

Article

Research on Flexural and Freeze–Thaw Properties of Polypropylene-Fiber-Reinforced Pavement Concrete Containing Waterborne Epoxy

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Abstract: In order to further enhance the reinforcing effectiveness of polypropylene (PP) fibers on pavement concrete, waterborne epoxy (WBE) was introduced in this research and its effect on the flexural properties and freeze–thaw resistance of PP-fiber-reinforced concrete was evaluated. Compressive-strength tests, flexural-strength tests, three-point bending tests, freeze–thaw cycling tests and a scanning electron microscopic observation were carried out to analyze mainly the influence of WBE on the flexural properties and freeze–thaw resistance of PP-fiber-reinforced concrete. WBE contents of 0, 5%, 10%, 15% and 20% by weight of the cement were employed. The experimental results indicated that WBE was beneficial to improving the flexural properties of PP-fiber-reinforced concrete. With increasing content of WBE, the flexural strength and the peak load showed significant increases. Although a slight degradation in the abovementioned flexural parameters was observed when the WBE content was above 15%, the deflection at the peak, the fracture energy and the fracture toughness still showed an upward trend. In addition, the freeze–thaw resistance of PP-fiber-reinforced concrete was improved remarkably with the increasing addition of WBE content, leading to smaller mass loss and higher residual flexural strength. Moreover, microstructural images revealed that with the addition of WBE, the PP fiber/concrete interfacial bonding was effectively improved, and the concrete matrix tended to be denser as well, which provided higher resistance for crack initiation and propagation. In consideration of maximally improving the flexural properties of PP-fiber-reinforced pavement concrete, and while ensuring the compressive strength and meeting the freeze–thaw requirements, it was recommended that the content of WBE in PP-fiber-reinforced concrete should be 15%.



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1. Introduction

Currently, improving the sustainability of construction and pavement projects is still one of the major challenges confronting the construction and infrastructure industry. Cementitious materials, however, as the most widely used construction materials, intrinsically possesses the well-known disadvantages of high brittleness, low tensile strength and low fracture toughness, which weakens its long-term durability and lowers the service life of construction projects, thereby hindering the achievement of sustainability. Concrete pavement is often utilized for structures such as highways, airport runways and bridge decks, which are directly subjected to repeated vehicle loads and environmental actions. Under these repeated loads, concrete pavement will suffer from the gradual deterioration



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of pavement performance, leading to the occurrence of various diseases, such as surface cracks, joint cracking and even fracture diseases during the service period and accordingly a reduced driving comfort and safety [1,2]. To guarantee the performance of concrete pavement and greatly postpone the occurrence of the diseases mentioned above, one of the most effective measures is to improve the flexural properties of the pavement concrete used.

As is well known, the incorporation of various kinds of fibers is deemed as a practical method to largely enhance the engineer properties of cementitious materials, such as flexural strength, ductility, fracture toughness and resistance to fatigue [3,4]. Polypropylene (PP) fibers, as one of the commonly used synthetic fibers, have been widely applied in cementitious materials in order to improve the toughness and deformability of them and restrain the appearance of cracks and the subsequent crack propagation, so as to prolong the service life of engineering projects due to their low cost, high tensile strength, excellent toughness and good corrosion resistance to chemicals [5–7]. Qin et al. indicated that compared to plain concrete, the compressive strength of PP-fiber-reinforced concrete showed a slight increase, and the fracture process was significantly lower [8]. Akça et al. and Das et al. discovered that the flexural tensile strength and splitting tensile strength of concrete were both enhanced through the introduction of PP fibers [9,10]. Investigations by Li et al. revealed that with the addition of 0.9 kg/m^3 of PP fibers, the flexural strength of concrete notably improved; thus, the formation and propagation of microcracks were reduced [11]. Wang et al. performed a series of laboratory tests and found that with the PP fibers, the flexural strength of concrete was remarkably enhanced [12]. Islam and Gupta found that except for the increase in tensile strength, the crack width and propagation of plastic shrinkage cracks could also be reduced by incorporating PP fibers into concrete [13]. In addition, Del Savio et al. investigated the relationship between toughness and PP macrofiber volume and found that the toughness of the concrete was enhanced with increases in the PP macrofiber volume [14]. To obtain these excellent performances of PP-fiber-reinforced concrete (PFRC), the key factor is that the PP fibers should be tightly bonded to their surrounding concrete matrix so as to ensure a consistent load transfer from the concrete matrix to PP fibers [15,16].

However, owing to the hydrophobicity and surface smoothness of PP fibers, the fiber-matrix connection zones may be weaker due to the generation of voids in these zones, which may lead to a reduction in PFRC flexural performance. With an increasing PP fiber content, this reduction can be even greater because of the formation of fiber balling to trap a considerable amount of air. Various methods have been adopted to enhance the interfacial bonding and reduce the porosity between PP fibers and the cementitious matrix; among those methods, it is reported that the addition of polymers can be an effective method [15–18]. Our previous studies also found that the interfacial bonding between PP fibers and their surrounding matrix was improved through the addition of appropriate content of waterborne epoxy (WBE) [19]. Generally, the incorporation of polymers in PFRC is to ensure the toughening effect of PP fibers, so as to effectively reduce cracking in the PFRC and further improve the fracture toughness. Therefore, from the viewpoint of enhancing the actual engineering application, it is essential to study the impact of the polymers on the flexural properties (mainly the fracture properties) of PFRC to obtain an in-depth understanding of polymer-modified PFRC. Presently, the study's focus is mainly on the flexural properties of concrete containing PP fibers, and it is certainly demonstrated that the addition of PP fibers plays an active role in restricting the cracking in concrete [20,21]. However, there is limited research information concerning the impact of polymers on the fracture properties of PFRC, which may impose restrictions on the efficient application of polymers in PFRC.

Moreover, because concrete pavement is directly exposed to the changeable climate environment, the effect of temperature change on the performance of pavement concrete should be attached importance to as well, especially when the concrete pavement is built in an area characterized by extreme low temperatures. Previous studies conducted by other researchers have revealed that the durability properties of cementitious materials

(not limited to the freeze–thaw resistance) were improved through the incorporation of PP fibers. Chen et al. investigated the impact of PP fibers on the frost resistance of airport pavement concrete and discovered that the addition of 0.1% PP fiber could significantly increase the frost resistance grade of the concrete [22]. Nam et al. found that after the freeze–thaw cycles, the mass loss of concrete was greatly reduced by adding 1.5% PP fiber by volume [23]. Richardson et al. pointed out that PP fiber was capable of improving the frost resistance of concrete and reducing the water absorption [24]. Zhang and Li found that the durability properties of concrete composites were remarkably improved with the inclusion of PP fibers, and the freeze–thaw resistance increased when the PP fiber volume percentage was below 0.08% [25]. In addition, studies were also conducted to investigate the influence of additive materials, mainly the supplementary cementitious materials, on the frost resistance of PFRC. Karahan and Atiş investigated the durability of PFRC and found that with the addition of fly ash, the frost resistance of PFRC was significantly improved [26]. Similar research was carried out by Abadel and Alghamdi to investigate fly ash and ground blast furnace slag on the freeze–thaw resistance of geopolymer mortar and found that the two additives had positive effects [27]. However, studies about the impact of polymers on the freeze–thaw resistance of PFRC are limited.

