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Study of Concrete Properties of Recycled Glass Fibres from Decommissioned Wind Turbine Blades

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Abstract: *As an environmentally friendly and renewable energy solution, wind power is rapidly gaining favour worldwide due to its gentle impact on the environment. Nevertheless, the potential environmental risks posed by discarded wind turbine blades still need to be brought to our attention. Therefore, exploring ways to recycle and reuse discarded wind turbine blades has become an urgent task in the field of environmental protection. This study focuses on the incorporation of recycled glass fibres from crushed wind turbine blades into concrete to assess their benefits in engineering practice. In this study, we used four different particle sizes of recycled glass fibres, 0-5mm, 5-10mm, 10-15mm and 15-20mm, and incorporated them into the concrete at four different admixture levels of 0.2%, 0.4%, 0.6% and 0.8%. By comprehensively examining its workability, mechanical properties and microstructure, we found that although the incorporation of glass fibres reduced the apparent density, slump and compressive strength of the concrete to a certain extent, it significantly improved the split tensile and flexural strengths of the concrete, as well as effectively improved the brittleness of the material and enhanced its toughness. These findings reveal the feasibility of recycling glass fibres from decommissioned wind turbine blades and applying them to concrete. This study not only opens up a new path for environmentally friendly recycling and reuse of wind turbine blades, but also provides a valuable reference for practical engineering applications, with significant social and economic benefits.*

Keywords: *Wind turbine blades, Glass fibre, Concrete, Compressive strength, Split tensile strength, Flexural strength*

1. Introduction

Wind energy is a non-polluting, renewable and clean energy source. It is therefore growing rapidly worldwide, with a cumulative global installed wind power capacity of 923GW by 2022 [1]. Since 2011, China has been ranked as the world's number-one producer of wind power. Although wind power is one of the sustainable industries, wind turbine blades are non-recyclable materials. The rapid growth of the wind energy industry over the past 20 years has led to a corresponding rapid increase in the amount of wind blade waste that will need to be disposed of shortly. Global annual waste from end-of-life blades is expected to increase significantly in the coming decades, approaching 500,000 tons/year and 1 million tons/year by 2030 and 2040, respectively [2]. A wind turbine blade is a key component to convert air kinetic energy into rotor mechanical energy, with excellent aerodynamic performance structural characteristics and high strength, high toughness, lightweight and fatigue resistance [3, 4]. Blades include leaf roots, main beams, webs and housings, etc. In these structures, glass fibre reinforced plastics (GFRP) and/or carbon fibre reinforced plastics (CFRP) are commonly used for the blade roots and main beams. The web and shell form a sandwich-type sandwich structure, with GFRP material used for the external panels and lightweight balsa wood and foam for the internal filling. Wind turbine blades typically have a service life of 15-20 years [5, 6].

Currently, decommissioned wind turbine blades are usually treated by chemical recovery, thermal recovery and mechanical recovery. The main technologies for chemical recovery include supercritical fluid treatment and solvent decomposition. Okajima et al [7] achieved the recovery of carbon fibres on a clean surface by decomposing carbon fibre reinforced plastics under subcritical and supercritical water

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conditions. Chemical recycling of thermoset composites is more complex and challenging than mechanical recycling, but has the advantage of enabling more efficient recycling and producing high-quality recyclates. With the advancement of pyrolysis technology, pyrolysis methods have evolved from the initial fixed-bed pyrolysis and fluidised-bed pyrolysis to more advanced forms, including diverse technologies such as moving-bed pyrolysis, microwave pyrolysis, and concentrating light pyrolysis [8]. Thermal recovery methods have the advantage of being technically simple and cost-effective, but the disadvantages are the complexity of the pyrolysis oil separation and purification process and the reduced strength of the recovered reinforcing fibres. Researchers such as Ribeiro [9] explored the possibility of repurposing GFRP (Glass Fibre Reinforced Plastic) fragments obtained through mechanical recycling as aggregate and filler materials for concrete-polymer composites. FOX [10] assessed the economic and environmental impacts of the use of waste wind turbine blades in the manufacture of concrete, and the results of the study confirmed the utility of blade fragments as concrete aggregate under certain conditions. In contrast, mechanical recycling is a more environmentally friendly and sustainable method of disposing of GFRP waste.

In order to address the recycling of fibre plastics, researchers have focused their research on the construction sector, particularly concrete. Concrete, which is a mixture of cement, water and aggregates.it is widely used in construction due to its low cost and the good mechanical properties as well as the durability of the obtained material after moulding. Research on fibre-reinforced concrete (FRC) has shown that dispersed metallic and non-metallic fibres help to improve the mechanical properties of concrete, particularly tensile strength, tensile ductility and resistance to crack opening and extension [11-13]. In recent years, to minimise the environmental impact of the concrete industry, a variety of fibres recovered from industrial wastes have been added to concrete, such as steel fibres recovered from tyres [14, 15], plastic fibres recovered from synthetic polymers [16], and plant-based fibres recovered from agricultural and forest wastes [17, 18].

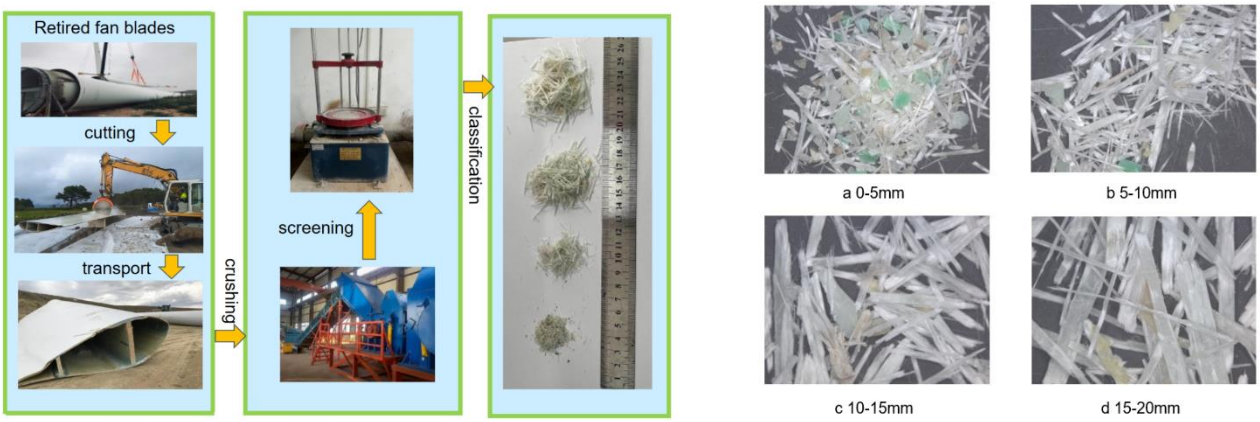
Dmitry Baturkin et al [19] investigated the effect of waste glass fibre reinforced polymer (GFRP) material extracted from wind turbine blades (WWTB-GFRP) as powder, aggregate and fibre on the properties of concrete. Cement replacement was 10-30%. Coarse aggregate replacement levels were 33-100% and fibre addition rates were 1-1.75 vol.%. The results showed that the morphology of WWTB-GFRP (powder, aggregate or fibre) had a significant effect on the properties of concrete. Thus, although WWTB-GFRP powder leads to a significant increase in setting time (due to the wood content and its associated soluble sugars) as well as a significant decrease in compressive and flexural strengths, the compressive strength at 90 days of a mixture in which 10% of the cement was replaced with WWTB-GFRP powder (after removing the wood content) was comparable to that of the reference mixture (without WWTB-GFRP). When WWTBGFRP was incorporated into concrete as a fibre reinforcing agent, the flexural capacity increased by 15% without any significant decrease in the compressive strength. Yazdanbakhsh A et al [20] used wind turbine blade shells made of glass fibre reinforced polymers (GFRP) to replace 5% and 10% of the coarse aggregates by volume ratio, and the results showed that the stability and ease of the freshly mixed concrete were not a negative impact. Although the incorporation of needles did not significantly affect the compressive, tensile and flexural strength of the concrete, it led to a significant increase in the energy absorption capacity (toughness) of the concrete. Fu B et al. [21] utilized the mechanically recycled method by processing the GFRP wastes into macroscopic fibres used for reinforcing the concrete, which was termed as Macro Fibre Reinforced Concrete (MFRC). The mechanical properties of MFRC were investigated. The test results show that: the macroscopic fibre admixture has two main effects on the concrete:(1) the macroscopic fibre volume ratio has a greater effect on the concrete's ease of use, and when the macroscopic fibre volume ratio is increased from 0% to 1.5%, the slump value decreases from 176 mm to 83 mm; (2) the admixture of macroscopic fibres significantly improves the flexural strength and toughness of the concrete, and the concrete's compressive strength is slightly increased, with the maximum 4.4% enhancement. The split tensile strength increases approximately linearly with the increase of macro fibre content. When the macrofibre content is 1.5%, the average split tensile strength of concrete is 4.86 MPa, which is 52% higher than that of the reference specimen without added macrofibre.

