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Performance Study of Environmentally Friendly Construction Gypsum Prepared from Recycled Phosphogypsum and Waste Glass Fibers

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Abstract: *Phosphogypsum, as a by-product of the wet process phosphoric acid industry, is in urgent need of resource utilization due to the environmental risks caused by its massive accumulation; at the same time, the green recycling of used wind turbine blades (including glass fibers) is also a hotspot of global concern. In this study, a synergistic regenerative preparation method of environmentally friendly construction gypsum is proposed using phosphogypsum and recycled glass fibers from waste wind turbine blades as raw materials. The matrix material was prepared by mixing physically treated phosphorus building gypsum with natural building gypsum (8:2 ratio) and blended with recycled glass fibers of different lengths (0–5, 5–10, 10–15, 15–20 mm) and blending amounts (1.0%, 1.5%, 2.0%, 2.5%), and the effect on the performance of the gypsum was systematically analyzed. The results showed that the incorporation of glass fibers significantly reduced the slurry extension (maximum drop of 30 mm) and setting time (final setting time shortened by 115 s), but significantly improved the mechanical properties. The flexural strength reached 5.6 MPa when 15–20 mm glass fibers (2.0% doping) were doped, which was 51.35% higher than that of the blank control group; the compressive strength was raised to 11.3 MPa (24.17% higher) when 10–15 mm fibers (2.5% doping) were doped. The softening coefficient reached 0.67 at 15–20 mm fiber (dosing 1.5%), an enhancement of 32.37%. The microstructure shows that the glass fibers fill the pores inhibit crack extension through the bridging effect, and present a composite damage mode of fiber fracture and matrix debonding. This study provides a new way for the efficient synergistic utilization of phosphogypsum and waste wind turbine blades, with both environmental benefits and engineering application potential.*

Keywords: *Wind turbine blades, phosphogypsum, glass fiber, work performance, flexural strength, compressive strength, softening factor*

1. Introduction

Phosphogypsum is a byproduct of the wet process used to produce phosphoric acid. Calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) is its main component, and the production of phosphogypsum (4.5–5.5 t) is the result of every ton of phosphoric acid produced [1]. The total amount of phosphogypsum released around the world has reached about 6 billion tons, with an annual growth rate of 200 million tons. The industry is set to undergo significant growth between 2025 and 2045, during which time it is predicted that the total amount of phosphogypsum will double [2]. Only a small percentage of phosphogypsum is reused or recycled. The rest is sent to landfills, stockpiles, or discard [3]. Since phosphogypsum contains water-soluble phosphorus, fluorine, and heavy metals, long-term landfill disposal, and rainfall can cause nutrient enrichment and heavy metal element exceedance in the nearby soil, and the leachate enters the food chain with groundwater, which ultimately endangers human health [4]. Phosphogypsum, an industrial byproduct of gypsum, has high emissions, a complex impurity composition, difficult treatment, and a low utilization rate. The accumulation of large amounts

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of phosphogypsum can cause environmental risks because it releases toxic gases into the air and contaminates water sources. Phosphogypsum must be treated and used effectively, so there is an urgent need for this to happen [5]. At present, the recovered phosphogypsum is mainly used as gypsum building materials [6], cement retardant [7], soil conditioner [8], and road filler materials [9]. Recycling of phosphogypsum is greatly limited due to the large number of impurities it inevitably contains [10]. However, phosphogypsum has only a few applications in these low-value-added products. Cementitious materials can be produced by subjecting phosphogypsum to calcination. A significant application of the mineral β-hemihydrate gypsum in the construction industry is that it requires a relatively low temperature for its calcination [11]. However, poor toughness and mechanical properties of gypsum building materials hinder their application [12].

To improve the various properties of gypsum, researchers worldwide have extensively studied it. Researchers have found that blending fibers into gypsum can improve its mechanical properties. The main idea is that there's a kind of debonding, slipping, and pulling out happening between the fibers and the matrix. And then there's also the effect of the fracture of the fiber body on the external energy. This loss replaces the generation of cracks in the base material itself. Similarly, the presence of fibers reduces the width and number of cracks and their rate of development due to the bridging effect, which greatly improves the material properties [13]. Iucolano et al. [14] used 10 mm lengths of two different proportions of hemp fibers added to gypsum, the flexural strength of gypsum boards with 2 wt% of hemp fibers added increased significantly to 4.0 MPa, confirming the bridging effect of hemp fibers, which can sew up broken edges, thus preventing the brittle collapse of the material. Wu et al. [15] incorporated basalt fibers into phosphogypsum to study their effect on workability and mechanical properties. The results showed that incorporating basalt fibers reduced the fluidity and setting time of the gypsum material. The flexural and compressive strengths of the gypsum material increased significantly as the fiber content increased. With the addition of 1.2% 6 mm basalt fibers, the flexural and compressive strengths reached the highest values of 10.98 and 29.83 MPa, respectively, which were 67.7% and 69.0% higher than those of the blank group. Lu et al. [16] introduced 0.10~0.50 wt% polypropylene fibers into a powder mixture of gypsum and mullite as a reinforcing material to prepare thin-walled gypsum molds with high strength and permeability. The strength of the molds decreased and then increased as the fiber content increased, and the green flexural strength of the specimens reached a maximum value of 1.94 MPa when the polypropylene fiber content was 0.20 wt%, which was an increase of 36.6%, and the permeability of the specimens increased from 8.6% to 11.5% with the increase of the fiber content. However, there is not much research on how the amount and length of glass fibers affect how well these materials can be worked with and their mechanical properties, such as strength and durability. Hua et al. [17] found that by adding glass fibers into phosphogypsum mixtures, the flexural and impact strength of phosphogypsum mixtures increased with increasing glass fiber content. When the glass fiber content was 1.0%, the flexural strength reached 11.9 MPa and the impact strength reached 981.9 J/m^2. Álvarez et al. [18] found that the incorporation of glass fibers into lightweight gypsum enhances its flexural and compressive strengths, with all lightweight gypsum samples having flexural strengths above 2 MPa and compressive strengths over 3 MPa. Awang Ngah et al. [19] found that reinforcing gypsum with glass fibers was better than the previous reinforcement with coarse linen and the reinforcement exceeded the flexural strength of unreinforced α-gypsum, changing the damage mode from brittle to ductile. In all the above studies existing fibers were used to improve the properties associated with gypsum and some scholars are beginning to work on strengthening gypsum using waste recycled fibers.

