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Technical Study on the Rock Wool/Polyurethane Composite Insulation Board and Its External Insulation System for Ultra-low Energy Consumption Buildings

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Abstract. Ultra-low energy consumption buildings refer to the buildings which adapt to the climate characteristics and natural conditions, use the envelope structure with high thermal insulation and air tightness performance as well as efficient fresh air heat recovery technology to minimize the heating and cooling demand of buildings, and make full use of renewable energy to provide comfortable indoor environment with less energy consumption. As a key part of the ultra-low energy consumption building technology system, the external wall heat transfer coefficient K value is much higher than the external wall heat transfer coefficient required by the current ordinary energy-saving buildings in China. In order to achieve the thermal insulation performance required by the ultra-low energy consumption buildings, higher requirements are put forward for the thermal insulation materials and external thermal insulation system of building envelope. In this research, a new type of thermal insulation material for external wall of buildings which combines rigid polyurethane and rock wool is developed, and its application technology in ultra-low energy consumption building external wall thermal insulation system is also studied.

1. Introduction

In recent years, ultra-low energy consumption buildings have been developing vigorously in China, and demonstration projects of ultra-low energy consumption suitable for different climate zones, purposes and building forms are being vigorously developed all over the country. As a key part of the ultra-low energy consumption building technology system, the external wall heat transfer coefficient K value is much higher than the external wall heat transfer coefficient required by the current ordinary energy-saving buildings in China. In order to achieve the thermal insulation performance required by the ultra-low energy consumption buildings, higher requirements are put forward for the thermal insulation materials and external thermal insulation system of building envelope. Direct methods include increasing the thickness of traditional external insulation materials or using new external insulation materials with lower thermal conductivity. However, in the actual application, in addition to the thermal insulation performance of thermal insulation materials, the fireproofing, stability, safety of external wall thermal insulation materials and systems, as well as the operability in construction, process of system engineering and technical indicators and application indicators in the whole life cycle are equally important.

Polyurethane is considered to be one of the best thermal insulation materials in the world at present. Its proportion in building thermal insulation materials in China is far lower than that in developed countries in Europe and the United States, so there is a huge market space for polyurethane. Its good



thermal insulation performance meets the requirements of China's energy-saving policy, and it is one of the most policy-oriented thermal insulation materials at present. The so-called polyurethane (PU) for thermal insulation of external wall refers in particular to rigid polyurethane (PUR) or polyisocyanate (PIR), and polyisocyanate (PIR) is the object of this research. Rock wool is a grade-A thermal insulation material which has developed vigorously in recent years in China. It is non-flammable, non-toxic and harmless, with good durability, and can achieve the same service life as buildings. However, through the research and application of rock wool products in recent years, it is found that rock wool has a poor constructability, especially rock wool is easy to absorb water and seriously affects its thermal insulation effect after dampness; it has a low tensile strength, and the safety after installing on wall is worrying. PIR polyurethane material has good thermal insulation performance, mechanical properties and waterproofing performance, while rock wall has good fireproofing performance of rock wool and high flame rating. If they can be effectively combined, they will make full use of their strengths and weaknesses and integrate safety fire protection and energy-saving thermal insulation into new products, thus injecting new vitality into the field of building external wall thermal insulation in China.

In conclusion, the main content of this study is to study the preparation technology of rock wool/polyurethane composite thermal insulation board for ultra-low energy consumption buildings and the application technology of its external wall thermal insulation system.

2. Study on the Preparation Technology of Rock Wool/Polyurethane Composite Insulation Board for Ultra-Low Energy Consumption Buildings

2.1. Performance Analysis and Selection of Rock Wool Board

Rock wool board uses basalt and other natural ores as main raw materials, and it is prepared by melting to fibers at high temperature and solidifying with proper amount of binder. Compared with other inorganic thermal insulation materials, rock wool board has the following characteristics:

(1) The basic characteristic of rock wool board is good thermal insulation performance. Its thermal conductivity is $\leq 0.040 \text{ W/(m}\cdot\text{K)}$, which is relatively low in inorganic thermal insulation materials, and it still has application value in ultra-low energy consumption construction projects.

(2) Rock wool board has excellent sound insulation and sound absorption performance mainly due to the porous structure of rock wool products, which can effectively prevent the transmission of sound waves.