In this study, decommissioned wind turbine blades were crushed into four different lengths (0-5mm, 5-10mm, 10-15mm, 15-20mm) and added into concrete at four different admixture levels (0.2%, 0.4%, 0.6%, 0.8%). Concrete was tested for apparent density, slump, compressive strength, split tensile strength, flexural strength and microstructure. A new type of recycled glass fibre concrete with better performance was obtained, which not only has certain economic value but also provides a new way for the recycling of retired wind turbine blades.

2. Materials and methods

2.1. Glass fibre recycling

This test is to recover retired wind turbine blades by mechanical method, and its main recovery process is shown in Figure 1a. Firstly, the retired wind turbine blades are cut into blocks for easy transportation on-site; after entering the factory, the wind turbine blades are crushed into 80cm pieces by the crushing system. The length-compliant glass fibre bundles were made through the fibre making system and screened to obtain the four lengths of fibres (0-5mm, 5-10mm, 10-15mm, 15-20mm) for this experimental study.



(a) Recycling process (b) Appearance of different lengths

Figure 1. Recycled glass fibre

Glass fibre: The glass fibre selected for this test were glass fibre of different lengths recovered from waste wind turbine blades provided by Jilin Chongtong Chengfei New Materials Joint Stock Company. The glass fibre morphology is shown in Figure 1b. Glass fibre material properties are provided by the manufacturer as shown in Table 1.

Table 1 Performance parameters of glass fibre

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

2.2. Concrete ratios, equipment and production

As shown in Table 2, the mix ratios of the concrete in this study are detailed. In this experiment, we adjusted the length and admixture of glass fibres as variables to explore in depth the specific effect of glass fibres on the properties of concrete. The addition of glass fibres in concrete was calculated based on the design volume fraction and the actual density of glass fibres (1970 kg/m^3). To make a comprehensive assessment, a total of 17 sets of experiments were carried out with the following experimental programme:

The experimental groups Ga, Gb, Gc, and Gd represent four different lengths of glass fibre reinforced plastic (GFRP) of 0-5 mm, 5-10 mm, 10-15 mm, and 15-20 mm, which were blended at 0.2%, 0.4%, 0.6%, and 0.8%, respectively. The design strength of G-0, which served as the control group, was set at 30 MPa. Non-standard cubic dimensions of 100 × 100 × 100 mm were used for compressive and split tensile strengths, while beam dimensions of 100 × 100 × 400 mm were used for flexural strengths. Three specimens were made for each mix of concrete to ensure the reliability of the test results and the final results were averaged from each specimen.

For the selection of raw materials, the cement used is P.O42.5 grade ordinary silicate cement produced by the Anhui Conch brand. The fineness modulus of river sand is 2.7, which ensures a good particle size distribution. The particle size of granite stone is controlled within 5~20mm to meet the mechanical property requirements of concrete. In addition, the fly ash used was from the Class I product produced by Xinliang Building Material Processing Plant in Jixian Village, Peizhuang Township, Wanrong County, Shanxi Province. For water, ordinary tap water was used.

Table 2. Concrete mixing ratio

number	**Water** (kg/m3)	**Cement** (kg/m3)	**Sand** (kg/m3)	**Stone** (kg/m3)	**Fly ash** (kg/m3)	**GFRP**	
						Lengths(mm)	Ratio(%)
G-0	185	308	654	1214	77	/	/
Ga-0.2	185	308	654	1214	77	0-5	0.2
Ga-0.4	185	308	654	1214	77		0.4
Ga-0.6	185	308	654	1214	77		0.6
Ga-0.8	185	308	654	1214	77		0.8
Gb-0.2	185	308	654	1214	77	5-10	0.2
Gb-0.4	185	308	654	1214	77		0.4
Gb-0.6	185	308	654	1214	77		0.6
Gb-0.8	185	308	654	1214	77		0.8
Gc-0.2	185	308	654	1214	77	10-15	0.2
Gc-0.4	185	308	654	1214	77		0.4
Gc-0.6	185	308	654	1214	77		0.6
Gc-0.8	185	308	654	1214	77		0.8
Gd-0.2	185	308	654	1214	77	15-20	0.2
Gd-0.4	185	308	654	1214	77		0.4
Gd-0.6	185	308	654	1214	77		0.6
Gd-0.8	185	308	654	1214	77		0.8

The preparation process of fibre concrete is similar to that of conventional concrete, but the key lies in the timing and method of fibre incorporation. The uniformity of fibre dispersion is critical to the overall performance of the concrete. If aggregation or uneven distribution of glass fibres occurs in the concrete, the performance of the material will be seriously affected. To ensure that the fibres achieve uniform distribution in concrete, a fine strategy was adopted in this study. Glass fibres were gradually introduced during the mixing of coarse and fine aggregates, followed by the addition of cementitious materials and water to ensure adequate integration of the fibres with the concrete matrix.

After mixing, the concrete was first tested for apparent density and slump. After the tests were completed, the concrete was moulded and numbered. After 24 hours of curing in a standard curing room, the concrete specimens were demoulded and continued to be cured for 28 days to achieve optimum hardening. Subsequently, the concrete was tested for compressive and splitting tensile properties using a Sansi press manufactured by Shanghai Sansi Zongheng Machinery Manufacturing Company Ltd. The microcomputer-controlled electro-hydraulic servo universal testing machine made by Jinan Hengshi

Grand Instrument Co. was used to evaluate the flexural properties of concrete. In addition, to gain an in-depth analysis of the microstructure of concrete, an EVO 18 electron microscope manufactured by Carl Zeiss GmbH, Germany, was used to characterise the concrete in detail in terms of its micro-morphology.

3. Results and discussions

3.1. Apparent density

Figure 2 demonstrates the effect of different glass fibre lengths and admixtures on the apparent density of concrete. The results of the study show that the apparent density of pure concrete is 2368 kg/m³. As the glass fibre content increased from 0% to 0.8% and the fibre length increased from 0mm to 20mm, the apparent density of the concrete mix showed a decreasing trend with a total decrease of 55kg/m³. This phenomenon coincides with the findings of researchers such as [22]. In particular, the Gd group (15-20 mm length of glass fibres) showed the most significant decrease in apparent density, which was mainly because the density of the glass fibres was lower than that of the concrete matrix, thus pulling down the overall apparent density. At a fixed glass fibre length, the decrease in apparent density of glass fibre concrete mixes accelerated as the dosage was increased. On the contrary, when the dosage is kept constant, an increase in fibre length results in a gradual slowing down of the rate of increase in the apparent density of the mix. This trend can be explained by the fact that at higher dosages of glass fibre reinforced plastic (GFRP) fibre incorporation, fibre dispersion becomes more difficult, leading to the formation of fibre aggregates and voids in the concrete mix. These voids increase the porosity of the concrete mix, which in turn reduces its apparent density.

