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THE PREPARATION AND PERFORMANCE OF A COMPOSITE FOAMED CEMENT INSULATION MATERIAL IN BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) CONSTRUCTION

JUNJIE LIU

School of Architecture and Information Engineering, Shandong Vocational College of Industry, Zibo 256414, China

#E-mail: liumengqy_123456@163.com

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Energy conservation and emission reductions are becoming increasingly important in the construction industry due to the economy's rapid growth and the acute energy scarcity situation. Phase change composite foamed cement materials were researched and manufactured to address the performance of thermal insulation materials in the integrated construction of building photovoltaic systems. The results show that the phase change material mainly exists in the free form between the pores of the foamed cement, and a small part of it is adsorbed on the surface of the foamed cement. As the mass fraction of phase change materials increases, the thermal conductivity of foamed cement materials gradually decreases, from 0.0708 W·(m-K)$^{-1}$ to 0.0534 W·(m-K)$^{-1}$. The higher the density and quantity of the phase change material added to the foamed cement, the higher the foamed cement's thermal conductivity. The interior surface temperature of the roof increased by 1.6 °C at night and decreased by 2 °C during the day thanks to the phase-change composite foamed cement roofing. The direction of the heat flow on the inner surface of the ordinary roof and phase-change composite foamed cement roof is basically the opposite. The phase-change composite foamed cement roof absorbs heat during the day and emits heat at night, and it reduces the heat gain better, with an average heat gain reduction of 48.5 % and 59.9 %, respectively.

INTRODUCTION

With the world's energy constraints, clean energy and sustainable development are receiving more and more attention, and the building sector is also facing the need for energy emission and saving reduction and energy transformation. The Building Integrated Photovoltaic (BIPV) initiative is a significant endeavour aimed at achieving energy conservation and emission reduction in the building field. It involves applying photovoltaic (PV) power generation technology to a building's facade, roof, or other space, and integrating solar photovoltaic panels into the building's design to realise the building's power generation and energy conservation functions [1]. The process of assessing a building's energy consumption (EC) characteristics involves analysing and evaluating the building's energy utilisation as well as its EC structure, energy utilisation efficiency, and other factors. Based on these findings, recommendations for energy-saving (ES) improvements are made, which can help identify the building's EC status and any current issues with it. Additionally, the recommendations can support the selection of suitable photovoltaic integration solutions and equipment with data [2-3]. The development of BIPV, which can integrate the functions of PV power generation and building insulation to improve the energy utilisation efficiency and sustainability of buildings, is positively impacted by the selection and preparation of insulation materials in addition to the assessment of a building's EC. A combination of cement, sand, a foaming agent, and additional chemicals is used to make foamed cement (FC), a porous and lightweight building material. It produces a material with a specific strength and lightweight structure after foaming and curing, and because of its low density, excellent thermal insulation qualities, and adaptability, it is widely employed in the building industry [4-5]. However, traditional FC has a poor heat storage capacity and a poor thermal insulation effect on buildings. In this context, the study prepared phase change (PC) composite FC materials and analyse their thermal properties. This study's novelty is to combine phase-change materials with high thermal conductivity (TC) to increase the thermal insulation performance of conventional FC. The main structure of the study is divided into four parts, the first part analyses the current status of related research; the second part prepares the PC composite FC; the third part analyses the thermal properties of the prepared PC composite FC; and the last part summarises the whole study.

Related works

A novel approach to solar power generation is called BIPV, which entails installing solar photovoltaic (PV) arrays on a building's exterior envelope in order to generate electricity. Sun et al. tackled the problem of BIPV deployment in crowded urban areas by putting out a thorough mapping tool to look into the viability of adopting BIPV and adding a quantitative visual effect evaluation to the conventional energy yield projection. The findings demonstrate that the suggested strategy can facilitate the widespread adoption of BIPV and optimise its deployment in high-density urban settings [6]. Taşer et al. stated that BIPV is a key technology for achieving the ES design of buildings. They undertook research on the implementation of integrated photovoltaics in buildings and provided an up-to-date review of the recent developments in order to address the challenges of the overall performance of BIPV systems. The results showed that a building integrated PV system can help to mitigate future environmental issues [7]. Abdalgadir et al. suggested integrating the BIPV with the Heating, Ventilation and Air Conditioning (HVAC) system and performing a simulation analysis using Matlab Simulink to address the problem of how to lower the energy needed to heat the BIPV in the winter and prevent excessive PV cell temperatures in the summer. The findings demonstrate the effectiveness and viability of using exhaust cooling to lower PV cell temperatures [8]. In order to address the issue of operational checking of the BIPV system, Sarkar et al. introduced various forms of diode modelling and its comparative analysis of the BIPV system based on the Lambert W-function in the MATLAB/Simulink environment. They then compared it in terms of accuracy and unknown parameter extraction comparing existing diode models [9]. Özkalay et al. analysed the operating temperature and diurnal temperature variations of modules in BIPV installation configurations in response to the problem of limited or reduced building skin integration and rear-side ventilation, which leads to higher operating temperatures of BIPV modules and systems and affects their long-term performance and reliability. The results showed that BIPV modules in southern Switzerland need to be tested for indoor quality and safety under harsher environmental conditions [10]. Using building information modelling, Quintana et al. proposed an integrated simulation framework for a building design and energy performance analysis for building clusters of BIPV systems, addressing the problem that most studies do not sufficiently consider the comprehensive techno-economic evaluation of BIPV systems [11].

