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Study on the Reduction of Energy Consumption and Thermal Insulation Effect of the Use of High Performance Composite Materials in Urban Housing Buildings

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Abstract In the proportion of energy consumption of the whole society, the proportion of building energy consumption alone reaches 1/3, so for building practitioners, reducing building energy consumption is a very important direction of work. In this study, a new type of hydrated inorganic salt composite material with thermal insulation effect was prepared by utilizing expanded perlite as the support material of disodium hydrogen phosphate dodecahydrate. COMSOL Multiphysics software was used to simulate and analyze the effect of this high-performance composite material on the wall temperature and energy consumption of urban housing buildings in different climate zones. The results show that the inner surface temperatures of the walls of Harbin urban housing buildings applying composite materials and ordinary materials are 24.23℃ and 23.00℃ respectively in January, indicating that the composite materials have a better thermal insulation effect in cold regions. The application of high-performance composites can reduce the annual heating energy consumption in urban housing buildings in Beijing and Harbin from 4980.04kWh and 6026.20kWh to 4123.65kWh and 5526.35kWh. The new hydrated inorganic salt composites prepared in this paper have high engineering value, and they can provide solid material foundation for the development of urban green residential buildings. The new hydrated inorganic salt composites prepared in this paper have high engineering value and can provide a solid material foundation for the development of urban green residential buildings, which can help promote the development concept of “green and energy-saving” in China.

Index Terms COMSOL Multiphysics, building energy consumption, heat transfer modeling, composite materials, urban housing

I. Introduction

With global climate change becoming more and more significant, building energy efficiency has become an important issue worldwide. In the energy consumption of housing buildings, heating and cooling account for a huge proportion, and the thermal insulation and heat preservation system, as one of the important means of building energy efficiency, has received widespread attention. Therefore, in-depth research on the performance and construction technology of efficient thermal insulation and heat preservation materials is of great significance in promoting the development of green energy-saving building technology.

In the design and construction of green energy-saving buildings, high-efficiency thermal insulation and heat preservation materials are mainly categorized into radiant, reflective and barrier types. Radiation-type materials mainly improve the building's thermal insulation effectiveness by reducing the transmission of thermal radiation, and their structure introduces a high reflectivity layer that can reflect infrared rays, which can significantly reduce the heat brought about by radiation [1], [2]. Reflective materials work by reflecting radiation from the sun and other heat sources to reduce the absorption of heat energy, and these materials are usually coated with aluminum foils or other metallic films, which are used to reduce the temperature of building surfaces by taking advantage of the high reflectivity of these metallic films to reduce cooling needs and energy consumption [3], [4]. Barrier-type materials limit heat transfer through their unique physical structure; these materials often have closed-cell foam structures or use aerogel technology to block heat transfer by forming tiny gas compartments inside the material [5], [6].

Efficient thermal insulation and heat preservation materials play an important role in improving the thermal environment of buildings and reducing operating costs, especially during the construction of exterior wall insulation finishes, where precise material selection and construction techniques are decisive in ensuring long-term energy savings and the realization of environmental goals [7]-[9]. The study of these high-performance composites not only provides the construction industry with methods to optimize building design, but also provides reliable scientific support and practical guidelines for the development of green buildings, and promotes the progress of sustainable building technology.

In terms of radiant materials, Junasová, B. et al. studied radiant heating and cooling systems in building retrofits, where embedding densely spaced conductive cores with insulating cores in the interior of the walls maximizes the output of the system per energy input, while fixing metal fins to the ducts to achieve a compact design for the highest yield [10]. Fantucci, S. et al. used long-wave infrared reflective insulating materials under the use long-wave infrared reflective insulation underneath the roof tiles to reduce the energy exchanged by radiant heat through the thermal resistance of the roof, thus achieving effective insulation without increasing the thickness of the insulation [11]. Le, V. T. et al. tested the heat shielding performance of high temperature fiber insulation in insulated sandwich structures, comparing the insulation performance of fiber insulation by measuring the temperature of the backsheet of the sandwich structure, and also by studying the microstructure of the insulating material to gain insight into the difference in the radiation performance of the fiber insulation materials, and found that the saffron alumina fiber material has better performance [12]. Xu, R. et al. designed a carbon nanotube doped aerogel sandwich structure on polyimide fabrics by hot pressing, and the low emissivity alumina-doped zinc oxide coated on its surface effectively reduced the thermal conductivity of the aerogel in the intermediate interlayer, and experiments proved that the composites exhibited high infrared stealth performance and super-insulation effect [13].

In the research of reflective materials, Zhang, G. et al. established a simplified thermal resistance-heat capacity model of external walls to compare the heat loss of walls with reflective insulation composite coatings and traditional coatings, and the experiments showed that the composite coatings, with high solar reflectance and very low thermal conductivity, have a better regulation of outdoor climate change and are a new type of energy-saving materials for buildings [14]. González, B. et al. presented a circulating radiant heating floor with a strip of phase change material embedded in the concrete core, where the phase change material stores thermal energy during melting and releases it during solidification, significantly improving the energy efficiency of housing buildings [15]. Fang, Y. et al. showed that the hydrate salt phase change material (PCM) acts as a heat storage medium to provide energy-efficient and economical thermal insulation for the electric radiant floor heating system, and discussed the shape stability, thermal properties and thermal reliability of sodium acetate trihydrate-formamide (SAT-FA) eutectic mixtures as an ideal candidate material under expanded graphite carrier [16]. Plytaria, M. T. et al. designed a solar cooling system for a building with radiant walls by injecting the phase change material into the radiant walls of the building facade and the solar cooling system was utilized for the building's radiant walls to the optimal building energy consumption, solar coverage and indoor temperature for the material coverage area and chilled water storage tank volume combinations were calculated and specified [17].

For the study of barrier-type materials, Siligardi, C. et al. investigated the thermotropic microstructural development of fiber-reinforced silica aerogel mats and rockwool using in-situ techniques such as thermogravimetric measurements and thermal grade microscopy, and carried out non-in-situ analyses by x-ray powder diffraction and scanning electron microscopy through heat-treating the materials as a means of investigating the thermal insulation properties of the materials [18]. Chan, K. Y. et al. developed an anisotropically cooled aerogel sheet using boron nitride nanosheets to provide highly controllable and cumulative freezing dynamics using an additive freeze-casting technique to fabricate decimeter-sized aerogel sheets with consistent in-plane pore alignments, which have a very low out-of-plane thermal conductivity and high solar reflectivity [19]. Lamy-Mendes, A. et al. pointed out that silica aerogel, characterized by translucency, low thermal conductivity and low density, is a high-performance building insulation material in composites or framing systems, which not only effectively reduces the overall weight of the building envelope, but also significantly increases its thermal resistance [20]. Lucchi, E. et al. evaluated the aerogel technology-based insulation material for its thermal performance, material compatibility and reversibility, and experiments showed that the material fully meets the objectives of environmental quality, energy efficiency and conservation required for building renovation, and is a new material with excellent performance [21]. Leroy, A. et al. developed a polyethylene aerogel material (PEA) with high solar reflectance, high infrared transparency and low thermal conductivity, which can be integrated with existing emitters for integration to achieve better thermal insulation [22].

