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Fracture behavior of fly ash concrete containing silica fume

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Abstract. Effect of silica fume on fresh properties, compressive strength at 28 days and fracture behavior of fly ash concrete composite were studied in this paper. Test results indicated that the fluidity and flowability of fly ash concrete composites decreased and fly ash concrete composite are more cohesive and appear to be sticky with the addition of silica fume. Addition of silica fume was very effective in improving the compressive strength at 28 days of fly ash concrete composite, and the compressive strength of fly ash concrete composite has a trend of increase with the increase of silica fume content. Results also indicated that all the fracture parameters of effective crack length, fracture toughness, fracture energy, the critical crack opening displacement and the maximum crack opening displacement of fly ash concrete composite decreased with the addition of silica fume. When the content of silica fume increased from 3% to 12%, these fracture parameters decreased gradually with the increase of silica fume content. Furthermore, silica fume had great effect on the relational curves of the three-point bending beam specimen. As the silica fume content increased from 3% to 12%, the areas surrounded by the three relational curves and the axes were becoming smaller and smaller, which indicated that the capability of concrete composite containing fly ash to resist crack propagation was becoming weaker and weaker.

Keywords: fly ash concrete; fracture behavior; silica fume

1. Introduction

Fly ash is a by-product obtained in the process of hard coal combustion performed in electric power stations and in thermal-electric power stations (Ahmaruzzaman 2010). It is removed by mechanical collectors or electrostatic precipitators as a fine particulate residue from the combustion gases before they are discharged to the atmosphere. The use of fly ash as partial replacement of cement in concrete composite has numerous benefits, which includes reduced greenhouse gas emissions, good long term strength and durability characteristics, reduced water demand, reduced energy consumption and lessened pressure on natural resources (Bahgeri *et al*. 2013, Zhang *et al*. 2011a, Zhang and Li 2013a). Nowadays fly ash is probably the most frequently used pozzolanic waste materials in concrete composite worldwide, mainly because it is available in large amounts for low price (Golewski and Sadowski 2014). Despite the advantages of fly ash in concrete composite, there are a lot of practical problems in the application of fly ash. At early stages of the curing period, the strength of concrete composite containing a high volume of fly ash,

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which is considered as a partial cement replacement, is much lower than that of the control concrete composite, 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). Therefore, some other additives should be added to overcome the deficiency of fly ash concrete composite. One such important additive is silica fume.

Silica fume is a by-product of the smelting process in the silicon and ferrosilicon industry, and it is a very fine non-crystalline silica produced in electric arc furnaces as a by product of production of elemental silicon or alloys containing silicon, which has been recognized as a pozzolanic admixture that is effective in enhancing the mechanical properties of concrete composite to a great extent. It is well known that the use of silica fume can significantly improve the mechanical properties and durability of concrete composite (Koksal *et al*. 2008, Zhang and Li 2013a, Zhang and Li 2013b, Dilbas *et al*. 2014). The high content of amorphous silicon dioxide (more than 80%) and very fine spherical particle (100 nm average diameter) are the main reasons for its high pozzolanic reaction in improving the properties of concrete composite (Tanyildizi 2013). Development of the constitutive model for a material requires its fracture parameters. The fracture characteristics of a material are used to describe the formation and propagation of cracks in the material (Sarker *et al*. 2013). Despite the recent efforts, few studies are available, concerning the fracture behavior of concrete containing silica fume, especially no significant experimental data exist on the effect of silica fume on fracture behavior of fly ash concrete composite. Thus, it is necessary to study the fracture parameters of fly ash concrete composite containing silica fume to understand its failure behavior. In this study, the fracture properties of fly ash concrete composite specimens containing silica fume were determined from three-point bending test of notched beams. Fracture toughness, fracture energy, mid-span deflection, crack mouth opening displacement and crack tip opening displacement were measured for fly ash concrete composite containing different dosages of silica fume to compare with those of fly ash concrete specimens without silica fume.

2. Materials and experimental program

2.1 Materials

In this study, Ordinary Portland cement (Class 42.5R), Grade I fly ash and silica fume were used, whose properties are given in Table 1. Fly ash and silica fume were added in concrete by replacing the same quantity of cement. The water used in this study was the local tap water. The coarse aggregate used in this study has a maximum size of 20 mm and the fine aggregate has a 2.82 fineness modulus. Besides, a kind of polycarboxylate water reducing agent was used to adjust the workability of the concrete mixture. The mix proportions of the concrete composites are given in Table 2.

