coatings

MDPI

Article

Experimental Investigation on Physical Properties of Concrete Containing Polypropylene Fiber and Water-Borne Epoxy for Pavement

Li Wang [1,*], Hongliang Zhang [2], Bendong Zhao [3], Biao Wang [4], Quanman Zhao [1] and Min Sun [1]

[1] School of Transportation Engineering, Shandong Jianzhu University, Jinan 250101, China
[2] School of Highway, Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University, Xi'an 710064, China
[3] CCCC First Highway Consultants Co., Ltd., Xi'an 710000, China
[4] Shaanxi Road and Bridge Group Co., Ltd., Xi'an 710075, China
* Correspondence: wangli20@sdjzu.edu.cn

Abstract: Cement concrete pavement accounts for a large proportion of the road network due to its excellent mechanical strength and durability. However, numerous microcracks are generated due to the high brittleness of concrete, which poses a threat to the service life of concrete pavement. Currently, simultaneous addition of fibers and polymers is a feasible approach to resolving the issues associated with the brittleness of concrete. This study explores the properties of concrete mixtures containing different levels of polypropylene fibers and water-borne epoxy. Additionally, fly ash is also introduced to concrete mixtures. The tests performed include slump, compressive strength, flexural strength, shrinkage, depth of water penetration, and abrasion. The results indicate that water-borne epoxy, at all levels, contributed to improving the weak interfacial bonding between polypropylene fibers and concrete. In addition, the combined incorporation of polypropylene fibers and water-borne epoxy could improve the mechanical and durability properties of concrete, with the combined utilization of 0.1% polypropylene fibers and 10% water-borne epoxy exhibiting the best performance. Moreover, with the incorporation of 10% fly ash into concrete, the mechanical strength and abrasion resistance experienced a slight reduction, while the workability, drying shrinkage resistance, and impermeability were improved. The current findings indicate that the combined utilization of polypropylene fibers and water-borne epoxy at appropriate levels is beneficial for application in pavement; however, in spite of superior drying shrinkage resistance and impermeability, the incorporation of fly ash into concrete pavement should be properly treated according to the actual engineering conditions.

Keywords: concrete; polypropylene fiber; water-borne epoxy; interfacial bonding; microstructure

Citation: Wang, L.; Zhang, H.; Zhao, B.; Wang, B.; Zhao, Q.; Sun, M. Experimental Investigation on Physical Properties of Concrete Containing Polypropylene Fiber and Water-Borne Epoxy for Pavement. *Coatings* **2023**, *13*, 452. https://doi.org/10.3390/coatings13020452

Academic Editor: Matteo Sambucci

Received: 26 January 2023
Revised: 11 February 2023
Accepted: 14 February 2023
Published: 16 February 2023

1. Introduction

Concrete is a blend of cement, aggregate, and water, and owing to the wide availability and low cost of these raw materials, concrete is extensively used in construction and infrastructure projects [1,2]. Cement concrete pavement, as the primary pavement structure apart from conventional asphalt pavement, has characteristics of excellent mechanical strength, high performance, and good durability, which makes it a preferred design choice, particularly when it is subjected to heavy traffic loads [3,4]. However, in spite of a strong compressive strength, concrete has a poor tensile strength and toughness, which makes it vulnerable to cracking [5]. When cracks appear in concrete, they may propagate rapidly under the action of loading and eventually lead to structural damage if no anti-cracking measures are taken. With respect to concrete pavements that are directly exposed to extreme environments, and that suffer from continuous vehicle loads, rapid deterioration will inevitably occur in the presence of cracks, which eventually leads to the loss of serviceability and unsafe driving conditions [4]. In consideration of the easy cracking of concrete, various types of fibers and polymers are extensively applied in concrete, including road concrete, to improve its engineering properties and durability by restricting crack width and crack propagation [4,6–8].

In regards to fibers that are used in concrete, they can be classified into four types: metallic fibers (e.g., steel fibers), inorganic fibers (e.g., glass fibers), synthetic fibers (e.g., aramid fibers) and natural fibers (e.g., sisal fibers). Among these fibers, synthetic fibers, due to their lightness, chemical stability, and ductility, have been widely applied in concrete to improve its mechanical and durability properties through the crack bridging effect. Polypropylene (PP) fibers, as a kind of synthetic fiber with a low modulus, have many advantages such as high tensile strength, good ductility, excellent corrosion resistance, low cost, and abundant availability, which makes them a popular reinforcement fiber in cementitious materials [9]. The properties of PP fiber reinforced cementitious mixtures have been explored by many researchers, and it is reported that the addition of PP fibers can improve the performance of concrete [6]. For example, studies by Bendjillali et al. showed that PP fibers significantly improved the flexural strength of limestone mortars, while an improvement in compressive strength was not evident [10,11]. Yazici et al. indicated that, with the increase in ductility of roller-compacted concrete (RCC) containing PP fibers, the number of fracture impacts and toughness were accordingly improved [12]. Studies also showed that the flexural toughness of concrete with crimped-type PP fibers was enhanced, despite a reduction in the flexural strength, and the optimum fiber content was 2% by volume [13]. Additionally, researchers found that spalling of concrete could be avoided through the incorporation of PP fibers [13,14]. This is because the melting of PP fibers at high temperatures creates many empty channels in the concrete, which facilitates the release of vapor and prevents the occurrence of spalling. Sivakumar et al. also pointed out that the addition of PP fibers could reduce plastic shrinkage of the concrete, and that the use of hybrid fibers was more effective [15].

To better achieve these reinforcing effects of PP fibers in concrete, the interface between the concrete matrix and the PP fibers must be able to transfer load from the matrix to the fibers, which means that a strong interfacial bond between the concrete matrix and the PP fibers should be formed [5,16]. However, due to the hydrophobic nature of PP fibers, it is expected that the bonding between the PP fibers and the matrix could be weak, which may in consequence lead to an increase in porosity and a deterioration in the overall performance of the concrete. Some investigations have also indicated that, with the addition of PP fibers, the mechanical strength and durability of concrete exhibited a decline. For example, the findings of Gupta et al. showed that, compared to plain mortar, use of PP fibers in mortar, at 0.40 and 0.70% by weight of cement, increased the sorptivity by about 18 and 37%, respectively [5]. With the use of PP fibers in RCC, Yazici et al. found that the compressive strength of RCC mixtures decreased by 20% compared to the control mixture without PP fibers [12]. Wu et al. evaluated the permeability of PP fiber reinforced concrete and found that the bonding between the PP fibers and the concrete matrix was poor, and that the coefficient of chloride ion diffusion was the largest [17].

At present, the introduction of polymeric materials, such as liquid resins, dispersible polymer powder, latexes, and water-borne polymers, in concrete has been attracting more attention in the field of civil engineering [18]. It has been found that the addition of these polymers improves the bond strength, mechanical strength, impermeability, chemical resistance, and durability properties of cementitious composites [18–20]. Researchers have indicated that the physical filling effect of polymers in the porosity of cementitious composites is the main modification mechanism of polymer modified concrete [21]. With the incorporation of polymers, the holes in concrete could be filled, thereby reducing the porosity, enhancing the tensile strength, and preventing the propagation of microcracks [6]. Furthermore, the dispersed polymers, at a proper dosage, may form a film wrapping on cement hydrates and aggregates to generate an interpenetrating network. This three dimensional polymer film plays an important role in bridging micro-cracking and improving the toughness of concrete [6,11]. When it comes to water-borne polymers, i.e., modified polymers with hydrophilic groups, which are dispersed in water as a continuous phase in the form of particles or droplets. Water-borne epoxy (WBE), due to its excellent mechanical properties and good permeability and adhesion to cementitious materials, has been widely applied in construction projects [22]. In view of this, the combined use of WBE and PP fibers in cementitious mixtures could be an effective way of enhancing the performance of cementitious mixtures, since the poor interfacial bonding between PP fibers and the concrete matrix, that worries researchers, may be enhanced through the addition of WBE. On the other side, polymer modified concrete is often brittle and fragile, the introduction of fibers can in turn improve its tensile property [23]. The properties of concretes containing both polymers and fibers have also been explored by researchers [5,11,24].

