Thermal Conductivity of External Wall Insulation Materials for Buildings

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บทคัดย่อ การศึกษานี้ได้ดำเนินการตรวจสอบความสำคัญเชิงปฏิบัติของเทคโนโลยีฉนวนผนังภายนอกสำหรับการก่อสร้างอาคาร การศึกษาจะบ่งชี้ว่าฉนวนผนังภายนอกช่วยเพิ่มความสะดวกสบายให้กับผู้อยู่อาศัยและเพิ่มการปกป้องอาคาร และระบุถึงความสำคัญในการคัดเลือกวัสดุและวิธีการก่อสร้าง ด้วยกรณีศึกษาจากการวัดค่าการนำความร้อนโดยใช้วัสดุหลัก ได้แก่ แผ่นโพลีสไตรีน (EPS) แผ่นโฟมโพลีสไตรีนอัดรีด (XPS) ปูนฉนวนกันความร้อน แผ่นฉนวนโฟมซีเมนต์และสินแร่ฉนวนหายาก ผลการศึกษาพบว่า ค่าการนำความร้อนของวัสดุแต่ละชนิดจะแตกต่างกัน และสำหรับวัสดุชนิดเดียวกันภายใต้สภาวะที่ต่างกันมีค่าการนำความร้อนนที่แตกต่างกันโดยระดับความชื้นของวัสดุฉนวนจะส่งผลต่อการนำความร้อนเช่นกัน การศึกษานี้พบว่า EPS และ XPS มีความเหมาะสมสำหรับใช้เป็นฉนวนผนังภายนอกในประเทศจีนมากกว่าวัสดุอื่น ๆ ความจำเป็นในการเลือกวัสดุฉนวนที่เหมาะกับบริบทด้านสิ่งแวดล้อมที่เฉพาะเจาะจงชี้ให้เห็นว่า แม้ว่าฉนวนจะมีแนวโน้มที่ดี แต่ก็ยังควรมีมาตรฐานที่เข้มงวดในการก่อสร้างด้วย

คำสำคัญ : ฉนวนกันความร้อนผนังภายนอก, การนำความร้อน, วัสดุฉนวนกันความร้อน

Abstract This study examines the practical significance of external wall insulation technology in building construction. The study emphasizes that external wall insulation improves occupant comfort and increases building protection, and should focus on materials and methods, using case study methods and thermal conductivity measurements. The main materials include polystyrene panels (EPS), extruded polystyrene foam panels (XPS), thermal insulation mortar, cement foam insulation boards and rare earth insulation materials. The results of the study revealed different thermal conductivities of different materials, and the same materials under different conditions. The moisture levels of insulation materials affecting the thermal conductivities were also highlighted. The conclusion showed that EPS and XPS were more suitable for use as external wall insulation in China. The necessity of selecting insulation materials tailored to specific environmental contexts points out that although insulation is promising, there should still be strict standards in construction.

Keywords: External Wall Insulation, Thermal Conductivity, Insulation Materials.

1. Introduction

In China, with the escalation of urbanization and the improvement of people's living standards, the average yearly national energy consumption growth rate is about 7.5 % [1] and in current construction projects, the utilization of external wall insulation technology carries significant practical value, not only meeting China's energy conservation and emissions reduction obligations but also contributing to the establishment of a sustainable society [2]. Without this technology, occupants would face considerable discomfort during varying seasons. The implementation of external insulation considerably improves living conditions, improving the indoor environment and atmosphere [3].

External wall insulation technology has been applied as a building's protective outer layer [4]. This thermal insulation layer regulated itself, reducing wall cracks and ensuring public safety. Such external wall insulation materials have been found to be applied in domestic buildings across both northern and southern regions to maintain a comfortable indoor temperature. EPS (expanded polystyrene insulation utilizes a blowing agent, steam and molds to expand the polystyrene into the final product), XPS (Extruded polystyrene insulation using blowing agents, heat, and an extruding machine to create the insulation sheets), PU (Polyurethane) foam, rock wool, and glass wool, are commonly used for exterior wall insulation, each offering distinct advantages [5, 6, 7]. Researchers revealed that XPS and EPS insulation schemes were the compromise choices, while the rock wool insulation scheme was the last option. The study could facilitate the implementation of building envelope retrofit by providing useful guidance for the selection of external wall retrofit schemes.

