Periodica Polytechnica
Civil Engineering

60(2), pp. 289–296, 2016
DOI: 10.3311/PPci.8509

RESEARCH ARTICLE

Experimental Evaluation of Mechanical Properties and Fracture Behavior of Carbon Fiber Reinforced High Strength Concrete

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Received 17-08-2015, revised 01-12-2015, accepted 10-12-2015

Abstract

Concrete without reinforcement is brittle which is intensified in high strength concrete. Fibers have been utilized to improve the tensile and bending performance of concrete. Fibers primarily control the propagation of cracks and limit the crack width. Carbon fiber reinforced concretes are reliable structural materials with superior performance characteristics compared to conventional concrete. The addition of carbon fiber in concrete has been found to improve several properties, primarily cracking resistance, ductility and fatigue life. This paper reports a study on the mechanical and fracture properties of high strength concrete reinforced with different volume fractions of carbon fiber. Four different volume fractions between the range of 0.25% and 1.00% were chosen. Carbon fiber improved the compressive strength, load bearing capacity, fracture energy and toughness of concrete. Fiber volume fraction was more prominent factor in this regard. Fracture parameters showed better performance beyond 0.50% fiber inclusion.

Keywords

Carbon fiber · high strength concrete · mechanical properties · fracture parameters

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1 Introduction

Concrete is the most widely used construction material in the world, which can be attributed in large part to the fact that its characteristics can be altered to meet the needs of a wide variety of applications. Varying the proportions of the basic components of concrete – cement, water, coarse aggregate, and fine aggregate – significantly alters the properties of the fresh and hardened concrete. Concrete or mortar without reinforcement is brittle which is intensified in high strength concrete [1–3]. Fibres have been utilized to improve the tensile and bending performance of concrete. In order to increase the ductility and the strength of concrete or mortar, different types of reinforcements such as steel fibre, glass, polymer, wollastonite microfibre and carbon sheet are often used. The increase in ductility and strength is mainly achieved by the stress transfer from the matrix to the reinforcements through the adhesive contact of paste surrounding the reinforcements [4].

The experimental bending tests results have shown that fibres have an extended post-peak softening behaviour. The shape of the descending plot depends on the geometrical and mechanical parameters of the fibres and on the dosage of fibre [5]. Fibres primarily control the propagation of cracks and limit the crack width. High elastic modulus fibres such as steel and carbon fibres (CF) also enhance the flexural toughness and ductility of concrete. The beneficial effect of fibres can be noted mainly after matrix cracks in concrete, where they contribute in bridging the propagating cracks [6, 7]. However, if the steel fibres are added in high dosages, they show poor performance in terms of workability and increased cost. Also, due to the high stiffness of steel fibres, micro-defects such as voids and honeycombs can develop during the placement of concrete which can result in improper consolidation at low workability levels [8]. CF reinforced concretes are acceptable structural materials as they exhibit superior performance compared to ordinary concrete. The addition of CF in concrete has been found to improve several of its properties, primarily cracking resistance, ductility and fatigue life [9]. Further studies have shown that CF can provide significant reinforcement. Banthia and Sheng [10] have studied the methods to improve toughness and strength in paste and mortar by reinforcing with CF 6 - 10 mm in length. In this study, the test results showed that cement-based matrices reinforced at 1%, 2%, 3% by volume of CF, as the fibre content increased the load carrying capacity and toughness also increased. In another study, CF reinforced concrete showed a considerable beneficial effect on the behaviour of concrete subjected to flexure fatigue loading [9]. Barzin and Li [11] have studied the tensile and flexural properties of cementitious composites reinforced with CF, and the lower efficiency observed in the tests may be attributed to the CF with short length.

However, mechanical and fracture properties of carbon fibre reinforced high strength concrete has not been paid much attention by researchers. This paper reports a study on the mechanical and fracture properties of high strength concrete reinforced with CF. The effect of different parameters such as volume fraction on the fracture properties of concrete was also evaluated. There is also paucity of information regarding the flexural behaviours of concretes reinforced with CF.

