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Experimental Study on Mechanical and Durability Properties of Glass and Polypropylene Fiber Reinforced Concrete

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Abstract: The aim of the study is to validate the effect of glass fiber and polypropylene fiber on improving the mechanical and durability properties of concrete. In this regard, glass fiber, polypropylene fiber and hybrid fiber were added to concrete, respectively. This paper conducted the compressive and bending flexural tests to confirm that the fiber enhances the mechanical properties of concrete. In order to evaluate the durability of fiber reinforced concrete, the rapid chloride migration test and rapid chloride penetration test were carried out. The comparisons of experimental results illustrate that the hybrid fiber reinforced concrete has the most significant effect on the concrete properties improvements. Moreover, comparing with the glass fiber reinforced concrete, the polypropylene fiber reinforced concrete plays a better performance on mechanical and durability properties.

Keywords: Glass fiber, Polypropylene fiber, Hybrid fiber, Mechanical properties, Durability properties

Introduction

Concrete is the most widely used in the construction industry around the world. However, due to the low flexural strength and weak durability, the concrete is restricted in some structures and areas [1,2]. With the development of fiber and its specific characteristics, such as the excellent mechanical and durability properties, the fiber has been used as one of the common additions of concrete [3-6]. Comparing with plain concrete, the fiber reinforced concrete shows a better performance in durability and mechanical properties [7-10]. Moreover, the addition of fiber can effectively resist the initiation, propagation, or coalescence of cracks on the surface of structure [11,12]. Among the various fibers, polyethylene fiber (PF) and glass fiber (GF) show a better performance on improving the concrete properties and are widely used in the practical engineering, such as harbor, bridge and road pavement [13,14]. Therefore, the prediction of properties for fiber reinforced concrete is a key factor on the safety of buildings and infrastructure.

There have been several studies on the mechanical and durability properties of concrete incorporated with fibers by different experimental methods and theoretical models. Said *et al.* [15] investigated the effects of polyethylene fiber on the toughness and compressive and flexural strengths of engineered cementitious composite cubes and slabs, the funding shows that the fiber significantly increased the ultimate load and failure deflections, and the ultimate strength of slabs. Tassew *et al.* [16] establish the influence of chopped glass fibers on the mechanical and rheological properties of ceramic concrete produced using a phosphate cement binder, the results showed that the compression, the flexure and the shear toughness all increased with an increase in the fiber content, while the workability decreased with an increase in fiber content. Natarajan *et al.* [17] evaluate and compare the flexural strength of different provisional restorative materials reinforced with glass and polyethylene fibers, the test results show that the strength is increased by the addition of fibers. Chandramouli *et al.* [18] added 0.03 %, 0.06 % and 0.10 % glass fiber into the concrete and carried out rapid chloride permeability tests for 180 days, where the results showed that addition of glass fibers exhibit better performance. Toutanji *et al.* [19] added 0, 0.1 %, 0.3 %, and 0.5 % polypropylene fiber into the silica fume concrete, the study illustrated that the amalgamation of polypropylene fibers reduced the permeability of concrete. Singh *et al.* [20] added 0.1-0.3 % polypropylene fiber and 0.2-0.4 % glass fiber to concrete respectively and carried out rapid chloride permeability tests for 7 days, 14 days, 28 days and 56 days, the results illustrated that adding polypropylene fiber and glass fiber reduced the permeability of concrete.

According to the latest research results, scholars have studied the effect of polypropylene fiber or glass fiber on improving the compressive and flexural strength, as well as the chloride ion permeation resistance into concrete. However, there is rare researches focusing on the effects of hybrid fiber, which is the combination of GF and PF, on mechanical and durability properties of fiber reinforced concrete. In fact, concrete is a complex material with multiphases, the phases include large amount of C-S-H gel in micron-scale size, sands in millimeter-scale size, and coarse aggregates in centimeter-scale size. Thus, the properties of concrete will be improved in certain level, but not whole levels if reinforced only by one type of fiber [21]. In this regard, this paper compared the results of three different fiber reinforced concrete, which were GF, PF and GF+PF. For each group, the concrete were mixed with three different volume ratio of additions, including 0.5 %, 1.0 %

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and 1.5 %. The compressive and bending flexural tests was conducted to confirm that the fiber enhances the mechanical properties of concrete. In order to evaluate the durability of fiber reinforced concrete, the rapid chloride migration test and rapid chloride penetration test were carried out. Finally, using the scanning electron microscopy (SEM) to investigate the interfaces between fibers and cement paste. The findings of this research have the potential to significantly contribute toward expanding the use of high performance fiber reinforced concrete to different structural design and building service-life estimation.