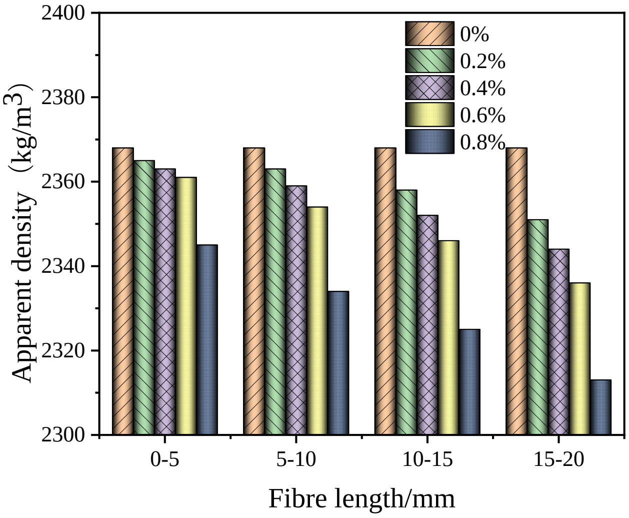


Figure 2. The apparent density of concrete

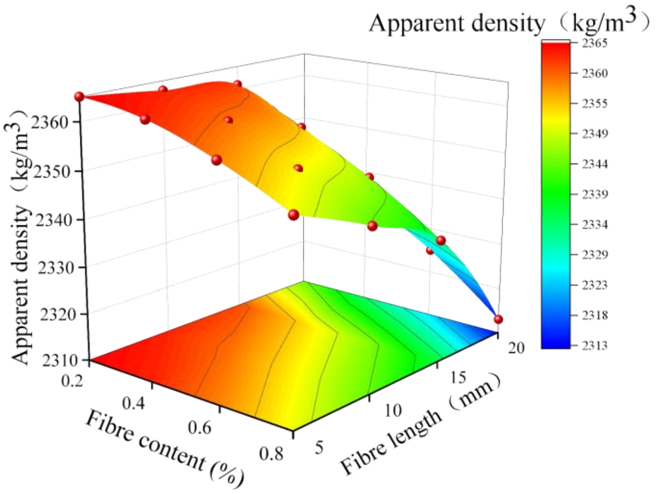


Figure 3. Analysis of factors affecting apparent density

Figure 3 visualises the joint effect of fibre admixture and fibre length on the apparent density of fibre concrete. It can be observed from the figure that when the fibre length is kept constant, the apparent density of fibre concrete shows a gradual decrease with the increase in fibre dosage. Similarly, the apparent densities of fibre concretes of different lengths follow a similar decreasing pattern when the fibre dosage is consistent. The contour lines in the graph show a regular variation, which indicates that both fibre length and dosage have a more significant effect on the apparent density of fibre concrete.

3.2. Slump of Fresh Concrete

Figure 4 demonstrates the effect of different lengths and dosages of glass fibres on the slump of concrete. The slump of plain concrete without added fibres was 28 mm. It is noteworthy that the glass fibre concrete with Ga-0.8 (0-5 mm length, 0.8% admixture) exhibited the highest slump, which was enhanced by 25% as compared to the plain concrete, whereas the slump of the concrete with Gd-0.8 (15-20 mm length, 0.8% admixture) was significantly reduced by 64.3%. Overall, the slump of concrete mixes showed a decreasing trend with increasing fibre length. However, the slump of the Ga group was abnormally higher than that of plain concrete, which is consistent with the findings of He P et al [23]. This phenomenon can be attributed to the impurities mixed with the short fibres during the screening process, which mainly consisted of resin matrix detached from the glass fibres, structural adhesive, PVC, and balsa wood (as shown in Figure 2-2a). The smooth surface and hydrophobic nature of these impurities provide them with less friction in the concrete, which enhances the flow and leads to an increase in slump. When the fibre length is in the range of 5-20 mm, the slump of concrete decreases gradually with increasing admixture, which is by the findings of Guang-Ti X et al [24]. This is mainly because the cement paste wraps around the surface of the fibre material, reducing the number of free-state paste particles and thus reducing the fluidity of the mortar. The increase in fibre length at a fixed admixture also leads to a decrease in slump, mainly because long fibres have a large surface area and are prone to entanglement in water, which increases the consistency of the concrete and makes it less fluid, thus reducing the ease of use of the concrete.

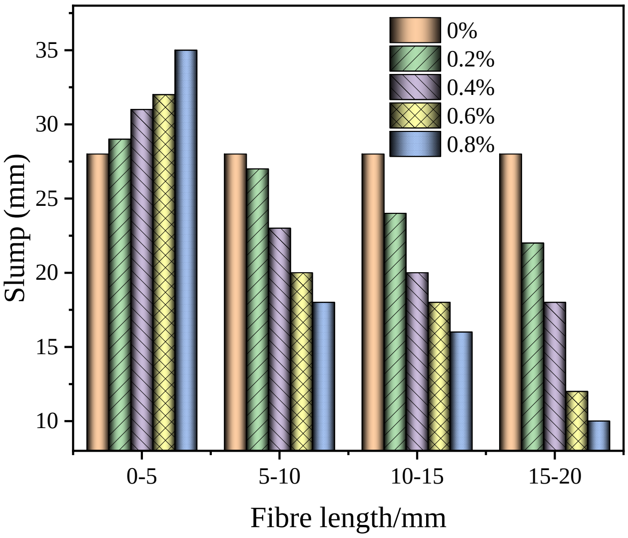


Figure 4. Concrete slump

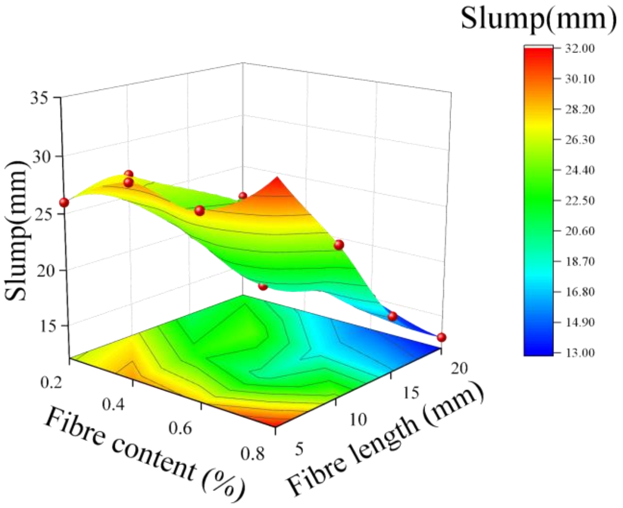


Figure 5. Analysis of slump influencing factors

The joint effect of fibre admixture and fibre length on concrete slump is depicted in detail in Figure 5, revealing a relatively complex surface relationship. The general trend shows that when the fibre dosage is fixed, the slump of concrete tends to decrease as the fibre length increases. However, the surface plot did not demonstrate a consistent trend when fixed fibre length was considered. In particular, in the range of fibre length 0-5 mm, the surface showed a fluctuating trend of increasing, then decreasing and then increasing, with the middle part of the surface being relatively flat. As for the fibre length of 15-20mm, the slump shows a decreasing trend with the increase of doping. This is corroborated by the changes in contour lines. These observations suggest that the effect of fibre admixture on the slump of fibre concrete is not very significant, whereas fibre length is a more critical factor affecting the slump.

