Thermal Performance Study of Vacuum Insulation Panel Embedded Composite Polystyrene Insulation Board

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Abstract. Under the guidance of "carbon peak and carbon neutrality" policies, there is an urgent need in the construction market for insulation materials that comply with the thermal transmission coefficient standards of the "Passive Ultra-Low Energy Green Building Technical Guidelines". This study addresses issues associated with traditional insulation materials such as excessive thickness and detachment of exterior insulation layers, as well as challenges with standalone vacuum insulation panels (VIPs) including high transportation and construction breakage rates, inability to cut, and high costs. This paper investigates the construction and physical properties of a composite insulation board (STC) that embeds VIPs into Class A fire-resistant expanded polystyrene (AEPS). Through computer simulation modeling and physical experiments, the advantages of thermal performance, strength, durability, cost, construction measures, and thermal performance after VIP failure for STC boards with different thicknesses and area ratios are analyzed. The study confirms the innovative features of using VIPs protected by AEPS, including low breakage rates, installation convenience, high thermal insulation and fire resistance characteristics.

Keywords: Vacuum insulation panel embedded in polystyrene insulation board; Ultra-low energy STC composite board; Thermal performance after VIP failure

1 Introduction

The "2023 China Building Energy Consumption and Carbon Emission Research Report" indicates that in 2021, carbon emissions during the operational phase of national buildings accounted for approximately 21.9% of the national total and 56.6% of the total energy consumption in the building life-cycle [1]. Wall heat loss accounts for about 40% of the total thermal losses of the building envelope, making the role of external wall structures in overall energy consumption significant [2]. The promotion of ultra-low energy building technology and the development of building envelope insulation

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materials with high thermal insulation performance and combustion performance of Class A are crucial for building energy conservation and the realization of the goal of "carbon peak and carbon neutrality".

Increasing the thermal transmission coefficient of building envelopes by increasing the thickness of traditional insulation materials leads to increased weight and external force displacement of the insulation layer, increasing the risk of cracking and detachment. Overly thick insulation layers reduce internal area, increase common areas, reduce developers' willingness to construct ultra-low energy buildings, and diminish promotional effects [3].

Vacuum insulation panels (VIPs) are primarily composed of inorganic fiber cores, gas adsorbent materials, and high-barrier composite films processed through vacuum treatment and scientific sealing technologies. VIPs offer highly efficient thermal insulation performance (0.002-0.008 W/m·K), approximately one-third that of polyurethane (PU), one-fourth of extruded polystyrene (XPS), and one-fifth of expanded polystyrene (EPS) and rock wool. They can significantly reduce the thickness of insulation layers in building insulation systems. However, using VIPs alone for building insulation poses challenges such as high costs, inability to cut on site, high transportation and construction damage rates, and a drastic decline in insulation performance if VIPs leak during use [2].

The purpose of this paper is to reduce the risk of the VIP by increasing the protection layer to reduce the probability of the damage of the VIP, reducing the thermal bridge and avoiding the loss of the VIP insulation. This study uses computer simulation and physical experiments to demonstrate the superior thermal, fire, and compressive properties of STC boards, including thermal performance after VIP failure. It also explores technical measures for applying STC composite insulation boards in building insulation systems in cold regions.

2 Technical Characteristics and Technological Route

This paper is an applied study based on the patented technology "Embedded Composite Insulation Board" (STC board) authorized by Wang Xinmin. This patent discloses a composite insulation board embedding VIPs into an A-grade thermal solid composite polystyrene board, forming a flat-faced and frame-shaped rear with a bottom-closed accommodation groove [4]. The innovative aspect of this technology is that the STC board not only protects the VIP but also provides thermal insulation performance itself, preventing drastic insulation failure after VIP leakage. AEPS wraps around the exterior of VIPs, minimizing deformation due to VIP water ingress.

This project compares STC composite insulation materials with VIPs in terms of material design, performance testing, and application research. The base material selection is an A-grade fire-resistant EPS insulation board enveloping VIPs. According to Fourier's law equation $q = -k\nabla T$, thermal conductivity measuring instruments are used to test the material's thermal conductivity and evaluate its insulation performance. Finite element analysis (Eco-tect) software is applied to simulate the material's thermal conductivity performance, gaining a deeper understanding of the thermal conduction characteristics of different area and thickness composite materials. Subsequently, research explores the application methods and technical measures of STC composite insulation boards in building envelope insulation.