(3) Excellent fireproof performance: in addition to class A flame retardant performance, rock wool board will not elongate, shrink and deform in the fire and will not produce smoke, combustion droplets or debris due to its good physical and chemical stability.

Rock wool is used for external thermal insulation of external wall, which can be in the form of whole wall using rock wool insulation board (fibers parallel to the wall surface), and it also has the function of external wall fireproof; it can also be used together with other thermal insulation materials, in which rock wool strips play the role of fireproof isolation (called fireproof isolation layer, with fibers perpendicular to the wall surface).

According to the provisions of Article 6.7.3 of GB 50016-2014 Code for Fire Protection Design of *Buildings*: "when the non-cavity composite thermal insulation structure of building external walls is composed of thermal insulation materials and wall body at two sides, the fire endurance of the structure should conform to the relevant provisions of this Code: when the combustion performance of thermal insulation materials is B1 and B2, the wall body on both sides of thermal insulation materials should be non-combustible materials, with the thickness not less than 50 mm". Therefore, the thickness of rock wool board used for the rock wool/polyurethane composite insulation board for ultra-low energy consumption buildings shall be set at 50mm.

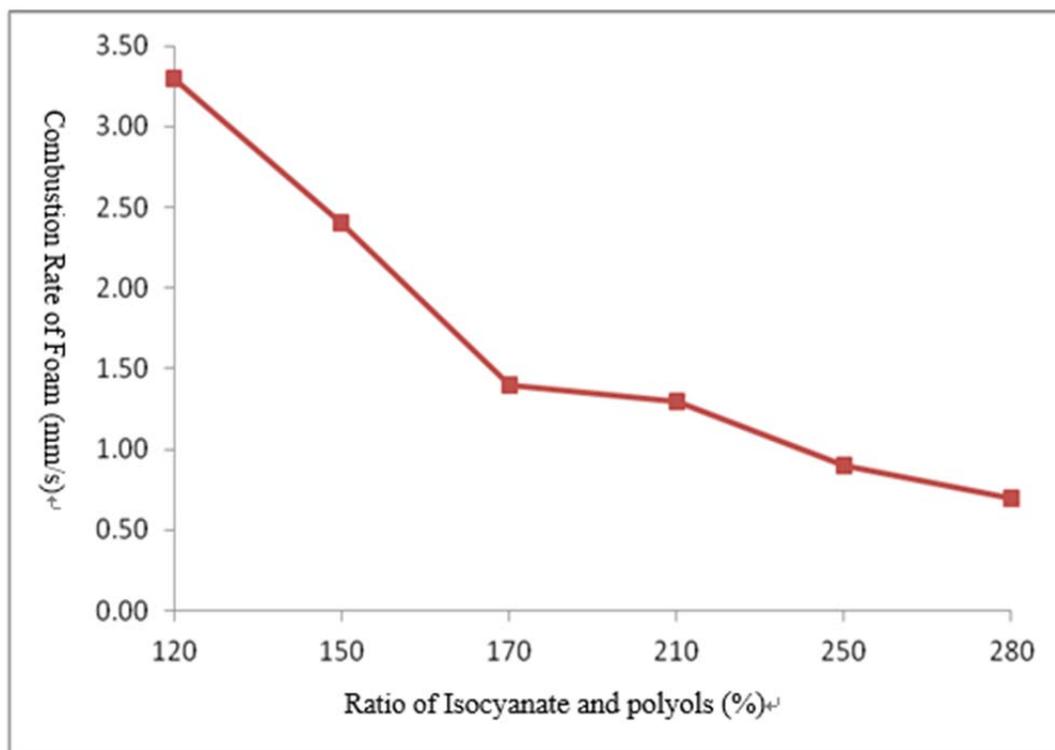
Based on the above factors, it is concluded that the performance indexes of rock wool board used for rock wool/polyurethane composite insulation board should meet the requirements of Table 1.

