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Effect of polypropylene fiber on fracture properties of high-performance concrete composites

Abstract: A parametric experimental study has been conducted to investigate the effect of polypropylene fiber on the workability and fracture properties of high-performance concrete (HPC) composites containing fly ash and silica fume, with the five fiber volume fractions (0.04%, 0.06%, 0.08%, 0.1%, and 0.12%) used. The results indicate that the addition of polypropylene fiber decreases the workability of the HPC composites containing fly ash and silica fume. With the increase in the fiber volume fraction, both of the slump and the slump flow decrease gradually. Furthermore, the addition of polypropylene fiber has greatly improved the fracture parameters of concrete composite containing 15% fly ash and 6% silica fume, such as fracture toughness, fracture energy, effective crack length, maximum midspan deflection, the critical crack opening displacement, and the maximum crack opening displacement of the three-point bending beam specimens. When the fiber volume fraction increases from 0% to 0.12%, the fracture parameters increase gradually. The variation rules of the fracture parameters indicate that the capability of the polypropylene fiber to resist the crack propagation of the concrete composite containing 15% fly ash and 6% silica fume is becoming stronger and stronger with the increase in fiber volume fraction with the fiber volume fraction not above 0.12%.

Keywords: fly ash; fracture property; high-performance concrete; polypropylene fiber; silica fume.

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1 Introduction

High-performance concrete (HPC) can be defined as the concrete that meets special performance and uniformity requirements that cannot always be achieved by conventional materials, normal mixing, placing, and curing practices [1, 2]. The requirements may involve enhancements of characteristics such as placement and compaction without segregation, long-term mechanical properties, early age strength, volume stability, or service live in severe environments. Swamy, R.N., states that HPC is that which is designed to give optimized performance characteristics for the given set of materials, usage, and exposure conditions, consistent with the requirements of cost, service life, and durability [3]. Architects, engineers, and constructors all over the world are finding that using HPC allows them to build more durable structures at a comparable cost. HPC is being used for buildings in aggressive environments, marine structures, highway bridges and pavements, nuclear structures, tunnels, precast units, etc. [1, 4]. The major difference between the conventional concrete and HPC is essentially the use of chemical and mineral admixtures. The use of chemical admixtures reduces the water content, thereby reducing the porosity within the hydrated cement paste [5]. Pozzolanic materials are crucial to HPC as far as flowability is concerned [6]. Mineral admixtures, also called cement replacement materials, act as pozzolanic materials as well as fine fillers, thereby the microstructure of hardened cement matrix becomes denser and stronger.

Because fly ash causes environmental pollution, and the cost of storage of fly ash is very high, the utilization of fly ash in HPC, both in regard to environmental pollution and the positive effect on a country's economy, are beyond dispute. The fly ash concrete composite offers a holistic approach that can help us to achieve the goals of meeting the rising demands for concrete, enhancement of concrete durability with little or no increase in cost (in some instances reduced cost), and ecological disposal of large quantities of the solid waste products from coal-fired power plants [7, 8]. Several investigations involving concrete composites containing fly ash had reported that they exhibit excellent mechanical and durability properties [9–12]. Despite the benefits of fly ash, practical problems remain in field application.

At the early stages of aging, the strength of concrete composites containing a high volume of fly ash as a partial cement replacement is much lower than that of the control concrete due to the slow process of the pozzolanic reaction of fly ash, and its contribution toward the strength development occurs only at the later ages [13–15].

Silica fume is a by-product of the silicon metal and ferrosilicon alloy industry, instead of a waste product, and its utilization in HPC has increased recently. Because of a significant improvements attained on the interfacial zone of cement paste-aggregate, silica fume is known to improve the early strength and durability of concrete composites and produce a high-strength concrete [16]. Silica fume is often used in two different ways: as a cement replacement, in order to reduce the cement content (usually for economic reasons), and as an additive to improve concrete properties (in both fresh and hardened states) [17]. Therefore, to increase the early strength of concrete composites containing fly ash, the application of silica fume together with fly ash provides an interesting alternative, and many researchers have recently conducted investigations using a combination of the two by-products [18–20]. However, a lot of research achievements indicate that the addition of silica fume can cause the concrete composites to have a more brittle structure, and ductility improvement is an important goal in concrete science and must be taken into account by researchers [21, 22]. Short fibers have been known and used for centuries to in reinforced brittle materials like cement or concrete composites. Now, there are numerous fiber types available for commercial use, the basic types being steel, glass, synthetic materials, and some natural fibers [23–27]. With low modulus of elasticity, high strength, excellent ductility, excellent durability, and low price, polypropylene fiber is often used in cement and concrete composites to improve the toughness and ductility of the matrix composite.

