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Application Research of a Biomass Insulation Material: Eliminating Building Thermal Bridges

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Abstract: Building joints always lead to water leakage, wind penetration, and thermal bridges, which especially cannot be ignored in prefabricated buildings. Thus, in order to solve this problem, we propose a novel and feasible insulating element with a multi-layered structure, which can realize waterproof and thermal insulation at the same time. Its performance was evaluated by experiments and scenario analysis, including its water resistance, moisture resistance, cohesiveness, fire resistance, weatherability, thermal insulation, etc. The research results show that, compared with building foundation materials, the proposed building element obtained satisfactory performance: water absorption was reduced from 35.7% to 18.5%; moisture absorption from 7.0% to 2.1%; and weatherability and fire resistance performance were good. The proposed novel insulating element can be applied in prefabricated buildings, and the research can open up new ideas for other related insulating elements with more advanced and better performance which focus on solving problems caused by cold or hot bridges and building joints.

Keywords: prefabricated building element; building thermal bridge; building joints; biomass insulation material

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1. Introduction

With the acceleration of China's urbanization process, building energy consumption has continues to trend upward and the construction industry has become the second largest energy-consuming industry in China's national economy [1,2]. The properties of prefabricated buildings in terms of energy savings, high efficiency, and recycling can meet the needs of sustainable building development, which is a major trend in the development of the construction industry [3]. However, unlike traditional construction methods, their assembly construction method makes thermal bridges more likely to occur at the joints of various components of prefabricated buildings. The existence of thermal bridges leads to concentrated heat loss, increased building energy consumption, and can even result in mold and damage to the building structure [4,5]. Therefore, it is necessary to eliminate the impact of thermal bridges.

A great deal of research has been carried out concerning reducing the influence of thermal bridges on the thermal performance of buildings, mainly divided into three methods, namely, structural design, local insulation, and material substitution.

Structural design means to reasonably design and transform the thermal bridge according to the actual situation of the building after analyzing the parts that produce the thermal bridge and heat loss. In order to reduce the impact of structural thermal bridge areas in residential buildings, Aelenei [6] proposed a new passive solar retrofit solution, named the Solar Bridge Retrofit System (SBRS), which uses transparent glazing to cover the load-bearing concrete frame of the facade to absorb solar radiation and conduct the heat slowly inward or to adjacent structures. In view of balcony thermal bridges, Ge [7] changed the structure of the floor and balcony and introduced a balcony insulation board composed of 80 mm EPS modules, which was inserted between the floor slab and the balcony cantilever. Through 2D heat transfer and whole-building energy simulations, the results show that the balcony heat insulation board can effectively reduce the heat transfer of the balcony board; the lowest floor temperature is increased from 6.1 °C to 12.5 °C, and the heating energy consumption is reduced by 5–13%. Kotti [8] proposed the introduction of “sunspace” in view of the thermal bridge effect of a single-family house in Greece by enclosing the balcony and semi-open space with glass. Glazing promotes solar gains, while overheating protection is achieved by setting openable glazing to maintain the natural ventilation during summer period. The results showed that the sunspace achieved the highest energy reduction, at 10%. The method of reducing the impact of thermal bridges through structural design requires targeted reconstruction of the building, which is not easy to popularize and apply, and often has a higher cost and a longer discount payback period. For example, the cost in article [8] was 120% of the annual energy bill of the house.

Material substitution refers to the substitution of existing materials with materials which have lower thermal conductivity or better performance. Aiming at the thermal bridge at the joint of the metal curtain wall, Oh [9] proposed replacing the metal frame with a plastic frame with lower thermal conductivity at the connection between the metal panel and the bracket. The results show that this method can effectively reduce heat loss at the metal plate connection and improve the building’s energy-saving potential. The thermal conductivity of the alternative metal curtain wall was reduced by 72%, and the annual heating energy demand was reduced by 26%. To improve the thermal performance of window systems, Ben-Nakhi [10] replaced the natural marble layer of the window trim with a resistive marble of thermal conductivity half that of natural type, and replaced the aluminum window frame with a wooden frame to solve the thermal bridge in the window system. To improve the thermal performance of the envelope, Brás [11] used cement–cork mortars instead of cement–EPS mortars to reduce condensation effects and minimize heat transfer in thermal bridges. Substitute materials cannot change the structural performance of the thermal bridge area, and need to have better thermal performance, which is difficult to explore and research.

Local insulation refers to installing a layer of insulation material in the thermal bridge area to improve its thermal performance. Theodosiou [12] studied the thermal bridge effect in a typical three-story apartment building. The results showed that the correction of the thermal bridges, mainly carried out by the installation of a 3-cm layer of extruded polystyrene on the outer surface of the concrete beams and pillars, reduced the building’s annual heating load by about 29%. Ibrahim [13] presented an innovative insulating coating based on a superinsulating silica aerogel material to tackle the thermal bridges resulting from windows offset from exterior walls. The study found that applying 1 and 2 cm of the insulating coating on thermal bridges reduced the windows’ offset energy load by about 24%, up to a maximum of 50%. Ben-Nakhi [10] addressed the thermal bridge of a window system by adding a 5-cm thick insulating layer around the windows which extended from original insulating layer to the internal plaster. The simulation results showed great improvement in the thermal performance of a classical window system when modified to the edge insulation window system. Local insulation is the most common way to solve thermal bridges, because it is easy to implement and is usually effective.