The utilization of polymers in PFRC should be a promising practice to improve its performance. Currently, although the influence of different types of polymers on the mechanical strength of PFRC have been reported in the literature, there is little research available on fracture properties and freeze–thaw resistance of PFRC-containing polymers, whereas this knowledge is of significant importance in promoting the rational application of polymers in PFRC. In this research, WBE was employed to modify PFRC as it is a kind of environmentally friendly polymer and has also been proved to be beneficial to improving the mechanical and durability properties of PFRC [19]. Furthermore, the current research regarding the effect of WBE on the fracture properties and freeze–thaw resistance of PFRC is limited. Therefore, the primary purpose of this paper is to investigate the flexural and fracture properties of PFRC containing different levels of WBE and to study the freeze–thaw resistance of this kind of concrete composite as well to obtain a comprehensive understanding of material behavior of PFRC containing WBE. In addition, microstructural analysis was conducted using a scanning electron microscopy (SEM) to explain the enhancement mechanism on the introduction of WBE into the PFRC. The results of this study can provide a reference for the efficient utilization of WBE in PFRC, while laying the foundation for the coupled application of PP fibers and WBE in concrete pavement.

2. Materials and Methods

2.1. Materials

In this study, raw materials involved are listed as follows: (1) ordinary Portland cement 42.5, produced by Yangchun cement Co., Ltd. in Shandong Province, Zhucheng, China. The initial setting time and final setting time are 160 min and 240 min, respectively. Its chemical composition is displayed in Table 1; (2) PP filament fiber produced by Ningxiang building materials Co., Ltd. in Hunan Province, Changsha, China. It has a length of 19 mm, with a diameter of about 50 μm . The density of the PP fiber used in this study is 0.91 g/cm^3 , whereas its tensile strength and elastic modulus are more than 486 MPa and 4.8 GPa, respectively. Figure 1 presents the image of the PP fiber used; (3) waterborne epoxy produced by Dongyang coating Co., Ltd. in Liaoning Province, Shenyang, China. Its primary properties and its matched curing agent are shown in Table 2 (provided by the manufactures); (4) natural river sand with a fineness modulus of 2.7; (5) crushed limestone with a continuous size from 0.5 to 2 cm.

Table 1. Chemical composition of cement (wt%).

Oxides	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	Na ₂ O	K ₂ O	LOI
Cement	58.34	20.87	5.83	3.64	1.06	3.61	1.36	0.94	4.35



Figure 1. Polypropylene fibers.

Table 2. Properties of WBE and its matched hardener.

Items	Exterior	Solid Content (%)	pH	Viscosity (mPa·s)	Epoxy Equivalent (g/eq)
WBE	Milky white	50 ± 3	6–8	1218	192.3
Hardener	Light yellow	50 ± 1	9.5–10.5	6000	-

2.2. Specimen Preparation

To satisfy the requirements of flexural strength and the workability, the mix proportions of PFRCs in this study were designed according to the JTG/T F30-2014 technical guidelines [28]. A total of five types of concrete specimens were fabricated with a constant water cement ratio of 0.4, as present in Table 3. The PP fibers content for all specimens was 0.1% by volume fraction of concrete, and this content was chosen according to JTG/T F30-2014 technical guidelines [28] with an aim to significantly improve the early-age crack-ing resistance of the concrete. Additionally, on the basis of our previous studies, PFRCs containing 0.1% PP fibers by volume of concrete exhibited superior performance in terms of workability and mechanical strength [19]. On the other hand, studies by other researchers also showed that the addition of 0.1% PP fibers by volume of concrete provided the best mechanical and durability properties [24]. Furthermore, five levels of WBE of 0, 5%, 10%, 15% and 20% by weight of cement were added to PFRC to investigate the impact of WBE on its fracture and freeze–thaw properties. It should be mentioned that the content of WBE was in solid content; thus, the water contained in WBE should be considered in the total water.

Table 3. Mixture proportions (unit: kg/m³).

Mixture Type	Cement	PP Fibers	Sand	Coarse Aggregate	Water	WEB		
						Total	Solid	Water
PFRC(control)	400	0.91	690	1170	160	-	-	-
PFRC-E5					140	40	20	20
PFRC-E10					120	80	40	40
PFRC-E15					100	120	60	60
PFRC-E20					80	160	80	80

According to the mixture proportions, concrete specimens were prepared in the following steps. First, cement, PP fibers, and fine and coarse aggregates were blended together in the concrete mixer for 3 min. Then, the mixing water, in which the water-reducing agent was dissolved in advance, was added to the dry mixtures and stirred for another 3 min to ensure that the concrete mixtures evenly distributed. After that, WBE was blended with its matched curing agent and then this epoxy mixture was subsequently added to the concrete mixtures and stirred for 3 min. After the mixing process, the fresh mixtures were immediately poured into plastic molds of different sizes and vibrated on a vibrating

table to obtain a desirable compactness. The concrete specimens were cured at ambient temperature and demolded after 24 h, then cured in the curing room at a temperature of $20 \pm 2^\circ\text{C}$ and a relative humidity of 95% until a specific age. Figure 2 presents the preparation procedures of the concrete specimens.

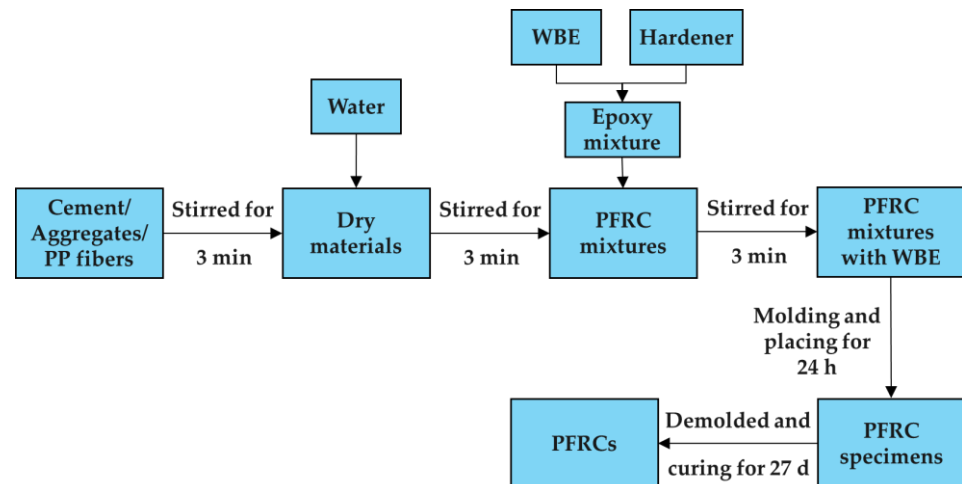


Figure 2. Preparation procedures of concrete specimens.

2.3. Experimental Methods

In this experiment, the mechanical and fracture properties, together with freeze–thaw resistance of PFRC containing different dosages of WBE were investigated. Cube specimens with a side length of 100 mm and beam specimens with a dimension of $100 \times 100 \times 400 \text{ mm}^3$ were employed.

2.3.1. Mechanical Properties

A compressive-strength test, which conformed to the JTG E30-2005 standard test method [29], was conducted on cube specimens after 28 day through the use of a WDW-300 universal testing machine manufactured by Shanghai Hualong Test instrument Co., Ltd., Shanghai, China. Three cube specimens were tested, and the average compressive strength was determined for each type of concrete mixture.

A flexural-strength test was performed on beam specimens in accordance with the JTG E30-2005 standard test method [29], and for each type of concrete, three beam specimens were tested and the average value was recorded.

2.3.2. Fracture Properties

A three-point bending test was conducted according to the JCI-S-002-2003 standard [30] to evaluate the fracture properties of PFRC containing different levels of WBE. The centrally notched beam specimens, with a 30 mm deep sawed notch at the midspan, were used to investigate the fracture properties of concrete at 28 day of curing. The effective span and the ligament length of the specimen were 300 mm and 70 mm, respectively. A WDW-300 universal testing machine was employed, and the load was applied at a displacement rate of 0.02 mm/min. During the test, two linear variable differential transformers (LVDTs) were installed at both sides of the beam to measure the deflections. Meanwhile, at the notch, a clip gauge was attached to the bottom of the beam to measure the crack width. Figure 3 provides the schematic diagram of the test set-up for notched-beam specimens. The fracture energy (G_f) and the critical stress intensity factor (K_{IC}) were determined from the three-point bending tests. Three notched-beam specimens were tested, and the average value was recorded for each type of concrete mixture.