Wind energy, the main source of energy under the carbon neutrality goal, has seen a dramatic increase in the demand for its most prominent component, the wind turbine blade (WTB), as the utilization of wind energy grows. Wind turbine blades are mainly made of composite materials, including thermoset resins and glass fibers (GF) or carbon fibers (CF). After a service period of 9–27 years, wind turbines are decommissioned, generating large amounts of blade waste [20]. Recycling wind turbine blades for reuse is also one of the pressing issues of the day, and currently, the easiest way to dispose of this waste is to pile it up or put it into large-scale landfills. However, this is not a green and sustainable method. The best way is recycling [21]. Recycling of used wind turbine blades is currently done by mechanical recycling, chemical recycling, and thermal recycling [22]. Gonçalves et al. [23] investigated the potential of recycled glass fibers in gypsum-based composites and compared their effectiveness with that of commercial glass fibers, to improve the mechanical properties of gypsum and promote the recycling of composites. Recycled and reclaimed glass fiber reinforcement is slightly less effective than commercial glass fiber, but it is inexpensive and can reduce waste generation and environmental pollution. The production process of recycled glass fibers consumes less energy than the direct production of commercial glass fibers, and the use of recycled glass fibers is in line with the concept of a circular economy that promotes the sustainable use of resources. Revilla-Cuesta et al. [24] incorporated recycled wind turbine blades (at 0.0%, 1.5%, 3.0%, 4.5%, and 6.0% proportions) into the concrete and evaluated the moisture transport and porosity characteristics of the recycled concrete through tests. It was found to increase the water absorption and porosity of the concrete and all the values met the limits of concrete use under the most unfavorable environmental conditions. Hurtado-Alonso et al. [25] used raw crushed wind turbine blades (RCWTB) with recycled concrete aggregate as the raw material for the concrete and optimized the model by Response Surface Methodology (RSM) to determine the optimum combination of RCA and RCWTB. It was found that limiting the RCWTB content to 3% to achieve compressive strengths higher than 45 MPa, while contents below 3% and above 7% would allow obtaining flexural strengths higher than 5.5 MPa. When the goal is to obtain high compressive strength, the RCA content should be optimized to about 50% and the RCWTB content should be minimized; when the goal is to increase the flexural strength, the RCWTB content should be higher, preferably in combination with about 50% RCA. The proportioning is optimized using Response Surface Methodology (RSM) to achieve synergistic recycling of waste and safeguard the mechanical properties of concrete. It is shown that used wind turbine blades have a wide range of applications in the construction field. Recycling phosphogypsum and using wind turbine blade fibers is an effective way to prepare new green building materials.

This study was carried out in the context of recycling phosphogypsum and using wind turbine blades for reuse based on green recycling. Phosphorus building gypsum was prepared by recycling waste stockpiles of phosphogypsum using a physical method, and due to the large amount of harmful impurities in the recycled phosphogypsum, a building-friendly building gypsum was prepared by using natural building gypsum to partially replace phosphorus building gypsum in the gypsum preparation process. The used wind turbine blades were made into four different lengths and mixed into the environmentally friendly construction gypsum at four different dosages using the mechanical recycling method, and their slurry expansion, setting time, flexural strength, compressive strength, softening coefficient, and microstructure were tested. A new type of recycled construction environmentally friendly building gypsum was obtained, which provides a new way to recycle phosphogypsum as well as used wind turbine blades.

2. Experiment

2.1. Environmentally friendly construction gypsum preparation

The environmentally friendly building gypsum in this test is a mixture of phosphorus building gypsum plus natural building gypsum. The purpose of adding natural building gypsum is to reduce the content of phosphorus and fluorine, which are harmful substances contained in phosphorus-building gypsum itself.

Natural construction gypsum: The natural construction gypsum purchased from Hebei Sheng Yun Mining Co., Ltd. was selected for this test, and its main component is calcium sulfate hemihydrate ($CaSO_4 \cdot 1/2H_2O$), with a fineness of 0.005%, and its appearance is white, powdery solid. The main performance parameters are shown in Table 1.

Table 1. Main performance parameters

Test material	Natural building plaster	Phosphorus construction gypsum
Water requirement for standard consistency (%)	62	60
Initial setting time (min)	7	5
Final setting time (min)	22	8
2 h compressive strength (MPa)	6.5	6.5
2 h flexural strength (MPa)	3.6	3.1

Phosphorus construction gypsum: it comes from a large gypsum dump in Hefei, Anhui Province, this is a byproduct of the industrial production of phosphate fertilizer. The main component is calcium sulfate dihydrate. The chemical formula for calcium sulfate dihydrate is $CaSO_4$-$2H_2O$, the appearance of its color is dark grey, and most of it is lumpy solid. The β-type hemihydrate gypsum. Phosphorus-building gypsum is the result of a physical treatment. The primary performance metrics are outlined in Table 1.

To know the composition of phosphorus building gypsum prepared by physical method, it was analyzed by X-ray fluorescence spectroscopy (XRF), and the results are shown in Table 2.

Table 2. Phosphorus building gypsum composition

Ingredient	CaO	SO_3	Fe_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	F
Content (wt%)	40.976	51.521	0.440	0.287	0.479	3.599	1.064	1.048

The content of P_2O_5 and F is high due to the lack of decontamination before preparation by physical method. Materials containing phosphorus and fluorine produce harmful substances when used for a long time, to reduce the content of harmful substances, the environmentally friendly building plaster was prepared by adding natural building plaster which does not contain the elements of phosphorus and fluorine to replace part of the phosphorus building plaster. To investigate the reasonable addition ratio of natural building plaster, five ratio schemes were designed, phosphorus building plaster than natural building plaster (9:1, 8:2, 7:3, 6:4, 5:5), and the test was carried out under the water-paste ratio of 0.6. The program is shown in Table 3.