3 Structure Characteristics and Thermal Performance of STC Composite Insulation Boards

This study selected thermal solid composite polystyrene foam insulation boards produced by Liaoning Chaoqiang Fireproofing Insulation Technology Co., Ltd., with a density of 129 kg/m³, thermal conductivity of 0.041 W/m·K, and fire rating of A2. Vacuum insulation panels produced by Jiangsu Shanyoudile Energy Saving New Material Manufacturing Co., Ltd., have a density of 300 kg/m³, thermal conductivity of 0.005 W/m·K, and fire rating of A2. Aerated concrete blocks measuring 190 mm x 390 mm x 190 mm produced by Liaoning Dongshen Building New Material Technology Co., Ltd., with a density of 380 kg/m³, thermal conductivity of 0.12 W/m·K, and Combustion grade A1, serve as the wall base layer.

3.1 Construction of STC Composite Insulation Boards

The application is in two aspects: When the external wall thin plaster external insulation system is used, the insulation nail is fixed to the base of the wall through the central position of the vacuum insulation board. When the exterior wall decoration insulation integrated board is used, the conventional integrated board installation method is used. This paper lists two types of STC boards: 600mm × 600mm STC insulation decorative integrated boards and 1200mm × 600mm STC embedded composite insulation boards.

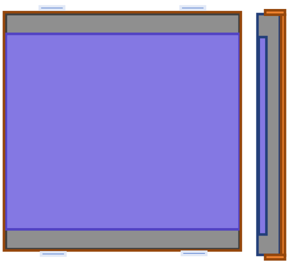

Fig. 1. [STC Insulation Decorative Integrated Board]

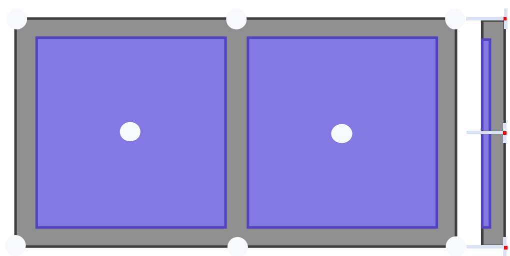

Fig. 2. [STC Insulation Board]

The STC Integrated Insulation and Decoration Board consists of an STC board with outer layers adhered to metal plates, calcium carbonate boards, non-asbestos calcium silicate boards, fiberglass resin boards, thin stone slabs, honeycomb aluminum panels, coatings, and other decorative finishes. As shown in Figure 1, the central VIP board measures 600mm × 500mm, with AEPS glued to its bottom and 50mm-wide top and bottom frames, surrounded by decorative surface layers. The bonding of VIP boards, AEPS boards, and aluminum plates utilizes modified silane adhesives. Half-wrapped aluminum plates with connection fittings are installed on the sides of the STC

Integrated Insulation and Decoration Board, with heat-insulating pads between the fittings and the keel or base wall connections. The two AEPS frames facilitate the installation of connection fittings, preventing damage to the VIP board. This STC Integrated Insulation and Decoration Board is characterized by low thermal conductivity, beautiful decoration, and secure installation, resistant to fading and peeling, ensuring long-term architectural beauty, and holds broad prospects for application in buildings [5].

The STC Embedded Composite Insulation Board combines the ultra-low thermal conductivity of VIP boards with the excellent toughness of AEPS. Its structure involves a central VIP board measuring 500mm×500mm, with AEPS on the outer bottom, a 100mm-wide middle frame, and 50mm-wide side frames, as shown in Figure 2. The STC insulation board is installed using a combination of pasting and anchor bolts, with an external wall insulation thin plastering system. AEPS on the outer side of VIP provides protection, insulation, resistance, and resilience against deformation after internal VIP damage. Construction methods to prevent VIP damage differ from those for VIP board installation, with STC installed according to benzene board construction techniques, which are simpler. Moreover, the dual-layer composite material of STC is processed in factories using automation, ensuring higher quality and greater construction efficiency compared to on-site installation of two layers of VIP boards.

3.2 Thermal Performance of STC Composite Insulation Boards

Table 1 shows the thermal transmission coefficients of STC composite boards with different combinations of VIP and AEPS: the horizontal column is VIP thickness of 10mm ~ 100mm, the vertical column is vacuum insulation plate thickness of 40mm ~ 10mm, with the middle numbers representing the thermal transmission coefficients calculated using Eco-tect software for two materials of the same size. The thermal insulation performance of the integrated board is calculated ignoring the thermal resistance of the decorative layer and backing plate. Material combinations from the Table 1 can be selected according to the corresponding standard requirements, design, and economic needs.