3.3. Compressive strength

Figure 6 illustrates the results of the compressive strength tests of glass fibre concrete, from which we can observe some key trends. The compressive strength of the plain concrete was 34.6 MPa. In the Ga group, the compressive strength was slightly increased by 1.34 MPa and 0.3 MPa when 0.2% and 0.4% of glass fibres were incorporated respectively. however, the compressive strength started to decrease as the glass fibre incorporation was further increased, and was reduced by 0.49 MPa and 0.8% of glass fibres when 0.6% and 0.8% of glass fibres were incorporated, respectively. 1.5 MPa. For the Gb group, the compressive strength was slightly higher than that of plain concrete only at 0.2% glass fibre admixture, with an increase of 0.34 MPa. At all other admixtures, the compressive strength of the Gb group was lower than that of the plain concrete. The performance of the Gc group was similar to that of the Gb, and the compressive strength was increased only at 0.2% glass fibre admixture, with an increase of 0.38 MPa.The Gd group showed the compressive strength decreased most significantly with the increase in admixture, by 0.66 MPa, 0.86 MPa, 3.24 MPa and 4.32 MPa, respectively. Overall, the compressive strength of concrete showed a decreasing trend with the increase in glass fibre admixture. This phenomenon was mainly attributed to the fact that the glass fibres were not pre-treated, resulting in insufficient bonding between them and the concrete matrix, creating a new weakness. In addition, although a small amount of glass fibres can slightly enhance the concrete strength by forming a mesh structure to share the load, more weak interfaces and unevenly distributed fibre aggregation phenomena with increasing fibre dosage and length increase the porosity within the concrete, thus weakening its compressive properties.

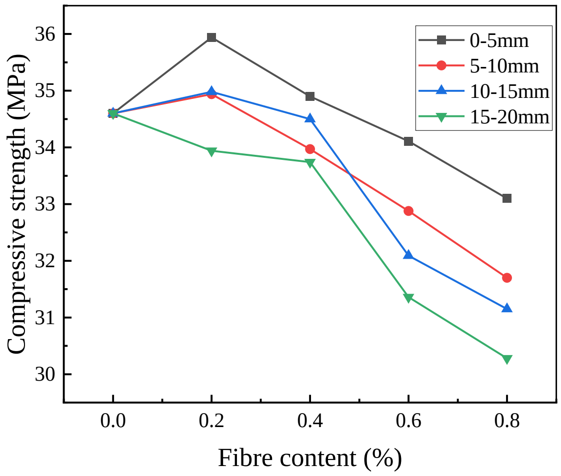


Figure 6. Compressive strength of concrete

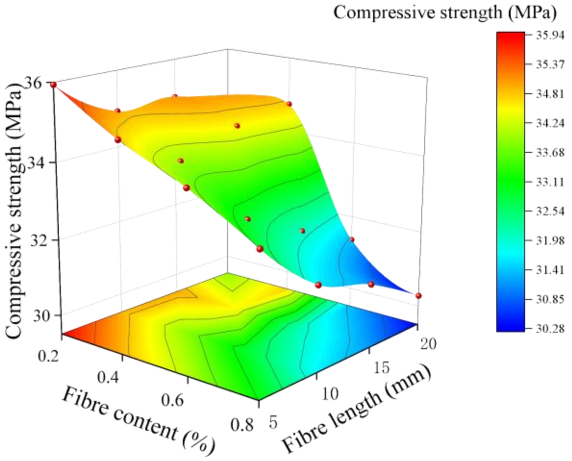


Figure 7. Analysis of factors affecting compressive strength

Figure 7 provides an in-depth analysis of the factors influencing the compressive strength of glass fibre concrete. It is evident from the figure that when the length of the glass fibres is fixed, the compressive strength of the concrete exhibits a consistent decreasing trend as the fibre admixture increases. However, when the admixture of glass fibres is kept constant, the change in compressive strength does not follow an obvious pattern and shows a certain degree of volatility. A comprehensive analysis of these data leads us to conclude that fibre admixture is a more significant factor affecting the compressive strength of concrete.

3.4. Splitting tensile strength

Figure 8 demonstrates the experimental results of splitting tensile strength of glass fibre concrete, revealing the effect of fibre admixture and length on the properties of concrete. As can be seen from the data in the figure, the splitting tensile strength of plain concrete was 3.54 MPa. In group Ga, the splitting tensile strength did not show any significant change after incorporating different proportions of glass fibres. In contrast, the split tensile strength of the Gb group was higher than that of the plain concrete at all dosages, with an increase ranging from 1.98% to 4.8%. the split tensile strength of the Gc group continued to increase with the increase in fibre dosage, with an increase ranging from 3.95% to 9.6%. the Gd group also exhibited higher split tensile strength than that of the plain concrete at all dosages, with an increase ranging from 5.08% to 10.73%. 10.73%. A comprehensive analysis of these results shows that the addition of glass fibres is generally beneficial in improving the splitting tensile strength of concrete, showing an increasing trend, which is consistent with the findings of Ali B et al. [25]. The glass fibres themselves have very high tensile strength, and when the concrete is subjected to large loads, the microcracks generated internally can be effectively controlled by the bridging effect of the fibres, thus inhibiting the crack extension. However, when short fibres were incorporated, the enhancement of split tensile strength was not obvious. This may be because the short fibres contain more impurities in the recycling process, as well as the short length of the fibres. It is difficult to form an effective lap in the cracks. In addition, when the fibre doping reaches a certain level, the splitting tensile strength may decrease. This is mainly because excessive fibre admixture will lead to increased agglomeration and the formation of more voids in the concrete. This adversely affects the splitting tensile properties and ultimately leads to a decrease in strength.