This paper proposes a new type of hydrated inorganic salt composite material with thermal insulation effect, which is inexpensive and non-toxic and harmless, and is extremely suitable for application in urban housing buildings to reduce building energy consumption. Using expanded perlite and sodium hydrogen phosphate hydrate as porous support material and nucleating agent, the liquid disodium hydrogen phosphate dodecahydrate was modified to obtain a new hydrated inorganic salt composite phase change material suitable for application in urban housing buildings for thermal insulation. Subsequently, COMSOL Multiphysics software was used as a simulation experiment platform, combined with the proposed heat transfer and energy consumption calculation method for urban housing buildings, to realize the simulation and analysis of energy consumption of urban housing buildings. In this study, the performance parameters of the new hydrated inorganic salt composite phase change materials are tested and inputted into the simulation software, and then Harbin, Beijing, Shanghai, Guangzhou, and Kunming are selected as the representative cities of five major climate zones. The simulation analyzes the temperature inside and outside the walls of housing buildings in different cities under the application of high-performance compliant materials and common materials, and analyzes the annual energy consumption of the buildings under different wall materials to explore the effect of high-performance composite materials on thermal insulation and reduction of energy consumption in buildings.

II. Methods for the preparation and performance analysis of high-performance composite materials

II. A. Novel hydrated inorganic salt composite phase change material preparation

The level of thermal insulation performance of enclosure materials in urban housing buildings directly affects the magnitude of indoor temperature fluctuations, which in turn relates to the amount of building energy consumption. Some studies have proved that the combination of phase change materials that utilize latent heat to store energy and cold housing structures can effectively increase the heat capacity value and thermal inertness of urban housing structures. Hydrated inorganic salt phase change materials have higher enthalpy value compared with organic phase change materials, and have the advantages of low price, non-combustibility and non-toxicity and harmlessness, which have greater potential for application in the field of building energy saving. Therefore, the development of new high-performance compliant materials with heat preservation and insulation ability is of great value for energy saving and heat preservation applications in urban housing buildings.

Disodium hydrogen phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$) [23] is a common solid-liquid inorganic hydrated salt phase change material, which is favored by many researchers for its high enthalpy, low price, and nonflammability. On the other hand, since the phase change temperature of $Na_2HPO_4 \cdot 12H_2O$ is about 35°C, which is close to the temperature of human comfort, it has great potential for application in the field of construction engineering. However, $Na_2HPO_4 \cdot 12H_2O$ suffers from drawbacks such as high subcooling and low cyclic stability, which require modification studies on its properties. In addition, solid-liquid phase change materials also suffer from the problem of leakage caused by their fluidity during the phase change process, which limits the scope of practical applications. Expanded perlite (EP) [24] is an excellent thermal insulation material for construction, with the advantages of lightweight and porous, low thermal conductivity, hydrophilic and low price. Utilizing EP as a porous support material to adsorb and shape liquid $Na_2HPO_4 \cdot 12H_2O$ not only prevents liquid leakage during its application, but also significantly increases the heat capacity of EP on the basis of retaining the excellent thermal insulation effect of EP particles. In addition, it has been found that adding the surface-modified hollow beads into the paint and coating the outer surface of the board can reduce the inner surface temperature of the board by 28°C. It can be seen that utilizing the heat-reflective properties of TiO_2 can effectively improve the thermal insulation capacity of building materials. If $Na_2HPO_4 \cdot 12H_2O$/EP high-performance composites can store/release latent heat in the process of phase change and TiO_2 has a combination of high heat reflective properties, it will be able to play the double effect of energy storage and reflection of heat insulation. It is worth noting that TiO_2 can also utilize its strong hydrophilicity to increase the bonding force between EP and hydrated salt, which in turn increases the adsorption capacity of EP on water molecules and the stability of the composite material.

Based on this, in this study, $Na_2SiO_3 \cdot 9H_2O$ was used as a nucleating agent to address the inherent drawbacks of $Na_2HPO_4 \cdot 12H_2O$. In order to increase the heat reflection ability of the composite material, modified expanded perlite (MEP) was prepared by coating a layer of TiO_2 on the surface of EP by sol-gel method, and the composite material was prepared by adsorption of MEP on $Na_2HPO_4 \cdot 12H_2O$ to solve the leakage problem of $Na_2HPO_4 \cdot 12H_2O$. A new type of hydrated inorganic salt composite phase change material suitable for the application of heat insulation in urban housing buildings was developed.

II. B. Test methods for composite properties

II. B. 1) Density testing

Bulk density is an important indicator of high performance in line with the physical properties of the material.

The formula for calculating the density of composite materials is as follows:

$$\rho = m/V \tag{1}$$

where ρ is the bulk density $\left(g \cdot cm^{-3}\right)$, m is the specimen mass (g), V is the specimen volume $\left(cm^3\right)$.

II. B. 2) Thermal Conductivity Testing

Thermal conductivity [25] is the amount of heat that passes through a unit thickness and a unit area in a unit time with a unit temperature difference under the condition of stable heat transfer, and it is one of the most important performance indexes of high-performance composite thermal insulation materials. In this experiment, the transient plane heat source method is used for testing, which has the volts point of fast measurement speed, wide application range and the ability to successfully avoid the influence of natural convection in the experimental process, which is the more popular test method at present. The measurement principle is as follows:

$$\lambda = 0.00111 - 0.0000424 \times \rho + 0.000115 \times T \pm 1.5\% \tag{2}$$

where λ is the thermal conductivity $\left(W \cdot (m \cdot K)^{-1}\right)$, ρ is the container density $\left(kg \cdot m^{-3}\right)$, T is the sample temperature (K).

II. B. 3) Compressive performance tests

The test selection NYL-2000D model universal press, pressurization speed (0.5 ~ 1.5) KN / s, pressurization should be maintained continuously and uniformly increase the load until the test block was destroyed, and recorded at this time the reading of the universal press, that is, the maximum destructive load.