Finding suitable building insulation materials is the key to solving the problem of thermal bridges effectively. Zhang [14] studied the influence of different water–cement ratios, coagulants, foaming agents, and foam stabilizers on the performance of foamed concrete, optimized the optimal mix ratio, and prepared low-density foamed concrete insulation material with low density and both good strength and heat preservation performance. Yan [15] used heat insulation particles to replace part of bamboo fibers to prepare a bamboo fiber–heat insulation particle composite core material vacuum insulation panel, which both reduced its production cost and effectively improved the thermal insulation performance of the vacuum insulation panels. Gao [16] used perlite to prepare new foam insulation materials, including perlite/sodium silicate, hydrogen peroxide, cetyltrimethyl ammonium bromide, and rock wool. This new foam insulation material was lighter than other inorganic materials, with lower thermal conductivity and higher mechanical strength.

In preliminary research work, our research team explored the feasibility of preparing building insulation materials from agricultural and forestry wastes [17–19]. The results show that this new type of biomass-based composite insulation material has good thermal insulation, high mechanical strength, and other excellent properties. In this study, we use this material as the basic material of thermal bridge insulation building components, improve the overall waterproof performance and moisture resistance performance through the composite structure design, and explores the feasibility of using it as a thermal bridge insulation building component.

The manuscript is organized as follows: Section 1 introduces the current research background and research status; Section 2 introduces the biomass insulation materials, waterproofing agents, and adhesives used in the research; Section 3 explains the research methods; Section 4 presents the results and discussion; finally, Section 5 provides the main conclusions of the study.

2. Material

2.1. Basis Material

The suggested protective component building thermal bridge has good thermal and mechanical properties. It is mainly made from a novel bio-insulation material which uses agricultural and forestry waste, wheat straw, rice husk, and wood chips as the aggregate and geopolymer (metakaolin) as the binder. The key production processes include pretreatment, stirring, curing, and drying. In order to evaluate the performance of the mentioned novel bio-insulation, colleagues on the authors' research team, e.g., Zou Si, Wang Shuang et al., have carried out related experiments; significant related research results are shown in Table 1.

Table 1. Basic material performance parameters.

Biomass Type	Thermal Conductivity/ [W/(m·K)]	Density/ [kg/m^3]	Compressive Strength/MPa	Water Absorption/%	Hygroscopicity/%
Wheat straw	0.092–0.0186	235–894	0.18–5.62	32–107	4–33
Rice husk	0.082–0.0184	174–813	0.26–7.24	28.3–93.6	9.7–18.6
Sawdust	0.091–0.125	225.6–939.4	0.14–28.26	-	-

Sawdust is used as aggregate in this study. Compared with wheat straw and rice husk, sawdust has relatively small particles, which is conducive to uniform distribution in biomass composites. The composition of the base material mixture is shown in Table 2 [19].

Table 2. The compound composition of the base material.

Composition	Metakaolin	Sawdust	Sodium Silicate Solution	Sodium Hydroxide Solid	Soap Powder	Hydrogen Peroxide Solution	Water
Quality ratio/%	35.18	6.81	32.19	4.41	0.69	2.27	18.45

2.2. Waterproofing Agent

The water-repellent agent forms a hydrophobic membrane layer on the surface of the porous material or in its pores and capillaries, which can reduce the water absorption of the base material or its water permeability under hydrostatic pressure, thereby significantly improving waterproof performance. In this study, three types of water repellents were selected: a silicone water repellent, a fatty acid water repellent, and an inorganic aluminum salt water repellent [20]. The basic properties are shown in Table 3.

Table 3. Basic properties of waterproofing agent.

Name of Waterproofing Agent	Appearance	Solid Content/%	pH	Fineness /μm	Density/ [kg/m^3]	Boiling Point /°C	Impermeability
Silicone waterproofing agent	Homogeneous white emulsion	50	7–8	-	0.98	120	High
Fatty acid waterproofing agent	Homogeneous colorless transparent liquid	35	6–8	30–40	0.96	120	High
Inorganic aluminum salt waterproofing agent	Homogeneous colorless transparent liquid	40	10–11	310–315	1.07	-	High

Through the specific molecular design of silicone polymer, the silicone waterproofing agent is able to form an extremely thin film on the surface, which has the characteristics of low bubble, fast penetration, and strong permeability. Fatty acid waterproofing agents (e.g., calcium stearate, zinc stearate, etc.) have relatively low costs and can be divided into reactive and non-reactive types [21]. Inorganic aluminum salt waterproofing agents are made of inorganic materials, which mainly have the functions of impermeability, micro-expansion, and increasing compactness in addition to being waterproof.

2.3. Adhesive

Table 4 lists the mechanical properties of the common structural adhesives. In this study, epoxy resin adhesive was selected because of its wide application in construction, adequate safety reserve, and good resistance to aging and chemical corrosion.

Table 4. Mechanical properties of several structural adhesives.