Table 1. Performance of rock wool board

Item	Performance Index
Heat conductivity coefficient, W/(m·K), 25°C	≤0.040
Acidity coefficient	≥1.8
Tensile strength perpendicular to the board surface, kPa	≥7.5
Short-term water absorption, kg/m ²	≤0.5

2.2. Study on Preparation Technology of PIR Polyurethane Insulation Board

There are two main raw materials for PIR polyurethane insulation board: black material and white material. Black material, i.e. polymethyl isocyanate, is a mixture containing a certain amount of isocyanate and diphenylmethane diisocyanate with a high degree of functionality (about 2.6-2.7), and it is a kind of dark gray liquid mainly produced by Basf and Wanhua. White material, i.e. conjugate polyether, is composed of polyols, flame retardants, catalysts, foaming agents and other auxiliaries; there are many producers, and their products are also slightly different from each other. The most important characteristic of PIR board is the excessive polyisocyanate in black material during the reaction, which can reduce the content of hydroxyl value in white material and increase the isocyanate content in black material, so that the later reaction can be transformed into the trimerization reaction of isocyanate itself, forming the fire-retardant six-membered ring and improving the combustion performance of polyurethane board^[1]. Therefore, the content of isocyanate has an important effect on the flame retardancy and product mix of polyurethane. The influence of different isocyanate contents on product combustion rate is tested, as shown in Figure 1.

**Figure 1.** Impact of Isocyanate Index on Combustion Rate of Foam

The curves show that the higher the isocyanate index, the smaller the combustion rate of the foam. However, it is found from the test that the index of isocyanate also cannot be increased too much. If the index is too high, the degree of crosslinking of foam is too high and easily brittle and has no use value. Therefore, the performance of the foam should be considered comprehensively in the actual selection, and the proper proportion of polyurethane and polyisocyanurate should be selected to

improve the board properties comprehensively. The recommended composition ratio is given below, as shown in Table 2. The properties of the PIR polyurethane board samples prepared according to this formula are shown in Table 3.

Table 2. PIR Polyurethane board material list

Ingredient	Formula 1-15
Polyester 2412	60
Polyether 4110	30
Polyether 403	10
Foam stabilizer AK8805	2
Water	0.5
Foaming agent 141b	36
Cyclohexane	1.2
Potassium isooctanate	1.0
Hexahydrotriazine	0.3
DMMP	6
TCPP	10
White material	27.4
Black material	41.1

Table 3. Property of PIR polyurethane board

	Density (Kg/m ³)	Compressive strength (Mpa)	Heat of combustion (MJ/kg)	Heat conductivity coefficient	Oxygen index (%)
Standard value	≥32	≥0.10	≤15	≤0.024	≥30.0
Test result	42.76	0.20	11	0.024	30.7

2.3. Preparation Technology of Rock Wool/Polyurethane Composite Insulation Board for Ultra-Low Energy Consumption Buildings

Effective combination of selected rock wool board and PIR polyurethane board to meet the utilization requirements of external insulation system of external wall is the key to prepare rock wool/polyurethane composite insulation board for ultra-low energy consumption buildings.

Compared with the low-pressure foaming machine, the high-pressure foaming machine has the advantages of more uniform mixing of materials, larger contact area of different components and easy cleaning, and it is suitable for foaming materials with lower viscosity of raw materials. Therefore, high-pressure foaming machine is selected as polyurethane resin casting equipment. Continuous conveyor laminator is selected as the polyurethane foaming equipment. The specific preparation process is as follows:

The rock wool board is transported to the continuous production laminator of polyurethane board by rolling conveyor and bonded with the cement fiberglass cloth which is laid on the lower chain board of the laminator, and at the same time, the casting of black and white materials for polyurethane is started on the upper surface of the rock wool board. With the forward operation of the chain conveyor of the laminator, the mixture of polyurethane black and white materials is gradually started and formed on the surface of the rock wool board, and then it is bonded into one unit with the upper cement fiberglass fabric and lower rock wool board by taking advantage of the adhesive property of polyurethane. Finally, after solidifying and cutting, the composite rock wool and polyurethane insulation board for external thermal insulation of external wall is produced. In the process of pouring polyurethane, the temperature of the laminated conveyor should be kept between 55°C and 65°C, and the proportion of black and white materials of polyurethane should be controlled between 1.4:1 and 1.8:1. The running speed of the chain board of the laminated conveyor should be between 3.5 m/min and 4.5 m/min, so as to ensure uniform foaming and good bonding strength of polyurethane.