Composite thermal insulation material is a comprehensive thermal insulation material made of a combination of several different thermal insulation materials, usually made of multiple layers of different types of thermal insulation materials combined according to a certain process and structure to achieve better thermal insulation. Graded microstructure flexible lightweight thermal insulation materials are widely employed in thermal management and protection systems, according to An et al. Moreover, in response to the problem of lack of mechanical ruggedness in ceramic aerogels, a lightweight flexible graded superhydrophobic ceramic nanocomposite was proposed. The results showed that the ceramic nanocomposite had better thermal insulation and robustness [12]. Adhamjon et al. discussed the application of gypsum thermal insulation composite veneer panels based on industrial waste residue in ES buildings and considered the composition and properties of the material [13]. Zhang et al. addressed current wood-plastic buildings with poor thermal insulation performance, designed two kinds of wood-plastic composite structural wood walls and investigated their thermal insulation performance. The findings revealed that the wood-plastic composite wall with a frame-shear structure has good stability and the excellent performance of wood-plastic composites [14]. Khamidov et al. discussed the application of gypsum insulation composite veneer panels made from industrial slag in ES buildings and considered the composition and properties of these materials, which can aid in lowering the building project's cost, and to achieve the ES and environmental protection purpose [15]. In response to the limited mechanical strength of carbon aerogels, Li et al. reported a high-pressure aided polymerisation process for the fabrication of crack-free carbon/carbon composites consisting of low carbon crystallinity fibre reinforcement and an aerogel-like carbon matrix. The results showed that the composites have high compressive strength and thermal insulation properties, which can be helpful for aerospace vehicles [16]. The thermal insulation qualities of blended panels made of agave and straw with varying compositions and densities, as well as loose agave or straw fibres, were investigated by Ali et al. The outcomes demonstrated that the blended specimens' flexural stress and flexural modulus had increased, supporting the use of sustainable and eco-friendly building materials [17].

In conclusion, despite the limited investigations on the TC of building insulation materials, extensive studies conducted by numerous earlier researchers on BIPV and composite thermal insulation materials has significant practical implications. This highlights the importance and relevance of further study on the creation and functionality of composite FC insulating materials, which could potentially revolutionise the field of building construction.

EXPERIMENTAL

Preparation of the phase change composite foamed cement insulation material

Research on the thermal insulation performance of materials at the building material level is essential to advancing the energy utilisation efficiency of BIPVs and improving the thermal insulation performance of structures. Therefore, in this study, PC composite FC insulation materials will be prepared by introducing high TC PC materials based on traditional FC.

Preparation of materials and programmes

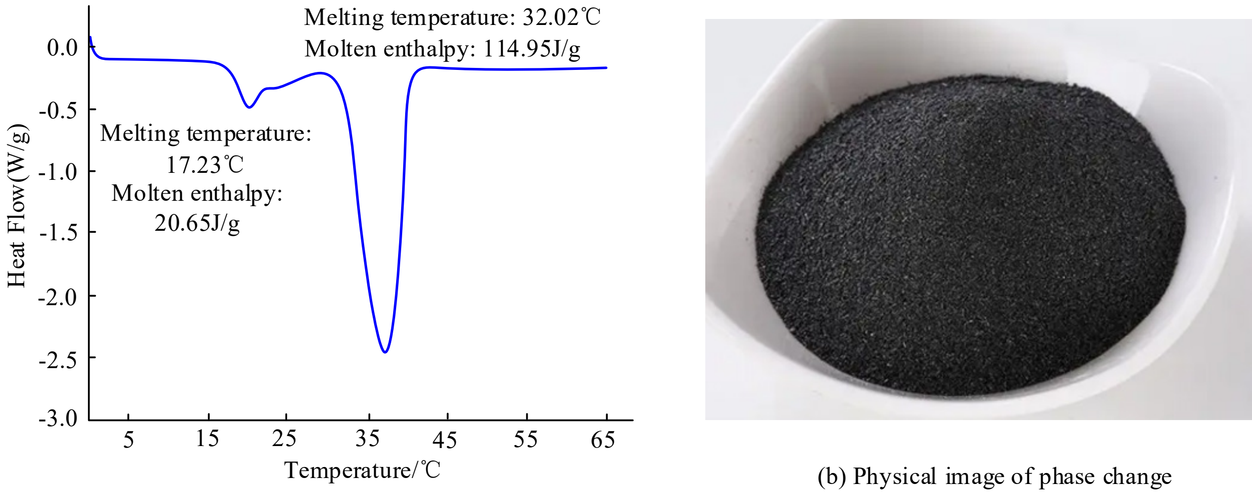
FC is a kind of lightweight porous material that forms a porous material with relatively low density by adding a foaming agent to cement to generate a large number of air bubbles in concrete. FC has become a key research direction because of its advantages in terms of thermal insulation, fire resistance, water resistance, good frost resistance and ES, environmental protection, etc. However, the FC's potential to store heat is significantly reduced due to the volume of air inside it. PC materials have a strong heat storage capacity and approximate the isothermal PC process, which can be applied to the building envelope to improve the heat storage capacity of the envelope [18]. For this reason, in this study, PC materials are added into FC in order to produce composite FC insulation materials with a low TC and high thermal storage capacity. Cementitious material is the main material for the preparation of FC, and its properties, such as the density and compressive strength, will directly affect the comprehensive engineering performance of composite thermal insulation materials. Ordinary silicate cement has a faster setting and hardening speed, good frost resistance, high strength and low price, is widely distributed and easily available, which is more suitable for the production of foam concrete [19]. Therefore, in this study, considering all aspects of the performance of cementitious materials, the final choice of ordinary silicate cement with specifications of P.O42.5 and a density of 3.1×10^3 kg·m^3 was chosen. Based on how bubbles are introduced, FC can be classified into two categories: physical foaming method and chemical foaming method. In this study, the chemical foaming method, which is a more stable foaming method, is used. The chemical foaming method requires the introduction of additives such as a foaming agent, a foam stabiliser, a water reducer, a coagulant promoter and a fibre filament material to ensure the stability and efficiency of the foaming. Additionally, Table 1 displays the additives' precise specifications.

PC materials are energy storage materials that are capable of undergoing a phase transformation from one state to another at a specific temperature, accompanied by the phenomenon of heat absorption or exothermic properties. During the PC process, the PC material possesses a higher thermal energy storage capacity, while storing and releasing more thermal energy at an almost constant temperature. In this study, high TC PC materials with a particle size of 0.1 - 0.3 mm, a TC of 3 - 5 W·(m-K)$^{-1}$, and a PC temperature of 32.02 °C were used, which were produced by Hubei Saimo New Energy Technology Co. The differential scanning calorimetry (DSC) curve and the physical figure of the selected high TC PC material are shown in Figure 1.