Table 3. Environmentally friendly construction gypsum preparation program

Programmatic	Phosphorus building plaster (g)	Natural building plaster (g)	Water (g)
Scheme 0	600	0	360
Scheme 1	540	60	360
Scheme 2	480	120	360
Scheme 3	420	180	360
Scheme 4	360	240	360
Scheme 5	300	300	360

The test results are shown in Figure 1. Gypsum using Scheme 2 8:2 ratio can both reduce the phosphorus and fluorine content of environmentally friendly construction gypsum and maximize the utilization rate of phosphorus construction gypsum. Therefore, the environmentally friendly construction gypsum produced in this test is made by adopting the ratio of Scheme 2.

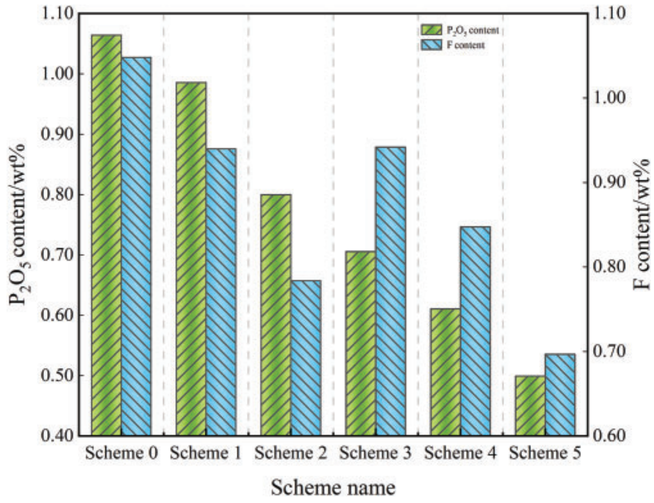

Figure 1. Eco-friendly building gypsum elemental content

2.2. Recycling of waste glass fibers

In this experiment, the glass fiber recovered from waste wind turbine blades is treated mechanically, and the recycling process is shown in Figure 2. Firstly, the waste wind turbine blades are cut into the shape of blade blocks for easy transportation at the site, and then they are crushed into flakes by the pulverizer into the glass fibers of suitable lengths through the fiber-making system, and then the glass fibers of four different lengths (0–5, 5–10, 10–15, 15–20 mm) are screened by manual screening. Four different lengths of glass fibers (0–5, 5–10, 10–15, 15–20 mm) are produced through manual screening.

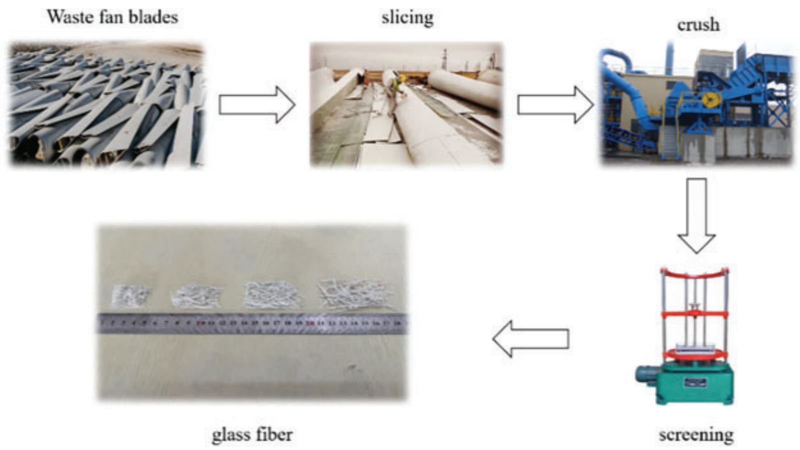

Figure 2. Glass fiber recycling process

Glass fiber: The glass fiber used in this test is recycled from used wind turbine blades of different lengths provided by a Chinese company, and the performance parameters are shown in Table 4.

2.3. Preparation of enhanced environmentally friendly construction gypsum

As shown in Table 5, the mixing ratios of environmentally friendly building gypsum in this study are listed. The length and amount of glass fibers added were used as independent variables in this test to investigate the specific effect of glass fibers on the properties of environmentally friendly building gypsum. The amount of glass fiber added to the gypsum was calculated according to the mass fraction. The test groups Ga, Gb, Gc, and Gd represent four different lengths of glass fibers, 0–5, 5–10, 10–15, and 15–20 mm, respectively, and were doped with 1.0%, 1.5%, 2.0%, and 2.5%, respectively. And G0 was designed as the control group.

Table 4. Performance parameters of glass fiber

Causality	Average L/D ratio	Average diameter	Average length	Average density	Tensile modulus	Compressive strength
Parameters	29.6	384.54 μm	9.3 mm	1820 kg/m^3	37.7 GPa	737.75 MPa

Table 5. Environmentally friendly construction gypsum mixing ratios

Number	Phosphorus building plaster (g)	Natural building plaster (g)	Water (g)	Glass fiber length (mm)	Glass fiber doping (%)
G0	800	200	600	/	/
Ga-1.0%	800	200	600	0–5	1.0
Ga-1.5%	800	200	600	0–5	1.5
Ga-2.0%	800	200	600	0–5	2.0
Ga-2.5%	800	200	600	0–5	2.5
Gb-1.0%	800	200	600	5–10	1.0
Gb-1.5%	800	200	600	5–10	1.5
Gb-2.0%	800	200	600	5–10	2.0
Gb-2.5%	800	200	600	5–10	2.5
Gc-1.0%	800	200	600	10–15	1.0
Gc-1.5%	800	200	600	10–15	1.5
Gc-2.0%	800	200	600	10–15	2.0
Gc-2.5%	800	200	600	10–15	2.5
Gd-1.0%	800	200	600	15–20	1.0
Gd-1.5%	800	200	600	15–20	1.5
Gd-2.0%	800	200	600	15–20	2.0
Gd-2.5%	800	200	600	15–20	2.5