Name of Adhesive	Tensile Modulus/GPa	Lap Shear Strength/MPa	Elongation at Break/%
Phenolic adhesive	800–1000	28–40	0–5
Epoxy adhesive	100–700	10–26	3–60
Acrylate adhesive	100–800	10–24	10–80
Polyurethane adhesive	90–300	9–20	10–95

3. Research Methods

3.1. The Component Design

The structure and location of the building thermal bridge insulation component are shown in Figure 1: The component is a right-angle component placed at the junction of the floor and the external wall, and plays a role in local heat preservation and insulation. It can be applied both internally and externally. Figure 2 shows the structural composition of the component; it is divided into three layers: the bonding layer, the waterproof layer, and the base material. In addition, there is a surface protective film which is removed during the actual construction process.

3.2. Sample Preparation

The preparation process of thermal bridge insulation components includes three stages, substrate preparation, waterproof coating, and adhesive coating treatment. The specific operation process in this study was as follows.

Base preparation: the alkali activator was prepared and the sawdust was immersed in water for pre-wetting. Metakaolin and the alkali activator were mixed, stirring at a constant speed to obtain a geopolymer slurry, and foam stabilizer and foaming agent were added. The slurry was is injected into the mold under normal temperature and pressure, and after standing still, was cured for ten days after being sealed with plastic film and silicone oil [19].

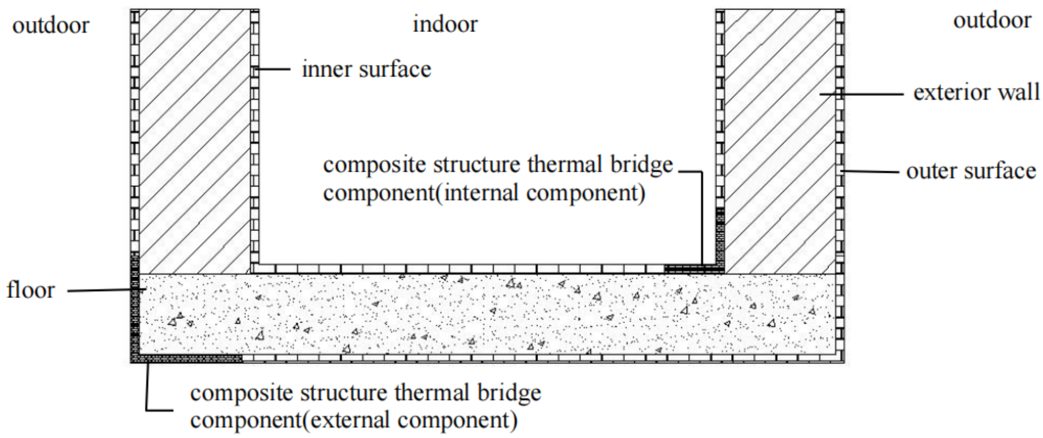


Figure 1. Thermal bridge node structure and component location at the junction of floor and exterior wall.

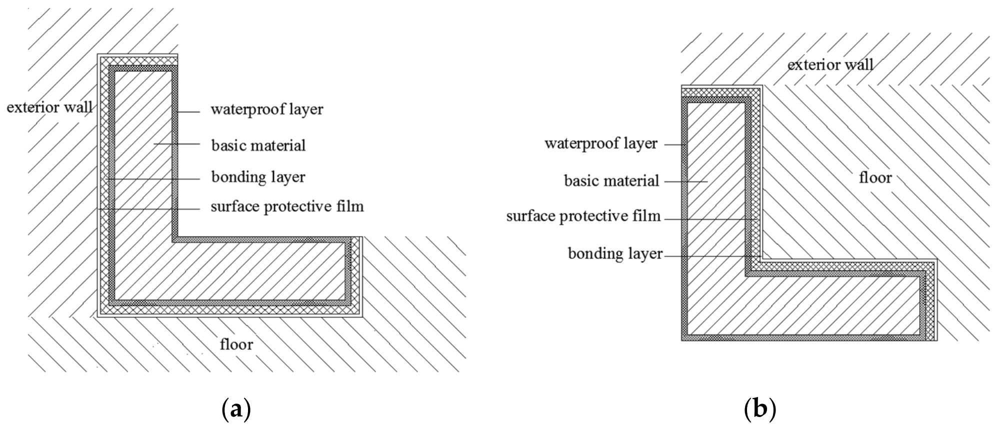


Figure 2. Structure composition of thermal bridge insulation components: (**a**) internal component structure composition; (**b**) external component structure composition.

Waterproof coating treatment: the water-repellent agent was brushed, immersed, or sprayed onto the surface of the prepared base material sample and let stand for 48 h to form a waterproof coating. The specific sample treatment is shown in Table 2.

Adhesive coating: the surface in contact with the floor and exterior wall of the component was uniformly coated with adhesive and maintained for 24 h to ensure hardening and solidification of the adhesive.

3.3. *Research Method of Multi-Objective Performance*

Any basic material used to make building thermal bridge insulation components should have good thermal performance and a specific mechanical strength. In order to study the feasibility of the novel component for different applications and in various circumstances, we evaluated several key parameters, including proof against water and moisture-, bonding strength, and thermal insulation. The weatherability and fire resistance of the component were analyzed as well.