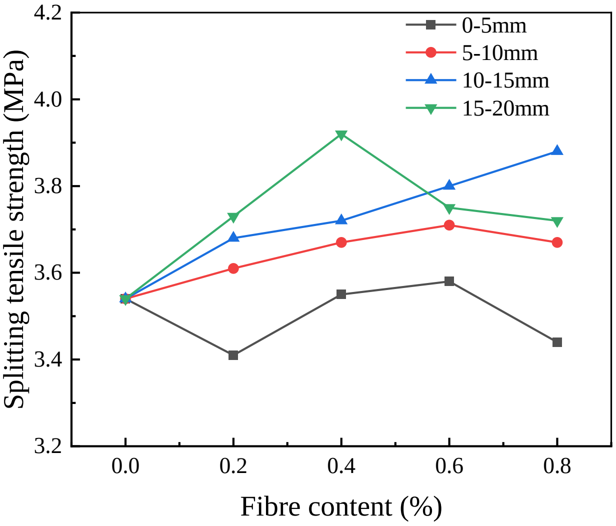


Figure 8. Concrete splitting tensile strength

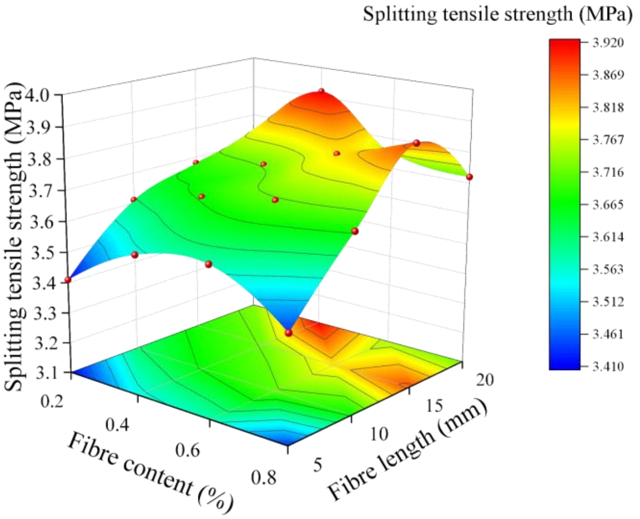


Figure 9. Analysis of factors affecting split tensile strength

Figure 9 provides an exhaustive analysis of the factors influencing the splitting tensile strength, revealing a complex surface map. Four prominent regions can be identified in the figure, which corresponds to the regions of extreme values of split tensile strength for different glass fibre lengths and dosages. Specifically, these regions include those with lengths of 0-5 mm and doping levels of 0.2% and 0.8%, as well as those with lengths of 15 mm and doping levels of 0.8%, and those with lengths of 20 mm and doping levels of 0.4%. They represent the regions of minimum and maximum values of split tensile strength, respectively. From the overall trend, when the glass fibre doping is kept constant, the splitting tensile strength shows an increasing trend with the increase in fibre length. However, when the fibre length is fixed, the splitting tensile strength does not show a clear pattern of change. This suggests that the length of glass fibres is a more critical influence when considering the split tensile strength.

3.5. Tension-to-compression strength ratio

The tensile-compression ratio of concrete is an important mechanical property index, which is determined by comparing the splitting tensile strength of concrete with its compressive strength. This ratio profoundly reflects the brittle characteristics of the concrete material and is essential for assessing and understanding the mechanical behaviour of concrete. When the tensile-to-compressive ratio is high, this indicates that the concrete has a lower brittleness as well as a higher toughness. It means that the material is more likely to undergo plastic deformation rather than sudden fracture when stressed. On the contrary, when the tensile-to-compression ratio is low, the concrete is more brittle and less ductile, and the material is more likely to break by fracture when stressed. Figure 10 shows the tension-compression ratio data for different types of concrete specimens, providing a visual benchmark for comparison. These data allow the performance of various types of concrete to be evaluated, thus providing a scientific basis for material selection and engineering design. Concretes with high tensile-to-compression ratios are particularly favoured in structural design because they provide better seismic performance and greater structural safety.

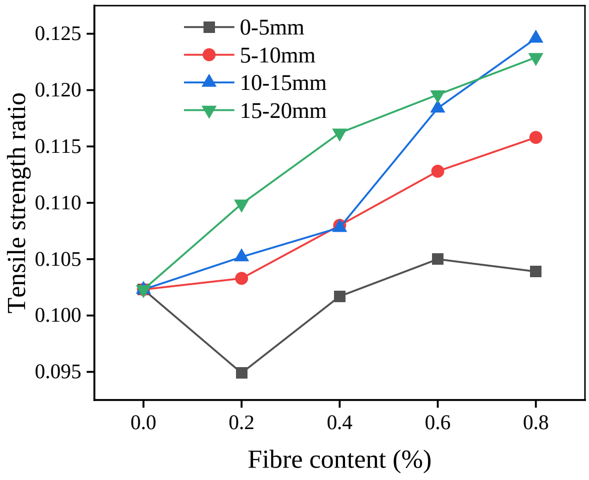


Figure 10. Concrete tension/compression ratio

(a) concrete (b) fibre concrete

Figure 11. Concrete damage patterns

Figure 10 reveals the effect of incorporating glass fibres of different lengths on the concrete tensile ratio. The observed results show that when short glass fibres of 0-5 mm are incorporated, the tensile compression ratio undergoes a process of first decreasing and then increasing. Specifically, the maximum decrease in the tensile compression ratio was 7.23% while the maximum increase was 2.64%. This indicates that the doping of short glass fibres does not have a significant effect on the tensile ratio. However, when long glass fibres ranging from 5-20 mm were incorporated, the tensile ratio increased steadily with the increase in fibre incorporation, with the enhancement ranging from 0.98 to 21.8%. This trend indicates that, overall, the incorporation of glass fibres increased the splitting tensile strength of the concrete and exceeded the compressive strength, thus significantly improving the toughness of the concrete. Figure 11 demonstrates a comparison of the morphology of plain concrete and glass fibre concrete during splitting tensile damage. The plain concrete shows almost no significant change at the beginning of loading, but as the load increases, the specimen quickly cracks and eventually splits into two halves, showing typical brittle damage characteristics. In contrast, fibre concrete only formed small cracks during loading, and the surface of the specimen was partially dislodged at the time of damage, and the sound was more subdued. The overall integrity of the specimens remained good, indicating that the addition of glass fibres significantly enhanced the tensile toughness of the concrete. In addition, with the increase of ordinary glass fibre admixture, the sound of concrete damage became lower, the cracks became smaller, and the expansion speed was also slowed down. These phenomena further confirm that the incorporation of glass fibres can effectively improve the brittleness of concrete and enhance its toughness, thus improving the durability and reliability of the material.

3.6. Flexural strength

Figure 12 shows the results of the flexural strength tests of glass fibre concrete, providing insight into the effects of the different types of glass fibres. As can be seen from the data in the figure, the flexural strength of the plain concrete is 4.52 MPa. The Ga group does not show a significant increase in its flexural strength due to the use of short fibres, with the highest value of 4.79 MPa. In contrast, the Gb group shows a more pronounced increase in its flexural strength than the Ga group, with increases of 0.24 MPa, 0.47 MPa, 0.49 MPa and 0.43 MPa.The increase in flexural strength of the Gc group ranged from 0.37 MPa to 0.61 MPa. The Gd group, as a representative of long fibres, showed the most significant increase in flexural strength up to 5.59 MPa. In the case of 0-5 mm short glass fibres, the flexural strength showed a decreasing and then increasing trend with the increase in admixture, but the overall change was not significant. This is mainly because the short fibres failed to play an effective bridging role in the concrete, while the impurities contained in the short fibres during the recycling process may have also affected their performance. For other lengths of glass fibres, the admixture was able to enhance the flexural strength of concrete to varying degrees, which is consistent with the findings of Erfan M A et al [26]. This enhancement is mainly because the glass fibres are uniformly distributed in the concrete, forming a three-dimensional network structure. When subjected to loads, these fibres were able to effectively bridge cracks and disperse stresses, reduce stress concentration, and reduce cracking, thus significantly increasing the flexural strength of concrete. As the fibre length increases, the increase in flexural strength of concrete is more significant, which is because longer fibres can play a better bridging role when under load and are more likely to form an effective three-dimensional network structure.