Fracture properties are extremely important for the safety of concrete composite structures. The improved pore structure of concrete by applying chemicals, mineral admixtures, and fiber materials causes densification of the paste-aggregate transition zone, which in turn affects the fracture properties. Hence, it is necessary to investigate the effect of polypropylene fiber on the fracture properties of HPC containing fly ash and silica fume. However, little information is presently known regarding this. Therefore, we conducted this experimental study and measured the fracture toughness, fracture energy, midspan deflection (δ), crack mouth opening displacement (CMOD), and crack tip opening displacement (CTOD) of the notched beam specimens to reveal the effect of polypropylene fiber on the fracture properties of HPC containing fly ash and silica fume.

2 Experimental program

2.1 Raw materials

Ordinary Portland cement (Class 42.5R) produced by Tongli Cement Co., LTD., Xinxiang, Henan Province, China, Grade I fly ash produced by Yaomeng Power Fly Ash Development Co., LTD., Pingdingshan, Henan Province, China, and silica fume produced by Gongyi Silicon Powder Economic & Trade Co., LTD., Gongyi, Henan Province, China were used in this work. The cement, fly ash, and silica fume properties are given in Table 1. The polypropylene fiber used in this investigation was a single short fiber, which was produced by Danyang Synthetic Fiber Plant in the Jiangsu Province of China. This fiber was manufactured by mixing modified polypropylene short fibers with different lengths and section shapes together in proportion in by special production techniques. There are two different section shapes, which are "Y" shaped (50%) and "X" shaped (50%). The proportion of the fibers with the length of 10–15 mm is about 60%, and the other 40% of the fibers have the length of 15–20 mm. The basic physical properties of polypropylene fiber in this study are shown in Table 2. Coarse aggregate with a maximum size of 20 mm and fine aggregate with a 2.82 fineness modulus (FM) were used in this experiment. FM is defined as an empirical figure obtained by adding the total percentage of the sample of an aggregate retained on each of a specified series of sieves and dividing the sum by 100. The sieve sizes are 150 μm, 300 μm, 600 μm, 1.18

Composition (%)	Cement	Fly ash	Silica fume
Chemical compositions			
SiO_2	20.17	51.50	93.72
Al_2O_3	5.58	18.46	0.82
Fe_2O_3	2.86	6.71	0.48
CaO	63.51	8.58	0.34
MgO	3.15	3.93	1.44
Na_2O	0.12	2.52	0.40
K_2O	0.57	1.85	1.22
SO_3	2.56	0.21	0.47
Physical properties			–
Specific gravity	3.05	2.16	2.30
Specific surface (cm^2/g)	3295	2470	–

Table 1 Properties of cement, fly ash, and silica fume.

Density (g/cm^3)	Linear density (dtex)	Fiber length (mm)	Tensile strength (MPa)	Elastic modulus (MPa)	Melting point (°C)
0.91	10–20	10–20	≥450	≥4100	160–170

Table 2 Physical properties of polypropylene fiber.

mm, 2.36 mm, 4.75 mm, 9.5 mm, 19.0 mm, 38.1 mm, and larger increasing in the ratio of 2:1. The same value of FM may be obtained from several different particle size distributions. In general, however, a smaller value indicates a finer aggregate and a higher value a coarser aggregate. Fine aggregates range from a FM of 2.00 to 4.00, and coarse aggregates smaller than 38.1 mm range from 6.50 to 8.00. A high-range water reducer agent with a commercial name of polycarboxylate HJSX-A produced by Shanxi Yellow River New Chemical Co., LTD., Shanxi Province, China was used to adjust the workability of the concrete mixture. Fly ash and silica fume were mixed in concrete composites by replacing the same quantity of cement, and the polypropylene fiber was mixed in concrete with the dosage of cementitious materials unchanged. Fly ash content (by mass) is 15% and silica fume content (by mass) is 6%, and the dosage (by volume) of the polypropylene fiber is from 0.04% to 0.12%. Mix proportions are given in Table 3.