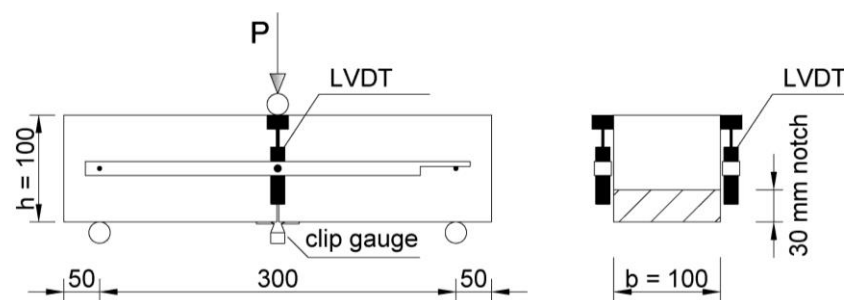


Figure 3. The schematic diagram of the three-point bending test.

2.3.3. Freeze–Thaw Resistance

The freeze–thaw resistance test was conducted on PFRC containing different dosages of WBE according to JTG E30-2005 standard test method [29]. Beam specimens were used, and after 28 day of curing, they were subjected to freeze–thaw cycles. Each freeze–thaw cycle consisted of a 2 h freeze at -18 ± 2 °C and 2 h thaw at 5 ± 2 °C. After 0, 25, 50, 75 and 100 cycles, the mass loss and flexural strength of the concrete specimens were tested. For each type of concrete, three beam specimens were examined and the average value was recorded.

2.3.4. SEM

Microstructural images of the concrete mixtures were obtained using SEM (VEGA II XMU, TESCAN CO., LTD., Brno, Czech Republic). The specimens used for SEM test were obtained from fractured specimens after 28 day. The specimens were immersed in anhydrous ethanol, and before the observation, they were dried and sprayed with gold to make them conductive.

3. Results and Discussion

3.1. Mechanical Properties

3.1.1. Compressive Strength

The compressive strength of PFRC containing different contents of WBE is presented in Figure 4. It is well known that the compressive strength of concrete is strongly linked to the porosity, as well as the quantity of the cement hydrates [31]. According to the results, it can be found that the compressive strength was gradually improved with the increase in WBE content up to 10%. This phenomenon can be attributed to the filling effect of epoxy particles to fill the voids and defects in PFRC and decrease the porosity of PFRC, thus the compressive strength showed an upward trend compared with the control PFRC. This result is in harmony with findings of other researchers indicating that superior compactability of the polymer-modified concrete was achieved to obtain a denser microstructure and, accordingly, a higher compressive strength compared to plain concrete, as the “ball bearing” effect of polymer particles enhances the workability of polymer-modified concrete [32,33]. In addition, WBE may act as a binder to bind the concrete components tightly together due to its high viscosity after polymerization [34]. In general, with a lower quantity of added WBE, the components in PFRC may be bonded together to obtain a denser structure, which improves the compressive strength of PFRC. However, the compressive strength showed a decreased tendency when the content of WBE exceeded 10%. This tendency was mainly because the formation of polymer film is a gradual process and the higher incorporation of polymers may result in the formation of a thicker polymer film to adhere to the surfaces of cement particles, which could depress the diffusion of ions and, accordingly, retard the hydration of cement, thus leading to a reduced quantity of hydration products, whereas the quantity of hydration products is closely related to the compressive strength of concrete [15,35]. On the other hand, with the large addition of WBE content, polymer phases may be regarded as defects in concrete because epoxy film has a lower mechanical capacity compared to concrete [34,36]. Therefore, the compressive

strength of PFRC-E15 and PFRC-E20 exhibited a gradual decrease, leading to a rather lower mean compressive strength of PFRC-E20 by about 2.6% compared with the control PFRC, whereas the compressive strength of PFRC-E15 was still slightly higher compared to the control PFRC.

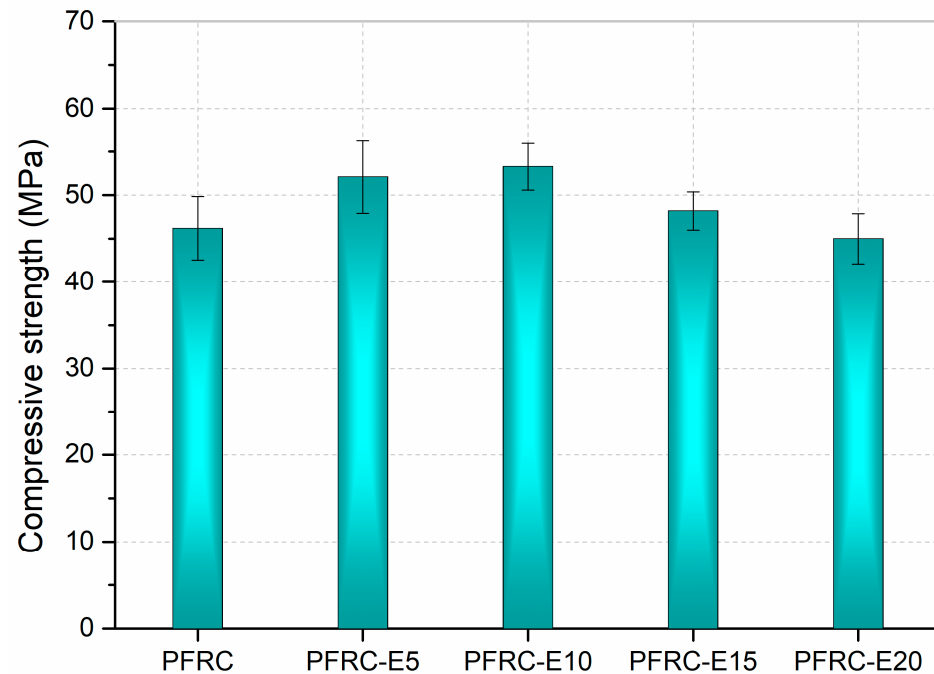


Figure 4. Compressive strength of PFRC with different contents of WBE.

3.1.2. Flexural Strength

The flexural strength of PFRC with different levels of WBE is displayed in Figure 5. It can be observed from the results that with the increased addition of WBE, the flexural strength of PFRC was improved obviously, and this result is in harmony with the investigations of other researchers [36–38]. Compared to the control PFRC, the flexural strength of PFRC with 5% WBE increased by about 16%. This improvement may probably be attributed to the pore-filling effect of epoxy particles, which can effectively fill the internal porosity in concrete and reduce the porosity between PP fibers and their surrounding concrete matrix and thus improve the bond between PP fibers and concrete matrix and, accordingly, enhance the reinforcing effect of PP fibers [37]. Well-bonded discrete fibers can arrest microcracks in concrete; hence, the crack resistance of concrete can be enhanced, and eventually the flexural strength can be improved. On the other hand, as the dosage of WBE continued to increase, PFRC-E15 exhibited the highest flexural strength, with an increase of approximately 40% compared to the control PFRC. This notable increase in flexural strength could have resulted from the formation of a fully developed, coherent polymer film, which could effectively dissipate part of the energy under the flexural loads [34,38]. Additionally, due to the active groups in epoxy chains, the epoxy film and hydrates may connect with each other to form a strong organic–inorganic cross-linking structure to withstand higher flexural loads, thereby postponing the appearance and propagation of cracks [34,38]. However, a slight reduction in flexural strength was observed in PFRC-E20 compared to PFRC-E15. This may be due to the fact that the over-percolation of polymer film may negatively affect the cement hydration and destroy the continuity of hydration products, which is consistent with the findings of other researchers indicating that there is a threshold polymer-to-cement ratio, beyond which the properties of concrete could not be improved [36]. Moreover, with a higher content of WBE in concrete, epoxy phase is likely to mutually reunite and form larger colloidal particles. These solidified particles are

relatively soft compared to plain concrete and may be regarded as localized weak zones in concrete to decrease the strength [34].

