. In cold regions, heat loss is high. If effective insulation measures are not taken, indoor temperatures are difficult to maintain at appropriate levels, which will lead to a significant increase in energy consumption of heating systems. This not only increases energy consumption, but may also affect the comfort and health of residents. So it is necessary to use special building structures or materials for thermal insulation to improve building energy efficiency. Therefore, a cold region construction method using foam concrete is designed and a related energy efficiency analysis method is developed, to provide a feasible material selection scheme and energy efficiency analysis method for cold region construction.

3. Foam concrete combined with pcm in cold regions of building applications and energy efficiency analysis method design

Concrete performance can greatly affect the energy efficiency of a building. This section will focus on the methods used to analyze the energy efficiency of concrete materials and material parameters optimized for use in research designs.

3.1. Design of foam concrete combined with PCM for building applications in cold regions

In cold regions, the energy-saving property of buildings is influenced by the thermal insulation level. The structures that play the role of thermal insulation are walls, exterior wall coating patches, etc., of which the walls occupy the largest volume and play the most important role of thermal insulation [16]. Foam concrete uses aqueous solutions of blowing agents for foam manufacturing and is mixed with silica-containing compounds, calcium-containing compounds, etc. The pore information is associated with the throat information, which forms a large number of fine mesh cavity structures within the concrete after the concrete is completely set. The mesh cavity structure provides better sound insulation, thermal insulation, and seismic resistance of the concrete, but it leads to an increase in the possibility of concrete cracking, so aggregates and crack-resistant fibers are added to enhance the strength [17]. The study is based on concrete thermal properties for concrete selection and thermal conductivity measurements of concrete using the transient planar heat source method, which uses a detection sensor equipped with a metal probe. The temperature change at the point on the face where the thermal resistance generated by the heat-sensing resistive wire on the metal probe is shown in Eq. (3.1) [18].

$$\Delta v(y,z,\tau) = \frac{1}{4\pi^{3/2}aK} \times \int_0^{\tau} \frac{d\sigma}{\sigma^2} \int_A dy'\,dz' Q\left(y'z't - \frac{\sigma^2 a^2}{\sigma^2}\right) \exp\left(\frac{-(y-y')^2-(z-z')^2}{4\sigma^2 a^2}\right) \tag{3.1}$$

In Eq. (3.1), Q represents for thermal resistance generated by hot wires on metal probes; $y-z$ represents the surface where the thermal resistance is located; t represents the measurement elapsed time; τ represents the dimensionless characteristic time; k represents the thermal diffusivity; σ is the integration variable; a represents the heat exchange radius of the annular heat source set. The average temperature change on the metal probe is shown in Eq. (3.2).

$$\Delta v(\tau) = \frac{P_0}{\pi^{3/2}aN} D(\tau) \tag{3.2}$$

In Eq. 3.2, $\Delta v(\tau)$ represents the average temperature change on the metal probe; P_0 is the probe's thermal power; $N$is the material's thermal conductivity; $D(\tau)$ represents the average length of the hot wire. Eq. (3.3) displays the relationship in metal probe and temperature rise.

$$R = R_0[1 + \alpha \Delta v(t)] \tag{3.3}$$

In Eq. (3.3), R represents the resistance value; R_0 represents the initial resistance value; α represents the temperature coefficient of resistance; and $\Delta v(t)$ stands for the average temperature rise of the probe surface. The poor thermal inertness of ordinary foam concrete leads to large fluctuations in the thermal environment in buildings constructed using ordinary foam concrete [19]. A study was conducted to add paraffin phase change capsules as aggregate components to foam concrete and mix it with other components to make foam concrete combined with PCM. In masonry wall buildings in cold regions, the insulation is generally attached to the exterior wall structure, and the study designed 100 mm thick concrete plus 200 mm thick blocks as the base reference structure, see Fig. 1.

