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Research Article

Fracture Properties of Polypropylene Fiber Reinforced Concrete Containing Fly Ash and Silica Fume

Peng Zhang and Qingfu Li
School of Water Conservancy and Environment Engineering, Zhengzhou University, Zhengzhou 450001, China

Abstract: A parametric experimental study has been conducted to investigate the effect of polypropylene fiber on the fracture properties of concrete containing fly ash and silica fume, with five fiber volume fraction (0.04, 0.06, 0.08, 0.1 and 0.12%) used. The results indicate that 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 mid-span 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 with the increase of fiber volume fraction. The variation rules of the fracture parameters indicate that the capability of polypropylene fiber to resist crack propagation of concrete composite containing 15% fly ash and 6% silica fume is becoming stronger and stronger with the increase of fiber volume fraction with the fiber volume fraction not beyond 0.12%.

Keywords: Concrete, fly ash, fracture property, polypropylene fiber, silica fume

INTRODUCTION

Because fly ash causes environmental pollution and the cost of storage of fly ash is very high, the utilization of fly ash in concrete technology, 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 (Berry and Malhotra, 1980; Malhotra, 1990). Several investigations (Zhang *et al*., 2012b; Malhotra, 2002; Langey *et al*., 1992; Han *et al*., 2003) involving concrete composites containing fly ash had reported to exhibit excellent mechanical and durability properties. Despite the benefits of fly ash, practical problems remain in field application. At 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 control concrete, due to the slow process of the pozzolanic reaction of fly ash and its contribution towards the strength development occurs only at later ages (Malhotra *et al*., 2000; Swamy *et al*., 1983; Barbhuiya *et al*., 2009).

Silica fume is a by-product of silicon metal and ferro-silicon alloy industry instead of a waste product and its utilization in concrete technology has increased recently. Because of a significant improvements attained on 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 (Lee and Lee, 2010). 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) (Nochaiya *et al*., 2010). 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 (Erdogdu *et al*., 2010; Yazici, 2008; Zhang *et al*., 2011) have recently conducted investigations using a combination of the two by-products. However, a lot of research achievements (Nili and Afroughsabet, 2010; Tanyildizi, 2008) 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. Short fibers have been known and used for centuries to reinforced brittle

Corresponding Author: Peng Zhang, School of Water Conservancy and Environment Engineering, Zhengzhou University, No. 100 Science Road, Zhengzhou 450001, China

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 (Ferreira, 2007; Deng, 2005; Reis and Ferreira, 2004; Fan *et al*., 2011; Zhang *et al*., 2012a). 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 structures. The improved pore structure of concrete by applying chemical, mineral admixtures and fiber materials causes densification of 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 concrete 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, mid-span 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 concrete containing fly ash and silica fume.

MATERIALS AND EXPERIMENTAL PROGRAM

Raw materials: Ordinary Portland cement (Class 42.5R) produced by Tongli Factory, Grade I fly ash and silica fume were used in this study. The cement, fly ash and silica fume properties are given in Table 1. The polypropylene fiber used in this investigation was bunchy single short fiber, which was produced by Danyang Synthetic Fiber Plant in the Jiangsu Province of China. The basic physical properties of polypropylene fiber in this study are shown in Table 2. The water to be mixed was local tap water. Coarse aggregate with a maximum size of 20 mm and fine aggregate with a 2.82 fineness modulus were used in this experiment. A high range water reducer agent with a commercial name of polycarboxylate HJSX-A 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 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 polypropylene fiber is from 0.04 to 0.12%. Mix proportions are given in Table 3.

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

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)	3295.00	2470.00	-

Experimental method: In order to distribute 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 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 silica fume and the fibers has great effect on the working performance of the mixture and fracture properties of concrete composite. If 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 concrete composite reinforced with polypropylene fiber, it can be seen that silica fume and the fibers of this study were distributed well.

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 mid-span of the lower surface to produce a precast crack, the depth of which is 40 mm, respectively. All the specimens were stored at temperature of about 23^{o}C in casting room. They were demolded after 24 h and then cured at 100% relative humidity and controlled temperature (21±2^{o}C) for 28 days before testing.

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 (Rilem, 1985). The experiment was carried out on a hydraulic pressure testing machine, whose measure range of the load transducer is 0-30 kN. The Crack Mouth Opening Displacement (CMOD) and Crack Tip Opening Displacement (CTOD) were measured by clamp type

Table 2: Physical properties of polypropylene fiber

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

Table 3: Mix proportions of the concrete mixtures

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

extended instruments. 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 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.