The compressive strength is calculated according to the following formula:

$$\mathrm{f} = \frac{F}{A} \tag{3}$$

where f is the compressive strength of the specimen (MPa), F is the maximum destructive load (N), and A is the compressed area of the specimen (mm^2). Among them, the compressive strength of each group of specimens should be the average of the compressive strength of three specimens, accurate to 0.01MPa.

III. Simulation and analysis model for heat transfer and energy consumption in urban housing buildings

III. A. Simulation software

In this paper, the simulation and analysis of heat consumption and energy consumption in urban housing buildings is achieved using COMSOL Multiphysics software [26], a powerful interactive environment for modeling and solving a wide range of scientific and engineering problems. The software provides a powerful integrated desktop environment with a model builder that gives you a comprehensive overview of the model and access to all features. COMSOL Multiphysics can be easily extended to a type of physical model that solves physical phenomena with multiple coupled physical fields, while making traditional models into accessible, well-characterized multidimensional graphics under the manipulative processing of the versatile software. There are a variety of different operating procedures and computational spaces in COMSOL Multiphysics. The combination of various theoretical principles ensures that the simulation process is carried out correctly and in an orderly manner. The modeling and analysis process consists of several steps, including the creation of a geometric model, the definition of basic material properties, the determination of boundary conditions, mesh delineation, the study of the solution and the post-processing of the results of the calculations. Compared with other finite element software such as ANSYS, ABAQUS, etc., the operation is very user-friendly, COMSOL Multiphysics in a large number of predefined applications based on a large number of models, covering heat transfer, fluids, electromagnetic fields, structural mechanics, earth sciences, chemical reactions and multi-field coupling models, as well as custom mathematical partial differential equations. It is always possible to apply these variables, expressions, or numbers directly to solid and fluid domains, boundaries, edges, and points in finite element COMSOL Multiphysics without the need for computational meshing, and a set of equations representing the entire model is written internally in COMSOL Multiphysics.

III. B. Calculation of heat and energy consumption

III. B. 1) Heat transfer models

In this paper, based on the law of conservation of energy, it is assumed that the amount of change in braising within a cell is equal to the inflow of all energy into the cell under control. The energy conservation equation can be expressed as Eq:

$$\frac{\partial}{\partial t} c_{p,m} \rho_m T + c_{\rho,m} \rho_m \nabla T = -\nabla q + Q \tag{4}$$

where T is the time (s), $c_{p,m}$ is the specific heat capacity of the material $\left(J/(kg\cdot K)\right)$, ρ_m is the density of the dry material $\left(kg/m^3\right)$, T is the temperature (K), ∇T is the temperature gradient (K).

The thermally conductive heat flow density can be expressed by Fourier's theorem as shown in Eq:

$$q=-\lambda\nabla T \tag{5}$$

where λ is the material thermal conductivity $\left(W/(m\cdot K)\right)$.

III. B. 2) Methods for analyzing building energy consumption

The indicator of energy consumption of urban housing buildings is expressed as q_H in units of W/m^2, which indicates the amount of heat supplied by the indoor heating equipment to maintain the calculated temperature of the interior design under the conditions of the average outdoor temperature during the heating period in order to offset the consumption of a unit of floor space per unit of time. The index of heat consumption of buildings is used as a basis for determining the thermal properties of urban housing buildings in cold and frigid regions.

(1) The heat consumption index of urban housing buildings [27] is calculated by the following formula:

$$q_H=q_{HT}+q_{INF}-q_{IH} \tag{6}$$

where q_H is the heat consumption index of the building, W/m^2. q_{HT}, q_{INF}, q_{IH} is converted to a unit of time per unit of floor area through the building of urban housing building heat transfer, building air infiltration heat consumption, building internal heat gain, internal heat gain $3.8W/m^2$. The rest of the unit W/m^2.

(2) q_{HT} The formula is as follows:

$$q_{HT}=q_{Hq}+q_{Hw}+q_{Hd}+q_{Hmc}+q_{Hy} \tag{7}$$

where q_{Hq}, q_{Hw}, q_{Hd}, q_{Hmc}, q_{Hy} is converted to a unit of time per unit of floor area through the walls, roofs, floors, doors, windows, non-heated closed balcony heat transfer $\left(W/m^2\right)$.

(3) q_{Hq} Calculation formula:

$$q_{Hq}=\frac{\sum q_{Hqi}}{A_0}=\frac{\sum \varepsilon_{qi}K_{mqi}F_{qi}\left(t_n-t_e\right)}{A_0} \tag{8}$$

where q_{Hq} is the amount of heat transfer through the external wall per unit time per unit floor area $\left(W/m^2\right)$, t_n is the calculated indoor temperature, taken as 18℃. When the inside of the exterior wall is a stairwell, take 12℃. t_e is the average outdoor temperature during the heating period $(°C)$, ε_{qi} is the correction coefficient for the heat transfer coefficient of the external wall. K_{mqi} is the average heat transfer coefficient of the external wall $\left[W/\left(m^2\cdot K\right)\right]$, F_{qi} is the area of the external wall $\left(\mathrm{m}^2\right)$, A_0 is the floor area $\left(\mathrm{m}^2\right)$.

(4) q_{Hw} Calculation formula:

$$q_{Hw}=\frac{\sum q_{Hwi}}{A_0}=\frac{\sum \varepsilon_{wi}K_{wi}F_{wi}\left(t_n-t_e\right)}{A_0} \tag{9}$$

where q_{Hw} is the amount of heat transfer through the roof per unit time per unit floor area $\left(W/m^2\right)$. ε_{wi} is the correction factor for the roof heat transfer coefficient, K_{wi} is the roof heat transfer coefficient $\left[W/\left(m^2\cdot K\right)\right]$, and F_{wi} is the area of the roof $\left(\mathrm{m}^2\right)$.

(5) q_{Hd} Calculation formula:

$$q_{Hd}=\frac{\sum q_{Hdi}}{A_0}=\frac{\sum K_{di}F_{di}\left(t_n-t_e\right)}{A_0} \tag{10}$$

where q_{Hd} is converted to the amount of heat transfer through the ground $\left(W/m^2\right)$ per unit of urban housing floor area per unit of time, K_{di} the heat transfer coefficient of the ground $\left[W/\left(m^2\cdot K\right)\right]$ and F_{di} the area $\left(\mathrm{m}^2\right)$ of the ground.