To make its glass fiber distribution more uniform, this test adopts the first dry mixing of gypsum powder and glass fiber, and then the wet mixing method. Pour the weighed phosphorus construction gypsum powder and natural construction gypsum powder into the mixing container, turn on the NJ-160A cement mortar mixer produced by Zhejiang Geotechnical Instrument Manufacturing Co., Ltd., and mix the two kinds of gypsum powders fully dry for 1 min, and then pour the weighed glass fibers into the mixing container for dry mixing and mixing, and then add the city tap water to wet mixing after the glass fibers are fully dispersed for 1 min, and then pour into the triple mold. Put the full triple molds into the ZT-96 cement sand vibration table produced by Tianjin Gang yuan Testing Instrument Factory for full vibration, and wait for it to fully harden for demolding treatment. At the end of demolding, the environmentally friendly construction gypsum is put into the YH-40C constant temperature and humidity maintenance box produced by Wuxi Jian Yi Instrument Machinery Co., Ltd. for maintenance, with the ambient conditions of a temperature of 20 ± 5°C and humidity of 50 ± 5% for 7 days. After the end, it will be put into the electric heating constant temperature blast drying box produced by Zhejiang Geotechnical Instrument Manufacturing Co., Ltd. to carry on the adiabatic treatment, and its environmental condition is 40 ± 5°C. After molding, the gypsum samples were continued to be tested for flexural and compressive properties using the YAW-2000 microcomputer-controlled electro-hydraulic servo pressure tester produced by Shanghai Sansi Zong Heng Machinery Manufacturing Co., Ltd. To understand the microstructure of the glass fiber gypsum composites, the TESCAN MIRA LMS scanning electron microscope produced by TESCAN, Czech Republic was used to characterize the micromorphology.

2.4. Experimental plan

Determination of expansion degree and setting time of slurry according to the national standard of GB/T17669.4-1999. The flexural strength and compressive strength were determined by the national standard GB/T17669.3-1999. The gypsum specimens that were maintained for seven days were dried completely, and their compressive strength was tested. Then, the dried gypsum specimens were immersed in water for 24 h to reach a saturated, water-absorbing state. The compressive strength was measured again in this state to calculate the softening coefficient. The specimens of flexural strength and compressive strength in the test were in the size of 40 × 40 × 160 mm^3 rhombus, and three specimens of environmentally friendly construction gypsum were made for each proportion to ensure the reliability of the test results, and the final results were taken as the average value of each specimen.

3. Experimental results and discussion

3.1. Slurry extension

Figure 3 demonstrates the effect of different glass fiber dosages and lengths on the degree of expansion of environmentally friendly building gypsum slurry. The results of the experimental study showed that the expansion degree of the environmentally friendly building gypsum in the blank control group was 182 mm. With the glass fiber doping from 0% to 2.5% and the length from 0 to 20 mm, the expansion degree of the environmentally friendly building gypsum slurry decreased by 30 mm. This phenomenon is in line with the findings of Fan et al. [26]. Especially, the most obvious decrease in the expansion degree of Gd group slurry is mainly due to the incorporation of a large number of glass fibers with excessive length, and the longer glass fiber fibers are more likely to form a network structure, which leads to the formation of fiber flocculent accumulation to form a network structure within the environmentally friendly construction gypsum slurry, the fluidity of the gypsum slurry is affected by this, which in turn reduces the expansion degree of the environmentally friendly construction gypsum slurry.

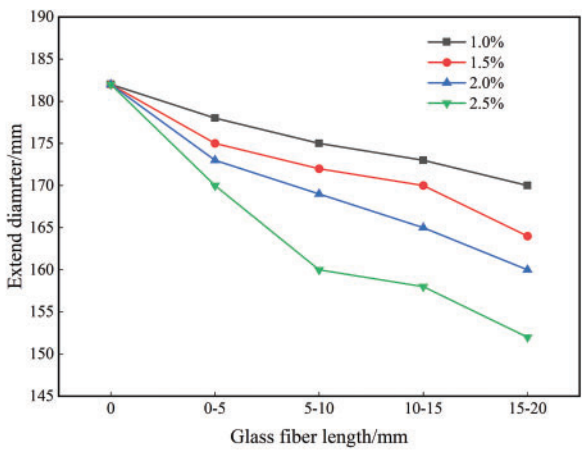

Figure 3. Gypsum extensibility

Figure 4 visualizes the combined effect of glass fiber doping and length on the extensibility of environmentally friendly building gypsum slurry. As can be seen from Figure 4, when the length of glass fibers is fixed, with the increase of glass fiber dosage, the extension degree of environmentally friendly building gypsum slurry shows a decreasing trend. When the amount of glass fiber doping is fixed, the extension degree of environmentally friendly construction gypsum slurry with different lengths of glass fiber doping is also similar to the decreasing trend. From the contour distribution in the figure, it can be seen that both the dosage and length of glass fibers have a relatively obvious effect on the extensibility of environmentally friendly building gypsum slurry.

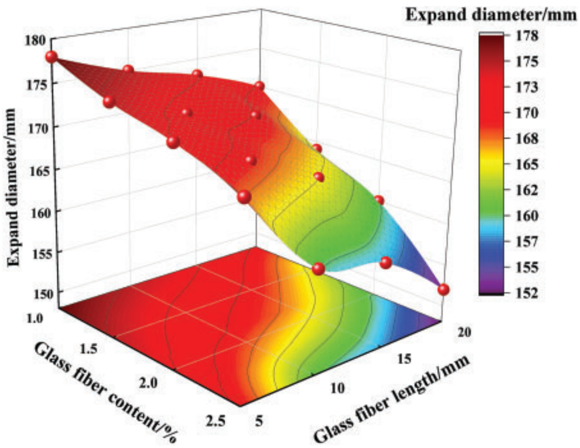

Figure 4. Analysis of factors influencing the degree of expansion

3.2. Condensation time

Figures 5 and 6 show how different dosages and lengths of glass fibers affect the setting times of environmentally friendly building gypsum. These times are divided into initial and final setting times. The experimental study results show that the initial and final setting times of environmentally friendly construction gypsum without added glass fibers are 400 and 550 s, respectively. With the glass fiber dosage from 0% to 2.5%, and the length from 0 to 20 mm, the setting time of environmentally friendly construction gypsum decreases compared with that of the control group, and the decrease of the Gb group is not as great as that of the Ga group in the high dosage of the initial setting time, and the decrease is most obvious in the Gd-2.5% group, with the initial setting time decreasing by 110 s. In this case, the decrease in the initial setting time is more than that of the Gb group. The Gd-2.5% group showed the most significant decrease, with the initial setting time decreasing by 110 s and the final setting time decreasing by 115 s. This phenomenon is consistent with the findings of Li et al. [27]. This phenomenon is because the addition of glass fibers increases the viscosity of the gypsum slurry. The increase of viscosity will limit the flow and diffusion of water in gypsum slurry, which will make gypsum slurry lose fluidity faster, prompting water to fix faster, and indirectly accelerate the speed of coagulation.

