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Tension and impact behaviors of new type fiber reinforced concrete

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Abstract. This paper is concentrated on the behaviors of five different types of fiber reinforced concrete (FRC) in uniaxial tension and flexural impact. The complete stress-strain responses in tension were acquired through a systematic experimental program. It was found that the tensile peak strains of concrete with micro polyethylene (PEF) fiber are about 18-31% higher than that of matrix concrete, those for composite with macro polypropylene fiber is 40-83% higher than that of steel fiber reinforced concrete (SFRC). The fracture energy of composites with micro-fiber is 23-67% higher than that of matrix concrete; this for macro polypropylene fiber and steel fiber FRCs are about 150-210% and 270-320% larger than that of plain concrete respectively. Micro-fiber is more effective than macro-fiber for initial crack impact resistance; however, the failure impact resistance of macro-fiber is significantly larger than that of micro-fiber, especially macro-polypropylene-fiber.

Keywords: polypropylene fiber; polyethylene fiber; steel fiber; concrete; uniaxial tension; crack; complete stress-deformation curve; flexural impact behavior.

1. Introduction

So far, there are many types of synthetic fiber used in civil engineering. Synthetic fiber's diameter may be large or small. A fiber with diameter larger than 0.1 mm is also defined as macro-fiber. So for synthetic fiber, contain macro-fiber and micro-fiber. The micro-fiber often is used to control early plastic shrinkage cracking, the macro-fiber is not only used to restrain early plastic crack, but also to improve the properties of hard concrete. Barchip fiber was selected as a representative of macro-synthetic fiber in this program.

In the past, only macro-fiber of steel was used as reinforcing material in concrete. In recently year, many new types of synthetic macro-fiber, such as Barchip fiber and Forta fiber, were used as reinforcing materials in civil structures (Barchip fiber's diameter is larger than 0.1 mm). Steel fiber rusts easily in concrete pavement and marine structures. Macro synthetic fiber such as Barchip fiber (made in Japan) advantages include no rusty, a reduction of cracking, and enhancements to ductility, impact resistance, and toughness, along with economic benefits of reduced placement labor and overall savings in reinforcement costs. In addition, Macro synthetic fiber reinforced concrete is capable of sustaining superior energy absorption values when compared to steel fiber reinforced concrete and is undoubtedly the most suitable reinforcement selection where high ground

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deformations (earthquake) are expected.

For synthetic micro-fiber, polypropylene (PP for short) fiber was often used as early retrain material for cement based materials; PEF fiber with high elastic modulus can improve the toughness and impact performances of concrete.

Much attention has been paid by researchers in recent years to impact problems (Gupta, *et al.* 2000, Banthia, *et al.* 1998, Bindiganavile and Banthia 2001, Lok 2004). There are many reasons behind this increasing interest. New types of macro synthetic fiber reinforced concrete have been used in many civil engineering structures, but little is known of their impact performance and tensile property. Some structures such as concrete pavements for highways or bridge decks, marine structures are usually subjected to impact and other dynamic loads. There is increasing recognition that the effects of impact loading on the behaviors of the materials may be significant under service loading, even if the impact loading does not cause an impact failure. Airport pavements are also subjected to many hundred thousand cycles of impact loading. Brittle nature of concrete allows for easy damage and catastrophic failure under impact load. Such as concrete pavements usually were failures under impact and fatigue loads. Some of the impact studies to date have dealt with steel fiber reinforced concrete (Banthia, *et al.* 1998, Bindiganavile and Banthia 2001, Lok 2004), and only limit understanding exists of the resistance of concrete with synthetic fiber reinforcement to impact load. Consequently, understanding and comparing the impact properties for composites with different type fiber are also needed. One purpose of the present study was to examine the impact behaviors of synthetic macro-fiber reinforced concrete using instrumented drop weight impact machines.

A number of researches have been performed in the past to evaluate the tensile performances of plain concrete (Ansari 1987, Wang, *et al.* 2000, Van Mier and Van Vliet *et al.* 2002, Li, *et al.* 1993, Evans and Marathe 1968, Banthia and Sheng 1996). Fiber reinforced concretes are structural materials developed through extensive research and development during the last two decades (Banthia, *et al.* 1994). Micro polypropylene and polyethylene fiber have generally been used as a secondary reinforcement for concrete, and micro-fiber volume fraction ranged from 0.05-0.2%. Serious tensile cracking problems are also encountered in shell panel/plate structures. There is a need to know whether there are other changes in the tensile strength and peak strains and elastic modulus of concretes reinforced with micro synthetic fiber at such small volume fraction. Macro synthetic polypropylene and steel fiber have generally been used as reinforcement for concrete, and fiber volume fraction ranged from 1-1.5%. There is a need to research the tensile behaviors of concrete with synthetic macro-fiber and compare the effectiveness of synthetic macro-fiber and steel fiber in improving tensile behaviors of concrete.