RESULTS AND DISCUSSION

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 (Gao and Zhang, 2007):

$$K_{IC} = \frac{P_{V\max} S}{BH^{\frac{3}{2}}} f(\frac{a}{H}) \quad (1)$$

where,

K_{IC} : Fracture toughness, $kN/m^{3/2}$
P_{vmax} : Peak vertical load, kN
S : Span length of the beam specimen, m
H : Height of the beam specimen, m
B : Width of the beam specimen, m
α : Depth of the precast crack, m
$f(\frac{\alpha}{H})$: A function relevant to α/H, the expression of which is as follows:

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

It is easy to calculate K_{IC} of the three-point bending beam specimen using Eq. (1) and (2). In order to get the actual K_{IC} of HPC containing silica fume, the depth of the precast crack in Eq. (1) and (2) should be replaced by the effective crack length (α_c) because the subcritical expanding displacement of the precast crack tip of the three-point bending beam specimen is not considered in Eq. (1) and (2), the K_{IC} calculated by which can't reflect the actual fracture property of HPC. The effective crack length of the three-point bending beam specimen can be calculated as follows (Xu and Reinhardt, 2000):

$$a_c = \frac{2}{\pi} h \times arctg \sqrt{\frac{Eb}{32.6 P_{v\max}} CMOD_c - 0.1135} \quad (3)$$

where,

α_c : Effective crack length of the three-point bending beam specimen, m
P_{vmax} : Peak vertical load, kN
CMODc : Critical crack mouth opening displacement, m
E : Elastic modulus of HPC, MPa
H : Height of the beam specimen, m
b : Width of the beam specimen, m

With the measured ultimate mid-span deflection and the relational curve of P_v-δ of the three-point bending beam specimen, the fracture energy of cement stabilized aggregate can be calculated as follows (Yu *et al*., 1987):

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

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

where,

G_F : Fracture energy, N/m
A_{lig} : Area of the fracture ligament of the specimen, m^2
H : Height of the beam specimen, m
B : Width of the beam specimen, m
α : Depth of the precast crack, m
g : Gravitational acceleration ($g = 9.8 m/s^2$)
m_1 : Weight of the specimen between the two supports, kg
m_2 : Additive weight of the loading facilities

δ_{max} : Ultimate deflection in span centre of the beam specimen, m
W_0 : Area under the relational curve of P_v-δ, N, m

Effect of polypropylene fiber on fracture toughness and fracture energy: The variations of the effective crack length (α_c) and fracture toughness (K_{IC}) of polypropylene fiber reinforced concrete versus 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 Fig. 1 and 2, respectively. As can be seen from the figures, in general, the addition of polypropylene fiber can increase α_c and K_{IC} of the concrete containing fly ash and silica fume. Compared with the concrete without polypropylene fiber, the increase of α_c and K_{IC} were determined as 11.8 and 6.4% for the concrete with 0.12% fiber volume fraction respectively. With the increase of fiber volume fraction, both of α_c and K_{IC} are increasing gradually with the fiber volume fraction not beyond 0.12%, however, the increase effect of polypropylene fiber on K_{IC} is not obvious when the fiber volume fraction is less than 0.06%. There is 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 3 shows the variation of fracture energy (G_F) of concrete containing 15% fly ash and 6% silica fume at 28 days curing period with the increase of the fiber volume fraction of polypropylene fiber. From Fig. 3, it can be seen that the variation rule of G_F of concrete containing fly ash and silica fume with the increase of 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 concrete without polypropylene fiber, the increase of G_F was determined as 77.4% for the concrete composite with 0.12% fiber volume fraction. Figure 4 presents the variation of the maximum mid-span deflection of concrete containing fly ash and silica fume of the three-point bending beam specimens with the increase of fiber volume fraction. As can be seen, there is an increasing tendency in the maximum mid-span deflection with the increase of fiber volume fraction. The variation rules of α_c, K_{IC}, G_F and the maximum mid-span deflection indicate that the addition of polypropylene fiber has great positive effect on the improvement of the fracture properties of the concrete containing fly ash and silica fume with the fiber volume fraction not beyond 0.12%.

Effect of polypropylene fiber on CMOD and CTOD: Figure 5 and 6 illustrate the variations of the critical crack opening displacement ($CMOD_c$ and $CTOD_c$) and