Known for superior thermal insulation performance, EPS has been widely used in external wall insulation systems [8]. XPS possesses a closed-cell honeycomb structure, resulting in low water absorption, high compression resistance, and resistance to aging [6]. PU foam is excellent in insulation properties and fire resistance [7]. Rock wool and glass wool serve as inorganic fiber insulation materials with resistance to high temperatures and fire [9]. Further, thermal insulation mortar and foamed cement technology contribute to constructing building surface insulation layers and concrete structures, respectively [10]. white, heat preservation paint, when applied to surfaces, provides insulation, contributing to energy efficiency [11].

Thermal conductivity, denoted by the coefficient λ (W/m·K), indicates the amount of thermal conductivity through an object per unit area, a unit of the temperature difference, and time [12]. Insulation materials, often porous or fibrous, are greatly influenced by density and humidity. Materials with a thermal conductivity below 0.2 (W/m·K) are generally termed thermal insulation materials, with those below 0.12 (W/m·K) considered high-efficiency thermal insulation materials [5]. The greater the thermal conductivity, the less effective the insulation. Therefore, thermal conductivity points out the inverse relationship between temperature change and insulation.

Density, represented by ρ (kg/m^3), can be determined by measuring mass per unit volume. Materials with higher porosity led to increased heat transfer through pores. The porosity that is percentage volume occupied by pores (N) can be evaluated from

$$N=(V1/V2) \times 100 \quad \ldots (1)$$

where V1 is pore occupied by the volume (m^3) and V2 is the overall volume of material (m^3). Porosity significantly impacts thermal conductivity. The higher porosity results in lower conductivity. It is critically practiced to balance density to ensure minimal moisture absorption and meet strength requirements without compromising performance.

Moisture content in insulation materials is affected by both free water and surrounding humidity. The percentage humidity (W) can be calculated using the formula,

$$W=(G1-G2)/G2 \times 100 \quad \ldots (2)$$

where G1 is the wet specimen weight and G2 is the weight in a dry state [11]. Managing moisture is essential, considering its influence on material weight, volume, and water content. Maintaining optimal density, balancing porosity, and addressing moisture concerns contribute to the effectiveness of insulation materials collectively.

Upon exposure to moisture, the material's thermal conductivity significantly increases. The pore space gas typically consists of air with a low thermal conductivity of 0.03 (W/m·K). In comparison, water exhibits much higher thermal conductivity, approximately 0.58 (W/m·K), which is 20 times that of air. Conversely, ice registers a thermal conductivity of about 2.3 (W/m·K), 78 times that of air and four times that of water, particularly when the temperature drops below zero [12]. The initial freezing involves unrestricted water in rough pores and capillaries, and as the temperature further decreases, restrained water progressively solidifies, resulting in an elevated thermal conductivity coefficient [13].

Table 1 shows the variation of the thermal conductivity of red bricks in their natural state with moisture content [14]. Change of thermal conductivity of red bricks with moisture content is common in the natural state. The wet condition of the thermal insulation material has a great influence on the thermal conductivity coefficient. Therefore, the moisture-proof construction of the enclosure is very important, and it must be ensured that the thermal insulation material is not seriously affected by moisture. And can timely discharge moisture to the outside.

Table. 1 Thermal conductivity of red bricks.