Fiber's volume fraction of micro and macro fiber ranged from 0.05-0.2% and 1-1.5% respectively tested in this paper is generally application volume of civil engineering.

In addition to the basic mechanical parameters, the stress-crack width (σ-w) curve or the descending branch of the tension stress-deformation curve can be used to characterize the tensile behaviors of fiber reinforced concrete. In principle, the response of an FRC can be predicted from such a σ-w curve which show the material constitutive relation along the matrix cracks in the structure. In addition, the widely recognize R-curve behavior associated with the formation and growth of the fiber bridging zone in the tip region of a macroscopic crack can be predicted once the σ-w curve relationship is known. Therefore, the σ-w curve directly reflects the composite internal failure performance and deformation mechanism, for these reasons, considerable interest has been generated in experimental evaluation of the direct tensile behavior of FRC, although most of the work has been on the use of steel fiber as the reinforcing materials (Mobasher and Cheng 1996, Deng 2000).

The fracture energy and tensile properties of FRC strongly affect cracking, deformation, shear, and bond behavior in structural members. To date, there are limited experimental data available concerning the fracture energy and tensile properties for un-notched synthetic macro-fiber FRC specimens in direct tension. Consequently, the test research on the fracture energy of fiber reinforced concrete is necessary.

Accordingly, the objectives of this investigation were as follows:

1. To compare the uniaxial tensile and flexural impact properties between synthetic micro-fiber FRCs and macro-fiber (both synthetic and steel fibers) FRCs at similar fiber volume fraction, to acquire the complete stress-deformation responses in tension, and to obtain the basic and fracture mechanical parameters: tensile strengths, peak strains, elastic modulus and fracture energy.
2. To understand the reinforcing effects on tensile behavior at different fiber volume fractions and to develop an empirical model for axial stress-crack width curves of synthetic and steel fiber reinforced concrete.
3. To compare the reinforcing effects of low elastic modulus synthetic PP micro-fiber and high elastic modulus PEF fiber based on flexural impact and tensile behaviors at close fiber volume fraction (0.045-0.14%);
4. To compare the reinforcing effects of synthetic macro-fiber and steel fiber on flexural impact and uniaxial tensile behaviors at similar fiber volume fraction (1-1.2%).

2. Research significance

The investigation reported herein introduces some experimental data for five type fibers reinforced concrete (FRC) in uniaxial tension and flexural impact. Different type fibers include micro polypropylene and polyethylene fibers and macro polypropylene and steel fibers. The experimental data pertain to flexural impact life, tensile strength, fracture energy and stress-crack width curves of composites in uniaxial tension. This information has not been previously available for macro-polypropylene fiber FRCs and micro-polyethylene fiber FRCs. The comparison shows an evident effect of fiber type on the behavior of composite in uniaxial tension and flexure impact.

3. Materials and sepecimens

3.1. Materials and mix proportions

Type I Portland cement conforming to ASTM C 150 was employed in all mixes. The 20 mm crushed granite rock conforming to the ASTM C 33 gradation requirements was employed as the coarse aggregate. ASTM No.2 grade river sand was employed as the fine aggregate.

The water-to-cement ratio used for all mixes was 0.45. All mixes contained 360 kg/m^3 of cement, 1100 kg/m^3 of coarse aggregate, 647 kg/m^3 of sand.

Synthetic fiber used in the FRC test specimens included both high elastic modulus and high strength polyethylene (PEF) and low modulus polypropylene fiber (PP).

Table 1 Fiber's properties and geometer parameters

Fiber type	Length, mm	Diameter, mm	Tensile strength, MPa	Modulus, GPa	Density, kg/cm^3	Manufacturer
Polypropylene (PP micro-fiber)	19	0.048	330-414	3.7	0.91	American Hill Brothers Chemical Co.(Durafiber)
Polyethylene (PEF micro-fiber)	20	0.02	3000	95	0.97	Zhejiang-China
Polypropylene (Barchip macro-fiber)	30	0.55	547-658	3.5	0.90	Japan (Barchip)
Dramix (macro-fiber)	30.5	0.5	1100	210	7.8	Shanghai-China
Harex (macro-fiber)	32	1.43	730	210	7.8	Metalwork of Shanghai-China

Polypropylene fiber used in the FRC specimens included both micro monofilament fiber (fiber's diameter is lesser than 0.1 mm) and macro-fiber (Barchip fiber's diameter is larger than 0.1 mm). Steel fiber included Dramix and Harex fibers. The fiber properties are shown in Table 1.

3.2. Mixing and casting

Composites mixtures were prepared in a drum-type mixer. The flexibility of the mixing chamber allows the breakup of the fiber and contributes to the mixing action, while a vigorous shearing action distributed the fiber homogeneously.