3. Study on the External Thermal Insulation System Technology of External Wall of Rock Wool/Polyurethane Composite Insulation Board for Ultra-Low Energy Consumption Buildings

3.1. Thickness Calculation of Rock Wool/Polyurethane Composite Insulation Board for Ultra-Low Energy Consumption Buildings

Referring to the *Code for Thermal Design of Civil Buildings* GB50176-2016 and *Rock Wool Products for Exterior Insulation and Finish Systems* GB/T 25975-2010, the following calculation parameters are obtained:

Table 4. Composite insulation board thickness calculation parameters

Material Name	Heat conductivity coefficient λ W/(m·K)	Material thickness d m	Thermal resistance R $m^2 \cdot K/W$	Correction factor β
Ordinary reinforced concrete	1.74	0.2	0.115	—
Cement mortar	0.93	0.02	0.022	—
Rock wool board	0.040	0.05	1.250	1.10
Polyurethane insulation board	0.024	—	—	1.1

The correction factor in the above table refers to the correction of thermal conductivity due to the change of moisture content of thermal insulation materials caused by environmental impact during the use of thermal insulation materials when the current domestic standards are formulated. In foreign countries, the declared value of the manufacturer is usually used directly without any correction. According to the results of the previous research on the properties of boards, the properties can meet the national standards, and the water absorption and hygroscopicity are very low, so the modification may not be required.

In order to obtain more comprehensive experimental data, the data containing correction coefficients or not containing correction coefficients are calculated by the project team. According to the requirement of heat transfer coefficient $K \leq 0.15$ of ultra-low energy consumption building wall and combining with the current situation of production line, the thickness of composite insulation board is calculated as 200 mm with correction coefficient and 170 mm without correction coefficient. The performance test of composite board is shown in Table 5.

Table 5. Physical property of 200mm rock wool/polyurethane composite board

Item	Performance index	Test result	Test basis
Density, kg/m^3	≥ 60	70.1	GB 6343
Heat conductivity coefficient, W/(m·K), 25°C	Rock wool	≤ 0.040	GB/T 10294
	Polyurethane	≤ 0.024	
Compressive strength, kPa	≥ 60	63	GB/T 8813
Tensile strength perpendicular to the board surface, kPa	≥ 7.5	7.6	GB/T29906
Short-term water absorption a, kg/m^2 (partial immersion, 24h)	≤ 1.0	0.3	GB/T29906
Dimensional stability b, $\%$ (70°C \pm 2°C, 48h)	≤ 1.5	0.6	GB/T8811

Note: a) only tests the rock wool insulation board; b) only tests the polyurethane.

3.2. Construction of External Insulation System for External Wall of Rock Wool/Polyurethane Composite Insulation Board for Ultra-Low Energy Consumption Buildings

External insulation system for external wall of rock wool/polyurethane composite insulation board for ultra-low energy consumption buildings is fixed mainly by anchoring method with bonding as its auxiliary way, and uses the double-layer glass fiber mesh reinforced plastering layer. The anchor plate

of anchor bolt is set between two layers of glass fiber meshes, and exterior facing is made by using the lightweight coating materials such as paint. The system structure diagram is shown in Table 6.

Table 6. Structure of rock wool/polyurethane composite insulation board external wall insulation system applied in ultra-low-energy buildings

Basic Construction		Schematic diagram for structure
Plastering layer		
Base wall①	Bonding layer②	
Concrete wall, various masonry walls	Thermal insulation layer③	
Adhesive	Base course④	
Rock wool/polyurethane composite insulation board	Reinforcing material⑤	
rendering coat mortar	Joining piece⑥	
Fiberglass mesh	Middle layer⑦	
Anchor bolt	Reinforcing material⑧	
rendering coat mortar	Surface course⑨	
Fiberglass mesh	Finish coating⑩	
rendering coat mortar		
Coatings or facing mortar, etc		

3.3. Study on the Construction Technology of Rock Wool/Polyurethane Composite Insulation Board External Wall Insulation System for Ultra-Low Energy Consumption Buildings

After determining the rock wool/polyurethane composite insulation board external wall insulation system structure for ultra-low energy consumption buildings, the construction technology of this system is studied immediately, and the basic points of construction technology are summarized as follows:

(1) In the construction of rock wool/polyurethane composite insulation board exterior wall insulation system for ultra-low energy consumption buildings, the supporting system materials and matching materials should be selected and the adjacent materials of the system should be compatible with each other.