Currently, most of the studies have put an emphasis on the chemical treatment of PP fibers to improve their adhesion to cementitious composites, while few studies have been performed to investigate the influence of polymer latex on the properties of PP fiber reinforced concrete. In this regard, the aim of this study is to examine the properties of concrete with the combined addition of PP fibers and WBE, and evaluate its possible application in pavement. For this purpose, the mechanical and durability properties of normal concrete (NC), PP fiber reinforced concrete (PC), WBE modified concrete (EC), and concrete with a combination of PP fibers and WBE (PEC), including slump, mechanical strength, shrinkage, water penetration, and abrasion, were analyzed through a series of tests. In addition, fly ash (FA), which is an environmentally friendly pozzolanic material, was introduced in this study in consideration of environmental protection and energy conservation.

2. Materials and Methods

2.1. Raw Materials

Ordinary Portland cement (OPC) 42.5, which met the requirements of the ASTM C150 standard [25], was used in this study. Class F FA, which met the requirements of the ASTM C618 standard [26], was used as a supplementary cementitious material. The chemical compositions of the cement and FA, as provided by the suppliers, are displayed in Table 1. Natural river sand, with a fineness modulus of 2.7, was chosen for use as the fine aggregate. The coarse aggregate used in this study was crushed limestone with a continuous grading of 5–20 mm. PP monofilament fibers were employed, and Table 2 shows their physical and mechanical specifications. WBE was also used in this work, and the properties of the WBE and its matched hardener are given in Table 3. Polycarboxylic-type water-reducing agent conforming to the specifications of the ASTM C494 standard [27] was used in this study, to improve the workability of the concrete.

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

Oxides	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	LOI
Cement	58.34	20.87	5.83	3.64	1.06	3.61	1.36	0.94	4.35
Fly ash	4.39	62.46	22.16	5.28	1.26	0.14	0.68	1.15	2.48

Table 2. Physical and mechanical properties of PP fibers.

Characteristic	Specification
Fiber length (mm)	19
Fiber diameter (μm)	Around 50
Density (g/cm^3)	0.91
Tensile strength (MPa)	More than 486
Elastic modulus (GPa)	More than 4.8
Corrosion resistance to acid and alkali	Very strong
Sorptivity	0

Table 3. Properties of WBE and its matched hardener.

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

2.2. Specimen Preparation

In order to evaluate the mechanical and durability properties of PP fiber and WBE modified concrete for its possible use in pavements, different types of specimens were fabricated. In this study, the contents of PP fibers were 0, 0.1%, and 0.2% by volume of the concrete; the dosages of WBE were in a range from 0 to 10% by weight of binder, with an increment of 5%; and the water to binder ratio was held constant at 0.4 for all the concrete mixtures. In general, two sets of concrete specimens were involved in this study, in terms of with or without FA. In each set, a total of nine concrete mixtures were designed; for the set without FA, one NC, two PC, two EC, and four PEC were included, and for the other set, with FA, 10% FA by weight of binder was included in mixtures as a fixed cement substitution to make one NC-F, two PC-F, two EC-F, and four PEC-F. Details of all the mix proportions of the concretes involved in this work are presented in Table 4.

Table 4. Mix proportions of mortars (unit: kg/m^3).

Mixture Type	Cement	PP Fibers	Sand	Coarse Aggregate	FA	Water	WBE		
							Total	Solid	Water
NC (Control)		0							
PC0.1		0.91				160	-	-	-
PC0.2		1.82							
EC5		0				140	40	20	20
EC10	400	0			0	120	80	40	40
PEC0.1/5		0.91				140	40	20	20
PEC0.1/10		0.91				120	80	40	40
PEC0.2/5		1.82				140	40	20	20
PEC0.2/10		1.82	690	1170		120	80	40	40
NC-F		0							
PC0.1-F		0.91				160	-	-	-
PC0.2-F		1.82							
EC5-F		0				140	40	20	20
EC10-F	360	0			40	120	80	40	40
PEC0.1/5-F		0.91				140	40	20	20
PEC0.1/10-F		0.91				120	80	40	40
PEC0.2/5-F		1.82				140	40	20	20
PEC0.2/10-F		1.82				120	80	40	40

With regard to the process of specimen preparation, an electrically driven mixer was used according to the following steps and the graphical procedure of specimen preparation is shown in Figure 1. Firstly, all of the dry materials, including cement, FA, PP fibers, sand, and coarse aggregate were stirred evenly for 3 min. After that, WBE was mixed with its matched hardener uniformly to make an epoxy mixture. Then the epoxy mixture, the remaining water and the water reducing agent were slowly added to the dry materials and mixed for 3 min to achieve the proper workability. In addition, an extra 5 min of mixing was adopted to make sure that a homogeneous mixture was achieved. Subsequently, the concrete mixture was poured into molds and vibrated for 3 min on a vibrating table to achieve a desirable compaction and consolidation. After 24 h of curing, the hardened concrete specimens were demolded and cured in a standard moist room at a temperature of 20 ± 2 °C until the time of testing.

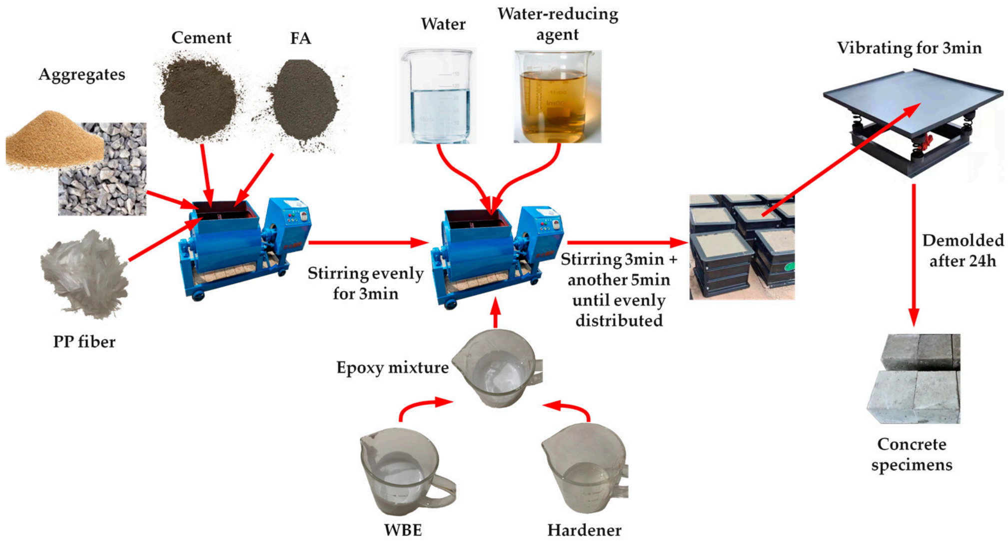


Figure 1. Graphical procedure of concrete specimen preparation.

2.3. Slump

The slump test was conducted following the ASTM C143 standard [28] to examine the influences of PP fibers and WBE on the workability of the concrete. The fresh concrete was poured into a 300 mm-high conical apparatus, whose top and base diameters were 100 mm and 200 mm, respectively, and this cone was tamped 25 times and then its top surface was smoothed. After that, the cone was removed, by raising it carefully in a vertical direction with no lateral or torsional motion. The slump was then determined by the vertical difference between the top of the cone and the top point of the distorted concrete.

2.4. Mechanical Strength

The mechanical properties of the concrete specimens, including their compressive strength and flexural strength, were tested in accordance with the JTG E30-2005 specification [29]. For the compressive strength test, cube specimens, with dimensions of 150 × 150 × 150 mm^3 were prepared, while beam specimens with dimensions of 150 × 150 × 550 mm^3 were fabricated for the flexural strength test. These specimens were tested on a universal testing machine (WAW-1000, Shanghai Hualong Test instrument CO., LTD., Shanghai, China) and three specimens were tested and averaged for each recorded strength value.

2.5. Shrinkage

As one of the main properties of concrete for highway engineering, the drying shrinkage of the concrete specimens was tested [29]. After removing the molds, specimens with dimensions of 100 × 100 × 400 mm^3 were placed in a chamber at a humidity of 60% ± 5%, and then the lengths of the concrete specimens were recorded at ages of 3, 7, 14, 28, 35, 49, 56, 72, and 90 days, to calculate the shrinkage of the concrete.