2.2 Slump and slump flow test

The workability of the fresh fly ash concrete composites was evaluated by slump test and slump flow test. The slump flow can be expressed as the spreading diameter of the fresh concrete composite in the slump test. The slump can reflect the fluidity of the fresh concrete composite, and the slump flow can reflect the cohesive properties of the fresh concrete composite. Slump flow test

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	2470	-

Table 2 Mix proportions of the concrete composites

Mix no.	Cement (kg/m^3)	Fly ash (%)	Fly ash (kg/m^3)	Silica fume (%)	Silica fume (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Water reducer agent (kg/m^3)
1	419.9	15	74.1	-	-	647	1151	158	4.94
2	405.1	15	74.1	3	14.8	647	1151	158	4.94
3	390.3	15	74.1	6	29.6	647	1151	158	4.94
4	375.4	15	74.1	9	44.5	647	1151	158	4.94
5	360.6	15	74.1	12	59.3	647	1151	158	4.94

is also the most commonly used and gives a good assessment of filling ability. This test is used to evaluate the horizontal free flow (deformability) of concrete in the absence of obstructions (Memon *et al*. 2013). To perform the test, a slump cone is placed on a rigid and non- absorbent leveled plate and filled with concrete composite. After the fresh concrete composite was tamped, the slump cone was raised vertically and concrete is allowed to flow out freely. The difference of the maximum height of the fresh concrete composite and the height of the slump cone was measured as the value of slump. The diameter of concrete in two perpendicular directions is measured, and the average of the two measured diameters is recorded. The larger values of slump and slump flow indicate that the fresh concrete composite has better workability. The higher the slump flow, the better the filling ability of concrete to fill formwork is.

2.3 Preparation of specimens

Series of cube specimens with the length of 150 mm for each side were used to determine the compressive strength. In the fracture test, a series of notched beam specimens with the size of 100×100×515 mm were prepared to determine the fracture parameters. A large number of researchers have applied the method of three-point bending to study the fracture properties for concrete composites. In their studies and the authors' previous study work, the fracture parameters

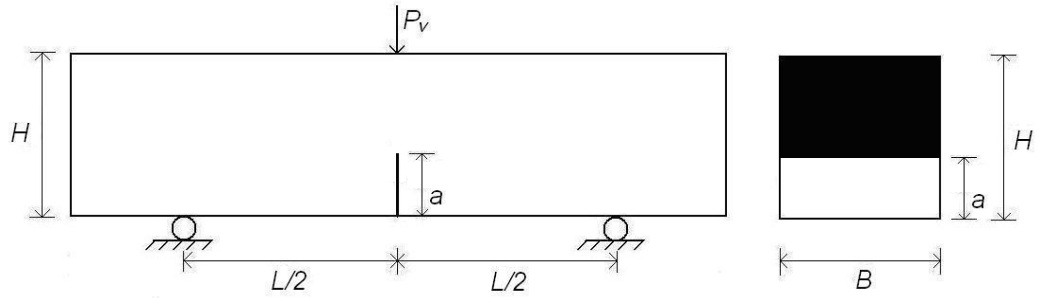

Fig. 1 Shape and size of beam specimen

of concrete composites were measured successfully with the specimen size of 100×100×515 mm (Gao *et al*. 2006, Gao and Zhang 2007, Zhang *et al*. 2011b, Zhang and Li 2013c). Therefore, the size of 100×100×515 mm was chosen in this study. In order to produce a precast crack, the specimen was sawed from the mid-span of the bottom surface, and the depth of the precast crack is 40 mm. Fig. 1 shows the shape and the size of the beam specimen. The prepared specimens were placed in the casting room with the temperature of 23°C. After staying in the casting room for 24 h, the specimens were demolded, and then they were cured in the curing room for 28 days, in which the relative humidity is 100% and the controlled temperature is 21±2°C. In order to decrease the dispersion of the test data, 6 specimens were prepared for each mixture.

2.4 Compressive strength test

The tests of compressive strength were carried out by hydraulic pressure universal testing machine according to the Chinese Standard (JTJ E30-2005 2005). Before testing, the specimen was put onto the pad of the elevating platform of the test machine. The loading rate of compressive strength test was controlled between 0.5 MPa/s and 0.8 MPa /s. Each set includes 3 specimens, and the average value of the 3 data was computed as the final result.