(2) Thermal bridge blocking treatment should be implemented for the external wall around the external door and window, external wall protruding component and accessory wall component, etc.

(3) Rock wool/polyurethane composite insulation board external wall insulation system for ultra-low energy consumption buildings adopts the jointing mode which combines bonding with anchoring and uses anchoring as the main method. The plastering layer should be reinforced by double-layer meshes, and the anchor bolt pressure plate should withhold the bottom fiberglass mesh. Different types of anchor bolts should be selected according to the type of base wall. The number of bolts shall be determined according to the design and meet the requirements of the following formula.

$$N_A \geq \gamma W_d / F \quad (1)$$

where:

N_A — Number of bolts per unit area, piece/m²;

γ — Safety coefficient, $\gamma=2$;

W_d — The design value of maximum wind load at corresponding height, which is 1.5 times of the standard value of wind load, kN/m²;

F — Standard value of in-situ tensile strength or standard value of penetration strength of single anchor bolt, whichever is smaller, kN.

The horizontal load of external thermal insulation system is mainly negative wind pressure. The basic wind pressure W_o in Beijing is 0.45 kN/m². Considering the ground roughness category B and taking 1.5 as the design safety factor γ_s , by taking the rural areas with sparse housings as an example, the calculated standard value W_k and design value W_d of wind load are shown in the table 3.2. The number of bolts should be calculated according to formula 1. New buildings in Beijing are mostly concrete base walls. According to the standard value of wind load in Beijing and the technical requirements of this code on the anchor bolts, the number of anchor bolts required by the rock wool board external insulation system at different building heights is calculated as shown in the table 3.3. When the base wall is of other types, it should be designed separately according to the standard value of the tension capacity of anchor bolt and standard value of penetration force.

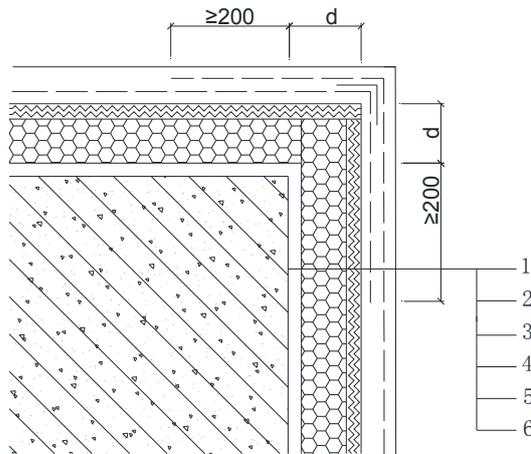
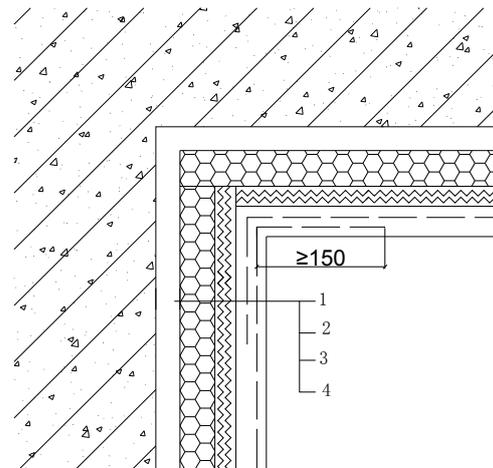
Table 7. Standard value (W_k) and design value (W_d) of maximum wind load at different heights in beijing area with sparse housings, kN/m²

Height, m	β_{gz}	μ_s	μ_z	W_o	W_k	γ_s	W_d
20	1.63	1.7	1.25	0.45	1.53	1.5	2.30
50	1.55		1.67		1.92		2.88
100	1.50		2.09		2.30		3.45
150	1.47		2.38		2.53		3.80

Table 8. Quantity of anchors for rock wool board external insulation system applied on concrete base

Elevation of buildings	<20m	20m≤H<50m	50m≤H<100m	H≥100m
Number of anchor bolts, piece/m ²	≥8	≥10	12	12

(4) In order to ensure the fireproofing performance of the composite insulation board external wall insulation system, special treatment should be done at the external corner: the polyurethane layer of composite insulation board located at the outside should be partially cut off, with the cutting thickness equalling to the thickness of the composite insulation board (see Figure 2), and the external corner protector should be added between the two layers of glass fiber meshes at the external corner. In order to ensure the thermal insulation effect at the internal corner, a part of rock wool layer should be cut off, with the cutting thickness equalling to the thickness of the composite insulation board (see Figure 3).