2 Experimental Study

2.1 Materials and mixture proportions

The mix proportion of concrete used in this study is summarized in Table 1. R represents the reference concrete, CF represents carbon fibre added concretes. The numbers written after CF letters indicates the addition of fibre percentages by volume. w/b ratio of 0.45 was applied to all test specimens. CEM I 42.5 R Portland cement and fly ash were used as cementitious materials, the physical properties and chemical compositions are listed in Table 2. The aggregates used in this research were limestone coarse aggregate with a particle density of 2.77 kg/dm^3, natural river sand with a particle density of 2.75 kg/dm^3, crushed limestone sand with a particle density of 2.65 kg/dm^3. Maximum particle size of the coarse aggregate, natural river sand and limestone sand was 11.2 mm, 2 mm and 4 mm respectively. In addition, to satisfy the slump requirement of concrete, polycarboxylate superplasticizer (SP), a high performance water-reducing agent, was added. For investigating the effect of fibre content on the properties, CFs having a length of 12 mm and a diameter of 7 μm were incorporated in four different volume fractions (V_f = 0.25%, 0.50%, 0.75%, and 1%). Detailed properties of the carbon fibres used are listed in Table 3. After casting, the surface of the concrete was covered with a plastic sheet, and they were cured at room temperature for 24 h before demolding. After demolding all samples were kept in lime saturated water till testing day.

2.2 Test setup and procedure

2.2.1 Compression test

Cube specimens with dimensions of 150 mm were casted in order to determine the effect of CF addition on compressive strength. Compressive strength was determined on three specimens for each mixture according to EN 12390-3.

2.2.2 Determination of modulus of elasticity

A cylindrical specimen having dimensions of 100/200 mm was used for static modulus of elasticity determination in accordance with ASTM C469M using the stress-strain response, as expressed by Eq. (1).

$$E = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.00005)} \tag{1}$$

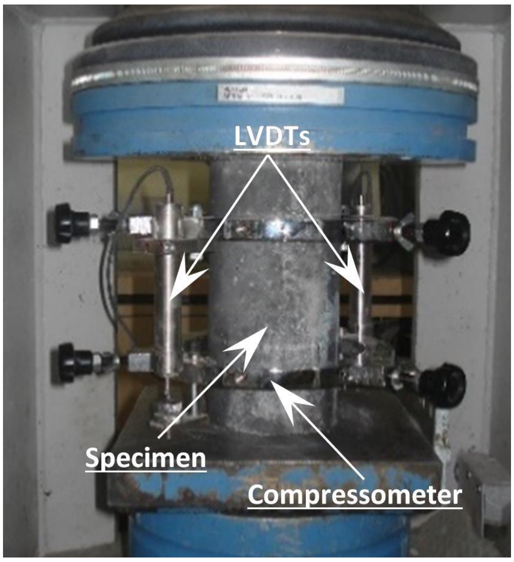

Fig. 1. Test set up for determination of modulus of elasticity

where S_1 is the stress corresponding to a longitudinal strain, ε_1, of 50 μm, S_2 is the stress corresponding to 40% of ultimate load, ε_2 is the longitudinal strain produced by stress S_2. The average compressive strain was measured by using two LVDTs (Fig. 1).

2.2.3 Splitting tensile strength test

The splitting tensile strength tests were performed according to ASTM C496. Splitting tensile strength was calculated as follows:

$$T = \frac{2P}{\pi dl} \tag{2}$$

Where T is the splitting tensile strength, P is the maximum applied load, l is the sample length and d is the diameter of sample.

2.2.4 Three point bending test and determination of fracture behaviour

A three-point bending test was performed according to JCI-S-002 to evaluate the flexural performances and fracture properties of concrete having various fibre contents. The 100 × 100 × 350 mm sized beam specimens with a 30 mm notch (≈ 0.3 × the depth) at mid-length were fabricated and tested. The clear span was considered as 300 mm and the load was applied through displacement control at a rate of 0.05 mm/min using a MTS with a maximum load capacity of 250 kN (see Fig. 2). Deflection at the center of specimen was measured using the

Tab. 1. Mix proportions and fresh properties of concrete mixtures

Materials		Concrete mixtures				
		R	CF0.25	CF0.50	CF0.75	CF1.00
Cement (kg/m^3)		360	360	360	360	360
Fly ash (kg/m^3)		40	40	40	40	40
Water (kg/m^3)		180	180	180	180	180
Coarse aggregate (kg/m^3)		931	931	931	931	931
Crushed sand (kg/m^3)		509	509	509	509	509
River sand(kg/m^3)		436	436	436	436	436
Fiber content	By weight (kg/m^3)	0	4.4	8.8	13.2	17.6
	By volume (%)	0	0.25	0.50	0.75	1.00
SP (kg/m^3)		0.8	0.8	1.2	1.4	1.5
Slump (cm)		18	10	7	12	10
Fresh density (kg/m^3)		2444	2419	2390	2395	2380

Tab. 2. The chemical compositions and physical properties of cement and fly ash

Composition (%)	CEM I 42.5 R	Fly ash
CaO	62.98	1.17
SiO_2	20.54	53.26
Al_2O_3	5.12	19.54
Fe_2O_3	3.26	6.25
MgO	1.14	4.56
SO_3	3.04	2.12
Loss on ignition	1.32	7.56
Insoluble residue	0.47	-
Specific gravity	3.14	2.65
Specific surface (cm^2/g)	3640	4900

two installed LVDTs. Additionally, a clip gage was attached to the specimen bottom for measuring the crack width. The crack mouth opening displacement (CMOD) was measured using a gauge clipped to the bottom of the beam and held in position by two 1.5 mm (H_0) steel knife edges glued to the specimen (Fig. 2).