Experimental

Materials and Specimens Preparation

Materials

In this study, P·O 42.5 Portland cement produced by Harbin Yatai Group Company, China was used for preparing concrete. Its physical and mechanical properties conforming to EN197-1:2009 and the properties was presented in Table 1. The chemical composition of the ordinary Portland cement (OPC) was tested by alternative method [23], then listed in Table 2. The washed river sand then naturally dried were prepared as fine aggregates, the crushed limestone aggregates as coarse aggregates, the Figure 1 shows the sieving curves of aggregates. According to ASTM C136, the technical specifications of the aggregates were tested and the results are shown in Table 3. Glass fiber and polypropylene fiber are high strength fiber materials, the properties of glass fibers and polypropylene fibers were tested in this research and listed in Table 4. When mixing concrete, the curing water is added. The 5581F polycarboxylic-based water reducer was prepared to maintain concrete slump at 80-100 mm, and the characteristics of water reducer are

Table 1. Physical and mechanical properties of OPC

	Specific surface area (m^2/kg)	Initial setting time (min)	Final setting time (min)	Compressive strength (MPa)		Flexural strength (MPa)		Soundness
				3 days	28 days	3 days	28 days	
Experimental result	338.972	186	519	26.323	49.852	7.833	8.623	Qualified

Soundness refers to the ability of a hardened cement paste to retain its volume after setting without delayed destructive expansion [22].

Table 2. Chemical compositions of OPC

Chemical composition	Al_2O_3	SiO_2	Fe_2O_3	CaO	K_2O	SO_3	Na_2O	MgO	Loss
Cement weight percent (%)	5.86	21.5	2.85	59.81	0.67	2.06	0.2	2.23	4.82

Table 3. Technical specifications of aggregates

Aggregate	Mud content (%)	Apparent density (kg/m^3)	Loose bulk density (kg/m^3)	Tapped bulk density (kg/m^3)	Porosity (%)	Crushing value (%)	Fineness modulus	Maximum size (mm)
Fine aggregate	1.32	2604	1534	1653	41.1	-	2.53	5
Coarse aggregate	0.2	2690	1445	1625	46.2	8.7	-	20

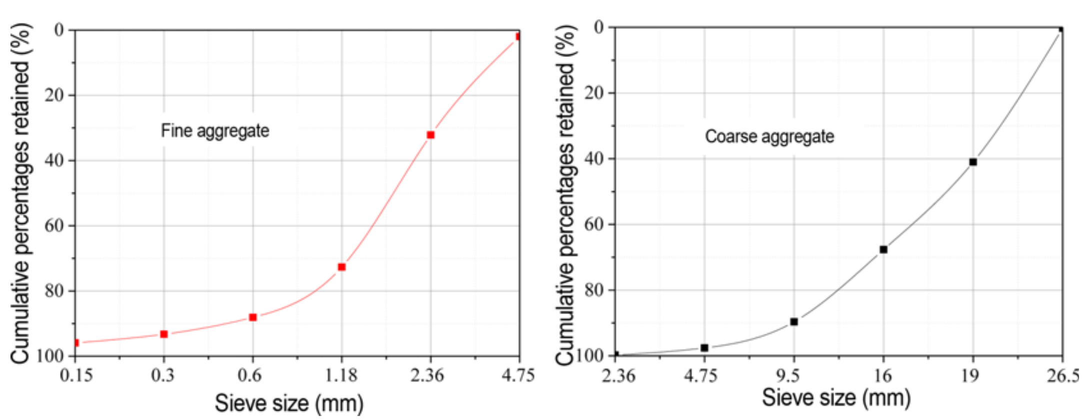

Figure 1. Sieving curves of fine aggregate and coarse aggregate.

