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Mechanical behaviors of concrete combined with steel and synthetic macro-fibers

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Abstract. In this paper, hybrid fibers including high elastic modulus steel fiber and low elastic modulus synthetic macro-fiber (HPP) as two elements were used as reinforcement materials in concrete. The flexural toughness, flexural impact and fracture performance of the composites were investigated systematically. Flexural impact strength was analyzed with statistic analyses method; based on ASTM and JSCE method, an improved flexural toughness evaluating method suitable for concrete with synthetic macro-fiber was proposed herein. The experimental results showed that when the total fiber volume fractions (V_f^a) were kept as a constant (V_f^a=1.5%), compared with single type of steel or HPP fibers, hybrid fibers can significantly improve the toughness, flexural impact life and fracture properties of concrete. Relative residual strength *RSI'*, impact ductile index λ and fracture energy G_F of concrete combined with hybrid fibers were respectively 66-80%, 5-12 and 121-137 N/m, which indicated that the synergistic effects (or combined effects) between steel fiber and synthetic macro-fiber were good.

Keywords: hybrid fibers; steel fiber; synthetic macro-fiber; residual strength; flexural impact; fracture; toughness; concrete

1. Introduction

Concrete is considered a brittle material as it has low tensile strength and failure strain, the incorporating of fiber into vulnerable concrete is useful and effective, but reinforcing effects of only one type of fiber are limited. For concrete consisting of hardened cement, aggregates pore and micro-cracks of different sizes, hybrid fibers of different types and sizes may play important roles in resisting crack-opening at different scales to achieve high performance (Sun, *et al.* 2003). It is natural evolution that one single type of fibers develops into hybrid fibers (Hancox 2003). Concrete, as the most commonly construction material is developing towards high performance, so that a number of research works have been carried out on hybrid fiber reinforced concrete (say HFRC for short) (Yao, *et al.* 2003, Qian and Stroeven 2000, Chen and Liu 2004, 2005, Song, *et al.* 2004), however, most of the studies of hybrid fiber reinforcement are about composites with hybrid fibers of steel fiber and synthetic micro-fiber (Qian and Stroeven 2000, Chen and Liu 2004, 2005, Song, *et al.* 2004), especially, concrete combined with hybrid fibers of steel fiber and polypropylene fiber. Using hybrid macro-fibers as reinforcement to improve the performance of concrete is seldom reported.

With the development of synthetic fiber, synthetic macro-fiber (fiber's diameter is larger than 0.1

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mm is defined as macro-fiber (CECS 2004)) has been used widely in civil engineering. Compared with steel fiber, the synthetic macro-fiber offers the advantages of light, evenly distributed and high corrosion resistance; compared to synthetic micro-fiber, synthetic macro-fiber not only provides resistance for early crack, but also obviously improves the impact resistance, flexural toughness and fracture properties. Synthetic macro-fiber, such as Barchip, Forta Feero, HPP 152 and so on, is a new type and very useful reinforcement material in concrete.

Steel fiber is not often used in pavement, blast resistant structures, underground structures, underground tunnels and in bridge decks due to high cost, weak corrosion and lower impact resistance. Synthetic micro-fiber is high effectively in resisting plastic shrinkage cracking, but does not strengthening the performance of harden concrete because of its low dosages and small diameter. Whereas synthetic macro-fiber can partly replace steel fiber, and thus decrease cost, improve toughness, endurance, fatigue life and impact resistance. Hybrid fibers of steel fiber and synthetic macro-fiber would have a broad developing prospect in civil engineering.

The engineering characteristics of HFRC have already received an attention in the concrete literatures (Yao, *et al.* 2003, Qian and Stroeven 2000, Chen and Liu 2004, 2005), whereas the impact resistance of the concrete has not been clarified yet (Song, *et al.* 2004). As a practical matter, the HFRC has a potential for use in raceways, railroad sleepers, hydraulic structures, pre-cast piles and blast resistant structures. In these cases, the HFRC are frequently exposed to impact loads, dynamic loads or suddenly applied loads. Because of the frequent exposure, the resistance of the HFRC to these impact-like loads turns out to be a matter of great concern. The impact resistance of HFRC can be determined by using a variety of tests, including an explosive test, a projectile impact test and a drop-weight test. Among these tests, the drop-weight test is recommended by ACI committee 544 (ACI committee 544, 1988). But above tests methods are all pressed impact experiments, it does not reflect completely the impact properties of HFRC in flexural conditions. Many structures are generally in flexural conditions under impact loads, such as bridge deck slab, so the research of flexural impact resistance is needed and has engineering significance.

In this paper, the properties of flexural toughness, flexural impact and fracture performance of concrete combined with hybrid fibers of steel fiber and synthetic macro-fiber were investigated systematically. Flexural impact life was measured via newly designed drop weight flexural impact equipment, and these test results were analyzed by statistic analyses method. Experimental results showed that the flexural toughness, flexural impact and fracture performance of composites combined with hybrid fibers were better than that of composites only with one single type of fibers when fiber's hybrid proportion was suitable. This research would provide experimental data for understanding the reinforce mechanism and popularizing the application of concretes combined with hybrid macro-fibers.

