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Mechanical Properties and Thermal Conductivity of Insulation Boards Prepared from Recycled Glass Fibers and Recycled Thermosetting Polyurethane

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Abstract: *In this study, fan blades and thermosetting polyurethane foam were mechanically recycled, and glass fibers of different lengths and polyurethane powders of different particle sizes were separated by crushing and screening. The recycled materials with different particle sizes and mass fractions were selected and homogeneously mixed with the matrix thermoplastic polypropylene powder, and nine groups of different composite insulation boards were prepared using hot press molding method. The tensile strength, flexural strength and thermal conductivity of different insulation boards were analyzed. The results show that when the glass fiber mass fraction is 20%, the mechanical properties can reach the maximum value, and its tensile strength and bending strength are 7.196 MPa and 13.2 MPa, respectively. The thermal conductivity can reach the minimum value of 0.091 W/(m·K) when the glass fiber mass fraction is 10%. In this study, polyurethane and glass fibers were recycled at the same time to obtain insulation boards with good mechanical strength and thermal insulation properties, which provides new possibilities for the development of insulation materials.*

Keywords: *recycling and regeneration, thermosetting polyurethane, glass fibre, hot-pressing molding, composite insulation board*

1. Introduction

Polyurethane foam is widely used in the automotive industry, wind power generation, building insulation and biomedical materials because of its high strength, ease of processing, good thermal insulation and light weigh t [1]. In terms of global market consumption, the polyurethane market size is estimated to be USD 83.54 billion in 2024 and is expected to reach USD 111.16 billion by 2029 [2]. However, due to the characteristics of its internal mesh cross-linking structure, it cannot be melted or remodeled by heating after disposal, which makes it difficult to be recycled and reused, and easy to cause environmental pollution. Glass fiber is an inorganic non-metallic material with heat resistance, high stability and excellent mechanical properties, generally acting as reinforcement and bridging in composite materials [3]. In total, up to 1.3 million tons of glass fiber is used for wind turbine blades alone each year, and by 2050, 43 million tons of blade waste is expected globally. Of which China accounts for 40%, Europe accounts for 25%, the United States accounts for 16%, the rest of the world accounted for 19%, which leads to wind turbine blades in the end of life if not properly disposed of, will cause a serious waste of resources [4]. Therefore, how to scientifically carry out the recycling and reuse of glass fiber and polyurethane for wind turbine blades has become a major issue related to the environment and resources.

Thermosetting materials such as polyurethane and fan blades are mainly incinerated and landfilled, which are easy to operate and low-cost, but cause great harm to the environment and are not in line with the requirements of the green and sustainable development strategy. Most countries have introduced policies to restrict the incineration and landfill of thermosetting waste [5]. Currently, recycling is the best treatment method for waste thermoset polyurethane, which mainly includes physical recycling, chemical recycling, biological recycling and pyrolysis [6-8]. Physical recycling is a simple and inexpensive process, but the output particles are not sufficiently reactive, limiting its application and

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economic value. Although chemical recycling technology can theoretically achieve more thorough material decomposition and recycling, its technical requirements are higher, and most decomposition technologies are still in the laboratory research and development stage, and have not yet realized large-scale industrial applications. The biodegradation method has not yet found microorganisms that can effectively decompose polyurethane foam, and the problem of production costs has not yet been solved. Due to the corrosion-resistant properties of polyurethane, it is difficult to replace traditional polyurethane with degradable polyurethane. Although the pyrolysis method is suitable for the recovery of fiber reinforced materials, the product diversity is high, the separation is difficult, the cost is high and easy to cause pollution, which does not meet the requirements of industrial production. Therefore, more and more researchers and scholars are exploring new methods to recover polyurethane and glass fibers more efficiently.

Quadrini et al. [9] investigated the molding process of rigid thermosetting polyurethane foam by means of a hot press. The polyurethane foam was mechanically crushed to 1-5 mm particles, and was hot-pressed using a hot press without the addition of chemical additives, and the properties of the molded materials were tested. The results show that rigid thermoset polyurethane foam particles develop some plasticity in the 150-200^{o}C interval. When the hot pressing pressure reaches 4.2 MPa and the hot pressing time reaches 15 min, the polyurethane particles have remodeling characteristics, and the compressive resistance of the recycled products can be 2.3 MPa. This study provides an important idea for the research on the resourcing of waste thermosetting polyurethanes. Cao et al. [10] investigated the mechanical pulverization of rigid polyurethane insulation boards into granular form, which was then directly mixed into concrete to prepare a new type of insulated concrete. Different proportions of polyurethane granules are stirred and mixed with cement, sand and water before being placed in the mould for maintenance. The concrete material made by this method has good thermal insulation and is lighter in weight than ordinary concrete. Shin et al. [11] used glycolysis to recover rigid polyurethane insulation foam materials from discarded refrigerators to obtain recycled polyols and study their properties. Isocyanate-derived amine adducts in the internal structure of polyurethane were modified by the addition of propylene oxide during the depolymerisation process. The recycled polyurethane sheets were prepared by mixing the polyols with two hydroxyl values obtained from recycling with virgin polyether polyol. The micro-structure, mechanical properties and thermal conductivity of the recycled sheets were also tested and analysed. The results showed that the recycled polyurethane foam panels exhibited good mechanical strength and thermal insulation properties.

Garcia et al. [12] studied the mechanical recycling of glass fibres from glass fibre reinforced plastics to prepare concrete components with different contents and different lengths as variable parameters. Glass fibres of different lengths were obtained by shearing and sieving methods, and then the parameters were adjusted to prepare composite planar micro-concrete elements, and then the materials were tested and characterised for their properties.The results showed that the concrete material specimens prepared using glass fibres of shorter lengths obtained by the mechanical milling process showed an increase in flexural and compressive strengths of 16% and 22%, respectively, compared to concrete specimens without added glass fibres. Kouparitsas et al. [13] recovered carbon and glass fibres from glass-polyester composites and glass fibre epoxy matrix composites, respectively, and incorporated the recovered fibres into polypropylene to prepare new materials. Short fibre rods were obtained by pulverising the composite material and then added to the thermoplastic polypropylene material in different proportions and lengths for hot compression moulding. It was found that the mechanical properties of the recycled material were enhanced with increasing fibre size. When the fibre content in the composites was in the range of 5-20%, the mechanical properties of the composites increased with the increase in glass fibre content. Akesson et al. [14] used microwave pyrolysis to recover glass fibres from discarded wind turbine blades, compared the mechanical strength of the recovered fibres with the virgin fibres, and then blended the recovered fibres with the virgin fibres to prepare laminates. It was found that the amount of glass fibres recovered by microwave pyrolysis accounted for more than 70% of the glass fibres in the original composite. The mechanical strength of the recycled fibres was reduced and their toughness was about

75% of the original fibres. The new hybrid laminates have good mechanical properties under the condition that the ratio of recycled fibres to original fibres is 1:4. In addition, the removal of residues on the surface of the recycled glass fibres by oxidation treatment can further enhance the properties of the final product.