(6) q_{Hmc} Calculation formula:

$$q_{Hmc}=\frac{\sum q_{Hmci}}{A_0}=\frac{\sum\left[K_{mci}F_{mci}\left(t_n-t_e\right)-I_{tyi}C_{mci}F_{mci}\right]}{A_0} \tag{11}$$

$$C_{mci} = 0.87 \times 0.70 \times SC \tag{12}$$

where q_{Hmc} is converted to a unit of time per unit of floor area through the external window (door) of the heat transfer (W/m^2). K_{mci} for the window (door) of the heat transfer coefficient $\left[W/\left(m^2 \cdot K\right)\right]$, F_{mci} for the window (door) of the area $\left(\mathrm{m}^2\right)$. I_{tyi} for the window (door) heating period of the external surface of the average solar radiation (W/m^2), C_{mci} for the window (door) of the solar radiation correction coefficient, SC for the window of the integrated shading coefficient, 0.87-3mm for the glass of the solar radiation transmittance, 0.70 for the discount factor.

(7) q_{Hy} Calculation formula:

$$q_{Hy} = \frac{\sum q_{Hyi}}{A_0} = \frac{\sum\left[K_{qmci}F_{mqci}\zeta_i\left(t_n - t_e\right) - I_{tyi}C_{mci}F_{mci}\right]}{A_0} \tag{13}$$

$$C_{mci} = \left(0.87 \times SC_W\right) \times \left(0.87 \times 0.70 \times SC_N\right) \tag{14}$$

where q_{Hy} is converted to a unit of time per unit of floor area through the non-heating closed balcony heat transfer $\left(W/m^2\right)$. K_{qmci} for the average heat transfer coefficient of the interior of the walls, windows (doors) and separated closed balcony $\left[W/\left(m^2 \cdot K\right)\right]$. F_{mqci} for the interior of the walls, windows (doors) and separated closed balcony area $\left(\mathrm{m}^2\right)$. ζ_i for the balcony of the temperature correction factor. I_{tyi} is the average solar heat radiation on the external surface of the closed balcony during the heating period (W/m^2). F_{mci} is the area of the windows (doors) and separated closed balconies in the interior $\left(\mathrm{m}^2\right)$. C_{mci} is the correction factor for solar radiation of the windows (doors) and separated closed balconies in the interior. SC_W is the combined shading coefficient of the exterior window, and SC_N is the combined shading coefficient of the interior window.

(8) q_{INF} Calculation formula:

$$q_{INF} = \frac{\left(t_n - t_e\right)\left(C_p \cdot \rho \cdot N \cdot V\right)}{A_0} \tag{15}$$

where q_{INF} is converted to a unit of time per unit of floor space on the building air exchange heat $\left(W/m^2\right)$. Cp for the specific heat capacity of air, take $0.28Wh/\left(kg \cdot K\right)$. ρ for the density of air $\left(\mathrm{kg/m^3}\right)$, take the heating period of the average outdoor temperature te corresponding value. N for the number of air changes, take $0.5\mathrm{h}^{-1}$, V for the volume of air changes $\left(\mathrm{m}^3\right)$.

(9) $R_{0\cdot\min}$ Calculation formula:

$$R_{0\cdot\min} = \frac{t_i - t_e}{\Delta t} R_i \cdot n \tag{16}$$

t_i is the calculated indoor temperature in winter, which is generally taken as 20°C, t_e is the calculated outdoor temperature of urban housing buildings in winter, $(^\circ\mathrm{C})$, Δt is the permissible temperature difference between the indoor air and the inner surface of the urban housing building, $(^\circ\mathrm{C})$, n is the correction coefficient for the temperature difference between the outer surface of the urban housing building and the outside contact conditions, and R_i is the heat exchange resistance of the inner side of the urban housing building, $\left(m^2K\right)/W$.

IV. Analysis of the thermal insulation and energy-saving effects of high-performance composite materials

IV. A. Calculation results of high-performance composite material properties

Before the simulation analysis of the application of high-performance composite materials in urban housing construction, the performance parameters of high-performance composite materials need to be calculated and analyzed to provide relevant parameters for the operation of the simulation software. In this paper, the new hydrated inorganic salt composite phase change materials prepared by the performance parameters of the test results are shown in Table 1, the new hydrated inorganic salt composite phase change materials prepared by the thermal conductivity, density and compressive strength of the test results are listed in the table. It can be seen that the new hydrated inorganic salt composite phase change material can achieve a very low density (474.040 kg/m^3) and thermal conductivity (0.117 W/(m·k)), and still has a good compressive strength (1.407 MPa). Because of its wide range of density, wide range of strength and lower thermal conductivity under the same conditions, it has good application prospects in surface insulation, road bridge and reinforcement filling, and as an urban housing construction and industrial insulation material. From the results of performance parameter analysis, the new hydrated inorganic salt composite phase change material, as a composite material with high performance, presents different properties such as lightweight, temperature insulation, fire resistance, etc., which can be actively promoted for use in urban housing construction.

Table 1: Performance parameters of high-performance composite materials

Experimental number	Volume content			Thermal conductivity (W/(m·k))	Density (kg/m^3)	Compressive strength (MPa)
	Cement	Aerogel	Porosity			
1	0.153	0.208	0.772	0.1	513.38	1.581
2	0.109	0.128	0.422	0.141	403.14	1.659
3	0.147	0.188	0.524	0.116	401.86	1.83
4	0.106	0.148	0.789	0.104	421.55	1.03
5	0.168	0.109	0.645	0.1	452.26	1.323
6	0.192	0.102	0.754	0.107	522.32	1.14
7	0.144	0.195	0.603	0.139	556.3	1.152
8	0.193	0.232	0.731	0.111	579.66	1.68
9	0.116	0.221	0.643	0.109	408.34	1.406
10	0.196	0.197	0.525	0.139	481.59	1.271
Average	0.152	0.173	0.641	0.117	474.04	1.407

IV. B. Analysis of the thermal insulation effect of composite materials

IV. B. 1) Thermophysical parameters of building walls

According to the climate zoning of urban housing buildings, China is divided into five climate zones, such as severe cold region, cold region, hot summer and cold winter region, hot summer and warm winter region, mild region, etc. Therefore, Harbin, Beijing, Shanghai, Guangzhou and Kunming are selected as the representative cities of the five climate zones for simulation and analysis in this study. According to the general specification for building energy efficiency and renewable energy utilization, the exterior wall parameters are selected for the five typical cities, and the limitations of thermal parameters of the exterior wall in the five climate zones are shown in Table 2. The limit values of heat transfer coefficients of external walls in each climate zone are gradually increasing from north to south, and the requirements for wall thermal insulation performance are gradually decreasing, and the limit values of heat transfer coefficients of external walls in urban housing buildings in Harbin and Kunming are ≤0.20 $K[W/(m^2 \cdot K)]$ and ≤0.95 $K[W/(m^2 \cdot K)]$, respectively. The types of building exterior wall materials used and the thermophysical parameters of the materials are shown in Table 3. In order to reduce the parameter variables, the thickness of the finish layer of the wall in the five major climate zones is set at 25 mm, and the thickness of the insulation layer is the same thickness of the insulation layer for the exterior walls of buildings in the same climate zone under the premise of meeting the limit value of the heat transfer coefficient of the exterior walls of the climate zones in which they are located. Common thermal insulation materials are chosen as a comparison, the thermal conductivity and dry density of common thermal insulation materials are 0.120W/(m·k) and 521.36 kg/m^3.