2. Materials and specimens

2.1. Materials

Normal type I Portland cement with a 28 day compressive strength of 32.5 MPa was used for all mixes, fine aggregate used was river sand with specific gravity of 2.65, and the coarse aggregate was crushed limestone with continuous grading (5-20 mm) and maximum size of 20 mm.

The properties of all the fibers are listed in Table 1. A new type of high performance synthetic macro-

Table 1 Properties of fibers

Type of fiber	Specific gravity (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Diameter (mm)	Length (mm)
HPP fiber	0.97	530	7.19	15	0.91	40
Steel fiber	7.8	685	154~168	4.0	0.64	32

Table 2 Concrete mix proportions

Material	Quantity
Type I cement (kg/m^3)	360
Sand (kg/m^3)	647
Crushed limestone (kg/m^3)	1100
Water (kg/m^3)	170

fiber (say HPP fiber for short, made in China) used in this research is made of polypropylene and polyethylene, with specific gravity of 0.97.

2.2. Mixes and operation

Table 2 presents the control concrete mix proportions used in this testing program. The mixtures were batched in a 30 cubic feet capacity drum mixer. The cement, sand and fibers were dry-mixed for 30 s, this was followed by addition of coarse aggregate and water, with a mixing time of 2 min, after pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1d, and then cured under standard conditions (20 ± 3°C, RH > 90%) for 28d. For 7h prior to the tests, the specimens were allowed to air dry in the laboratory.

2.3. Specimens

The following specimens were cast from each mix: 3 beams 100×100×400 mm for flexural toughness tests, 10 beams 100×100×400 mm for flexural impact tests, and 3 beams 100×100×400 mm with initial notch depth 20 mm for static fracture tests.

A total of 96 beams, as shown in Table 3, were used in the testing program.

Table 3 Test series

Test series	V_f^a (%)	Proportion of hybrid fiber (%)	
		HPP	steel
C	0	0	0
PPC	1.5	1.5	0
SSC	1.5	0	1.5
SPC1	1.5	0.5	1.0
SPC2	1.5	0.75	0.75
SPC3	1.5	1.0	0.5

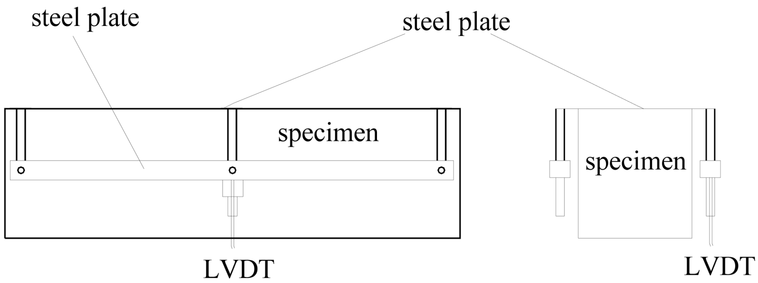

Fig. 1 Flexural toughness test

3. Experimental program

The experimental program was designed to evaluate the flexural toughness, fracture parameters, and the flexural impact resistance of concrete combined with hybrid fibers of steel fiber and HPP fiber.

3.1. Flexural toughness

The four-points loading flexural tests were carried at a deflection rate 0.10 mm/min on the beams according to the requirements of ASTM. The load and midspan deflection were recorded on a computerized data recording system during tests, as shown in Fig. 1.

According to ASTM-C1018 (ASTM C1018, 1991), the indices I_5, I_{10}, and I_{30} are calculated as ratios of the area under the load-deflection curve up to 3, 5.5 and 15.5 times the first crack deflection, divided by the area up to first crack deflection, respectively.

$$I_5 = \frac{A_1 + A_2}{A_1} \tag{1}$$

$$I_{10} = \frac{A_1 + A_2 + A_3}{A_1} \tag{2}$$

$$I_{30} = \frac{A_1 + A_2 + A_3 + A_4}{A_1} \tag{3}$$

where A_1 is the area under the load-deflection up to first crack deflection, A_2, A_3, and A_4 the area under the load-deflection curve 1.0 up to 3.0 times, 3.0 up to 5.5 times, and 5.5 up to 15.5 times the first crack deflection respectively.

Based on ASTM-C1399-98 (ASTM C1399-98, 1998), the loads supported by beam at 0.5, 0.75, 1.0 and 1.25 mm are averaged and normalized to obtain residual strength ARS value by simple elastic analysis:

$$ARS = \frac{s}{bh^2}\left[\frac{P_{0.5} + P_{0.75} + P_{1.0} + P_{1.25}}{4}\right] \tag{4}$$

where $P_{0.5}$, $P_{0.75}$, $P_{1.0}$ and $P_{1.25}$ correspond to the load values at 0.5, 0.75, 1.0 and 1.25 mm beam deflection respectively; s is the test span; b pertains to width of the beam; and h the depth of the beam. Notice that the ARS is the residual strength, and thus has the units of MPa. Further, relative residual strength RSI can be calculated from the ARS as below:

$$RSI(\%) = \frac{ARS}{MOR} \times 100 \tag{5}$$

where *ARS* is the residual strength as defined in Eq. (4), and *MOR* the modulus of rupture, is calculated by the maximum load in the four-points loading flexural test.