2.6. Depth of Water Penetration

Cylindrical specimens, whose diameter and height were both 150 mm, were employed to measure the depth of water penetration through the concrete, using water penetration equipment [29]. Prior to the test, the specimens were dried in an oven at 60 °C for 24 h and then the side surfaces of these specimens were cleaned and thereafter coated with heated paraffin solution to avoid any leakage of water. During the test, water was required to penetrate into the specimens under a constant pressure of 0.8 ± 0.05 MPa for 24 h. The specimens were then split into two halves longitudinally and the average depth at the measuring points was recorded as the final value.

2.7. Abrasion Resistance

Cube specimens, with a side length of 150 mm, were used to test the abrasion under a specified abrasion tester in accordance with the JTG E30-2005 standard [29]. For 28 d abrasion test, after 27 days of curing, specimens were placed in the air to allow them to dry naturally for 12 h, and then they were put in an oven at 60 °C for 12 h to a constant weight. After that, the abrasion of the specimens was calculated according to Equation (1). Where Ac, m_1 and m_2 denote abrasion per unit area (kg/m^2), initial mass (after 30 grinds, kg), and final abrasion (after another 60 grinds, kg), respectively.

$$A_C = \frac{m_1 - m_2}{0.0125} \quad (1)$$

2.8. Scanning Electronic Microscopy (SEM)

The microstructural images of specimens were analyzed using SEM (VEGA *II* XMU, TESCAN CO., LTD., Brno, Czech Republic). Samples with dimensions of about 10 mm^3 were cut from the middle part of the specimens and then immersed in anhydrous ethanol to stop hydration. It should be noted that the samples should be dried and coated with gold to be conductive prior to the observation.

3. Results and Discussion

3.1. Slump

The slump values of different types of concrete are presented in Figure 2. It can be seen from Figure 2a that compared with NC, the slump of PC was lower, and this trend was more obvious with the increase in the amount of PP fibers. This can be attributed to the fact that the number of PP fibers is numerous, since PP fiber is the lightest synthetic fiber, therefore this large amount of PP fibers may wrap around and form a network in the concrete, thereby increasing the flow resistance and reducing the workability of the concrete [30]. On the other hand, EC exhibited a higher slump value in comparison with NC, and this difference was even larger when the amount of WBE was 10%. This may be because of both the "ball bearing" effect of uniformly dispersed polymer particles, and the existence of the active surfactants on the surface of these particles that can reduce the surface tension of the water around the cement particles, therefore the workability of EC was improved compared with NC [31,32]. Additionally, although the incorporation of PP fibers resulted in a relatively poor workability, this phenomenon was compensated through the addition of WBE. As displayed, the slump of PEC exhibited an increase when compared with the corresponding PC, regardless of the amount of PP fibers, and in general, the more WBE, the larger the increase in the slump of PEC. As for the set of concrete specimens with 10% FA, it can be seen in Figure 2b that compared to the specimens without FA, the corresponding specimens with FA had larger slump values, indicating that the incorporation of FA could improve the workability of concrete. This is due to the "ball bearing" effect of spherical fly ash particles, which can reduce the friction between components of fresh concrete during mixing of the concrete, thereby improving its workability [33].

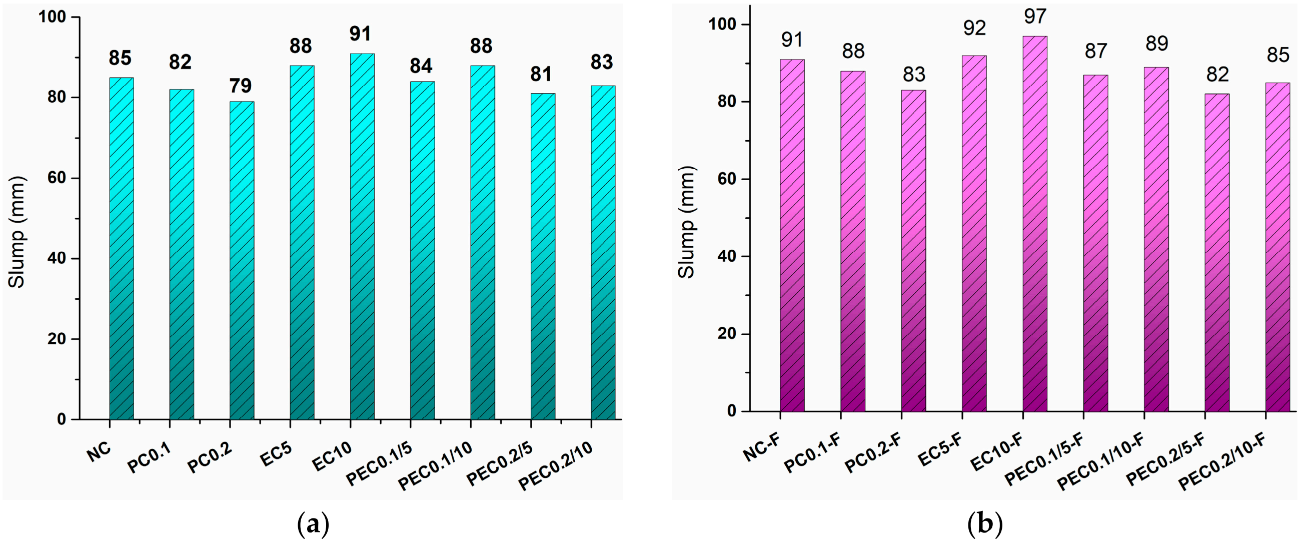
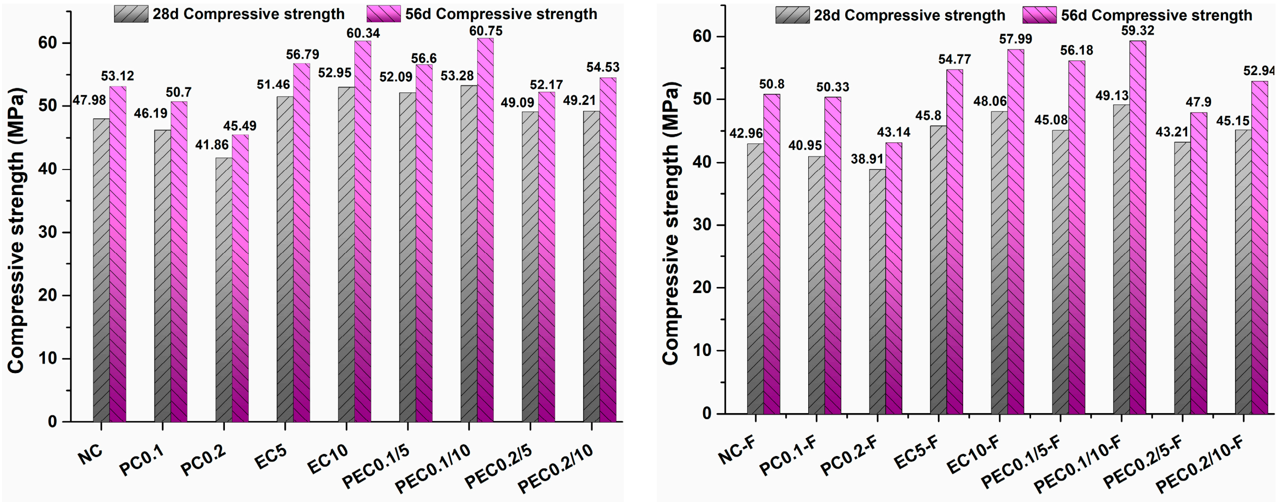


Figure 2. Slump of different types of concrete: (**a**) OPC; (**b**) 90% OPC + 10% FA.