2.2 Preparation of fresh HPC

In order to distribute the silica fume and the fibers uniformly, a forced mixing machine was adopted. Fibers were dispersed by hand in the mixture to achieve a uniform distribution throughout the mixture. The mixing procedure, which was designed by trial and error, was chosen as follows: the coarse aggregate and fine aggregate were mixed initially for 1 min, and the binder and the polypropylene fiber were mixed for another 1 min. Finally, the high-range water reducer agent and water were added and mixed for 3 min. The distribution of the silica fume and the fibers has a great effect on the working performance of the mixture and fracture properties of HPC. If the silica fume and the fibers are not distributed well, they will be assembled altogether. From the working performance of the mixture, and the fracture section of the specimen of the HPC reinforced with the polypropylene fiber, it can be seen that the silica fume and the fibers of this study were distributed well.

2.3 Workability test

The workability of the fresh HPC composites can be evaluated by the parameters of the slump and the slump flow. The slump flow can be expressed as the spreading diameter of the fresh HPC composite in the slump test. The slump can reflect the fluidity of the fresh HPC composite, and the slump flow can reflect the cohesive properties of the fresh HPC composite. From the spreading process in the slump test, the segregation-resistance ability of the fresh HPC composite can be assessed. The values of the slump and the slump flow can be measured using a standard slump cone made of thin steel sheet; the height, the diameter of the upper open mouth, and the diameter of the bottom are 300 mm, 100 mm, and 200 mm, respectively. The slump cone should be placed on a smooth and flat plate before the fresh HPC composite was put into the slump cone in three layers, and each layer was tamped 25 times by a tamping bar. The excessive fresh HPC composite should be scraped off with a trowel. After the slump cone was lifted vertically, it should be placed on the flat plate alongside the fresh HPC composite slumped from the slump cone. The difference of the maximum height of the fresh HPC composite and the height of the slump cone was measured as the value of the slump. The final maximum and minimum diameters of the spreading fresh HPC composite were measured to calculate the value of the slump flow. If the difference of the maximum and the minimum diameters is <50 mm, the average of the two diameters can be taken as the value of the slump flow.

Mix no.	Cement (kg/m^3)	Fly ash (%)	Silica fume (%)	Fiber volume fraction (%)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Water reducer agent (kg/m^3)
1	390.3	15	6	–	647	1151	158	4.94
2	390.3	15	6	0.04	647	1151	158	4.94
3	390.3	15	6	0.06	647	1151	158	4.94
4	390.3	15	6	0.08	647	1151	158	4.94
5	390.3	15	6	0.10	647	1151	158	4.94
6	390.3	15	6	0.12	647	1151	158	4.94

Table 3 Mix proportions of the HPC.

The larger values of the slump and the slump flow indicate that the fresh HPC composite has a better workability.

2.4 Preparation of notched beam specimens

A series of notched beam specimens with the size of 100×100×515 mm were prepared to determine the fracture toughness and the fracture energy. The beam specimen was sawed from the midspan of the lower surface to produce a precast crack, the depth of which is 40 mm. The shape and size of the beam specimen are provided in Figure 1. All the specimens were stored at a temperature of about 23°C in a casting room. They were demolded after 24 h and then cured at 100% relative humidity and controlled temperature (21±2°C) for 28 days before testing.

2.5 Fracture test

The three-point bending beam method was employed to measure the fracture parameters in this study, which is an appropriate fracture testing method recommended by the Committee Fracture Mechanics of Concrete of International Union of Laboratories and Experts in Construction Materials, Systems and Structures [28]. The experiment was carried out on a hydraulic pressure testing machine, whose measure range of the load transducer is 0–30 kN. The CMOD and the crack tip opening displacement (CTOD) were measured by clamp clamp-type extended instruments. The clamp clamp-type extended instrument can be called a butterfly stretched instrument, which was composed of two connected clamping pieces, a strain gauge, and some connecting wires. The displacement of the crack can be measured by the strain gauge according to the space between the two clamping pieces. The mid-span deflection (δ) of the beam specimen was measured using a displacement meter fixed on one side face of the specimen by an angle bracket. During the course of the testing, the loading was kept continual and consistent, and the loading rate was reduced properly when the specimen was approaching failure. The relational curves between the vertical load and the mid-span deflection (P_v-δ) were obtained, respectively, from the X-Y dynamic function recorder.