3.2. Flexural impact resistance

Based on ACI 544 committee recommendations (ACI committee 544, 1988), a new type drop weight flexural impact equipment was proposed in this paper, as shown in Fig. 2. In this test, the specimen was set on two lugs with a span of 340 mm, and impacted by repeated blows. The blows were introduced through a 2.5 kg hammer falling continually from a 400 mm height, which dropt freely on to a steel plate (thickness is 10 mm, length and width is all 100 mm) at the top surface of the specimen. For measurement of specimen displacements, a LVDT was placed at the middle point of neutral axis of the beam (Japan Yoke deflection measuring method). Tow accelerometers were mounted under the beam for recording impact response. During the blows impacted onto the beam, the number of blows, which made beam cracked firstly, is defined as the first-crack impact number N_c; the number of blows that made the first crack develop to the top of beam is defined as the impact failure life N_f. Ratio of impact failure life and first-crack impact number is defined as impact ductile index μ_i, which is shown as $\mu_i = N_f / N_c$.

3.3. Static fracture parameters testing method

The three-points bending beams with a central notch were used for determining the fracture parameters. The fracture tests were all carried out in an Instron 1343 universal testing machine with a closed-loop control system.

The deflection of the loading point at the middle was measured using two standard dynamic Instron extensometers type 2620, with12.5 mm gauge length, fitted on each side of the specimen on a special measuring device. This special device, as shown in Fig. 3, and the deflection data was

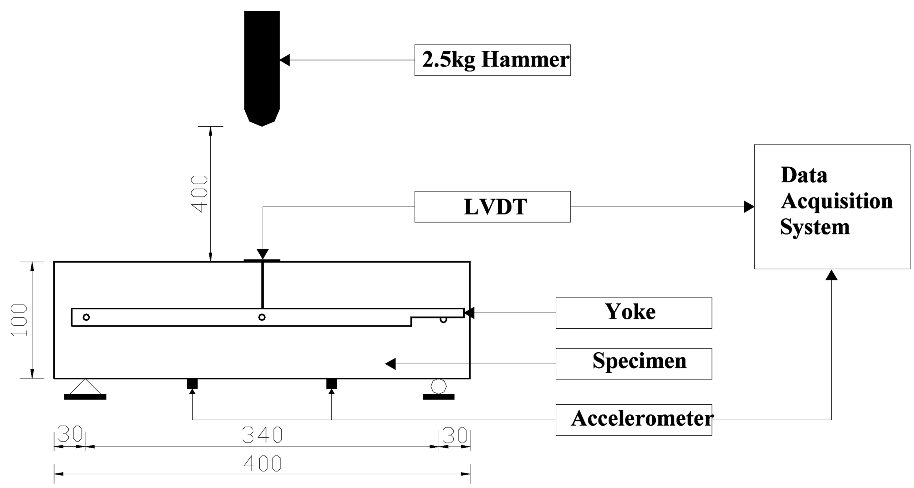

Fig. 2 Drop weight flexural impact equipment

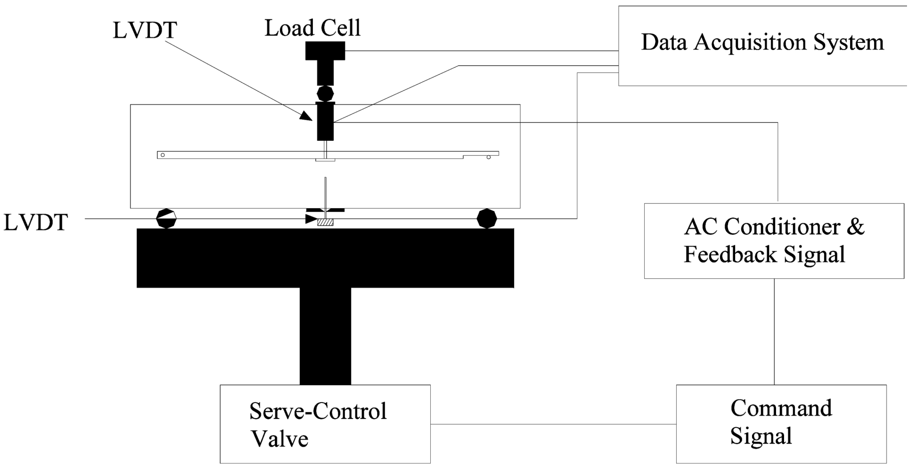

Fig. 3 Schematics of flexural test setup

used as the feedback signal to control the loading process. The loading process was controlled by a constant deflection rate of 0.10 mm/min. The crack mouth opening displacement was measured using a displacement sensor, LVDT.