In the mixing procedure, micro-PP, PEF fiber or macro-Barchip fiber, the fine and coarse aggregate were first mixed together with 2/3 of the required water and mixing was continued for 3 minutes. Next the cement was added followed by the reminding 1/3 of the water. Thereafter, the mixing was continued for a further 2 minutes.

For steel fiber, the mixer was first loaded with the coarse, fine aggregate and fiber, mixing for 3 minutes. After that, cement and water were added into the mixer and mixing was continued for 3 minutes. There was no problem for fiber dispersion during mixing.

3.3. Specimens and curing

Tension and impact specimens were cast in 100×100×550 mm prism steel molds, whereas static flexural specimens were cast in 150×150×550 mm prism steel molds.

Freshly cast specimens were kept in the mould for 24 hours at which time they were demolded. Then all of specimens were stored in standard curing condition room. Both ends of the tension specimen were cut to 70 ± 2 mm by a diamond circular saw. At approximately 48 hours prior to testing all specimens were kept in a normal room for desiccation. Specimens were tested at about 28 days.

A total of 252 specimens, as shown in Table 2, were used in the testing programme. In Table 2 and Fig. 2 and 3, C present plain concrete; PP1, PP2 and PP3 present composites with monofilament micro polypropylene fiber and fiber's volume fraction is 0.05, 0.095 and 0.14% respectively; where PEF1, PEF2 and PEF3 present composites with monofilament polyethylene micro-fiber and fiber's volume fraction is 0.045, 0.082 and 0.12% respectively; Barchip1-3 present

Table 2 Fiber volume fraction in specimen and number of specimen

Specimen designation	Fiber percent by volume, %	Number of specimens		
		Static flexural beams	Tensile specimens	Impact specimens
C	0	6	3	12
PP1	0.05	6	3	12
PP2	0.095	6	3	12
PP3	0.14	6	3	12
PEF1	0.045	6	3	12
PEF2	0.082	6	3	12
PEF3	0.12	6	3	12
Barchip1	1.0	6	3	12
Barchip2	1.2	6	3	12
Barchip3	1.4	6	3	12
Dramix	1.0	6	3	12
Harex	1.0	6	3	12

composites with different fiber volume fractions of macro-fiber (Barchip fiber), Dramix and Harex present composites with Dramix and Harex steel fiber.

4. Testing procedure for uniaxial tension and flexural impact

Acquisition of complete stress-deformation response in uniaxial tension tests requires a very stiff testing machine and closed-loop test methods. Also proper grips and extreme care in alignment of load line of action are important in order to avoid larger eccentric loading. The requirements were met by using a very stiff frame servo-hydraulic closed-loop testing machine designed for testing of high strength materials with upper and lower spherical joints. The stiffness of the testing frame is 6×10^6 N/mm with a load capacity of 3000 kN. The rotation angles of the spherical joints are both twenty degrees, which guarantees the relative eccentric extent lower than 10%. A microcomputer provided the command signals for the closed-loop control of the experiments. The same microcomputer was employed for acquisition of data. Specimens were glued to end-platens with epoxy 88 hours prior to the experiments. Once the glue has had time to set, the specimens were attached to the spherically seated upper and lower joints in order to ensure the concentricity of the axial loading. Four extensometers were used across the whole specimens for measurement of axial deformations. All the extensometers have a displacement range of ±5 mm. The average displacement from the output of four extensometers was employed in computation of strain. The maximum displacement from the output of four extensometers was used as the feedback signal in order to obtain the complete stress-deformation curve for each specimen (Hillerborg, *et al.* 1976). All specimens were tested in strain control mode at the rate of 2 micro strains per minute until completion of the experiment.

Impact test on the beams were carried out in three-point flexural on a span of 340 mm as shown schematically in Fig. 1. This test was performed in an instrumented drop-weight impact machine. The machine has a 1.4 kg hammer that was dropped from a height of 0.4 m in a test. At this drop height, the hammer had a potential energy of 55 J, and an approach velocity of 2.8 m/s just striking the specimen.

