QINGDAO KERUI GROUP

Study Report

of

An Integrated Study on the Application of Vacuum Insulation Panels in Ultra-Low-Energy-Consumption Concrete Prefabricated Buildings

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Contents

Abstract

Based on the application status of vacuum insulation panels (VIPs) in domestic building exterior wall insulation systems and the prospects of development of prefabricated buildings, the advantages and disadvantages of polyurethane and cement mortar as VIP layer protection layers were discussed. The required thickness of VIP and the protective layer for a heat transfer coefficient of 0.15W/(m^2·K) was determined. The heat transfer coefficient of the prefabricated walls made by seamless fabrication and female mold technique were determined respectively, which provides a reference for the promotion and application of VIP in prefabricated buildings.

1 Background and objectives

1.1 Background

Nowadays in china, in order to control the emission of the greenhouse gases with an aim of 40% - 50% reduction of CO_2, as well as to control the air pollution, the government has addressed the development of the environmental friendly ultra-low-energy-consumption buildings to the national strategy. Moreover, the mode of building-construction is going through tremendous change seeking for transformation and upgrade. Thus, the ultra-low-energy-consumption prefabricated building is under rapid development.

The quality of the prefabricated buildings is highly dependent on the wall materials, insulation materials, doors and windows, pipe fittings, exterior finishes and many other components. Only by fully industrialization of the production of all these components, the industrialization of the prefabricated buildings, or even of the whole construction industry, can be finally achieved. Compared to the requirements for the traditional building components, the ultra-low-energy-consumption prefabricated buildings have higher requirements on the air tightness of doors and windows and the insulation performance. Therefore, in order to achieve the fully industrialization of the components for prefabricated buildings and to ensure the high thermal insulation performance of the exterior walls, the doors and windows, it is necessary to carry out a study on the VIP-integrated-precasted-walls for prefabricated buildings with decorative surface layers.

In the past, the 'sandwich-structure' insulation methods were mainly adopted by the construction of prefabricated buildings, with expanded polystyrene (EPS), extruded polystyrene foam (XPS) etc. as insulation layers. By applying the VIP-integrated-precasted-walls (prefabricated external insulation), several problems will be solved, including reducing the thickness of the enclosure wall, avoiding the cold-bridge generated by the connection of inner and outer walls and also lowering the fire risks.

1.2 State of the art

In the IEA/ECBCS Annex 39 project report, the actual case of applying vacuum insulation panel (VIP) to precast concrete components was reported [1]. A precast concrete member having a total thickness of 27 cm and an average heat transfer coefficient of 0.15 W/(m2·K) was prepared by using a composite insulating layer of polyurethane foam and VIP. Voellinger et al. studied the application of VIP in prefabricated concrete sandwich structures [2]. The concrete components were produced by a composite insulation layer of 4 cm EPS-graphite, 6 cm VIP, 4 cm EPS-graphite, resulting in a heat transfer coefficient less than 0.125 W/(m2·K). Sprengard et al. studied the thermal bridge effect of anchors in VIP precasted concrete components [3]. The result shows that when there are anchors with density of 4 pieces per square meter, the U value is only increased by 2%.

Previous studies on the application of VIP in prefabricated buildings, mostly focused on the composite insulation layer of VIP and other insulation materials, lacked the case studies of VIPs independently applied to precast concrete components. In particular, most of these studies are applicable to low-rise, prefabricated buildings, and there is no practical application of precast concrete members in high-rise residential buildings. As a high-efficiency insulation material, using VIP alone in precast concrete components, rather than combining with other insulation materials to form sandwich panels, is of great significance for the development of high-rise assembly buildings.

It is well known that there are higher requirements for the safety and fire resistance of the envelope structures in high-rise buildings. On June 14, 2017, the fire in the Glenfell Tower in London, England caused heavy casualties. It was a pity that the main reason was that the exterior wall of the high-rise residential building caught fire. Therefore, for high-rise building construction, it is necessary to reduce the thickness of the insulation layer in precast concrete components as much as possible and to eliminate the fire hazard caused by flammable insulation layers such as polyurethane.