2.5 Three-point bending fracture test

There are several test methods suitable for studying fracture of concrete including three-point bending beam method (Gao and Zhang 2007), indirect diametric tensile testing (Piratheepan *et al*. 2012), direct tensile test (Zhao *et al*. 2009a), compact tensile test (Zhao *et al*. 2009b) and wedge splitting test (Zhao *et al*. 2010). However, excepting three-point bending beam method, the requirements on the testing machine of the other methods to measure the fracture parameters are very high. Therefore, three-point bending beam method was adopted in this study, which was carried out on a hydraulic pressure testing machine according to RILEM standard (RILEM 50-FMC 1985). The crack mouth opening displacement (*CMOD*) and crack tip opening displacement (*CTOD*) were measured by clamp type extended instruments (Fig. 2). There are 2 clamp type extended instruments in Fig. 2. The above clamp type extended instrument was fixed to record the crack tip opening displacement, and the other one was fixed on the bottom of the specimen to record the crack mouth opening displacement. 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. During the course of loading, the load applied using the method of load controlling. On the screen of the computer, the value of the load applied, which was transferred from the load sensor, was shown in the form of strain value. Therefore, the load can be applied according to the strain value of the load sensor. The rate of loading was controlled as 10 N/s. In this study, there are three kinds of data including the vertical load (P_V), the deflection in span centre of the beam specimen (δ) and crack mouth opening displacement (*CMOD*), and crack tip opening displacement (*CTOD*). Firstly, all the data was collected and transferred to the strain acquisition instrument in the form of strain value from the load sensor, the electric displacement meter and the clamp type extended instruments. Then these strain values were transferred to the computer. The relational curves between the vertical load and the mid-span deflection (P_V-δ), crack mouth opening displacement (P_V-*CMOD*), and crack tip opening displacement (P_V-*CTOD*) were obtained respectively from the *X*-*Y* dynamic function recorder. The testing apparatus and the specimen being loaded in fracture test are presented in Figs. 3 and 4.

Fig. 2 Clamp type extended instruments

Fig. 3 Loading device of three-point bending test

Fig. 4 Specimen being loaded

2.6 Calculation of fracture toughness and fracture energy

With the measured peak vertical load of the three-point bending beam specimen, the fracture toughness of concrete composite can be calculated as follows (Gao and Zhang 2007)

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

where, K_{IC}, fracture toughness, kN/m$^{3/2}$; $P_{V\max}$, 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; a, depth of the precast crack, m. $f(\frac{a}{H})$ is a function relevant to $\frac{a}{H}$, the expression of which is as follows

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

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 concrete composite containing fly ash and 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} calculated by which can't reflect the actual fracture property of concrete composite. The effective crack length of the three-point bending beam specimen can be calculated as follows (Xu and Reinhardt 2000)

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

where, a_c, effective crack length of the three-point bending beam specimen, m; $P_{V\max}$, peak vertical load, kN; *CMOD*, critical crack mouth opening displacement, m; *E*, elastic modulus of concrete composite, 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-

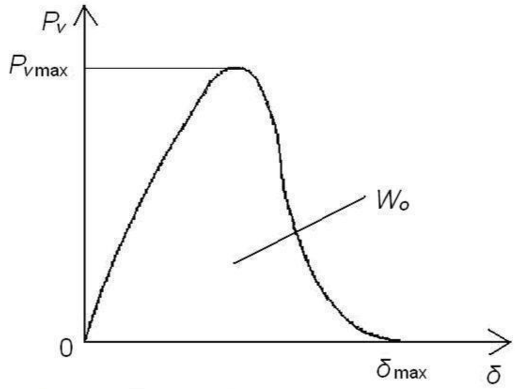

Fig. 5 Full curve of "P_v-δ"

point bending beam specimen, the fracture energy of concrete composite can be calculated as follows (Shah *et al.* 1995, Yu *et al.* 1987)

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

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

where, G_F, 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; a, 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; $\delta_{\max}$, ultimate deflection in span centre of the beam specimen, m; W_0, area under the relational curve of P_V-δ (Fig. 5), N·m.

