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Envelope Materials for Building: A Comparative Analysis for Enhanced Energy Efficiency and Sustainable Construction

Yunsheng Zhai

Yunnan College of Foreign Affairs & Foreign Language, Kunming, Yunnan, China

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Abstract: Against the backdrop of continuous growth in energy consumption and increasing environmental pressure, improving building energy efficiency has become an important issue that people have to face. The building envelope plays a crucial role in this. Although traditional building materials have superior structural performance, they have significant deficiencies in heat conduction and sound insulation. To solve this problem, this study compared the differences in energy efficiency, heat conduction performance, economy and sound insulation performance between traditional concrete, thermal insulation foam materials and nano thermal insulation materials. Among them, nano thermal insulation materials had the best performance in improving energy efficiency, with an increase rate of 48.7%. In the thermal conductivity performance test, the thermal conductivity of nano insulation materials was the lowest, with an average of 0.01 W/m·K. The cost-benefit ratio of nano thermal insulation materials in economic analysis was 0.2. In the final 24-hour sound insulation performance test, the average STC value of the nano insulation material was 65, indicating the most stable performance. From the specific experimental values, it can be seen that nano thermal insulation materials have significant advantages in improving building energy efficiency and improving sound insulation performance.

1. Introduction

With the continuous increase in global energy consumption and the increasingly prominent environmental issues, improving building energy efficiency has become an important issue in current society. The building envelope structure plays a crucial role in energy efficiency optimization, but traditional building materials still have many shortcomings in terms of heat conduction, sound insulation performance, and economy. In response to these issues, this study aims to evaluate the performance of different new insulation materials in terms of energy efficiency, thermal conductivity, economy, and sound insulation performance, and explore their potential in building applications.

Through four independent experiments, this study systematically analyzes the performance of three kinds of building materials, traditional concrete, thermal insulation foam materials and nano thermal insulation materials in many aspects. The research results indicate that nano thermal insulation materials have significant advantages in improving building energy efficiency and improving sound insulation performance. These findings provide new perspectives and basis for architectural design and material selection, promoting the development of green building technology.

This article first introduces the importance of improving building energy efficiency and the shortcomings of existing materials. In the method stage, material thermophysics is introduced, and strategy simulation is designed to integrate with intelligent control systems. The experimental results are presented and analyzed during the experimental phase, and the performance of different materials is compared. The final conclusion summarizes the main findings and proposes future research directions and practical application recommendations.

2. Related Works

A large amount of research has been devoted to improving the energy efficiency of building envelope structures. For example, in order to explore the influence of external surface materials on the thermal insulation effect of composite walls, Fan Zhixuan et al. studied the building composite walls in hot summer and cold winter areas (Ganzhou), established a one-dimensional unsteady thermal conductivity differential control equation to simulate the heat transfer process under periodic outdoor meteorological parameter conditions, and applied finite element method to numerically solve the heat transfer process of composite walls [1]. SiO2 aerogel is a kind of lightweight solid material with high porosity, which has low thermal conductivity, high transmittance, high specific surface area and excellent fire and moisture resistance. Li Binbin combined SiO2 aerogel with traditional building materials to produce new building wall insulation materials with excellent thermal insulation performance, such as new gel wallboard, aerogel felt, aerogel coating and aerogel gel mortar concrete [2]. In today's world energy situation, buildings account for nearly one-third of total energy consumption, with a considerable portion used for indoor air conditioning. Dong Y aimed to examine the quality, advantages, and disadvantages of several exterior wall insulation technologies, and provide suggestions on how to use various forms of exterior wall insulation under different climate conditions [3]. Given the current energy issue, building envelope structures must achieve insulation by consuming the least amount of energy, thereby minimizing energy consumption to the greatest extent possible. Aslan A determined the optimal thermal insulation thickness of exterior walls, ceilings and floors of 81 central buildings in Turkey, as well as the energy-saving effect and payback period [4]. Insulation has great potential in reducing building energy consumption. Danaci H M aimed to provide an overall perspective and understand the current state of technological development by reviewing the insulation materials used in the construction industry's history [5]. In cold regions, utilizing building exhaust gas to ventilate multi pane glass windows is an effective technique that can minimize window heat loss and save energy. Lami M introduced a method for managing the utilization of exhaust gases in window ventilation to optimize energy efficiency [6]. In the construction industry, carbon dioxide is the biggest environmental issue, which prompts people to research and develop new building systems and technologies to reduce greenhouse gas emissions that are harmful to the ozone layer. Therefore, Bangre A outlined the glass window technology for optimizing building energy efficiency [7]. However, these studies face issues such as high material costs and complex construction in practical applications, which limit their promotion.