Table 2: Requirements for limiting external wall thermal parameters

Thermal partition	City	External wall heat transfer coefficient limit $K[W/(m^2 \cdot K)]$	Thickness (mm)			External wall heat transfer coefficient $K[W/(m^2 \cdot K)]$	
			Interior facing	Composite material	Exterior coating	High performance composite	General material
Very cold	Harbin	≤0.20	25	300	25	0.1928	0.2422
Cold	Beijing	≤0.32	25	300	25	0.198	0.2812
Summer heat and winter cooling	Shanghai	≤0.55	25	300	25	0.219	0.2851

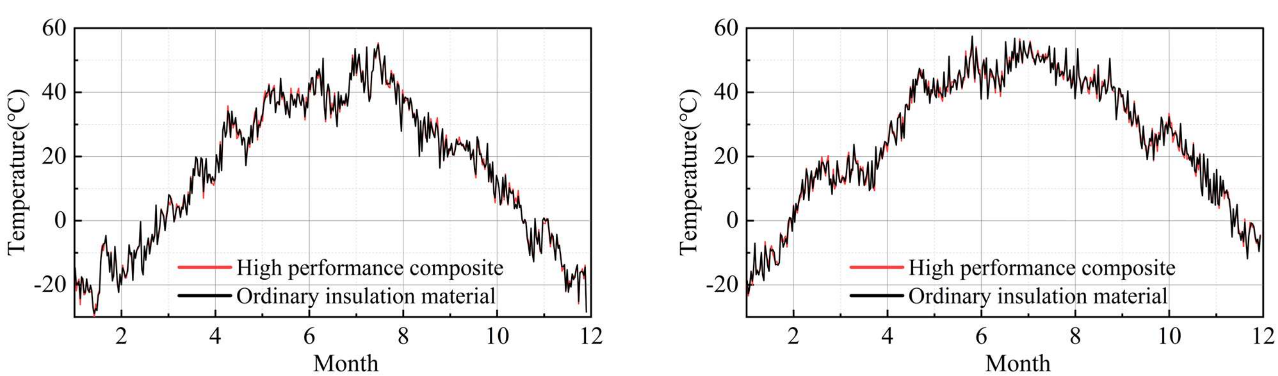
Summer heat and winter warmth	Guangzhou	≤0.75	25	300	25	0.2223	0.3043
Warmth	Kunming	≤0.95	25	300	25	0.2294	0.3878

Table 3: Thermal property parameters of exterior wall materials

material	Heat conductivity factor (W/(m · k))	Dry density (kg/ m^3)	Specific heat capacity
Interior facing	0.823	1650.23	1.25
Composite material	0.117	474.04	2.34
General material	0.120	521.36	1.25
Exterior coating	0.875	1785.59	1.25

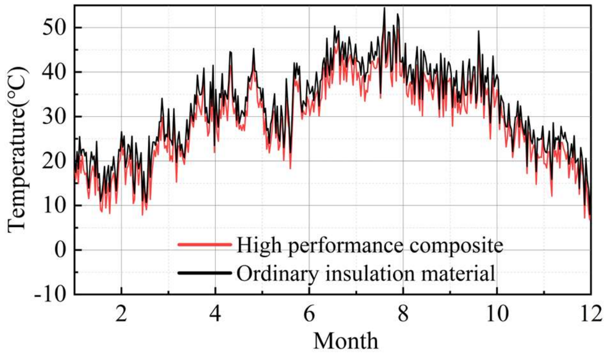
IV. B. 2) Analysis of external surface temperatures of housing building walls

COMSOL Multiphysics software and housing building thermal analysis methods are used to simulate and calculate the dynamic thermal performance of the high-performance composite material and ordinary material walls proposed in this paper in various climate zones, and the results of the calculations are shown in Fig. 1, where (a)-(e) represent the analytical results in Harbin, Beijing, Shanghai, Guangzhou and Kunming, respectively. The results of the analysis can be found in the external surface temperatures of the high-performance composite walls and ordinary material walls in different climate zones representing the city. It can be seen that the difference between the external surface temperature of the new hydrated inorganic salt composite wall and that of the ordinary insulation material wall in a particular climate zone is small. This is due to a specific climate zone in the new hydrated inorganic salt composite wall and ordinary insulation material wall outdoor boundary conditions remain consistent, in addition to the wall itself used in the thermal insulation materials are different, the exterior finish layer and the outdoor environment involved in the heat exchange of solar radiation absorption rate, outdoor convective heat transfer coefficient, long-wave emissivity are the same. Therefore, the factors affecting the external surface temperature of the wall are only determined by the meteorological conditions of the climatic zone where the wall is located, which provides a prerequisite for the comparison of the dynamic thermal performance of the new hydrated inorganic salt composite wall and the wall with ordinary thermal insulation materials in different climatic zones on behalf of the city. Harbin is located in the severe cold region, the winter temperature is low and lasts a long time, the temperature of the outer surface of the wall in the coldest month can be up to -28 ℃ or so, which is a temperature difference of 54.5 ℃ with the indoor set comfort temperature of 26.5 ℃, so that the thermal insulation needs of this climatic zone is greater. Beijing is second, in January and December, the external surface temperature of the wall appears to be below 0 ℃, the city housing building exterior walls also have a certain insulation needs. In Shanghai and Guangzhou, where the duration of high temperatures in summer is relatively long, there is a greater need for thermal insulation in the exterior walls of urban housing buildings. In the mild region where Kunming is located, the fluctuation of the external surface temperature of the wall is small throughout the year.