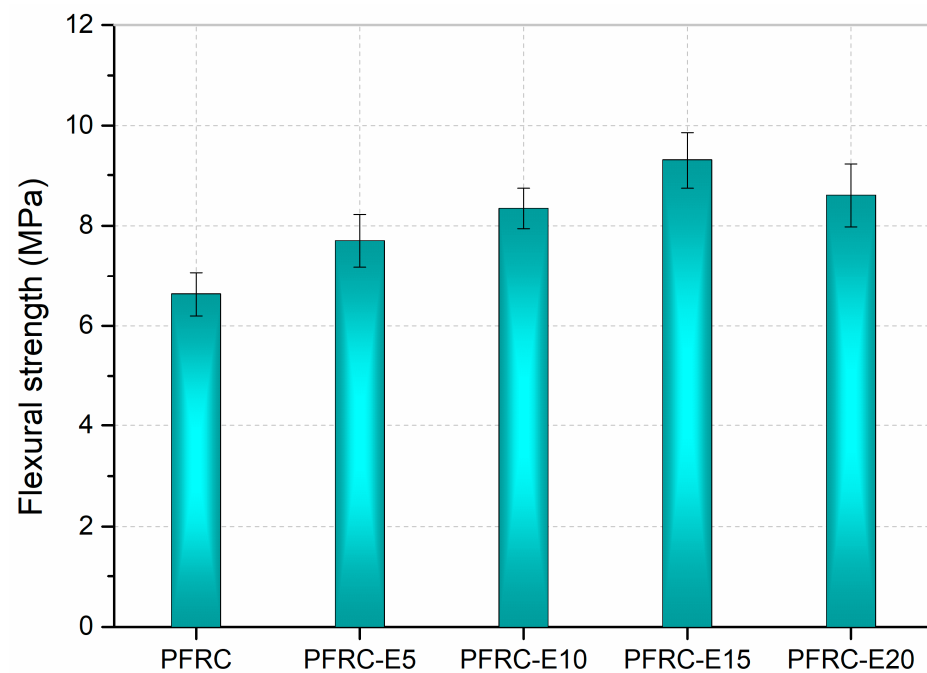


Figure 5. Flexural strength of PFRC with different contents of WBE.

3.1.3. Flexural Strength/Compressive Strength Ratio

To some extent, the ratio of flexural strength to compressive strength is a significant index that represents the toughness of the concrete; the higher the strength ratio, the larger the toughness of the concrete [36,39]. The flexural strength-to-compressive strength ratios of PFRC containing different levels of WBE are shown in Table 4. According to Table 4, the strength ratios of PFRCs increased with an increasing content of WBE until the WBE content exceeded 15%, indicating that the toughness of PFRC-E15 was the highest. When the WBE content was 20%, a subtle reduction was observed.

Table 4. Ratio of flexural strength to compressive strength.

Mixture Type	PFRC	PFRC-E5	PFRC-E10	PFRC-E15	PFRC-E20
Flexural strength/compressive strength	0.143	0.148	0.157	0.193	0.191

3.2. Fracture Properties

3.2.1. Load versus Deflection Response

The load versus deflection curves were obtained through the three-point bending test for PFRC with different dosages of WBE, as shown in Figure 6. These curves were plotted according to a method suggested by other researchers [40,41]. The deflection value was assumed to increase in 0.002 mm increments, and the load data were calculated on the basis of a linear interpolation of the measured data, which is to say that the load value was the mean value at the same deflection value.

It has long been established that the flexural and fracture properties of PFRC are influenced by three parameters, which are the properties of the matrix, the bonding properties of the interfaces between the fibers and their surrounding matrix and the properties of fibers. Among the three parameters, the properties of the matrix and the bonding properties of the interfaces between the fibers and matrix play a significant part [42]. From Figure 6, it can be observed that the load deflection curve of the control PFRC reached the peak load and then dropped suddenly. This brittle behavior likely resulted from the poor adhesion between PP

fibers and their surrounding matrix. On the other hand, as the addition of WBE increased up to a 15% content, the peak loads, and deflections at the peak gradually increased. In contrast, for a WBE content beyond 15%, no further increase in the peak load was observed. Meanwhile, it is noteworthy that the slopes in the pre-peak region were increasingly smaller, and the curves descended relatively gently in the post-peak region with the increase in WBE content, which indicated that the deformability and ductility of PFRC with incorporated WBE were higher compared to PFRC without WBE. In particular, it was evident that the load-carrying capacity of PFRCs in the post-peak region showed an upward trend with the increase in WBE. This is because with the addition of WBE, the total porosity of the PFRC can be reduced, and the adhesion between PP fibers and their surrounding matrix can be enhanced as well through the filling effect of WBE to fill in the voids in concrete. As a result, the strength of matrix and the reinforcing effect of PP fibers can both be enhanced to obtain a higher load-carrying capacity. In addition, the formation of highly viscous and ductile epoxy films can reduce the defects and microcracks in concrete and improve the interfacial bonding properties so as to improve the ability to withstand external loads. Therefore, with the incorporation of WBE, the dense microstructure of the matrix and the improved interfacial bonding between PP fibers and the matrix yield a higher matrix strength and higher debonding resistance of PP fibers than for PFRC without WBE, eventually leading to higher peak load and higher deflection at the peak. Furthermore, with high addition of WBE, the fully developed epoxy film and hydrates may also interpenetrate to form a strong reinforcement so as to withstand higher flexural loads, which is in agreement with the findings of other researchers [34,38]. Ultimately, even if cracking occurs in the concrete matrix during the test, both the PP fibers and the epoxy film across the crack surfaces can still bear the loads and maintain a relatively higher postcracking strength. When the incorporation of WBE reaches 20%, the reduction in the peak load may be because the hydrates lose the continuity, but the deformability of PFRC-E20 was still the largest.

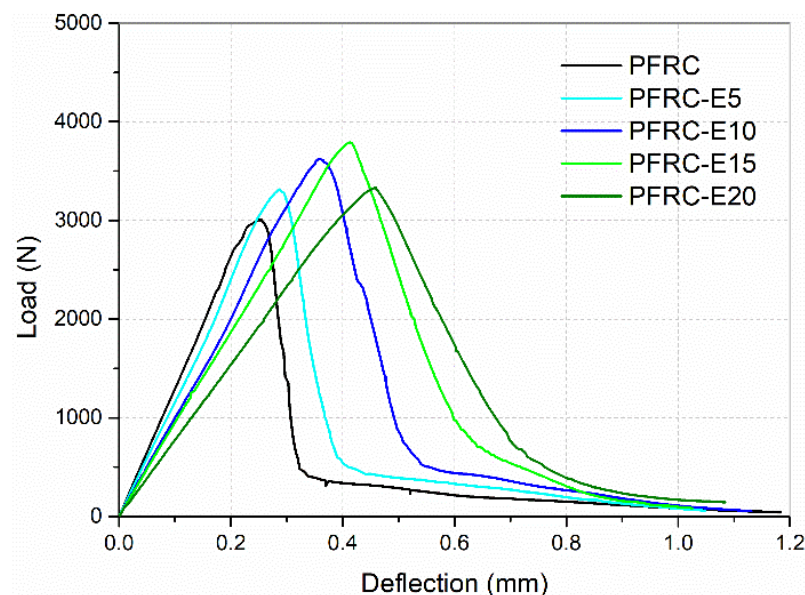


Figure 6. Load versus deflection curves of PFRC with different contents of WBE.