3. Results and discussion

3.1 Fresh properties

The variations of the slump and slump flow of concrete composite containing fly ash with the increase of silica fume content are shown in Figs. 6 and 7, respectively. As can be seen from the figures, in general, the addition of silica fume decreases the slump and slump flow of the concrete composite with 15% fly ash, which indicates that the addition of silica fume has adverse effect on the workability of concrete composite containing fly ash. Compared with the concrete composite without silica fume, the decrease of the slump and slump flow were determined as 13% and 28.6% for the concrete composite with 12% silica fume content respectively. With the increase of silica fume content, both of the slump and slump flow are decreasing gradually, however, the effect of silica fume on the workability is not obvious when the silica fume content is less than 6%. There is great decrease in the slump and slump flow when the silica fume content increases from 6% to 9%, and the decrease rate in the slump and slump becomes smaller after the silica fume content exceeds 9%. Because of the higher surface area and extremely fine particle size, silica fume increased the water requirement of concrete composite.

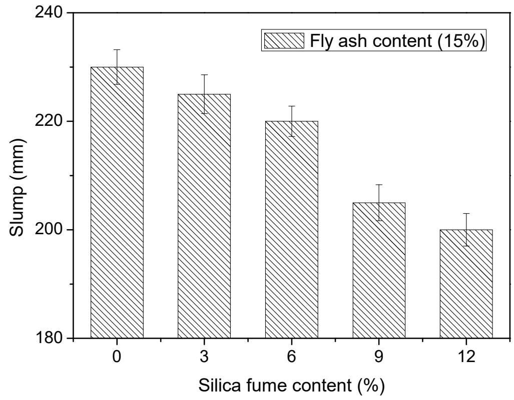

Fig. 6 Effect of silica fume content on slump

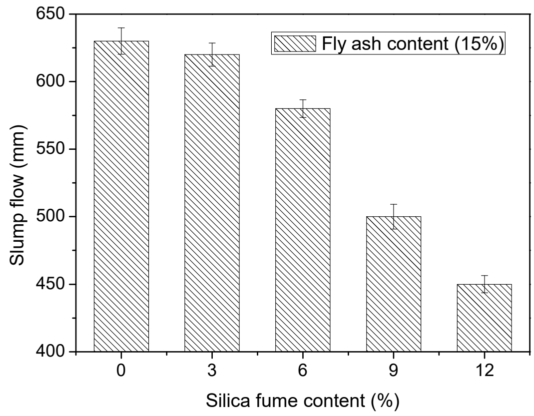

Fig. 7 Effect of silica fume content on slump flow

The addition of silica fume as a partial replacement of cement in fly ash concrete composite resulted in the loss of workability. This might be explained by the increased surface area of silica fume particles. Generally, the mixtures containing silica fume exhibited worse performance than the control mix in regards to the fresh properties. It was observed that the concrete mixes containing higher percentages of silica fume were more cohesive and appeared to be sticky. It has been shown in research that silica fume reduces the setting time and bleeding. Silica fume, because of its higher surface area than cement and fly ash, absorbed the excessive water in the concrete composite system (Li *et al*. 2011).

3.2 Compressive strength

Fig. 8 illustrates the variation of compressive strength at 28 days of fly ash concrete with the increase of silica fume content. As can be seen from the figure, the strengths of the concrete composites containing silica fume are higher than that of the concrete composite only containing 15% fly ash. When the silica fume content is less than 3%, the addition of silica fume has no significant influence on the compressive strength at 28 days of fly ash concrete. However, the