For a notched beam specimen with center point loading, flexural strength is obtained using Eq. (3) as follows.

$$f = \frac{3PL}{2b\,(h - a_0)^2} \tag{3}$$

where P is the maximum load, L is the span length, b is the average width of specimen, h is the average depth of specimen, and a_0 is the notch depth.

The fracture properties were characterized using a two-parameter fracture model (TPFM). The fracture parameters, the critical stress intensity factor (K_{IC}) and the critical crack tip opening displacement ($CTOD_C$), were calculated from three-point bend tests on notched beams as shown in Fig. 2. For each mixture two replicate beams were tested. The beams were tested in a deflection controlled mode during the loading. The test was terminated at a final load carrying capacity limit of 100 N.

3 Results and Discussion

3.1 Effect of carbon fibres in compressive strength and modulus of elasticity

Fig. 3 represents the compressive strength test results of cubic concrete samples with and without CF. It can be seen that although CF concretes have lower workability than plain concrete the compressive strength increased as the fibre content increased. The strengths were in range for 60.4 to 69.0 MPa highest being for CF0.75 and lowest for CF0.25 samples. The compressive strength of CF0.75 is 9% higher than plain (R) concrete. This can be attributed to the greater resistance of sliding of pre-existing micro-cracks by reducing the driving energy for the crack growth. Also, if the fibres are aligned in the direction of crack growth or in a direction lateral to compressive axis, they refine the fracture toughness via crack bridging. These results were corroborated by the findings of other studies [12, 13]. Further, it was observed that unlike polyvinyl alcohol fibre reinforced concrete, or reinforcing concrete with metallic fibres enhances the compressive strength of the concrete [14].

From Fig. 4(a) it can be observed that there was no significant change in the pre-failure elastic zone of samples with different dosages of CF which can be also noticed from the modulus of elasticity values from Fig. 4(b) although the strain capacity increased. Comparing the shape of the curves, it is clear that the fundamental relationships of the samples are not identical, but

Tab. 3. Properties of carbon fiber

Diameter (μm)	Length (mm)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)
7	12	1.76	4200	240	1.80

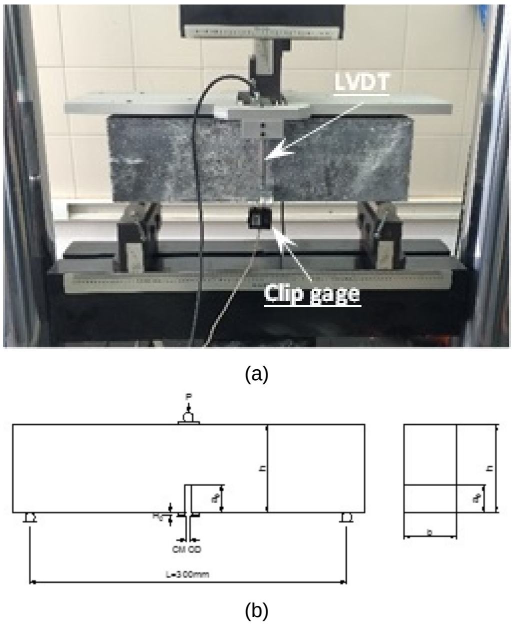

Fig. 2. Three point bending test with notched beam (a) and testing configuration (b)