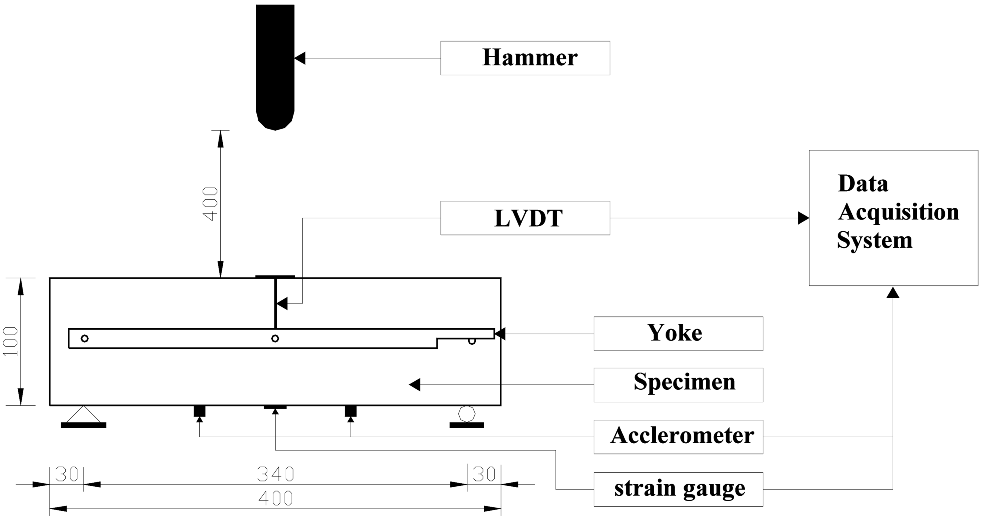

Fig. 1 Schematics of flexural impact test setup

Static flexural strength test on beam was carried out in four-point flexural on a span of 450 mm.

5. Results and discussions

The fresh concrete with fiber was observed to have less segregation than plain concrete and exhibited a significant reduction of surface bleeding. This test supports the fact there is no correlation between slump and workability, specifically for fiber reinforced concrete. All fiber was observed to uniformly distribute in the matrix. The distribution performance of macro-fiber is better than micro-fiber in composite.

5.1. Tensile properties

Three specimens were tested in tension for each mix and least two specimens were completed without unexpected specimens' failure. Figs. 2(a-b) depict stress-deformation behavior of the composites with macro-fiber and micro-fiber in tension respectively.

The mechanical properties of the FRC were evaluated from the stress-deformation relationships and given in Table 3. In Table 3, f_t' is the tensile strength, ε_{tf} the strain in tension at maximum stress, E_t the secant modulus of elasticity in tension evaluated at 50% of peak stress on the ascending branch of stress-strain curve, G_F the fracture energy, w_f the maximum crack width that will be explained in the following section, f_{rt} from flexural test the flexural strength. These test results clearly indicate the reinforcing effects of tensile and impact behavior for the different type fiber at different fiber volume fractions.

5.2. Tensile strengths

From Table 3 it is seen that the tensile strength measured by flexural tensile tests is generally

