

# The Influence of Phase Change Aggregate Dosage on the Performance of Cement-based Self-insulating Wall Materials under Natural Curing Conditions

Qiuwang Jiang<sup>1</sup>, Liang Zhao<sup>1,\*</sup>, Liping Tian<sup>2</sup>, Xiaolong Li<sup>1</sup>, Xianliang Yin<sup>1</sup>

<sup>1</sup> College of Civil Engineering and Architecture, Yangtze Normal University, Chongqing, China

<sup>2</sup> Shaanxi Province Design and Research Institute of Building Materials Industry Co., Ltd., Xi'an, China

*\*Corresponding Author*

**Abstract:** In the process of urbanization in China, the high energy consumption of building wall materials has restricted the development of building energy conservation. Phase change materials (PCM) with phase change latent heat characteristics provide a way to improve the energy-saving performance of walls. This study focuses on the influence of phase change aggregates on the performance of self-insulating wall materials and explores the optimal dosage. The experiment uses water, cement, sand, and ceramsite as the base materials, and solid/liquid paraffin is used to prepare phase change aggregates. The dosage is adjusted to prepare cement-based specimens. After 7 days and 28 days of natural curing, the thermal conductivity, compressive and flexural strength are tested. The results show that the apparent density and water absorption rate affect the thermal conductivity through the coupling of pores and water conduction; the reduction of cement paste (thermal conductivity 1.2~1.5 W/(m·K)) will affect the thermal conductivity and weaken the mechanical properties. When the content of phase change aggregates: cement: water is 1.5:1:0.4, the comprehensive performance is the best: the thermal conductivity is 0.078 W/(m·K) (meeting the standard), the compressive strength is 19.93 MPa (meeting the non-load-bearing requirements), and the water absorption rate is 8.98% (which can be optimized by curing).

**Keywords:** Self-insulating Wall Materials; Phase Change Aggregates; Thermal Properties; Mechanical Properties

## 1. Introduction

Energy is closely intertwined with the

development of human society, and sustainable development has become a shared global goal. Since the 21st century, China has designated energy strategy as a major national development priority. Statistics show that current building energy consumption in China accounts for approximately 30% of the total social energy consumption [1]. Taking Shenzhen as an example, electricity remains the primary energy source for civil buildings in the city. Moreover, with the accelerated pace of urbanization, building energy consumption continues to rise. From the perspectives of energy structure and environmental impact, coal accounts for roughly 67% of China's energy mix. Its combustion gives rise to air pollution and solid waste discharge issues. Meanwhile, the construction industry, as a fundamental sector supporting the high-quality development of infrastructure and the rapid advancement of urbanization, is also a major consumer of energy and emitter of carbon. Lifecycle carbon emissions in the construction sector account for approximately half of China's total carbon emissions [2]. It is evident, therefore, that addressing energy and environmental challenges is crucial to achieving sustainable development.

Wall insulation constitutes a key link in building energy efficiency, and the performance of insulation materials directly determines insulation effectiveness. At present, the application of both organic and inorganic insulation materials is plagued by inherent shortcomings.

In the realm of organic thermal insulation materials, existing research has quantitatively compared the carbon emissions of five typical organic thermal insulation materials for construction—including EPS boards, XPS boards, rigid polyurethane boards, polyethylene boards, and phenolic resin boards—by

integrating the Life Cycle Assessment (LCA) method with the emission factor approach. Additionally, studies investigating the impact of photoaging on organic thermal insulation materials have been conducted [3-5]. Nevertheless, despite their widespread application, organic thermal insulation materials (e.g., polystyrene boards and polystyrene particles) are plagued by issues such as difficult-to-control construction quality and high fire risk [6]. In contrast, inorganic thermal insulation materials, while boasting advantages like flame retardancy and durability and witnessing rapid development, still pose challenges for traditional buildings in the selection of external wall insulation materials, particularly their low thermal insulation efficiency and high self-weight [7]. As such, both categories of materials hold room for performance optimization.

Phase Change Materials (PCMs), leveraging their latent heat storage capacity during phase transitions, offer a novel pathway for building energy efficiency. Research has demonstrated that the rational design and deployment of PCMs can reduce the peak load of heating systems; furthermore, the phase change temperature, thermal conductivity, and placement of phase change thermal storage materials exert a significant influence on energy-saving effectiveness. However, conventional PCMs suffer from poor compatibility with cement-based materials and insufficient thermal stability. These drawbacks can be effectively mitigated by encapsulating PCMs within porous aggregates to fabricate phase change aggregates.

