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EXPERIMENTAL STUDY ON THE COMPRESSIVE STRESS-STRAIN BEHAVIOR AND MICROSTRUCTURE OF POLYPROPYLENE FIBER REINFORCED CONCRETE

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Abstract: In this study, compressive stress-strain behavior and microstructure of polypropylene fiber reinforced concrete (PFRC) were investigated. Four fiber volume fractions of 0.05%, 0.10%, 0.15% and 0.20%, and three fiber aspect ratios of 167, 280 and 396 were selected as the main variations. The failure pattern, compressive strength, stress-strain curves and compressive toughness were studied. Scanning Electron Microscope (SEM) was used to observe the crystal structures at the aggregate/cement and fiber/cement interfacial transition zones (ITZs). The modification mechanism of PF was discussed. It is observed that addition of PF can significantly improve the failure behavior and mechanical properties of concrete. The mechanical behavior of PFRC, especially for post-peak ductility, is improved due to fiber crack arresting and bridging effect，while the improvement is insignificant or negative when the volume fraction exceeds 0.15%. The toughness and ultimate strain are enhanced as fiber volume fraction increased, while there is an optimum value for fiber aspect ratio. No obvious effect on compressive strength and peak strain can be found. It could be concluded that the volume fraction of PF shall be under 0.15%, and the optimum value of aspect ratio is 280. Results from SEM indicate that PF alters the microstructures of aggregate/matrix ITZ, with reducing the crystallization and orientation of CH and decreases micro-voids. The ITZ between fiber and matrix seems to be the weakest region in PFRC, and the poor bond is due to the voids and cracks existing at the fiber/matrix ITZ.

1. INTRODUCTION

As is known, PF has low modulus, light density, small diameter and not susceptible to corrosion. Polypropylene fiber reinforced concrete (PFRC) has been a promising construction material. The tensile, flexural, impact, and abrasion strength, deformation capacity as well as toughness of concrete can be enhanced by incorporation of fibers into matrix [1]. Moreover, when added into reinforced concrete (RC) structures, the bond performance between steel bar and concrete can be improved [2]. In addition, PF can be manufactured from the waste plastics, which is benefit to recycle the wastes. The economic cost of PF is low. Given these advantages, PFRC has been widely used in constructions, bridges, surface of pavements, tunnel linings and hydraulic structures.

Considerable efforts have been conducted to investigate the mechanical properties of PFRC [3-10]. However, the stress-strain behavior of PFRC is rarely reported. The limited studies showed that PF can improve the ductile behavior of concrete [11]. The toughness and failure strain can be enhanced by PF with higher content [12]. In addition, PF changes the post-peak failure behavior, from brittleness to ductility [13]. However, there is not enough studies on the influence of basic parameters, such as fiber content and fiber length, concerning on the mechanical behavior of PFRC. To facilitate PF used in RC, the compressive stress-strain behavior of PFRC, which is of critical importance for the structure engineering design, needs to be further investigated.

Macro mechanical response is closely related to the microstructures. The modification mechanism of PF has been studied by some researchers [14, 15]. They claimed that PF significantly alters the microstructure of concrete, reduces the crystallization and orientation of $Ca(OH)_2$, decreases micro-voids at the aggregate/cement interfacial transition zone (ITZ). However, the bond between fiber and matrix degrades and the gap increases with increasing the curing time [16] due to the hydrophobic nature of PF [15, 17]. All this may be owing to the effect of matrix shrinkage results in debonding of fiber and matrix, which enlarges the space between the two phases [18]. In addition, results from MIP showed that the harmful pores in PFRC are more than those in pure concrete [16]. The amount of weak interfaces increases with increasing dose of PF. From the above review, it can be observed that the modification mechanism of PF is not very clear, and controversial lights still exist. The effect of fiber parameters on the microstructures, especially at ITZs, has not been reported according to the author's knowledge.

The objective of this paper is to study the compressive stress-strain curves and microstructure of PFRC. The influences of PF on the basic mechanical parameters, stress-strain curve and toughness were investigated. The microstructures of ITZs were observed and the modification mechanism of PF in concrete was analyzed.