In summary, mechanical recycling of polyurethane and glass fibres is feasible, which can increase the reaction rate and yield to a certain extent, and provides a new route for chemical synthesis and preparation. Researchers and scholars have already conducted studies on the use of mechanical force chemistry for different substances on the basis of physical methods [15]. Hu et al. [16] used mechanical force chemical method of comminution to recover thermosetting phenolic resin materials and adjusted and optimised the parameters such as machine rotational speed, comminution duration and feed size. The results showed that the tensile and flexural strengths of the prepared recycled plates were 8.13 MPa and 17.76 MPa under the conditions of rotational speed of 2820 r/min, time of 80 min, feed size of 0.43 mm and feed quantity of 60 g, respectively. Mutua et al. [17] used mechanical force chemical method to recover carbon fibres from carbon fibre reinforced materials, applied different concentrations of triethoxysilane to surface treat the recovered fibres and then characterised the recovered fibres. It was found that the surface of the carbon fibres recovered by the mechanical force chemical method was free from cracks, but their surface properties were affected. As the concentration of triethoxysilane increased, the properties of the recycled fibres were closer to those of the original fibres, but lower than those of the original fibres.

In this paper, waste polyurethane foam boards were used as a research object to obtain polyurethane powders that are more active and can be processed and moulded again by using thermosetting plastics recycling and regeneration technology by mechano-physical method [18]. The activated polyurethane powder is mixed with polypropylene powder and recycled glass fibres, and no other chemical additives are added on the basis of environmentally friendly recycling principles and cost considerations. Finally, the polyurethane recycled composite panels with different mesh counts and mass ratios are prepared using hot pressing technology according to the different lengths and blending amounts of glass fibers. The mechanical and thermal insulation properties of the composite panels were then tested, and the process parameters were adjusted to achieve the best overall performance. This not only reflects the concept of resource recycling, but also meets the requirements of sustainable development.

2. Materials and methods

2.1. Test material

There are three test materials for this experiment, recycled rigid polyurethane foam board, recycled wind turbine blade glass fibre and thermoplastic polypropylene. The material parameters are shown in Table 1.

Table 1. Test material parameters

Test material	Thermoset Polyurethane	Glass fibre	Polyethylene
Factory owners	Shandong Langfang Aoyangsu Material Co	Jilin Chongtong Chengfei New Material Co	Zhonglian Plastics Co
Density (g/cm^3)	0.4-0.6	1.82	0.89-0.92
Bending strength (MPa)	<1	>3×10^4	30-40
Tensile strength (MPa)	2-2.7	>550	29
Thermal conductivity W/(m·K)	<0.12	0.7-1.28	0.24
Grain size (mesh count)	40-200	5-15	100

2.2. Polyurethane recycling methods

Rigid polyurethane foam board crushing and regeneration process includes polyurethane coarse crushing, fine crushing (mechanical force chemical effect), mixing and regeneration links, as shown in Figure 1.

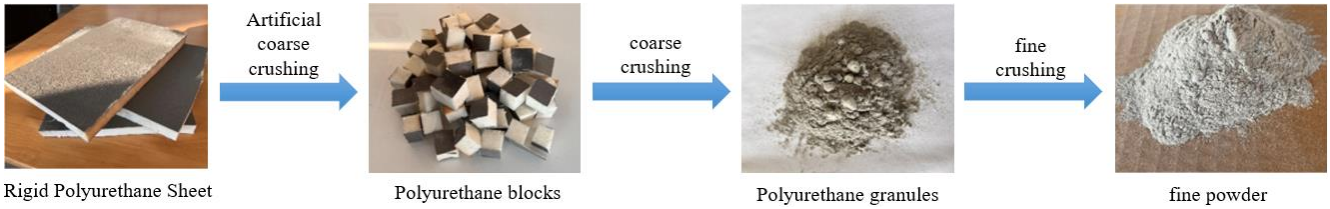


Figure 1. Flow chart of polyurethane recycling process by mechanical force chemical recovery method

Recycled polyurethane sheets get polyurethane lumps after manual shearing and coarse crushing. These blocks of polyurethane are put into a laboratory 10B pulverizer (Changzhou Lixiong Machinery Manufacturing Co., Ltd., China) for coarse crushing into granular form. The polyurethane is then finely pulverized in a high-speed multifunctional pulverizer (Wuyi Haina Electric Co., Ltd., China) to obtain fine polyurethane powder. Finally, the polyurethane powders were manually screened by different particle size screens to obtain different mesh sizes, in preparation for the following plasticity analysis and test.

2.3. Glass fibre recycling methods

Recycling of wind turbine blades using the mechanical shredding method, where glass fibres are separated by multi-stage shredding and crushing. Through the new regeneration process, the glass fibres are applied to composite products reinforcing materials, plastic modification and other fields.

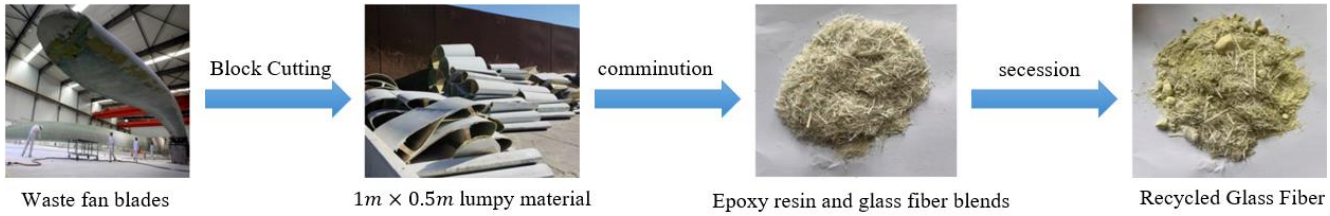


Figure 2. Flow chart of glass fibre recovery of wind turbine blades by mechanical shredding method

After the waste wind turbine blades have been cut into blocks in multiple stages in the wind farm, these blocks are put into the crushing device of the plant for coarse crushing to obtain a mixture of glass fiber and matrix epoxy resin. Then the matrix is separated from the fibers through a screen to obtain recycled glass fibers. Finally, glass fibers of different lengths are obtained through a vibrating sieving machine.