Figures 7 and 8 visualize the joint effect of glass fiber admixture and length on the initial and final setting time of environmentally friendly building gypsum. From the figure, it can be found that the glass fiber doping has a greater effect on the initial setting time of environmentally friendly building gypsum, and the initial setting time shows a fluctuating trend of decreasing and then increasing when the length of glass fiber grows from 0–10 mm, and the rest of the parts follow a decreasing trend with the increase of the length and doping of glass fiber. Taken together, the decreasing trend of the initial setting time fluctuates, while the decreasing trend of the final setting time is more moderate.

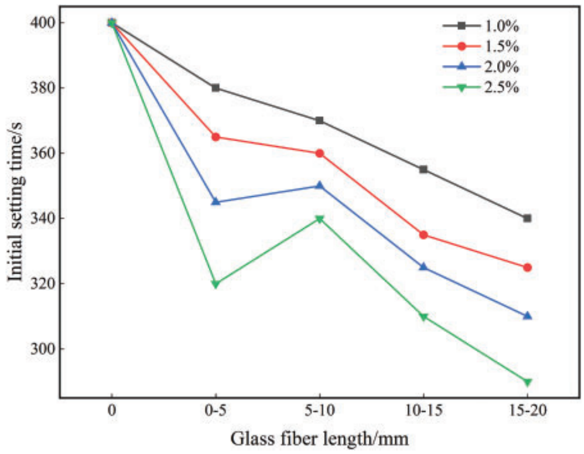

Figure 5. Initial setting time of gypsum

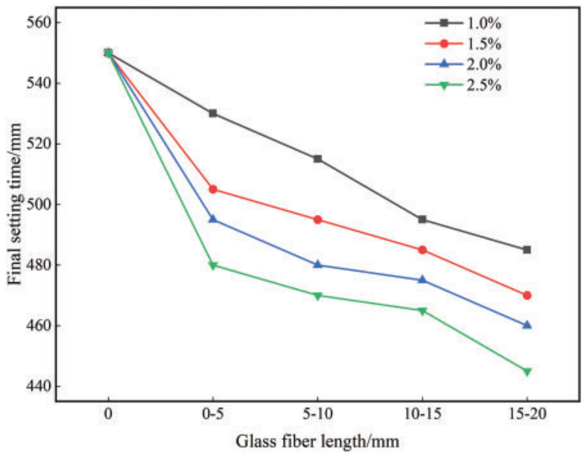

Figure 6. Final setting time of gypsum

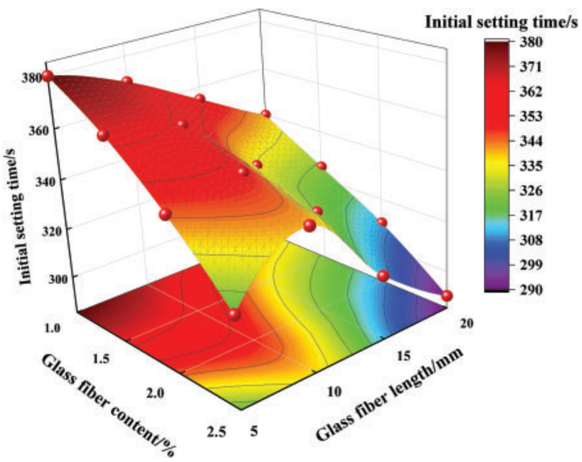

Figure 7. Analysis of factors affecting initial setting time

3.3. Flexural strength

Figure 9 demonstrates the effect of glass fiber doping and length on the flexural strength of environmentally friendly construction gypsum, as can be seen from the data in the figure, the flexural strength of the blank control group was 3.7 MPa. When 0–5 mm glass fibers with 1% doping were doped in, the flexural strength slightly decreased by 0.1 MPa compared to the blank control group; with the increase in doping, the flexural strength began to increase, and when the doping was 2%, the flexural strength was the highest, which was 4.7 MPa, and it was improved by 27.03% relative to the blank group; when the length of the doped glass fiber was 5–10 mm, the flexural strength steadily increased with the increase of doping amount, and the flexural strength reached 4.8 MPa when the doping amount was 2.5%; when the length of the doped glass fiber was changed to 10–15 mm, the phenomenon was similar to that of 5–10 mm but the flexural strength increased by 0.1 MPa when the doping amount was 2.5%. 2.5%, the flexural strength reached 5.1 MPa, which was 37.84% higher relative to the blank group; when the length of the blended glass fibers was changed to 15–20 mm, it was similar to the phenomenon of 0–5 mm, and the highest flexural strength was found at the blending amount of 2%, which was 5.6 MPa, which was 51.35% higher relative to the blank group. This phenomenon is consistent with the findings of Yang et al. [28]. Overall, the flexural strength of gypsum showed an increasing trend with the increase of glass fiber doping. The doping of waste glass fibers in gypsum can increase its flexural strength, and this phenomenon is mainly attributed to the formation of a three-dimensional network structure of glass fibers in the gypsum matrix, when microcracks appear in the matrix, the fibers prevent the cracks from expanding through the bridging effect and delay the fracture process.