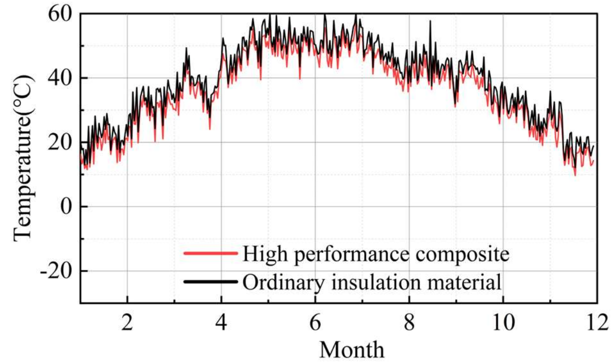


(a) Harbin

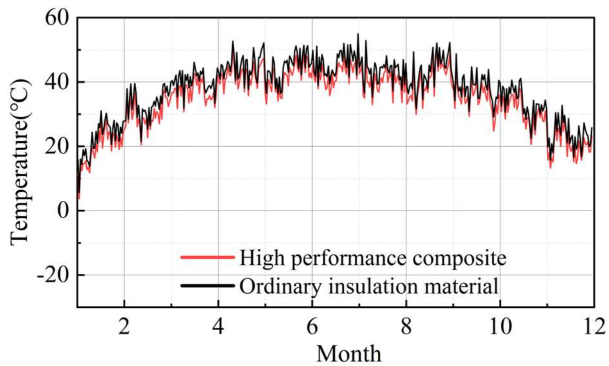
(b) Beijing



(c) Shanghai



(d) Guangzhou

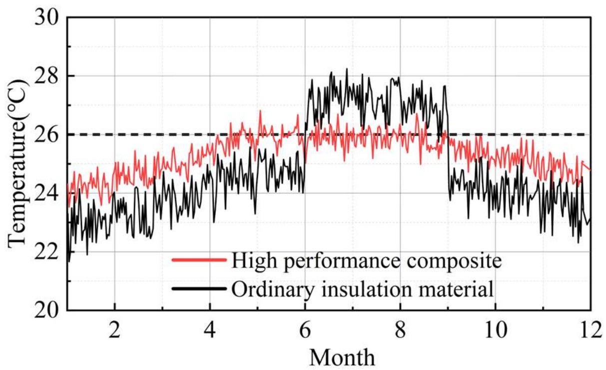


(e) Kunming

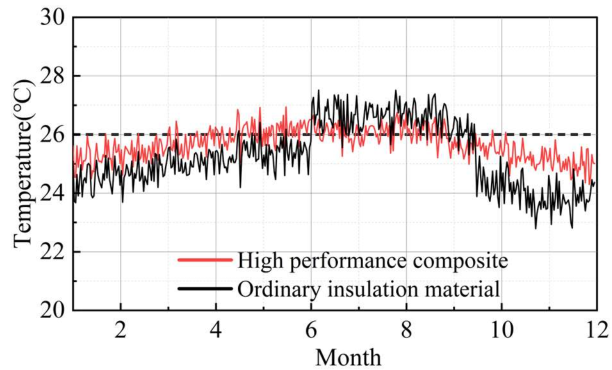
Figure 1: External surface temperature of representative cities

IV. B. 3) Results of surface temperature analysis inside the walls

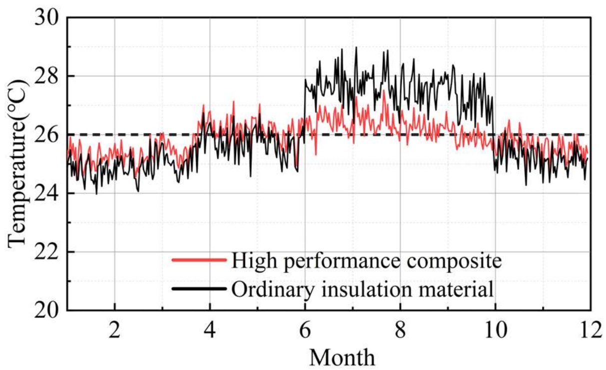
The results of the analysis of the internal surface temperature of the new hydrated inorganic salt composite wall and the wall of ordinary thermal insulation material in the representative cities of different climate zones are shown in Fig. 2, where (a)-(e) represent the results of the analysis of the surface temperature of the internal wall of the urban housing building in Harbin, Beijing, Shanghai, Guangzhou and Kunming, respectively. The temperature difference between the internal surface temperature of the wall and the temperature of the indoor comfort environment is used to characterize the wall thermal insulation effect. The smaller the temperature difference between the internal surface temperature of the wall and the indoor comfortable environment temperature, the better its ability to maintain a comfortable indoor thermal environment. The less heat is exchanged between urban housing buildings and the outdoor environment through the walls, the less energy is consumed by air-conditioning equipment to maintain the indoor thermal comfort environment. For simplicity of calculation, the indoor environment is set at 26°C, so the closer the internal surface temperature of the wall is to the 26°C reference line (black dotted line) and the smaller the fluctuation, the better the thermal insulation of the wall is represented. In all climatic zones, the internal surface temperature of the wall of the new hydrated inorganic salt composite material is closer to the indoor thermal comfort temperature than that of the ordinary thermal insulation material. And the fluctuation amplitude is smaller, which indicates that the new hydrated inorganic salt composite material has better thermal insulation effect than ordinary thermal insulation material in all climate zones, and has the effect of "peak cutting and valley filling". Compared with other climate zones, Harbin is located in the cold region of the wall surface temperature almost all year round in the indoor thermal comfort temperature of 26 ℃ or less, which indicates that the wall almost all year round is mainly thermal insulation, in order to block the heat loss to the outdoors. In the cold months of January and November, the gap between the internal surface temperature of the wall of the new hydrated inorganic salt composite material (averaging 24.23°C and 24.79°C, respectively) and that of the wall of the ordinary thermal insulation material (averaging 23.00°C and 23.63°C, respectively) is even more pronounced, which further verifies that the wall of the new hydrated inorganic salt composite material has better thermal insulation effect in the cold region. In Shanghai, which is a hot summer and cold winter region, the months in which the internal surface temperature of the wall of the urban housing building is below and above the indoor thermal comfort temperature of 26℃ each account for almost half of the year. Among them, the walls in this climate zone are mainly heat-insulated during January to March and October to December, and heat-insulated during April to September. In the hot months of June-August, the difference between the internal surface temperature of the new hydrated inorganic salt composite wall and the internal surface temperature of the wall of ordinary thermal insulation materials is large. Moreover, the internal surface temperature of the new hydrated inorganic salt composite wall is closer to the indoor thermal comfort temperature, indicating that the new hydrated inorganic salt composite wall has a better thermal insulation effect in the hot summer phase.