As a core functional material for building energy efficiency, phase change materials (PCMs) offer three primary advantages: first, high heat storage efficiency—they exhibit high latent heat during phase transitions (e.g., paraffin-based PCMs can achieve a latent heat of 150–250 J/g), and their heat storage density far exceeds that of traditional materials, enabling efficient buffering of temperature fluctuations [8]; second, precise temperature regulation—their phase transition temperature can be tailored to the 20–30 °C range suitable for buildings, effectively maintaining stable indoor temperatures [9]; third, strong adaptability—they can be compounded with various building materials, and through technologies such as microencapsulation and

porous encapsulation, practical challenges including leakage, poor thermal conductivity, and high costs can be addressed [10]. Currently, global research on PCMs has shifted toward multi-functional composites; domestic research has yielded notable outcomes (e.g., PCM exterior wall application systems, high-stability composite PCMs), and their application scenarios have expanded from residential insulation to multiple fields, emerging as a key growth area for green building materials [11].

In this study, water, cement, sand, and ceramsite were used as base materials, while solid paraffin and liquid paraffin served as phase change components, and phase change aggregates were prepared via an encapsulation process. Subsequently, cement-based specimens were fabricated with different phase change aggregate contents and cured under natural conditions (for 7 days and 28 days, respectively). By analyzing the specimens' physical properties (apparent density, water absorption), thermal properties (thermal conductivity, heat storage and release efficiency), and mechanical properties (compressive strength, flexural strength), the mechanism by which phase change aggregate content influences the performance of phase change energy-storage self-insulating wall materials was revealed, providing a theoretical basis for advancing the development of phase change energy-storage wall materials.

## 2. Experiments

### 2.1 Experimental Materials

The raw materials for cement mortar preparation in this experiment are specified as follows: the cementitious material is P.O 42.5 Portland cement from China United Cement, with a density of 3.25 g/cm<sup>3</sup> and a specific surface area of 350 m<sup>2</sup>/kg; the fine aggregate is manufactured sand, which is classified as medium sand with a fineness modulus of 2.5 and conforms to the standard GB/T 14684-2022; the lightweight aggregate is ceramsite, featuring a particle size range of 0.5–0.8 cm, a bulk density of 500 kg/m<sup>3</sup>, and a cylinder compressive strength of 3.7 MPa; the mixing water is laboratory tap water; and the phase change materials (PCMs) include refined solid paraffin (composed of C18–C22 alkanes, with a melting point > 25 °C) and liquid paraffin (composed of C14–C16 alkanes or mineral oil, with a melting point < 20 °C).

## 2.2 Experimental Preparation

### 2.2.1 Preparation of composite paraffin prior to testing

The preparation of composite paraffin begins with raw material weighing using the differential method: first, the mass of an empty container is measured (accurate to 0.0001 g). Subsequently, solid paraffin (2–3 mm in particle size) and liquid paraffin (dispensed via a dropper) are added sequentially, with their masses recorded; the total deviation is controlled to be less than  $\pm 0.02$  g. After weighing, the sample is transferred to a beaker containing a magnetic stir bar and placed in an 80 °C water bath (with the water level reaching at least 2/3 of the beaker's depth). Stirring is initiated at a speed of 200–300 rpm, and the temperature difference of the melt is monitored to remain within 2 °C. Once the melt becomes transparent and homogeneous, stirring is continued for 30 minutes, with its state recorded every 5 minutes. The phase change temperature is measured using an infrared thermometer. If the temperature is higher than the target range, additional liquid paraffin is added; if lower, solid paraffin is supplemented. This adjustment process is repeated until the temperature stabilizes within  $23 \pm 2$  °C.

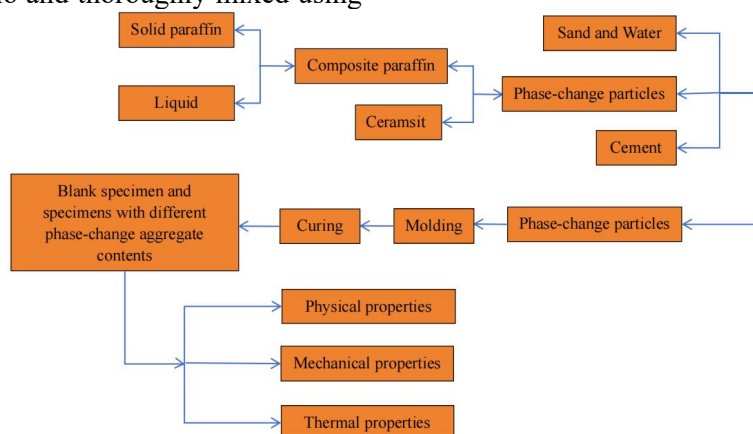
### 2.2.2 Preparation of phase-change aggregates