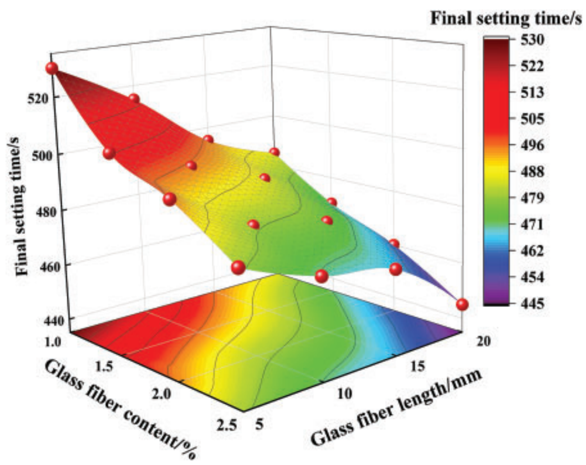

Figure 8. Analysis of factors affecting final setting time

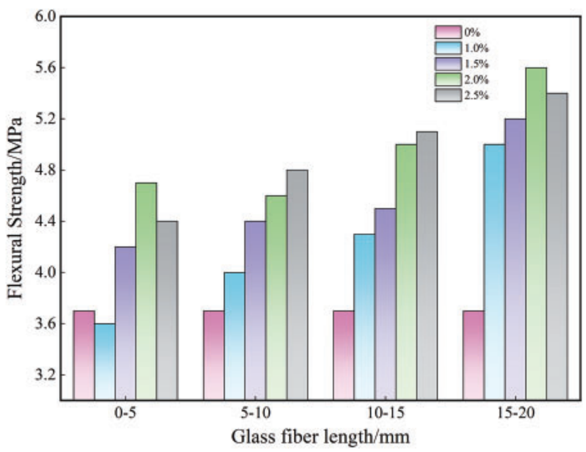

Figure 9. Gypsum flexural strength

Figure 10 shows the three-dimensional visual diagram of the analysis of the factors affecting the flexural strength of glass fiber gypsum, from which it can be seen that the flexural strength of gypsum exhibits an increasing trend with the increase of fiber doping when the length of glass fibers is fixed when the glass fiber doping amount is fixed, the flexural strength shows an increasing trend. The overall rising trend is relatively gentle, when the length of glass fiber doped is 15–20 mm and the dosage is 2%, it shows the best flexural performance. From the overall analysis, the glass fiber length is a more significant factor affecting the flexural strength of gypsum.

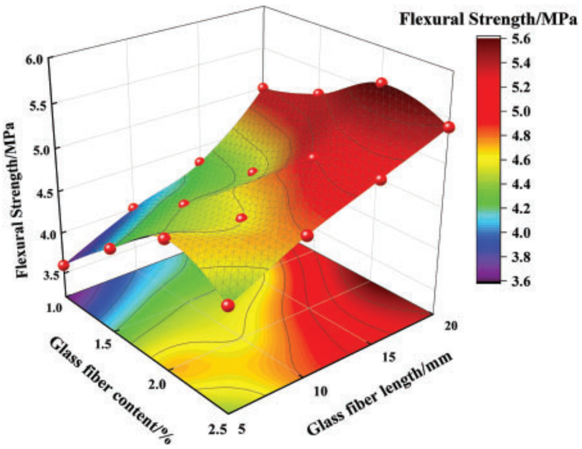

Figure 10. Analysis of factors affecting flexural strength

3.4. Compressive strength

Figure 11 demonstrates the effect of glass fiber doping and length on the compressive strength of environmentally friendly building gypsum. The compressive strength of the control blank group was 9.1 MPa. When 0–5 mm glass fibers were added, the compressive strength increased with the dosage. The highest compressive strength, 10.6 MPa, was achieved with a 2% dosage; the phenomenon was similar to that when 0–5 mm was doped when 5–10 mm was doped, but the compressive strength of the doped glass fibers was 10.5 MPa when the dosage was 2%; and the compressive strength of the doped glass fibers showed an increasing trend with the increase of the dosage when the length of glass fibers was 10–15 versus 15–20 mm. When the length of glass fiber is 10–15 and 15–20 mm, with the increase of doping, the compressive strength shows an increasing trend and reaches the highest when the doping amount is 2.5%, which is 11.3 and 10.3 MPa, respectively. Overall, the compressive strength increases with the increase of the length of glass fibers doped, given a fixed amount of glass fibers. The best compressive strength was obtained when 2.5% of glass fibers with a length of 10–15 mm were doped, which increased by 24.17% compared to the blank control group. This phenomenon is consistent with the findings of Romero-Gómez et al. [29]. This phenomenon occurs because phosphorus-building gypsum is inherently brittle, and the addition of fibers indirectly enhances the compressive strength by absorbing the energy of crack expansion and improving the toughness of the material. The incorporation of glass fibers can fill the pores in the phosphorus gypsum matrix to play the role of dispersing stress, thus enhancing the compressive strength of gypsum.

Figure 12 shows the three-dimensional visualization of the analysis of the factors affecting the compressive strength of fiberglass gypsum, as can be seen from the figure, this surface map is more complex, there are three regions are more obvious, respectively, the length of 5–10 mm, the doping rate of 1%–1.5%; the length of 15–20 mm, the doping rate of 1%–1.5%; the length of 10–20 mm, the doping rate of 1.5%–2.5% of the three regions. From the overall trend, when the glass fiber length is fixed, the compressive strength increases with the increase in doping. When the dosage is fixed, there is no significant trend of change in compressive strength with the change in glass fiber length. So the effect of glass fiber doping on the compressive strength of glass fiber gypsum composites is more pronounced.