Table 1. Thermal Transmission Coefficients of STC Composite Boards with Different Thickness Combinations of VIP and AEPS (Composite board thickness ≥ 120mm for blank spaces)

AEPS (mm) / VIP (mm)	10	20	30	40	50	60	70	80	90	100
40	0.12	0.12	0.11	0.11	0.11	0.10	0.10			
35	0.13	0.13	0.13	0.12	0.12	0.12	0.11	0.11		
30	0.16	0.15	0.14	0.14	0.14	0.13	0.13	0.12		
25	0.18	0.18	0.17	0.16	0.16	0.15	0.15	0.14	0.14	
20	0.23	0.21	0.20	0.19	0.19	0.18	0.17	0.16	0.16	
15	0.29	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.19	0.18
10	0.41	0.36	0.32	0.29	0.27	0.25	0.23	0.22	0.20	0.19

Table 1 shows the thickness of the composite insulation board required to achieve the above thermal transmission coefficient. The thickness of the integrated STC board can be calculated using the following formula:

$\overline{R} = \frac{F_1 + F_2}{\frac{F_1}{R_1} + \frac{F_2}{R_2}} - (R_i + R_e)]\varphi$; $K_o = 1 / R_o$; $R_o = R_i + \sum R + R_e$; $R = d / \lambda$. Using the thermal conductivity in Eco-tect software, the required thickness of the composite insulation board corresponding to the thermal transmission coefficient is shown in Table 2. The table horizontally indicates the composite insulation board thickness composition, and vertically shows the corresponding external wall thermal transmission coefficient values.

3.3 Application of STC Board in Building Insulation

Table 2. Thickness of STC Board Corresponding to Different Thermal Transmission Coefficients (T. T. C.), Based on a base layer of 190mm thick aerated concrete blocks

T. T. C. ($W/m^2 \cdot K$) / **Material** (mm)	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**	**0.35**
VIP(mm)	20+30	30	20	15	10	10
STC(mm)AEPS+VIP	90+30	50+20	20+15	20+10	10+10	10+10
AEPS(mm)	360	220	140	100	70	50

From Table 2, for a base layer of 190mm thick aerated concrete blocks or ALC panels, achieving an external thermal transmission coefficient of $0.1 W/m^2 \cdot K$ requires three types of insulation board thickness: a double layer of 20mm + 30mm VIP boards; 90mm AEPS + 30mm VIP of STC composite board; and a 360mm thick AEPS board.

4 Comparison of Physical Properties of STC and VIP

4.1 Comparison of Compressive Strength

The STC composite insulation board is in 5 bread-coated AEPS board to protect VIP from the external influence of the external wall, and the inner wall is fitted with the foundation wall without protection. The WDW-10 microcomputer-controlled electronic universal testing machine was used in this study to test and determine that the compressive strength of AEPS board is 0.16 MPa, VIP board is 0.159 MPa, and the compressive strength of STC board (VIP 28mm + AEPS 50mm) is 0.23 MPa. The ratio of compressive strength of STC board to VIP board is 0.230/0.159 = 1.45 times, indicating an increase of approximately 30%. This proves that the idea of improving the mechanical performance of materials by wrapping AEPS boards around the outer side of VIP boards is valid.

4.2 Comparison of Thermal Bridging

Seams between VIP boards during installation are prone to thermal bridging [6]. The AEPS boards on the outer frame of STC boards have better material toughness and can easily be equipped with waterproof grooves on the sides. During installation, PE rods or foam agents can be inserted into the joints between boards to form interlocking structures, thereby enhancing thermal insulation and sealing. When using VIP boards alone, the pre-drilled holes for anchor bolts can also create thermal bridges. The high toughness of AEPS boards on the outer side of STC embedded composite insulation boards allows them to tightly fit with anchor bolts [7]. During insulation nail installation, part of the anchor bolt can be embedded in the AEPS thickness, and thermal break plugs can be applied for sealing, utilizing foam agents for filling and covering.

4.3 Comparison of Surface Temperature under Solar Radiation

Placing AEPS boards on the outer side of VIP boards can mitigate the extreme cold and heat effects on the outer surface temperature of the building enclosure structure. For instance, when the external wall surface temperature is 80°C, taking AEPS with a thickness of 80mm and ALC board with a thickness of 190mm as an example, the following formula can be used to calculate: $\theta_2 = \theta_i - R_1 / R_o (t_i - t_e) = t_i - (R_i + R_1) / R_o (t_i - t_e) = t_i - (0.11 + d_1 / \lambda_1) / (d_o / \lambda_o) (t_i - t_e) = 27°C$. "Because the thermal radiation of the surface is directly proportional to the three-dimensional average temperature of the internal material, the impact of the temperature on the VIP insulation performance can be significantly enhanced due to the increased thermal conductivity of radiation. In addition, long-term high temperatures can cause the aging of VIP gas barrier properties to deteriorate rapidly." Therefore, under the thermal protection of AEPS boards, the external surface temperature of VIP boards can be substantially reduced, thereby extending the effective thermal insulation performance and service life of the material [8].