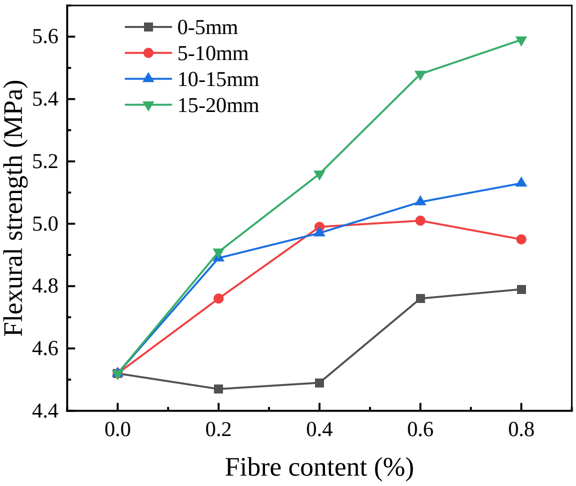


Figure 12. Flexural strength of concrete

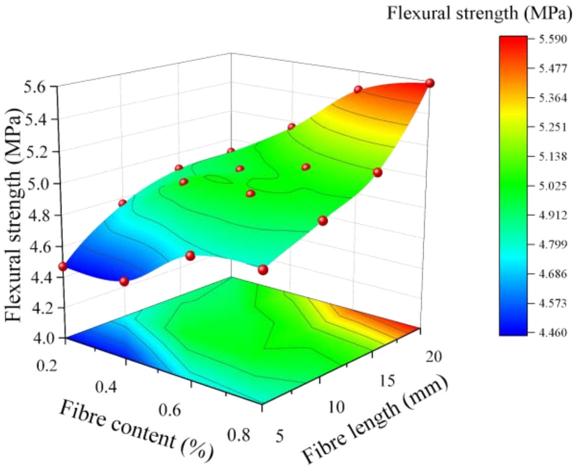


Figure 13. Analysis of factors affecting flexural strength

Figure 13 provides a detailed analysis of the factors affecting the flexural strength of glass fibre concrete, revealing the combined effect of glass fibre admixture and length on flexural strength. The results of the analysis show that at constant fibre admixture, the flexural strength of the concrete increases as the length of the glass fibres increases. Similarly, when the length of the glass fibres is kept constant, the flexural strength is enhanced with an increase in the admixture. Combining these data, we can observe a positive correlation between the flexural strength and the admixture and length of glass fibres. Specifically, the lowest values of flexural strength are usually found in the region of low dosage and short fibres, while higher values are concentrated in the region of high dosage and long fibres. This distribution pattern indicates that both factors, doping and length, have a significant effect on flexural strength.

3.7. Flexural-to-compressive strength ratio

Figure 14 illustrates the flexural compression ratio data for glass fibre concrete which reflects the effect of glass fibre incorporation on the brittleness characteristics of the concrete. It is clear from the figure that the majority of the concrete samples with glass fibre admixture have improved folding pressure ratios. In particular, two samples, Ga-0.2 and Ga-0.4, in the Ga group have lower folding pressure ratios than the plain concrete, with a reduction of 4.75% and 1.45%, respectively. However, the fold-compression ratio of the Gb group increased significantly with the increase of fibre admixture from 4.29% to 19.6%. The fold-compression ratio of the Gc group increased even more significantly from 7.04% to 26.11%. The Gd group shows the most significant increase in the folding pressure ratio, which ranges from 10.8% to 41.35%. For the incorporation of 0-5 mm short glass fibres, the folding pressure ratio decreases and then increases with the increase of fibre incorporation, showing a non-linear trend. For other lengths of glass fibres, the folding pressure ratio shows a continuously increasing trend with the increase in dosage. Overall, the trend of the folding compression ratio is similar to that of the tensile compression ratio, which further confirms that the incorporation of glass fibres helps to reduce the brittleness and enhance the toughness of concrete.

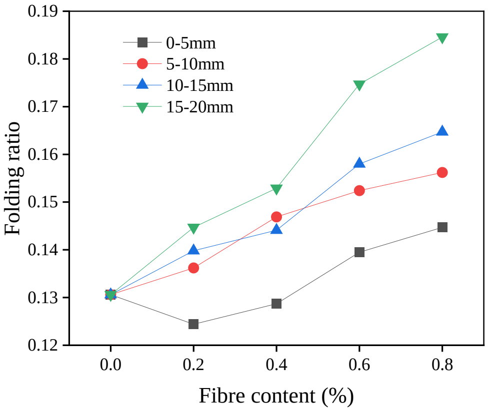


Figure 14. Concrete Folding Ratio

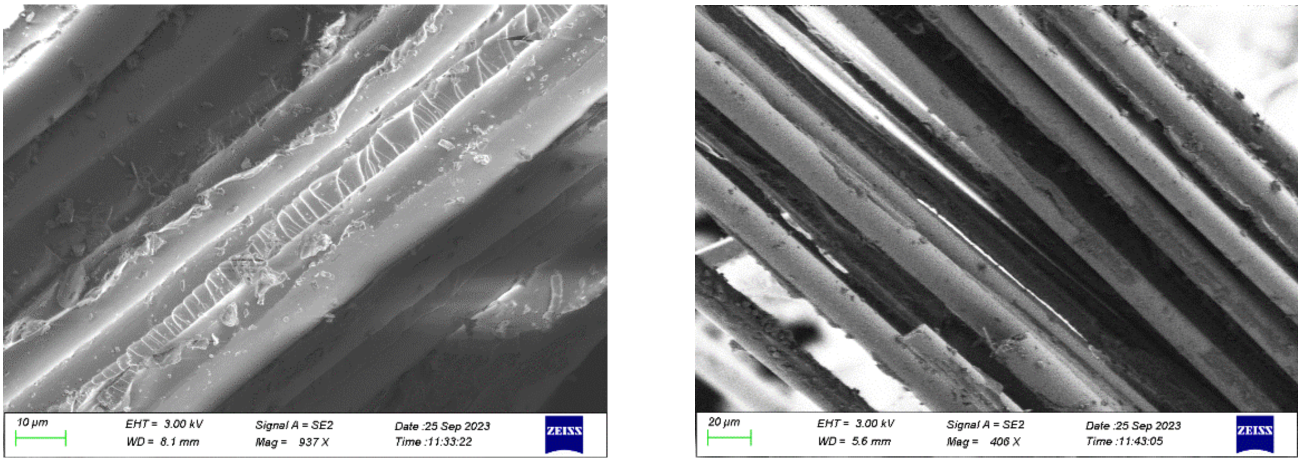
(a) Concrete (b) Glass fibre concrete

Figure 15. Concrete damage patterns

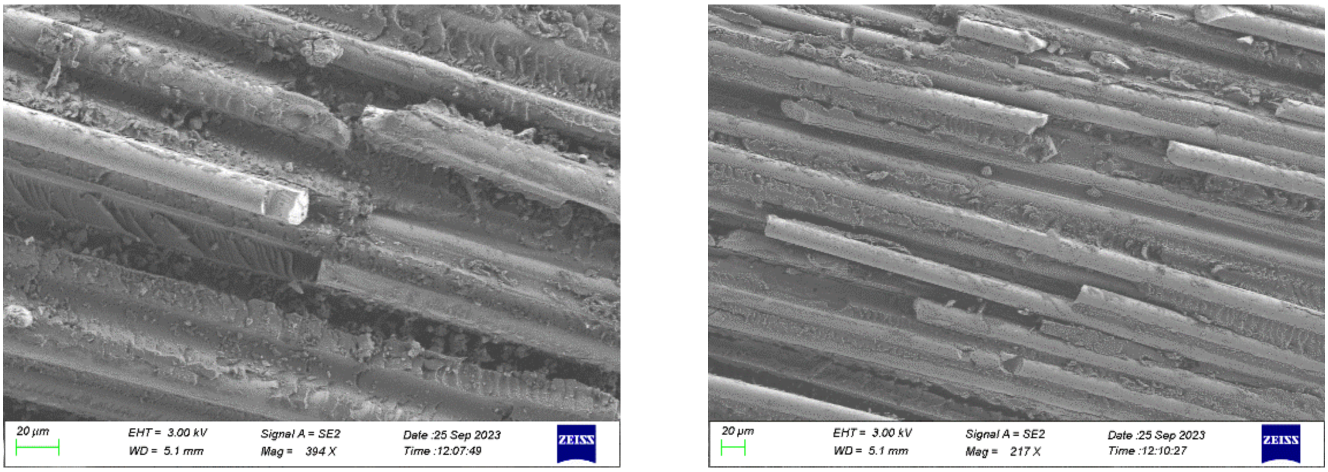
Figure 15 vividly demonstrates the morphological differences between plain concrete and glass fibre concrete during flexural damage. In the flexural test of plain concrete, the specimen usually suddenly emits a clear and sharp fracture sound as the load is gradually increased. This is accompanied by a significant crack spreading rapidly upwards from the bottom of the specimen, as shown in Figure 15a. This process usually occurs very rapidly and eventually results in the specimen splitting in half along the crack. For glass fibre concretes with lower dosages and shorter fibres, the flexural damage characteristics are similar to those of ordinary concretes, with the cracks also spreading rapidly upwards to the top of the specimen and leading to fracture. This phenomenon may be attributed to the fact that the fibre dosage and length are not yet sufficient to fully play its role in toughening and bridging cracks. However, as the glass fibre dosage and length increased, a significant change in the damage pattern of the concrete was observed. In the concrete with high glass fibre admixture, the cracks formed at the bottom of the specimen spread upwards despite the continuous application of external forces. However, after destruction, the specimen still maintains a certain degree of integrity, as shown in Figure 15b. This destructive process is relatively slow and the post-destructive morphology of the specimen shows a more complex crack pattern and a larger destructive surface. It shows that the addition of glass fibres significantly improves the toughness and crack resistance of concrete.