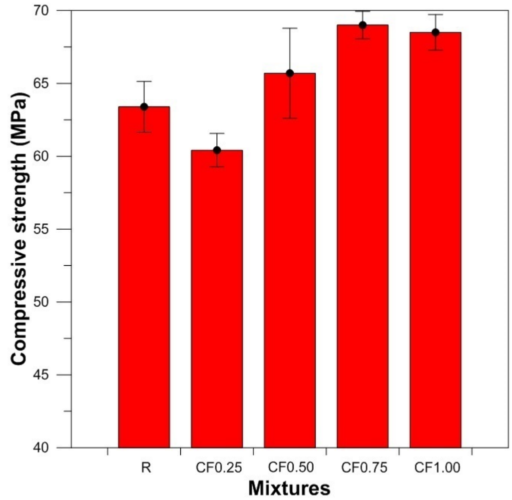

Fig. 3. 28 days compressive strength of the samples

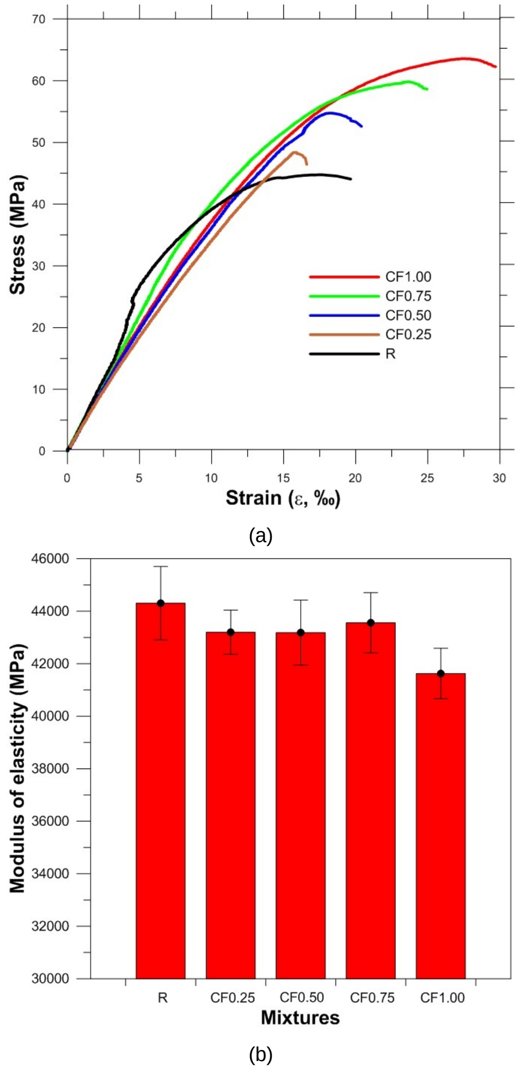

Fig. 4. (a) Stress-strain relation under compression test for samples (b) Modulus of elasticity

they can be generalized for the benefits of the fibre inclusion in concrete as concrete in itself is a highly heterogeneous material with a high composite structure. The area under the stress-strain curve also increased with the increase in fibre content. This increment is more distinct for 0.75% and 1.0% CF reinforced samples. The strain capacity of these samples at peak load is 1.35 and 1.58 times higher than the plain concrete. Form Fig. 4(a) it can be easily deduced that inclusion of fibre in the matrix enhances the stress distribution, reduces the strain localization and delays the micro-crack formation enhancing its stress and strain fields. But the efficiency of the fibres may depend on the volume and distribution of fibre. This reasoning is confirmed by the findings of [15–17].

3.2 Splitting tensile and flexural strengths

From Fig. 5 it is observed that splitting tensile strength and flexural strength increased with increasing dosage of CF depicting trends similar to compressive strength. The addition of fibre volume fractions 0.25%, 0.50%, 0.75%, and 1% causes the splitting tensile strength to increase 9.8%, 16.4%, 16.7%, and 49.5%, respectively, with respect to the plain specimen. The higher the number of fibres bridging the diametric splitting crack, the higher would be the splitting tensile strength [8]. The addition of fibre volume fractions 0.25%, 0.50%, 0.75%, and 1% causes the flexural strength to increase 8.9%, 10.7%, 15.9%, and 16.6%, respectively, with respect to the plain concrete. The reasoning applied to describe the increase in compressive strength can be used to explain this improvement of flexural and splitting tensile strength. But the non-monotonic trends of increase observed in Fig. 5 for splitting tensile strength and flexural strength can be attributed to the composite and heterogeneous nature of concrete.