3.3.1. Analysis of Waterproof and Moisture-Proof Performance

When a composite structure thermal bridge insulation component is directly in contact with moist air or even water, its thermal insulation performance is affected, and waterproof treatment may be required. There are two kinds of waterproof treatment methods, surface waterproofing and built-in waterproofing [20]. Built-in waterproofing has a certain influence on the performance and curing effect of the basic material. Therefore, in this study we chose the surface waterproofing enhancement method with an external waterproof coating. The waterproof and moisture-proof properties of the samples were tested in order to explore the influence of various factors, including the type of waterproofing agent, the surface treatment method, and the coating times. The sample sizes were all 65 mm × 65 mm × 35 mm; the sample treatments are shown in Table 5.

Table 5. Test sample processing for waterproof and moisture-proof performance of composite structure thermal bridge insulation component.

Sample Number [1]	Waterproof Agent Type	Surface Treatment Method	Coating Times
1(1-1, 1-2)	None	None	0
2(2-1, 2-2)	Silicone waterproofing agent	Brushing	2
3(3-1, 3-2)	Fatty acid waterproofing agent	Brushing	2
4(4-1, 4-2)	Inorganic aluminum salt waterproofing agent	Brushing	2
5(5-1, 5-2)	Fatty acid waterproofing agent	Brushing	1
6(6-1, 6-2)	Fatty acid waterproofing agent	Brushing	3
7(7-1, 7-2)	Fatty acid waterproofing agent	Brushing	4
8(8-1, 8-2)	Fatty acid waterproofing agent	Dipping	2
9(9-1, 9-2)	Fatty acid waterproofing agent	Spraying	2

[1] Sample 1 had no water-proofing agent added and served as a control group. Sample 1.2.3.4 explores the influence of the type of waterproofing agent. Sample 1.3.8.9 explores the influence of surface treatment with the waterproofing agent. Sample 1.3.5.6.7 explores the influence of the coating time of the waterproofing agent.

The water absorption rate of the sample with applied waterproof coating was measured. The process included three steps, as follows: Step 1: the sample coated with waterproofing agent was placed in a drying oven at 105 °C for 4 h and the dry mass of the sample was weighed; Step 2: the sample was immersed in a beaker filled with water and left standing; Step 3: the sample was removed after 72 h, the surface moisture wiped away, and the mass of the sample after it had absorbed water was immediately weighed [22]. The calculation formula for water absorption is

$$R_1 = \frac{M_w - M_{d1}}{M_{d1}} \times 100\% \tag{1}$$

where R_1 = water absorption rate (%), M_w = the mass of the sample after absorbing water (g), and M_{d1} = the dry mass of the sample in the waterproof test (g).

The waterproof performance test process of thermal bridge insulation components is shown in Figure 3.

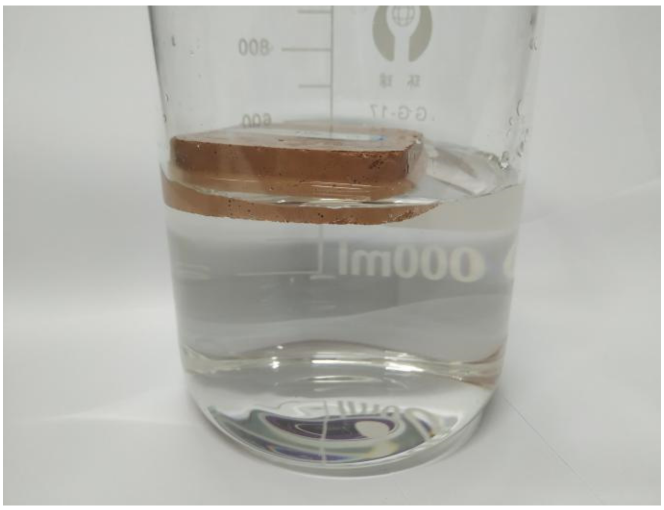


Figure 3. Waterproof performance test of composite structure thermal bridge insulation component.

The moisture absorption rate of the sample with waterproof coating was measured. The process includes two steps, as follows: Step 1: the sample coated with waterproofing agent was placed in a drying oven at 105 °C for 4 h and the dry mass of the sample was weighed; Step 2: the sample was placed in a sealed water-containing glassware with relative humidity close to 100% and weighed it every 24 h until the mass changes at three consecutive times were less than 0.1% of the total mass, which can be regarded as reaching constant weight, then the mass of the sample after moisture absorption was recorded [23]. The calculation formula of water absorption is

$$R_2 = \frac{M_m - M_{d2}}{M_{d2}} \times 100\% \tag{2}$$

where R_2 = moisture absorption rate (%), M_m = the mass of the sample after moisture absorption (g), and M_{d2} = the dry mass of the sample in the moisture resistance test (g).

The moisture-proof performance test process of thermal bridge insulation components is shown in Figure 4.

Figure 4. Moisture-proof performance test of composite structure thermal bridge insulation component.

3.3.2. Efficiency of Adhesive Connection

The thermal bridge insulation component, which does not need to bear pressure, can be connected with the external wall and floor by adhesive connection. Compared with joints formed by other connection methods, such as riveting, screwing, etc., the adhesive joint has a uniform stress distribution [24]. It can connect components of different materials, avoiding sporadic thermal bridges, and is relatively simple to operate.