2.4. Sample preparation

The polyurethane powder obtained by mechanical crushing and the glass fiber and thermoplastic polypropylene powder are evenly mixed and spread in the mold. Because the polyurethane powder and glass fiber and polypropylene powder have a high packing density, in order to ensure the transfer of pressure. The use of compression mold compaction several times after filling the powder, to ensure that the height of the powder in the concave mold can reach about 3mm. A layer of polyester film (to prevent the melt from bonding with the mould) was placed on each of the upper and lower hot presses to cover the press mould. Before each experiment, the temperature of the mould was set to 190°C and preheated for 10 min. Then, the hot pressing was carried out under air atmosphere and 190°C for 20 min. After the hot pressing, the air was let out for 5 min, and then the heat was kept warm for another 5 min. Finally,

the mould was removed and cooled down to room temperature for demoulding. The size of the veneer was 100mm×100mm×2mm, as shown in Figure 3.

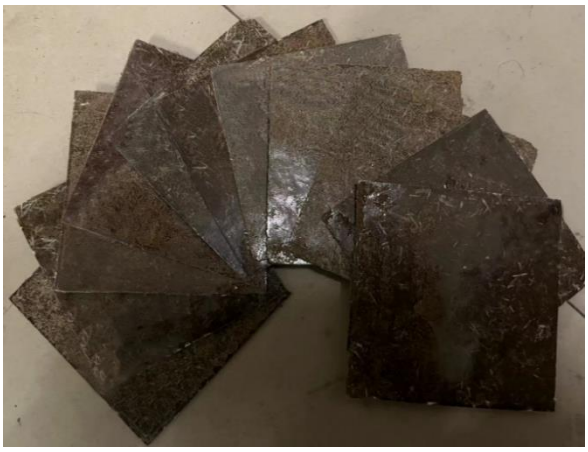


Figure 3. Polyurethane/fibreglass composite panel

2.5. Test methods

(1) Fourier Transform Infrared Spectrometer (Japan-Shimadzu-IRTracer 100). This technique is used to identify chemical bonds within molecules by analysing the absorption of infrared light by a substance, resulting in a unique spectral pattern [19]. In this study, the discussed thermosetting polyurethane powders were sieved to obtain 40 mesh and 200 mesh, and these different particle sizes and the original rigid polyurethane foam were analyzed using Fourier transform infrared spectroscopy.

(2) Laser thermal conductivity test [20]: According to GB-T 22588-2008 standard, laser thermal conductivity is used to test the thermal diffusion coefficient of materials. At a certain temperature, the light pulse emitted by the laser source is uniformly irradiated on the lower surface of the sample, so that the specimen is uniformly heated. The corresponding temperature rise process on the upper surface of the sample is measured by an infrared detector, and the relationship curve between the temperature (detector signal) rise and time is obtained, and then the heat diffusion coefficient is obtained by using a suitable model fitting. By testing the specimen, the specific heat data are obtained by reference, and the thermal conductivity is calculated as follows:

$$\lambda = \alpha \cdot C \cdot \rho \quad (1)$$

where: λ is the thermal conductivity, α is the thermal diffusion coefficient, C is the specific heat capacity, and ρ is the density.

(3) Laser particle size analyser (UK-Malvern-Mastersizer 2000). This technique uses a laser beam to measure the size distribution of particles and works on the basis of the scattering properties of particles to the laser beam. By measuring the intensity and angular distribution of the scattered light, combined with the Mie scattering theory, the size distribution of the particles can be inferred [21]. By using laser particle size analysis, the particle size distribution of crushed polyurethane powder can be determined.

(4) Scanning electron microscope (German-Zeiss-sigma300), a technique based on scanning the surface of a sample with an electron beam emitted by a high-voltage accelerating field, where high-resolution images are obtained by detecting secondary and back-scattered electrons generated by the interaction of the sample with the electron beam [22]. In order to investigate the microscopic morphology of polyurethane, due to its poor electrical conductivity, it is necessary to apply a metal coating on the surface of the polyurethane powder by vacuum coating technique before the experiment.In addition, the choice of an accelerating voltage of 20 kV is not only suitable for a wide range of materials to be examined, but also leads to a sharper image resolution compared to lower voltage settings, which is particularly important for analysing the internal features of polyurethane materials.

(5) Mechanical properties test: in accordance with GB-T 1040.2-2006 standard, the plate will be made into a dumbbell standard specimen, tensile test speed of 0.25mm/min, test the tensile strength of the re-moulded plate; in accordance with GB/T 9341-2008 standard, the plate will be made into a block standard specimen, bending test speed of 0.25mm/min, test the re-moulded plate. The bending strength of the re-moulded sheet is tested. The mechanical properties are tested on UTM-5105 universal testing machine.

3. Results and discussions

3.1. Laser particle size analysis

The powder in Figure 4 is the regenerated powder obtained from rigid thermosetting polyurethane insulation board under the continuous action of mechanical force of high-speed multifunctional pulverizer (rotational speed of 36000r/min, pulverizing time of 5min). After sieving the crushed incomplete large particles to get mixed powder, and then analyze the particle size distribution and content of the powder with a laser particle size analyzer to get Figure 4. The test is divided into three groups of mixed powder detection, the figure line 1 and line 2 for the same pulveriser crushed at different times of the powder particle size distribution, line 1 and line 3 for the same type of pulverizer crushed powder particle size distribution. Specific particle size distribution as shown in the figure.

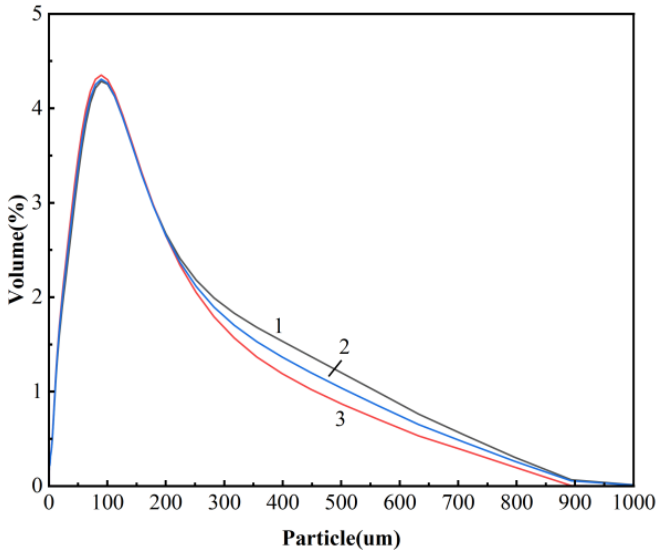


Figure 4. Laser particle size distribution of polyurethane powder

(1) Particle size range 0.44-1000um, powder after continuous crushing, powder size range is large, crushing to produce a small amount of nano-level powder.