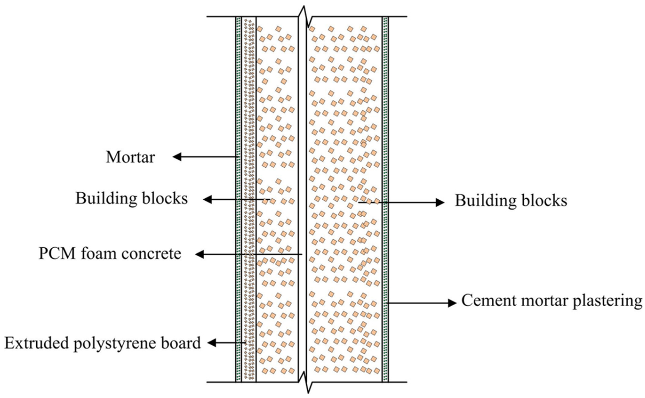

Fig. 1. Wall structure (Author's self drawing)

In Fig. 1, the impacts on the structure performance of mortar leveling is relatively small. The waterproof coating is omitted, and foam concrete combined with PCM is placed in the middle of two layers of blocks, forming a hierarchical structure of mortar-extruded polystyrene panel-block-foam concrete combined with PCM layer-block-cement mortar plaster, which is a sandwich insulation method. The thickness of mortar, cement mortar plaster and foam concrete combined with PCM is 10 mm, the thickness of extruded polystyrene board is 20 mm, and the thickness of both layers of blocks is 100 mm. the designed wall model size is 400 mm high and 240 mm thick.

3.2. Design of energy-saving analysis method of foam concrete combined with PCM

After the preliminary design of the building is completed, the relevant properties of the building need to be analyzed and then the relevant parameters of the design are optimized. The properties involved in concrete in walls are mainly physical compressive strength (CS) and energy efficiency [20, 21]. The physical CS can be analyzed using common regression analysis methods, while the energy efficiency can be analyzed with different structures for different materials [22, 23]. To simplify the calculation process, the heat transfer process is treated as a two-dimensional unsteady heat transfer, with the mortar layer, the block layer and the foam concrete combined with PCM layer all considered as a medium with uniform density. A stable phase change layer is set to represent foam concrete combined with PCM, and the two-dimensional unsteady state Eq. is shown in Eq. (3.4) [24].

$$\rho_w \frac{\partial T_w}{\partial t} = \lambda_w \left(\frac{\partial^2 T_w}{\partial x^2} + \frac{\partial^2 T_w}{\partial y^2} \right) \tag{3.4}$$

In Eq. (3.4), ρw represents the material density; T_w represents the specific enthalpy of foam concrete combined with PCM. Then the enthalpy of phase change layer is calculated as shown in Eq. (3.5).

$$H = h_{ref} + \int_{T_{ref}}^{T} C_p dT + \beta L_p \tag{3.5}$$

In Eq. (3.5), H indicates the enthalpy of phase change layer; T indicates the temperature; C_p indicates the specific heat (SH) of foam concrete combined with PCM; L_p is the latent heat of foam concrete combined with PCM; andβ represents the partial liquid fraction. The equivalent SH capacity of the phase change layer is calculated using the mass-weighted average method, as shown in Eq. (3.6).

$$C_{sp} = E(mC_p + (1-m)C_h) + (1-E)C_s \tag{3.6}$$

In Eq. (3.6), E represents the volume fraction of paraffin phase change capsule; m is volume fraction of PCM; C_p is the SH of PCM; C_h represents the SH of HDPE; C_s represents the SH of foam concrete. The Maxwell Eucken was introduced to calculate the equivalent thermal conductivity of the wall composed of foam concrete combined with PCM as shown in Eq. (3.7).

$$\lambda_{sp} = \frac{2\lambda_s + \lambda_p + 2E(\lambda_p - \lambda_s)}{2\lambda_s + \lambda_{pm} + 2e(\lambda_p - \lambda_s)} * \lambda_s \tag{3.7}$$

In Eq. (3.7), λ_{sp} represents the equivalent thermal conductivity of the wall; λ_s represents the thermal conductivity of the foam concrete; λ_p represents the thermal conductivity of the PCM. Walls in the natural environment generally have two ways of receiving sunlight: directly and by receiving reflections from other objects. The received sunlight passes through places with transparency or cavities after being somewhat attenuated, and is partially absorbed and partially reflected in places where it cannot pass through. Sunlight is absorbed by the surface of the wall and causes an increase in the temperature of the wall surface. Formula (3.8) represents the outer surface boundary condition of the wall.

$$\varphi_e = h_e(T_e - T_w(x=0, y, t) + vq_s(t)), \qquad y \in [0, H] \tag{3.8}$$

In Eq. (3.8), v represents the solar absorption wall coefficient; h_e represents the external convective heat transfer coefficient. Eq. (3.7) is the boundary condition of convection on the external surface.