3.2.2. Fracture Energy

Fracture energy represents the energy required to create a crack of unit area in the material; thus, higher fracture energy indicates a higher capacity for cracking resistance. Figure 7 presents the fracture energy of PFRC with different levels of WBE. The fracture energy (G_f) was calculated according to the following equation [43,44]:

$$G_f = \frac{W_0 + mg\delta}{A} \quad (1)$$

where W_0 , m , g , δ and A denote the area under the load versus deflection curve (N·m), the mass of the concrete (kg), the gravity acceleration (N/kg), the deflection at the midspan of the beam (m) and the ligament area (m²), respectively.

According to Equation (1), the fracture energy depends on the area under the load versus deflection curve to a large extent. It can be found from Figure 7 that the inclusion of WBE had a pronounced effect on the fracture energy of PFRC, and increasing the WBE content significantly increased the fracture energy of PFRC until the WBE content reached 15%, beyond which the improvement in fracture energy was subtle. Compared to the control PFRC, the improvements in fracture energy in PFRC-E5, PFRC-E10, PFRC-E15 and PFRC-E20 were 20.5%, 64.3%, 88.9% and 91.5%, respectively. The reason may be that with the addition of WBE, the interfacial bonding between PP fibers and their surrounding matrix can be strongly enhanced because the porosity of the interfaces can be reduced due to the pore-filling effect of WBE; therefore, more energy will be consumed for cracks to propagate and, accordingly, the propagation rate of the cracks will be reduced because fibers may cross the fracture surfaces to carry and transfer the load to the matrix [44]. In addition, the concrete matrix can be strengthened due to the addition of WBE to reduce the porosity in concrete, which also increases the energy consumption for the formation of cracks and crack propagation. Moreover, with a high dosage of WBE, the three-dimensional interpenetrating structure of epoxy film and cement hydrates could act as strong macro-reinforcements, and much more energy will be consumed for crack propagation because this interpenetrating organic–inorganic structure can retard the extension of tiny cracks and decrease the rigidity of concrete. Both the improved bonding between PP fibers and the concrete matrix and the interpenetrating organic–inorganic structure benefit from increasing the energy consumption for crack propagation because cracks in concrete can be bridged with PP fibers and the interpenetrating structure; thus, the coalescence of cracks will be postponed. As a result, PFRC-E20 exhibited the highest fracture energy among the five concretes. As presented in Figure 8, a regression analysis was performed to visually illustrate the relationship between fracture energy (G_f) and WBE content by weight of cement (W_f), and the fitting degree was 0.913 in the proposed relation.

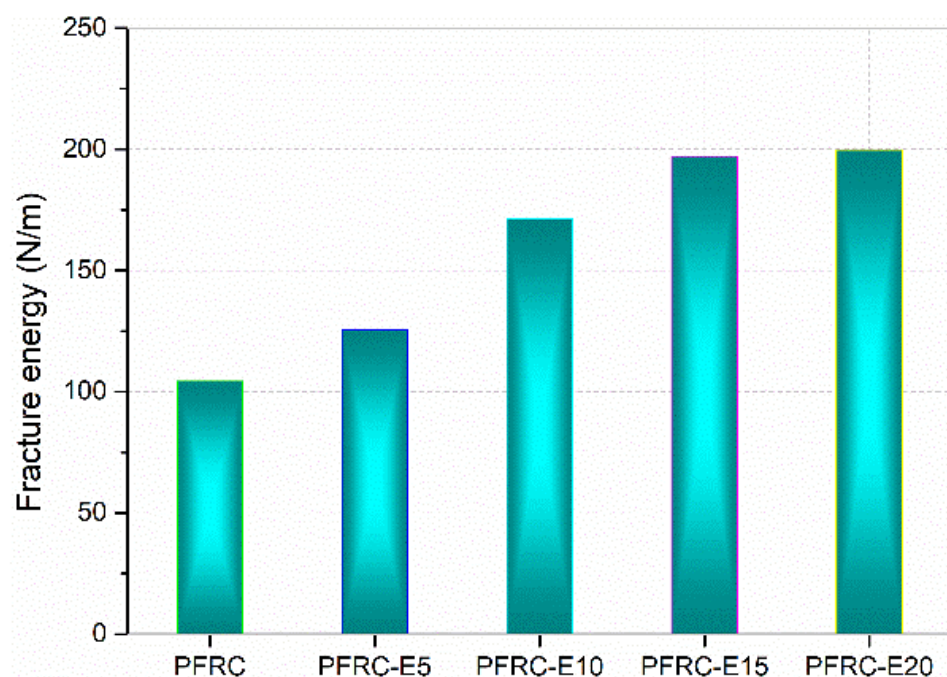


Figure 7. G_f of PFRC with different contents of WBE.

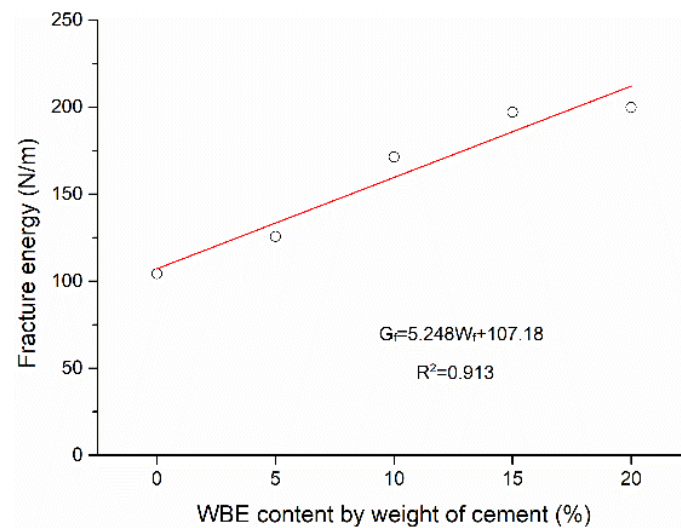


Figure 8. Proposed relation between G_f and W_f .

3.2.3. Fracture Toughness

The fracture toughness is determined using the critical stress intensity factor (K_{IC}) by using the following equation [45,46]:

$$K_{IC} = \frac{PL}{bh^{1.5}} F\left(\frac{a}{h}\right) \quad (2)$$

$$F\left(\frac{a}{h}\right) = \left[2.9\left(\frac{a}{h}\right)^{0.5} - 4.6\left(\frac{a}{h}\right)^{1.5} + 21.8\left(\frac{a}{h}\right)^{2.5} - 37.6\left(\frac{a}{h}\right)^{3.5} + 38.7\left(\frac{a}{h}\right)^{4.5} \right], \quad (3)$$

where P , L , b , h and a stand for the peak load (N), the clear span of the specimen (mm), the width of the specimen (mm), the height of the specimen (mm) and the effective crack length (mm), respectively.

As is well known, the critical stress intensity factor is a material property index at which the crack in the concrete begins to propagate; therefore, if the concrete material has a large critical stress intensity factor, it may present ductile fracture, and its ability to resist brittle fracture will be high [40,44]. The values of the critical stress intensity factors for PFRC with different dosages of WBE are presented in Figure 9, and it can be evidently observed from the results that with an increasing WBE content, the critical stress intensity factor showed an upward tendency compared to PFRC. The critical stress intensity factors of PFRC-E5, PFRC-E10, PFRC-E15 and PFRC-E20 were 22.3%, 43.5%, 62% and 71.7%, respectively, which were higher than that of the control PFRC, indicating that the ductility of PFRC was enhanced through the addition of WBE. This was because the inclusion of PP fibers probably creates some defects in the concrete, mainly in the interfaces of the PP fibers and their surrounding matrix, leading to a lower load-carrying capacity of the matrix, as well as a limited improvement in ductility via the PP fibers. However, with the addition of WBE, these defects may be improved through the physical filling of WBE; therefore, the reinforcing effect of the PP fibers was enhanced, and the ductility of PFRC was improved accordingly. In addition, the ductility of PFRC can be further improved when a high quantity of WBE is incorporated because the polymer film can be interlinked with hydrates to make the concrete much more ductile and to reduce the rigidity of the concrete [34,38]. Compared with the control PFRC, the higher capacity of PFRCs with WBE for resisting the initiation of cracks may be attributed to the dense microstructure of the concrete matrix, the effective toughening effect brought about by PP fibers and the interpenetrating organic-inorganic structure, all of which had the beneficial effect of inhibiting the appearance of cracks. In the present study, the relationship between the critical stress intensity factor and the WBE content was obtained. The relationship proposed in Figure 10 had a fitting degree

of 0.976, showing that there was a strong correlation between the critical stress intensity factor (K_{IC}) and WBE content by weight of cement (W_f).