The effective fracture toughness is determined based on an effective crack method using principle of linear elastic fracture mechanics. The analysis of this test results is based on the earlier work of Shah (Shah 1990). The Young's modulus E is calculated from the below equation:

$$E = \frac{6sa_0V_1(\alpha)}{C_ih^2b} \tag{6}$$

in which C_i is the initial compliance calculated from the load-CMOD curve, also:

$$V_1(\alpha) = 0.76-2.28\alpha+3.87\alpha^2-2.04\alpha^3+\frac{0.66}{(1-\alpha)^2} \tag{7}$$

$$\alpha = \frac{a_0+\Delta a}{h} \tag{8}$$

where s, h and b represent respectively the span, depth and specimen thickness, a_0 is the initial notch length (a_0=20 mm).

The critical effective crack length a_c is determined from the Young's modulus E calculated from Eq. (6) and the unloading compliance C_u measured at the maximum load. Using an iteration process, the critical effective crack length a_c is found when Eq. (9) is satisfied:

$$E = \frac{6Sa_cV_1(\alpha)}{C_uh^2b} \tag{9}$$

in which C_u is the unloading compliance at 95% of peak load.

Critical effective crack length $a_c=a_0+\Delta a$, Δa is incremental crack growth. The critical stress intensity factor K^s_{IC} can be obtained by:

$$K^s_{IC} = 3F_{\max}\frac{S\sqrt{\pi a}F(\alpha)}{2h^2b} \tag{10}$$

in which:

$$F(\alpha) = \frac{1.99-\alpha\,(1-\alpha)(2.15-3.93\,\alpha+2.7\,\alpha^2)}{\sqrt{\pi}\,(1+2\,\alpha)(1-\alpha)^{3/2}} \tag{11}$$

The critical crack tip opening displacement $CTOD_c$ is determined using below equation:

$$CTOD_c = \frac{6F_{\max}SaV_1(\alpha)}{Eh^2b}[(1-\beta)^2+(1.081-1.149\,\alpha)(\beta-\beta^2)]^{1/2} \tag{12}$$

where $\beta = a_0/h$.

In the present study, toughness of composites is quantified by the fracture energy denoted as G_F, which is the energy required to create one unit area of crack surface. G_F is calculated by RILEM proposal (RILEM 1985). W_0 the total energy supplied to break the specimen completely is measured using the load-deflection curves of the fracture test. The G_F is calculated using:

$$G_F = (W_0 + mg\delta_0)/A \tag{13}$$

where $mg\delta_0$ is the energy produced by the specimen weight (m is the specimen mass, g the gravitation acceleration, and δ_0 the maximum deflection of beam at peak load), and A the crack path area.

4. Test results and discussed

4.1. Modulus of rupture (say MOR for short)

MOR is based on the peak load in flexural toughness tests, results are listed in Table 4. Fiber addition increased *MOR* for all fibers. When one single type of fibers was used, the *MOR* of the concrete with steel fiber was larger than that of PPC and the control concrete 24.5% and 63.5% respectively. When the fibers were used in a hybrid form, these slightly increased *MOR* compared to HPP fiber and decreased compared to steel fiber at the same total fiber volume fractions.

4.2. Flexural toughness

Toughness is generally defined as deformation and energy adsorption capacity. Many standard test methods for obtaining toughness of fiber reinforced concrete are available from ASTM, JSCE and other standards organizations. These methods have themselves advantages and disadvantages.

4.2.1. Toughness characterization by ASTM method

The flexural toughness indices and residual strength calculated by ASTM method are presented in Table 4. The data in Table 4 showed that concretes with a single type of steel fiber or HPP fiber were demonstrated similar flexural toughness. For concrete combined with hybrid fibers, the toughness indices of SPC1 and SPC3 were larger than that of the concretes with a single type of fibers, especially, SPC3 obtained the largest flexural toughness indices (I_5, I_{10} and I_{30} were respectively 4.66, 9.06 and 17.82). The toughness indices of SPC2 were not as larger as those of adding a single type of fibers, and significantly decreased compared with that of SPC1 or SPC3, which indicate that toughness indices don't evaluate well the flexural toughness of concrete with

Table 4 Flexural toughness results

Test series	*MOR* (MPa)	Toughness indices			Residual strength			
		I_5	I_{10}	I_{30}	*ARS* (MPa)	*RSI* (%)	*ARS'* (MPa)	*RSI'* (%)
C	2.49	1.27	1.38	1.56	0.08	4.51	0.05	2.84
PPC	3.27	3.77	6.35	11.11	1.65	50.44	1.67	51.01
SSC	4.07	3.80	6.91	12.38	2.95	71.54	2.71	65.48
SPC1	3.92	4.12	7.69	14.25	2.95	75.20	2.59	66.07
SPC2	3.87	2.46	4.11	7.13	3.73	73.43	2.55	65.94
SPC3	3.79	4.66	9.06	17.82	3.22	84.85	3.02	79.63

synthetic macro-fiber. Concrete with synthetic macro-fiber has good deformability after peak load (Li and Deng 2005). Toughness indices are strongly depended on first-crack point, however, first-crack point is hard to determine, and disperse for concrete with macro-fiber.