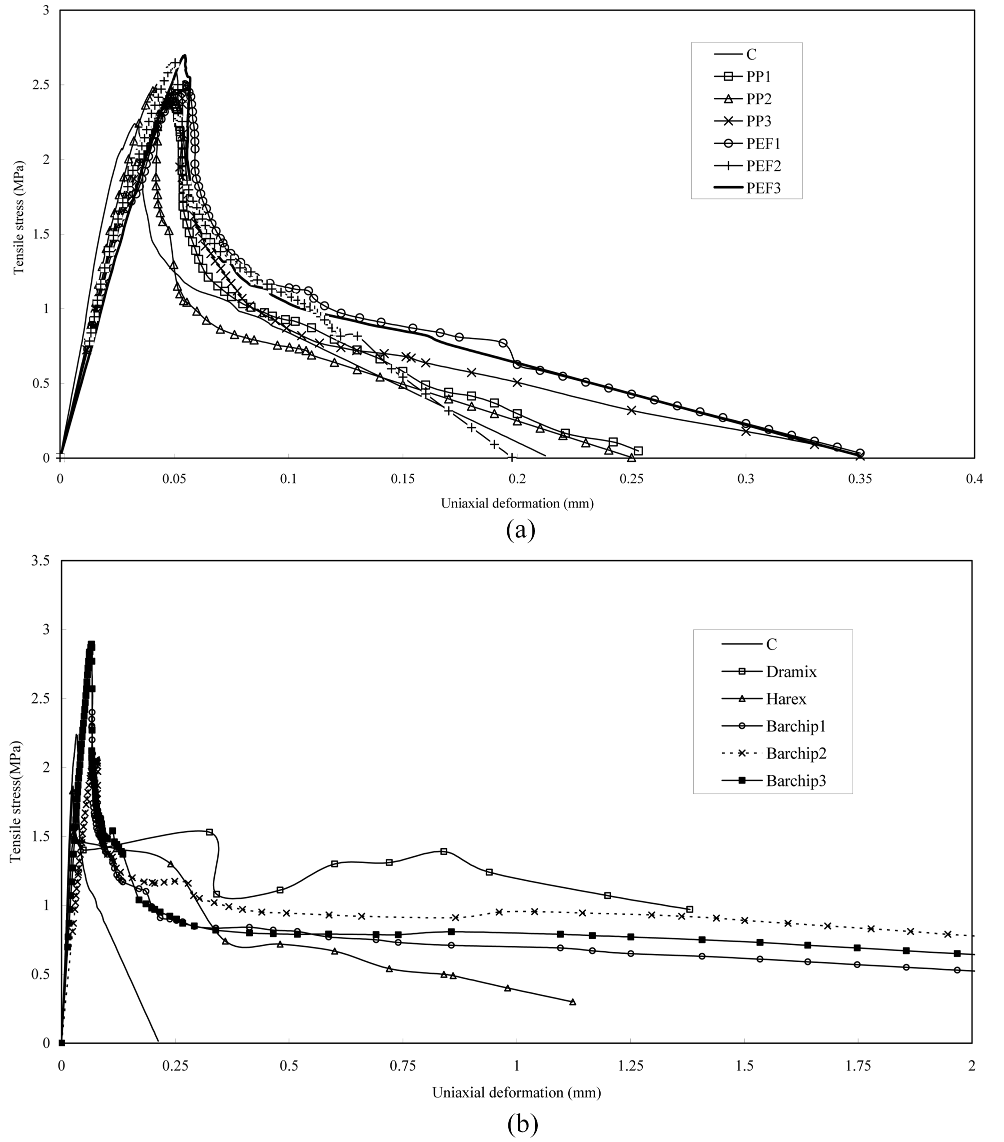

Fig. 2 Axial stress-deformation curves of macro-fiber reinforced concrete in uniaxial tension

larger than that by the direct tensile tests.

Composite with 0.05-0.14% of PP micro-fiber (mixes PP1-PP3), tensile strength is about 4-8% larger than matrix concrete. Low-modulus PP micro-fiber could provide small resistance to crack forming and developing. The tensile strengths of micro-PEF FRC (mixes PEF1-PEF3) are about 7-9% higher than that of composites with PP micro-fiber, this may be due to PEF fiber with high elastic modulus and strength.

For macro-fiber, the tensile strength of composites with Barchip fiber is close to composite with Harex steel fiber at same fiber volume fraction. With the reinforcement of 1% of Barchip macro-fiber, the tensile strength is about 12% larger than plain concrete.

Table 3 Mechanical properties of fiber reinforced concrete in tension and flexural

Specimen designation	Mechanical parameters in uniaxial tension										f_{rt}	
	f_t'		ε_{tf}		E_t		G_F		w_f			
	MPa	CV%	10^{-6}	CV %	GPa	CV%	N/m	CV%	mm	CV%	MPa	CV%
C	2.24	12.4	122	14.2	21.7	12.1	129.4	24.1	0.179	18.1	4.01	26.4
PP1	2.33	3.7	141	5.6	19.3	13.8	172.3	28.9	0.237	12.8	3.76	20.1
PP2	2.40	5.7	149	4.8	19.0	5.6	190.7	9.5	0.247	9.6	4.01	16.7
PP3	2.43	11.6	152	10.1	19.4	9.5	217.3	6.5	0.251	11.5	4.22	14.2
PEF1	2.50	6.7	144	11.3	20.8	10.8	158.6	11.4	0.261	12.8	3.97	21.4
PEF2	2.61	5.1	152	7.5	21.3	7.6	165.0	10.0	0.264	10.9	4.05	18.6
PEF3	2.64	10.6	157	10.8	21.6	8.4	189.7	7.6	0.259	11.2	4.41	23.7
Barchip1	2.50	12.7	178	10.2	19.1	10.1	328.6	11.4	0.421	12.4	5.36	12.7
Barchip2	2.68	13.9	240	10.9	18.6	7.9	404.0	8.8	0.463	13.8	5.47	11.8
Barchip3	2.70	11.4	244	12.0	18.2	10.4	441.2	9.6	0.540	14.6	5.51	9.62
Dramix	2.58	4.7	138	9.4	21.9	6.1	549.0	12.1	0.357	11.5	5.56	10.5
Harex	2.48	4.0	129	11.8	25.4	12.7	481.0	13.2	0.327	12.8	5.37	12.8

Note: CV represent coefficient of variation (100%), in following tables are the same mean.

5.3. Modulus of elasticity

Modulus of elasticity in tension is defined herein as the secant modulus at 50% of the peak stress on the stress-strain curve of a composite. Secant modulus of elasticity in tension of composites with PP micro-fiber and Barchip macro-fiber is slightly lower than matrix concrete; however, this for composite with steel fiber is slightly larger than that of matrix concrete. This may be due to synthetic PP fiber with lower elasticity modulus than matrix concrete.