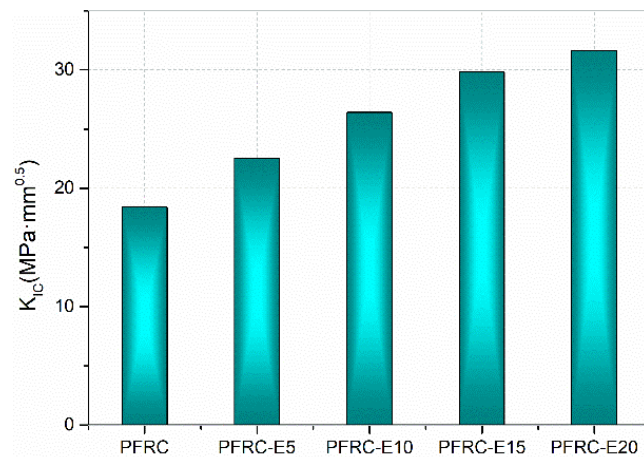


Figure 9. K_{IC} of PFRC with different contents of WBE.

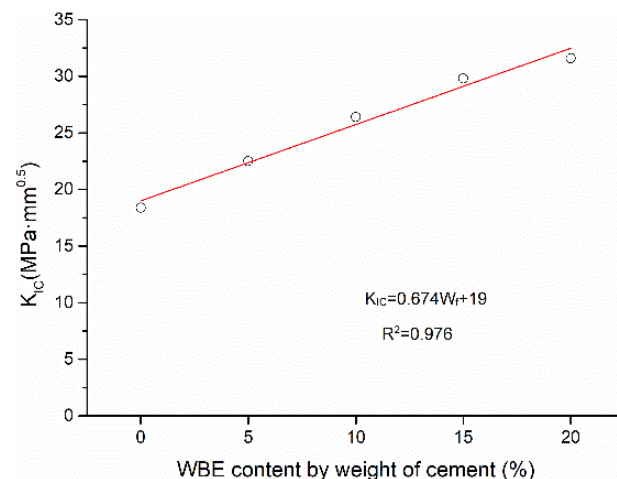


Figure 10. Proposed relation between K_{IC} and W_f .

3.3. Freeze–Thaw Resistance

In order to promote the application of PFRC with WBE in concrete pavement, the freeze–thaw resistance of PFRC with different dosages of WBE was evaluated in terms of mass loss rate and residual flexural strength.

3.3.1. Mass Loss Rate

Figure 11 exhibits the mass loss rate of PFRC with different contents of WBE subjected to 0, 25, 50, 75 and 100 freeze–thaw cycles. As shown in Figure 11, the mass loss rate of all the concrete mixtures exhibited an increase with the increase in freeze–thaw cycles. This is because the repeated freezing and thawing causes the internal water in the concrete to continuously freeze and melt. During this process, static pressure and penetration pressure are created in the surrounding concrete when the volume of water expands due to freezing. As a consequence, cracks may be induced when these pressures finally exceed the tensile strength of the concrete. With increasing freezing and thawing cycles, this damage will be more severe, and the concrete stripping off will arise [45]. Therefore, the freeze–thaw resistance of concrete could be improved by reducing the ingress of water.

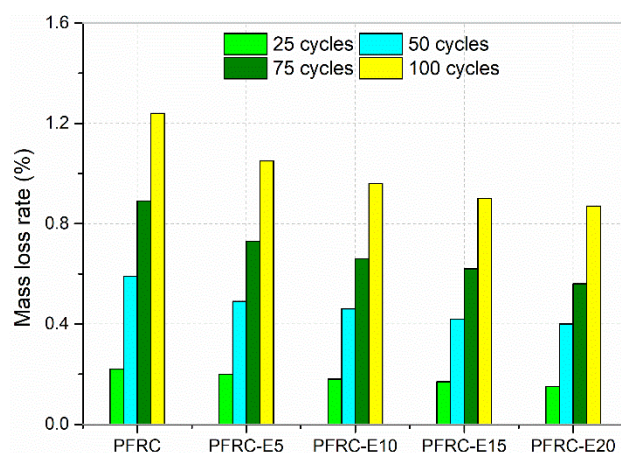


Figure 11. Mass loss rate of PFRC with different contents of WBE.

It can be found that among the five PFRCs, the control PFRC had the largest mass loss rate of approximately 1.2% after 100 cycles. The reason why the control PFRC had the largest mass loss rate may lie in the fact that, with the addition of PP fibers, the defects in PFRC might increase because the adhesion between PP fibers and their surrounding concrete matrix may be weak, leading to a relatively higher porosity in the PP fiber/matrix interfaces. Additionally, the inclusion of PP fibers may negatively affect the workability of concrete and result in a reduction in compactness. Therefore, stripping off of the control PFRC will be larger under the repeated freeze–thaw cycles. After the addition of WBE, the mass loss rate showed a decreased tendency. The mass loss rates of PFRC-E5, PFRC-E10, PFRC-E15 and PFRC-E20 after 100 cycles were 15.3%, 22.6%, 27.4% and 29.8% lower than that of the control PFRC, respectively. This phenomenon may be attributed to the fact that epoxy particles are capable of filling the voids and blocking the capillaries in PFRC to lower the porosity of PFRC and make PFRC denser; thus, water ingress can be reduced to improve the freeze–thaw resistance [26]. In addition, as the adhesion between PP fibers and their surrounding concrete matrix is improved, the PP fibers can assist in reducing the freeze–thaw damage because a large amount of discrete fibers may intertwine together to maintain the integrity of the concrete and effectively restrain cracking, bridging the cracks so as to reduce the peeling off of the concrete. Furthermore, due to the low modulus of the PP fibers compared to the surrounding concrete, PP fibers may yield before concrete under the hydrostatic pressure, thereby relieving the pressure and improving the freeze–thaw resistance [26]. Furthermore, the workability of PFRC can be improved through the “ball-bearing” effect of WBE to increase the compactness of PFRC, which also contributes to its freeze–thaw resistance [33,46]. On the other side, the impermeability and integrity of PFRC can be strengthened through the formation of the continuously interpenetrating structure of epoxy film and hydrates; therefore, the damage to freeze–thaw cycles can be reduced as well.

3.3.2. Residual Flexural Strength

The residual flexural strength of PFRC with different contents of WBE after 0, 25, 50, 75 and 100 freeze–thaw cycles is exhibited in Figure 12, and the residual flexural strength is determined as the ratio of flexural strength subjected to the specific freeze–thaw cycles to the flexural strength without freeze–thaw cycles.