Currently, the main foaming methods include the high-speed mixing method, the Roche method, the compressed air method, the shock method, etc. In this study, the high-speed mixing method was used to explore the foaming agent. The high-speed mixing method thoroughly mixes the raw materials. It generates bubbles through high-speed mixing and finally forms the moulding material of the FC, which has the advantages of uniform mixing and high production efficiency [20]. The high-speed mixing method includes five steps: raw material proportioning, high-speed mixing, foaming, moulding and maintenance. Firstly, 100 ml of the mother liquor of the foaming agent was prepared and placed in a 1 L measuring cup, and then stirred at high speed with a mixer at more than 1000 r·min^{-1}. The foaming agent was gradually added and mixed to produce more bubbles until the volume no longer changed. The stirred material was poured into the mould for moulding. Finally, the moulded material was fully cured to ensure that it reached the design strength and stability. In this study, the used FC preparation process is categorised into bubble making, slurry making, mixing, pouring and maintenance. Various experimental tools and equipment are needed to prepare PC composite FC materials.

Table 1. Detailed parameter table for the additives.

Additive name	Main chemical components	Specifications	Manufacturer
Foaming agent	Hydrogen peroxide	-	Beijing Kaili Tianwei Science and Trade Co., Ltd
Foam stabiliser	Calcium Stearate	Screening rate ≥ 99	Hebei Billion Union Chemical Co.
Water reducing agent	Naphthalene	Water reduction rate ≥ 45	Shandong Yousuo Chemical Technology Co.
Coagulant	Lithium	Product content ≥ 98	Sichuan Borui New Materials Technology Co.
Fibre silk material	Polypropylene	-	Hebei Jianfang Energy saving Chemical Building Materials Co.



(a) DSC curve

(b) Physical image of phase change materials

Figure 1. DSC curves and physical images of the phase change materials.

Table 2. Experimental equipment and instrument specifications.

Instrument name	Instrument model	Manufacturer
Electronic scale	FA1204B	Shanghai Youke Instrument and Meter Co., Ltd
Hand mixer	MS1900	Hangzhou Yitian Tool Manufacturing Co.
Thermal conductivity tester	DRE-III	Xiangtan Xiangyi Instrument Co., Ltd
Electric constant temperature drying oven	DHG-9070A	Shanghai Shenxian Constant Temperature Equipment Factory
Wooden moulds	200 × 200 × 20 mm	-

The equipment and instruments required for the preparation of the specific experimental materials and their specifications and models are shown in Table 2.

Phase change composite foamed cement material preparation

PC composite FC materials were prepared based on the relevant provisions of the Technical Regulations for Bubble Mixed Lightweight Soil Filling Engineering. The preparation process of the PC composite FC material is mainly divided into two parts: Firstly, the cement, foam stabiliser, water reducing agent, coagulant promoter and PC material were added to a certain amount of water according to a certain proportion and mixed well to prepare cement mixed specimen. Then, the foaming agent and distilled water were mixed homogeneously according to a certain proportion to prepare the foaming agent mixture. The specific flow of the PC composite FC material preparation is shown in Figure 2.

First, a quantitative amount of cement, foam stabiliser, coagulant promoter, water reducer and PC material was weighed with an electronic balance in accordance with the proportioning scheme and added to a mixing drum and mixed thoroughly to form a mixed dry material. Subsequently, an appropriate amount of foaming agent powder was weighed into a beaker and distilled water at 40 °C was added to it and stirred thoroughly to configure a foaming agent solution. A hand-held electric mixer was utilised to continuously stir the foaming agent solution at high speed for 5 minutes so that the foaming agent solution was fully foamed. Then, the prepared foam mixture was added to the mixed dry material, and an appropriate amount of distilled water was added to it with a measuring cylinder, and it was fully stirred until the slurry was evenly distributed with fine bubbles, that is, it was prepared into a phase-change composite FC mortar. Secondly, the slurry was introduced into the wooden mould in the PC composite FC mortar to add quantitative fibre silk material and make it evenly distributed. It is then covered with plastic wrap in the mould above the static level for 36 hours to prevent water evaporation. When the FC slurry was completely solidified, the mould was demoulded to obtain the PC composite FC test block. Finally, the maintenance temperature of the electric thermostatic oven was set to 20 ± 2 °C, the humidity was set to more than 95 %, and the demoulded phase-change composite FC test pieces were placed into the electric thermostatic

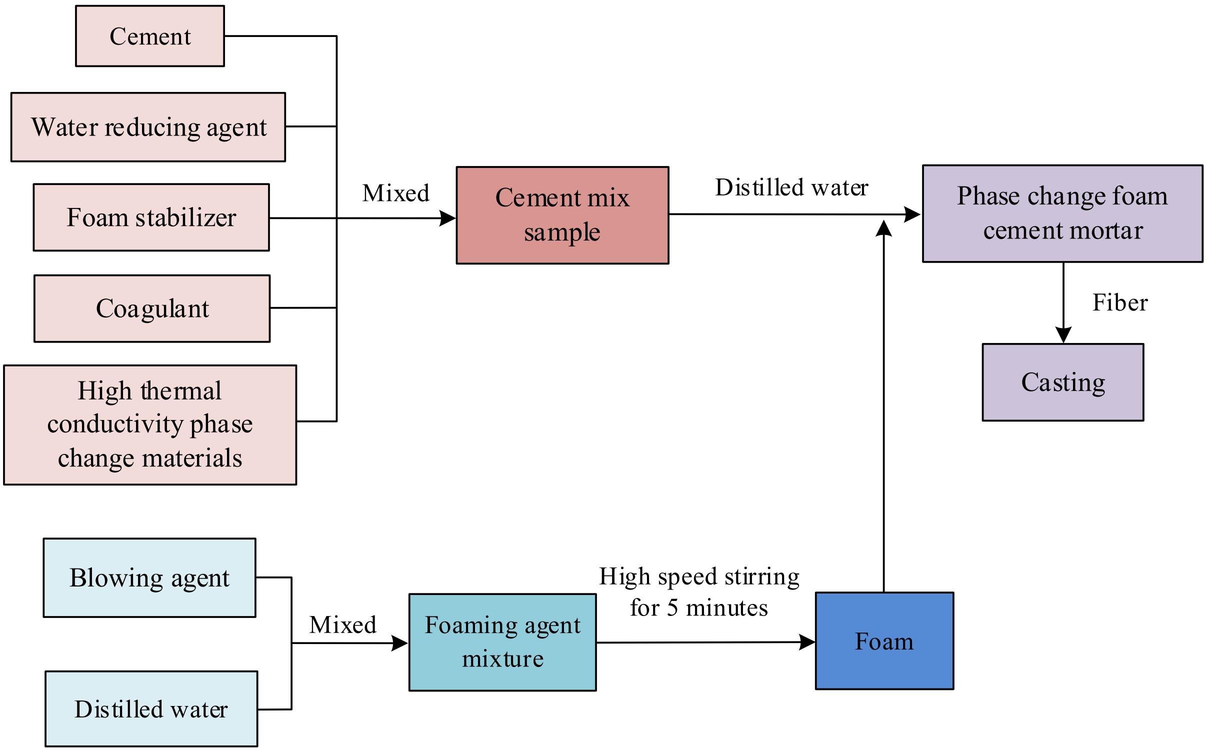


Figure 2. Preparation process diagram of phase change composite foam cement material.

oven for maintenance for 7 d. After the maintenance was finished, the phase-change composite FC test pieces were placed in a cool place for drying for 24 h. The phase-change composite FC test pieces were then placed into the wooden moulds to avoid water evaporation.