It can be seen from Table 4 that, the relative residual strength of SSC was 21.1% higher than that of PPC; concretes combined with hybrid fibers, the *RSI* varied from 73.43% to 84.85%, and were higher than that of the concrete with a single type of fibers. These indicate that residual strength may be better to reflect the flexural toughness of concrete with macro-fiber than toughness index, because the residual strength is not depended on first-crack point.

4.2.2. Toughness characterization by JSCE method

The toughness gene values evaluated by JSCE method are also listed in Table 5. The Japanese standard unlike the ASTM method sets the deflection as equal to 1/150 of its span (JSCE 1984). The test span for beams used in this program was 300 mm. The order of toughness gene values was SPC3 > SPC2 > SSC > SPC1 > PPC > C. Toughness gene value is calculated by average method, which may introduce that toughness gene values of two obviously different load-deflection curves are same.

4.2.3. Improved toughness evaluating method

Based on the above analyses, among toughness index, residual strength and toughness gene, residual strength is very useful to reflect the flexural toughness of concrete with macro-fiber. However, synthetic macro-fiber can significantly improve the flexural toughness of concrete, as shown in Fig. 4. It can be seen that if beam deflection was larger than 1.25 mm, the load of PPC

Table 5 Toughness gene results by JSCE method

Test series	First-crack toughness (N·mm)	Toughness (T_b) (N·mm)	Toughness gene (MPa)
C	717	1350	0.20
PPC	512	11600	1.74
SSC	1014.5	19000	2.85
SPC1	761	18350	2.75
SPC2	817	19200	2.88
SPC3	427	20400	3.06

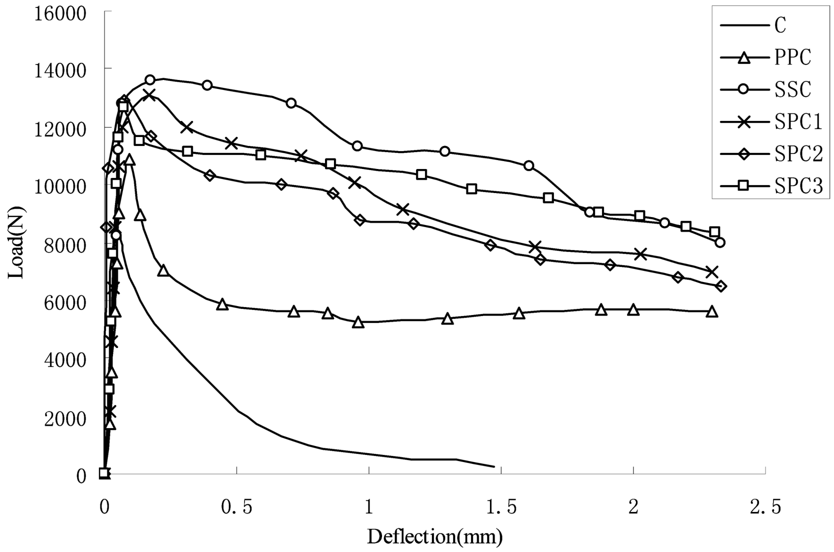

Fig. 4 Type load-deflection curves in flexural toughness tests

was tended to increase continuously with the deflection, the load of HFRC decreased slowly with increase of deflection, but load in all curves still kept in a relative high level. Therefore the flexural toughness evaluating for concrete with synthetic macro-fiber should take into account residual strength when beam deflection was larger than 1.25 mm. Meantime, if beam's deflection was larger than 2.0 mm, the loads decreased rapidly with deflection for PPC and HFRC, which indicate that the residual strength value calculated up to deflection of 2.0 mm, can reflect well toughness reinforcing effect of synthetic macro-fiber, and save time for surveying load-deflection curve. So we propose residual strength formula as follow:

$$ARS' = \frac{s}{bh^2}\left[\frac{P_{0.5}+P_{1.0}+P_{1.5}+P_{2.0}}{4}\right] \tag{14}$$

where signs are same mean as Eq. (4).

The residual strength evaluated by improved method (denoted as *RSI'*) are summarized in Table 4. Compared to the relative residual strength *RSI* calculated by ASTM method, the relative residual strength *RSI'* ($RSI' = ARS'/MOR$) of PPC increased by 1%, while SSC and HFRC decreased by 5-10%. This preferred to reflect that HPP fiber with low elastic modulus obviously influences the postpeak flexural softening response by bridging across macro-crack and restraining cracks opening. Among concretes with hybrid fibers, SPC3 had the highest value of relative residual strength *RSI'*, this value was 14-29% higher than that of the concrete with one single type of fibers and 77% higher than that of plain concrete, but SPC2 provided the lowest relative residual strength *RSI'*. The flexural toughness test results indicated the positive interaction between the steel fiber and HPP fiber in improving the flexural toughness of cement-based composite materials.