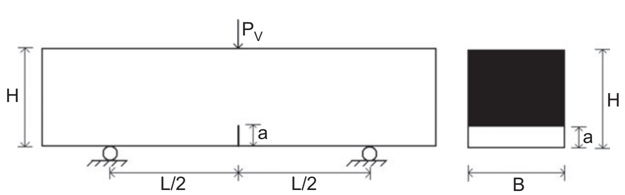

Figure 1 Sketch picture of the three-point bending beam specimen.

3 Results and discussion

3.1 Calculation of fracture toughness and fracture energy

With the measured peak vertical load of the three-point bending beam specimen, the fracture toughness of HPC can be calculated as follows [29]:

$$K_{IC}=\frac{P_{Vmax}S}{BH^{\frac{3}{2}}}f\left(\frac{a}{H}\right) \tag{1}$$

where K_{IC} is the fracture toughness in kN/m$^{3/2}$; P_{Vmax} is the peak vertical load in kN; S is the span length of the beam specimen in m; H is the height of the beam specimen in m; B is the width of the beam specimen in m; and a is the depth of the precast crack in m. $f\left(\frac{a}{H}\right)$ is a function relevant to $\frac{a}{H}$, the expression of which is as follows:

$$f\left(\frac{a}{H}\right)=2.9\left(\frac{a}{H}\right)^{\frac{1}{2}}-4.6\left(\frac{a}{H}\right)^{\frac{3}{2}}+21.8\left(\frac{a}{H}\right)^{\frac{5}{2}}-37.6\left(\frac{a}{H}\right)^{\frac{7}{2}}+38.7\left(\frac{a}{H}\right)^{\frac{9}{2}} \tag{2}$$

It is easy to calculate K_{IC} of the three-point bending beam specimen using Eqs. (1) and (2). In order to get the actual K_{IC} of the HPC-containing silica fume, the depth of the precast crack in Eqs. (1) and (2) should be replaced by the effective crack length (a_c) because the subcritical expanding displacement of the precast crack tip of the three-point bending beam specimen is not considered in Eqs. (1) and (2), the K_{IC} is calculated wherein the actual fracture property of HPC cannot be reflected. The effective crack length of the three-point bending beam specimen can be calculated as follows [30]:

$$a_c=\frac{2}{\pi}h\times \text{arctg}\sqrt{\frac{Eb}{32.6P_{Vmax}}CMOD_c-0.1135} \tag{3}$$

where, a_c is the effective crack length of the three-point bending beam specimen in m; P_{Vmax} is the peak vertical load in kN; CMOD is the critical crack mouth opening displacement in m; E is the elastic modulus of HPC in MPa; h is the height of the beam specimen in m; and b is the width of the beam specimen in m.

With the measured ultimate midspan deflection and the relational curve of P_V-δ of the three-point bending beam specimen, the fracture energy of HPC can be calculated as follows [31]:

$$G_F = \frac{1}{A_{lig}} [W_0 + (m_1 + 2m_2) g\delta_{max}] \tag{4}$$

$$A_{lig} = B(H-a) \tag{5}$$

where, G_F is the fracture energy in N/m; A_{lig} is the area of the fracture ligament of the specimen in m^2; H is the height of the beam specimen in m; B is the width of the beam specimen in m; a is the depth of the precast crack in m; g is the gravitational acceleration (g=9.8 m/s^2); m_1 is the weight of the specimen between the two supports in kg; m_2 is the additive weight of the loading facilities; δ_{max} is the ultimate deflection in the span center of the beam specimen in m; W_0 is the area under the relational curve of P_v-δ (Figure 2) in N·m.

3.2 Effect of polypropylene fiber on workability

Figures 3 and 4 illustrate the variations of the slump and the slump flow of the HPC composites with 15% fly ash and 6% silica fume with the increase in polypropylene fiber volume fraction, respectively. It can be seen from the figures that the addition of polypropylene fiber decreases the slump and the slump flow of the HPC composite with 15% fly ash and 6% silica fume. With the increase in fiber volume fraction, both of the slump and the slump flow decrease gradually. Compared with the HPC composites without the polypropylene fiber, the decreases in the slump and the slump flow were determined as 7.7% and 10.7% for the HPC composite with 0.12% fiber volume fraction, respectively. For the slump, there is a sharp decrease when the fiber volume fraction increases from 0.08% to 0.1%. The addition of the polypropylene fiber may be adverse to the workability of fresh HPC composites containing fly ash and silica fume. The same conclusion on concrete composite without fly ash and silica fume can be drawn based on the existing research results [32].