The density and internal pore structure of the FC can be directly impacted by the dosage of the foam. A reduced foam dose allows the cement paste to adequately enclose and restrict the foam, resulting in a generally reduced internal pore structure inside the FC and an increase in its density and compressive strength. Conversely, an excessive amount of foam causes the cement paste to be unable to adequately encase it, reducing the force acting on it and making it more prone to floating, rupturing, and expanding. It also causes the foam liquid film's thickness, stability, and pore structure to increase. The pore structure will expand, the stability will decrease, and the thickness of the foam liquid sheet will increase. As a result, the FC's adiabatic density and compressive strength will both decline. In this investigation, a 1:1 foam dose ratio was ultimately selected in consideration of FC's compressive qualities and adiabatic density. Furthermore, in order to investigate the impact of the cement density and the addition of the PC components on the FC's TC, this study assessed the FC's TC [21].

The FC can be regarded as a flat plate TC mode, the two sides of the surface for the flat plate and the temperature are equal everywhere, so that the two sides of the flat plate become two isothermal surfaces and there is a certain temperature difference in the FC flat plate that will produce a reverse to the temperature gradient of the descending direction of the heat flow, the calculation of the coefficient of the TC of the FC concrete is shown in Equation 1.

$$\lambda = \frac{\Delta\delta\Delta Q}{\Delta TS} \quad (1)$$

In Equation 1, $\Delta\delta$ indicates the thickness of the flat plate; ΔQ indicates the heat flow through the flat plate; ΔT indicates the temperature difference, and S indicates the area of the flat plate. The amount of PC material will have an effect on the foaming efficiency of the FC, which will change the density value of the FC. The density of the FC is calculated as shown in Equation 2.

$$\rho = \frac{m}{v} \quad (1)$$

In Equation 2, m denotes the dry mass and v denotes the volume. In summary, in this study, for the problem of poor thermal storage performance of the FC, high TC PC materials were introduced to improve the FC, and a PC composite FC was prepared to improve the thermal insulation performance of the building.

Thermal properties analysis of the phase change composite foamed cement material

In this study, a PC composite FC was developed with the goal of improving the building's thermal insulation performance; nevertheless, additional verification is required to confirm its thermal insulation efficiency. The study primarily examines two factors: first, the PC composite FC's TC is ascertained, and then, the study examines the PC composite FC's thermal performance.

Determination of the thermal conductivity of phase change composite foamed cement

To explore the influence of the PC materials on the performance of the composite thermal insulation materials and further design the proportioning scheme of the experiment, this study formulated five groups of PC composite FC preparation schemes with different mass ratios. Among them, the main matrix of the experiment is cement and high TC PC materials, so the mass of the cement is used as a fixed value, and then the appropriate amount of high TC PC materials is added according to the developed programme. In this study, the water-cement ratio of the FC base was taken as 0.45 with reference to the relevant studies, with a water reducing agent of 1.55 %, a foam stabiliser of 3.1 %, a coagulant promoter of 1.55 %, a foaming agent of 4.4 %, and a fibre yarn of 0.1 %. The specific material design proportioning scheme is shown in Table 3.

The scanning electron microscopy diagrams of the PC composite FC materials with mass fractions of 0 % and 5 % were compared in this work in order to examine the microstructure of the PC composite FC and further explore the coupling relationship between the PC material and the FC. Figure 3 displays the two samples' 45000 × electron micrographs. It is evident from Figure 3a that the FC's sheet structure is more complete without the PC material added. It is evident from Figure 3b that the fibre filaments have a strip-like structure and the PC composite FC has a lamellar structure. A tiny amount of the PC material was adsorbed on the FC's surface, but the majority of the PC materials were present in the free form in between the FC's pores. The findings demonstrate that the PC material alters the FC's pore structure, increases its density, and induces destructive fractures. It also affects the FC's continuity and integrity of the structure.

To further analyse the physical properties of the phase change composite FC insulation materials and explore the influence of the PC materials on the thermal conductivity

Table 3. Phase change composite foam cement ratio scheme.

Mass ratio (%)	Material (g)						
	Cement	Fibre	Foaming agent	Foam stabilizer	Coagulant	Water reducing agent	Phase change materials
0	500	0.5	22	15.5	7.75	7.75	0
5							25
10							50
15							75
20							100