(2) The average particle size of the sample powder was measured to be 122.50 um (approximately 120 mesh), with a median particle size of approximately 75.25um (approximately 200 mesh). Since 50% by volume of the powder particles had a particle size of less than 200 mesh, this indicates that the comminution process achieved the desired efficient comminution results.

(3) Powders with a particle size of more than 75um account for about half of the volume ratio, due to the fact that the polyurethane particles are crushed into an irregularly shaped powder. The larger mesh size powder has a certain plasticity and can flexibly penetrate the 200mesh sieve, indicating that mechanical force chemical effect occurs during the fine pulverization process and the powder has higher surface activity.

(4) 3 groups of particle size distribution data test results <5%, indicating that the crushing effect of the crusher is stable, reducing the particle size distribution error changes in this parameter on the powder activity and moulding results.

3.2. Infrared spectral analysis

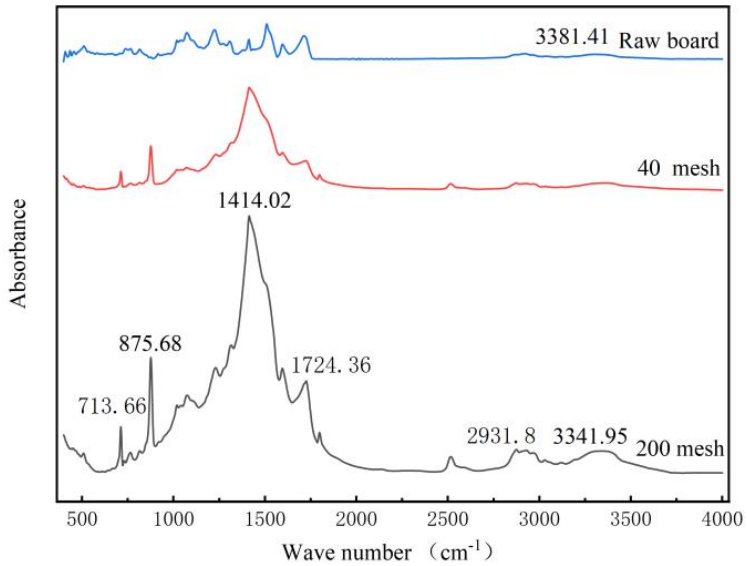


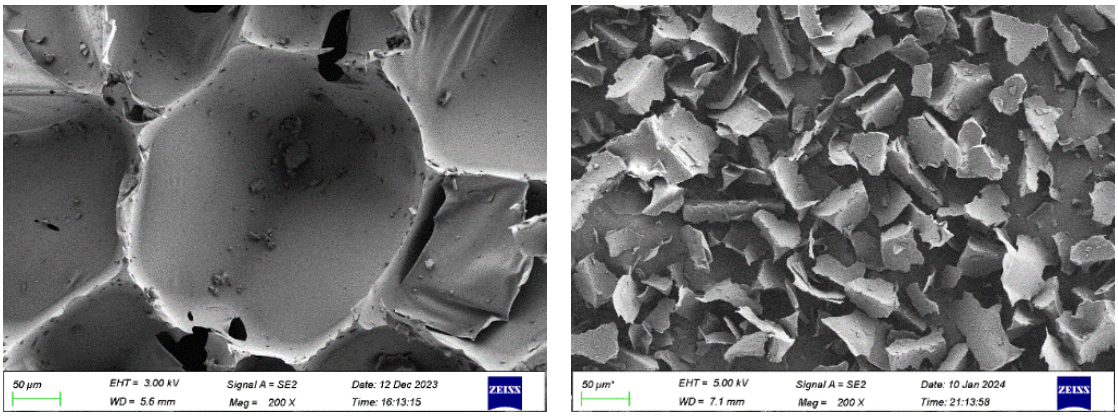
Figure 5. Infrared spectra of polyurethane Sheets and powders of different mesh sizes

In order to investigate the internal chemical bonding changes of polyurethane powder before and after crushing and at different degrees of crushing, infrared spectroscopy tests were carried out on the original rigid polyurethane foam sheet and 40 mesh and 200 mesh polyurethane powder, and the results are shown in Figure 5.

As can be seen in Figure 5, the polyurethane powder and the original foam board samples exhibit multiple absorption peaks in the infrared spectra, which reflects their complex monomer structure. The amino (-NH-) absorption peak observed at 3381.41 cm^{-1} gradually shifted to 3341.95 cm^{-1} and broadened as the powder mesh increased, and this change may be related to the hydroxyl group (-OH-) produced by the degradation of the powder. The absorption peaks of methyl (-CH-) and methylene (-CH-) were located at 2931.8 cm^{-1}, while the absorption peak of aldehyde group (-CHO) was at 1724.36 cm^{-1}. The intensity of the absorption peaks of the aldehyde group decreased with increasing mesh size, which indicates that the methyl and methylene bonds as well as the aldehyde group bonds were broken under mechanical and thermal forces, resulting in damage to the crosslinked molecular chains of the polyurethanes. In particular, the characteristic peak at 1414.02 cm^{-1} in the infrared spectrum of the 200mesh sample indicates the presence of the isocyanate dimer, which is due to the decomposition of the urethane groups. The enhancement of this characteristic peak implies that the mechanical action effectively disrupted the crosslinked network of the polyurethane, thus increasing the activity of the powder.

3.3. Scanning electron microscope analysis

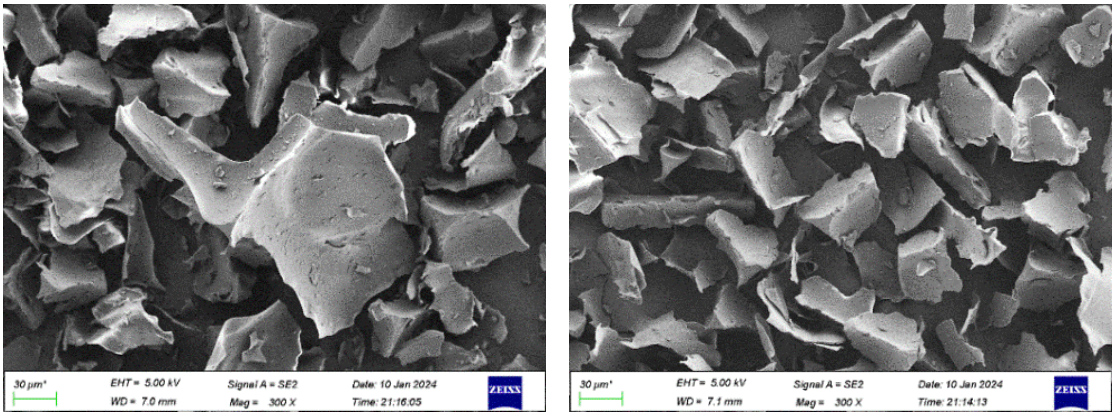
In order to investigate the micro-morphological changes of polyurethane powder before and after crushing and at different degrees of crushing, scanning electron microscope observation was carried out on the original sheets of rigid polyurethane foam and 40mesh and 200mesh polyurethane powder, and the results are shown in Figure 6.