(3.9) $$\varphi_i = h_i(T_i - T_w(x = L, y, t) + vq_s(t)), \qquad \nabla y \in [0, H]$$

In Eq. (3.9), h_i represents the heat transfer coefficient of horizontal heat flow convection. The heat exchange process inside and outside the wall is shown in Fig. 2.

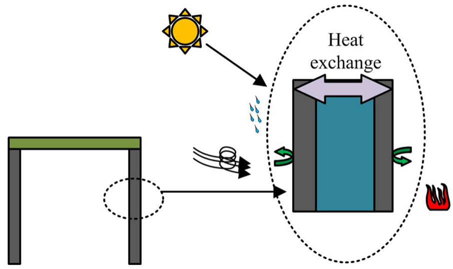

Fig. 2. Heat exchange inside and outside the wall (Author's self drawing)

In Fig. 2, the temperature influencing factors on the exterior of the wall are outdoor air temperature, solar radiation, wind speed, and rainfall, etc. The temperature influencing factors on the interior of the wall are indoor air temperature and indoor heat source. Among them, the biggest and most lasting influence on the temperature of the outer surface of the wall is solar radiation. The heat of the wall propagates towards each other in opposite directions to reach equilibrium. Because the sun changes with the season, the time of day, and the relative position of the building, causing the amount of radiation produced by the sun at different times to different directions of the wall will also change, and the change in radiation causes the outer surface's temperature to change accordingly. The heat gain per unit area of the wall is shown in Eq. (3.10).

(3.10) $$tem = tem_{\text{air}} + \frac{\partial l}{\partial_{\text{out}}} - \frac{q}{\partial_{\text{out}}}$$

In Eq. (3.10), q represents the long-wave radiation heat exchange in the external surface and the environment; tem_{air} represents the outdoor air temperature; ∂_{out} represents the convective heat exchange coefficient of the external surface, which is taken as 0.65. The phase change temperature of PCM determines the heat storage process, and the performance calculation sequence is performed for the building energy efficiency and peak flow rate, as shown in Eq. (3.11).

(3.11) $$\begin{cases} f = \frac{KN - KP}{KN} * 100\% \\ E_e = \int_0^t q(t)\, dt \end{cases}$$

In Eq. (3.11), f represents the building energy efficiency; $Q_{\max}$ represents the peak heat flow; KN represents the original energy consumption; KP represents the present energy consumption; and $q(t)$ represents the heat flow through the wall per unit time. The enthalpy-temperature function is generated using an implicit finite difference format for the energy change, as illustrated in Eq. (3.12).

(3.12)
$$C p\rho\Delta x\frac{T_i^{j+1}-T_i^j}{\Delta t}=1/2\left(kw\frac{T_{i+1}^{j+1}-T_{i+1}^{j+1}}{\Delta x}+ke\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x}+ke\frac{T_{i+1}^{j}-T_i^{j}}{\Delta x}+ke\frac{T_{i-1}^{j}-T_i^{j}}{\Delta x}\right)$$

In Eq. (3.14), Δx represents the finite difference layer thickness; kw andke represent the thermal conductivity between the nodes and the front and back nodes. The enthalpy of phase change material is calculated in Eq. (3.13).

$$H_i = HTF(T_i) \tag{3.13}$$

In Eq. (3.13), H_i represents the enthalpy of the node; HTF is the enthalpy-temperature function. The algorithm contains an iterative step, and the iteration will update the node enthalpy, and the SH needs to be updated continuously, and the SH update is shown in Eq. (3.14).

$$C_p = \frac{h_{i,\text{new}} - h_{i,\text{old}}}{T_{i,\text{new}} - T_{i,\text{old}}} \tag{3.14}$$

In Eq. (3.14), $h_{i,\text{new}}$ and $h_{i,\text{old}}$ represent the enthalpy of the nodes before and after the update. The energy efficiency analysis is used to optimize the ratio of foam concrete combined with PCM to complete the final design of the building.