5.4. Peak strains

Peak strain is defined as the stain corresponding to the peak stress and can be obtained from the stress-strain curve of concrete in uniaxial tension. The experimental results for peak strains of FRC are illustrated in Table 3. It can be seen that, the peak strain of micro PP and PEF fiber reinforced concrete is higher than that of plain concrete about 15-25% and 18-31%, respectively; for macro-fiber, the peak strains of composite with Barchip fiber vary from 178 to 244 $\mu\varepsilon$, i.e., 40-83% higher than that of steel fiber FRCs. For all FRC mixes, the peak strain increases with fiber volume fraction.

5.5. Axial stress-crack width curves

The total deformation of the specimen at any point on the axial stress-deformation curve, δ can be expressed (Hillerborg, *et al*. 1976, Van Vliet and Van Mier 1999, Li and Deng 2004) as

$$\delta = \delta_e + \delta_0 + w \tag{1}$$

where δ_e and δ_0, the elastic and residual deformations outside the fracture zone at any point on the stress-deformation curve respectively, are dependent upon the length of the specimen and computed by

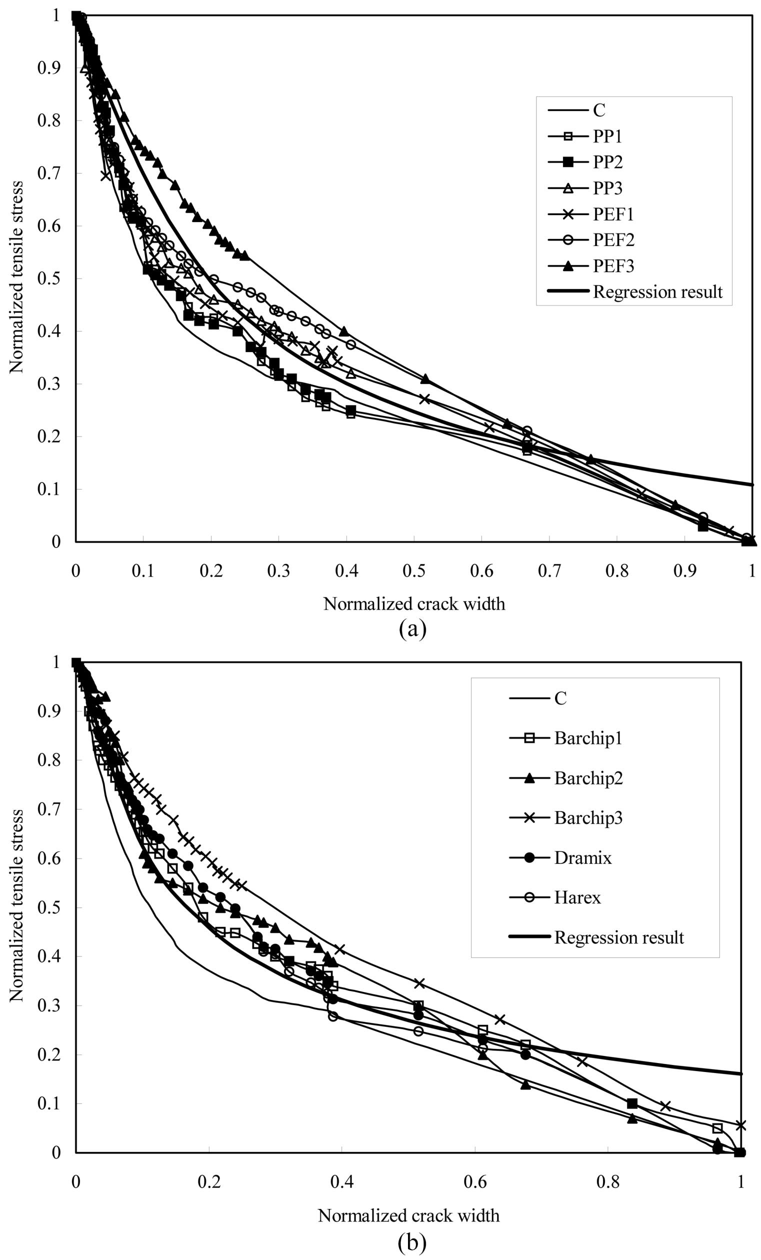

Fig. 3 Normalized axial stress-crack width curves of micro-fiber reinforced concrete in uniaxial tension

$$\delta_e = \frac{\sigma}{E_t} l \tag{2}$$

and

$$\delta_0 = \delta_p - \delta_e \tag{3}$$

respectively, and w is the crack width which is independent of l and assumed to be zero at the prepeak branch of stress-deformation curve. It should be noted that before the peak point no crack width exists. In Eqs. (2) and (3), δ_p is the deformation at peak on the axial stress-deformation curve, E_t is the modulus in tension, and l is the length of the specimen. From Eq. (1), the crack width of the specimen can be derived as