We measured the bonding performance of the sample after applying the adhesive coating. The shear strength of the adhesive layer was measured using a universal tensile testing machine. The load was applied at a constant speed of 5 mm/min, recording the corresponding load value when the sample was damaged. The shear strength, τ, is calculated according to Formula (3):

$$\tau = \frac{F_{\max}}{S} \tag{3}$$

where τ = shear strength (MPa), $F_{\max}$ = maximum load when the specimen is broken (N), and S = shear area(mm^2).

The bonding performance test of composite structure thermal bridge insulation component is shown in Figure 5.

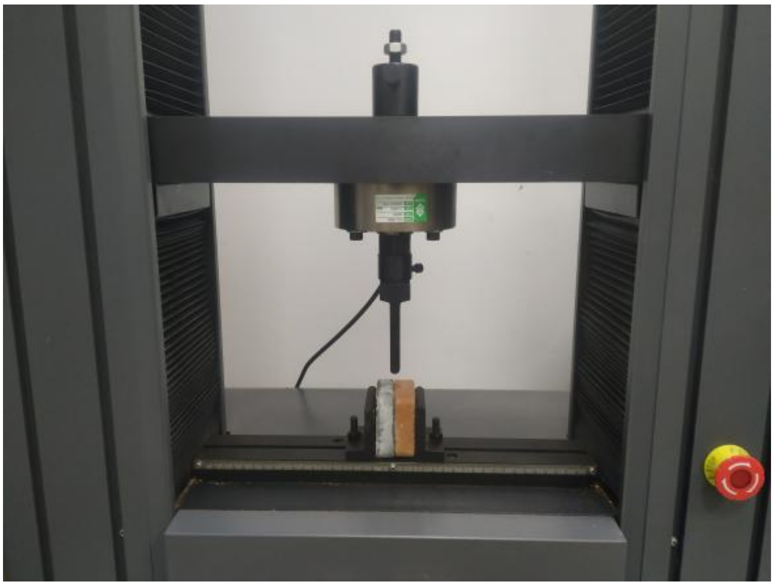


Figure 5. Sample shear strength test.

3.3.3. Analysis of Weatherability

Prefabricated building materials should have certain chemical and physical stability (i.e., good weatherability performance) in order to avoid damage under different effects, e.g., high temperature, humidity, shrinkage, expansion, etc. After the sample was bonded with the concrete material, freeze–thaw cycle and cold–heat cycle tests were carried out.

Freeze–thaw cycle: a visual inspection of the sample was performed and its original condition was recorded. Then, the sample was placed into water at a temperature of 5 °C for 2 h with one side of the component facing down; the depth of immersion was 3 mm–10 mm. The sample was then frozen in a refrigerator at a temperature of −20 °C for 2 h, which was considered one cycle.

Cold–heat cycle: The sample was placed in a dry oven at a temperature of 50 °C for 2 h, and then in a refrigerator at a temperature of −20 °C for 2 h as one cycle.

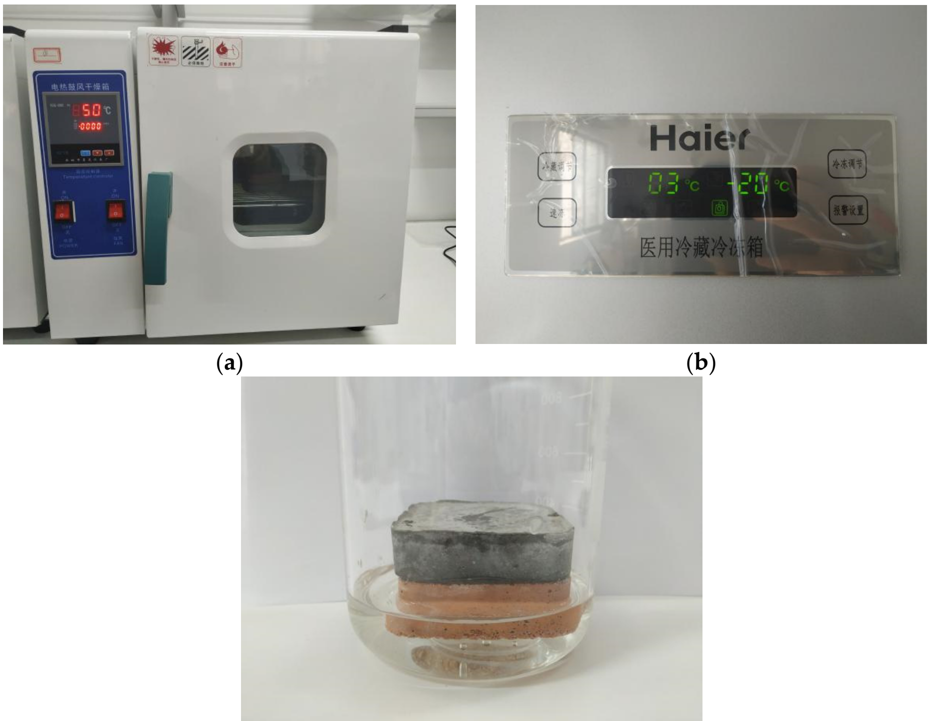
After eight cycles each of freeze–thaw and cold-heat cycles, the samples were maintained at 10 °C and 70% relative humidity for more than 1 h to observe the surface of the sample, and the length, width, and thickness of the sample were measured with vernier caliper before and after the test (uncertainty = 0.02 mm).