**Figure 2.** Schedule of external corner**Figure 3.** Schedule of internal corner

(5) Lightweight materials such as coatings and facing mortar should be selected for the finish coat of the external thermal insulation project, and the finish coat should be compatible with other component materials of the external thermal insulation system.

(6) The construction of external thermal insulation system should comply with the current national and municipal standards, norms and regulations on fire safety.

3.4. Verification Test of Rock Wool/Polyurethane Composite Insulation Board External Wall Insulation System for Ultra-Low Energy Consumption Buildings

According to the system structure and construction technology, the test samples for the thermal insulation system of external wall are prepared with 200 mm thick rock wool/polyurethane composite thermal insulation board, including 7m² of large weatherproof experimental wall and 5m² of wind-proof experimental wall. The test results of weather resistance, wind load resistance, water absorption, impact strength, freeze-thaw resistance, moisture flow density and impermeability of water vapor meet the requirements of relevant standards. The results are shown in table 9.

Table 9. System test result

No.	Test Item	Test Result	Judgment
1	Weather resistance	No surface cracks, pulverization and glass phenomena	Qualified
2	Wind load resistance, kPa	8.0	Qualified
3	Impermeability of water	No water infiltration at the inner side of the protective layer	Qualified
4	Impact strength	≥10J	Qualified
5	Moisture flow density of water vapor, g/(m ² ·h)	2.06	Qualified
6	Freeze-thaw resistance	No surface cracks, hollow drums, bubbles, glass phenomena	Qualified
7	Thermal resistance, (m ² ·K)/W	6.54	Qualified

4. Conclusion

(1) By comparing and analysing the performance of rock wool, the thickness of rock wool is determined to be 50mm in this study in order to ensure the fire protection performance of the system.

(2) The B1 grade polyurethane board was studied, and the formula of various raw materials and the formula after adding flame retardant were determined. In order to improve the combustion performance and the index of isocyanate, the single use of polyether polyol in the original

polyurethane formula was changed to the use of part of polyester polyol instead of part of polyether polyol. The effect of different isocyanate contents on the combustion rate of the product was studied, and the results showed that the higher the isocyanate index, the smaller the combustion speed of the foam. But in the course of the experiment, it was found that the isocyanate index could not be increased excessively, and ratio of white material to black material was 1:1.6-1:1.95.

(3) After calculating the energy-saving efficiency and thickness of rock wool/polyurethane composite insulation board, it can be seen that when the calculation is made according to the requirement of $K \leq 0.15$ of the external wall for ultra-low energy consumption buildings, the thickness of rock wool board is 50 mm, the thickness of polyurethane is 150 mm and the total thickness of them is 200mm in the case of containing the correction factor; and when the correction factor is not included, the thickness of polyurethane is decreased to 120mm and the total thickness is 170mm.

(4) The construction and schedule of main joints of the rock wool/polyurethane composite thermal insulation board external wall thermal insulation system for ultra-low energy consumption buildings are studied and described. The enterprise standards such as *the Rock Wool/Polyurethane Composite Thermal Insulation Board* and *the Rock Wool/Polyurethane Composite Thermal Insulation Board External Wall Thermal Insulation System* are compiled.

(5) The rock wool/polyurethane composite insulation board and the external wall insulation system made of composite insulation board were tested. The thermal resistance of the 200 thick rock wool/polyurethane composite insulation board external wall insulation system was tested to be 6.54 ($\text{m}^2 \cdot \text{K}$)/W, and the converted average heat transfer coefficient of wall was 0.1494 W/($\text{m}^2 \cdot \text{K}$), which met the standard requirements. All other test results met the standard requirements.

5. References

[1] Fang Yusheng 2005 *Zhu Lvmin. Polyurethane Foaming Plastic* (Beijing: Chemical Industry Press)