Moisture (%)	7.57	3.54	2.01	0.00
λ	1.60	1.20	0.80	0.60
λ: Thermal conductivity, W/m·k				

Examining influential characteristics such as exterior surface, brick wall thickness, brick and insulation material, and orientation differential insulation thickness has been crucial in previous investigations [15]. Researchers were concerned with the numerical simulation of external wall insulation system durability for buildings in regions with hot summers and cold winters. This study focused on the durability of EPS insulation, offering valuable insights for the design and durability assessment of other insulation materials. Common durability issues in external thermal insulation systems, like cracking, hollowing, and detachment, significantly impact safety and energy efficiency [16]. In addition, the thermal performance of the three usual insulation materials (polyurethane, polystyrene, and mineral wool) dimension at 2.4 m. × 2.4 m. × 2.4 m. were constructed and measured throughout a year of summer and winter conditions [17]. Further, Zhang and coworkers emphasized that extruded polystyrene (XPS) and expanded polystyrene (EPS) insulation schemes were the compromise choices, while the rock wool insulation scheme is considered the last option. The study had the potential to ease the implementation of building envelope retrofit projects by offering useful guidance for selecting external wall retrofit schemes [18].

A significant disparity in the design standards for the heat transfer coefficient of residential building envelopes exists between China (Northern and Southern) and foreign countries [16]. Table 2 provides a brief comparison of the thermal conductivity of domestic and international building envelopes [19].

The identification of materials suitable for domestic buildings in both northern and southern regions to maintain a comfortable indoor temperature is a fascinating pursuit. This study explored different external wall insulation materials under various conditions to identify the most suitable for improving insulation efficiency. It included assessing the thermal conductivity of building materials' fresh and dry external wall insulation, as well as analyzing engineering practice cases.

Table. 2 Thermal conductivity of building envelopes.

No.	Area	Thermal conductivity, λ (W/m*K)		
		Roofs	Exterior Walls	Exterior Windows
1	Beijing	1.26	1.70	6.40
2	Harbin	0.77	1.28	3.26
3	England	0.45	0.45	2.40
4	Japan	0.23	0.42	2.33
5	Sweden	0.12	0.17	2.00
6	Canada	0.17	0.27	2.22
7	Denmark	0.20	0.30	2.90
8	Germany	0.22	0.50	1.50

2. Materials and Methods

2.1 Apparatus

A thermal conductivity apparatus in our laboratory was employed to determine the thermal conductivity of a given material (Figure 1). According to Fourier's law of heat conduction, the testing procedure could be founded on the law of one-dimensional thermal conduction, which describes how heat is transferred through materials (Figure 2). The device's testing method involved precisely gauging the temperature change on a sample and utilizing the law of thermal conduction to compute the thermal conductivity.

In the conventional approach, an unknown sample was sandwiched between two known reference samples in a plate method thermal conductivity tester. Additional consideration was given to minimizing even the minute heat losses. The procedures to measure and evaluate the thermal conductivity of materials were employed as following.

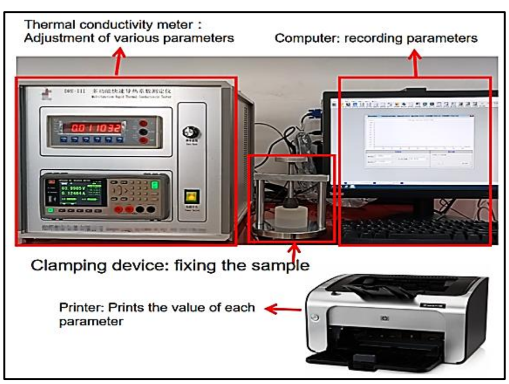

Fig. 1. Thermal conductivity meter.

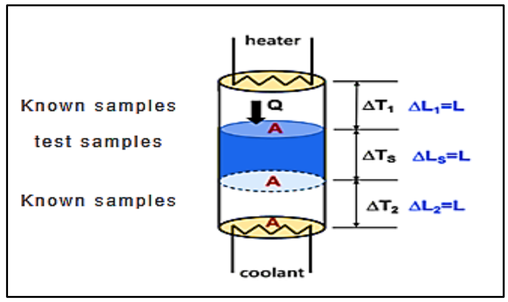

Fig. 2. The principle of conduction.

1). Pre-treatment: A thermal conductivity meter with a certificate of conformity was used. Before switching on the instrument, the whole instrument had to be pre-treated, mainly to enable the components to achieve relatively stable state, such as heaters, temperature measurement resistors and so on.