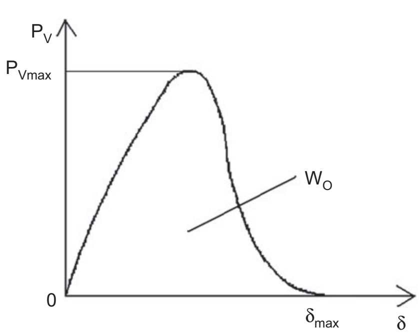

Figure 2 Full curve of P_V-δ.

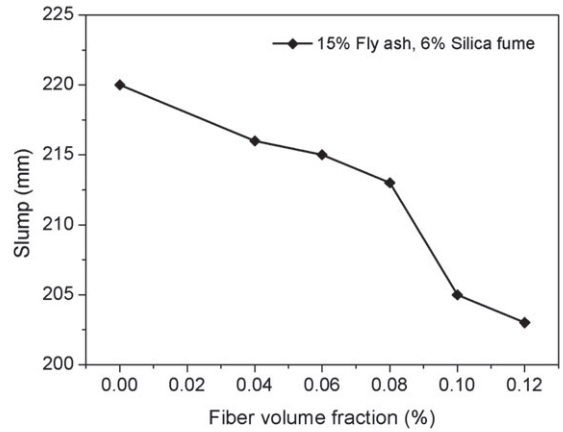

Figure 3 Effect of the polypropylene fiber on the slump.

3.3 Effect of polypropylene fiber on fracture toughness and fracture energy

The variations of the effective crack length (a_c) and fracture toughness (K_{IC}) of the polypropylene fiber-reinforced HPC composites vs. the fiber volume fraction of the three-point bending beam specimen at 28 days curing period, with the fly ash content of 15% and the silica fume content of 6%, are illustrated in Figures 5 and 6, respectively. As can be seen from the figures, in general, the addition of the polypropylene fiber can increase a_c and K_{IC} of the HPC composites containing fly

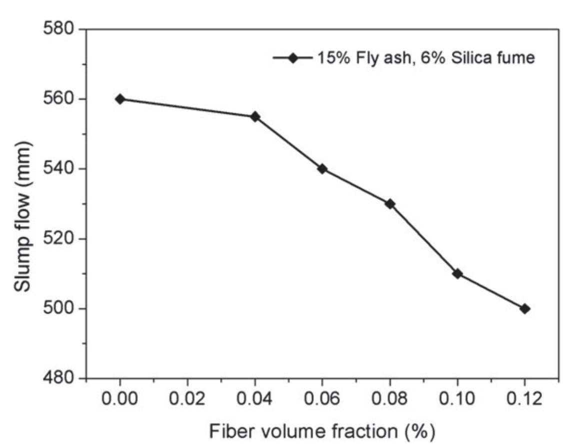

Figure 4 Effect of the polypropylene fiber on the slump flow.

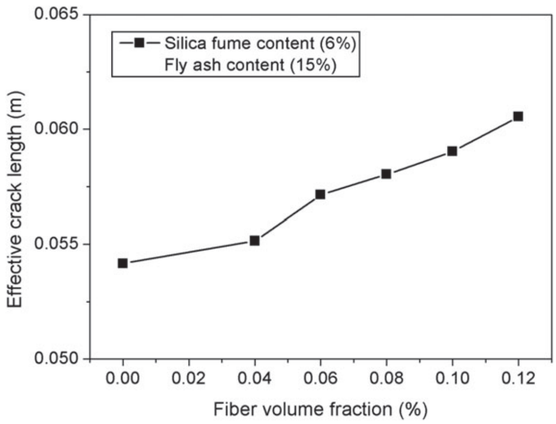

Figure 5 Effect of the polypropylene fiber on effective crack length.