3.2. Mechanical Strength

3.2.1. Compressive Strength

The influences of PP fibers and WBE on the compressive strengths of the concretes are presented in Figure 3. As can be seen from Figure 3a, the compressive strength of PC showed a downward trend compared with that of NC regardless of the curing age, with the strength reduction in PC0.1 at 28 d and 56 d by 3.7% and 4.6%, respectively, and that the reduction in PC0.2 was more notable. It is well known that the incorporation of fibers in concrete is mainly aimed at enhancing the flexural properties of the concrete, provided that there is a tight bonding between the fibers and the concrete matrix, otherwise the reinforcing effect brought about by the fibers may be greatly reduced [5]. However, PP fibers are hydrophobic and, in consequence, the interfaces between PP fibers and the concrete matrix may be weak and some voids may be generated in these interfaces, which may increase the overall porosity of the concrete and lead to a reduction in its strength. The opposite phenomenon was discovered in EC, the compressive strength of EC exhibited a gradual improvement when compared to NC. Compared with NC, the compressive strength of EC5 at 28 d and 56 d was increased by 7.3% and 6.9%, respectively, and this improvement was more evident when 10% WBE was introduced into the concrete. This may be due to the filling effect of WBE, since the pores in the concrete can be filled by epoxy particles, therefore the overall porosity of the concrete can be reduced and a denser microstructure is accordingly formed to improve the compressive strength of the concrete [32]. In addition, functional groups in the polymer chains, such as hydroxyl, may absorb calcium ions in the pore solution to form an interconnected structure. Within this structure, hydration products and polymers are cross-linked, which may further enhance the compactness of the concrete [22]. Figure 4 shows a microstructural image of EC 10, it can be seen that fibrous polymers were generated and cross-linked with hydration products and epoxy particles filled in the pores. The reason why EC10 had a superior compressive strength than EC5 may be that an inadequate amount of polymers has difficulty in forming an interlinked polymer network. Furthermore, it should be noted that polymers at an appropriate content may have a positive effect on the strength formation of concrete, while an adverse effect may be generated with the addition of excess polymers, since a thick polymer film may be formed to depress the hydration process [34,35].



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

Figure 3. Compressive strength of different types of concrete: (**a**) OPC; (**b**) 90% OPC + 10% FA.

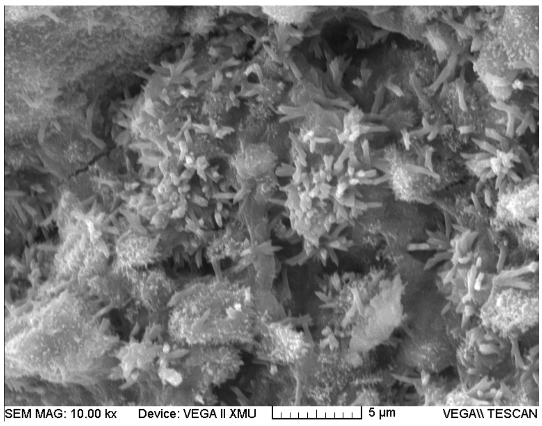
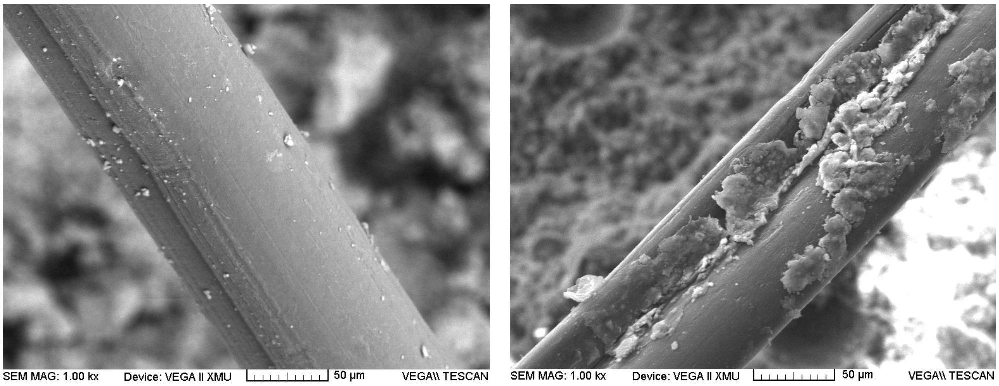


Figure 4. Microstructural image of EC10 by SEM.

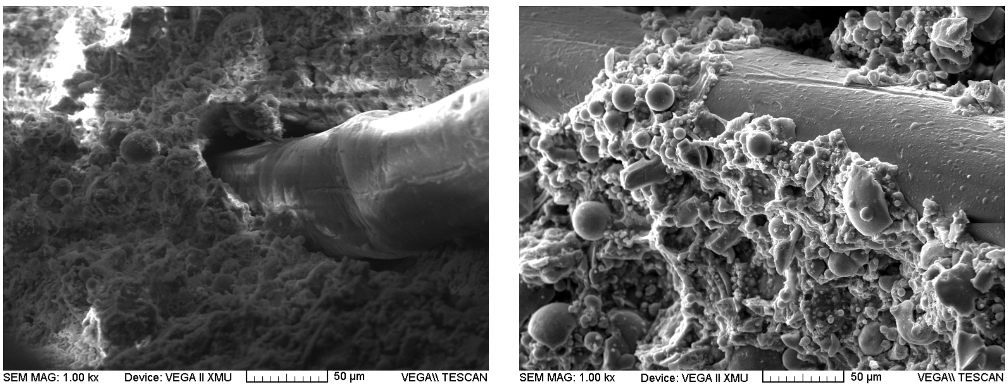
With regard to the concretes containing a combination of PP fibers and WBE, both PEC0.1 and PEC0.2 showed a rapid improvement in compressive strength when compared with their corresponding specimens PC0.1 and PC0.2, respectively. This is because, WBE particles can physically fill the voids between the PP fibers and the concrete matrix, to form a relatively denser interface, therefore the interfacial bonding between the PP fibers and the concrete matrix can be improved; chemically, the functional groups in WBE may absorb calcium ions to form the crosslinking structure of hydration products and polymers, which may also enhance the bonding between the PP fibers and the concrete matrix, since the PP fibers may be wrapped by this crosslinked structure. The microstructural images of PC0.1 and PEC0.1/10 exhibited in Figure 5 show the tight bonding between the PP fibers and the concrete matrix with the addition of WBE. It can be seen from Figure 5 that after fracture, there were still some hydration products and polymer film adhering to the PP fibers in PEC0.1/10. The most obvious improvement in compressive strength was found in PEC0.1/10, with an improvement at 28 d and 56 d by 15.4% and 19.8%, respectively, compared with PC0.1. Similarly, the compressive strength of PEC0.1/5 was 12.8% and 11.6% higher than that of PC0.1 at 28 d and 56 d, respectively. In addition, the compressive strengths of both PEC0.1/10 and PEC0.1/5 showed an increase when compared with NC. Moreover, it can be found that at the same WBE content, the compressive strength of PEC0.2 was lower than that of PEC0.1, which indicates that a negative effect may occur with an increase in the amount of PP fibers.



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

Figure 5. Microstructural images of different types of concrete by SEM: (**a**) PC0.1; (**b**) PEC0.1/10.

As shown in Figure 3b, the compressive strength of the concrete with 10% FA was slightly lower than that of the corresponding specimens without FA, regardless of the curing age, e.g., the compressive strength of PEC0.1/10-F was 7.8% and 2.4% lower than that of PEC0.1/10 at 28 d and 56 d, respectively. This may be due to the fact that the pozzolanic reaction of FA is a slow process, therefore the partial replacement of cement by FA will lead to a reduction in hydration products, whose amount is directly related to the compressive strength, thus resulting in a reduction in the compressive strength of the concrete with FA [36]. Figure 6 presents microstructural images of the concrete specimens with FA at 28 d. As can be seen from Figure 6a, the interfacial bonding between the PP fibers and the concrete matrix was loose in PC0.1-F, while a tight bonding was discovered in PEC0.1/10-F, with hydration products and polymer film wrapping on the surface of the PP fibers, demonstrating the beneficial effect of WBE in improving the interfacial bonding. However, it is worth noting that both the two specimens had a lot of unhydrated FA particles, which proved the decrease in compressive strength at 28 d in comparison with the corresponding FA free concrete. In addition, the presence of WBE, to some extent, delays the pozzolanic reaction of FA, since the epoxy film may separate the FA particles from the already generated calcium hydroxide, thus leading to a relative reduction in hydration products. Therefore, although PEC with FA showed a more rapid improvement in strength from 28 d to 56 d due to the pozzolanic reaction of FA, these specimens still exhibited a slight decline in strength when compared with their corresponding specimens without FA at 56 d.