To address the aforementioned challenges, researchers have proposed various innovative methods. For example, Chihab Y investigated the advantages of incorporating passive technology into multi-layer hollow clay brick walls to improve their dynamic thermal performance. The dynamic thermal response of walls under real thermal excitation in the Marrakech climate was analyzed using finite element method [8]. Carlier R evaluated the energy efficiency of switchable insulation systems in dynamic insulation of residential window sunshades and exterior walls in European countries such as Belgium and Spain. By analyzing the independent houses and apartments of typical residential buildings in Belgium, the energy performance of this system in terms of deployment on windows and exterior walls and rule-based operation control was determined [9]. Ji X studied the seismic performance of glass curtain wall systems under various load conditions and developed experimental devices and methods to test the performance of full-size fully tempered hollow glass curtain wall systems under three load schemes [10]. However, these methods still have shortcomings such as complex monitoring and high maintenance costs in practical applications. This article adopts a comprehensive evaluation method to comprehensively evaluate three types of building materials, in order to address these issues in current research.

3. Methods

3.1 Introduction to Material Thermophysics

In this study, three representative building materials, namely traditional concrete, thermal insulation foam materials and nano thermal insulation materials, are selected to evaluate their thermophysical properties. These materials are widely used in the construction industry, each with different physical properties and application advantages.

Traditional concrete is one of the most commonly used materials in construction, with good structural strength and durability. However, the high thermal conductivity of concrete means that it is prone to conducting heat, resulting in buildings being prone to heating up in summer and dissipating heat in winter, thereby increasing the energy consumption of air conditioning and heating. Although concrete has irreplaceable advantages in structural applications, its performance in energy conservation is relatively poor. The calculation formula for thermal conductivity (λ) is shown in Formula (1):

$$\lambda = \frac{Q \cdot d}{A \cdot \Delta T} \tag{1}$$

Among them, in Formula (1), Q is the heat conduction; d is the material thickness; A is the heat transfer area; ΔT is the temperature difference.

Thermal insulation foam is a kind of material widely used in building envelope in recent years. Its main component is usually polystyrene or polyurethane. This type of material has a lower thermal conductivity, approximately 0.03 to 0.06 W/m·K, which can effectively reduce heat conduction and improve the energy efficiency of buildings. In addition, the heat insulation foam material is light in weight and convenient in construction, which is suitable for heat insulation treatment of walls, roofs and other parts. However, the durability and anti-aging performance of thermal insulation foam materials are relatively weak, which requires regular maintenance and replacement.

Nanothermal insulation materials are currently one of the most advanced insulation materials, manufactured using nanotechnology and having extremely low thermal conductivity, typically between 0.005 and 0.015 W/m·K. Due to the microstructure characteristics of nanomaterials, they can significantly prevent heat conduction and provide excellent insulation performance. Nano thermal insulation materials can not only effectively reduce the energy consumption of buildings, but also have good durability and anti-aging performance, with a long service life. However, due to its complex manufacturing process and high cost, it still faces certain challenges in large-scale applications.

To sum up, traditional concrete, thermal insulation foam materials and nano thermal insulation materials have their own advantages and disadvantages, showing obvious differences in thermal physical properties. Although traditional concrete has high structural strength, its thermal insulation performance is poor; thermal insulation foam material has good thermal insulation performance and construction convenience, but its durability needs to be improved; nano thermal insulation materials exhibit excellent thermal insulation performance and durability, but their high cost and complex manufacturing processes limit their widespread application. By comprehensively evaluating the thermal and physical properties of these materials, scientific basis can be provided for selecting the most suitable materials for different building needs, thereby achieving optimization of building energy efficiency and energy-saving goals [11-12].