Table 4. Properties of glass fibers and polypropylene fibers

Type of fiber	Length (mm)	Diameter (μm)	Density (g/cm^3)	Tensile strength (N/mm^2)	Dispersion	Picture of fiber
Glass fiber	12	40	2.36	1200	Good	
Polypropylene fiber	12	15	0.91	276	Good	

Table 5. Characteristics of 5581F polycarboxylic-based water reducer

PH	Chloride ion content (%)	Na_2SO_4 content (%)	Rate of water content (%)	Surface tension (mN/m)
8.2	0.02	3	2.5	71.5-72.0

Table 6. Mix proportions of concrete mixes

Group no.	Mix ID	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water reducer (kg/m^3)	Glass fiber (%)	Polypropylene fiber (%)
1	OPC	300	126	825	1100	0.6	0	0
2	0.5GF	300	126	825	1100	0.6	0.5	0
3	0.5PF	300	126	825	1100	0.6	0	0.5
4	0.25GF+0.25PF	300	126	825	1100	0.6	0.25	0.25
5	1.0GF	300	126	825	1100	0.6	1	0
6	1.0PF	300	126	825	1100	0.6	0	1
7	0.5GF+0.5PF	300	126	825	1100	0.6	0.5	0.5
8	1.5GF	300	126	825	1100	0.6	1.5	0
9	1.5PF	300	126	825	1100	0.6	0	1.5
10	0.75GF+0.75PF	300	126	825	1100	0.6	0.75	0.75

presented in Table 5.

Mix Proportion and Preparation of Specimen

In order to study the effect of glass fiber and polypropylene fiber on the ability of concrete to resist chloride attack, concrete mixtures with three different fiber volume fraction for each group were prepared in this paper. The total glass fiber volume fraction of all mixtures was 0.5 %, 1.0 % and 1.5 % according to Kizilkanat *et al.* [24], the total polypropylene fiber volume fraction of all mixtures was 0.5 %, 1.0 % and 1.5 % according to Zhang *et al.* [25], the total glass and polypropylene fiber volume fraction of all mixtures was 0.5 %, 1.0 % and 1.5 % like in the study of Zhu *et al.* [26]. The 0.6 kg/m^3 water reducer was added to increase the liquidity and durability of concrete. The w/c ratio of the concrete mixture prepared is 0.42. The OPC concrete were prepared as the contrast group. Table 6 presented the mix proportions of 1 m^3 concrete for each group.

The single horizontal-axis forced mixer was used to prepare fiber reinforced concrete mixtures. The fiber reinforced concrete samples were sent into the curing room for 24 h where the temperature is (20±5) ^{o}C. Then the specimens were take out from the mould and placed into curing water for 27 days which the temperature is (20±2) ^{o}C. According to the Chinese standard GB/T50081-2016 [27], this process meet the requirement of 28 days standard curing.

Testing Methods

Compressive and flexural strength, rapid chloride migration test (RCM) test, rapid chloride penetration test (RCPT) and scanning electron microscopy (SEM) observation were carried out in this study.

Compressive Test

Based on Chinese standard GB/T50081-2016 [27] the compressive test was conducted. Cubic specimens with each mixture were produced which the size is 100×100×100 mm^3 and the compression test was carried out at the age of 3 days, 7 days, 14 days and 28 days respectively. The hydraulic universal testing machine (WE-30) was used to conduct the compression test with a loading control of 0.5-0.8 MPa/s.

Three-point Bending Flexural Test

Based on Chinese standard GB/T50081-2016 [27] the

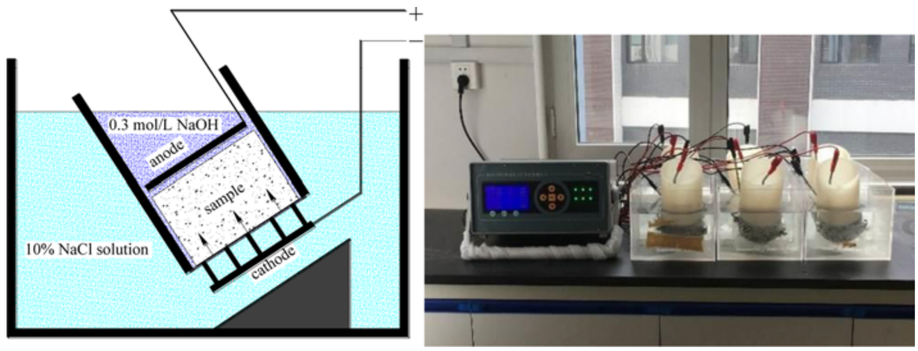

Figure 2. RCM test.

three-point bending flexural test was conducted. Beam specimens with each mixture were produced which the size is 400×100×100 mm^3 and the three-point bending flexural test was carried out at the age of 3 days, 7 days, 14 days and 28 days respectively. The hydraulic universal testing machine (WE-30) was used to conduct the three-point bending flexural test with a loading control of 0.5-0.8 MPa/s.