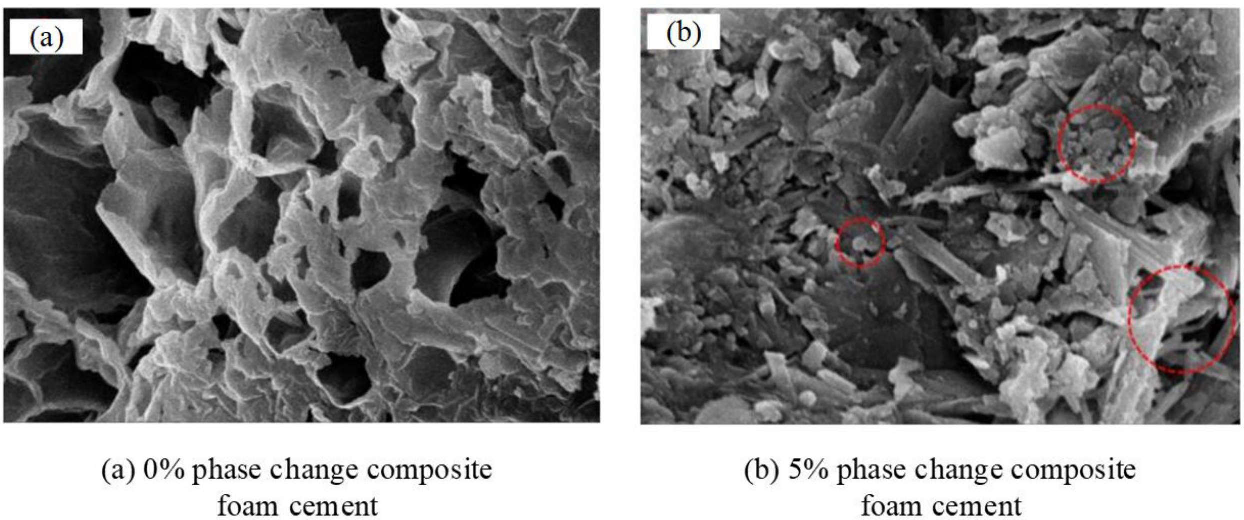


Figure 3. Scanning electron microscopy images of the phase change composite foamed cement materials.

of FC, this study measured the thermal conductivity of the PC composite FC insulation materials with a dry density of 780 kg·m^{-3} using the instrument measurement and formula calculation. The TC of the PC composite FC materials with different mass fractions is shown in Figure 4. In Figure 4, the mass fraction of the phase change materials increases from 0 % to 5 %, the average TC of the FC significantly decreases by 0.0079 W·(m-K)$^{-1}$. When increasing from 10 % to 15 %, the TC decreases by 0.0042 W·(m-K)$^{-1}$. The findings demonstrate that as the PC material doping increases, the TC of the PC composite FC material progressively rises.

The temperature coefficient (TC) of the FC was established in this study by setting the temperature to 26, 28, 30, 32, 34, 36, and 38 °C. This allowed for the further investigation of the impacts of various densities and potencies of the PC materials. The results of the TC determination of the different PC composite FC test blocks are shown in Figure 5. Figure 5a illustrates that, generally speaking, the TC of each test block grew as the temperature rose, and that the TC of the FC increased as the density increased. At 0.96 W·(m-K)$^{-1}$), the pure cement has the greatest TC. It is evident from Figure 5b that the TC of the FC increases with the amount of PC material added. In addition, the thermal conductivity of each test block in Figure 5 is significantly higher than that of the test block in Figure 4, because the thermal conductivity of the foamed cement is affected by two

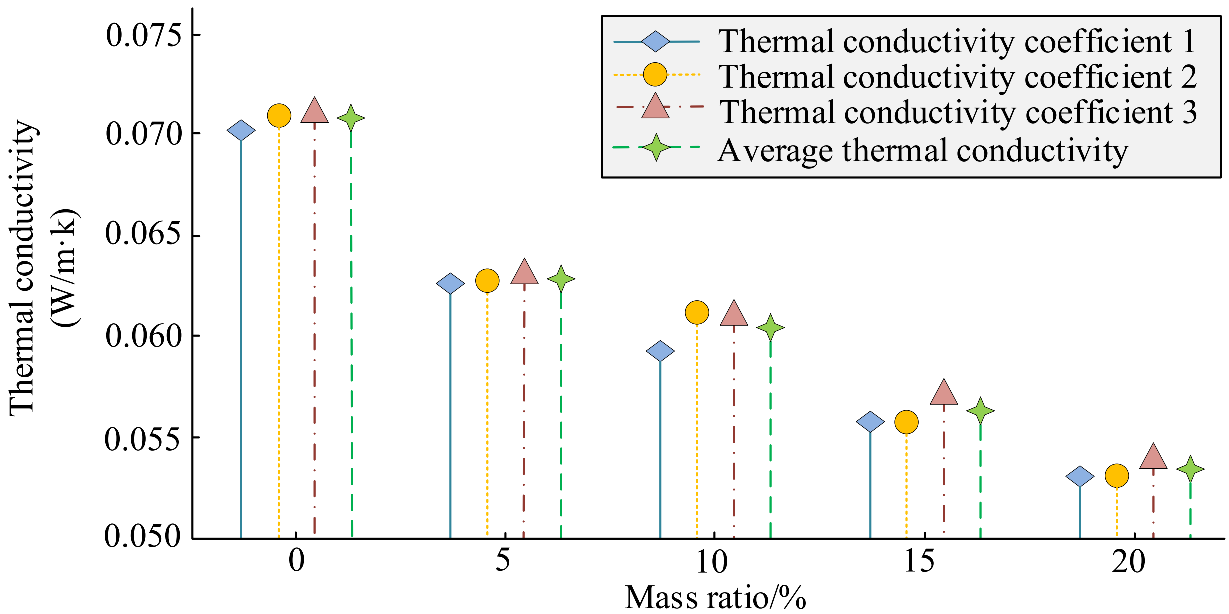


Figure 4. Thermal conductivity of the phase change composite foamed cement materials with different mass fractions.

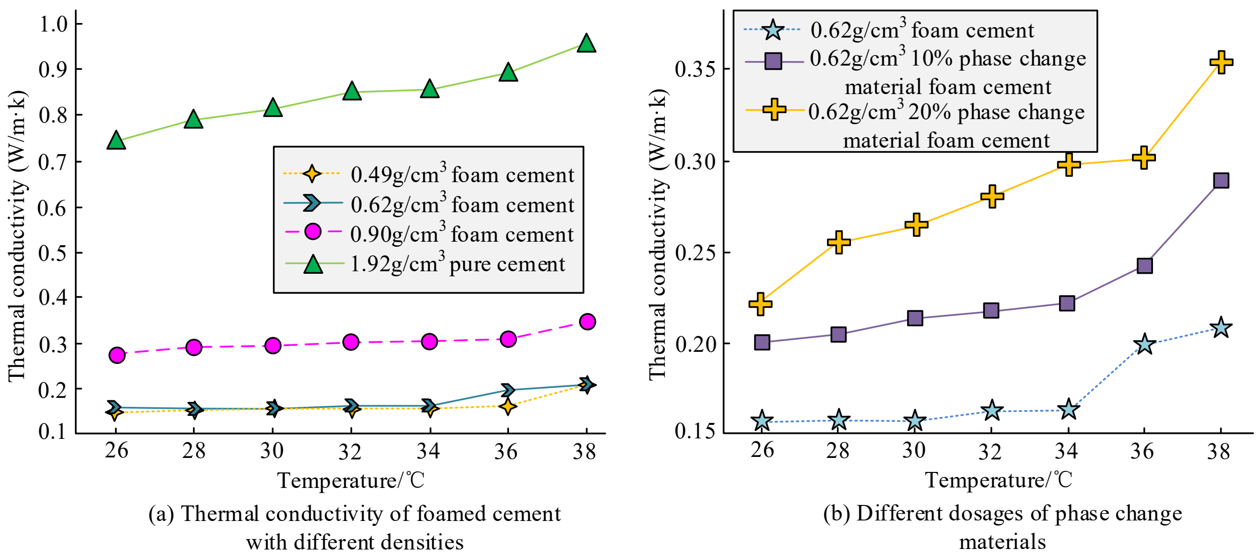


Figure 5. The influence of the different densities and phase change material dosages on the thermal conductivity of the foamed cement.