3.2 Design Strategy Simulation

When studying the optimization of building energy efficiency, the advanced computer simulation technology is used to analyze the energy efficiency impact of different design schemes in detail. This is not only about considering materials, but also includes various factors such as wall thickness, window configuration and size. Especially for the thickness of the wall, several different thicknesses of 10 centimeters, 20 centimeters, and 30 centimeters are tested, and it is found that the thickness of the wall directly affects the thermal conductivity. Thick walls can better prevent heat penetration, help reduce the temperature difference between indoor and outdoor, and thus save energy. However, thickening the walls also means more materials and construction costs. The total thermal resistance of the wall can be expressed by Formula (2):

$$R_{total} = \sum_{i=1}^{n} R_i \tag{2}$$

In Formula (2), R_i represents the thermal resistance of each layer of material.

Window design is another key variable. The performance of single-layer glass, double-layer glass, and three-layer glass windows is simulated. The results show that multi-layer glass windows have better thermal insulation performance than single-layer glass windows, which can significantly reduce heat conduction through the windows. Especially three-layer glass windows can effectively reduce indoor heat loss in winter and prevent external heat from entering the room in summer, thereby reducing energy consumption for air conditioning and heating. However, despite the excellent energy efficiency of multi-layer glass windows, their manufacturing and installation costs are relatively high. Therefore, the selection of window types should comprehensively consider energy efficiency and economy.

When simulating building energy efficiency optimization, the position and size of windows are crucial. A good window design not only fully utilizes natural light and reduces reliance on artificial lighting, but also utilizes natural ventilation to reduce the use of air conditioning, which can save a lot of energy. The simulation software is used to analyze the impact of different window configurations on energy efficiency, especially the different effects of north-south windows in different seasons. Research has found that in winter, the south window can utilize solar heat to increase indoor temperature; in summer, the north window helps to reduce solar thermal radiation entering the house. These data help make more scientific decisions in design, greatly improving the energy efficiency of buildings and helping to achieve energy-saving and environmental protection goals by optimizing wall thickness, selecting the right window type and layout. These simulation studies not only lay a theoretical foundation for this research, but also provide practical reference for future building design and energy efficiency optimization [13].

3.3 Integration of Intelligent Control Systems

In the research on improving building energy efficiency, modern buildings not only rely on materials and design, but also need to optimize energy consumption management through intelligent control systems. This study applies advanced intelligent control technology and combines it with building envelope structures to achieve dynamic energy-saving optimization through real-time monitoring and adjustment of internal environmental parameters. The core of an intelligent control system is to monitor environmental parameters such as temperature, humidity, and light intensity inside and outside the building in real-time through a sensor network. Humidity control is achieved by arranging humidity probes inside the warehouse, collecting temperature and humidity signals into the PLC and enabling the humidity control function block in the program to control the start and stop of the humidifier. Temperature control is similar to humidity control, which is achieved by comparing the actual value of sensors with the set value, using control function blocks such as compressors and expansion valves in the program, as well as corresponding data blocks. Wind speed control detects the deviation between the set wind speed value and the measured value, and calls the corresponding wind speed control function block. The PLC outputs voltage signals to the frequency converter for variable speed regulation. In addition, the designed system can automatically adjust the lighting and ventilation system according to the intensity of indoor personnel activities, achieving optimal energy efficiency.

The intelligent control system not only ensures the efficient operation of equipment, but also achieves long-term monitoring of building energy use. By analyzing the environmental and energy data collected over a year ago, it is found that the energy consumption of the office building is abnormally high from noon to afternoon in summer. After further investigation, it is recommended to install a smart window system to reduce the use of air conditioning. This type of window can automatically adjust its light transmittance according to changes in sunlight and temperature, which not only helps reduce energy consumption but also improves the comfort of the indoor lighting environment. By integrating with other intelligent systems in the building, these smart windows can also be optimized and adjusted according to the overall energy efficiency strategy.