4.3. Flexural impact behavior

4.3.1. First-crack impact number

The number of blows when beam was firstly cracked is defined as the first-crack impact number. The first-crack impact number and statistic analysis results are given in Table 6. The first-crack impact numbers of specimens have such statistical properties as a mean χ, a coefficient of variation CV, and 95% confidence interval CI, the 95% confidence interval indicates that in approximately 95% of the first-crack impact number data, this interval includes the true average first-crack impact number. SSC obtained the highest first-crack impact number, $\chi = 9.18$, CV = 64% and CI = (5.69, 12.67). The composite combined with steel fiber and HPP fiber showed relatively high first-crack impact number, this value was higher than that of concrete only with HPP fiber and lower than that of concrete with steel fiber at same fiber volume fraction. High elastic modulus steel fiber can obviously increase first crack strength concrete.

4.3.2. Impact failure life

The impact numbers that beam's the main crack just came through the cross-section is defined as the impact failure life. As shown in Table 7, HPP fiber shown the highest impact failure life, χ=77.82, CV=48% and CI=(55.70, 99.94) for PPC; The impact failure life of HFRC was higher than that of SSC; among SPC1, SPC2 and SPC3, the impact failure life of the latter was higher than that of the former. Low elastic modulus HPP fiber can significantly improve impact behavior of concrete.

Table 6 Statistic analyses for first-crack impact number in flexural impact tests

	C	PPC	SSC	SPC1	SPC2	SPC3
Minimum value (blows)	1	3	4	3	4	3
Maximum value (blows)	3	10	21	16	15	15
Mean value, χ (blows)	1.91	5.36	9.18	7.64	6.55	6.44
Standard deviation, σ (blows)	0.70	1.80	5.91	4.15	2.98	2.30
Standard error of mean (blows)	0.21	0.53	1.75	1.23	0.89	1.32
Coefficient of variation, CV (%)	37	34	64	54	46	36
95% confidence interval, CI (blows)						
Upper bound	2.32	6.43	12.67	10.09	8.33	9.08
Lower bound	1.50	4.29	5.69	5.19	4.77	3.8

Table 7 Statistic analyses for impact failure life in flexural impact tests

	C	PPC	SSC	SPC1	SPC2	SPC3
Minimum value (blows)	2	28	10	13	14	18
Maximum value (blows)	5	138	76	53	72	104
Mean value, χ (blows)	3.27	77.82	24.73	24.91	33.18	48.89
Standard deviation, σ (blows)	0.90	37.42	19.33	13.39	19.37	27.45
Standard error of mean (blows)	0.27	11.06	6.92	3.96	5.72	8.97
Coefficient of variation, CV (%)	28	48	78	54	58	56
95% confidence interval, CI (blows)						
Upper bound	3.80	99.94	38.57	32.82	44.63	66.82
Lower bound	2.74	55.70	10.89	17.00	21.73	30.96

Table 8 Statistic analyses for impact ductile index in flexural impact tests

	C	PPC	SSC	SPC1	SPC2	SPC3
Minimum value	1.33	6.00	1.94	1.94	2.80	3.88
Maximum value	3.00	34.67	3.62	5.00	10.83	11.56
Mean value, χ	1.82	15.88	2.64	3.41	5.08	7.39
Standard deviation, σ	0.47	9.43	0.44	0.95	2.26	2.39
Standard error of mean	0.14	2.79	0.19	0.28	0.65	0.70
Coefficient of variation, CV (%)	26	59	17	28	45	32
95% confidence interval, CI						
Upper bound	2.10	21.46	3.02	3.97	6.37	8.79
Lower bound	1.54	10.30	2.26	2.85	3.79	5.99

4.3.3. Impact toughness

The ratio of impact failure life to first-crack impact number is defined as impact ductile index, which reflects impact toughness of concrete. Impact ductile index results are listed in Table 8. Similar to first-crack impact number, the order of impact ductile index values was PPC > SPC3 > SPC2 > SPC1 > SSC > C. Impact ductile index values of concrete combined with hybrid fibers were 0.3 to 2 times greater than that of the concrete with steel fiber and 1 to 3 times greater than that of control specimen. This demonstrated that fibers with different elastic modulus could resist cracking at different scales under impact load, and that the combined addition of steel fiber and HPP fiber would be significantly beneficial to the impact toughness of concrete.

4.4. Fracture performance

Type load-deflection and load-CMOD curves are respectively shown in Figs. 5 and 6, and the average fracture parameters are summarized in Table 9.

The results of the critical effective crack length a_c are listed in Table 9. It can be seen that the critical effective crack growth length of concrete with fiber was larger than that of plain concrete. SSC shown the largest the critical effective crack length, which was 31.4% larger than that of concrete without fiber, and a_c of HFRC was larger than that of PPC. Comparing SPC1, SPC2 and SPC3, a_c of the latter was larger than that of the former. $CTOD_c$ and a_c had same variation law.