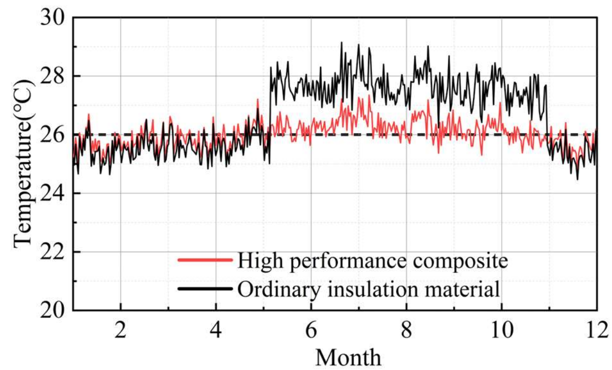
(a) Harbin



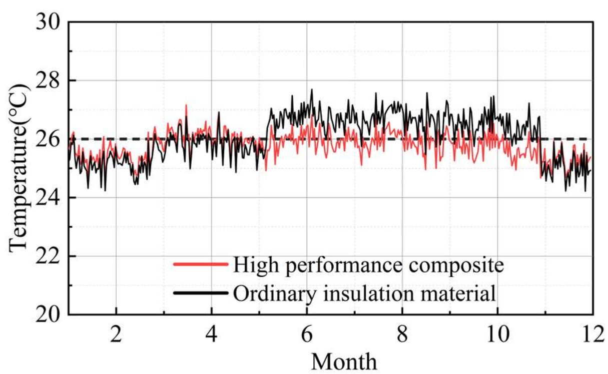
(b) Beijing



(c) Shanghai



(d) Guangzhou



(e) Kunming

Figure 2: Internal surface temperature of representative cities

IV. C. Results of simulation and analysis of energy consumption in urban housing buildings

In this section, the energy consumption simulation analysis of urban housing building models with ordinary insulation materials and high-performance composite materials is carried out respectively, and the results of the simulation analysis of the energy consumption of urban housing buildings in different climate zones are shown in Table 4. Compared with ordinary thermal insulation materials, the heating and cooling energy consumption of urban housing buildings mixed with high-performance composite materials in different climate zones is reduced. It can be seen that the application of new hydrated inorganic salt composite phase change materials in the walls of urban housing buildings can effectively reduce the energy consumption of buildings, and this energy-saving effect has been demonstrated in various climate zones in China. Further analysis shows that Harbin, which is in a cold region, is mainly dominated by heating energy consumption, while Guangzhou, which is in a hot summer and warm winter region, is mainly dominated by cooling energy consumption. Meanwhile, the heating energy consumption in Harbin is much higher than the cooling energy consumption in Guangzhou. Analyzing from the perspective of energy saving rate, for the application of high-performance composites in cities with different climate zones, the annual energy saving rate of housing buildings is 15.72% in Beijing, 14.80% in Kunming, 13.79% in Shanghai, 13.33% in Guangzhou, and 9.18% in Harbin in order of high to low. According to the data analysis, it can be seen that the energy saving rate and energy saving of cities in various climate zones are not consistent, and for such cities as Beijing and Harbin, which are mainly heating cities, have high energy saving efficiency, and the application of high-performance composite materials can reduce the heating energy consumption of Beijing and Harbin from 4,980.04kWh and 6,026.20kWh to 4,123.65kWh and 5,526.35kWh. In the In terms of refrigeration energy consumption, the annual refrigeration energy consumption of urban housing buildings in Shanghai and Guangzhou is 3925.84kWh and 4559.84kWh, respectively, and the simulation results show that the application of the new high-performance composite materials can reduce the refrigeration energy consumption to 3642.52kWh and 4112.35kWh, and the refrigeration energy-saving rate reaches 7.22% and 9.81%, respectively. The above results show that compared with ordinary thermal insulation materials, the new hydrated inorganic salt composite phase change materials have energy-saving benefits in urban housing buildings in various climatic zones in China, and such energy-saving benefits are more significant in cities with higher heating demand.

Table 4: Analysis of energy consumption of urban housing buildings (kWh)

City	Energy consumption		Refrigeration energy consumption		Total energy consumption	
	High performance material	General material	High performance material	General material	High performance material	General material
Harbin	5526.35	6026.2	1556.24	1772.49	7082.59	7798.69
Beijing	4123.65	4980.04	2942.56	3403.93	7066.21	8383.97
Shanghai	3564.25	4433.96	3642.52	3925.84	7206.77	8359.8
Guangzhou	625.34	906.68	4112.35	4559.84	4737.69	5466.52
Kunming	2234.52	2728.46	2765.35	3139.68	4999.87	5868.14

V. Conclusion

In this paper, a new type of high-performance hydrated inorganic salt composite material suitable for application in urban housing construction is prepared, which can achieve a very low density (474.040 kg/ m^3) and thermal conductivity (0.117 W/(m · k)), and still has a good compressive strength (1.407 MPa). It has a good application prospect in being used as an urban housing building and industrial thermal insulation material. COMSOL Multiphysics software was used to simulate and analyze the wall temperature and energy consumption in different urban housing buildings after the application of this material. Simulation results found that Harbin urban housing buildings in cold January and November, the application of composite materials wall body surface temperature (average respectively 24.23 ℃ and 24.79 ℃) and ordinary thermal insulation materials wall body surface temperature (average respectively 23.00 ℃ and 23.63 ℃) of the gap is more obvious, verified that mixed with composite materials of the wall in the cold region has a better thermal insulation effect. It was also found that the internal surface temperature of the composite wall was closer to the indoor thermal comfort temperature in June-August in Shanghai, which indicated that the wall with this material also had a better thermal insulation effect in summer. In addition, compared with ordinary thermal insulation materials, the application of the new hydrated inorganic salt composite phase change materials in the walls of urban housing buildings can effectively reduce the energy consumption of the building, and the annual energy saving rate of the housing building from high to low is 15.72% in Beijing, 14.80% in Kunming, 13.79% in Shanghai, 13.33% in Guangzhou, and 9.18% in Harbin. The above results show that the new composite materials prepared in this paper have high applicability in urban housing buildings in the five major climate zones in China, and can significantly reduce the energy consumption of housing buildings and achieve good thermal insulation and heat preservation effects.

References

[1] Liu, L., Zou, S., Li, H., Deng, L., Bai, C., Zhang, X., ... & Li, N. (2019). Experimental physical properties of an eco-friendly bio-insulation material based on wheat straw for buildings. Energy and Buildings, 201, 19-36.