4. Foam concrete combined with pcm building performance test and application analysis in cold regions

The material properties of concrete are important parameters for energy efficiency in buildings in cold regions. This section will test the performance of the research design method from four aspects: changes in compressive strength, changes in internal surface temperature of the wall, changes in liquid to liquid ratio of the wall at different phase transition temperatures, and internal surface heat flux and delay of the wall at different volume fractions of additives. And analyze the effectiveness of the research method in practical application, in order to determine the effectiveness of the research method.

4.1. Building performance testing of foam concrete combined with PCM in cold regions

Cold regions refer to areas where the average temperature of the coldest months over the years is between 0°C and –10°C. Building materials in cold regions not only require sufficient strength, but also certain insulation and energy-saving performance. In order to verify the effectiveness of foam concrete combined with PCM for use in buildings in cold regions, the study began with a simulation of the building performance of foam concrete combined with PCM in cold regions. The study was carried out using a thermal constant analyzer model Keysight_34972A. 50,000 grids were selected for the simulation, and the skewness was kept below 0.95 with an aspect ratio not exceeding 1:35. The temperature variation of the inner surface of the wall constructed by the study method under cold conditions was tested and is shown in Fig. 3.

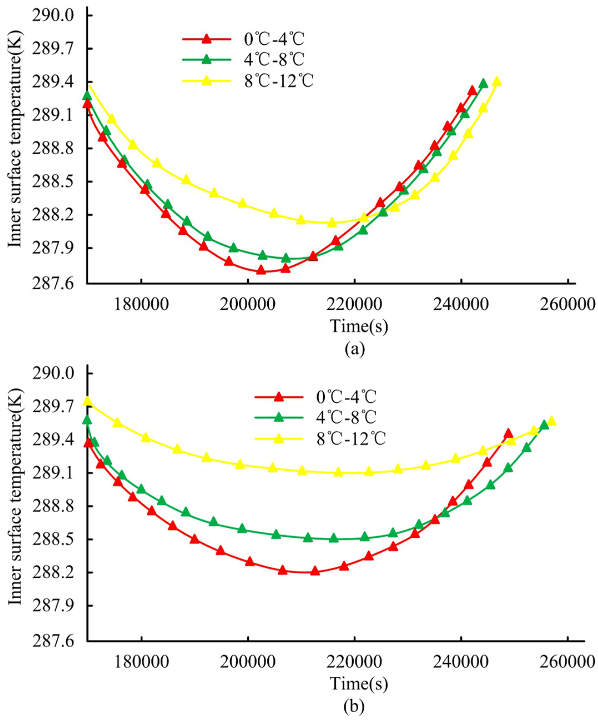

Fig. 3. Temperature changes on the inner surface of the wall (Author's self drawing); (a) Wax ball foam concrete, (b) Foam concrete combined with PCM

As seen in Fig. 3, the minimum internal surface temperature of foam concrete combined with PCM decreases to 287.7 K when the external temperature is 0°C to 4°C, and 288.1 K when the external temperature is 8°C to 12°C. The minimum internal surface temperature of foam concrete combined with PCM decreases to 288.1 K when the external temperature is 0°C to 4°C. This indicates that the wall constructed by the research method has better thermal insulation performance and the internal surface temperature is less affected by the external surface temperature. The variation of the liquid rate ratio of the wall constructed by the research method at different phase change temperatures was tested as shown in Fig. 4.