factors: the amount of phase change microcapsules added and the content of bubbles in the test block. The reason for this is that the PC material has a higher TC than the regular cement, therefore adding the PC material will raise the TC of the entire system.

Analysis of the thermal properties of the phase change composite foamed cement

To analyse the thermal properties of PC composite FC material, a study was carried out in a full-size actual room with dimensions size of 2 × 1.5 × 2.7 m. The walls of the room were three-layered with a 75 mm thick rock wool board in the middle layer and 1.2 mm thick colour steel board in the inner and outer layers. The south wall of the room has a single glazed window of 121 × 96 mm. PC composite FC prepared in this study was laid on half of the external surface of the roof of this room, and ordinary roofing was generally laid. The experiments were conducted for 6 and 5 days under two working conditions starting at 10:00 on the first day. Case 1 had a highly reflective membrane and Case 2 did not, and the meteorological parameters during the experimental period for the two cases are shown in Figure 6.

Each temperature measurement point has two probes and the average value is taken. Figure 7 displays the findings of the inner surface (IS) temperature test of the roof for this room under the two operating scenarios. As demonstrated in Figure 7a, the PC composite FC roof decreased the IS temperature of the roof by 2 °C during the day, which is 0.9 °C more than that of the ordinary roof. During the day, the ordinary roof decreased the IS temperature of the roof by 1.1 °C. During the night, the IS temperature of the roof was raised by 1.1 °C by the conventional roof and 1.6 °C by the PC composite FC roof, which was 0.5 °C higher than the ordinary roof. As shown in Figure 7b, the phase-change composite FC roofing raised the roof's IS temperature by 0.9 °C at night and decreased it by 2.9 °C during the day.

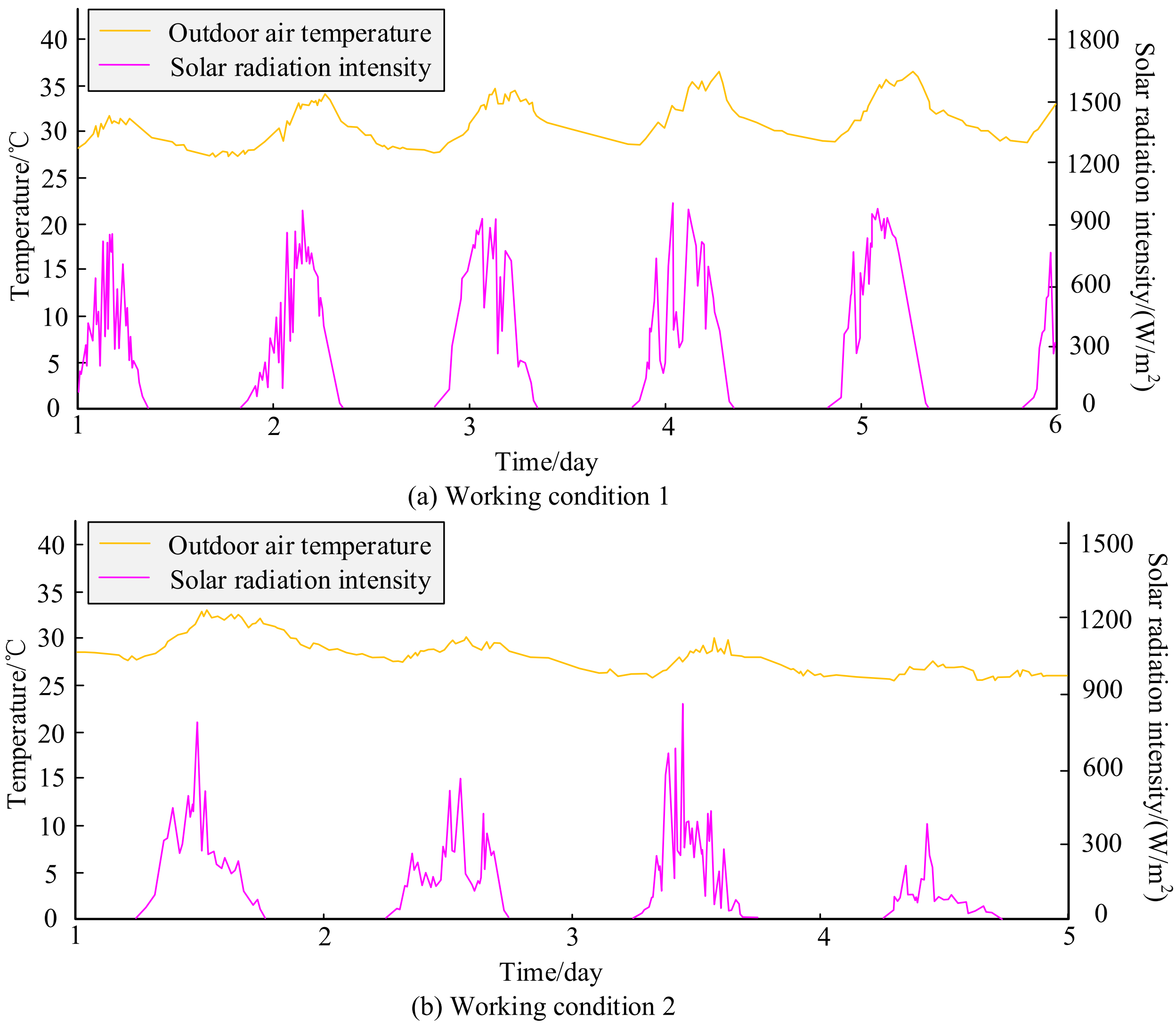


Figure 6. Meteorological parameters during the two experimental conditions.