$$w = \delta - \delta_e - \delta_0 \tag{4}$$

By using Eq. (4) for the axial stress-deformation curves shown in Figs. 2(a-b), the axial stress-crack width curves, shown in Figs. 3(a-b), can be obtained. Based on the experimental results, a theoretical model for the axial stress-crack width of concrete was proposed as

$$\sigma = f_t' \left\{ 1 - \varphi \exp\left[-\left(\frac{\frac{\lambda}{w}}{w_f} \right)^n \right] \right\} \tag{5}$$

where w is crack width at any point on the stress-deformation curve; w_f is the maximum crack width; λ, n and φ are material parameters affected by composites proportion. Those parameters were evaluated as through least square scheme as λ=0.155, n=0.7, φ=1.17 for the micro fiber reinforced concretes with correlation coefficient R^2=0.94; and λ=0.113, n=0.60 and φ=1.1 for the macro fiber reinforced concretes with correlation coefficient R^2=0.920, respectively.

The theoretical curve of normalized axial stress $\sigma/f_t'(T)$ Vs. normalized crack width is also drawn in Figs. 3(a-b). The comparison between the theoretical and experimental results implies that a good agreement was achieved. The fiber volume fraction influence significantly upon the deformation curves and tensile stress, but most slightly upon the normalized axial stress, the normalized crack width , and the shape of the corresponding curve.

For micro-fiber, it can see from Figs. 3(a-b) that for composite with PEF fiber, the normalized axial stress $\sigma/f_t'(T)$ is larger than that of PP fiber FRC at same normalized crack width w/w_f. There are higher resistance for crack formation and growth in composites with high modulus and strength PEF fiber.

For macro-Barchip fiber FRC, the post-peak stress decreases with crack opening less rapidly than does that of steel FRC.

5.6. Maximum crack widths

It is difficult to measure the deformation of concrete at the complete failure (i.e. at zero stress) called as maximum deformation. This value is empirically obtained by extrapolation of the measured curve. The maximum crack widths are consequently obtained from the complete stress-deformation curves, shown in Table 3. The maximum crack widths vary from 0.24 to 0.26 mm for micro-fiber FRC and from 0. 42 to 0.54 mm for Barchip FRC.

It can be seen that the maximum crack width of composite with macro-fiber is significantly larger than that of composites with micro-fiber, and that fiber volume fraction does not regularly affect the maximum crack width.

5.7. Fracture energies

The fracture energy, G_F, is the total energy dissipated on a unit crack surface and is equal to the area under the axial stress-crack width curve, i.e.,

$$G_F = \int_0^{w_f} \sigma(w)dw \tag{6}$$

The fracture energies are shown in Table 3. The test data show that the fracture energy of composites with micro PP and PEF fiber is 33-67% and 23-47% higher than that of matrix concrete respectively. This could be indicated that the bond strength between PP fiber and matrix is larger than that of PEF fiber. The fracture energy, for macro Barchip and steel fiber reinforced concretes is about 150-210% and 270-320% larger than that of matrix concrete respectively. The major mechanism contributing to the post-cracking resistance was fiber's pulled out. As a result, the fracture energy of concrete reinforced by steel fiber with two larger ends is higher than of Barchip FRC. It can be seen that the fracture energy increases with fiber's volume fraction for all FRC mixes.

5.8. Softening response in uniaxial tension

From Fig. 2(a), one can see that the post-peak stress of FRC with micro PEF fiber decreases less rapidly than does that of micro PP fiber. For macro fiber (Fig. 2b), the maximum axial deformation of Barchip FRC is significantly larger than that of steel fiber reinforced concrete and the post-peak stress of Barchip FRC decreases less rapidly than does that of steel FRC. Dramix FRC has three different peak loads, which due to this fiber's special geometry character. The Harex steel fiber shows a tendency to these reinforcing effects, but the effects are not as significant as in the case of Dramix fiber in ultimate stresses, deformation capacity and fracture energy. A multiple cracking response is still achieved in composites with macro Barchip fiber.

5.9. Static flexural strength

The static flexural strength of composites with micro PP fiber is not expected to be influenced strongly by the fiber. Static flexural strength of Barchip and steel fiber FRCs is larger than that of control specimens 34-37% and 33-38% respectively. Flexural strength is significantly larger than that of uniaxial tensile strength for macro fiber FRCs.

5.10. Flexural impact properties

5.10.1. Initial crack impact number

The number of blows to develop the first visible crack on the beam's lower surface is defined herein as the initial-crack impact number N_{cr}, i.e., the maximum tensile strains of beam are larger than that of ultimate strains of composites during impact testing. The flexural impact test results are shown in Table 4, where the impact number is the average value of 12 specimens. For micro-fiber, the initial-crack impact numbers of PP and PEF FRCs are 1.1-1.5 and 1.5-3.3 times that of plain concrete respectively; those for macro fiber, the steel FRCs are 1.6-1.7 times that of Barchip fiber reinforced concretes.