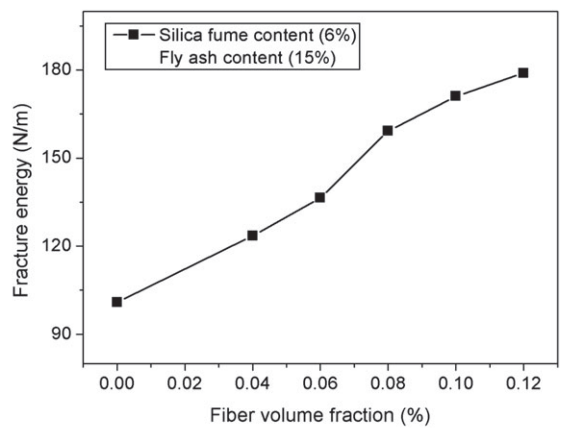

Figure 7 Effect of the polypropylene fiber on the fracture energy.

ash and silica fume. Compared with the HPC composite without the polypropylene fiber, the increase in a_c and K_{IC} was determined as 11.8% and 6.4% for the concrete with 0.12% fiber volume fraction, respectively. With the increase in fiber volume fraction, both of a_c and K_{IC} are increasing gradually with the fiber volume fraction not above 0.12%; however, the increase effect of the polypropylene fiber on K_{IC} is not obvious when the fiber volume fraction is less than 0.06%. There is a great increase in K_{IC} when the fiber volume fraction increases from 0.06% to 0.08%, and the increase rate in K_{IC} becomes smaller after the fiber volume fraction exceeds 0.08%. Figure 7 shows the variation in fracture energy (G_F) of the HPC composites containing 15% fly ash and 6% silica fume at 28 days curing period with the increase in the fiber volume fraction of polypropylene fiber. From Figure 7, it can be seen that the variation rule of G_F of the HPC composites containing fly ash and silica fume with the increase in fiber volume fraction is similar with that of K_{IC}, and G_F reaches a maximum when the fiber volume fraction is 0.12%. Compared with the HPC composite without the polypropylene fiber, the increase in G_F was determined as 77.4% for the concrete composite with 0.12% fiber volume fraction. Figure 8 presents the variation of the maximum midspan deflection of the HPC composites containing fly ash and silica fume of the three-point bending beam specimens with the increase in fiber volume fraction. As can be seen, there is an increasing tendency in the maximum midspan deflection with the increase in fiber volume fraction. The variation rules of a_c, K_{IC}, G_F, and the maximum midspan deflection indicate that the addition of the polypropylene fiber has a great positive effect on the improvement of the fracture properties of the HPC composites containing fly ash and silica fume with the fiber volume fraction not above 0.12%.

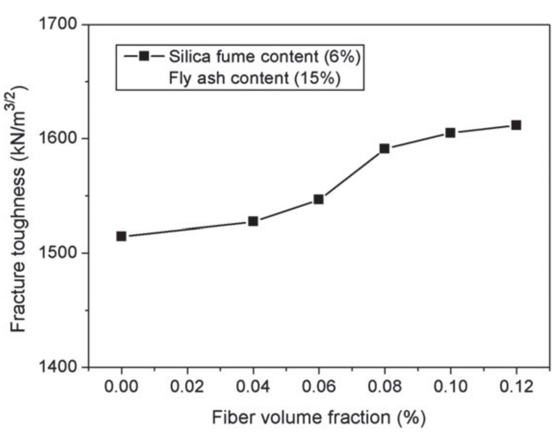

Figure 6 Effect of the polypropylene fiber on fracture toughness.

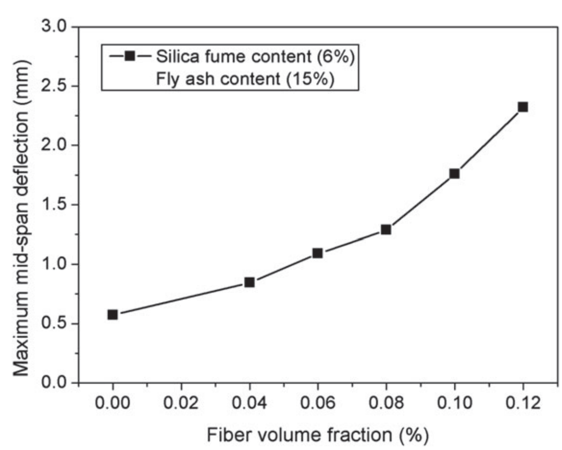

Figure 8 Effect of the polypropylene fiber on the maximum midspan deflection.