2). Sample preparation: The sample preparation was also a key step in the thermal conductivity experiment; the size and geometry of the sample must meet the requirements of the general requirements of the sample area was greater than the area of the shape of the insulation plate, in order to ensure effective heat transfer.

3). sample clamping: the sample was placed between two pieces of spacing between the insulation plate and would be clamped to ensure that the sample would not move and fall off.

4). Mounting the thermistor: The thermistor was fixed in the middle of the sample to measure the temperature difference and heat flux of the sample.

5). Apply temperature gradient: The heater was fed into the constant current source to start heating, and the temperature of the location on another holding plate was measured to ensure that a certain temperature difference was created. All tests were performed at room temperature of 20 ℃, the sampling time interval was 1,000 ms, and the over all test took 160 seconds.

6). Calculation of experimental data: The measurement data (λ) were collected to obtain the thermal conductivity of the sample.

With the previous moisture content combined with a thermal conductivity meter, we could derive different thermal conductivities.

2.2 Materials

Ten pieces of samples representing 5 major external wall insulation materials (1. EPS, 2. XPS, 3. insulation mortar, 4. fly ash or cement foam insulation board, and 5. rare earth) were prepared for experimentation. The samples, sizing 300 mm x 300 mm and with a thickness not exceeding 50 mm, were prepared according to thermal conductivity tester specifications. The insulation panel samples, and slurry materials obtained from the construction site and manufacturers, respectively, were the primary selections for building insulation material. Following the consideration of moisture absorption effects, the materials were stored under laboratory conditions with normal temperature and humidity for over 90 days.

3. Results and Discussion

The tested thermal conductivity of various samples was shown in Table 3. Such data were calculated from fresh and dry samples.

Without considering external factors, it was evident from this dataset that thermal insulation mortar containing XPS, EPS, and polystyrene particles exhibited lower thermal conductivity and better insulation effectiveness than the others. Specifically, XPS and EPS showed the best outcomes; these materials were commonly used in construction for thermal insulation.

Another set of data would be acquired upon placing experimental blocks in a highly arid setting, completely secluded from water vapor and safeguarded against any moisture or water. The blocks would then be left to be tested for a duration of 90 days. Subsequently, the resulting thermal conductivities were also shown in Table 3.

Table. 3 Thermal conductivity of the tested material.

External wall material insulation		**Thermal conductivity, λ (W/m*K)**		
		Before drying	After 90 days drying	The Difference
1. XPS	from A	0.027	0.028	≅ 0.000
	from B	0.033	0.031	≅ 0.000
2. EPS	Rigid from C	0.039	0.040	≅ 0.000
	Lightweight from D	0.070	0.069	≅ 0.000
3. Mortar	Interior from E	0.095	0.066	≅ 0.030
	Exterior from F	0.146	0.069	≅ 0.077
4. Fly ash	from K	0.162	0.068	≅ 0.094
5. Rare earth	from L	0.157	0.080	≅ 0.077

From the experimental data, the results were clearly indicated as follows. XPS possessed low density (from its nature) and low thermal conductivity and provided good strength and aging resistance. EPS also exhibited low thermal conductivity but offered poor strength and aging resistance. The EPS wall, used in building construction, was very easy to break. Measured data from the field sampling could be seen in many projects using such materials were not only a large thermal conductivity and poor strength could not meet the requirements.

While mortar (polystyrene particles thermal insulation), a big category in the building insulation materials market, was still the mainstream. Its lower prices and convenience in construction were the priority choice of customers. However, the mortar showed thermal conductivity. Finally, rare earth showed the largest thermal conductivity value of 0.080 – 0.090.

Upon comparing and analyzing the data, it was apparent that the measured thermal conductivity of both XPS and EPS panels from various manufacturers coincided well under adiabatic conditions. It was necessary to note that other external factors were not taken into consideration. Common insulation materials had varying market appeal depending on cost and construction requirements. Within the new construction sector, the XPS board held a promising future due to its systematic and professionally supported construction team. This material had the potential for further development. Existing building renovation projects benefited from polystyrene granule thermal insulation mortar, which had practical use.