In Fig. 4, the liquid rate ratio of wax spherical foam concrete first decreases and then increases, reaching a minimum of about 0.6 and a maximum of 1 at the phase change temperature of 0°C to 4°C. PCM The liquid rate ratio of foam concrete combined with PCM decreased slightly and then increased slightly, reaching a minimum of about 0.8 and a maximum of 1 at the phase transition temperature of 0°C to 4°C, a minimum of about 0.4 and a maximum of about 0.6 at the phase transition temperature of 4°C to 8°C, and a minimum of 0 and a maximum of about 0.3 at the phase transition temperature of 8°C to 12°C. This indicates that the research method has higher material stability and less morphological changes occur. The heat flux and delay on the inner surface of the walls constructed by the study method at different volume fractions of the additive were tested as shown in Fig. 5.

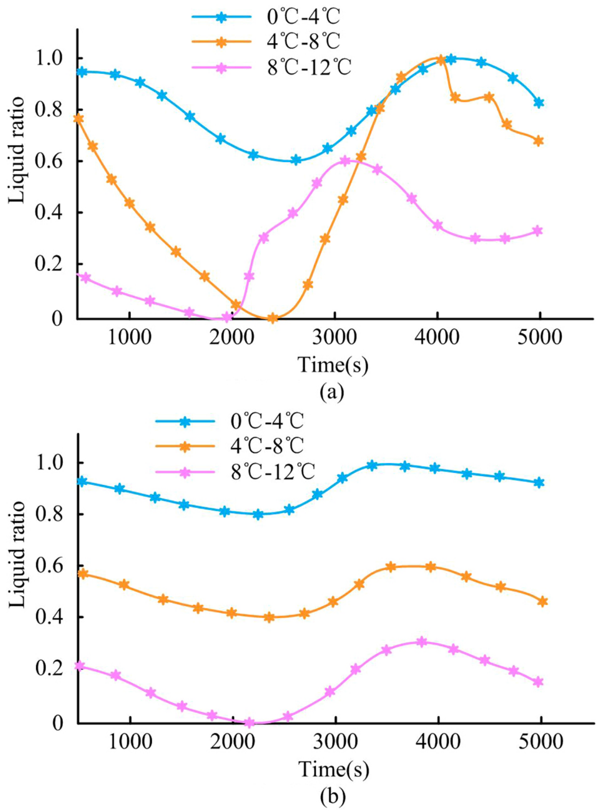

Fig. 4. Change in liquid to liquid ratio (Author's self drawing); (a) Wax ball foam concrete, (b) Foam concrete combined with PCM

As seen in Fig. 5, the peak internal surface heat fluxes of both wax sphere foam concrete and foam concrete combined with PCM increase with increasing volume fraction. The peak internal surface heat flux of wax sphere foam concrete at 5% volume fraction reaches about 31 W/m^2 with a delay time of about 6 s. The peak internal surface heat flux of foam concrete combined with PCM at 5% volume fraction is about 26 W/m^2 with a delay time of about 4.5 s; the peak internal surface heat flux at 100% volume The peak internal surface heat flow at 100% volume fraction reaches about 32 W/m^2 with a delay time of about 7 s. This indicates that the studied method has better heat flow control capability.

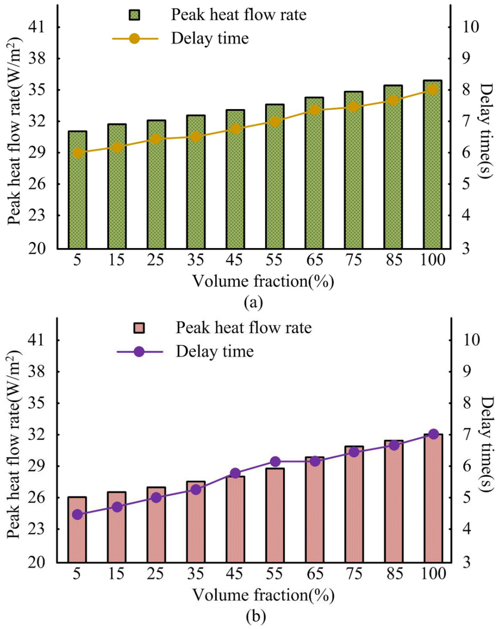

Fig. 5. Internal surface heat flow rate and delay (Author's self drawing); (a) Wax ball foam concrete, (b) Foam concrete combined with PCM