Rapid Chloride Migration (RCM) Test

In order to evaluate the chloride migration coefficient in fiber reinforced concrete, cylindrical concrete specimens (cured standardly for 28 days) with diameter of 100±1 mm and height of 50±2 mm were prepared to conduct the RCM test [28]. According to NT BUILD 492, RCM steps are as follows. First, the tested specimens were put into a vacuum pump and the pressure reduced to 1-5 kPa within 5 minutes, and the pressure should be maintained for 3 hours. Then the saturated $Ca(OH)_2$ solution prepared by distilled water should be injected while the vacuum pump is still in operation to keep the pressure, and the solution height should be ensured to immerse the specimen. After the specimens were immersed for an hour, the pressure should reach the atmospheric pressure and continue to immerse the specimen for another 18±2 h. Then the rubber barrel was installed in the test tank, which was equipped with test specimen, and the anode plate is installed. The 0.3 mol/L NaOH solution was injected into the rubber barrel to immerse anode plate and specimen surface in solution. The 10 % NaCl solution was injected into cathode test tank, and the liquid level was the same as the NaOH solution in the rubber barrel. At last, applying 30 V DC voltage to both sides of the anode and cathode after connecting the power line.

Samples were separated and sprayed with 0.1mol/L $AgNO_3$ solution to measure the chloride migration depth after the rapid penetration test, and the chloride migration coefficient during the RCM test was calculated by equation (1) [29,30].

$$D_{\mathrm{RCM}} = \frac{0.0239\times(273+T)L}{(U-2)t}\left(X_{\mathrm{d}} - 0.0238\sqrt{\frac{(273+T)LX_{\mathrm{d}}}{U-2}}\right) \quad (1)$$

where D_{RCM} represents non-steady-state chloride diffusion coefficient, 10^{-12}m^2/s; U represents absolute value of the applied voltage, V; T represents average value of the initial and final temperatures in the anolyte solution, $^{\circ}$C; L represents thickness of the concrete sample, mm; X_{d} represents average value of the penetration depths, mm; t represents testing duration, hour.

Rapid Chloride Penetration Test (RCPT)

In order to evaluate the chloride ion penetration resistance of fiber reinforced concrete, cylindrical concrete specimens (cured standardly for 28 days) with height of 50±2 mm and diameter of 100±1 mm were prepared to conduct the rapid chloride penetration test (RCPT). Based on ASTM C1202 - 12, RCPT steps are as follows. First, the tested specimens were put into a vacuum pump and keep the pressure at minus 1-5 kPa three hours. Then deionized water was injected into the machine until the specimen is immersed, maintained the pressure for an hour. After one hour, the pressure is released to atmospheric pressure and the sample were immersed for another (18±2) hours. At last, the saturated specimens were put into the glass tank, 0.3 mol/L NaOH solution was injected into the positive glass tank, and 3.0 % NaCl solution was injected into the negative glass tank, and the temperature of the solution should keep at 20-25 $^{\circ}$C. After injection the solution, the seal between the specimen and the glass tank was checked (Figure 3).

Applying 60 V DC voltage to both sides of the positive and negative glass tank after connecting the power line. Because of the great change of concrete during the initial period of electrification, the current value is recorded every 5 minutes. When the current tends to be stable, the instrument will record the current value every 10 or 30 minutes until the end of the 6-hour test. The total charge passed of RCPT for six hours was evaluated by equation (2) [31].

$$Q = 900\left(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_t + 2I_{300} + 2I_{330} + I_{360}\right) \quad (2)$$

where Q represents the total charge passed, Coulombs; I_0 represents current immediately after voltage is applied,

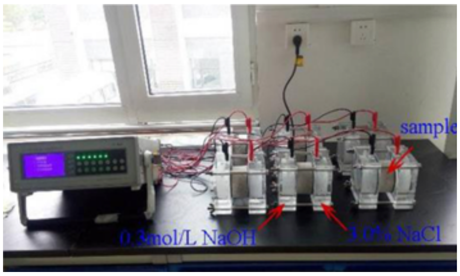

Figure 3. Rapid chloride penetration test.