4.4 Comparison of Insulation Layer Fixing

Techniques In terms of insulation layer quality, the dual-layer VIP boards are fixed with insulation nails and cement mortar, while single-layer STC boards can utilize additional brackets or insulation top fixtures. The two-layer materials of STC boards are bonded in the factory using optimal temperature, humidity, binding agent, and equipment. Their quality is superior to the on-site bonding of dual-layer VIP boards. The outer side of dual-layer VIP boards for external walls lacks AEPS protection, making them more susceptible to damage, expansion, and deformation, thereby increasing the risk of detachment compared to STC boards [2]. Furthermore, the benzene boards on the edges of STC boards can be cut and adjusted on-site, reducing the construction difficulties encountered with single-layer vacuum insulation boards. Therefore, both product and construction quality are better when applying STC boards in external wall insulation systems.

4.5 Comparison of Waterproof

The surface water absorption rate of VIP board is 50g/m², and the waterproof performance is good. However, VIP board may expand due to internal stress changes or damage after puncture [9]. STC board is protected by AEPS board, which has stable and good waterproof performance. AEPS board volume water absorption rate of 7%, dry shrinkage rate of 0.3%, bending strength of 0.23MPa. Therefore, AEPS boards with outer waterproof and decorative protection can provide certain waterproof and anti-expansion effects for VIP boards.

4.6 Comparison of Thermal Performance After VIP Insulation Failure

Currently there is no practical verification that the thermal insulation performance of VIP boards can match the service life of buildings. Therefore, it is necessary to study the thermal conductivity of VIP after insulation failure and the degree to which it affects building quality [10].

Taking the example of an outer enclosure structure with a base layer of 190mm thick ALC board and a thermal transmission coefficient of 0.10 W/m²·K, the change in thermal transmission coefficient after insulation failure using 20mm + 30mm thick dual-layer VIP boards as insulation layer and 90mm AEPS + 30mm VIP boards as insulation layer is compared. After air leakage insulation failure of dual-layer VIP boards, using the thermal conductivity coefficient of 0.035 W/m·K for fiber core materials as a reference, the thermal conductivity coefficient is 7 times the original 0.035/0.005 = 7 times. The thermal insulation performance of the external enclosure structure subsequently decreased to a thermal transmission coefficient of 0.31 W/m²·K, which is 3.1 times the original 0.31/0.1=3.1 times, an increase of 210%. After air leakage insulation failure of 30mm VIP boards in STC boards, with 90mm AEPS insulation still in place, the thermal insulation performance of the external enclosure structure decreased to a thermal transmission coefficient of 0.21 W/m²·K, which is 2.1 times the original 0.21/0.10 = 2.1 times, an increase of 110%.

Therefore, it is evident that the application of STC boards in the thermal insulation system of ultra-low energy consumption buildings reduces the risk after VIP board insulation failure.

5 Economic Viability

According to the Shenyang City "Ultra-Low Energy Residential Building Energy Efficiency Design Standard" DB2101/T 0048-2022, the thermal transmission coefficient for building exterior walls should be ≤ 0.10 to 0.15 W/m²·K. When using dual-layer VIP boards as insulation layers, a minimum thickness of 50mm is required: 20mm VIP board costs 120 yuan/m², 30mm VIP board costs 160 yuan/m², and installation cost for two layers is 2 layers x 40 yuan/m² = 80 yuan/m², totaling approximately 360 yuan/m². In contrast, using single-layer STC composite insulation boards (30mm VIP + 80mm AEPS): AEPS board costs 220 yuan/m², installation cost for one layer is 40 yuan/m², totaling approximately 260 yuan/m². Comparing the cost of the two insulation layers, STC boards with AEPS on the outer side can save about 100 yuan/m² per square meter. Cost ratio = VIP board cost / STC board cost = 360/260 = 1.38 times, reducing costs by about 28%. From a cost-benefit analysis perspective, STC boards achieve the same thermal insulation effect and are more likely to be accepted in the market.

Additionally, during the transportation of VIP boards, frames and packaging are required to prevent material damage due to compression, significantly increasing costs. Disposable frames and packaging materials used for transportation contribute to resource waste and environmental pollution.

6 Conclusion

This paper introduces a structure and characteristics of embedded vacuum insulation composite insulation boards, utilizing A-grade fireproof polystyrene board wrapping to reduce the damage rate during the transportation and installation of VIP boards. The benzene boards on the edges of the composite boards can be cut and adjusted on-site, reducing material costs and construction difficulties compared to using single vacuum insulation boards. Through analysis of the thermal transmission coefficients of VIP and AEPS at different thicknesses, basic data is provided for the application of STC boards in building energy efficiency standards in various regions. Experimental research shows that STC boards outperform the use of VIP boards alone in building insulation systems: STC boards have improved compressive strength, reduced thermal bridging between board joints and anchor bolt holes, significantly reduced summer surface temperatures of VIP under solar radiation, better product quality and construction quality, superior waterproof performance, and lower thermal transmission coefficient growth rate after VIP insulation failure. STC composite insulation boards are urgently needed ultra-low energy building insulation materials in the construction industry, conducive to achieving carbon neutrality and peak carbon targets, with extensive application prospects.

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