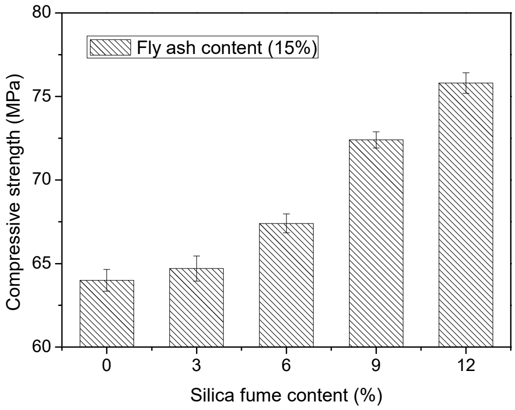

Fig. 8 Effect of silica fume content on compressive strength

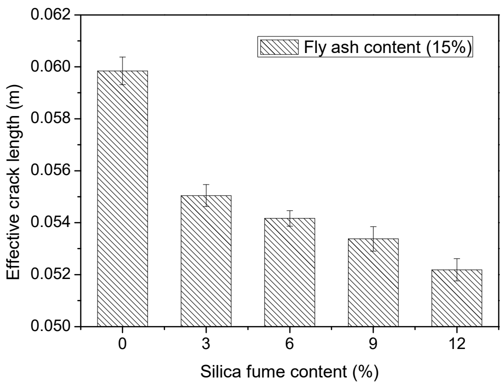

Fig. 9 Effect of silica fume content on effective crack length

higher contents of silica fume greatly increase the compressive strength at 28 days of fly ash concrete, and the compressive strength has a trend of increase with the increase of silica fume content. Silica fume acts as the filler due to its smaller particle size, and the pozzolanic reaction of the silica fume produces additional C-S-H gel, which grows into the capillary spaces that remain after the hydration of the cement in mortar mixes (Blanco *et al*. 2006). Therefore, it would appear that silica fume acts both physically (as filler) and chemically (reacting with $Ca(OH)_2$ to form C-S-H) to aid in the strength improvement of fly ash concrete composites.

3.3 Fracture toughness and fracture energy

Figs. 9 and 10 present the variations of the effective crack length and fracture toughness of the concrete composite containing fly ash of the three-point bending beam specimens at the curing period of 28d with the increase of silica fume content. As can be seen from the two figures, there is a considerable decrease for the effective crack length and fracture toughness after silica fume was added into the concrete composite containing fly ash. When the silica fume content increase from 0 to 12%, both of the effective crack length and fracture toughness of the concrete composite decrease gradually. The effective crack length and fracture toughness of the concrete composite

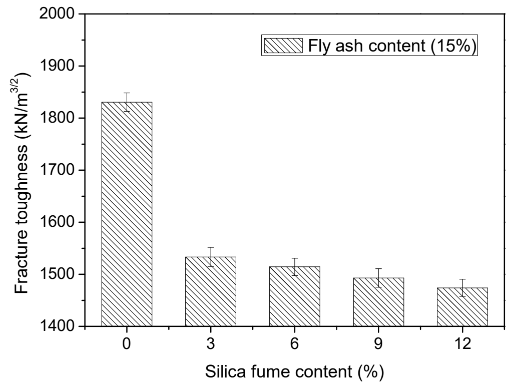

Fig. 10 Effect of silica fume content on fracture toughness

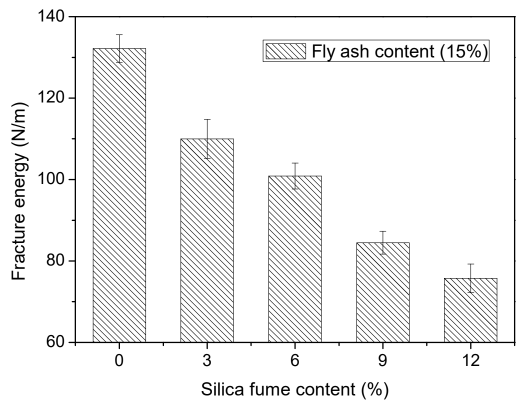

Fig. 11 Effect of silica fume content on fracture energy

with 12% silica fume content decrease by 12.8% and 19.5%, respectively, compared with the concrete composite without silica fume. Fig. 11 illustrates the varying rule of fracture energy of the concrete composite containing fly ash and silica fume as the silica fume content increases. From Fig. 11, it can be seen that the varying rule of the fracture energy of the concrete composite containing fly ash with the increase of silica fume content is similar with that of the fracture toughness. Compared with the concrete composite without silica fume, the fracture energy of the concrete composite was decreased by 42.7% when the silica fume content is 12%. From the varying rules showing in Figs. 10 and 11, it can be seen that silica fume has negative effect on the fracture property of concrete composite. The former research results also indicate that 5% replacement of cement will reduce the fracture properties of the high strength concrete (Lam *et al.* 1998). Fig. 12 illustrates the effect of silica fume contents on the typical complete curves of P_V-δ of the three-point bending beam specimens of concrete composite containing fly ash. It can be seen from the complete curves that the content of silica fume has great effect on the shape of the curve. As he silica fume content increases from 3% to 12%, the area between the relational curve of P_V-δ and the coordinate axis becomes smaller and smaller, and the mid-span deflection also becomes smaller and smaller. However, the mid-span deflection of the beam specimen when the load reaches the peak vertical load varies little. The smaller area between the relational curve of