(a) (b)

Figure 6. Microscopic morphology of polyurethane before and after crushing

The microstructure of the polyurethane foam before and after the comminution process is shown in the figure. The test material chosen for this study is rigid polyurethane foam. Looking at Figure 6a, the honeycomb structure of the uncrushed polyurethane foam can be clearly recognised, which is the key to its excellent thermal insulation performance. Observing Figure 6b, after the polyurethane has been crushed, its microstructure is mainly presented in two parts: firstly, the frame area, which still maintains the characteristics of the original honeycomb structure even after crushing, thanks to its high strength; and secondly, the part of the honeycomb wall, which is destroyed during the crushing process and forms agglomerates. These agglomerates still contain air and offer new possibilities for the regeneration of polyurethane sheets and the preparation of new insulation materials.



(a) (b)

Figure 7. Microscopic morphology of polyurethane powder

The microscopic appearance of the mechanically force-chemically treated polyurethane powders is demonstrated in figure. Observation at a magnification of 300x reveals morphological and structural similarities between the 40 mesh and 200 mesh powders, both of which exhibit irregular shapes and finer powder particles adhering to the surface. This phenomenon suggests that after the comminution process, the finer particle size powder exhibits more significant adhesion, thus increasing the reactivity of the powder. Further observation of the powder shown in Figure 7a shows that it maintains the honeycomb configuration of the initial polyurethane foam board more intact. This honeycomb configuration provides a useful reference for reducing the thermal conductivity of polyurethane composites.

3.4. Experimental design and results

When it is necessary to find an optimal solution among several possible solutions or to improve an existing process, orthogonal experiments can quickly identify the most efficient combination of factors.

It can also identify which factors have a significant impact on the results through polarization, ANOVA methods, which can help in data-driven decision making [23]. Also, to meet the requirement of at least 50% mass fraction of recycled material, the experiments were configured according to specific mass ratios (60% polyurethane and glass fibre combined and 40% thermoplastic polypropylene in the recycled material.In order to follow the principle of environmentally friendly recycling, the surface of the recycled material powder was not surface pre-treated and no other chemical additives were added to the moulding process). The experimental variables included: the proportion of glass fibre A (the total proportion of glass fibre and polyurethane was fixed at 60%, and when the mass fraction of glass fibre was adjusted, the proportion of polyurethane was adjusted accordingly, and the two were inversely proportional), the length of glass fibre B, and the number of mesh of polyurethane C. Three different levels were set for each variable, 10%, 15%, and 20% for A, respectively; 5 mm, 10 mm, and 15 mm for B; and 40 mesh, 120 mesh, and 200 mesh for C, respectively.40 mesh, 120 mesh, and 200 mesh, respectively. In addition, in order to more fully investigate the effect of fiber content on the performance of the composites, a control group without glass fiber was added to the test. The design parameters for the control group were 60% mass fraction of polyurethane (120 mesh) and 40% mass fraction of polypropylene as shown in Table 2.

Table 2. Polyurethane/fibreglass composite insulation test programme

Number	Glass fibre mass fraction A (%)	Glass fibre length B(mm)	Polyurethane mesh C (mesh)	D (error column)
1	10	5	40	1
2	10	10	120	2
3	10	15	200	3
4	15	5	120	3
5	15	10	200	1
6	15	15	40	2
7	20	5	200	2
8	20	10	40	3
9	20	15	120	1

In this experiment, considering three different levels for each of the three influencing factors, we chose the three-factor, three-level orthogonal test table L9(34) to design the experiment. In this table, columns A, B and C correspond to the mass fraction of glass fibre, length and mesh number of polyurethane respectively, while D is the blank error column.Since errors are inevitable during the experiment, they need to be evaluated in order to test the reliability of the experimental results.The specific experimental design is detailed in Table 2.

Based on the test criteria, tensile strength, flexural strength and thermal conductivity were tested on nine different panels and a control group. Among them, the tensile strength of the control group was 1.44 MPa, the bending strength was 2.68 MPa, and the thermal conductivity was 0.085 W/(M·K), and the test results of the nine plates are shown in Table 3.

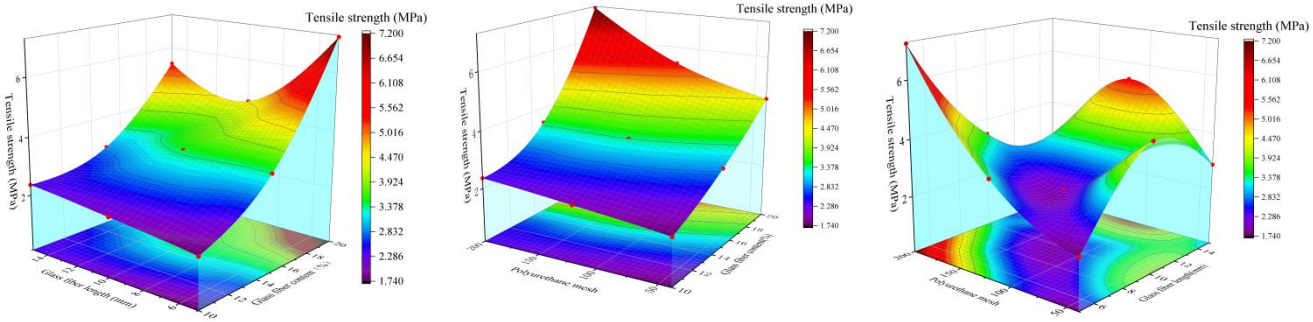
Table 3. Polyurethane/glass fibre performance test results

Number	A (%)	B (mm)	C (mesh)	Tensile strength (MPa)	Bending strength(MPa)	Thermal conductivity W/(M·K)
1	10	5	40	1.751	4	0.091
2	10	10	120	2.084	5.91	0.097
3	10	15	200	2.361	6.02	0.102
4	15	5	120	3.375	7.52	0.104
5	15	10	200	3.455	9.08	0.108
6	15	15	40	2.888	10.59	0.106
7	20	5	200	7.196	10.84	0.114
8	20	10	40	4.484	12.68	0.111
9	20	15	120	5.402	13.2	0.121

From the test data in Table 3, it can be seen that the tensile strength, bending strength, and thermal conductivity of the nine sample panels were improved compared with the control group. It indicates that the increase of glass fibre content in the recycled material can effectively enhance the mechanical properties of the composites, while slightly reducing the thermal insulation properties of the composites. Except for the thermal conductivity 0.121W/(M·K) of No.9 plate, which is higher than the requirement of China's industry standard for thermal insulation materials, the rest of the materials comply with the use standard.