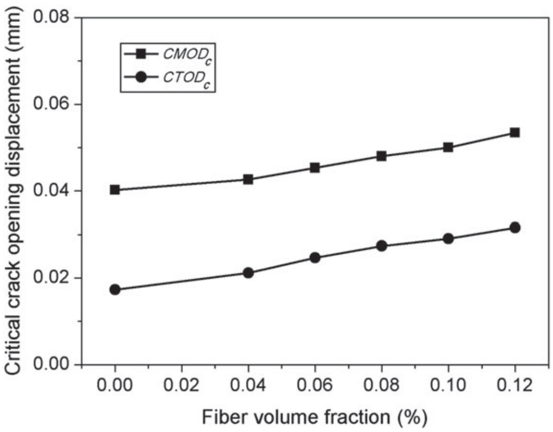

Figure 9 Effect of the polypropylene fiber on the $CMOD_c$ and $CTOD_c$.

3.4 Effect of polypropylene fiber on CMOD and CTOD

Figures 9 and 10 illustrate the variations in the critical crack opening displacement ($CMOD_c$ and $CTOD_c$) and the maximum crack opening displacement ($CMOD_{max}$ and $CTOD_{max}$) of the three-point bending beam specimens of the HPC composites containing 15% fly ash and 6% silica fume of different fiber volume fractions, respectively. It can be generally seen that the effect of the fiber volume fraction on the crack opening displacements is significant, and CMOD and CTOD increase gradually as the fiber volume fraction increases from 0% to 0.12%. Compared with the HPC composite without the polypropylene fiber, the increase in $CMOD_c$ and $CMOD_{max}$ was determined as 32.8% and 278.1%, respectively, and the increase in $CTOD_c$ and $CTOD_{max}$ was determined as 82.7% and 270.1%,

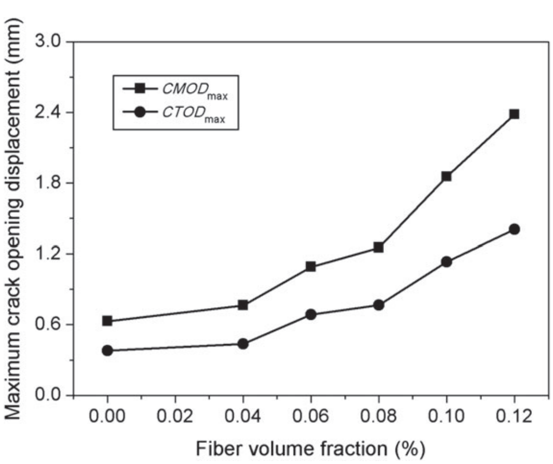

Figure 10 Effect of the polypropylene fiber on the $CMOD_{max}$ and $CTOD_{max}$.

respectively, for the HPC composite with 0.12% fiber volume fraction. From the results of CMOD and CTOD, it can also be seen that the fracture property of concrete with 15% fly ash and 6% silica fume at 28 days curing period are becoming better and better with the increase in the polypropylene fiber volume fraction.

4 Conclusions

This paper reported the experimental results of the fracture property investigation conducted on polypropylene fiber-reinforced HPC composites containing fly ash and silica fume. Based on the findings of the present investigation, the following conclusions can be drawn:

- Addition of the polypropylene fiber decreases the workability of the HPC composites containing fly ash and silica fume. With the increase in the fiber volume fraction, both of the slump and the slump flow decrease gradually.
- Addition of the polypropylene fiber has greatly improved the fracture parameters of the HPC composites containing 15% fly ash and 6% silica fume, such as fracture toughness, fracture energy, effective crack length, maximum midspan deflection, the $CMOD_c$ and $CTOD_c$, and the $CMOD_{max}$ and $CTOD_{max}$ of the three-point bending beam specimens.
- When the fiber volume fraction increases from 0% to 0.12%, the fracture parameters increase gradually with the increase in fiber volume fraction. The variation rules of the fracture parameters indicate that the capability of the polypropylene fiber to resist the crack propagation of the concrete composite containing 15% fly ash and 6% silica fume is becoming stronger and stronger with the increase in fiber volume fraction with the fiber volume fraction not above 0.12%.

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