As shown in Figure 12, with the increasing freeze–thaw cycles, the residual flexural strength of all the PFRCs exhibited a gradual decline. This is because that with the increase in freeze–thaw cycles, the damage in PFRC mixtures will be much more severe since more cracks will be formed, the width of cracks will be bigger and the stripping off of the concrete will be larger, leading to a loosely distributed microstructure and a smaller load bearing area to withstand lower flexural loads. For the control PFRC, the flexural strength was reduced by about 37.8% after 100 cycles, whereas for PFRCs with 5%, 10%,

15% and 20% WBE, the reductions in flexural strength were 32.5%, 29.2%, 26.1% and 24.9%, respectively. It can be obviously observed that the control PFRC had the lowest residual flexural strength after 100 freeze–thaw cycles, and this phenomenon is probably due to the relatively higher porosity in the PP fiber/matrix interfaces. Furthermore, under the freeze–thaw actions, damages may initiate from these interfaces. Moreover, the repeated freeze–thaw cycles may further impair the bonding in these interfaces, leading to rather higher porosity in these interfaces and even the debonding of PP fibers; therefore, the flexural strength of the control PFRC showed a notable decline. On the other hand, the incorporation of WBE can fill the pores in PFRC to make it denser, so as to improve the adhesion between PP fibers and matrix, inhibiting the ingress of water as well, thereby improving the freeze–thaw resistance of PFRC and increasing the residual flexural strength compared to the control PFRC. Furthermore, the interpenetrating structure of epoxy film and hydrates can significantly improve the flexural strength of PFRC and hold the integrity of PFRC under the action of freeze–thaw cycles, because the epoxy film can hinder the penetration of water.

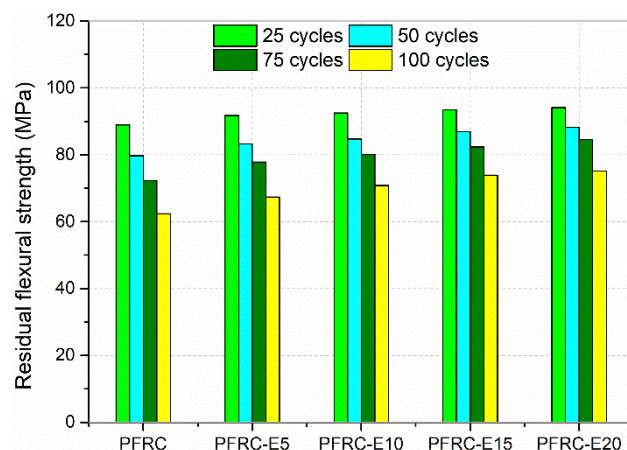


Figure 12. Residual flexural strength of PFRC with different contents of WBE.

3.4. SEM Analysis

According to the results of above experiments, it could be concluded that the addition of WBE improved the mechanical properties and freeze–thaw resistance of PFRC and the improvement was more significant with the increase in WBE content. However, the incorporation of 20% WBE decreased the compressive strength and the flexural property of PFRC. Therefore, from the viewpoint of engineering application, PFRC with 15% WBE was suggested as the optimum content, which synthetically considered the requirements of strength, toughness and durability. Figures 13 and 14 present the SEM images of the control PFRC and PFRC-E15 to reveal the reinforcing mechanism of the WBE in PFRC.

It can be seen from Figure 13a that PP fibers were scattered in the fractured surface of the control PFRC. In addition, there were some holes where PP fibers were pulled out under the external loads. Figure 13b,c show the intact surface of a PP fiber that remained smooth after fracture and the loose bonding between the PP fiber and the matrix. The three images indicated that the adhesion between PP fibers and the surrounding matrix was relatively weak, and some fibers were easily pulled out from the matrix under the loads; therefore, the bridging effect provided by PP fibers was not effective. This was consistent with our previous study in which the interfacial bonding between PP fibers and their surrounding matrix was relatively weak [19]. Meanwhile, Figure 13d presents the microstructural image of a concrete matrix in the control PFRC. It can be seen from Figure 13d that the cement hydrates, such as calcium silicate hydrate, calcium hydroxide and ettringite, were distributed in the concrete, while the structure was not very dense and there were some pores and cracks in the concrete. Therefore, the formation of the cracks

and crack propagation may easily occur in the control PFRC due to the poor adhesion between PP fibers/concrete matrix and the less-dense microstructure of the matrix.

Figure 14 displays the microstructural images of PFRC-E15. In Figure 14a,b, it can be observed that the PP fibers were distorted, and some scratch marks were found on their surfaces. This degradation of PP fibers, which could have resulted from the friction during the loading process, confirmed the improved bonding between PP fibers and their surrounding matrix. In addition, some materials, probably hydrates and epoxy films still attached to the surfaces of PP fibers after fracture, which might be attributed to the cement–epoxy reaction to form the interpenetrating organic–inorganic structure [34], can also be observed in Figure 14a,c. The existence of the attachments also indicated the improved bonding between PP fibers and their surrounding matrix. This strong bonding could be attributed to the physical effect of WBE, filling the holes and cracks in concrete, and the chemical effect of WBE, absorbing calcium ions to form strong cross-linking structures [34]. With higher interfacial bonding, better flexural properties for PFRC can be achieved. The reason may be that when the fibers are tightly bonded with the surrounding concrete matrix, fibers can consume partial energy owing to the increased pull-out resistance; therefore, more energy will be required for the formation of cracks and the subsequent crack propagation. Moreover, Figure 14d presents the microstructural image of the matrix, from which it can be seen that the microstructure was dense, and the epoxy film wrapped on the surfaces of hydrates and bonded tightly with the hydrates. Therefore, additional energy will be needed for crack initiation and propagation in this matrix, because epoxy film has the larger deformability in contrast to concrete. This phenomenon also implied that with the combination of concrete and WBE as the matrix, PFRC had the superior performance compared to the only concrete as the matrix.

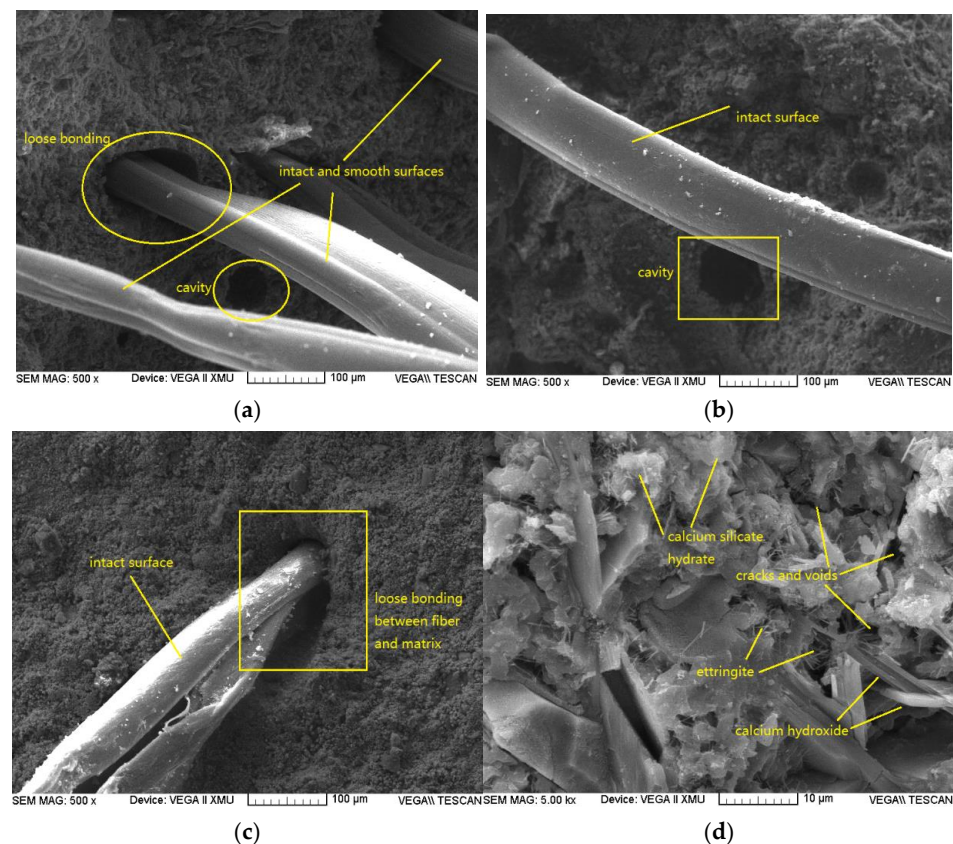


Figure 13. Microstructural images of PFRC by SEM. (a–c) PP fiber surfaces and interfacial bonding between PP fibers and the matrix, (d) the matrix.