3.5. Tensile properties analysis

Based on the tensile strength test results, the effect of different factors on tensile strength could not be determined intuitively.In order to intuitively get the effect of glass fibre mass fraction A, glass fibre length B, polyurethane mesh number C and their interaction on tensile strength.In this paper, the vertical axis is the tensile strength response value, and the horizontal axis corresponds to the two different factors, respectively, and the surface projection diagrams were drawn, as shown in Figure 8 to.



(a) (b) (c)

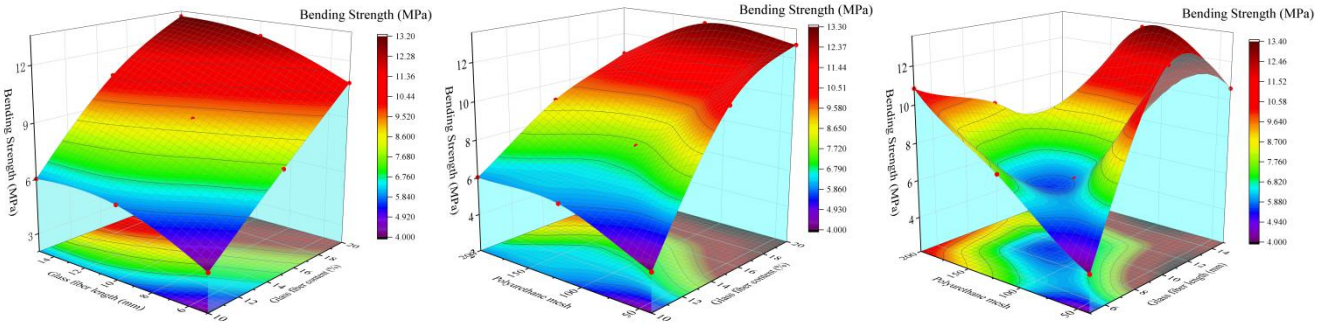
Figure 8. Projection surface diagram of the effect of different factors on tensile strength

From Figure 8a, it can be seen that at constant glass fibre length, the tensile strength shows an overall increasing trend with the increase in its mass fraction. At shorter glass fibre lengths, the tensile strength increases more significantly with the fibre mass fraction and vice versa, the increase is slower.At constant glass fibre mass fraction, the tensile strength increases with its length in a more complex manner. When the glass fibre mass fraction is low, the tensile strength increases slowly with its length. At higher fibre mass fraction, the tensile strength tends to decrease and then increase with its length. This situation indicates that there is some interaction between the effect of glass fibre mass fraction and its length on tensile strength and the effect of glass fibre mass fraction on tensile strength is more significant. From Figure 8b, it can be seen that the tensile strength increases with increase in glass fibre mass fraction at constant number of polyurethane mesh. This increasing trend is more pronounced at higher number of polyurethane mesh. The tensile strength increases with increasing number of polyurethane mesh at constant glass fibre mass fraction. Again, this increasing trend is more pronounced at higher glass fibre mass fraction. This indicates that there is no significant interaction between glass fibre mass fraction and polyurethane mesh number on the effect of tensile strength. The variation of surfaces and projections in Figure 8c is complex, but it can be seen that the tensile strength tends to decrease and then increase with increasing glass fibre length when the number of polyurethane mesh is small. When the number of polyurethane mesh is large, the tensile strength decreases with increasing glass fibre length and the decreasing trend is more obvious. When the glass fibre length is short, the tensile strength increases with the polyurethane mesh number and the increasing trend is more obvious. For longer glass fibre lengths, the tensile strength increases and then decreases with increasing polyurethane mesh. This occurs because the effect of polyurethane mesh and glass fiber length on tensile strength is perturbed by another factor, which is the glass fiber mass fraction. The effect of this perturbation is greater than the sum of the effects of polyurethane mesh and glass fibre length on tensile strength.

From the test results it is clear that glass fibre mass fraction and tensile strength are positively correlated and glass fibres play a good role in tensile strength in composite sheets, which is in agreement with the findings of Kumar M. et al. [24]. As the glass fibre length increases, the tensile strength decreases and then increases, this variability may be related to the arrangement of the glass fibres in the material and the homogeneity of the mix, shorter glass fibres facilitate the homogeneous mixing of the material, which results in an increase in the tensile strength. The positive correlation between tensile strength and polyurethane mesh size suggests that the finer the polyurethane particles, the better the tensile strength, and also verifies that the finer powders are more active under mechanical force chemistry, resulting in a stronger bond between the glass fibres and polypropylene.

3.6. Bending performance analysis

In order to visualise the effect of glass fibre mass fraction A, glass fibre length B, polyurethane mesh number C and their interaction on flexural strength.The surface projections were plotted with the vertical axis as the bending strength response value and the horizontal axis corresponding to the two different factors, respectively, as shown in Figure 9.



(a) (b) (c)

Figure 9. Projection surface plot of the effect of different factors on tensile strength

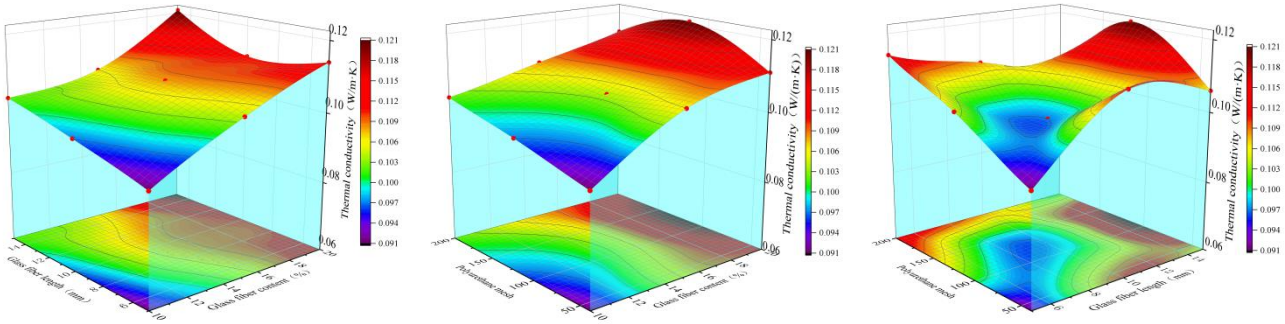
From Figure 9, it can be seen that when the glass fibre length is constant, the bending strength increases with increasing glass fibre mass fraction. This increasing trend is almost constant at shorter or longer fibre lengths. When the glass fibre mass fraction is constant, the bending strength increases with the increase in its length. At higher glass fibre mass fractions, this increasing trend slows down.It can be seen that there is no significant interaction between glass fibre mass fraction and its length. By observing and comparing the amount of change in bending strength at the same nodes of both, the glass fibre content changes more at the nodes, indicating that the effect of glass fibre mass fraction on bending strength is more significant.From Figure 9b, it can be seen that the bending strength increases with the increase in glass fibre mass fraction when the number of polyurethane mesh is constant. As the number of polyurethane mesh increases, the trend of increase in bending strength gradually becomes slower. When the glass fibre mass fraction is constant, the bending strength trend is more complex. When the glass fibre mass fraction is small, the bending strength increases with increasing polyurethane mesh number, and when the glass fibre mass fraction is large, the bending strength decreases with increasing polyurethane mesh number. It can be seen that there is a certain interaction between glass fibre mass fraction and polyurethane mesh number on the bending strength, and the glass fibre mass fraction has a more significant effect on the bending strength. The variation of the surface in Figure 9c is more complex. At constant polyurethane mesh, the bending strength varies with glass fibre length from increasing then decreasing, decreasing then increasing, decreasing. When the glass fibre mass fraction is constant, the bending strength varies with the polyurethane mesh from decreasing, then decreasing, then increasing, then increasing, then decreasing. The reason for this phenomenon is that there are three factors in this test, in which the effect of glass fibre mass fraction on bending strength is stronger than the sum of the effects of glass fibre length and polyurethane mesh number, so the results are complex