Amperes; I_t represents current at t min after voltage is applied, Amperes.

Scanning Electron Microscopy

The microscope (JSM-7500F) is used to take the SEM images. The internal structure (holes and microcracks) of concrete can be better understood through SEM images. At the microstructural level, the bonding surface between glass fibers and cement paste, polypropylene fibers and cement paste or hybrid fibers (GF+PF) and cement paste can also be observed.

Results and Discussion

Compression and Bending Flexural Test Results

The test results of compressive strength test results for different volume fractions and types of fiber reinforced concrete at the ages of 3, 7, 14 and 28 days were presented in Table 7. The beam bending flexural strength test results for different volume fractions and types of fiber reinforced concrete at the ages of 3, 7, 14 and 28 days are listed in Table 8.

As one can see from Table 7 and Table 8, when the concrete age reaches 28 days, with the volume fraction increase of GF, PF and GF+PF, the compressive and flexural strength of fiber reinforced concrete increases continuously. When the fiber volume fraction reach to 1.5 %, the compressive strength of GFRC, PFRC and HFRC (GF+PF) are 31.80, 32.25 and 33.32 MPa at 28 days respectively, which are increased by 4.36 %, 5.84 % and 9.35 % compared to the OPC concrete. The flexural strength of GFRC, PFRC and HFRC (GF+PF) are 7.10, 7.18 and 7.33 MPa at 28 days respectively, which are increased by 16.58 %, 17.90 % and 20.36 % compared to the OPC

Table 7. Compressive strength of fiber reinforced concrete (cubic specimens)

Group no.	Mix ID	Compressive strength (MPa)				Improvement over OPC concrete (%)			
		3d	7d	14d	28d	3d	7d	14d	28d
1	OPC	21.89	25.04	26.99	30.47	100.00	100.00	100.00	100.00
2	0.5GF	18.99	22.66	27.86	30.6	86.75	90.50	103.22	100.43
3	0.5PF	18.08	23.28	25.21	30.65	82.59	92.97	93.40	100.59
4	0.25GF+0.25PF	19.5	22.92	24.69	32.82	89.08	91.53	91.48	107.71
5	1.0GF	19.51	21.56	29.88	30.9	89.13	86.10	110.71	101.41
6	1.0PF	19.05	22.11	27.48	31.16	87.03	88.30	101.82	102.26
7	0.5GF+0.5PF	19.59	23.68	27.26	33.62	89.49	94.57	101.00	110.34
8	1.5GF	18.01	22.86	24.11	31.8	82.28	91.29	89.33	104.36
9	1.5PF	18.08	23.55	28.71	32.25	82.59	94.05	106.37	105.84
10	0.75GF+0.75PF	18.41	21.59	25.67	33.32	84.10	98.63	95.11	109.35

Table 8. Flexural strength of fiber reinforced concrete (Beam specimens)

Group no.	Mix ID	Flexural strength (MPa)				Improvement over OPC concrete (%)			
		3d	7d	14d	28d	3d	7d	14d	28d
1	OPC	1.79	5.12	5.7	6.09	100.00	100.00	100.00	100.00
2	0.5GF	1.91	5.02	5.68	6.26	106.70	98.05	99.65	102.79
3	0.5PF	1.96	4.89	5.92	6.46	109.50	95.51	103.86	106.08
4	0.25GF+0.25PF	1.67	5.12	5.94	6.56	93.30	100.00	104.21	107.72
5	1.0GF	1.75	5.15	5.76	6.57	97.77	100.59	101.05	107.88
6	1.0PF	1.7	5.22	5.78	6.62	94.97	101.95	101.40	108.70
7	0.5GF+0.5PF	1.5	5.33	5.86	7.2	83.80	104.10	102.81	118.23
8	1.5GF	1.65	5.44	5.87	7.1	92.18	106.25	102.98	116.58
9	1.5PF	1.45	5.34	5.91	7.18	81.01	104.30	103.68	117.90
10	0.75GF+0.75PF	1.4	5.57	6.13	7.33	78.21	108.79	107.54	120.36