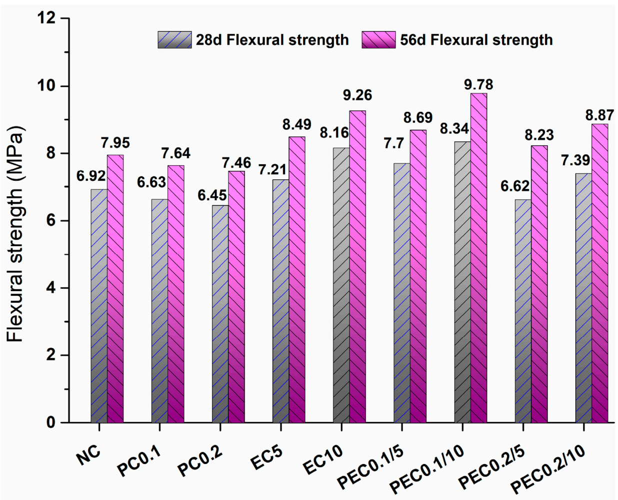


(**a**) (**b**)

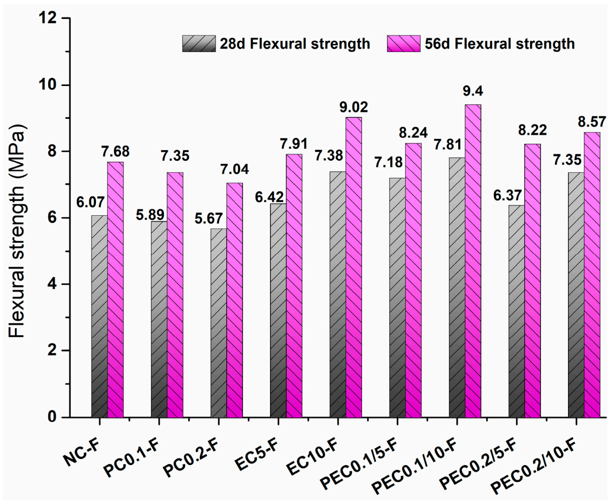
Figure 6. Microstructural images of different types of concrete with FA by SEM: (**a**) PC0.1-F; (**b**) PEC0.1/10-F.

3.2.2. Flexural Strength

Figure 7 presents the flexural strength of different types of concrete containing PP fibers and WBE. It can be found from Figure 7a that the flexural strength of PC experienced a slight downward trend compared with that of NC, while EC exhibited an improvement in flexural strength. PP fibers are incorporated in concrete with the purpose of enhancing the toughness and improving the flexural strength of the concrete, however, the opposite phenomenon was observed in this study, probably due to the weak interfacial bonding between the PP fibers and the concrete matrix, and hence, efficient load transfer by the PP fibers was not realized [5]. This may be because the interfaces between the PP fibers and the concrete matrix may have some voids, owing to the surface hydrophobicity of PP fibers, therefore the fiber toughening effect is difficult to fully achieve when cracks occur in the concrete. A rapid decrease in flexural strength was discovered in PC0.2, which may be regarded as a negative effect resulting from the clumping of PP fibers, which may create localized weak zones in concrete [5]. On the other hand, the reason why the flexural strength of EC was improved compared with that of NC is due to the filling effect of epoxy particles, to fill the pores and the interpenetrating structure of hydration products and polymers formed to withstand larger flexural stress [22].



(**a**)



(**b**)

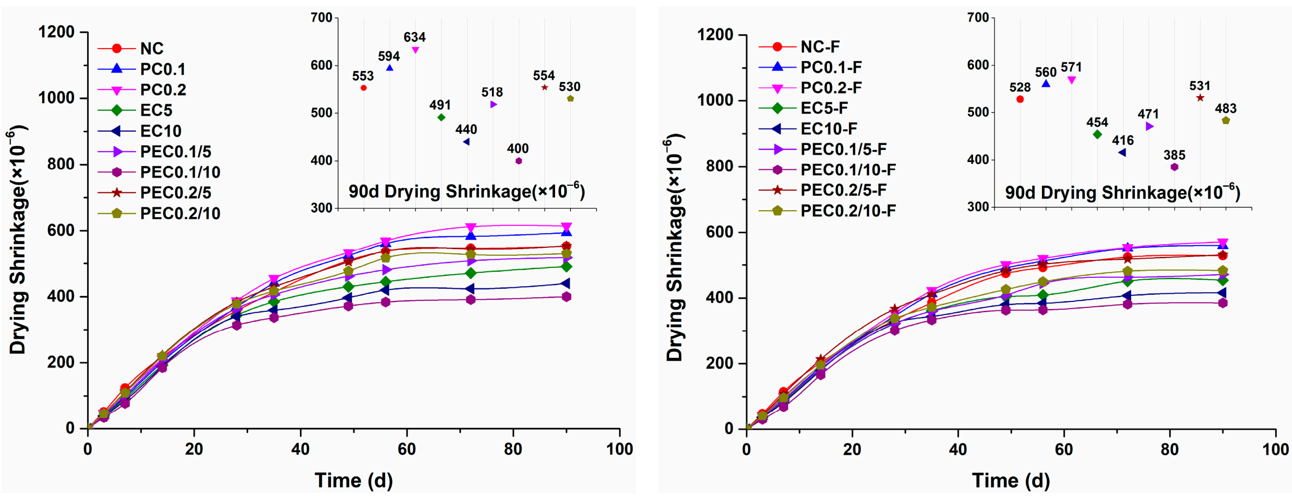
Figure 7. Flexural strength of different types of concrete: (**a**) OPC; (**b**) 90% OPC + 10% FA.

With respect to the concretes containing a combination of PP fibers and WBE, PEC, showed an outstanding improvement in the flexural strength when compared with PC at the same fiber content, and this increase was more notable at the 10% WBE. PEC0.1/10 had the highest flexural strength, which was 25.8% higher than that of PC0.1 at 28 d. In addition, it can be found that with the increase in the amount of PP fibers, the flexural strength of PEC at the same level of WBE experienced a decline, e.g., the flexural strength of PEC0.1/10 was 10.3% higher than that of PEC0.2/10 at 56 d. This indicated that there was an optimal amount of PP fibers, and excess fibers may cause fiber clusters that reduce the strength of the concrete. Moreover, it should be noted that the improvement in flexural strength of PEC0.1/10 was more obvious than that in its compressive strength. This is because PP fibers are aimed at improving the toughness of concrete through achieving an efficient load transfer from the concrete matrix to the PP fibers, therefore the concrete and PP fibers will work jointly to support against the flexural load, thereby leading to an increase in flexural strength. However, the compressive strength is closely related to the amount of hydration products and the porosity in concrete, so the addition of well-bonded PP fibers has little effect on the compressive strength. Moreover, the crosslinking structure of hydration products and polymers is also more beneficial to the flexural properties of modified concrete [22].

When it comes to the concrete specimens with FA, it can be found in Figure 7b that the flexural strength of PEC with FA exhibited a reduction at 28 d when compared with their corresponding PEC without FA. This phenomenon is mainly due to the slow process of the pozzolanic reaction of FA, which is only beneficial to the long-term strength of concrete. At 56 d, the flexural strength of the PEC with FA was more or less the same as that of the PEC without FA, this may be because of the high density of calcium silicate hydrate that was generated through the pozzolanic reaction of FA [36].

3.3. Shrinkage

The drying shrinkage of different types of concrete is presented in Figure 8 and, as can be seen from the results, the drying shrinkage of all the specimens increased with time up to 60 d, after which it was almost unchanged. In regard to the PC without FA, a reduction in shrinkage was observed at the early age (before 14 d) compared with NC, and this reduction was more significant with an increase in the amount of PP fibers. This may be because PP fibers have the ability to reserve the water in the cement paste, thereby reducing the water loss from the specimen [37,38]. Afterwards, the drying shrinkage of PC was even higher than that of NC, with the increase in PC0.1 and PC0.2 at 90 d by 7.4% and 14.7%, respectively. This is because, in the hardened concrete, the drying shrinkage of PC is mainly dependent on the restraint by the fibers [37]. However, the poor interfacial bonding between the PP fibers and the concrete matrix may result in a dramatic loss in shrinkage restraint by PP fibers, therefore the drying shrinkage of PC was higher than that of NC [39]. With regard to the WBE modified concretes EC5 and EC10, the drying shrinkage of the two specimens exhibited a downward trend in contrast to NC, with the reduction in shrinkage at 90 d by 11.3% and 20.4%, respectively. This phenomenon can be linked to the fact that epoxy particles can fill in the pores in concrete and form a cross-linked epoxy film to make the microstructure denser, thus restricting water loss. In addition, the epoxy can tightly bind the components of the concrete to limit the volume change of the concrete due to its high viscosity.