2. EXPERIMENTAL PROGRAM

2.1. Materials and specimens preparation

The prism specimens with a dimension of 150mm×150mm×300mm were employed in this study. The basic mix proportions of plain concrete are 1:1.74:2.60:0.42 (cement/sand/gravel/water) according to the code JGJ-2011 [19]. Portland cement type 42.5R was used as the binder. Gravel stones (size 5-20mm) were used as the coarse aggregates. Natural river sands with the fineness modulus of 2.6 were used as fine aggregates. A highly efficient superplasticizer was used. Its reducing rate is about 20%. Three types of PF, namely PFA (length=8mm, aspect ratio=167), PFB (length=13.6mm, aspect ratio=280), PFC (length=19mm, aspect ratio=396), were used. The diameter of them was fixed as 48μm. Four volume fractions of 0.05%, 0.10%, 0.15% and 0.20% were selected.

Mixing of the materials was according to JGJ-2011 [19]. Once the mixing process completed, the fresh concrete was cast into plastic molds. After vibrated 3-5min using a vibration table, the samples were kept under laboratory condition for 24h. They were then removed from the molds carefully and kept in a standard curing room until 28-day strength achieved. Each mixing design included six cubic molds (side=150mm) for compressive strength (f_{cu}) and splitting tensile strength (f_{st}) tests, three prism specimens for uniaxial monotonic compressive loading tests. The test results are listed in Table 1.

Table 1: Basic mechanical properties and monotonic loading results of PFRC

Specimens	V_f (%)	l_f/d_f	Basic properties		Monotonic loading results			
			f_{cu}(MPa)	f_{st} (MPa)	σ_{cu}(MPa)	ε_{cu}(10^{-3})	ε_{ul}(10^{-3})	E_0 (GPa)
PF000	-	-	47.53	2.75	36.57	1.775	6.294	2.463
PFA05	0.05	167	47.62	3.24	33.40	1.688	7.085	2.616
PFA10	0.10	167	46.43	3.35	33.66	1.854	7.767	2.679
PFA15	0.15	167	45.84	3.47	34.27	1.987	7.336	2.725
PFA20	0.20	167	43.22	3.17	29.06	2.016	5.586	2.224
PFB10	0.10	280	47.26	3.42	33.12	1.833	7.686	2.642
PFB15	0.15	280	46.45	3.68	34.00	1.895	8.271	2.748
PFC10	0.10	396	46.14	3.55	34.34	1.765	7.029	2.730
PFC15	0.15	396	44.65	3.58	33.68	1.694	7.583	2.926

2.2. Test methods

Compressive stress-strain behavior test was conducted on a universal electro-hydraulic servo rock testing machine INSTRON-1346. The test setup and details of instrumentations are schematically shown in Fig.1. For each batch of mix type, three specimens were tested under monotonic compression. A displacement control method with a speed of 0.002mm/s was used. The loading process was terminated until the concrete specimens collapsed into failure.

The microstructures of PFRC were observed by using the Hitachi Quanta-200 Scanning Electron Microscope (SEM). The aggregate-paste and fiber-paste interfacial transition zones were focused to be investigated.

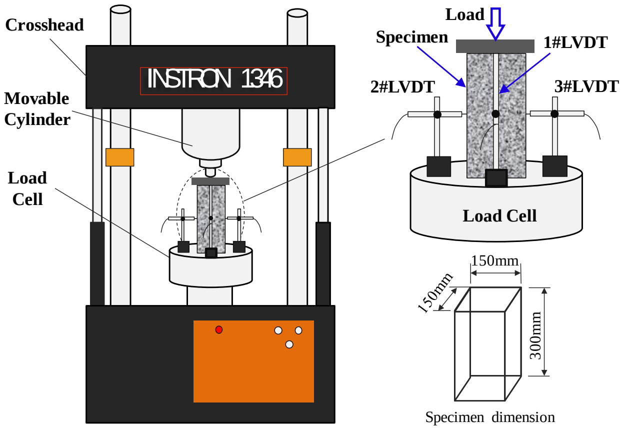

Figure 1: Schematic diagram of experimental set-ups.