The weatherability test of the composite structure thermal bridge insulation component is shown in Figure 6.

3.3.4. Analysis of Fire Resistance

Building materials should be fire resistant; thus, the components were tested for flammability after adding the waterproof coating and adhesive coating in order to observe whether the components were flammable. The sample was fixed vertically and a piece of ignition paper was placed underneath it. The surface of the component was ignited with a flame spray gun for 15 s, 30 s, 60 s, and 90 s [25]. Observations were made as to whether the sample burned or emitted smoke and whether there were any burning droplets that ignited the paper. After the end of the test, the surface condition of the sample was observed.

The fireproof performance test of the composite structure thermal bridge insulation component is shown in Figure 7.



(**a**) (**b**)

(**c**)

Figure 6. The weatherability test process of composite structure thermal bridge insulation component: (**a**) the drying oven with temperature set at 50 °C; (**b**) the refrigerator with freezing temperature of −20 °C; (**c**) sample immersion.

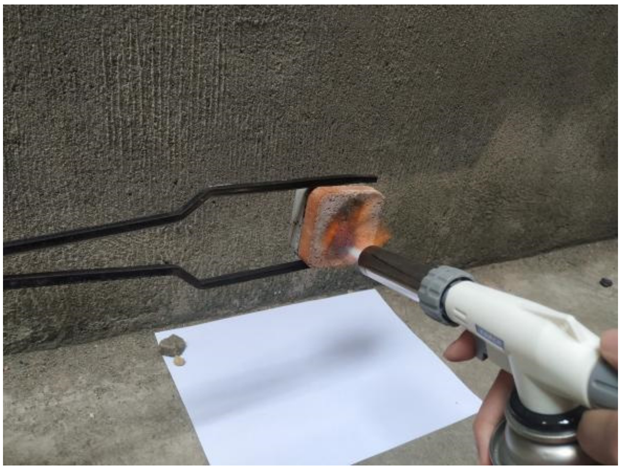


Figure 7. Igniting the surface of the component.

4. Results and Discussion

4.1. Waterproof and Moisture-Proof Performance

The waterproof and moisture-proof performance test results are shown in Tables 6 and 7. The measurement error of the mass involved in the experiment is controlled within ±0.1 g. Compared with the non-waterproof coating, the water absorption rate of the sample with the waterproof coating is significantly reduced, and the silicone waterproof agent is the best, reducing the water absorption rate by 38.92%. This is because the metakaolin in the base material contains silica and reacts with alkali to form silicate in the preparation process. The active ingredients of the silicone waterproofing agent can react with the hydroxyl groups on the surface of the silicate to form a mesh waterproof membrane layer; thus, it has good waterproof performance. Among the different surface treatment methods, brushing has the best effect, as it is more uniform than spraying and has better penetration than dipping. As the coating is brushed on more times, the waterproof effect becomes better. The water absorption rate of the water repellent agent applied four times is only 18.54%, which is 42.40% lower than the sample with one coating paint.

Table 6. Test results of waterproof performance of composite structure thermal bridge insulation component.

Sample Number	The Dry Mass of the Sample in the Waterproof Test (M_{d1}) */g	The Mass of the Sample after Absorbing Water (M_w) */g	Water Absorption Rate (R_1)/%
1-1	25.8	35.0	35.66
2-1	34.9	42.5	21.78
3-1	27.0	32.9	21.85
4-1	33.5	41.8	24.78
5-1	35.1	46.4	32.19
6-1	35.6	43.8	23.03
7-1	41.0	48.6	18.54
8-1	40.7	50.4	23.83
9-1	41.4	51.9	25.36

* In each experiment, the quality of each sample was measured five times, and the values in the table are the average values of the five measurements. After error analysis, the relative standard deviation of all data is less than 3%, which proves that the data are reliable.

Table 7. Test results of moisture-proof performance of composite structure thermal bridge insulation component.

Sample Number	The Dry Mass of the Sample in the Moisture Resistance Test (M_{d2}) */g	The Mass of the Sample after Moisture Absorption (M_m) */g	Moisture Absorption Rate (R_2)/%
1-2	37.2	39.8	6.99
2-2	42.6	43.7	2.58
3-2	36.1	37.6	4.16
4-2	29.6	31.2	5.41
5-2	33.8	35.7	5.62
6-2	36.0	37.6	4.44
7-2	37.8	38.6	2.12
8-2	38.1	39.8	4.46
9-2	32.6	34.1	4.60

* In each experiment, the quality of each sample was measured five times, and the values in the table are the average values of the five measurements. After error analysis, the relative standard deviation of all data is less than 3%, which proves that the data are reliable.

Specific data and error analyses are shown in Tables 8 and 9.

Table 8. Dry mass measurement data of samples in waterproofing test.