All in all, in this the project, we abandoned the usage of VIP composite insulation layer and used inorganic material to treat the VIP surface in order to applied it as an independent insulation layer in the prefabricated building. The treated VIP insulation layers were used to prepare precast concrete components and fabricated walls and their related performance were tested.

1.3 Tasks and Methods

To develope a method to protect the surface of the VIPs at the pouring step of the concrete assemblies. A low-cost protection mortar shall be coated on the surfaces of VIPs through a mortar spray machine, forming a dense protective layer, which shall lower the impact from the construction aggregates on VIPs as well as the damage caused by the concrete vibrator spear. The cement mortar should have the characteristics of low cost and strong bonding strength with the VIP board.

Female mold fabrication method was applied to produce VIP integrated precasted walls with decorated surface layer. An average heat transfer coefficient of 0.15 $W/(m^2·K)$ of the integrated precasted walls with decorative surface layer shall be achieved to fulfill the requirements for the enclosure walls of the ultra-low-energy-consumption buildings. The heat transfer coefficient of the envelope structure was determined on site by a temperature control box and heat flow meter. Combined with the numerical analysis method, the appropriate correction coefficient was calculated to correct the heat loss caused by the thermal bridge.

2 Equipment and materials

2.1 Equipment

2.1.1 Thermal conductivity analyzer

The HFM 436/3/1E heat flow method thermal conductivity analyzer was manufactured by NETZSCH, Germany. The heat flow meter was used to measure the thermal conductivity of the test pieces. The measurement method conforms to ASTM C 518 or ISO 8301.

Figure 2-1 Netzsch thermal conductivity analyzer

2.2.2 Intelligent Electronic Tensile Testing Machine

Figure 2-2 Intelligent electronic tensile testing machine

The intelligent electronic tensile testing machine XLW (PC) was developed and produced by Saicheng Technology. It is specially used to test the mechanical properties such as stretching and puncture of plastic film and composite materials. The measurements meet relevant standards including GB/T 1040.

2.2.3 Temperature and heat flow detector

Figure 2-3 Temperature heat flow detector

Temperature and heat flow detector R50B, developed by Beijing Jianyantianrun Technology Co., Ltd., is suitable for measuring the insulation performance of various walls and other materials. It combines the characteristics of heat flow meter method and hot-box method, and conforms to the requirements in GB13475- 2008 "Adiabatic steady-state heat transfer properties determination and hot box method".

2.2 Materials

2.2.1 Vacuum insulation panels for construction

The VIPs were provided by Qingdao Kerui New Environmental Material Group Co., Ltd. The performance of the products meets the requirements for Type I products in JG/T 438-2014 "Vacuum Insulation Panels in Buildings". Product specifications: 300 × 300 × 15 mm, thermal conductivity < 0.0035 W / (m · k).

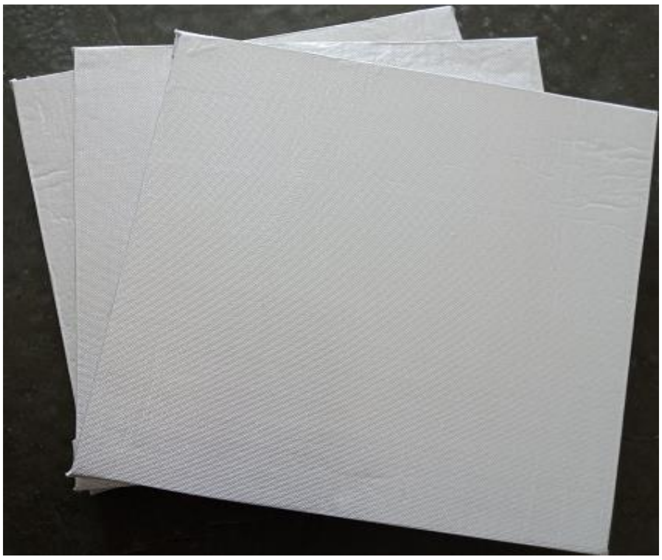

Figure 2-4 Vacuum Insulation Panels from Qingdao Kerui

2.2.2 Cement mortar

The cement mortar was provided by Qingdao Kerui New Environmental Material Group Co., Ltd. The performance of the products was in line with the requirements in JGJ70-2009 "Basic Performance Test Methods for Building Mortar". The bonding strength with VIP boards was above 0.08MPa.