3. RESULTS AND DISCUSSIONS

3.1. Failure pattern

Fig.2 shows the typical failure pattern of PFRC. The results indicate that PF has a remarkably improvement on the failure behavior of concrete by addition of PF. The failure pattern of pure concrete is brittleness, while that of PFRC transfers from brittleness to ductility with increasing the volume fraction of PF. For plain concrete, at the failure stage, large vertical cracks can be seen that slice the prismatic specimens into some small columns, which undertake the total ultimate loads. While for PFRC, distinct ductile failure pattern can be observed. The tensile stress between two sides of a crack is transferred to fibers, which makes the specimens remain entirety. Due to the high elongation and large deformation of PF, they can bridge the cracks during the failure stage. During the loading process, only little concrete spalls from the PFRC specimens when compared to plain concrete. Cross diagonal cracks appear on the surface of PFRC specimen, showing an obvious shear failure mode. Moreover, the plain concrete collapses into two inverted cones at the final loading stage. While for PFRC, the specimen remains a whole, in general.

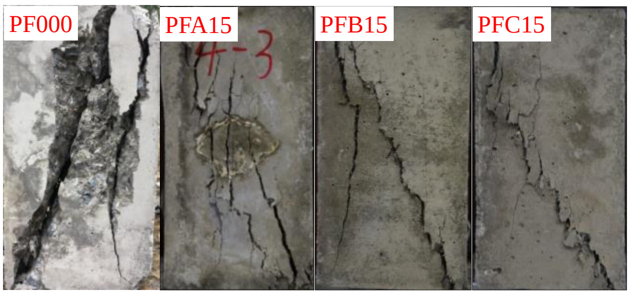

Figure 2: Failure patterns of PFRC.

3.2. Stress-strain curves

The complete stress-strain curves of PFRC are plotted in Fig.3. Each curve represents the average results of three specimen tests conducted at the same age and conditions. It can be seen that the stress-strain curves for different concrete mix proportions are similar generally. Overall, the ascending branch is almost tracing together until the stress reaches the 70-80% of peak strength. The peak stress and peak strain all have a fluctuation for different fiber volume fractions and aspect ratios. The ascending slope after 70-80% of peak strength decreases as the fiber volume fraction increased. For plain concrete, the curvature at the descending branch is larger than that of PFRC, resulted in a poor ductility. In general, an increase in fiber volume fraction improves the post-peak ductile behavior of concrete. In terms of fiber aspect ratio, the variations between the stress-strain curves are slight. The ductility of concrete increases initially when the fiber aspect ratio comes from 167 to 280 and reduces afterwards. The concrete reinforced by PF of aspect ratio 280 shows the best ductility.

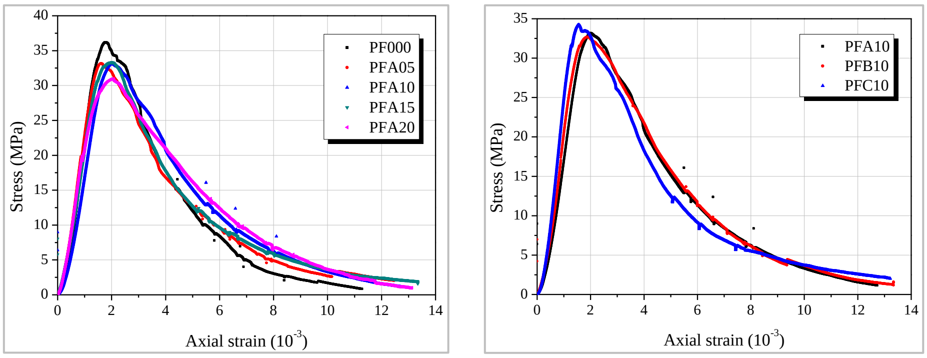

Figure 3: Stress-strain curves of PFRC. (a) Effect of fiber volume fraction. (b) Effect of fiber aspect ratio.

3.3. Compressive strengths

Fig.4 shows the mean results of cubic and prismatic compressive strengths at 28 days. For each mix batch, three specimens were measured. Results obtained are listed in Table 1. The results indicate that addition of PF decreases the compressive strength for both cubic and prismatic specimens. The compressive strengths for the volume fraction of 0.10% are all slightly higher than those for the volume fraction of 0.15%. Compared to pure concrete, insignificant increase is observed by the amount of 0.19% for PFA05. They decrease slightly with an increase in fiber volume fraction, except for the volume fraction of 0.2% with a significant reduction, which may be owing to the balling effect of fibers during the mixing procedure. For both fiber volume fraction (up to 0.15%) and aspect ratio, the variation of compressive strength is small. This finding is consistent with the conclusions in literatures [3-7]. However, in some researchers' studies, when increasing the fiber aspect ratio, the compressive strength increases as well, the main reason for that is the longer fiber has a stronger bridging effect and pull-out resistance contributing to the concrete strength [17, 20]. Therefore, in an attempt to study the effect of PF on compressive strength of concrete, further studies on a large amount of specimens are needed.