Sample Number	Measured Value (g)					The Average (g)	Standard Deviation	Relative Standard Deviation
	Group 1	Group 2	Group 3	Group 4	Group 5			
1-1	25.3	25.6	26.1	25.9	26.1	25.8	0.31	1.2%
2-1	34.5	34.7	35.5	34.1	35.7	34.9	0.61	1.7%
3-1	26.1	27.6	27.2	26.5	27.6	27.0	0.60	2.2%
4-1	33.8	33.4	32.9	33.4	34.0	33.5	0.38	1.1%
5-1	35.4	35.1	34.8	34.6	35.6	35.1	0.37	1.1%
6-1	35.8	35.4	35.1	36.0	35.7	35.6	0.32	0.9%
7-1	41.4	40.8	41.2	41.5	40.1	41.0	0.51	1.2%
8-1	41.0	40.9	40.3	40.5	40.8	40.7	0.26	0.6%
9-1	41.7	41.2	41.9	41.1	41.1	41.4	0.33	0.8%

Table 9. Measurement of the quality of the sample after water absorption.

Sample Number	Measured Value (g)					The Average (g)	Standard Deviation	Relative Standard Deviation
	Group 1	Group 2	Group 3	Group 4	Group 5			
1-1	35.0	35.6	34.8	34.6	35.0	35.0	0.33	1.0%
2-1	42.1	42.7	42.2	42.4	43.1	42.5	0.36	0.9%
3-1	32.4	33.1	33.2	32.6	33.2	32.9	0.33	0.9%
4-1	41.1	42.3	41.6	41.7	42.3	41.8	0.47	1.1%
5-1	46.1	46.8	46.3	46.7	46.1	46.4	0.30	0.7%
6-1	44.3	43.6	43.6	43.7	43.8	43.8	0.26	0.6%
7-1	48.2	49.0	48.3	48.8	48.7	48.6	0.31	0.6%
8-1	50.1	50.3	51.0	50.8	49.8	50.4	0.44	0.9%
9-1	51.4	51.6	52.5	51.8	52.2	51.9	0.40	0.8%

Specific data and error analyses are shown in Tables 10 and 11.

Table 10. Dry mass measurement data of samples in the moisture resistance test.

Sample Number	Measured Value (g)					The Average (g)	Standard Deviation	Relative Standard Deviation
	Group 1	Group 2	Group 3	Group 4	Group 5			
1-2	36.8	36.7	37.6	37.5	37.4	37.2	0.37	1.0%
2-2	42.0	42.9	42.8	42.3	43.0	42.6	0.38	0.9%
3-2	36.6	35.8	36.4	35.6	36.1	36.1	0.37	1.0%
4-2	29.0	29.5	30.1	29.9	29.5	29.6	0.38	1.2%
5-2	33.4	33.7	34.3	34.0	33.6	33.8	0.31	0.9%
6-2	35.6	35.9	36.4	36.1	36.0	36.0	0.26	0.7%
7-2	38.2	38.4	37.5	37.3	37.6	37.8	0.42	1.1%
8-2	38.5	37.9	37.5	38.6	38	38.1	0.40	1.0%
9-2	32.6	32.1	32.5	33.4	32.4	32.6	0.43	1.3%

Table 11. Measurement of the quality of the sample after moisture absorption.

Sample Number	Measured Value (g)					The Average (g)	Standard Deviation	Relative Standard Deviation
	Group 1	Group 2	Group 3	Group 4	Group 5			
1-2	39.5	40.3	39.6	39.9	39.7	39.8	0.28	0.7%
2-2	43.4	43.8	44.2	43.5	43.6	43.7	0.28	0.6%
3-2	37.2	37.9	37.4	38.1	37.4	37.6	0.34	0.9%
4-2	31.9	31.4	30.8	30.6	31.3	31.2	0.46	1.5%
5-2	36.2	35.9	35.4	35.1	35.9	35.7	0.39	1.1%
6-2	37.0	37.3	37.8	38.0	37.9	37.6	0.38	1.0%
7-2	38.5	38.9	38.2	38.4	39.0	38.6	0.30	0.7%
8-2	39.4	39.8	40.1	39.6	40.1	39.8	0.28	0.6%
9-2	33.8	34.4	33.9	34.2	34.2	34.1	0.22	0.6%

Similarly, the moisture absorption rate of the sample without waterproof coating was 6.99%; the moisture absorption rate of Sample 7 was the lowest at 2.12%, a decrease of 69.67%. This sample used the silicone water-proofing agent as waterproof coating, and the surface was brushed four times.

In practical engineering applications, the silicone waterproof agent is recommended as a waterproof coating, adopting a brushing surface treatment method. When jointly considering the engineering waterproof level requirements and economic costs, it is recommended that two coats of the waterproof agent be applied.

Although the water absorption and hygroscopic rate of the component are greatly reduced after waterproof treatment compared with the existing thermal insulation materials, such as foam concrete thermal insulation board, the component cannot meet requirements of water absorption below 10%. Therefore, adding waterproof agent during the preparation process may have a better effect, which will be further studied in future experiments.

4.2. Bonding Performance

The bonding performance test result of the composite structure thermal bridge insulation component is shown in Table 12, and Figure 8 shows the results of sample adhesive damage. The measurement error of the size involved in the experiment is controlled within ±0.1 mm, and the load is controlled within 100 N.