concrete. When the fiber volume fraction reach to 0.5 %, the increase ratio of compressive and flexural strength of HFRC (GF+PF) compared to the OPC concrete is the similar to the result presented by Wu *et al.* [32], which evaluated the mechanical and durability properties of carbon fiber, steel fiber and hybrid fiber reinforced concrete. The test results illustrate that the flexural strength of fiber reinforced concrete increases effectively with the addition of fiber material, but the compressive strength increases not obviously. When the same volume fraction of GF or PF are added into concrete respectively, the compressive and flexural strength of PFRC is stronger than GFRC. All the results show that adding GF+PF into concrete is the best mixture to improve the compressive strength and flexural strength of fiber reinforced concrete. It is noteworthy that the compressive strength and flexural strength of fiber reinforced concrete is lower than the OPC concrete at the initial stage of strength formation (e.g. the 3, 7 and 14 days). There are two main reasons for this phenomenon. Firstly, the addition of fiber materials will reduce the hydration reaction rate of cement paste in fiber reinforced concrete, and the bond strength between cement paste and aggregate will be lower than the OPC concrete. Secondly, the mechanical bonding force between fiber and cement paste will be affect by the low strength of cement. Therefore, it is necessary to concentrate on the curing of fiber reinforced concrete at the initial stage.

Rapid Chloride Migration Result

In this paper, the permeability of fiber reinforced concrete is evaluated by RCM test. The migration depth of chloride is measured and the migration coefficient of chloride is calculated. The permeability classification of fiber reinforced concrete is evaluated according to the experimental results. The chloride migration depth and coefficient for different volume fractions and types of fiber reinforced concrete are listed in Figure 4 and Figure 5. Table 9 shows the relationship between classifications of resistance to chloride penetration and chloride migration coefficients [33].

The results shown in Figure 4 and Figure 5 illustrate that adding the fiber material in concrete could significantly reduce the chloride migration depth and coefficient of the fiber reinforced concrete. According to the results shown from Figure 4, with the volume fraction increase of GF, PF and GF+PF, the depth of chloride ion migration decreases continuously. When the fiber volume fraction is 1.5 %, the depth of chloride ion migration of GFRC, PFRC and HFRC (GF+PF) are 22.7, 19.8 and 19.5 mm respectively, which are reduced by 10.9 %, 21.7 % and 23.3 % compared to the OPC concrete, the result is similar to the Teng *et al.* [34], which predicted the depth of chloride ion migration of polyvinyl alcohol fiber, steel fiber and hybrid fiber reinforced concrete. When the same volume fraction of GF or PF are added into concrete respectively, the chloride ion penetration resistance of PFRC is better than GFRC. All the result show that adding GF+PF into concrete is the best mixture to reduce chloride migration depth and migration coefficient. According to the results showed in Figure 5 and the classification in Table 9, the classification of resistance against chloride penetration for OPC concrete is high. When the volume fraction of PF or GF+PF is 1.0 % and 1.5 %, the classification of resistance against chloride penetration for fiber reinforced concrete is very high. According to the research result [35-39], when the volume fraction of fiber

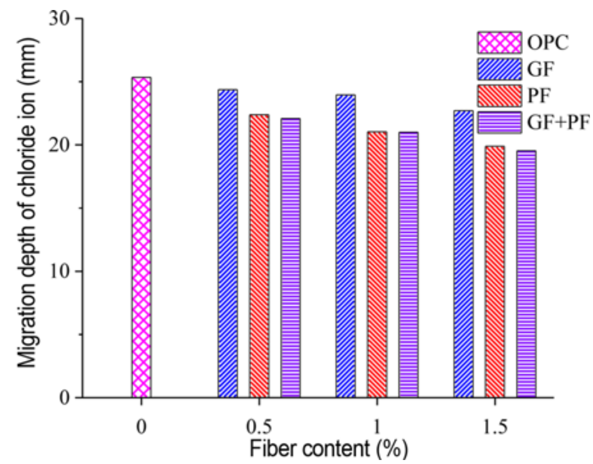

Figure 4. Chloride migration depth Figure 5. Chloride migration coefficients.