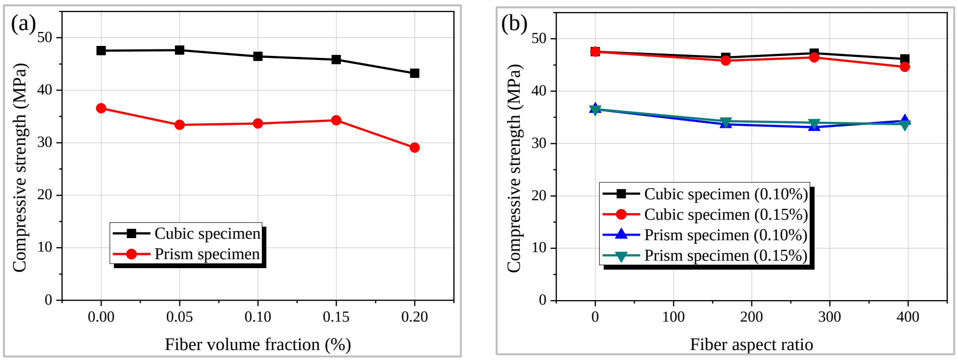

Figure 4: Compressive strengths of PFRC. (a) Effect of fiber volume fraction. (b) Effect of fiber aspect ratio.

3.4. Peak strain and ultimate strain

Fig.5 illustrates the peak strain and ultimate strain of PFRC for variable fiber volume fractions and aspect ratios. The peak strain is the corresponding strain at the peak stress. In this study, the ultimate strain is determined as the strain when the descending stress reaches 20% of the peak stress [21]. The calculated strains are listed in Table 1. It can be seen that addition of PF has insignificant effect on peak strain, but influences the ultimate strain notably. An increase in fiber volume fraction increases the peak strain as well, with a slight bias slope, while it almost remains constant with increasing the fiber aspect ratio. For ultimate strain, an increase with increasing fiber volume fraction can be firstly observed, but it decreases when the volume fraction exceeds 0.10%, the reduction is obvious especially for the volume fraction of 0.2%. As stated before, this finding may be owing to the initial damages in concrete matrix accounting for the large dosage of PF. The variable tendency is alike a parabola (see in Fig.5a). For fiber aspect ratio, the similar phenomenon can be seen in Fig.5b, but all the ultimate strains of PFRC are over those of pure concrete. It can be concluded that the length of PF exists an optimum value. The long fiber may have large embedded depth between the two sides of a crack, the fraction resistance and ultimate bond strength are large against the fiber pulled out from the matrix. On the other hand, for a constant fiber volume fraction, the longer fiber reduces the amount of fibers in the concrete composite, thus induces less fibers bridging a crack. Therefore, the absorbed energy during fiber pull-out and fracturing turns small. Based on the current study, considering the mechanical properties and deformation behavior, the aspect ratio of 280 is appropriate for the concrete designed in this work.

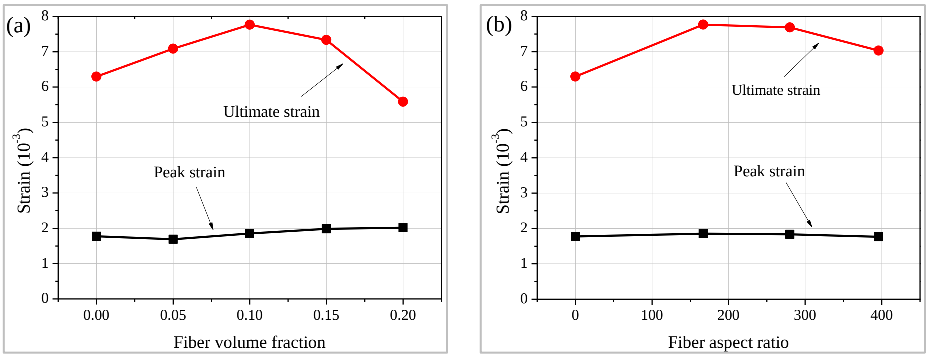

Figure 5: Peak and ultimate strain of PFRC. (a) Effect of fiber volume fraction. (b) Effect of fiber aspect ratio.