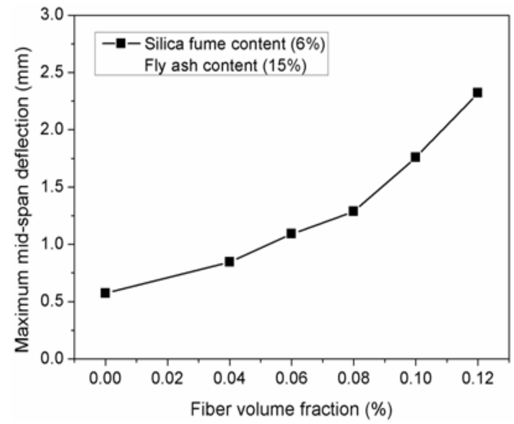

Fig. 1: Effect of polypropylene fiber on effective crack length

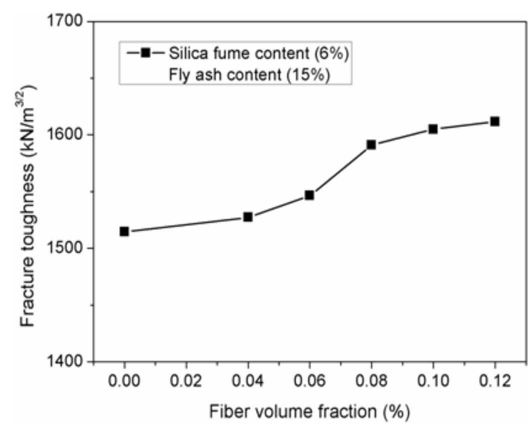

Fig. 2: Effect of polypropylene fiber on fracture toughness

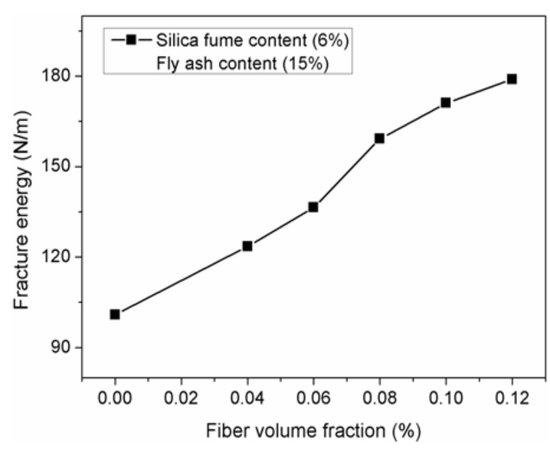

Fig. 3: Effect of polypropylene fiber on fracture energy

the maximum crack opening displacement ($CMOD_{max}$ and $CTOD_{max}$) of the three-point bending beam specimens of concrete containing 15% fly ash and 6% silica fume of different fiber volume fraction,

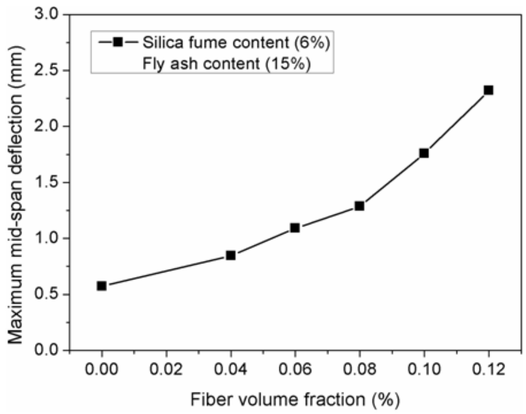

Fig. 4: Effect of polypropylene fiber on maximum mid-span deflection

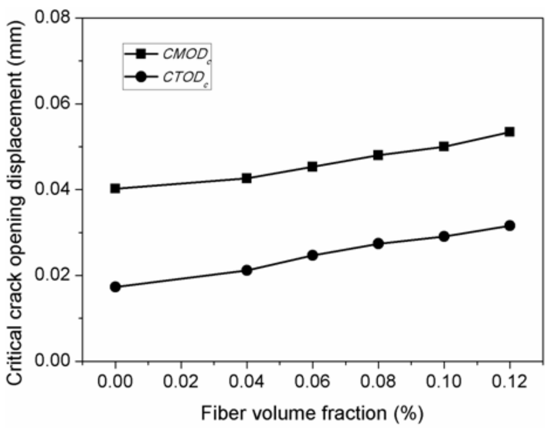

Fig. 5: Effect of polypropylene fiber critical crack opening displacement

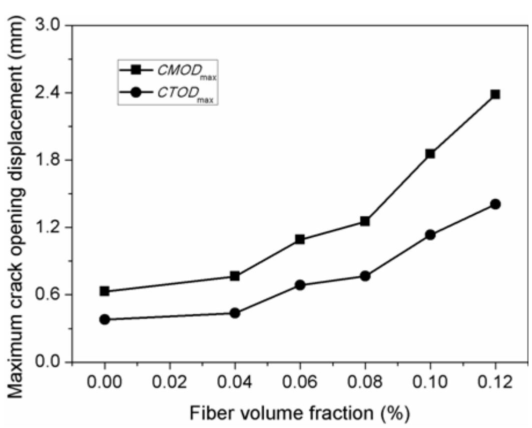

Fig. 6: Effect of polypropylene fiber maximum crack opening displacement

respectively. It can be generally seen that, the effect of 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 concrete composite without polypropylene fiber, the increase of $CMOD_c$ and $CMOD_{max}$ were determined as 32.8 and 278.1%, respectively and the increase of $CTOD_c$ and $CTOD_{max}$ were determined as 82.7 and 270.1%, respectively for the concrete 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 of polypropylene fiber volume fraction.

CONCLUSION

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

- 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 mid-span 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 with the increase of fiber volume fraction. The variation rules of the fracture parameters indicate that the capability of polypropylene fiber to resist crack propagation of concrete composite containing 15% fly ash and 6% silica fume is becoming stronger and stronger with the increase of fiber volume fraction with the fiber volume fraction not beyond 0.12%.

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