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

Figure 8. Drying shrinkage of different types of concrete: (**a**) OPC; (**b**) 90% OPC + 10% FA.

In addition, the drying shrinkage of PEC showed a further reduction when compared with that of PC. This is because, due to the weak interfacial bonding, the drying shrinkage of PC was increased at a later age, while this undesirable phenomenon was compensated through the addition of WBE. In other words, WBE enabled a relatively tight bonding between the PP fibers and the concrete matrix. The reason for this is twofold. Physically, the epoxy particles enable the formation of a denser microstructure through filling the pores in concrete, therefore the porosity between the PP fibers and the concrete matrix may be lower;

chemically, although no chemical reaction occurs, the functional groups in WBE, such as hydroxyl, may absorb calcium ions in pore solution to form an interconnecting structure of the hydration products and polymers, to further improve the bonding between the PP fibers and the concrete matrix [22]. Therefore, the volume change of PEC was restricted due to this tight bonding between the PP fibers and the concrete matrix. As can be seen from the results, the drying shrinkage of PEC0.1/10 at 90 d was 27.6% and 32.6% lower than that of NC and PC0.1, respectively.

As for concrete with FA, a reduction in drying shrinkage in Figure 8b was observed compared with the corresponding concrete without FA regardless of the type of concrete. This is because FA particles can fill the pores in concrete, reducing the connectivity of capillary pores, thereby preventing the internal water from evaporating outside, which is beneficial to reducing the shrinkage deformation. On the other hand, the pozzolanic reaction of FA also leads to a reduction in the drying shrinkage since the high density calcium silicate hydrate gel generated densifies the microstructure of the concrete, thereby leading to a lower drying shrinkage [36]. Besides, the partial replacement of cement by FA can result in a reduction in the cement hydration rate, therefore the drying shrinkage of concrete with FA may be lower compared to that of ordinary concrete [40].

3.4. Depth of Water Penetration

The depth of water penetration for the different types of concrete is shown in Figure 9. It can be seen from the results that the depth of water penetration at 56 d exhibited a decline compared to that at 28 d regardless of the type of concrete, indicating a higher hydration degree of the concrete and a lower capillary pore volume at 56 d. In regard to PC, the depths of water penetration of PC0.1 and PC0.2 at 28 d was increased by 18.1% and 29.4% compared with that of NC, respectively. This is mainly due to the increased porosity resulting from the incorporation of the hydrophobic PP fibers. However, the depths of penetration of EC5 and EC10 were decreased, with the reductions at 28 d by 23.6% and 30.2% compared with that of NC, respectively, which is mainly because the addition of WBE could fill the pores and bond the components of the concrete together to generate a compact microstructure.

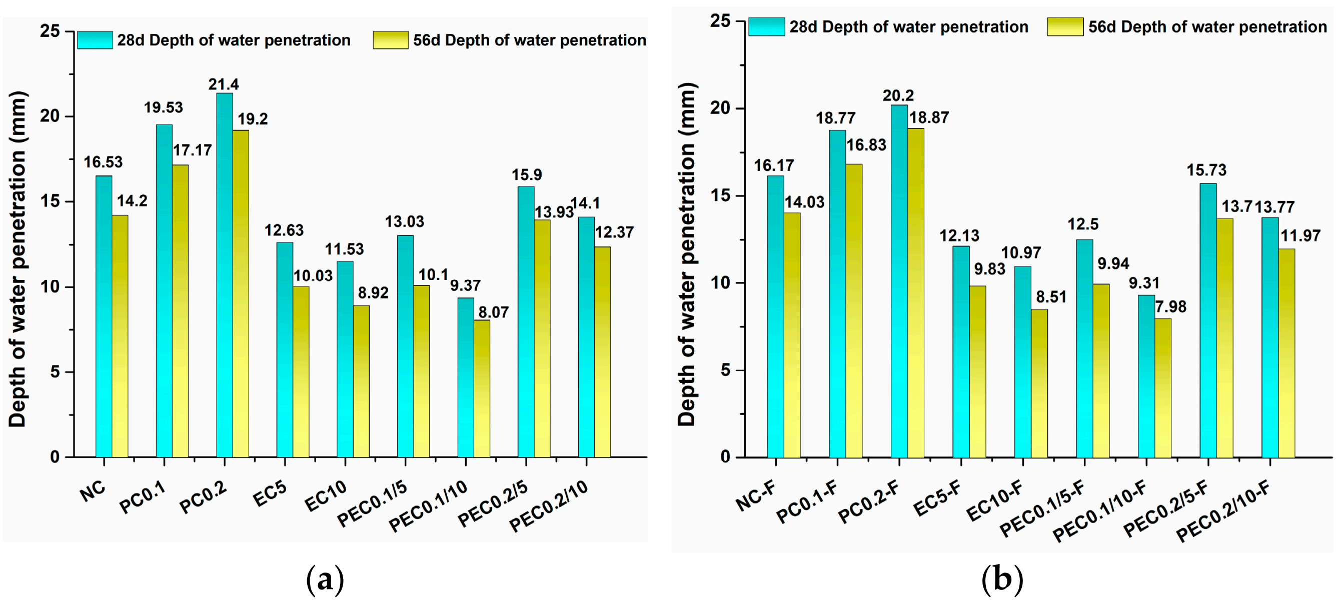


Figure 9. Depth of water penetration of different types of concrete: (**a**) OPC; (**b**) 90% OPC + 10% FA.

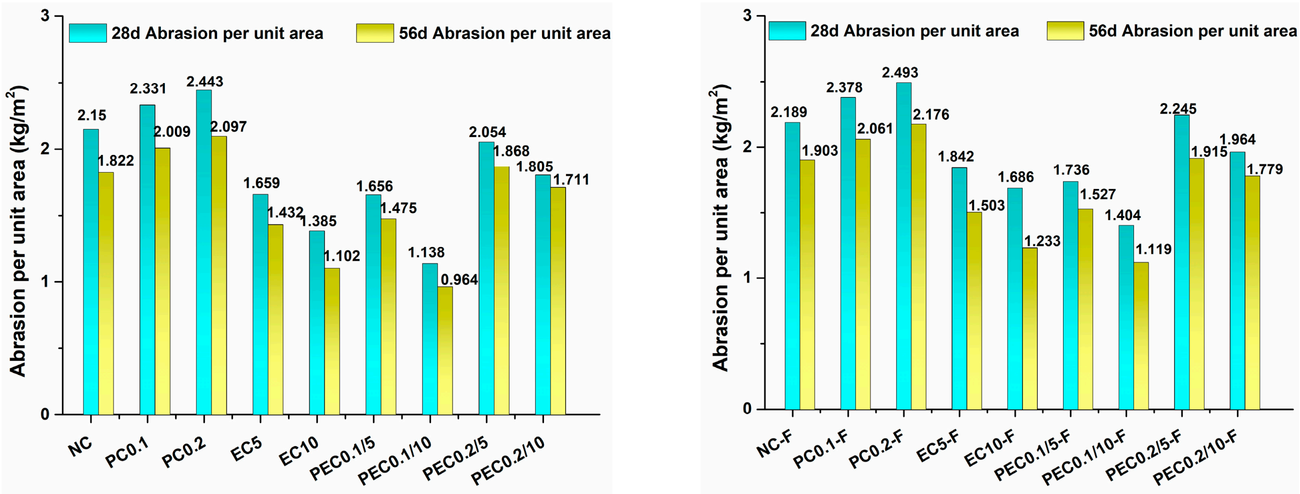
With respect to PEC, the adverse effects on depth of penetration of concrete brought about by PP fibers were expected to be compensated through the addition of WBE, since the microstructure of PC could be densified by the use of WBE. It can be seen from the results, that the depths of penetration of PEC0.1/5 and PEC0.1/10 were dramatically reduced when compared with their corresponding specimen PC0.1, with notable reductions in PEC0.1/5 and PEC0.1/10 at 28 d by 33.2% and 52.1%, respectively. In addition, the depths of penetration of PEC0.2/5 and PEC0.2/10 also exhibited a downward trend compared to their corresponding specimen PC0.2, with reductions of 25.7% and 34.1% at 28 d, respectively. It should be noted that, at the same amount of added WBE, the PECs that had higher fiber contents showed larger depths of penetration. This can be attributed to the fact that WBE may not be adequate to fill the porosity in concrete, as well as the interfacial porosity between the PP fibers.