2.2.3 Polyurethane foam material

The polyurethane foam was provided by Zibo Huide Polyurethane Products Co., Ltd. The performance of product meets the requirements for Class B1 in GB8624-2012 "Classification of Combustion Performance of Building Materials and Products". The thermal conductivity was 0.022 W/(m·k).

3 Methods

3.1 Determination of puncture strength of composite films

According to the experimental method specified in GBT10004, five pieces of composite films with a diameter of 100 mm were cut. The puncture experiment was carried out at a speed of (50 ± 5) mm/min and the arithmetic mean was taken.

3.2 VIP alkali resistance test

The size of the VIPs was 300 x 300 x15 mm. They were divided into three groups, six panels in each group, one of which was used as a control group. The other two groups were treated with alkali solutions. The alkaline solutions were selected from the leaching solution of ordinary Portland cement or low alkali sulphoaluminate cement. The experimental procedure refers to "EN 13496-2002 Thermal Insulation Products in Buildings. Determination of Mechanical Properties of Glass Fiber Insulation Network". (1 part of cement was mixed with 10 parts of water, stirred for 30 minutes and was left overnight. The supernatant was taken afterwards.) The VIPs were Soaked for 24 hours at 60 ° C and were rinsed with water to a pH of 7. They were dried in the oven at a constant temperature of 60 ° C and were placed at 23 ° C for 24 h. The thermal conductivity and the tensile strength perpendicular to the panel were tested.

3.3 Bond strength test of cement mortar

The cement mortar produced in the workshop was used for experiments to determine the bond strength with the VIP board. The size of the samples was 100 x 100 x 15 mm and 6 pieces of samples were tested. A mortar layer of 5 mm thick was sprayed on the surface of the VIP board, and placed under standard curing conditions for 28 days. The bond strength was measured afterwards. The cement mortar formula was as follows:

Table 3-1: Formula of coating mortar

Component	**Mass (g)**
Cement 42.5R	40
Quartz sand 40-70 mesh	55
Water reducing agent	0.1
Hydroxypropylation	0.2
Rubber powder	3
Water cement ratio	1 : 0.18

3.4 Experiments on VIP protective layer

The size of VIP samples was 300 x 300 x 15 mm, and a set of six panels were in one experimental group. The VIPs with protective layer were prepared. The protective layer was made of cement mortar or polyurethane foaming agent. The thickness of the protective layer was 2 mm, 5 mm, 10 mm, 30 mm and 50 mm respectively. After the test samples were fully cured, their thermal conductivity was measured, the heat transfer coefficient was calculated, and the thickness of the protective layer for further experiments were determined.

3.5 Determination of the required VIP thickness

VIPs with thicknesses of 1 mm, 1.5 mm, 2.0 mm, 2.5 mm, and 3.0 mm were prepared respectively, the protective mortar layers of the determined thickness (section 3.4) were sprayed, the thermal conductivities were measured, the heat transfer coefficient was calculated, and the required thickness of the VIP board with heat transfer coefficient $\leqslant 0.15$ W/m^2 K was determined.

3.6 Heat transfer coefficient of prefabricated walls

According to the requirements of the heat transfer experiment of walls, the proper size of the VIP board was determined and the VIP board was made. The protective mortar layer of the determined thickness (section 3.4) was sprayed. Two methods, seamless fabrication and the female mold technique, were used to produce the VIP prefabricated walls. The heat transfer coefficient of the envelope structure was determined on site by a temperature control box and heat flow meter. Combined with the numerical analysis method, the appropriate correction coefficient was calculated to correct the heat loss caused by the thermal bridge.

4. Experimental results and analysis

4.1 Puncture experiment on composite films

The results of the puncture experiment on composite films are as follows:

Table 4-1: Puncture strengths of composite films.

Item	Puncture Strength (N)					Average (N)
VIP composite films	18.25	19.03	18.75	19.10	18.89	18.8
VIP films sprayed with protective mortar layer	45.08	47.28	44.93	46.29	48.15	46.35

The experimental results show that the anti-puncture performance was improved with the cement mortar, which was more conducive to reducing the damage rate of the VIPs in the cast-in-place concrete construction.