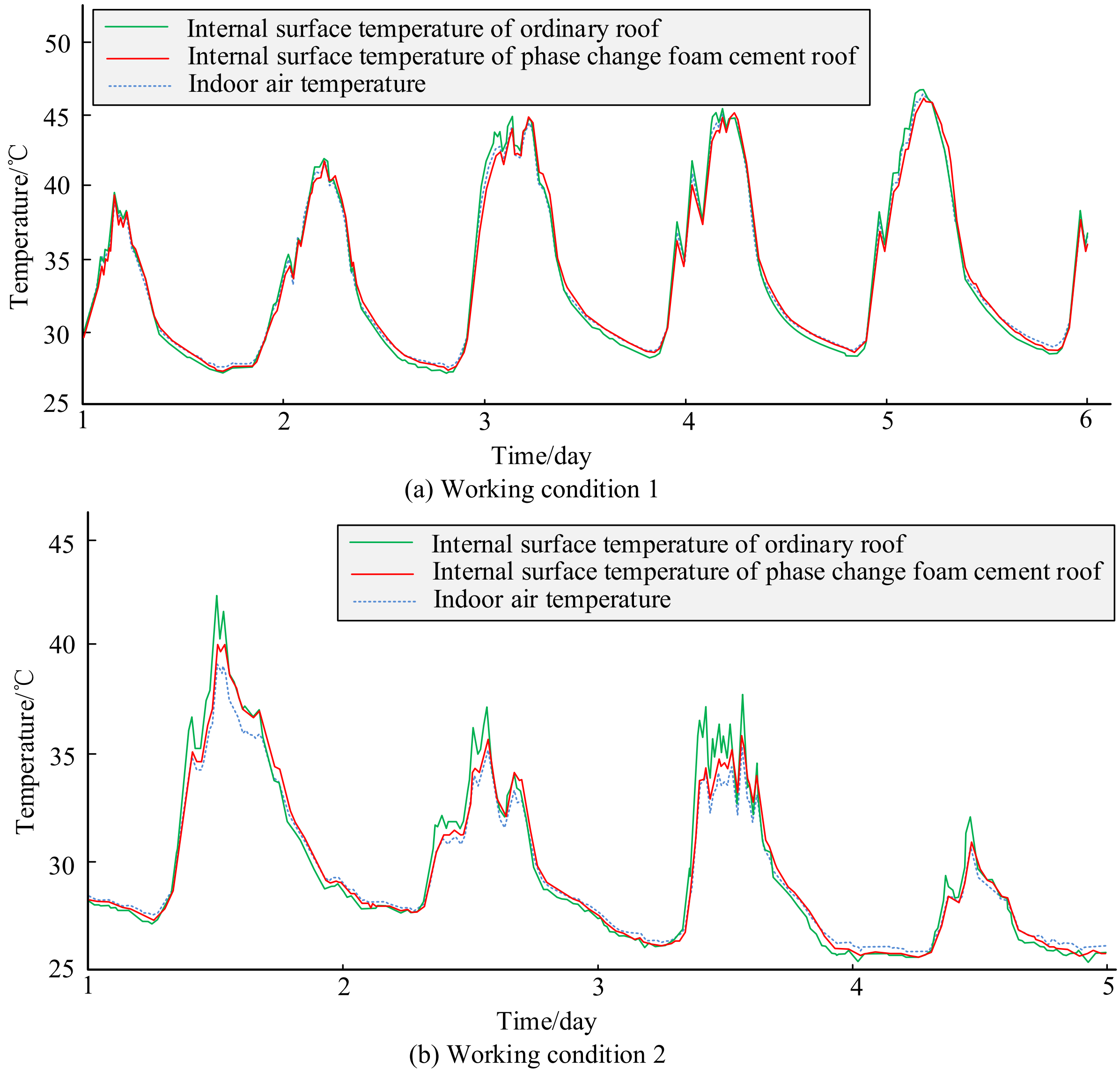
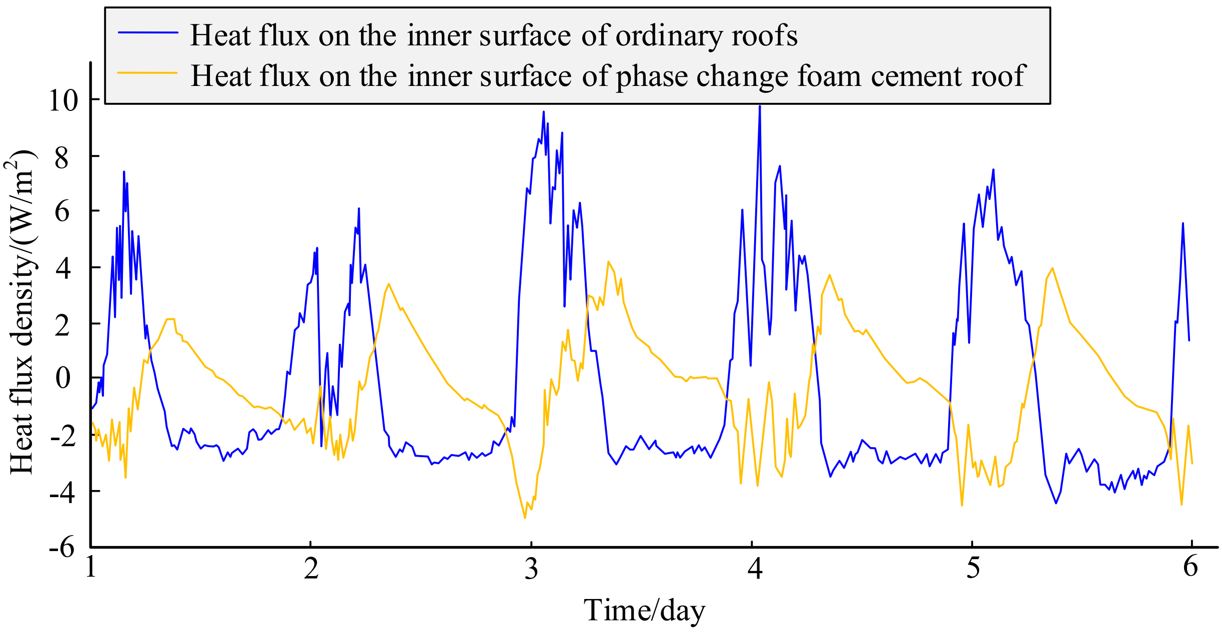


Figure 7. Test results of the temperature on the inner surface of the roof under the two working conditions.