Ceramsite with a particle size of 0.5–0.8 cm (sintered from industrial solid waste, with a porosity > 60%) and composite paraffin featuring a phase change temperature of  $23 \pm 2$  °C were placed in an iron container at a predetermined ratio and thoroughly mixed using

a glass rod. The container was then transferred to a vacuum drying oven. After sealing, the vacuum valve was opened gradually, and the vacuum pump was activated 30 seconds later, allowing the vacuum gauge reading to increase at a rate of 0.02 MPa/min. Once the pressure reached -0.09 MPa and stabilized for 5 minutes, the vacuum valve was closed first, followed by the vacuum pump (a one-way check valve could be installed to prevent back-suction). The adsorption process was completed by setting the appropriate adsorption temperature and duration. After adsorption, the ceramsite was sieved to remove excess solution and transferred to an electric thermostatic blast drying oven at 80 °C for 12 hours of static drying, thereby completing the preparation of phase-change energy-storage aggregates.

### 2.2.3 Preparation of specimens

Cement-based specimens were prepared by mixing water, cement, sand, and the prefabricated phase-change aggregates in a predetermined ratio. The mixture was thoroughly stirred to ensure uniform integration of all components. Subsequently, the stirred mixture was molded into cement-based specimens. After molding, the specimens were subjected to natural curing for 7 days and 28 days, respectively. This process yielded a blank specimen (without phase-change aggregates) and specimens with different phase-change aggregate contents, which were used for subsequent tests of physical properties, mechanical properties, and thermal properties, as shown in Figure 1.



**Figure 1. Scope of Research**

## 2.3 Performance Testing

Cement mortar was mixed using a UJZ-15 mixer (mix proportion: 400g water + 1000g

cement + standard sand; mixing duration: 4min). Phase-change aggregates were placed, followed by mortar pouring and vibration compaction. After air-drying and demolding, the specimens

were cured in a YH-40B curing chamber ( $20 \pm 2^\circ\text{C}$ ,  $\geq 95\%$  humidity). The dry mass and volume of the dried specimens were measured, and the apparent density was calculated using the formula:

$$\text{Apparent Density} = \text{Dry Mass} / \text{Volume} \quad (1)$$

After curing, the specimens were dried and weighed. They were then immersed in water for 24 h to reach saturation; surface water was wiped off before weighing again. The water absorption rate was calculated using the formula:

$$\text{Water Absorption Rate} = (\text{Saturated Mass} - \text{Dry Mass}) / \text{Dry Mass} \times 100\% \quad (2)$$

The specimens were molded by vibration in molds. After curing, a DYE-2000 universal testing machine was used for compressive strength testing at a strength-controlled loading rate; the compressive strength was calculated by recording the load (formula:  $f_{cu} = P/A$ ). For flexural strength testing, a flexural testing machine was used with a loading rate of  $50 \text{ N/s} \pm 10 \text{ N/s}$ , and the flexural strength was calculated using the formula:

$$R_f = 1.5F_f L / b^3 \quad (3)$$

(Where  $L = 100 \text{ mm}$ ,  $b = 40 \text{ mm}$ ;  $F_f$  denotes the flexural failure load)

Specimens with dimensions of  $300 \text{ mm} \times 300 \text{ mm} \times 30 \text{ mm}$  were placed in a DRH-III thermal conductivity meter. Testing parameters were set for measurement, and the influence of aggregate content on thermal conductivity was analyzed.