[2] Wang, H., Chiang, P. C., Cai, Y., Li, C., Wang, X., Chen, T. L., ... & Huang, Q. (2018). Application of wall and insulation materials on green building: a review. Sustainability, 10(9), 3331.

[3] Abdelrady, A., Abdelhafez, M. H. H., & Ragab, A. (2021). Use of insulation based on nanomaterials to improve energy efficiency of residential buildings in a hot desert climate. Sustainability, 13(9), 5266.

[4] Huang, H., Zhou, Y., Huang, R., Wu, H., Sun, Y., Huang, G., & Xu, T. (2020). Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. Sustainable Cities and Society, 52, 101840.

[5] Chai, J., & Fan, J. (2022). Advanced thermal regulating materials and systems for energy saving and thermal comfort in buildings. Materials today energy, 24, 100925.

[6] Wang, J., Wu, X., Wang, Y., Zhao, W., Zhao, Y., Zhou, M., ... & Ji, G. (2023). Green, sustainable architectural bamboo with high light transmission and excellent electromagnetic shielding as a candidate for energy-saving buildings. Nano-Micro Letters, 15(1), 11.

[7] Streimikiene, D., Skulskis, V., Balezentis, T., & Agnusdei, G. P. (2020). Uncertain multi-criteria sustainability assessment of green building insulation materials. Energy and Buildings, 219, 110021.

[8] Xia, R., Zhang, W., Yang, Y., Zhao, J., Liu, Y., & Guo, H. (2021). Transparent wood with phase change heat storage as novel green energy storage composites for building energy conservation. Journal of Cleaner Production, 296, 126598.

[9] Jain, M., & Pathak, K. K. (2018). Thermal modelling of insulator for energy saving in existing residential building. Journal of Building Engineering, 19, 62-68.

[10] Junasová, B., Krajčík, M., Šikula, O., Arıcı, M., & Šimko, M. (2022). Adapting the construction of radiant heating and cooling systems for building retrofit. Energy and Buildings, 268, 112228.

[11] Fantucci, S., & Serra, V. (2019). Investigating the performance of reflective insulation and low emissivity paints for the energy retrofit of roof attics. Energy and Buildings, 182, 300-310.

[12] Le, V. T., Ha, N. S., Goo, N. S., & Kim, J. Y. (2019). Insulation system using high-temperature fibrous insulation materials. Heat Transfer Engineering, 40(17-18), 1523-1538.

[13] Xu, R., Wang, W., & Yu, D. (2019). A novel multilayer sandwich fabric-based composite material for infrared stealth and super thermal insulation protection. Composite Structures, 212, 58-65.

[14] Zhang, G., Wu, H., Liu, J., Yang, J., Huang, H., Ding, Y., & Xie, L. (2023, December). Dynamic performance and energy efficiency of reflective and insulative composite coating on building exterior wall. In Building Simulation (Vol. 16, No. 12, pp. 2245-2259). Beijing: Tsinghua University Press.

[15] González, B., & Prieto, M. M. (2021). Radiant heating floors with PCM bands for thermal energy storage: A numerical analysis. International Journal of Thermal Sciences, 162, 106803.

[16] Fang, Y., Ding, Y., Tang, Y., Liang, X., Jin, C., Wang, S., ... & Zhang, Z. (2019). Thermal properties enhancement and application of a novel sodium acetate trihydrate-formamide/expanded graphite shape-stabilized composite phase change material for electric radiant floor heating. Applied Thermal Engineering, 150, 1177-1185.

[17] Plytaria, M. T., Bellos, E., Tzivanidis, C., & Antonopoulos, K. A. (2019). Numerical simulation of a solar cooling system with and without phase change materials in radiant walls of a building. Energy Conversion and Management, 188, 40-53.

[18] Siligardi, C., Miselli, P., Francia, E., & Gualtieri, M. L. (2017). Temperature-induced microstructural changes of fiber-reinforced silica aerogel (FRAB) and rock wool thermal insulation materials: A comparative study. Energy and Buildings, 138, 80-87.

[19] Chan, K. Y., Shen, X., Yang, J., Lin, K. T., Venkatesan, H., Kim, E., ... & Kim, J. K. (2022). Scalable anisotropic cooling aerogels by additive freeze-casting. Nature Communications, 13(1), 5553.

[20] Lamy-Mendes, A., Pontinha, A. D. R., Alves, P., Santos, P., & Durães, L. (2021). Progress in silica aerogel-containing materials for buildings' thermal insulation. Construction and Building Materials, 286, 122815.

[21] Lucchi, E., Becherini, F., Di Tuccio, M. C., Troi, A., Frick, J., Roberti, F., ... & Bernardi, A. (2017). Thermal performance evaluation and comfort assessment of advanced aerogel as blown-in insulation for historic buildings. Building and Environment, 122, 258-268.

[22] Leroy, A., Bhatia, B., Kelsall, C. C., Castillejo-Cuberos, A., Di Capua H, M., Zhao, L., ... & Wang, E. N. (2019). High-performance subambient radiative cooling enabled by optically selective and thermally insulating polyethylene aerogel. Science advances, 5(10), eaat9480.

[23] Jun Ji,Chaoxiang Zhang,Wei Liu & Xuelai Zhang. (2024). Preparation of dodecahydrate disodium hydrogen phosphate shape-stabilized composite phase change materials and their experimental investigation in solar thermal storage and exothermic systems. Renewable Energy121284-121284.

[24] Nastasia Saca,Lidia Radu,Răzvan Calotă,Raul Augustin Mitran,Cosmin Romaniţan,Roxana Truşcă... & Ionuţ Radu. (2024). An investigation of the physic-mechanical properties of the expanded perlite mortars with thermal-activated concrete waste and microencapsulated paraffin. Heliyon(21),e39720-e39720.

[25] Peng Ai,Shuwei Tang,Da Wan,Wanrong Guo,Hao Wang,Pengfei Zhang... & Shulin Bai. (2024). Synergistic effect of lone-pair electron and atomic distortion in introducing anomalous phonon transport in layered PbXSeF (X= Cu, Ag) compounds with low lattice thermal conductivity. Materials Today Physics101572-101572.

[26] Dina Sami Kadhim,Jamela Saadi Aziz & Hawraa Khaleel Ibrahim. (2024). The Utilization of COMSOL MULTIPHYSICS and Exchanger Design Rating Software for Designing and Analyzing of Air Cooler. Defect and Diffusion Forum67-76.

[27] Sa Wang & Jun Zhao. (2014). Analysis on the Shape Features and Heat Consumption of the Qing-Official-Style Archaized Buildings. Applied Mechanics and Materials(584-586),99-103.