3.5. Compressive toughness

Toughness, defined as the area under the compressive stress-strain curve, can be used to represent the energy absorption capacity. In this study, the peak toughness is the area under stress-strain curve when it reaches the peak stress, and the total toughness is when it reaches the ultimate strain. The specific toughness is defined as the ratio of total toughness and peak strength of concrete [21].

Fig.6 represents the variation of the calculated pre-peak, post-peak, ultimate and specific toughness for different fiber volume fractions and aspect ratios. It can be observed from the two figures that, in general, all the toughness increase with increasing the fiber volume fraction up to 0.2%, in spite that a small drop in pre-peak toughness with the fiber volume fraction of 0.05%. They increase first and then decrease as fiber aspect ratio increased. The results provide that the fiber aspect ratio has an optimal value of 280. From the results in this study, it can be concluded that addition of PF can enhance the compressive toughness (energy absorption capacity) and improve the ductile behavior of concrete remarkably.

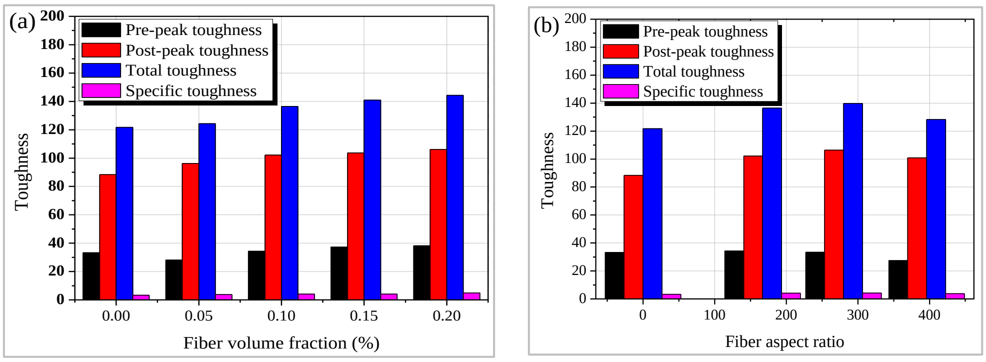

Figure 6: Toughness of PFRC. (a) Effect of fiber volume fraction. (b) Effect of fiber aspect ratio.

4. MICROSTRUCTURES

4.1. Microstructure at aggregate/matrix ITZ

The microstructures at the ITZ between aggregate and matrix are shown in Fig.7. The magnifying ratio is 5000x. From this figure, cracks in ITZs can be observed. Hydrated productions, alike CH crystalloid and C-S-H gel, cover on the surfaces of the cracks. A large amount of C-S-H gels heaps up on at the sides of the ITZs. The amount of them in PFRC is larger and the ITZ is denser than that in plain concrete. What's more, the voids of plain concrete are more than those of PFRC at the aggregate/matrix ITZ. This finding has been reported by other researchers [14]. As the fiber volume fraction increases from 0.1% to 0.15%, the C-S-H gels increase and CH decreases. PF alters the microstructures of ITZ between aggregate and cement paste, and changes the orientation and amount of productions, especially for CH. The increased C-S-H gels and reduced CH crystalloid improve the bond performance of aggregate and matrix. When comparing the microscopes of PFA15 and PFC15, the ITZ in PFC15 is denser than that in PFA15. More C-S-H gels can be observed in PFC15. The results indicate that the length of fiber has a significant effect on the microstructures of ITZs. When the fiber length increased, the microstructure at aggregate-matrix ITZ becomes dense.