4.2 VIP alkali resistance test

The comparison of VIPs before and after treatment with alkaline solution is as follows:

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Figure 4-1 Comparison of VIPs after cement leachate treatment. (①control group ② ordinary cement treatment ③ low alkali cement treatment)

(1) Determination of thermal conductivity of VIPs in alkali resistance test:

Table 4-2: Thermal Conductivity of VIPs with cement Leachate Treatment (W/(m·K))

Ordinary Portland cement treatment	**Before**	0.00325	0.00318	0.00324	0.00342	0.00337	0.00325
	After	0.00319	0.00320	0.00321	0.00336	0.00341	0.00328
Low alkali sulpho-aluminate cement treatment	**Before**	0.00336	0.00315	0.00336	0.00338	0.00340	0.00325
	After	0.00338	0.00325	0.00326	0.00342	0.00330	0.00320

(2) Determination of tensile strength perpendicular to the surface of the board:

Table 4-3: Tensile strength of VIP board after cement leachate treatment (/MPa)

Control group	0.087	0.086	0.088	0.086	0.087	0.086
Ordinary Portland cement treatment	0.084	0.083	0.085	0.083	0.083	0.085
Low alkali sulpho-aluminate cement treatment	0.086	0.086	0.087	0.086	0.085	0.084

The experimental results show that the VIPs treated by the two cement leaching solutions both had no obvious damage. The thermal conductivity was not obviously changed. The tensile strengths perpendicular to the plate surface was all greater than 0.08 MPa, which meets the tensile strength requirement for the composite VIPs insulation systems. In addition, treatment with ordinary Portland cement is superior to low alkali sulphoaluminate cement in terms of cost and water resistance. Therefore, using ordinary Portland cement to produce mortar binder fully meets the requirements for VIP insulation systems.

4.3 Bond strength of cement mortar

Determination of bond strength between cement mortar and VIP board:

Table 4-4: Bond strength between cement mortar and VIP board (MPa)

0.095	0.093	0.098	0.097	0.098	0.096

The experimental results show that the bond strength between the cement mortar and the VIP board was much larger than the tensile strength requirement of the VIP board, which meets the requirements of the composite VIP board insulation system. Therefore, this cement mortar can be used as the protective mortar layer for VIPs.

4.4 Experiments on VIP protective layer

Schematic figures of VIPs with polyurethane or cement mortar protective layer:

Figure 4-2: VIP with protective layer

(1) Polyurethane protective layer experiment

The thermal resistance of a single material envelope is R = δ / λc. δ is the material layer thickness (m) and λc is the calculated thermal conductivity of the material [W/(m·K)].

The multilayer material enclosure has a thermal resistance of R = Σ (δ / λc) with unit (m^2·K)/W.

Experimental results of polyurethane as a protective layer:

Table 4-5: Thermal conductivities, λ (W / (m · K)) and heat transfer coefficients, h (W / m^2 · K) when polyurethane was used as a protective layer

δ	Character	1	2	3	4	5	6	Average
2mm	λ (W/(m·K))	0.00376	0.00385	0.00390	0.00386	0.00378	0.00388	--
	h (W/m^2·K)	0.221	0.226	0.229	0.227	0.222	0.228	0.226
5mm	λ (W/(m·K))	0.00430	0.00442	0.00429	0.00438	0.00445	0.00436	--
	h (W/m^2·K)	0.215	0.221	0.214	0.219	0.223	0.218	0.218
10mm	λ (W/(m·K))	0.00528	0.00535	0.00519	0.00530	0.00538	0.00526	--
	h (W/m^2·K)	0.211	0.214	0.207	0.212	0.215	0.210	0.212
30mm	λ (W/(m·K))	0.00812	0.00797	0.00823	0.00806	0.00814	0.00819	--
	h (W/m^2·K)	0.181	0.178	0.183	0.179	0.181	0.182	0.181
50mm	λ (W/(m·K))	0.0105	0.00986	0.00991	0.00995	0.0108	0.00986	--
	h (W/m^2·K)	0.161	0.152	0.152	0.153	0.166	0.152	0.156

(2) Cement mortar protective layer experiment

Experimental results of cement as a protective layer:

Table 4-6: Thermal conductivities, λ (W / (m · K)) and heat transfer coefficients, h (W / m² · K) when cement was used as a protective layer

δ	Character	1	2	3	4	5	6	Average
2mm	λ (W/(m·K))	0.00402	0.00395	0.00397	0.00410	0.00406	0.00411	--
	h (W/m²·K)	0.236	0.233	0.234	0.241	0.239	0.242	0.238
5mm	λ (W/(m·K))	0.00458	0.00473	0.00459	0.00465	0.00478	0.00460	--
	h (W/m²·K)	0.229	0.236	0.229	0.233	0.239	0.230	0.233
10mm	λ (W/(m·K))	0.00579	0.00596	0.00571	0.00580	0.00583	0.00591	--
	h (W/m²·K)	0.231	0.239	0.228	0.232	0.233	0.236	0.233
30mm	λ (W/(m·K))	0.00995	0.0108	0.0106	0.0110	0.0109	0.0112	--
	h (W/m²·K)	0.221	0.240	0.234	0.238	0.242	0.248	0.237
50mm	λ (W/(m·K))	0.0158	0.0159	0.0161	0.0152	0.0153	0.0150	--
	h (W/m²·K)	0.243	0.244	0.247	0.234	0.235	0.231	0.238

(3) Determination of tensile strength perpendicular to the surface of the board:

Table 4-7: Tensile strength (MPa) of polyurethane and cement mortar as protective layer

Polyurethane	0.126	0.124	0.130	0.128	0.121	0.128
Mortar	0.089	0.087	0.087	0.086	0.088	0.084

According to the experimental results, when the polyurethane was used as the protective layer, the heat transfer coefficients of the VIPs with the same thickness were significantly better than that of the cement mortar as the protective layer. The tensile strength of both types meets the requirements by relevant standards. However, from the perspective of fire retardant, polyurethane is at B1 level and the fire performance is much worse than the mortar protective layer. The thickness of the protective layer with polyurethane is much larger than the protective layer with the cement mortar in order to achieve the same protective effect in preventing the damage from the coarse aggregate and vibration to the VIPs. Therefore, based on the overall consideration, using mortar as the protective layer for VIPs is a better choice for the VIP insulation system.

4.5 Determination of the required VIP thickness

The mortar with a thickness of 2mm was selected as the protective layer. The VIPs with thickness of 20mm, 25mm and 30mm were tested. The experimental results are as follows:

Table 4-8: Thermal Conductivity, λ (W/(m·K)) and Heat Transfer Coefficient, h (W/m2·K) of VIPs with different thicknesses

VIP thickness	Character	1	2	3	4	5	6	Average
20mm	λ (W/(m·K))	0.00359	0.00361	0.00352	0.00358	0.00355	0.00360	--
	h (W/m²·K)	0.163	0.164	0.160	0.163	0.161	0.164	0.163
25mm	λ (W/(m·K))	0.00356	0.00352	0.00358	0.00352	0.00351	0.00350	--
	h (W/m²·K)	0.132	0.130	0.133	0.130	0.130	0.129	0.131
30mm	λ (W/(m·K))	0.00350	0.00348	0.00351	0.00355	0.00350	0.00353	--
	h (W/m²·K)	0.109	0.109	0.110	0.111	0.109	0.110	0.110

The experimental results show that to achieve the heat transfer coefficient of 0.15 W/m^2 • K, VIPs with thickness of 25 mm should be selected.

4.6 Heat transfer coefficient of prefabricated walls

The size of the VIP board was determined based on the previous experiments, which was 480 x 480 x 25 mm. A protective mortar layer with a thickness of 2 mm was also selected based on the previous experiments. Prefabricated walls were produced by two methods: seamless fabrication and the female mold technique. The seam from female mold technique was 10 mm and was treated with polyurethane foam. The heat transfer coefficient of the envelope structure was determined on site by temperature control box and heat flow meter. The schematic diagram of the prefabricated walls is as follows:

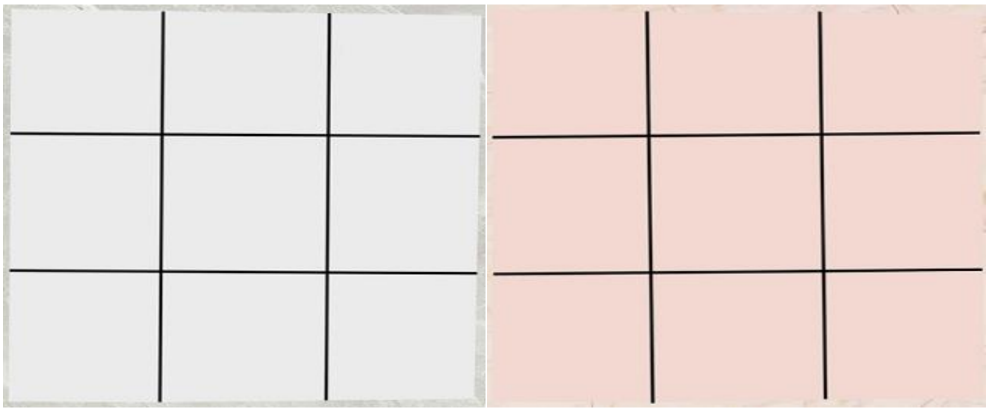

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Figure 4-3: schematic diagram of the prefabricated walls. (①female mold technique, ②seamless fabrication)

The heat transfer resistance (total thermal resistance) R_0 of the enclosure is the total resistance when heat transmitted from one side of the flat wall to the other side. It is an important thermal performance index of the beam envelope under constant heat transfer conditions with unit ($m^2 \cdot K$) / W.

$$R_0=R_i+(R_1+R_2+...+R_n)+R_e$$

In the formula:

R_i : heat transfer resistance of the inner surface.

R_e: heat transfer resistance of the outer surface.

R_1, R_2, ..., R_n: the thermal resistance of each layer of material.

Therefore, the actual heat transfer resistance of the envelope is:

$$R = \frac{t_1 - t_2}{23.2 \cdot (q_{cold} + q_{hot})/2}$$

In the formula:

t_1 is the hot box wall temperature, t_2 is the cold box wall temperature, q_{cold} is the heat flow of the cold box wall and q_{heat} is the heat flow of the hot box wall. 23.2 is the heat flow conversion factor of this equipment model.

The test results are as follows:

(1) Prefabricated wall by female mold technique:

Table 4-9: Heat transfer coefficient of prefabricated wall and correction factor

Thermal resistance of VIP (m^2 • K)/W	Heat transfer coefficient of VIP W/(m^2 • K)	Thermal resistance of seam (m^2 • K)/W	Heat transfer coefficient of seam W/(m^2 • K)	Heat transfer coefficient of wall W/(m^2 • K)	Correction factor
7.62	0.134	1.15	0.865	0.142	1.18

(2) Prefabricated wall by seamless fabrication:

Table 4-10: Heat transfer coefficient of prefabricated wall and correction factor

Thermal resistance of VIP (m^2 • K)/W	Heat transfer coefficient of VIP W/(m^2 • K)	Heat transfer coefficient of wall W/(m^2 • K)	Correction factor
7.68	0.133	0.138	1.09

Both two prefabricated walls meet the requirement of heat transfer coefficient less than 0.15 W/m^2·K. The heat transfer coefficient of the seamless fabricated wall was smaller than that of the wall made by female mold technique. The seamless fabrication technology can be used for non-high-rise buildings such as multi-storey buildings and houses that have low reinforcement and wind pressure requirements. For high-rise buildings, the female mold technique shall be adopted, and the reserved seams shall be used for reinforcement by nailing, which can increase the force with the wall and greatly improve wind pressure resistance of the buildings.

5. Summary and outlook

As the best thermal insulation material for thermal insulation, VIP insulation systems have been relatively well developed. Their thermal insulation performance has been widely recognized in the market. The proportion of using VIP for building insulation is increasing year by year. The composite protective layer technology for VIPs solves the problem of VIP damaged during concrete watering and vibration, which largely expands the application VIPs.

China is currently vigorously promoting the development of prefabricated buildings. More than 30 provinces and cities across the country have introduced relevant measures and special guidance. The number of newly built prefabricated components plants is constantly growing. The combination of the prefabricated building and the VIP insulation systems will provide a broader market prospect for VIPs.

References:

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