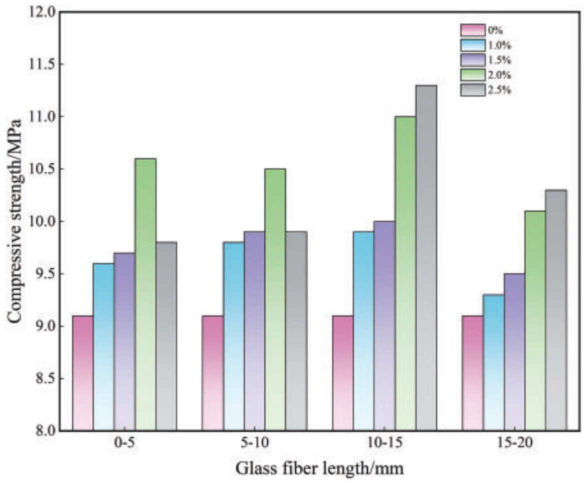

Figure 11. Gypsum compressive strength

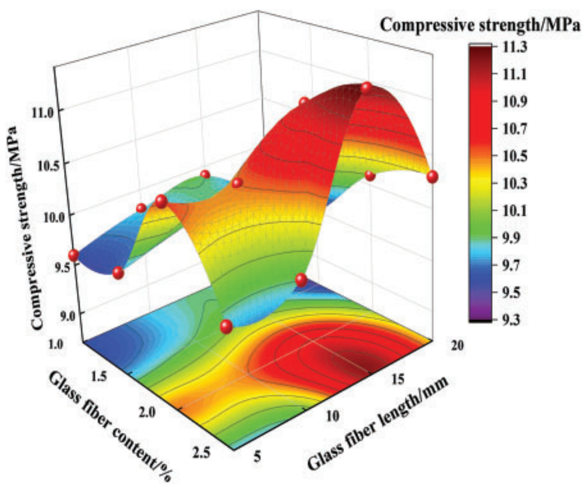

Figure 12. Analysis of factors affecting compressive strength

3.5. Softening coefficient

Figure 13 demonstrates the effect of glass fiber doping and length on the softening coefficient of environmentally friendly construction gypsum. The softening coefficient of the blank control group was 0.51, and when the length of glass fibers doped was 0–5 mm, the softening coefficient of gypsum showed a trend of growth and then decreased with the increase of doping amount. With the growth of the doped glass fiber length, also all show the same trend with 0-5mm, the maximum softening coefficient is produced when the doping amount is 1.5% the length of the glass fiber is 15–20 mm, and the softening coefficient is 0.67, which is increased by 32.37% relative to the blank control group. This phenomenon is consistent with the findings of Li et al. [27]. The incorporation of glass fibers affects the porosity of gypsum. An appropriate amount of glass fibers can act as a skeleton within the gypsum matrix. This makes the pore structure inside the material denser and reduces the channels through which water can penetrate. Thus, the material's water absorption rate is reduced and its softening coefficient is improved.

However, when the glass fiber is doped too much, it may lead to an increase in porosity in local areas, forming some large pores and defects, which will become channels for water penetration, so that the water resistance of the material decreases and the softening coefficient decreases.

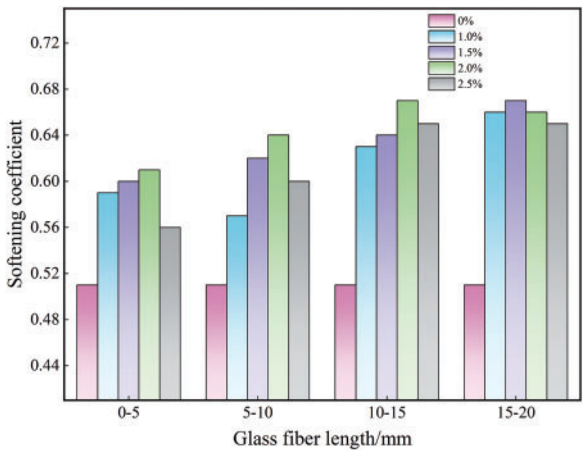

Figure 13. Gypsum softening factor

Figure 14 shows the three-dimensional visual diagram of the analysis of the factors affecting the softening coefficient of gypsum with glass fiber, from which it can be seen that when the length of the glass fiber is fixed, the effect of glass fiber doping on the softening coefficient of gypsum is not obvious; when the doping amount is fixed, the softening coefficient of gypsum is increased by the increase of the length of the glass fiber and the increase of the softening coefficient of gypsum. In summary, the glass fiber length has a more obvious effect on the softening coefficient of gypsum.

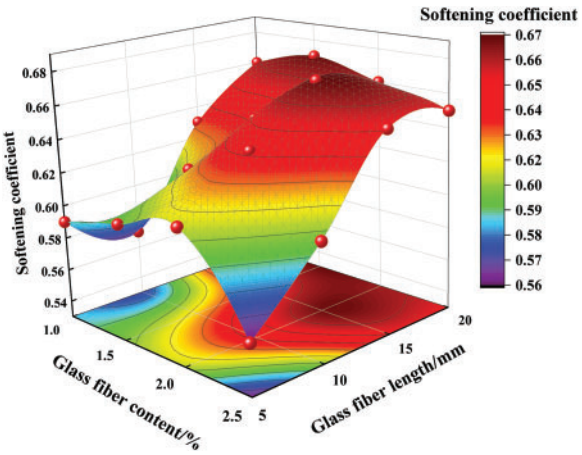

Figure 14. Analysis of factors affecting the softening coefficient

3.6. Microstructure analysis

The aim is to thoroughly investigate the impact of recycled glass fibers from waste wind turbine blades on the mechanical properties of environmentally friendly gypsum building composites and to accurately observe the microstructure of the doped glass fiber gypsum, the microstructure was tested by using an electron microscope with a total of eight specimens, and the results of the test are shown in Figure 15.