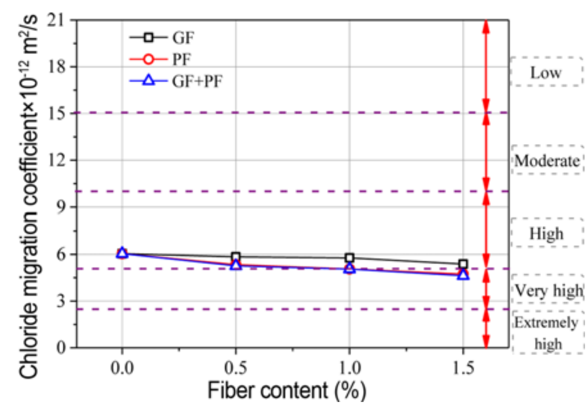

Figure 5. Chloride migration coefficients.

Table 9. Classifications of resistance to chloride penetration

Chloride migration coefficients×10^{-12} m^2/s	Classifications of resistance to chloride penetration
>15	Low
10-15	Moderate
5-10	High
2.5-5	Very high
<2.5	Extremely high

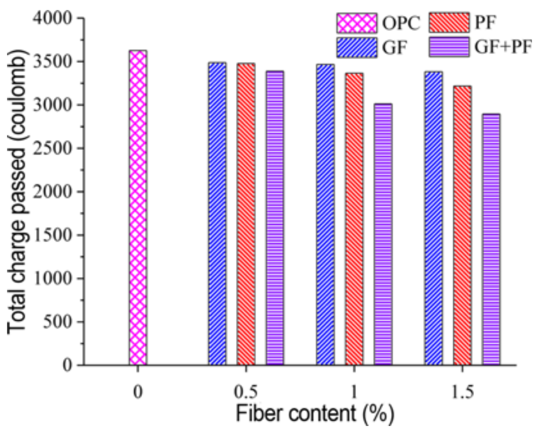

Figure 6. Total charge passed of fiber reinforced concrete.

more than 2 %, the working performance of concrete will decline. Therefore, the most effective way to improve the durability of fiber reinforced concrete is to add GF+PF with volume fraction 1.5 %.

Rapid Chloride Penetration Test Result

The total charge passed of the fiber reinforced concrete samples for different volume fraction of GF, PF and GF+PF is given in Figure 6. The experimental results show that total charge passed of fiber reinforced concrete decreases with the increase of GF, PF or GF+PF volume fraction. When the volume content of fiber in concrete is the same, GF+PF is significantly better than GF or PF in reducing the total charge passed. When the fiber volume fraction get 1.5 %, the total charges passed of GFRC, PFRC and HFRC (GF+PF) are 3381, 3217 and 2896 C respectively, which are reduced by 6.77 %, 11.3 % and 20.15 % contrasted to the OPC concrete. When the same volume fraction of GF or PF are added into concrete respectively, the total charges passed of GFRC is higher than PFRC. All the result show that adding GF+PF into concrete is the best mixture to reduce of total charges passed of concrete.

Scanning Electron Microscopy (SEM) Images

Figure 8 presents SEM images of OPC concrete and fiber reinforced concrete specimens. As one can see from the Figure 7, the glass fibers and polypropylene fibers are distributed linearly throughout the mixture and the bonding between the fibers and the surrounding cement paste is very good. When the fibers are added, the size of voids and the width of shrinkage cracks in concrete are obviously reduced. The hydrophobic fibers in concrete not only prevents the