Table 12. Shear strength value of composite structure thermal bridge insulation component.

Sample Number	Sample Size/mm × mm	Maximum Load When the Component Damaged/N	Shear Strength/MPa
1	65.8 × 66.5	1890.0	0.432
2	65.6 × 64.9	2284.5	0.536
3	66.6 × 66.6	2284.5	0.515
4	65.5 × 65.8	2066.5	0.480

Figure 8. The sample is damaged at the glue joint.

According to the proposed building component application scenario, attention should be paid to shedding. The bond point between the component and the concrete material is the most likely to be destroyed. According to the provisions in the performance indexes of common insulation system, the bond strength of the test piece, which has good bonding performance, should not be less than 0.10 MPa [26], and failure occurs in the test piece. The shear strength of the adhesive layer of the sample is shown in Table 8. Among the eight tested samples, the minimum shear strength is 0.432 MPa and the maximum is 0.536 MPa; the average shear strength is 0.491 mpa, which is greater than 0.10 MPa. Therefore, the component has good bonding performance.

It can be seen from the experimental data that the data from different samples are quite different, which may be related to the thickness of adhesive layer and bonding size. Because the component is small, the bonding method adopted is full bonding. Through experimental research, when the adhesive layer is uniform and the thickness is moderate, the bonding performance of the component is the best, and the thickness is best controlled within 0.03~0.15 mm.

4.3. Weatherability

The appearance of specimens in the weatherability test of the composite structure thermal bridge insulation component is shown in Figure 9, which shows a frost layer appearing on the surface of the sample after the freezing treatment. After freeze–thaw and heating–cooling cycles, the sample was left for 2 h without obvious delamination or cracking; the difference in sample's size is within a reasonable range of measurement error without obvious expansion or contraction, which indicates that the component has good weatherability.

Figure 9. Sample surface after freeze–thaw cycle.

The relevant data before and after the test are shown in Tables 12 and 13. While the specimen size increased after the test, the difference was small, within the reasonable range of 0.3%, and there was no obvious deformation of the specimen.

Table 13. Shear strength value of composite structure thermal bridge insulation component after weatherability test.

Sample Number	Sample Size/mm × mm	Maximum Load When the Component Damaged/N	Shear Strength/MPa
1	66.8 × 66.6	853.5	0.386
2	66.7 × 65.9	1311.0	0.491
3	67.6 × 66.8	1110.5	0.455
4	66.4 × 65.9	1065.0	0.428

It can be seen from the experimental data that the shear strength of the specimen decreases following the test. The minimum shear strength is 0.386 MPa, the maximum is 0.491 MPa, and the average is 0.440 MPa, all greater than 0.10 MPa. Therefore, the component has good weather resistance.

4.4. Fireproof Performance

After igniting the surface of the component with a flame spray gun, the sample did not smoke or burn, nor did the burning material drip. As shown in Figure 10, after burning, the center of the sample surface is carbonized and appears black, and the sample has no damage.

After the fire resistance test of the specimen, its length and width do not change, and although the thickness decreases slightly, this is controlled within a reasonable range of 0.3%. In addition, the strength of the specimen effectively did not change, the compressive strength only weakened by 1%, and the thermal stability of the specimen did not change. Therefore, the component has good fire resistance.

The component is in a closed state, avoiding direct contact with oxygen, and thus changes from combustible to nonflammable; because it has the function of thermal insulation, it experiences less heat penetration. At the same time, the size of the component does not change, that is, there is no thermal expansion. If there is a fire in an engineering application, the component will not crack. Moreover, when the component is applied to a building's exterior wall, combustion will not affect its bottom or its bonding performance.

Figure 10. Sample surface after burning.

5. Conclusions

The purpose of this research was to apply a novel bio-insulation material to prefabricated buildings. By adding waterproof coatings and bonding coatings, a composite structure thermal bridge insulation component was prefabricated to solve the problem of thermal bridges at the junctions of the outer envelope of prefabricated buildings. The main research conclusions are as follows:

1. The waterproof and moisture-proof properties of the component clearly improved after waterproof coating treatment. The water absorption rate of the components decreased from 35.66% to 18.54%, and the moisture absorption rate decreased from 6.99% to 2.12%. Compared with other types of water repellents, silicone water repellent agent and brush coating surface treatment appeared to have the best effect. It is recommended to use at least two coats.
2. After the outer surface bonding coating is processed, the component has a strong bonding force with the concrete material. The shear strength of the adhesive coating was up to 0.536 MPa in the tested samples.
3. The components are fireproof and have good weather resistance.

In this research, bio-insulation materials are used to weaken the influence of thermal bridges, which provides an application method for biomass insulation materials and adds a new perspective to the research on solving the thermal bridges in prefabricated buildings. There are various advantages to the proposed thermal bridge insulation component, such as simple preparation process, low construction difficulty, avoiding the influence of building type, easy popularization and application, and environmental friendliness, as it is made from agricultural waste. However, there are problems remaining with this component, such as water absorption, component aging, three-dimensional model research, and more. We intend to perform further research on these issues in the future.

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