5.10.2. Failure impact life

During impact testing, it is observed that one main crack develops rapidly from bottom to the top of composites beam with micro PP and PEF fibers; however, the Barchip and steel fiber reinforced

Table 4 Impact properties of fiber reinforced concrete

Specimen designation	Initial-crack impact		Failure impact		Impact ductility index
	Impact number	Comparing to plain concrete	Impact life	Comparing to plain concrete	
C	25.8(0.33)	1.0	26.8(0.32)	1.0	1.04
PP1	34.7(0.53)	1.3	46.5(0.52)	1.7	1.34
PP2	28.6(0.36)	1.1	30.4(0.33)	1.1	1.06
PP3	38.1(0.80)	1.5	40.1(0.76)	1.5	1.05
PEF1	37.7(0.64)	1.5	40.0(0.60)	1.5	1.06
PEF2	38.1(0.47)	1.5	40.3(0.45)	1.5	1.06
PEF3	85.1(0.62)	3.3	99.2(0.61)	3.7	1.12
Barchip1	68.9(0.41)	2.7	224.2 (0.71)	8.4	3.26
Barchip2	70.7(0.19)	2.7	712.7(0.14)	26.6	10.08
Barchip3	62.8(0.53)	2.4	831.0(0.23)	31.0	13.23
Dramix	119.5(0.27)	4.6	159.9(0.27)	5.9	1.34
Harex	101.0(0.69)	3.9	172.9(0.67)	6.5	1.71

Note: Values in parentheses represent coefficient of variation.

concretes only one main crack develops to half high of beam, and then the main crack develops to two to four cracks with increase impact number. The multiple cracking responses can be obtained for concrete incorporating Barchip and steel fiber under impact loading.

Failure impact life N_f is defined as the number at which one main macro-crack develops from beam bottom to top. For micro-fiber, the failure impact life of PP and PEF FRCs is 1.1-1.7 and 1.5-3.7 times that of plain concrete respectively; this for macro-fiber, Barchip FRC is 1.6-4.8 times that of steel fiber reinforced concretes. The larger the fiber volume fraction for composites, the greater the failure impact life.

Micro fiber are more effective than macro fiber for initial crack impact resistance; however, the failure impact resistance of macro Barchip fiber and steel fiber is significantly larger than that of micro PP and PEF FRCs.

Impact ductility index is defined herein as the ratio of failure impact life to initial crack impact number, which can be used to present the flexural impact ductility.

$$J = \frac{N_f}{N_{cr}} \tag{7}$$

where J is impact ductility index, which for plain concrete is 1.

From Table 4 one can see that the impact ductility index of composites with macro Barchip fiber is about 3.2-13.2 and increase with fiber volume fraction, this for steel fiber FRC is about 1.34-1.7. Impact ductility index of composites with macro fiber is significantly larger than that of micro fiber FRCs, i.e., macro fiber especially Barchip fiber have significant resistance for crack developing under impact loading.

6. Conclusions

The complete stress-deformation responses of the concretes with synthetic and steel fiber and different volume fractions subjected to uniaxial tension are acquired through a systematic experimental program. The strength and the complete stress-deformation responses in uniaxial tension are achieved by direct tension test for un-notched prism specimens. The flexural impact properties of FRC obtained from the impact experimental. Based on the experimental results the following conclusions are drawn:

1. The tensile strength of PEF FRC is about 7-9% higher than that of composite with PP fiber, this for composites with macro Barchip fiber is close to that with steel fiber.
2. Secant modulus in tension of composites with micro-PP, and macro-Barchip fiber is slightly lower than that of matrix concrete; however, this for composite with steel fiber is slightly larger than that of matrix concrete.
3. The peak strain of concrete with micro PEF fiber is about 18-28% higher than that of matrix concrete; this for macro-fiber, composite with macro Barchip fiber is 28-38% higher than that of steel fiber FRC at same fiber volume fraction.
4. The maximum crack widths vary from 0.24 to 0.26 mm for micro-fiber FRCs and from 0. 42 to 0.54 mm for macro Barchip FRC. The fiber volume fraction does not strongly affect the maximum crack width.
5. The fracture energy of composites with micro-fiber is 23-67% higher than that of matrix concrete, this for macro Barchip and steel fiber reinforced concretes is about 150-210% and 270-320% larger than that of plain concrete respectively.
6. Micro-fiber are more effective than macro-fiber for initial crack impact resistance; however, the failure impact resistance of macro Barchip fiber and steel fiber is significantly greater than that of micro-fiber, especially Barchip fiber. So, macro-fibers are useful to improve the impact life of concrete structures.

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