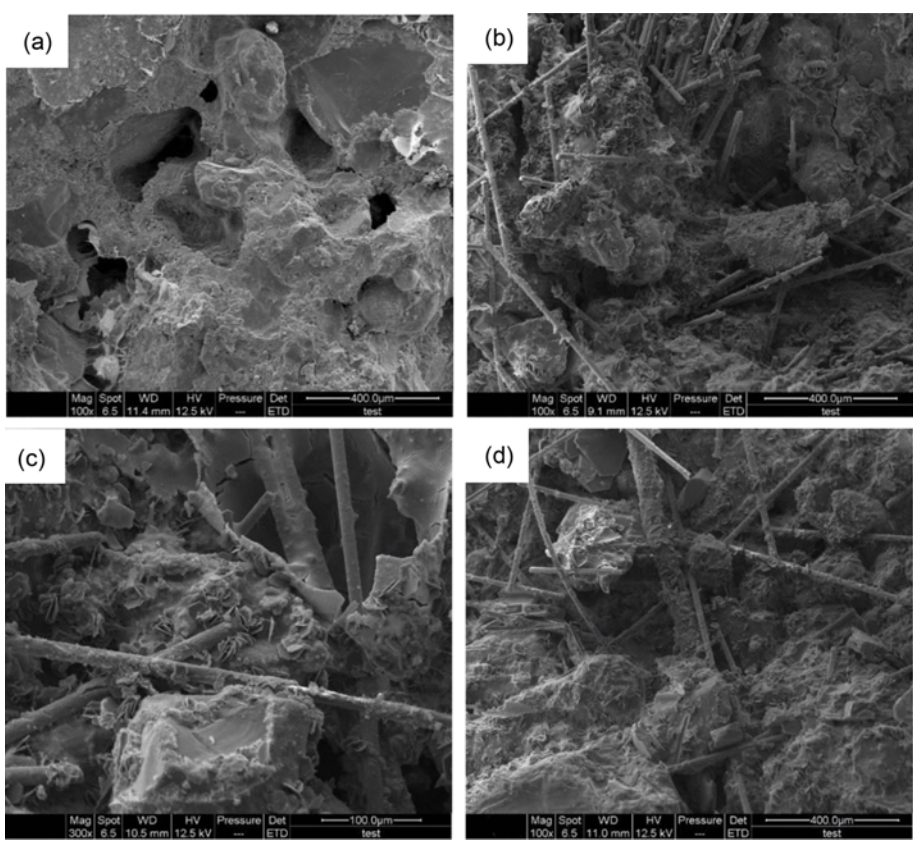

Figure 7. SEM image of OPC concrete and fiber reinforced concrete; (a) SEM image of OPC concrete, (b) SEM image of GFRC, (c) SEM image of PFRC, and (d) SEM image of HFRC (GF+PF).

development of shrinkage cracks, but also fills the voids to reduce the permeability of concrete, which is why the chloride ion resistance of fiber reinforced concrete is improved. Compared with the image of GFRC and PFRC (as shown in Figure 7(b), (c)), PFRC has smaller voids because of its smaller diameter, so the chloride ion penetration resistance of PFRC is stronger than GFRC. The SEM image of HFRC (GF+PF) as showed in Figure 7(d), the smaller diameter polypropylene fiber in the HFRC (GF+PF) fills the void generated by the larger diameter glass fiber, therefore, the porosity of hybrid fiber concrete is lower than the concrete mixed with one kind of fiber, which appears good hybrid effects.

Conclusion

The mechanical and durability properties of glass fiber, polypropylene fiber and hybrid fiber reinforced concretes have been obtained in this paper, respectively. Moreover, the paper considered the effect of volume ratio of additions on the fiber reinforced concrete. Because of the positive effect of bonding force between fibers and cement paste, the compressive and flexural strength of fiber reinforced concrete showed an obviously higher value than the plain specimen. In addition, comparing the other two fibers, the hybrid fiber reinforced concrete had the better effect on the concrete properties improvements. When the volume fractions of hybrid fiber was 1.5 %, the compressive and flexural strength increased 9.35 % and 20.36 % than plain concrete at 28 days, respectively. In this study, the concrete durability property is in terms of the chloride ions permeability resistance. From the chloride penetration tests, one can see that when the fiber volume fraction reach to 1.5 %, the migration depth of chloride ion of GF, PF and (GF+PF) reinforced concrete were reduced by 10.9 %, 21.7 % and 23.3 %, respectively. Especially when the volume ratio of PF and GF+PF was above 1.0 %, the resistance against chloride penetration reach very high level, which means the durability of concrete specimen is super improved. The reason resulting in the durability improvement should be that the addition fiber prevent the development of shrinkage cracks and reduce the total porosity. Moreover, this conclusion is also confirmed by the SEM image analysis. In general, the fiber reinforced concrete plays a better performance on the mechanical and durability properties than the plain concrete. Especially the hybrid fiber has the most obvious improvement. The findings of this research highly recommend these high performance fiber reinforced concretes widely applied in the practical constructions.

Acknowledgments

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