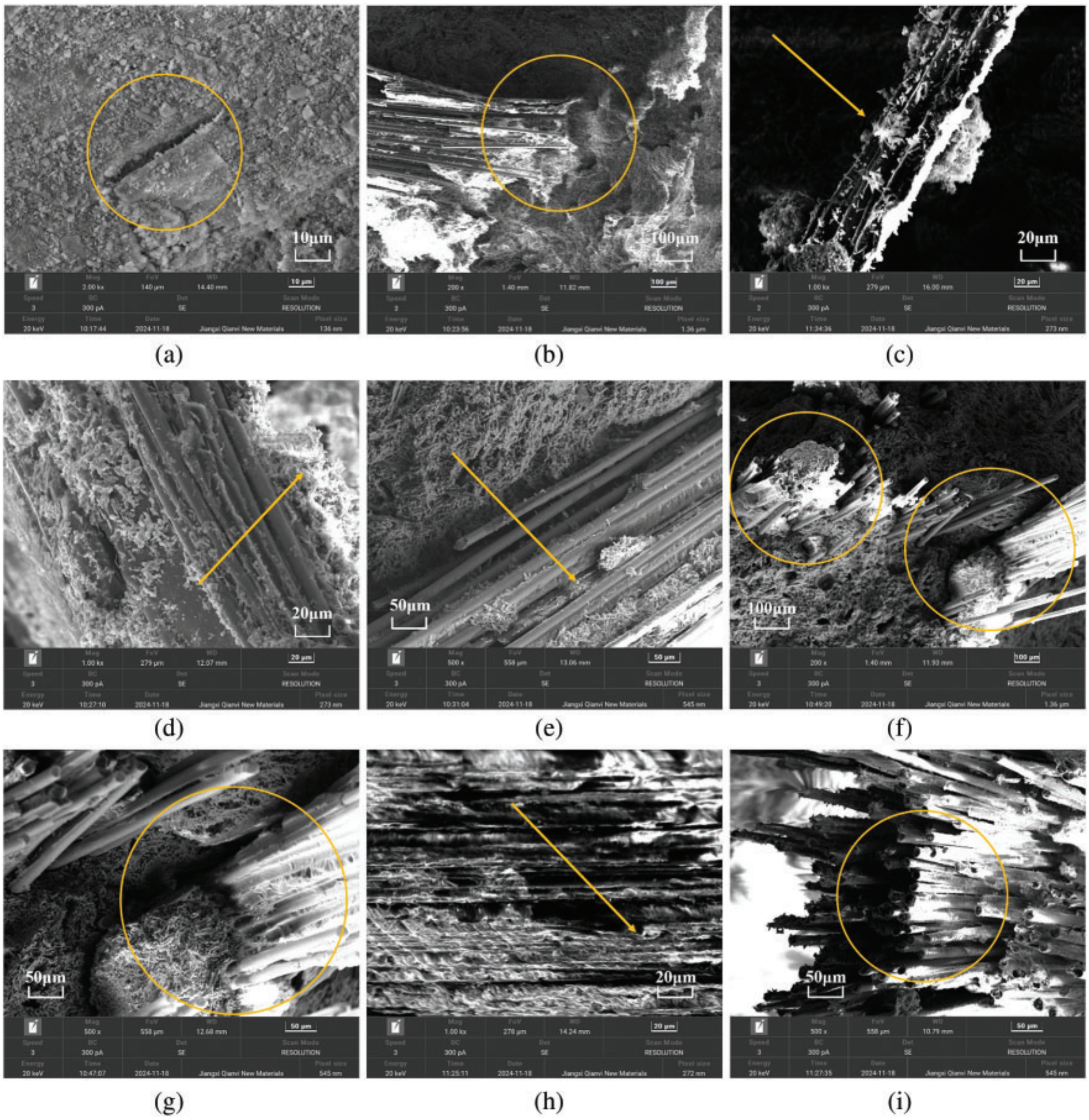

Figure 15. SEM image of glass fiber incorporated gypsum

Figure 15a shows the microstructure of the blank control group, which shows the existence of voids and cracks inside its gypsum, which verifies that gypsum itself is a material with a porous structure. The porous structure makes a large number of pores inside the gypsum, and these pores will be the source of cracks, which are easy to expand when subjected to force, leading to a decrease in the flexural and compressive strength of the material. Figure 15b shows the distribution of glass fibers in gypsum, filling some of the voids and cracks and binding the gypsum around them, which is responsible for the mechanical properties of glass fiber-reinforced gypsum composites. The large amount of hydrates attached around the doped glass fibers in Figure 15c and 15d indicate a good adhesion between the glass fibers and hydrates. Figure 15e and 15f shows the glass fibers are scattered inside the gypsum and well bonded to the surrounding gypsum. In Figure 15g–15i, the glass fiber pullout and fracture of the glass fibers from the gypsum material in the tests are shown, indicating the diversity of their damage modes in the gypsum composites. In addition to fiber pull-out and fracture, there are various damage modes such as matrix cracking and interfacial debonding, etc. The glass fibers play a good role in bridging and dispersing the stresses during the stressing process.

4. Conclusion

In this study, a synergistic regenerative preparation method for environmentally friendly construction gypsum is proposed using phosphogypsum and recycled glass fibers from waste wind turbine blades as raw materials, and the effects of glass fiber length and blending amount on gypsum properties are systematically investigated. The specific effects of these factors on the slurry expansion degree, setting time, flexural strength, compressive strength, and softening coefficient of gypsum are analyzed, and the experimental results are analyzed in depth. Combined with the observation of its microstructure by electron microscope, the following conclusions are drawn.

(1) By mixing phosphorus-building gypsum with natural building gypsum (8:2 ratio), the content of harmful impurities (P, F) in phosphorus gypsum was effectively reduced, while maintaining the basic properties of the gypsum matrix, which provided a feasible substrate for subsequent fiber reinforcement. The incorporation of glass fibers significantly reduced the slurry extensibility and setting time. The increase in fiber length with higher doping exacerbates the decrease in fluidity and setting time.

(2) The incorporation of glass fibers significantly improved the flexural and compressive strengths of environmentally friendly building gypsum.

(3) The incorporation of glass fibers significantly improves the softening coefficient of environmentally friendly building gypsum. The appropriate amount of glass fibers makes the internal pore structure of the material more dense and reduces the water infiltration channels, thus improving the water resistance.

(4) Microstructural analysis of the electron microscope reveals that the glass fibers in gypsum showed the phenomenon of pulling out and overall fracture in the gypsum during the mechanical property testing, which indicates that the glass fibers play a good role in bridging and dispersing the stresses in the gypsum. The addition of glass fibers can well fill the voids and cracks existing inside the gypsum. The good adhesion between the glass fibers and the matrix as well as the hydride attachment further enhanced the mechanical properties of the composites.

In summary, the use of partial substitution can reduce the content of harmful substances in gypsum, and the waste glass fibers blended into gypsum have a reduced effect on its working properties but an enhanced effect on its mechanical properties, and all these findings provide a valuable reference for the application of glass fibers in gypsum. It provides a new way for the recycling of phosphogypsum and waste wind turbine blades, which is an effective way to prepare new green building materials. In future practical applications, other properties of gypsum materials should also be considered, so properties such as thermal and acoustic insulation can be explored in future experiments.

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