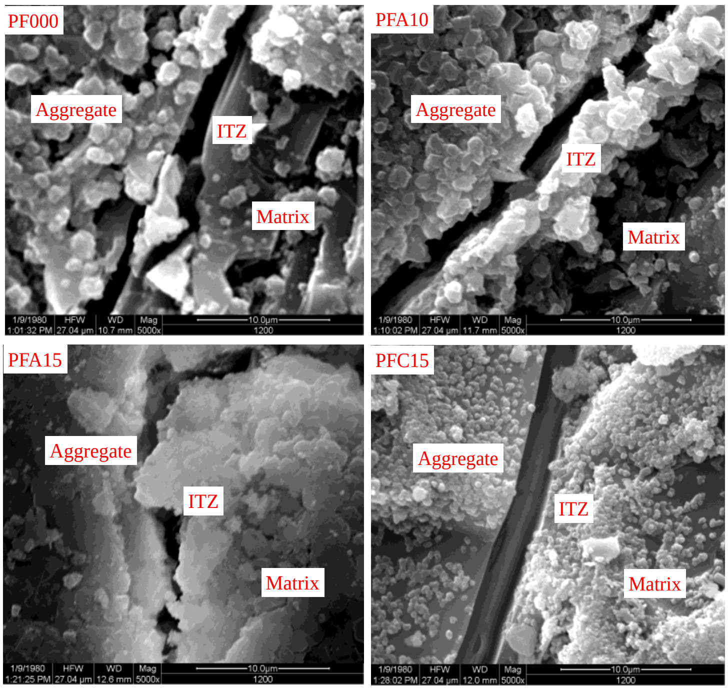

Figure 7: Microstructure at aggregate/ matrix ITZ (5000x).

4.2. Microstructure at fiber/matrix ITZ

Fig.8 presents the microstructure at ITZ between fiber and matrix. It can be seen that the fiber is wrapped by cement paste and some white hydrated production coats on the surface. The fiber and matrix are connected by C-S-H, which is the main component to determine the bond strength between fiber and matrix. This figure indicates that to some extent the bond between fiber and cement matrix is good. However, there still exists cracks between fibers and matrix and many micro voids can be observed at the fiber/matrix ITZ, which are dangerous to the bond performance of fiber and matrix. As far as we know, PF does not participate in any chemical reaction with cement because of its natural hydrophobicity. While the cement paste is hydrophilic, many air voids exist in the corrugations between fiber and matrix in fresh concrete composites. During the hardening process, shrinkage of concrete matrix occurs due to self-constriction. The initial crack between fiber and matrix turns larger [18]. Results in literatures [16] have shown that in the early curing time, the crack between fiber and matrix is small, however, the width increases at 28 days in comparison with that of 3 days. The hydrophobic nature of PF could be the main reason for poor bonding between the fiber and the matrix [18].

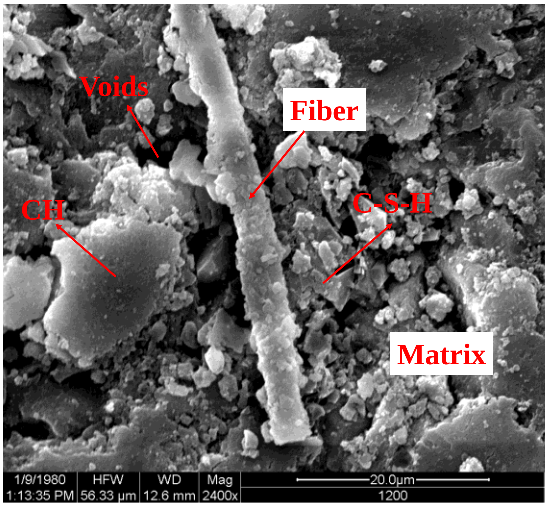

Figure 8: Microstructure at ITZ PF/ matrix.

5. CONCLUSIONS

Monotonic compressive loading and SEM tests were conducted to investigate the compressive stress-strain behavior and microstructure of PFRC. It is found that the mechanical behavior is improved by the inclusion of PF in terms of ductility and toughness. The results indicated that the failure pattern of concrete specimen transfers from brittleness to ductility to some extent by addition of PF. The compressive toughness is enhanced as fiber volume fraction increased, while for fiber aspect ratio, there is an optimum value. Insignificant effects on the compressive strengths and peak strain of concrete reinforced by PF can be observed. An increase in both volume fraction and aspect ratio leads to an increase first and then a decrease in the ultimate strain of concrete. It could be concluded from the above results obtained that 280 is the optimum aspect ratio of PF and the volume fraction of PF shall be under 0.15%. Results from SEM showed that PF alters the microstructures at ITZs. The increase in both fiber volume fraction and aspect ratio can induce an increase in the amount of C-S-H. The orientation and amount of CH at aggregate/matrix ITZ is changed by incorporation of PF. ITZ between fiber and matrix seems to be the weakest region in PFRC, the bond of which is poor due to the voids and cracks existed at the fiber/matrix ITZ.

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