The depth of water penetration of concrete with 10% FA was slightly smaller than that of concrete without FA, this is due to the higher fineness and ball bearing effect of FA particles, which can reduce the interconnecting voids in concrete, thereby lowering the volume of permeable pores in the concrete [40]. At 56 d, owing to the pozzolanic reaction of FA forming a high density calcium silicate hydrate gel, the volume of permeable pores in the concrete also reduced due to the formation of a denser microstructure [36].

3.5. Abrasion Resistance

The abrasion resistance test was performed and abrasion per unit area of different types of specimen was calculated by Equation (1), as shown in Figure 10. According to the results, the abrasions of all the concrete mixtures at 28 d were higher than those at 56 d, indicating a higher strength and denser microstructure at 56 d to resist wear. This is consistent with the studies of other researchers, which showed that the abrasion resistance of concrete is closely related to the strength of concrete [41,42]. It can be seen from the results that PC exhibited an increase in abrasion compared with NC, with the increase in abrasions of PC0.1 and PC0.2 by 8.4% and 13.6% at 28 d, respectively. In general, the reduction in abrasion of PC can be achieved through the crack arresting effect and crack bridging of PP fibers on the condition that a tight bonding exists in the interface of the PP fibers and the concrete matrix [41]. However, the interfacial bonding between PP fibers and concrete is normally weak due to the hydrophobicity of PP fibers, and this may be the reason why PC exhibited an increased abrasion compared with NC. Additionally, previous studies have demonstrated that the addition of modified PP fibers was capable of improving the abrasion resistance of concrete [41]. Conversely the abrasion of EC was reduced in contrast to NC, with the reductions in EC5 and EC10 by 22.8% and 35.6% at 28 d, respectively. This means that WBE can improve the compactness of concrete, so as to resist the wearing load and reduce the amount of wear. The results also revealed that the combined incorporation of PP fibers and WBE contributed to a reduction in abrasion. This is because the interfacial bonding between the PP fibers and the concrete was improved through the filling effect of WBE and the crosslinking structure of the hydration products and WBE, therefore the PP fibers and the concrete matrix will work jointly to resist the wear. For example, the abrasion of PEC0.1/5 and PEC0.1/10 showed a reduction by 23% and 47.1% at 28 d, respectively, compared with NC. In general, WBE in this study can be regarded as a modifier to improve the interfacial bonding between the PP fibers and concrete, thereby improving the strength and durability properties of PC.

A slight increase in abrasion was observed in the concrete with FA in contrast to that without FA, this is because that the pozzolanic reaction of FA is a slow process which may result in an inferior strength compared with the corresponding concrete without FA. Therefore, due to the reduction in strength, the abrasion of concrete containing FA showed a slight increase, which is consistent with findings of other researchers [42].



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

Figure 10. Abrasion per unit area of different types of concrete: (**a**) OPC; (**b**) 90% OPC + 10% FA.

4. Conclusions

The current study investigated the mechanical and durability properties of concrete containing different amounts of PP fibers and WBE for its possible use in pavements. Conclusions drawn from the results are listed as follows:

(1) The combined incorporation of PP fibers and WBE in concrete can maximize the advantages of the two materials. To be precise, the incorporation of PP fibers had a negative effect on the performance of the concrete due to the weak interfacial bonding between the PP fibers and the concrete, while WBE was found to be effective in improving this poor interfacial bonding owing to its filling effect densifying the microstructure, and its absorption of calcium ions to form a crosslinking structure of hydration products and epoxy polymers wrapping on the PP fibers to enhance their interfacial bonding with the concrete matrix.

(2) The incorporation of PP fibers reduced the slump of concrete, while the use of WBE could improve the workability of PC due to the "ball bearing" effect of WBE. Moreover, the presence of FA further led to an increase in the slump owing to the "ball bearing" effect.

(3) The compressive strength of PC was slightly lower when compared with that of NC due to the weak interfacial bonding between the PP fibers and the concrete, while EC showed an increase in compressive strength. With the combined incorporation of PP fibers and WBE, the compressive strength of PEC exhibited an improvement in comparison with the corresponding PC. PEC0.1/10 showed the highest compressive strength regardless of the curing age. The flexural strength of PEC0.1/10 was also the highest, and the increase in flexural strength was more obvious than that in compressive strength compared with PC, demonstrating the reinforcing effect of PP fibers was achieved.

(4) Drying shrinkage of concrete could be restricted by the addition of PP fibers at an early stage, while at later stages the effective utilization of PP fibers to restrain shrinkage can be achieved by adding WBE. The addition of PP fibers could increase the permeability of concrete owing to increased porosity, while a reduction in depth of water penetration was found in EC mainly due to the filling and bonding effect of WBE to reduce the capillary pores in concrete. Combined use of PP fibers and WBE contributed to the reduction in abrasion. With regard to FA free concrete in this study, PEC0.1/10 exhibited the best durability.

(5) After the replacement of 10% cement by FA, both the compressive strength and the flexural strength showed a slight decline due to the slow process of the pozzolanic reaction; moreover the abrasion also exhibited a slight increase. Despite this, the

drying shrinkage resistance and impermeability were improved through the use of FA. Therefore, the use of FA in pavements should be properly treated according to the actual engineering condition, such as road grade, construction period limit, etc.

The current study aims to evaluate the mechanical and durability properties of concrete containing PP fibers and water-borne epoxy for use in concrete pavement; however, further studies on the fracture properties and modification mechanisms of concrete with the combined use of the two materials will be conducted. In addition, the durability properties under temperature and humidity changes should be studied as well in the future. Moreover, the effects of the water-borne epoxy content, PP fiber characterization, and the hybrid use of PP fibers with other fibers on the mechanical, durability, fatigue and impact properties of pavement concrete should also be investigated in the future.

Author Contributions: Conceptualization, H.Z. and L.W.; methodology, Q.Z. and L.W.; validation, H.Z. and Q.Z.; investigation, L.W., B.Z. and Q.Z.; data curation, B.Z. and B.W.; writing—original draft preparation, L.W.; writing—review and editing, M.S.; supervision, H.Z.; project administration, B.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was sponsored by Shandong Jianzhu University Doctoral Fund (No. X20081Z01). This support is hereby acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to recognize numerous co-workers and research facility associates for giving specialized assistance on instrument examination.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yin, S.; Tuladhar, R.; Shi, F.; Combe, M.; Collister, T.; Sivakugan, N. Use of macro plastic fibres in concrete: A review. *Constr. Build. Mater.* **2015**, *93*, 180–188. [CrossRef]
2. Bozzoni, F.; Ozcebe, A.G.; Balia, A.; Lai, C.G.; Borzi, B.; Nascimbene, R.; Khairy, D.; Gabbianelli, G.; Ippoliti, L.; Berardi, S.; et al. Seismic ground response analyses at an international airport in northern Italy by using a stochastic-based approach. *J. Mec. Theor. Appl.* **2020**, *58*, 499–511. [CrossRef] [PubMed]
3. Khan, M.; Ali, M. Effectiveness of hair and wave polypropylene fibers for concrete roads. *Constr. Build. Mater.* **2018**, *166*, 581–591. [CrossRef]
4. Nobili, A.; Lanzoni, L.; Tarantino, A.M. Experimental investigation and monitoring of a polypropylene-based fiber reinforced concrete road pavement. *Constr. Build. Mater.* **2013**, *47*, 888–895. [CrossRef]
5. Gupta, S.; Kua, H.W.; Pang, S.D. Combination of polypropylene fibre and superabsorbent polymer to improve physical properties of cement mortar. *Mag. Concr. Res.* **2018**, *70*, 350–364. [CrossRef]
6. Sun, Z.; Xu, Q. Microscopic, physical and mechanical analysis of polypropylene fiber reinforced concrete. *Mater. Sci. Eng. A* **2009**, *527*, 198–204. [CrossRef]
7. Lanzoni, L.; Nobili, A.; Tarantino, A.M. Performance evaluation of a polypropylene-based draw-wired fibre for concrete structures. *Constr. Build. Mater.* **2012**, *28*, 798–806. [CrossRef]
8. Gupta, S.; Rao, V.K.; Sengupta, J. Evaluation of polyester fiber reinforced concrete for use in cement concrete pavement works. *Road Mater. Pavement Des.* **2008**, *9*, 441–461. [CrossRef]
9. Aly, T.; Sanjayan, J.G.; Collins, F. Effect of polypropylene fibers on shrinkage and cracking of concretes. *Mater. Struct.* **2008**, *41*, 1741–1753. [CrossRef]
10. Bendjillali, K.; Goual, M.S.; Chemrouk, M.; Damene, Z. Study of the reinforcement of limestone mortars by polypropylene fibers waste. *Phys. Procedia* **2011**, *21*, 42–46. [CrossRef]
11. Han, J.W.; Jeon, J.H.; Park, C.G. Bond characteristics of macro polypropylene fiber in cementitious composites containing nanosilica and styrene butadiene latex polymer. *Int. J. Polym. Sci.* **2015**, *2015*, 207456. [CrossRef]
12. Yazici, Ş.; Mardani-Aghabaglou, A.; Tuyan, M.; Üte, A.A. Mechanical properties and impact resistance of roller-compacted concrete containing polypropylene fibre. *Mag. Concr. Res.* **2015**, *67*, 867–875. [CrossRef]
13. Won, J.P.; Park, C.G.; Lee, S.W.; Jang, C.I.; Kim, H.Y. Performance of synthetic macrofibres in reinforced concrete for tunnel linings. *Mag. Concr. Res.* **2009**, *61*, 165–172. [CrossRef]