and irregular. It shows that the glass fibre mass fraction is the most significant effect on the bending strength among the three.

A positive correlation between glass fibre mass fraction and bending strength was derived from the test results.This is due to the fact that the glass fibres themselves can cope with high bending stresses, and when the glass fibres are added to the polyurethane/polypropylene matrix, the bending properties of the insulation boards are enhanced.In the range of 10%-20% glass fibre mass fraction, the bending strength increases as the glass fibre mass fraction increases. This also indicates that when preparing polyurethane/glass fibre composites, the flexural properties of the composites can be effectively in-creased by increasing the glass fibre mass fraction in the composites. As the glass fibre length increases, the bending strength increases, which indicates that longer fibres enhance the bending properties of the material, which is consistent with the findings of Mohammad Z. et al. [25]. The bending strength is positively correlated with the number of polyurethane mesh, which indicates that the finer the polyurethane particles, the better the bending properties, this is because when the particles of polyurethane are finer, the more dispersed they are in the polypropylene matrix, which results in an increased bonding of the insulation board, and the bending properties of the insulation board are strengthened as a result.It is verified that the finer powder is more active under mechanical force chemistry.

3.7. Thermal conductivity analysis

The surface projections were plotted with the vertical axis as the thermal conductivity response value and the horizontal axis corresponding to each of the two different factors, as shown in Figure 10.



(a) (b) (c)

Figure 10. Projected surface plot of the effect of different factors on thermal conductivity

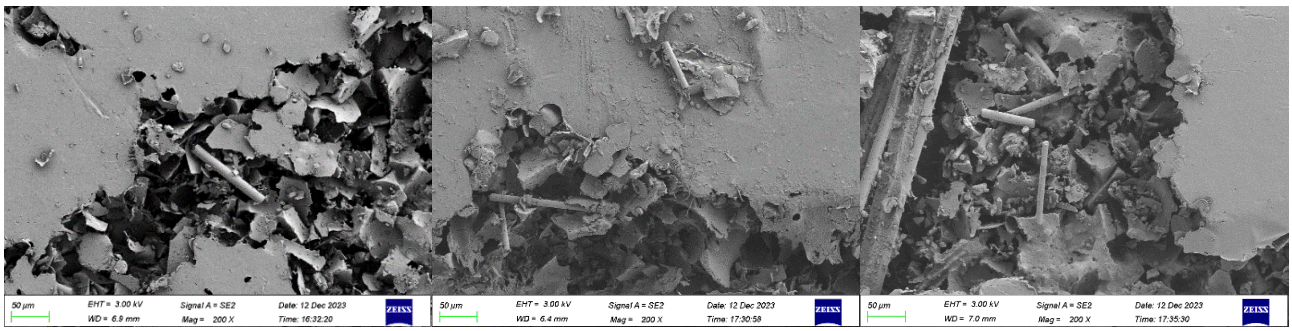
From Figure 10a, it can be seen that the thermal conductivity increases with the increase in the mass fraction of glass fibres when the glass fibre length is constant. And the change in thermal conductivity is almost independent of the change in glass fibre length. When the glass fibre mass fraction is constant, the thermal conductivity varies more with the glass fibre length. That is, when the glass fibre mass fraction is small, the thermal conductivity increases with its length.When the glass fibre mass fraction is large, the thermal conductivity decreases and then increases with its length. It shows that there is some interaction between the glass fibre mass fraction and its length and the thermal conductivity tends to increase with the growth of glass fibre content. From Figure 10b, it can be seen that the thermal conductivity increases with increasing glass fibre mass fraction when the mesh number of polyurethane is constant. This increasing trend increases with increasing mesh number and the growth rate slows down gradually. When the mass fraction of glass fibre is constant, the thermal conductivity shows an increasing, first increasing and then decreasing trend.Similarly, there is a certain interaction between the number of mesh of polyurethane and the mass fraction of glass fibre, and the thermal conductivity with the growth of glass fibre content of the trend is larger. The variation of the surface in Figure 10c is more complex. When the number of polyurethane mesh is constant, the thermal conductivity varies with the length of glass fibre from increasing to decreasing, decreasing to increasing, and decreasing to decreasing. When the glass fibre mass fraction is the same, the thermal conductivity varies with the polyurethane mesh number from decreasing, decreasing then increasing, increasing then decreasing. The

reason for this phenomenon is that there are three factors in this test, in which the effect of glass fibre mass fraction on thermal conductivity is stronger than the sum of the effects of glass fibre length and polyurethane mesh number, so the results are complex and irregular.It can be seen that the glass fibre mass fraction has the most significant effect on the thermal conductivity among the three.