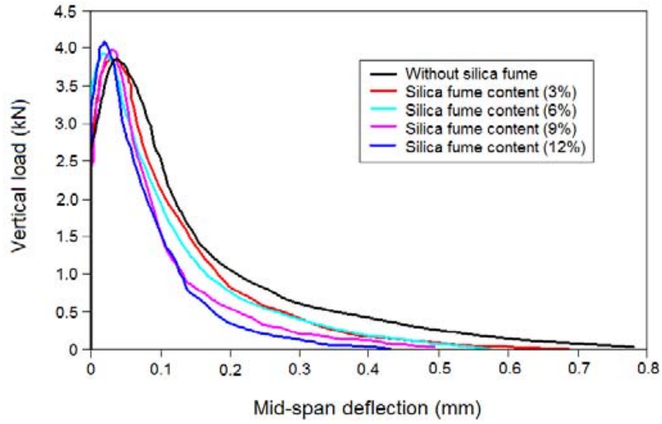

Fig. 12 Contrast of "P_v-δ" curves of different silica fume content

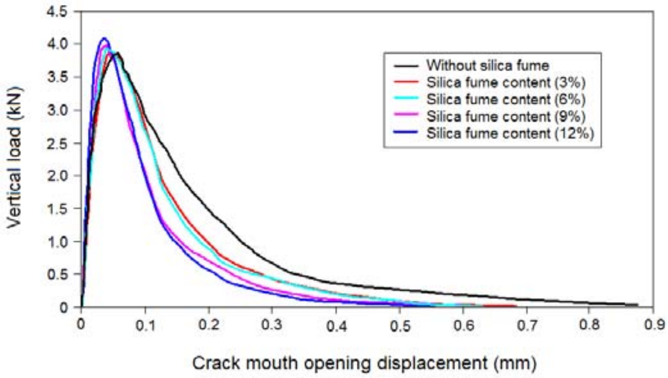

Fig. 13 Contrast of "*Pv-CMOD*" curves of different silica fume content

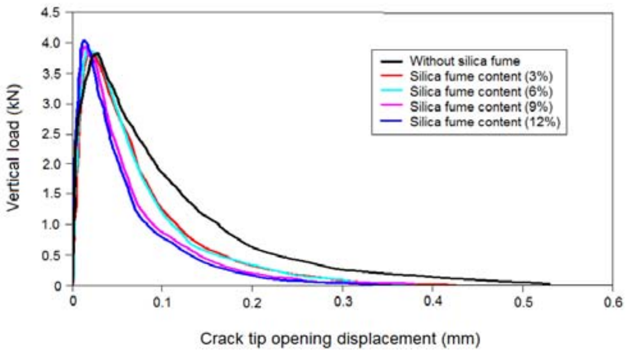

Fig. 14 Contrast of "*Pv-CTOD*" curves of different silica fume content

P_V-δ and the coordinate axis indicates that the three-point bending beam specimen has lower fracture property (Joshua *et al*. 2007). Accordingly, when the silica fume content is lower than 12%, the resistance to crack propagation of the concrete composite containing fly ash is gradually decreased with the increase of silica fume content.

3.4 CMOD and CTOD

The critical *CMOD* and critical *CTOD* are the values of *CMOD* and *CTOD*, respectively, when the vertical load reached the peak vertical load. Therefore, the critical *CMOD* and critical *CTOD* can be recorded through the curves of (P_v-*CMOD*) and (P_v-*CTOD*) obtained during the course of the experiment. Fig. 13 and 14 present the different relational curves of P_V-*CMOD* and P_V-*CTOD* of the three-point bending beam specimens for 28 days curing of the concrete composite containing fly ash with different contents of silica fume. From the curves in the two figures, it can be seen that silica fume content has great effect on the shape of P_V-*CMOD* and P_V-*CTOD* curves, and the area between the curve and the coordinate axis becomes smaller and smaller when the silica fume content increases from 3% to 12%. The varying rule of 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 for 28 days curing of the concrete composite containing fly ash with different contents of silica fume is illustrated in Figs. 15 and 16. As is shown in the figures, silica fume has great effect on *CMOD* and *CTOD*, and there is an increasing tendency of the *CMOD* and when the silica fume content decreases from 3% to 12%.