14. Zhang, D.; Tan, K.H. Effect of various polymer fibers on spalling mitigation of ultra-high performance concrete at high temperature. *Cem. Concr. Compos.* **2020**, *114*, 103815. [CrossRef]
15. Sivakumar, A.; Santhanam, M. A quantitative study on the plastic shrinkage cracking in high strength hybrid fibre reinforced concrete. *Cem. Concr. Compos.* **2007**, *2*, 575–581. [CrossRef]
16. Tu, L.; Kruger, D.; Wagener, J.B.; Carstens, P.A.B. Surface modified polypropylene fibres for use in concrete. *Mag. Concr. Res.* **1998**, *50*, 209–217. [CrossRef]
17. Wu, H.; Zhao, J.; Wang, Z. Study on micro-structure and durability of fiber concrete. *Res. J. Appl. Sci. Eng. Technol.* **2013**, *5*, 659–664. [CrossRef]
18. Esmaeili, J.; Andalibi, K.; Gencel, O.; Maleki, F.K.; Maleki, V.A. Pull-out and bond-slip performance of steel fibers with various ends shapes embedded in polymer-modified concrete. *Constr. Build. Mater.* **2021**, *271*, 121531. [CrossRef]
19. Fernández-Ruiz, M.A.; Gil-Martín, L.M.; Carbonell-Márquez, J.F.; Hernández-Montes, E. Epoxy resin and ground tyre rubber replacement for cement in concrete: Compressive behaviour and durability properties. *Constr. Build. Mater.* **2018**, *173*, 49–57. [CrossRef]
20. Ariffin, N.F.; Hussin, M.W.; Sam, A.R.M.; Bhutta, M.A.R.; Khalid, N.H.A.; Mirza, J. Strength properties and molecular composition of epoxy-modified mortars. *Constr. Build. Mater.* **2015**, *94*, 315–322. [CrossRef]
21. Wang, R.; Wang, P.M.; Li, X.G. Physical and mechanical properties of styrene–butadiene rubber emulsion modified cement mortars. *Cem. Concr. Res.* **2005**, *35*, 900–906. [CrossRef]
22. Pang, B.; Zhang, Y.; Liu, G. Study on the effect of waterborne epoxy resins on the performance and microstructure of cement paste. *Constr. Build. Mater.* **2018**, *167*, 831–845. [CrossRef]
23. Martinez-Barrera, G.; Menchaca-Campos, C.; Gencel, O. Polyester polymer concrete: Effect of the marble particle sizes and high gamma radiation doses. *Constr. Build. Mater.* **2013**, *41*, 204–208. [CrossRef]
24. Varghese, A.S.S. A Study on Properties of SBR Latex Modified Polypropylene Fibre Reinforced Concrete. *IJSTE-Int. J. Sci. Technol. Eng.* **2017**, *3*, 81–86.
25. *ASTM C150*; Standard Specification for Portland Cement. American Society for Testing and Materials: Philadelphia, PE, USA, 2009.
26. *ASTM C618*; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. American Society for Testing and Materials: West Conshohocken, PE, USA, 2012.
27. *ASTM C494*; TYPE F: Standard Specification for Chemical Admixtures for Concrete. American Society for Testing and Materials: Philadelphia, PE, USA, 2017.
28. *ASTM C143/C143M-15*; Standard Test Method for Slump of Hydraulic-Cement Concrete. American Society for Testing and Materials: West Conshohocken, PE, USA, 2015.
29. *JTG E30-2005*; Test Methods of Cement and Concrete for Highway Engineering. Ministry of Transport of the People's Republic of China: Beijing, China, 2005.
30. Soroushian, P.; Plasencia, J.; Ravanbakhsh, S. Assessment of reinforcing effects of recycled plastic and paper in concrete. *Mater. J.* **2003**, *100*, 203–207.
31. Sumathy, C.T.; Dharakumar, M.; Saroja Devi, M.; Saccubai, S. Modification of cement mortars by polymer latex. *J. Appl. Polym. Sci.* **1997**, *63*, 1251–1257. [CrossRef]
32. Liu, B.; Shi, J.; Sun, M.; He, Z.; Xu, H.; Tan, J. Mechanical and permeability properties of polymer-modified concrete using hydrophobic agent. *J. Build. Eng.* **2020**, *31*, 101337. [CrossRef]
33. Fang, G.; Ho, W.K.; Tu, W.; Zhang, M. Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature. *Constr. Build. Mater.* **2018**, *172*, 476–487. [CrossRef]
34. Peng, Y.; Zeng, Q.; Xu, S.; Zhao, G.; Wang, P.; Liu, X. BSE-IA reveals retardation mechanisms of polymer powders on cement hydration. *J. Am. Ceram. Soc.* **2020**, *103*, 3373–3389. [CrossRef]
35. Zeng, S.; Short, N.R.; Page, C.L. Early-age hydration kinetics of polymer-modified cement. *Adv. Cem. Res.* **1996**, *8*, 1–9. [CrossRef]
36. Rashad, A.M. An exploratory study on high-volume fly ash concrete incorporating silica fume subjected to thermal loads. *J. Clean. Prod.* **2015**, *87*, 735–744. [CrossRef]
37. Saje, D.; Bandelj, B.; Šušteršič, J.; Lopatič, J.; Saje, F. Shrinkage of polypropylene fiber-reinforced high-performance concrete. *J. Mater. Civ. Eng.* **2011**, *23*, 941–952. [CrossRef]
38. Afroughsabet, V.; Biolzi, L.; Monteiro, P.J. The effect of steel and polypropylene fibers on the chloride diffusivity and drying shrinkage of high-strength concrete. *Compos. Part B Eng.* **2018**, *139*, 84–96. [CrossRef]
39. Toledo Filho, R.D.; Ghavami, K.; Sanjuán, M.A.; England, G.L. Free, restrained and drying shrinkage of cement mortar composites reinforced with vegetable fibres. *Cem. Concr. Compos.* **2005**, *27*, 537–546. [CrossRef]
40. Saha, A.K. Effect of class F fly ash on the durability properties of concrete. *Sustain. Environ. Res.* **2018**, *28*, 25–31. [CrossRef]

41. Li, H.; Zhang, M.H.; Ou, J.P. Abrasion resistance of concrete containing nano-particles for pavement. *Wear* **2006**, *260*, 1262–1266. [CrossRef]
42. Naik, T.R.; Singh, S.S.; Hossain, M.M. Abrasion resistance of concrete as influenced by inclusion of fly ash. *Cem. Concr. Res.* **1994**, *24*, 303–312. [CrossRef]