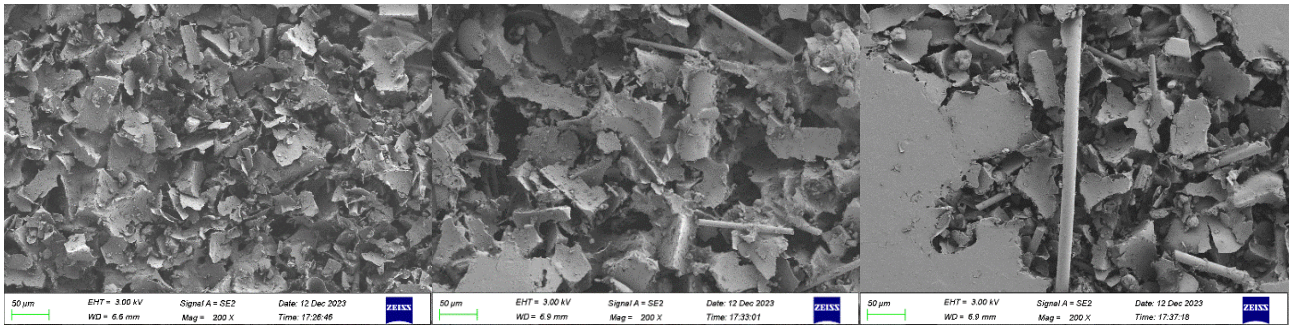
It can be concluded from the test results that there is a positive correlation between the glass fibre mass fraction and the thermal conductivity, in the glass fibre mass fraction in the range of 10%-20%, as the glass fibre mass fraction increases, the thermal conductivity increases.This can be explained by the fact that with the addition of glass fibres, the pores inside the polyurethane foam are filled, making the thermal conductivity of the insulation board increase. This also indicates that in the preparation of polyurethane/glass fibre composites, the thermal conductivity of the composites can be effectively reduced by reducing the mass fraction of glass fibres in the composites to increase their thermal insulation properties. The mesh size of polyurethane and thermal conductivity also showed a positive correlation, when the mesh size of polyurethane was increased from 40 mesh to 200 mesh, the thermal conductivity also increased, which is in agreement with the findings of Ping H. et al. [26]. This is due to the fact that as the mesh size of polyurethane increases, thus making the number of pores between the glass fibre and polypropylene less, leading to an increase in the thermal conductivity.

3.8. Scanning electron microscope analysis

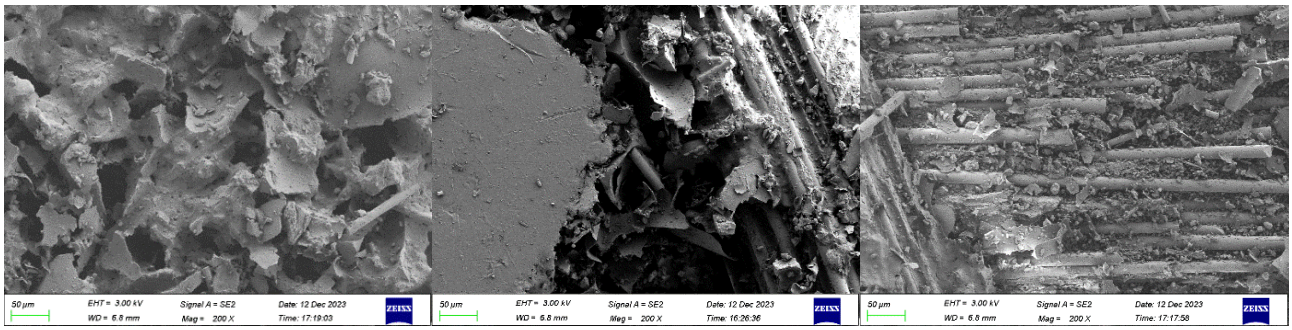
In order to study the composite properties, especially the dispersion state of polyurethane (PU)/glass fibre (r-GFRP) and matrix polypropylene (PP) in the composite plate, the micro-morphology of the specimens was observed using SEM scanning electron microscope. A standard observation specimen with dimensions of 10 mm × 10 mm × 2 mm was cut from the specimen. It was observed at 20KV and 200x magnification. The micro-morphology is shown in Figure 11, where a-i corresponds to test numbers 1-9 plates, respectively.



(a) (b) (c)



(d) (e) (f)



(g) (h) (i)

Figure 11. Micro-morphology of nine different composite plates

The overall microscopic morphology shows that the combination of polyurethane/glass fibres with the matrix molten polypropylene forms a more stable composite structure, and the different ratios of polyurethane/glass fibres have good compatibility with polypropylene.Compared to the micro-morphology of other sheets, it can be seen in Figure 11g that the molten polypropylene sufficiently wraps the polyurethane and glass fibres, which provides a good basis for the mechanical properties of the moulded composite sheet, which is the reason why Sheet No. 7 has the highest tensile properties. A large number of fibrous structures, polyurethane and molten polypropylene wrapped in the gaps of the fibrous structures, can be seen in Figure 11i, and the fibres are more neatly arranged relative to the microscopic morphology of the other sheets. This indicates that when the glass fibres are longer in length, their distribution in the composite sheet is more orderly relative to the shorter fibres.It is because of this more neat fibre arrangement that the bending properties of No. 9 composite sheet are enhanced. In addition to this, the disordered arrangement of glass fibres in Figures 11a~i affects the mechanical properties of the composite sheets, leading to a certain variability in the results of the mechanical properties of the composite sheets. The larger mesh size polyurethane powder and 5 mm glass fibres have a larger specific surface area, and the molten polypropylene fails to completely encapsulate them, and there are multiple pore structures where air can be retained, which is the reason for the best thermal insulation performance of the No. 1 sheet. In summary, shorter glass fibres with larger mesh sizes of polyurethane powder require more molten polypropylene to bond them adequately. Longer glass fibres have a more orderly arrangement in the composite compared to shorter glass fibres. When the mass fraction of polyurethane powders is larger, the polypropylene is unable to fully encapsulate these powders with the glass fibres, and the pore structure increases, resulting in a lower thermal conductivity of the composite.

4. Conclusions

Under the chemical action of mechanical forces, the cross-linked structure of polyurethane plastics is disrupted and the molecular chain is broken to form reactive groups. This mechanical force chemical reaction not only reduces the crosslink density of the material, but also gives the recycled material new reactive activity, giving it the ability to be processed and moulded again.

Polyurethane powder crushed to different mesh sizes and glass fibres with different mass fractions were mixed thoroughly with polypropylene and prepared into thermal insulation panels by hot press moulding process. It can be observed by SEM that the glass fibres are uniformly interspersed in the polyurethane/polypropylene matrix, and the adhesive effect of the three is good. When the mass fraction of glass fibre was 20% and the mesh number of polyurethane powder was 200 mesh, the tensile strength of the insulation board was 7.20 MPa and the flexural strength was 13.20 MPa, which were 393% and 424% higher than that of the unadulterated glass fibre, respectively. At this time, the thermal conductivity of 0.114 W/(m·k), although showing an increasing trend, but still meet the requirements of the insulation material.

Overall, the introduction of glass fibres provides significant mechanical enhancement of polyurethane foams, as well as an effective method for dual recycling and reuse of waste thermoset plastics and inorganic non-metallic materials.

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