The effective stress intensity factors K_{IC}^{s} of the concrete only with steel fiber was 28% higher than that of the concrete with HPP fiber. The SPC3 has the highest value K_{IC}^{s} among the composites combined with hybrid fibers. K_{IC}^{s} for composites combined with hybrid fibers was also higher than that of composite only with one type of fibers, and significantly larger than that of plain concrete.

Fracture energy G_F includes elastic and nonlinear fracture processes, and presents really fracture properties of composite. From Table 9, it can be seen that G_F of fiber reinforced concrete was about 2.5 to 3 times that of plain concrete. G_F of concrete combined with hybrid fibers was also larger than that of concrete with a single type of fibers, except the G_F of SPC2 was lower than that of SSC. The results showed that combining use steel fiber and HPP fiber would obviously improve the fracture properties of cement-based composite materials.

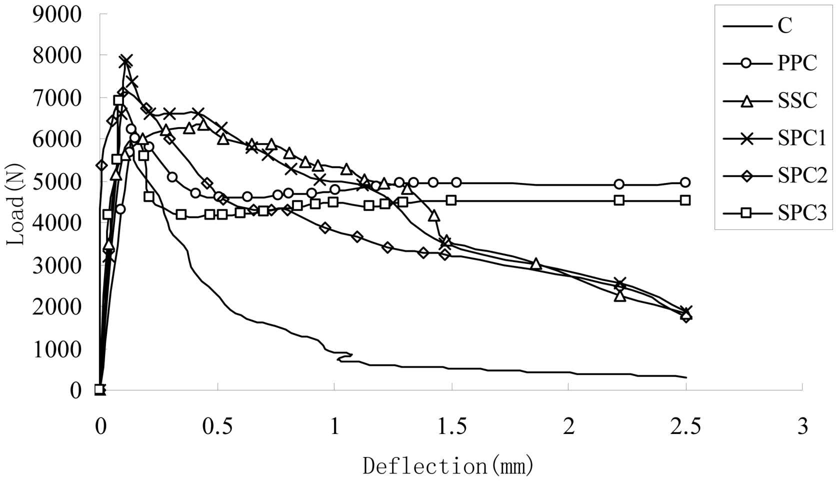

Fig. 5 Type load-deflection curves in fracture tests

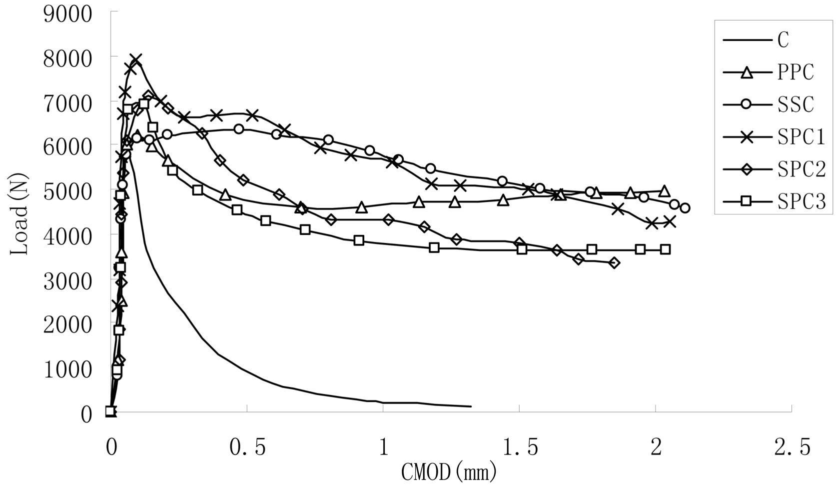

Fig. 6 Type load-CMOD curves in fracture tests

Table 9 Fracture parameter results

Test series	F_{max} (kN)	CMOD at peak load (mm)	Deflection at peak load (mm)	$C_i \times 10^{-6}$ (mm/N)	$C_u \times 10^{-6}$ (mm/N)	a_c (mm)	Δa_c (mm)	K^s_{IC} (MPa $\sqrt{m}$)	$CTOD_c$ (mm)	G_F (N/m)
C	5.98	6.04	0.06	2.14	3.29	30.75	10.75	0.885	0.0098	44.46
PPC	6.21	7.87	0.085	2.59	4.16	32.12	12.12	0.952	0.0133	110.88
SSC	6.35	10.41	0.440	3.01	6.08	40.40	20.40	1.214	0.0223	136.43
SPC1	7.91	9.29	0.115	2.78	4.49	32.30	12.30	1.217	0.0183	136.48
SPC2	7.11	9.24	0.140	2.85	5.12	35.93	15.93	1.203	0.0200	120.58
SPC3	6.90	9.04	0.180	2.91	5.48	37.66	17.66	1.223	0.0212	136.86