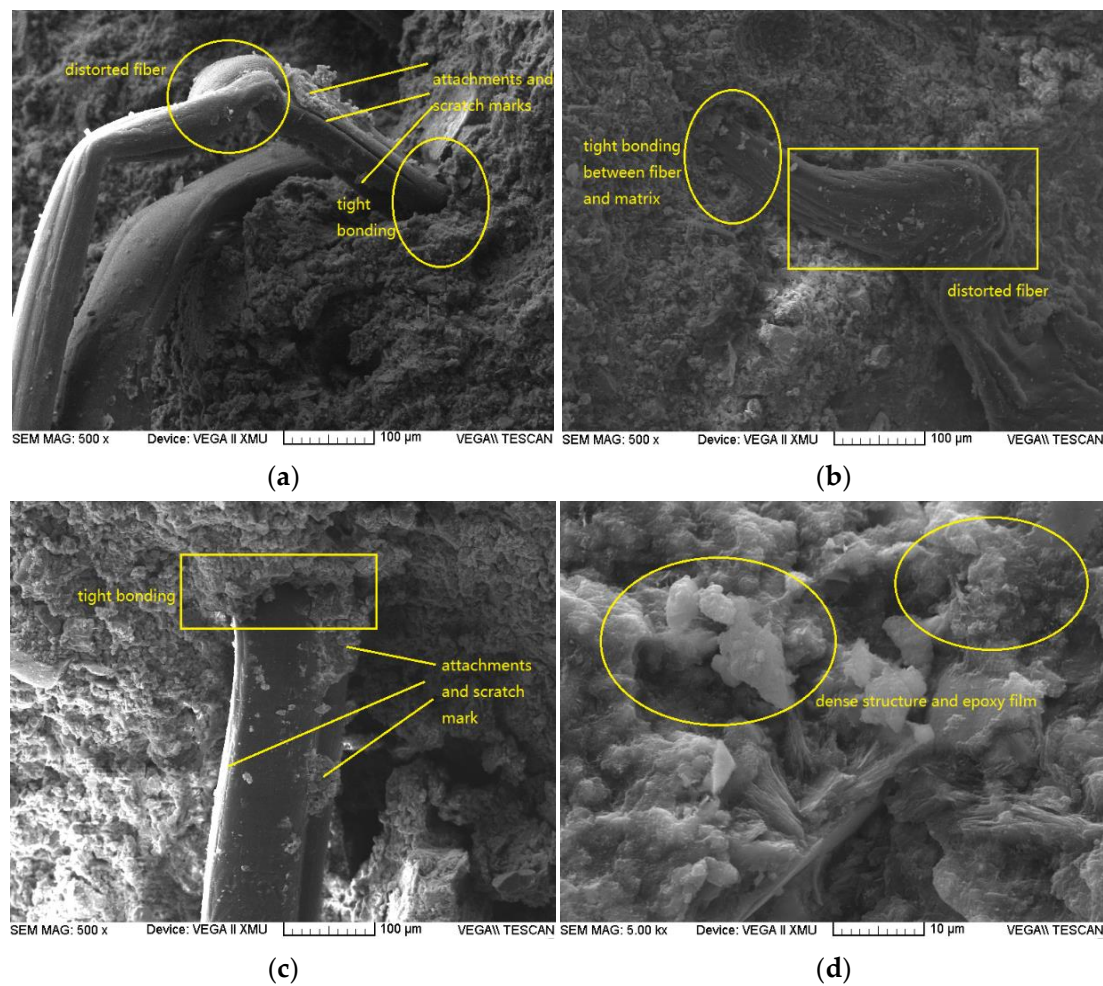


Figure 14. Microstructural images of PFRC-E15 by SEM. (a–c) PP fiber surfaces and interfacial bonding between PP fibers and the matrix, (d) the matrix.

4. Cost Analysis

Compared to ordinary concrete, the material cost of PFRCs has increased due to the existence of admixtures such as PP fibers and WBE. Therefore, the material cost per cubic meter of PFRC can be determined by:

$$C = C_0 + C_{pp} \times I_{pp} + C_{WBE} \times I_{WBE}, \quad (4)$$

where C and C_0 stand for the cost of PFRCs and the ordinary concrete per cubic meter, respectively; C_{pp} and C_{WBE} stand for the cost of PP fibers and WBE per unit kg, respectively; and I_{pp} and I_{WBE} stand for the content of PP fibers and WBE in PFRCs (kg), respectively.

According to the market survey, the price of PP fibers and WBE is 8.2 CNY/kg and 48 CNY/kg, respectively. Thus, compared to ordinary concrete, the material-cost increases per cubic meter for PFRC, PFRC-E5, PFRC-E10, PFRC-E15 and PFRC-E20 are CNY 7, CNY 1927, CNY 3847, CNY 5767 and CNY 7687, respectively. Considering that the thickness of the concrete slab is often around 25 cm, the material-cost increases per square meter for those five concretes are approximately CNY 1.8, CNY 482, CNY 962, CNY 1442 and CNY 1922, respectively. Although the material cost increases, it cannot reflect the total cost throughout the pavement life because the proportion of the construction, the management and the maintenance costs account for the larger part of the total cost. In addition, test results have indicated that the mechanical and durability properties were significantly enhanced by incorporating WBE; therefore, it can be reasonably expected that the service

life of PFRCs can be extended, and the total cost can be lowered, which still needs to be carefully evaluated in a future study.

5. Conclusions and Future Work

According to the results obtained in this study, the following conclusions can be drawn:

1. The compressive strength of PFRC exhibited a steady increase with the content of WBE, reaching up to 10%, and then decreased gradually. The addition of 20% WBE even resulted in an inferior compressive strength compared to the control PFRC.
2. With an increasing content of WBE, the flexural strength of PFRC showed significant improvement until the WBE was beyond 15%, at which point a slight reduction in flexural strength was observed.
3. The dosage of WBE had a pronounced effect on the load versus deflection responses of PFRC. The deformability of PFRC was remarkably enhanced as the content of WBE increased, and the largest deformation was achieved in PFRC-E20, whereas the load-carrying capacity of PFRC-E20 decreased. Moreover, as the content of WBE increased, the fracture energy and fracture toughness of PFRC were increasingly improved.
4. The freeze–thaw resistance of PFRCs was notably enhanced through the addition of WBE. With the increasing content of WBE, the mass loss rate decreased, and the residual flexural strength showed a significant increase compared to the control PFRC. When the WBE content exceeded 15%, the improvement in the freeze–thaw resistance slowed down.
5. In practical pavement engineering, it is necessary to maximize the flexural properties of the concrete and ensure the stiffness and the durability of the concrete. Meanwhile, the cost effectiveness should be considered. Therefore, in this research, the WBE content of 15% was recommended.
6. The distorted PP fibers after fracture and the scratch marks on the surfaces of the PP fibers indicated that the bonding between PP fibers and their surrounding concrete matrix was effectively strengthened, and PP fibers effectively consumed part of the energy during the pull-out process. The dense microstructure and the attachments on the PP fiber surfaces also represented a stronger matrix to resist the initiation and propagation of cracks.

The present study mainly investigated the fracture properties and the freeze–thaw resistance of PFRCs. However, the tests were limited to one type of micro-PP fibers, while the combined use of different sizes of PP fibers may have better impact on the characteristics of concrete. In addition, the curing method can affect the polymerization process of polymer-modified concrete as well. Therefore, more experiments should be performed to obtain an in-depth understanding of the characteristics of PFRCs. In this regard, the influence of the combined use of micro-PP fibers and macro-PP fibers on the characteristics of WBE-modified concrete, and the effect of curing method on the characteristics of PFRCs, should be further researched concerning mechanical and durability properties. Furthermore, the anti-impact and fatigue properties of PFRCs should also be studied to better evaluate the performance of PFRCs.

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