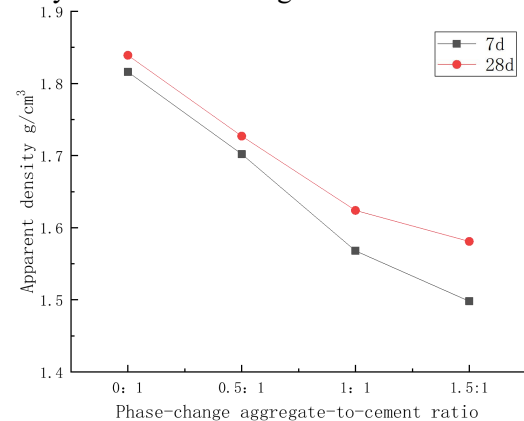
### 3. Analysis of Research Results

#### 3.1 Physical Properties of Specimens with Different Phase-Change Aggregate Contents (Apparent Density and Water Absorption)

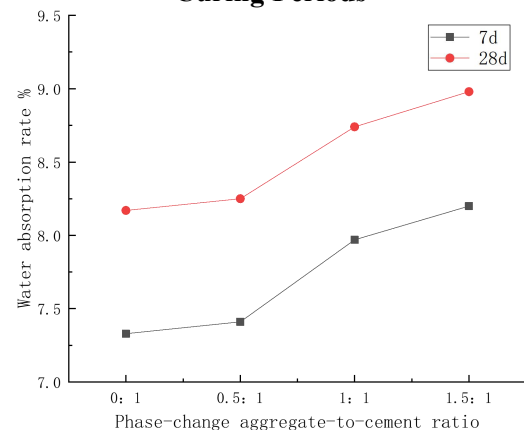
Mortar specimens prepared according to the optimized mix proportions were subjected to natural curing for 7 days and 28 days, respectively. After curing, tests for apparent density and water absorption were conducted on the specimens. A comparison of the test results between the 7-day and 28-day curing periods is presented in Figure 2 and 3.

From the perspective of apparent density variation, the apparent density of specimens cured for 7 days and 28 days both exhibited a decreasing trend with the increase in phase-change aggregate content. This phenomenon can be attributed to the intrinsic properties of phase-change aggregates, which exert a significant effect on reducing the overall

density of the cement mortar. Meanwhile, the apparent density of specimens cured for 28 days was generally higher than that of those cured for 7 days. This observation reflects that the evolution of the internal structure of cement mortar during extended curing periods exerts a certain influence on density; however, the core role of phase-change aggregates in reducing density remained unchanged.



**Figure 2. Comparison of Apparent Density Performance between 7-Day and 28-Day Curing Periods**



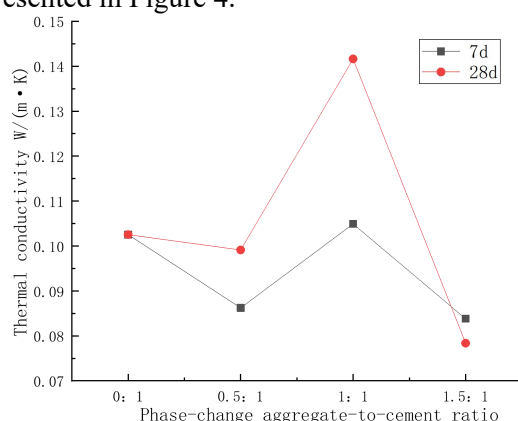
**Figure 3. Comparison of Moisture Content Performance between 7-Day and 28-Day Curing Periods**

In terms of water absorption variation, as the phase-change aggregate content increased, the water absorption of specimens cured for 7 days and 28 days both showed an upward trend. This indicates that phase-change aggregates possess a closed microporous structure internally. While this structure is conducive to the adsorption of phase-change materials, it also increases the channels for water adsorption. Furthermore, for specimens cured for 28 days, the continuous development of the internal structure enhanced the adsorption or retention effect of micropores on water, resulting in higher water absorption. In summary, an increase in phase-change

aggregate content leads to a decrease in the apparent density and an increase in the water absorption of cement mortar. Additionally, compared with specimens cured for 7 days, those cured for 28 days exhibited higher apparent density and water absorption. These results demonstrate that both curing duration and phase-change aggregate content jointly influence the physical properties of cement mortar.

### 3.2 Effect of Natural Curing on the Thermal Performance of Phase-Change Energy-Storage Self-Insulating Wall Materials

Mortar specimens fabricated according to the optimized mix proportions were subjected to natural curing for 7 days and 28 days, respectively. Subsequent to curing, thermal performance tests were conducted on the specimens, and a comparison of the test results between the 7-day and 28-day curing periods is presented in Figure 4.



**Figure 4. Comparison of Thermal Conductivity Performance between 7-Day and 28-Day Curing Periods**

The thermal conductivity of water is (0.6 W/(m·K)), which is significantly higher than that of air ((0.026 W/(m·K))) and phase-change aggregates (ceramsite) ((0.1–0.2 W/(m·K))). A higher water absorption rate of the material leads to a denser network of thermal conduction channels formed by internal moisture, thereby causing a more pronounced increase in thermal conductivity.