Effective management of engineering projects was a necessary prerequisite to ensure that the project ran smoothly. The construction unit had to pay great attention to it [20]. Hence, the supervision system and regulatory system were established with reference to the construction conditions and construction status. Effective management according to the regulations, especially the selection of materials [21].

Through the introduction of the mentioned types of materials and experimental calculations in different environments, while taking into account the humidity of the outside world, the common thermal insulation materials were applied to different environments. The practical experience from the construction sites' detailed recommendations was presented in Table 4.

Table. 4 Commonly used materials for exterior wall insulation

No.	Name	Application	Advantages:	Disadvantages
1	XPS	Common thermal insulation materials	1. More compact 2. Low water absorption	1. Costs more than EPS
2	EPS	Common thermal insulation materials	1. Easy to cut and install 2. Effectively reduce heat loss	1. Flammable
3	PU	Buildings requiring higher insulation properties	1. Better fire resistance 2. Quality is also lighter	1. High cost
4	Rock wool	Common materials	1. Inorganic fiber insulation materials 2. Good temperature/fire resistance	1. Absorb water easily 2 Crush/crack easily

Table. 4 Commonly used materials for exterior wall insulation (continue)

No.	Name	Application	Advantages:	Disadvantages
5	Glass wool	Common materials	1. Inorganic fiber insulation materials	1. Fragile 2. Single use only
6	External wall insulation coatings	Sprayed onto the surface of an exterior wall	1. Environmentally friendly 2. Convenient	1 High price 2 Poor fire performance
7	Cement Foam	Common thermal insulation materials	1. Non-combustible 2. Moisture resistant	1. Hight weight 2. High price
8	Rare earth	1. High-temperature environments 2. Special industrial buildings: 3. High-end construction projects	1. Excellent thermal insulation 2. High temperature resistance	1 Very high price 2 Resource constraints

4. Conclusion

1. It could be proved that in the natural dry state XPS, EPS sheet thermal conductivity coefficient by the material hygroscopicity effect was very small.

2. The polystyrene particles thermal insulation mortar, physical foaming of low alkali cement fly ash mechanical casting molding thermal insulation light board, rare earth perlite thermal insulation materials such as measured thermal conductivity and manufacturers in the adiabatic conditions measured thermal conductivity had a large difference, with some even showing differences of more than double. 3. The thermal conductivity of these insulation materials by the material hygroscopic influence. This discrepancy was attributed to the hygroscopic influence on the thermal conductivity of these insulation materials.

4. In essence, the thermal conductivity of these materials at room temperature was closely linked to the moisture content, with moisture content being a crucial factor affecting thermal conductivity.

5. Prospects and Shortcomings

Overall, the implementation of strict control measured at each stage of exterior wall insulation construction technology was essential to ensure that the insulation met the required standards [22]. The workforce should have a firm grounding in professional knowledge and skills, strictly adhere to specification requirements, and aim to enhance quality control and construction management [23]. A comprehensive analysis was carried out based on energy, environment, and economy criteria where the energy, environment, and economic costs of producing insulations were taken into account and mineral wool insulation with the thickness of 11 cm was the best optimum state among most investigated [24].

Further study, to guarantee the quality of the external wall insulation project, should focus on post-construction conservation and maintenance, which are vital to ensure the sustained effectiveness of external wall insulation. Such discussion primarily focuses on the application of external wall insulation in projects; many aspects that have not been taken into account, for example, the specifics of construction processes, quality control, costs, fire prevention, and waterproofing, should be considered. Therefore, a comprehensive evaluation encompassing all these facets is necessary for refining thermal insulation comparisons and selecting appropriate materials and strategies.

In practical application, it is necessary to start more from innovative research, deepen the existing production methods and performance enhancement methods of environmentally friendly materials as much as possible, and continuously improve the energy-saving effect in the field of building materials so that the building can better contribute to society.

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