4.2. Analysis of foam concrete combined with PCM in cold regions for building applications

The effect of the application of the research method in cold regions was tested, and the average temperature of the selected areas was about 18 degrees Celsius in summer and −15 degrees Celsius in winter. Use the materials used in the buildings in the Entrepreneurship City community of Daqing City, Heilongjiang Province, China as the application materials, and refer to the selected building material parameters for the building material parameters. The density of using cement mortar is 1500 kg/m^3, and the thermal conductivity is 0.93 W/(m·k). The density of using extruded polystyrene board is 1050 kg/m^3, and the thermal conductivity is 0.042 W/(m·k). The density of using concrete blocks is 1700 kg/m^3, and the thermal conductivity is 0.93 W/(m·k). The density of using gypsum board is 1050 kg/m^3, and the thermal conductivity is 0.33 W/(m·k). The density of using concrete is 1700 kg/m^3, and the thermal conductivity is 0.93 W/(m·k). The density of using an air layer is 2700 kg/m^3, and the thermal conductivity is 0.76 W/(m·k). The density of using fine aggregate concrete is 2100 kg/m^3, and the thermal conductivity is 1.28 W/(m·k). The energy consumption (EC) of a building built using the study method is tested throughout the year, as shown in Fig. 6.

As seen in Fig. 6, the EC of buildings using plain concrete and foam concrete combined with PCM reaches its highest value in winter and approaches its lowest value in May and September. The EC with plain concrete reaches the highest value of about 1010 kW·h in January, the lowest

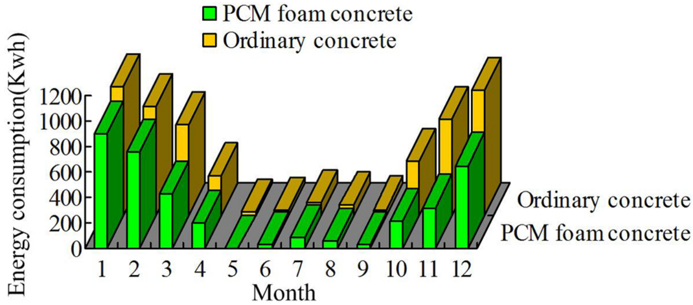

Fig. 6. Annual energy consumption test (Author's self drawing)

value of about 35 kW·h in May, and the increase of about 105 kW·h in summer. The EC with foam concrete combined with PCM reaches the highest value of about 900 kW·h in January, the lowest value of about 10 kW·h in May, and the increase of about 85 kW·h in summer. The research method can be effectively applied in cold regions and has good energy efficiency.

5. Conclusions

The thermal insulation performance of concrete is an important factor for energy saving in buildings in cold regions. In the study, paraffin phase change capsules were added into foam concrete aggregate to make foam concrete combined with PCM, and the wall foundation reference structure was designed, after which a two-dimensional non-stationary Eq. was constructed to build a concrete heat transfer model, the thermal conductivity was calculated by Maxwell Eucken model, the building plan was reconstructed by means of unit modules, and the concrete parameters were optimized by energy efficiency analysis. According to the fingdings, the lowest value of the internal surface temperature of the research method is 288.1 K in the interval of 0°C to 12°C for the external temperature; the liquid rate ratio of the research method is in the interval of 0–0.3 at the phase change temperature of 8°C to 12°C, and the fluctuation is significantly smaller than that of In the volume fraction of 5%, the peak internal surface heat flow of the research method is only about 26 W/m^2 with a delay of about 4.5 s; when conducting practical application tests, the research method reaches the lowest EC in May, about 10 kW·h, and the peak power consumption in summer is only 85 kW·h. It indicates that the research method can effectively improve the energy efficiency of the building in cold regions and ensure the CS of the wall. The current research only proves that the research method has good application effects in normal cold weather, but if extreme weather such as temperature drops, freezing rain, and blizzards occur, the research method cannot guarantee better performance. Subsequent research will focus on experiments and optimization for extreme weather. The research may arouse the interest of architectural engineers and experts and scholars in related fields.

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Received: 2023-10-09, Revised: 2024-02-06