4. Results and Discussion

4.1 Energy Efficiency Improvement Index Experiment

In the energy efficiency improvement index experiment, the impact of different building envelope structure schemes on energy efficiency improvement is evaluated. In the experiment, three materials are chosen: traditional concrete, thermal insulation foam and nano thermal insulation materials. The specific data situation is shown in Figure 1.

Among all the experimental conditions in Figure 1, the scheme using nano thermal insulation materials, a wall thickness of 30cm, and a three-layer glass window combination performs the best, with an energy efficiency improvement percentage of 48.7%. In contrast, the traditional concrete material, wall thickness of 10cm, and single-layer glass window combination scheme have the lowest improvement effect, with an energy efficiency improvement of only 12.3%. From the data conclusion, it can be seen that optimizing the design of building envelope structures can significantly improve energy efficiency and has important application value.

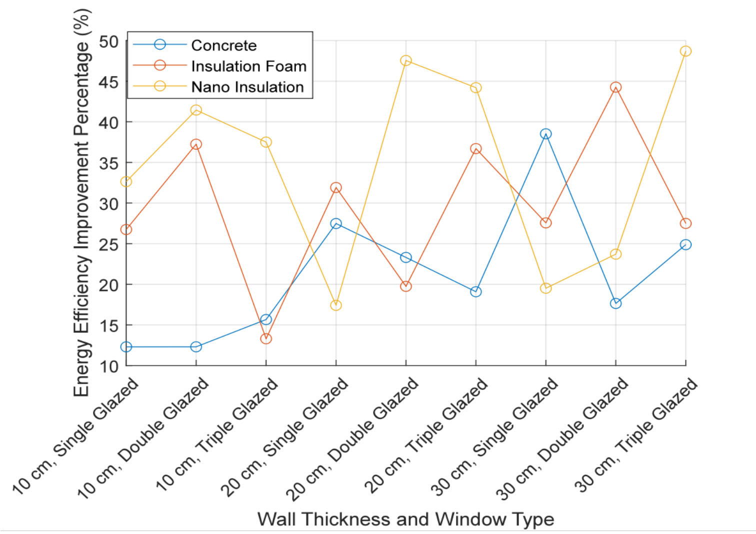

Figure 1: Evaluation of energy efficiency improvement indicators

4.2 Thermal Conductivity Evaluation Experiment

In the thermal conductivity evaluation experiment, the thermal conductivity of three building materials is evaluated, and each material is subjected to a heat flow meter test to measure its thermal conductivity. The experimental data includes 10 samples of each material, and the results are used to compare the thermal insulation performance of each material.

In Figure 2, it is found that the thermal conductivity of the nano thermal insulation material is the lowest, with an average of 0.01 W/m·K, indicating the best performance. The thermal insulation foam material takes the second place, and the average thermal conductivity is 0.045 W/m·K. Traditional concrete has the highest thermal conductivity, averaging 2.0 W/m·K. From the experimental data, it can be seen that selecting materials with lower thermal conductivity, such as nano insulation materials, can significantly improve the energy efficiency of buildings. As shown in Figure 2:

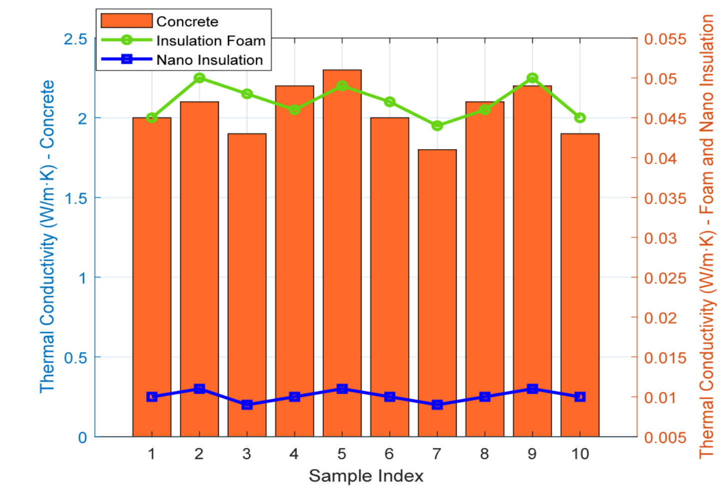

Figure 2: Evaluation of thermal conductivity performance

4.3 Economic Analysis Experiment

The purpose of this experiment is to evaluate the economy of three building materials (traditional concrete, thermal insulation foam materials, and nano thermal insulation materials). The cost-benefit ratio (CBR) for each material is determined by calculating the installation cost and energy-saving benefits per square meter of material. The experimental data shows that although the cost of nano thermal insulation material is high, its energy saving effect is significant, and the thermal insulation foam material has achieved a good balance between cost and energy saving benefits. The specific data situation is shown in Table 1:

Table 1: Economic analysis evaluation

Material	Cost(USD/m²)	Annual Savings(USD/m²)	Cost_Benefit_Ratio
Concrete	50	5	0.1
Insulation Foam	70	15	0.214
Nano Insulation	150	30	0.2

In Table 1, the cost-benefit ratio of traditional concrete is 0.1; the thermal insulation foam material is 0.214; the nano thermal insulation material is 0.2. Although the initial cost of nano thermal insulation materials is 150 USD/m², their significant energy-saving benefits of 30 USD/m² per year make them a cost-effective choice. The thermal insulation foam material achieves the best balance between the cost of 70 USD/m² and the energy-saving benefit of 15 USD/m² per year, and has the highest cost-benefit ratio. Therefore, when selecting building materials, a comprehensive consideration should be given to initial costs and long-term energy-saving benefits.

4.4 Sound Insulation Performance Analysis Experiment

In the sound insulation performance analysis experiment, the changes in sound insulation performance of three building materials within 24 hours are evaluated. In the experiment, the STC value is measured every hour and the fluctuation of sound insulation performance is recorded within 24 hours.

In Figure 3, after 24 hours of sound insulation performance testing, the average STC value of the nano insulation material within 24 hours is about 65, indicating the most stable performance. The average STC value of thermal insulation foam material is about 45, which is medium. The average STC value of traditional concrete is about 55, which is the most unstable. From the data results, it can be seen that the nano thermal insulation material has the most stable and superior sound insulation performance within 24 hours, and is suitable as a high-performance sound insulation material. The specific data situation is shown in Figure 3.

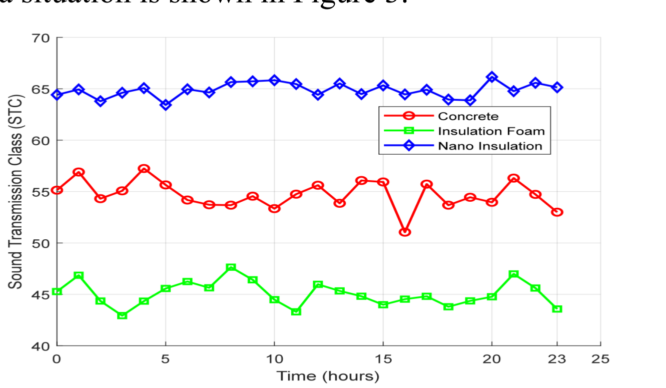

Figure 3: Sound insulation performance evaluation

5. Conclusion

The performance of traditional concrete, thermal insulation foam materials and nano thermal insulation materials in building energy efficiency, heat conduction, economy and sound insulation was compared. The research found that nano thermal insulation materials performed excellently in various aspects, especially in improving energy efficiency and sound insulation performance. Although the initial cost of this material is relatively high, its long-term energy-saving effect can compensate for this. However, in order for this material to be widely used, it is necessary to further reduce production costs and improve production processes. In addition, combined with intelligent control systems, the application effect of these high-performance materials may be more significant. It is hoped that future research can expand the sample size, cover more types of materials, and further validate the universality and reliability of these findings. Overall, this study provides valuable references for the selection of building materials and architectural design, and helps promote the development of the construction industry towards more energy-efficient and environmentally friendly directions.

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