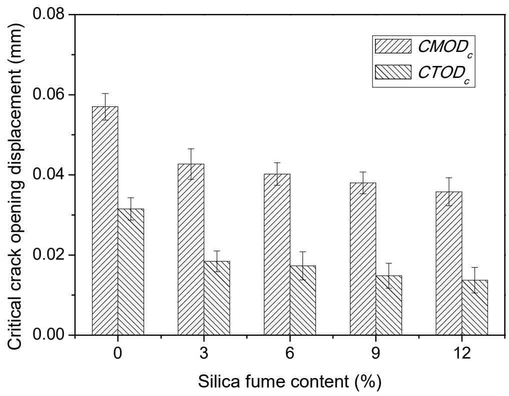

Fig. 15 Effect of silica fume content on critical crack opening displacement

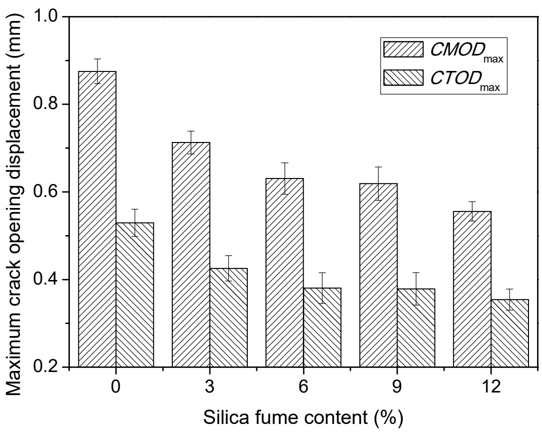

Fig. 16 Effect of silica fume content on maximum crack opening displacement

After 12% silica fume is added into the concrete, the $CMOD_c$ and $CMOD_{\max}$ decrease by 37.2% and 36.5% respectively, and the $CTOD_c$ and $CTOD_{\max}$ decrease by 56.5% and 33.1% respectively. The results of *CMOD* and *CTOD* also indicate that the addition of silica fume has adverse effect on the fracture property of concrete composite containing fly ash when the silica fume content increases from 3% to 12%. The inclusion of silica fume in concrete causes significant changes in the structure of the matrix by both a physical action and a pozzolanic reaction. The silica fume particles with small size and spherical shape can fill the voids created by free water in the matrix. This particle packing effect refines the microstructure of concrete, creates a much denser pore structure, and results in an increase in the mechanical properties of concrete. Meanwhile, the addition of silica fume particles makes the fly ash concrete composite become brittler than the control composite mixture.

4. Conclusions

Based on the findings of the present investigation, the following conclusions can be drawn. Fluidity and flowability of various fly ash concrete composites mixes decrease when the contents of silica fume increases. The concrete composite mixes containing higher percentages of silica fume are more cohesive and appear to be sticky. The addition of silica fume reduces the setting time and bleeding of fly ash concrete composite.

- Addition of silica fume by substitution to cement is proved to be very effective in improving the compressive strength of fly ash concrete composite at 28 days. The compressive strength of fly ash concrete composite has a trend of increase with the increase of silica fume content.
- All the fracture parameters of effective crack length, fracture toughness, fracture energy, the critical crack opening displacement and the maximum crack opening displacement of fly ash concrete composite decrease with different contents of silica fume addition into the concrete composite. When the content of silica fume increases from 3% to 12%, these fracture parameters decrease gradually with the increase of silica fume content. The inclusion of silica fume in concrete causes significant changes in the structure of the matrix by both a physical action and a pozzolanic reaction, which greatly influences the fracture properties of fly ash concretes.
- Silica fume has great effect on the relational curve of P_V-δ, P_V-$CMOD$, and P_V-$CTOD$ of the three-point bending beam specimen. As the silica fume content increases from 3% to 12%, the areas surrounded by the three relational curves and the axes are becoming smaller and smaller, which indicates that the capability of concrete composite containing fly ash to resist crack propagation is becoming weaker and weaker. Silica fume makes the fly ash concrete composite become brittler than the control composite mixture.

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