The influence of aggregate content is particularly prominent. When the aggregate content is low (less than (66.67%)), the water absorption rate rises with the increase in aggregate proportion — the water absorption rate of samples cured for 7 days increases from (7.33%) to (7.97%). The increased moisture

channels result in fluctuations in thermal conductivity. When the aggregate content is high (greater than (66.67%)), the insufficient cement paste interrupts the moisture channels, which in turn leads to a decrease in thermal conductivity. Specifically, the group with 28-day curing and an aggregate content of (160 g) exhibits a thermal conductivity as low as (0.078 W/(m·K)).

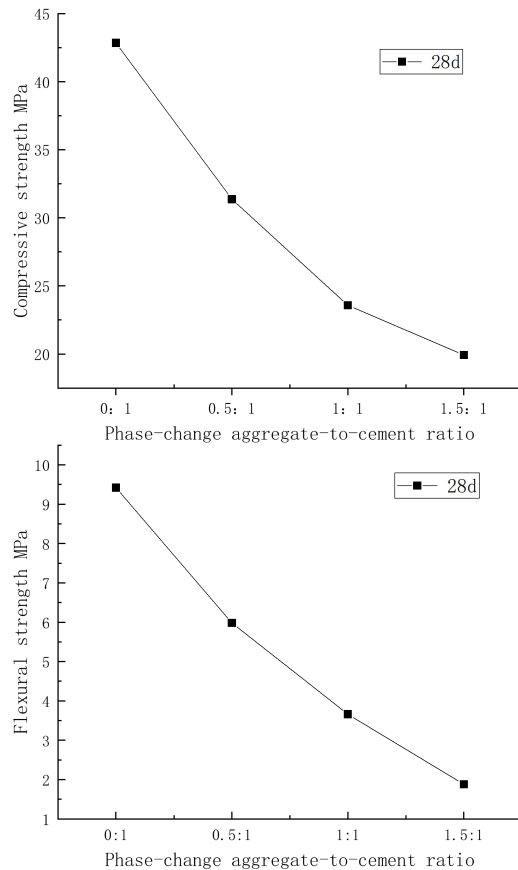
There is a coupling relationship between apparent density and water absorption rate. At low aggregate content, their effects offset each other, resulting in a relatively gentle change in thermal conductivity. At high aggregate content, the decrease in apparent density (the apparent density of the aggregate group is (1.581 g/cm<sup>3</sup>)) plays a dominant role, enabling the thermal conductivity to meet the thermal insulation standards. Additionally, phase-change aggregates can extend the thermal stability duration — the (160 g) aggregate group maintains thermal stability for approximately 2 hours, while the blank group only lasts for 1 hour. By leveraging the latent heat of paraffin (240 kJ/kg), these aggregates enhance thermal inertia, thereby buffering fluctuations in indoor temperature.

### 3.3 The Mechanical Properties (Compressive Strength and Flexural Strength) of Specimens with Different Phase Change Aggregate Contents

After 28 days of natural curing as conducted in the experiment, the tests for compressive strength and flexural strength were carried out, with the results presented in Figure 5.

As observed from the compressive strength variation in the left figure, the compressive strength of the specimens decreases continuously with the increase in aggregate content. When the aggregate content is 0%, the compressive strength is approximately 43 MPa; as the aggregate content increases to the phase-change aggregate-to-cement ratio of (1.5:1), the compressive strength drops to roughly 20 MPa, representing a significant decrease. This phenomenon indicates that the incorporation of aggregates significantly impairs the compressive capacity of the specimens, which may be attributed to factors such as the inherent strength of the aggregates themselves or their bonding performance with the mortar matrix.





**Figure 5. The Compressive Strength and Flexural Strength after 28 days of Natural Curing**

The variation trend of flexural strength in the right figure is consistent with that of compressive strength, also decreasing as the aggregate content rises. At an aggregate content of 0%, the flexural strength is about 9 MPa; when the aggregate content reaches the preset ratio (1.5:1), it falls to approximately 2 MPa. It is inferred that the addition of aggregates alters the continuity and integrity of the internal structure of the specimens, making them more prone to damage under bending loads. Consequently, the flexural performance of the specimens is notably adversely affected. In summary, under the condition of 28-day curing, the increase in aggregate content leads to a distinct downward trend in both the compressive and flexural strengths of the specimens. This finding reflects the significant influence of aggregate content on these two mechanical properties.