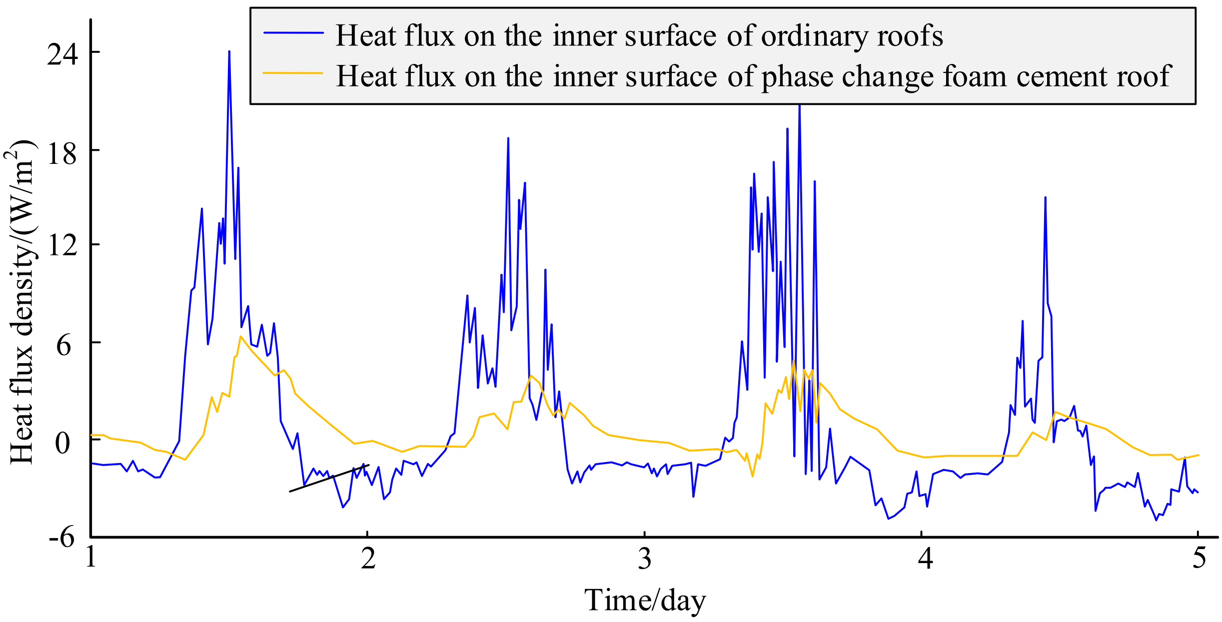
The outcomes demonstrate the good thermal insulation effect that the PC composite possesses, which is both practical and efficient.

Figure 8 displays the heat flow density test findings under two different operating situations on the IS of this room's roof. In Figure 8a, the direction of the heat flow on the ISs of the ordinary roof and phase-change composite FC roof is basically opposite, with the phase-change composite FC roof absorbing heat during the daytime and emitting heat at night. In Figure 8b, in Case 2, the PC composite FC roof can also effectively reduce the heat gain, but the delay time of the peak heat flow is obviously shorter than that in Case 1, and the heat absorption time from the indoor air is shorter, and the amount of heat gain is less. This is due to the highly reflective membrane's ability to deflect the majority of solar light, which lowers the FC's surface temperature. The findings demonstrate the strong thermal insulation effect of the PC composite FC and the highly reflecting membrane's ability to prolong the FC's melting time, thus enhancing the roof's thermal insulation value.

Table 4 displays the total heat gain of the IS of the room's roof under the two operating circumstances. From Table 4, the PC composite FC roof prepared in this study has a better heat gain reduction effect compared to the ordinary roof in the two working conditions, with an average heat gain reduction of 48.5 % and 59.9 %, respectively. The results demonstrate the excellent thermal insulation performance of the proposed phase-change composite FC, and the phase-change FC roof's performance is further enhanced by the addition of the high reflective film.



(a) Working condition 1



(b) Working condition 2

Figure 8. Test results of the heat flux density on the inner surface of the roof under the two working conditions.

Table 4. The total heat gain from the interior surface of the room's roof.

Time/day	Working condition 1		Working condition 2	
	Ordinary roof	The roof of this study	Ordinary roof	The roof of this study
1	97.1	50.1	429.6	212.4
2	107.6	77.0	301.6	116.9
3	268.8	119.5	326.4	129.5
4	199.8	91.9	105.0	38.0
5	199.6	87.9	-	-
Average heat reduction	-	48.5%	-	59.0%

CONCLUSIONS

With the increasingly serious energy shortage problem in the world, ES and environmental protection in buildings are also gaining more and more attention. Aimed at the problem of how to further improve the thermal insulation performance of materials in BIPV construction, a PC composite FC thermal insulation material was prepared in this study, and its thermal performance was analysed. The results show that the TC of the FC decreases significantly by 0.0079 W·(m-K)$^{-1}$ when the mass fraction of the PC material was increased from 15 % to 20 %. The TC decreased by 0.0042 W·(m-K)$^{-1}$ when it was increased from 10 % to 15 %. The higher the density of the FC and the amount of incorporated PC material, the higher the TC of the FC. The TC of the pure cement was at its maximum at 0.96 W·(m-K)$^{-1}$. The phase-change composite FC roof reduced the IS temperature of the roof by 2 °C during the day and increased it by 1.6 °C at night. The phase-change composite FC roof absorbed heat during the daytime and emitted heat at night, with an average heat gain reduction of 48.5 % and 59.9 %, respectively. In summary, the PC composite FC material prepared by the research has better thermal performance and can provide thermal insulation for the building. However, due to the limitation of the experimental conditions, the temperature and humidity were not measured and analysed at the same time in this study. Therefore, a larger experimental environment should be constructed for the simultaneous measurement of the temperature and humidity in the future research, so as to better investigate the thermal insulation effect of the PC composite FC on buildings and promote the development of BIPV.

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