3.8. Microstructural analysis

To deeply investigate the internal structural characteristics of glass fibres recovered from waste wind turbine blades. In this study, four glass fibre samples of different lengths were selected and their microstructures were observed in detail using the electron microscope technique. Through this high-precision imaging technique. We were able to visually observe the microscopic morphology and internal texture of the glass fibres. The test results are shown in Figure 16.



(a)0-5mm (b)5-10mm

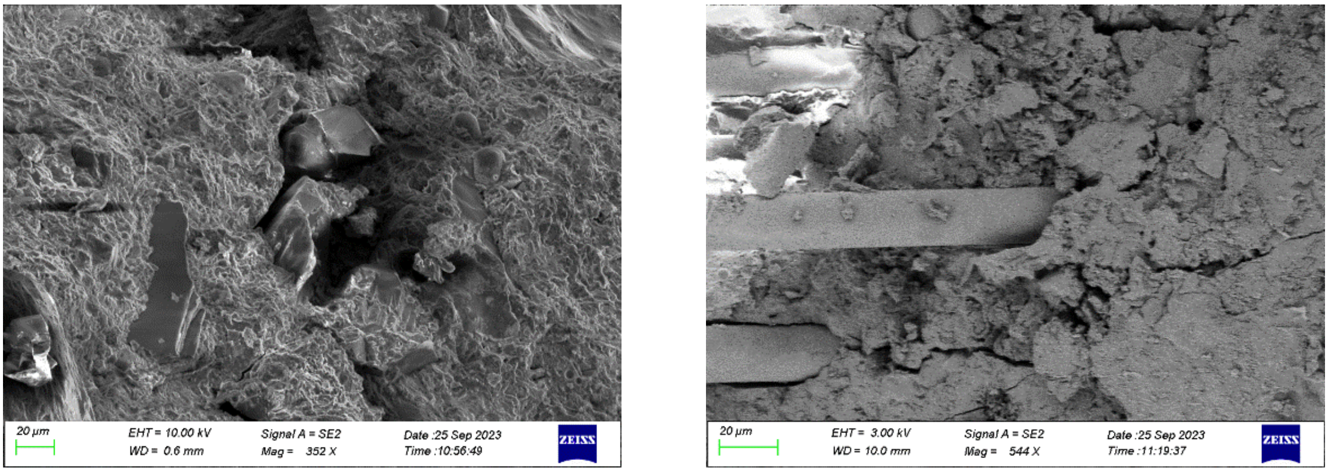


(c)10-15mm (d)15-20mm

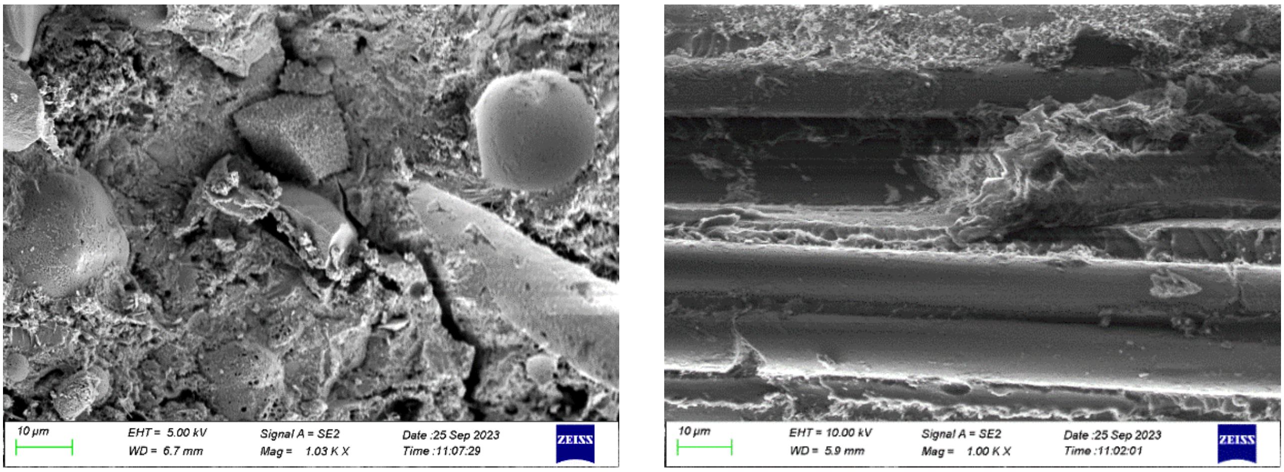
Figure 16. SEM image of glass fibre

Figure 16a-d shows microscopic images of four different lengths of recycled glass fibres from waste wind turbine blades obtained by scanning electron microscopy (SEM). These images reveal the fibre bundle structure of the glass fibres bonded to the epoxy resin matrix. In Figure 16a, we observed that the short glass fibres of 0-5 mm detach easily from the epoxy matrix. This may be because the short fibres are more likely to detach from the matrix during the screening process, resulting in a higher impurity content. Figure 16b reveals the fracture region of the glass fibres where detachment from the resin matrix is more significant. This may have affected the interfacial bonding properties of the fibres. Whereas in Figures 16c and 16d, the longer glass fibres show a tighter bond with the epoxy resin, but due to the increase in fibre length. We can see that some of the fibres break in the middle region. This fracture is especially noticeable in the longest 15-20 mm fibres, which suggests that the mechanical recycling process may have damaged the mechanical properties of the glass fibres to some extent.

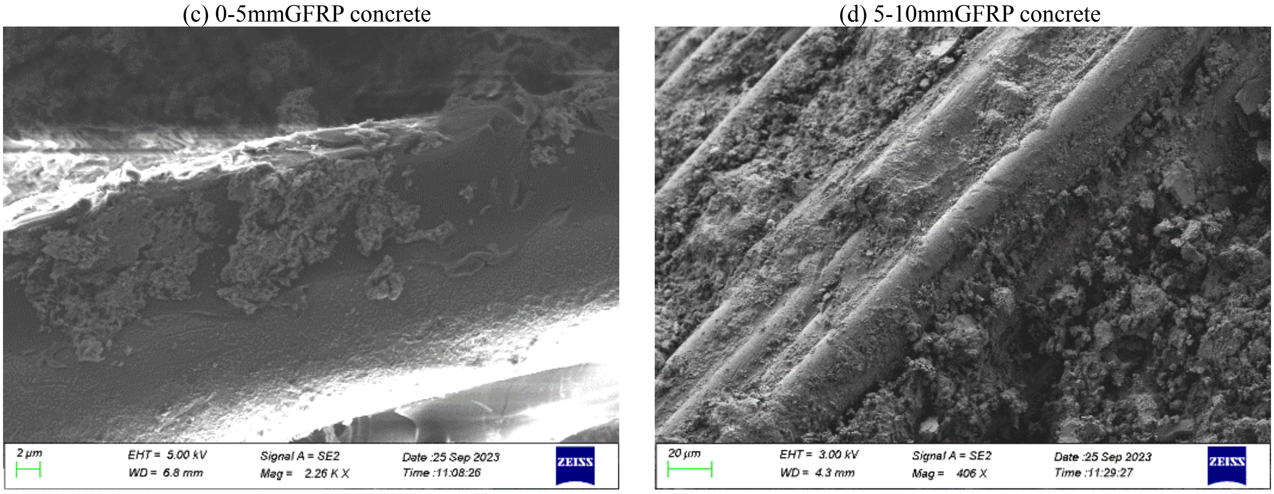
To observe more accurately the microstructure of glass fibre-added concrete. A total of eight specimens were made for this test and the microstructure of glass fibre concrete was tested using an electron microscope. The test results are shown in Figure 17.