#### 4. Conclusions

**Physical Properties:** An increase in the content of phase-change aggregates significantly reduces the apparent density of the mortar. The

density of specimens cured for 28 days is higher than that of those cured for 7 days, yet the core role of aggregates in reducing density remains unchanged. The micropores within the aggregates increase moisture adsorption channels, leading to a rise in water absorption rate as the aggregate content increases. Notably, specimens cured for 28 days exhibit a higher water absorption rate, which reflects the synergistic effect of aggregate content and curing age on physical properties.

**Thermal Properties:** Apparent density and water absorption rate jointly influence thermal conductivity through a pore-moisture conduction coupling mechanism, with the high thermal conductivity of water dominating this correlation. At low aggregate content (less than 66.67%), the increased water absorption rate causes fluctuations in thermal conductivity. At high aggregate content (greater than 66.67%), insufficient cement paste interrupts moisture channels; coupled with the effect of reduced density, this results in a decrease in thermal conductivity. Additionally, phase-change aggregates can enhance thermal inertia and buffer indoor temperature fluctuations.

**Mechanical Properties:** Under 28-day curing, both compressive strength and flexural strength decrease significantly with the increase in aggregate content. This is attributed to the insufficient strength of the aggregates themselves and their poor bonding performance with the mortar matrix, which damage the structural continuity of the specimens. The strength reduction becomes particularly pronounced when the aggregate content reaches the preset ratio.

**Comprehensive Optimization:** A reduction in cement paste content affects both thermal conductivity and mechanical properties. The optimal comprehensive performance is achieved when the mix ratio of phase-change aggregate: cement: water is (1.5:1:0.4), with corresponding properties as follows: thermal conductivity of 0.078 W/(m·K), compressive strength of 19.93 MPa, and water absorption rate of 8.98%. To balance the material properties, it is recommended to control the aggregate content at  $\leq 100\%$  and optimize the curing process accordingly.

#### Acknowledgements

The present work was funded by Chongqing University Student Innovation and

Entrepreneurship Project(S202510647024), the Natural Science Foundation of Chongqing (CSTB2025NSCQ-GPX0422) and the Science and Technology Research Program of Chongqing Municipal Education Commission of China (No. KJZD-K202501401).

## References

- [1] Li, T. Y., Du, Q. T., & He, Z. D. (2025). Statistical analysis of energy consumption in civil buildings in Shenzhen in 2023. *Residential & Real Estate*, (20), 4–7.
- [2] Zhu, H. Y. (2022). Establishing and improving the carbon emission accounting system in the construction field. *Engineering Construction Standardization*, (03), 28–29.
- [3] Lin, Z. J., An, Y., & Zhou, Y. Q. (2025). Carbon emission assessment of typical organic thermal insulation materials for buildings based on life cycle assessment. *China Building Materials Science & Technology*, 34(04), 86–91.
- [4] Dong, F. L. (2025). Research on the application of organic external wall thermal insulation materials in construction engineering. *Architecture and Budget*, (05), 64–66.
- [5] Zhang W, Pan R, Wang J, et al. Effect of light aging on combustion characteristics and fire hazard of organic thermal insulation materials. *Journal of Building Engineering*, 2025, 104112346-112346.
- [6] Seunghwan W, Sungwoong Y, Uk Y K, et al. Toxicity characteristics and fire retardant performance of commercially manufactured organic insulation materials for building applications. *Construction and Building Materials*, 2022, 341.
- [7] Yan, C. C. (2025). Research on the application of composite thermal insulation materials in external wall insulation of energy-saving buildings. *Synthetic Materials Aging and Application*, 54(02), 67–69.
- [8] Miao H, Dengdeng X, Lian Y, et al. Influences of reduction temperature on energystorage performance of paraffin wax/graphene aerogel composite phase change materials. *Materials Today Communications*, 2023, 34.
- [9] Lü, S. H., Dai, Y. P., Lü, L. W., et al. (2025). Study on organic multi-component composite phase-change energy storage thermal insulation mortar and its application in residential buildings. *Jushe*, (23), 72–74.
- [10] Huo M, Huang C, Guo A, et al. Coal gasification slag derived mesoporous carbon-silicon-based carrier for enhancing energy storage performance of phase change materials. *Journal of Energy Storage*, 2025, 132(PB):117788-117788.
- [11] Xiang, Y. L., & Yang, X. (2025). Study on the node structure of phase-change energy storage materials applied in green buildings. *Foshan Ceramics*, 35(07), 78–80.