5. Mechanism of improvement of concrete due to hybrid macro-fibers

Hybrid macro-fibers as reinforcing components could increase effectively the toughness and ability of resisting fracture, evidently improve the flexural impact resistance, which reflect adequately that synergistic reinforce effects between HPP fiber and steel fiber were good, the explanation lied in the fact that hybrid fibers with different elastic modulus played their corresponding roles at different scales. In micro-crack phase, HPP fiber can restrain crack developing to a limited extent due to it with low elastic modulus; however, steel fiber with high elastic modulus and two convex heads, the developing spread of micro-crack in matrix would be significantly decreased. Steel fiber with high elastic modulus brought into play strengthen role when crack of matrix was approximately microns in width. In macro-crack phase, steel fiber appeared to be less effective in controlling matrix crack opening, because many steel fibers had been pulled out, but where had relative larger interface strength between HPP fiber and matrix. When HPP fiber was elongated and pulled out from matrix, the energy would be consumed continuously, and the ductility of composite would be improved significantly.

When the total fiber volume fractions were kept the same, the reinforcement effects of hybrid fibers on mechanical properties were mainly depended on fiber's hybrid proportion. The value of residual strength, critical stress intensity factor K_{IC}^{s} and fracture energy G_F of concrete combined with hybrid fibers is SPC3 > SPC1 > SPC2, which indicated that fiber's hybrid proportion of SPC2 was not good, but the SPC3 were achieved optimization.

6. Conclusions

Synergistic reinforce effects of high modulus steel fiber and low modulus HPP fiber in improving the impact resistance, flexural toughness and fracture properties of concrete were investigated experimentally. A factorial experimental design was adopted to assess the synergistic reinforcing effects of the two reinforcing fibers at different volume fractions.

Based on the present experimental investigation the following conclusions can be made:

1. The flexural toughness of concrete combined with hybrid fibers were better than that of the concrete only with one single type of fibers, the relative residual strength of the concrete combine with 0.5% volume fraction steel fibers and 1% HPP fibers (SPC3) was about 80%.

2. When volume fraction of steel fiber is approximately equal to the HPP fiber, composites with steel fiber obtained the highest first-crack impact number; with HPP fiber obtained the highest impact failure life and impact ductile index. At same total fiber volume fraction, the first-crack impact number of concrete combined with steel ad HPP fibers were higher than that of the concrete only with HPP fiber, and impact failure life and impact ductile index of concrete with this hybrid fibers were higher than that of the concrete only with steel fiber.

3. Fracture energy G_F of the concrete combined with 0.5% volume fraction steel fiber and 1% HPP fiber (SPC3) was about two times larger than that of plain concrete, and about was 23% larger than that of the concrete only with HPP fiber where HPP fiber volume fraction is 1.5%.

References

ACI committee 544 (1988), "Measurement of properties of fiber reinforced concrete", *ACI Mater. J.*, **85**(6), 583-593.

ASTM C1018 (1991), "Standard test method for flexural toughness and first crack strength of fiber reinforced concrete", *Book of ASTM Standard*.

ASTM C1399-98 (1998), "Test method for obtaining average residual strength of fiber reinforced concrete", Annual Book of ASTM Standards.

CECS 38 (China Civil Engineering Institute Code) (2004), "Technical specification for fiber reinforced concrete structures", China Planning Press.

Chen, Bing and Liu Juanyu (2005), "Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability", *Cement Concrete Res.,* **35**, 913-917.

Chen, Bing and Liu, Juanyu (2004), "Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures", *Cement Concrete Res.,* **34**, 1065-1069.

Hancox, N. L. (1981), *Fiber composite hybrid materials*, Applied Science Publishers Ltd, London.

JSCE-SF4 (1984), "Method of test for flexural strength and flexural toughness of steel fiber reinforced concrete", *Concrete Library of JSCE*.

Li, Jianhui and Deng, Zongcai (2005), "Interfacial bond property between HPP fiber and mortar", *China Cement Concrete Products,* **142**, 38-40.

Qian, C. X. and Stroeven, P. (2000), "Development of hybrid polypropylene-steel fiber-reinforced concrete", *Cement Concrete Res.,* **30**, 63-69.

RILEM Committee 50-FMC (1985), "Determination of the fracture energy of mortar and concrete by means of three-points bend test no notched beams", *Mater. Struct. Res. Testing* (RILEM, Paris), **18**, 285-290.

Shah, S. P. (1990), "Determination of fracture parameters of plain concrete using three-point bend tests", *Mater. Struct.* **23**, 457-460.

Song, P. S., Wu, J. C., Wang, S. H., and Sheu, B. C. (2005), "Statistical analysis of impact strength and strength reliability of steel-polypropylene hybrid fiber-reinforced concrete", *Constr. Build. Mater.,* **19**, 1-9.

Sun, Wei, Chen, Huisu, Luo, Xin and Qian, Hongpin (2003), "The effect of hybrid and expansive agent on the shrinkage and permeability of high-performance concrete", *Cement Concrete Res.*, **31**, 595-601.

Yao, Wu, Li, Jie and Wu, Keru (2003). "Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction", *Cement Concrete Res.*, **33**, 27-31.

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