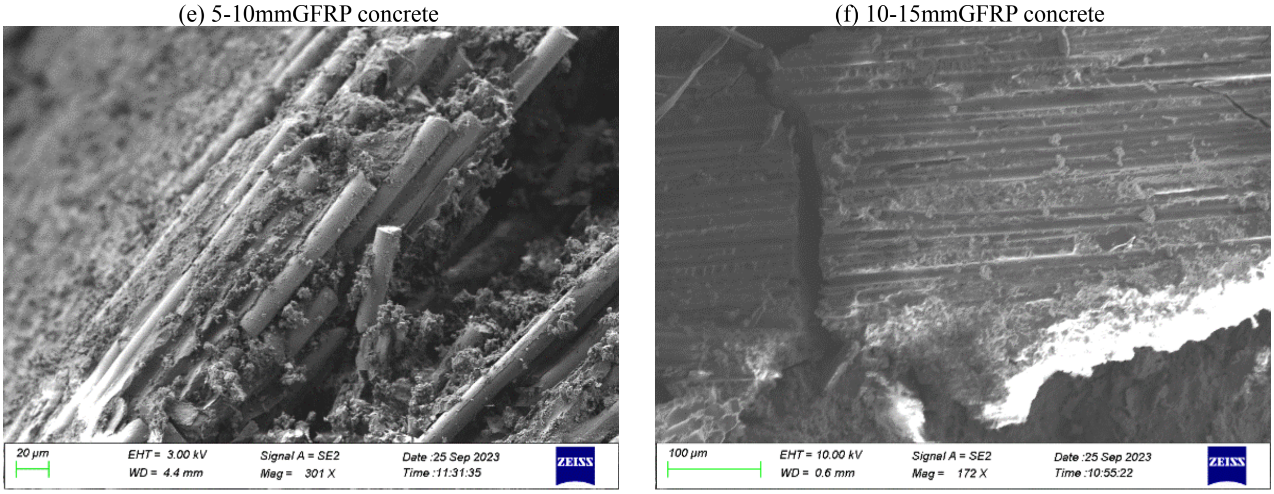
(a) concrete (b) 0-5mmGFRP concrete



(c) 0-5mmGFRP concrete (d) 5-10mmGFRP concrete



(e) 5-10mmGFRP concrete (f) 10-15mmGFRP concrete



(g) 10-15mmGFRP concrete (h) 15-20mmGFRP concrete

Figure 17. SEM image of glass fibre concrete

Figure 17a illustrates the microstructure of plain concrete, revealing the presence of holes and cracks within it. These defects may affect the overall performance of the concrete, especially its strength and durability when subjected to loads. Figures 17b and 17c, on the other hand, show the three-dimensional distribution of glass fibres in the concrete, which act as a constraint to the surrounding paste. However, it can also be seen that significant cracking has occurred at the bond between the glass fibres and the concrete matrix. This cracking is particularly noticeable for the longer fibres. The figure also shows that the fly ash is tightly attached to the cement matrix in a spherical form, and its lubricating effect helps to fill the small voids in the concrete. Further observation of Figures 17d and 17e shows that a large number of hydration products are attached to the surface of the glass fibres. This indicates a good bond between the glass fibres and the hydration products. However, Figures 17f and 17g reveal a loose structure of hydration around the glass fibres. This could be a weak point of the concrete when subjected to stress. Figure 17h particularly demonstrates the fracture of the glass fibre bundles during the mechanical property tests. This suggests that glass fibres play an active role in bridging and stress transfer in concrete, especially in terms of splitting tensile and flexural properties.

4. Conclusions

This study provides insight into the effectiveness of glass fibres recycled from waste wind turbine blades in concrete applications. By incorporating glass fibres of different lengths (0-5mm, 5-10mm, 10-15mm, 15-20mm) and admixture (0.2%, 0.4%, 0.6%, 0.8%) into concrete. The specific effects of these variables on apparent density, slump, compressive strength, split tensile strength and flexural strength of concrete were systematically analysed. An exhaustive analysis of the experimental results combined with electron microscopic observation of the glass fibres and their concrete microstructure. The following specific conclusions were drawn:

The incorporation of glass fibres led to a decrease in the apparent density of the concrete. The decrease in density gradually increased with increasing fibre length and admixture, with a maximum decrease of 55 kg/m³.

The inclusion of 0-5 mm short glass fibres resulted in a slight increase in slump with an increase in admixture. However, overall the addition of glass fibres decreases the slump of concrete. The most significant slump reduction was observed in the Gd-0.8 group with a reduction of 64.3%.

In terms of compressive strength, glass fibre incorporation showed an overall decreasing trend. In particular, the compressive strength decreased by 4.32 MPa with the increase in dosage and length. However, the compressive strength increased by only 1.34 MPa when a small amount of short fibres was doped.

Split tensile strength showed a tendency to increase and then decrease, with little change in the split tensile strength of the Ga group. The split tensile strength of the Gb group was generally higher than that of plain concrete. The increase ranged from 1.98% to 4.8%. The Gc group showed a continuous increase with the increase in fibre dosage, which ranged from 3.95% to 9.6%. The increase in the Gd group was more significant, which ranged from 5.08% to 10.73%. The Gd group showed a more significant increase, which ranged from 5.08% to 10.73%.

Flexural strength showed an overall increasing trend. The Ga group, as a short fibre group, showed a less significant increase in flexural strength, reaching a maximum of 4.79 MPa. The Gb group showed a significant increase in flexural strength relative to the Ga group, with an increase of 0.24 to 0.49 MPa. The Gc group showed an increase in flexural strength in the range of 0.37 to 0.61 MPa. The Gd group, as a long fibre group, showed the most significant increase in flexural strength, reaching a maximum of 5.59 MPa. The tensile compression ratio and folding compression ratio also showed a rising trend. It shows that the incorporation of glass fibres effectively improves the brittleness of concrete and enhances its toughness.

Micro-morphological analysis by electron microscopy reveals that the waste recovered from wind turbine blades is a bundle of fibres combined with glass fibres and epoxy resin. The mechanically recovered glass fibres showed some loss in mechanical properties. Cracks appearing at the bond between the glass fibres and the paste are more pronounced with increasing fibre length. This can adversely affect the mechanical properties of the concrete. The glass fibre bundles in the GFRP concrete showed an overall fracture during the stressing process. This indicates that the glass fibres play an active role in bridging and stress transfer in the concrete.

In summary, the incorporation of glass fibres has a complex effect on the performance of concrete. There are both positive aspects and some potential problems. These findings provide a valuable reference for the application of glass fibres in concrete. They provide guidance for future research directions and material design.

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