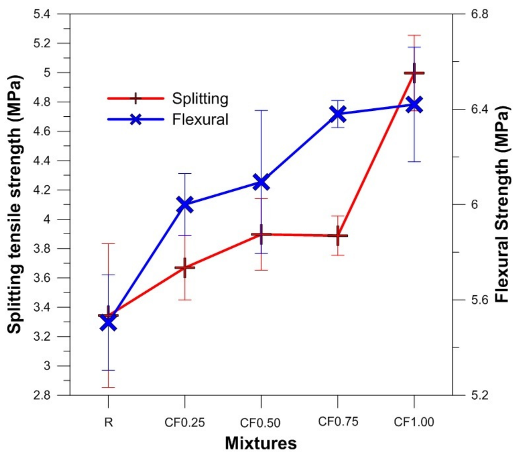

Fig. 5. Splitting tensile strength and flexural tensile strength of samples

3.3 Fracture Behaviour

In this paper, the fracture parameters of carbon fibre reinforced cement mortars are studied using an effective elastic crack approach. The two-parameter fracture model used herein incorporates the pre-peak non-linear behaviour in a notched beam (notch size a_0) through an equivalent elastic material containing a crack of effective length a_{eff} such that $a_{eff} > a_0$. Based on this method, K_{IC} and $CTOD_C$ can be quantified to characterize the fracture behaviour of the CF reinforced concrete mixtures.

3.3.1 Load-CMOD Responses

Representative load-CMOD responses, recorded during the bending tests, are shown in Fig. 6(a) for the reference mixture and carbon fibre reinforced mixtures (i.e., one with a 0.5% carbon fibre and the other with 1% carbon fibre). The results of deflection given here are taken as the average value of the two measurements performed at the front and rear end of the test specimen. The load-deflection plots of the test specimens show a linear branch till the first crack followed by non-linear behaviour up to the peak load. A stability in crack propagation near peak load is observed due to the crack controlling effect of the fibres in the concrete structure. Once the peak load is reached, the load carrying capacity started decaying. The loss was more prominent in the lower fibre volume content. Compared to ordinary concrete, the peak load increases with increase in the CF volume content (Fig. 6).

This increase can be attributed to the beneficial effect of randomly distributed carbon fibres. They provide bridging forces across micro-cracks and prevent them from growing. Thus, increasing the fibre volume fractions increases the maximum

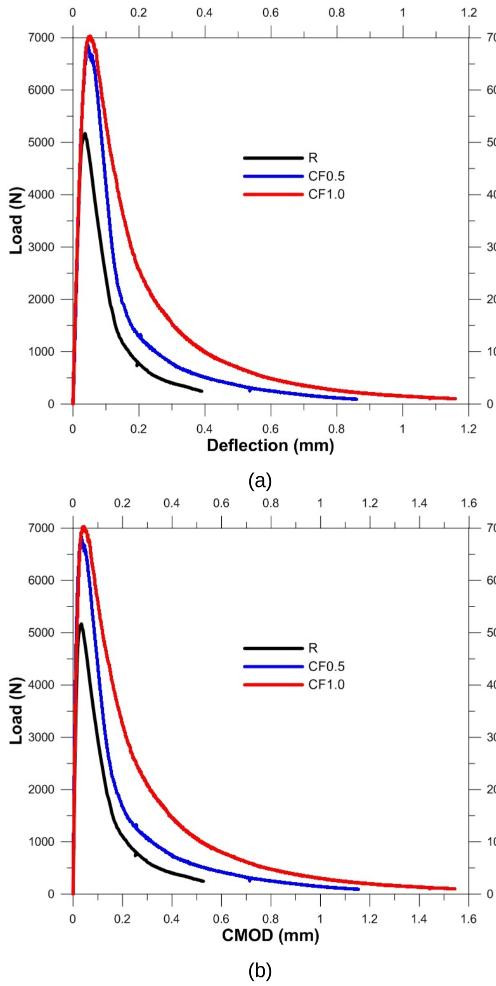

Fig. 6. (a) Load-deflection curve, (b) Load-CMOD curve

bending load of the beam specimens (Fig. 7(a)).

The ratios of residual load at a CMOD value of 0.20 mm to the peak load for all the notched concrete beams is evaluated in this study (Fig. 7(b)). The residual load ratio provides an indication of the crack tolerance and post-peak response of CF reinforced concrete. The concrete 0.25% CF addition show similar peak loads, comparable to the peak load of the reference concrete. However, the mixtures with 0.50, 0.75 and 1.0% CF addition demonstrate significantly increased residual capacity ratio as compared to the plain concrete; as much as 2 times or higher in some cases. So it is easy to conclude for this study that minimum 0.50% CF addition is required to improve the ductility of high strength concrete significantly.

3.3.2 Fracture Toughness and $CTOD_C$

Flexural toughness shows the ability of concrete to absorb energy. Flexural toughness, in fact, refers to the area under load-deflection curve. The amount of flexural toughness of a concrete beam is known as the absorbed energy of the concrete [18]. The fracture energy is defined as the amount of energy necessary to create a crack of unit surface area projected in a plane parallel to the crack direction [19, 20]. The curves in Fig. 8 display the absorbed energy in term of beam deflection.

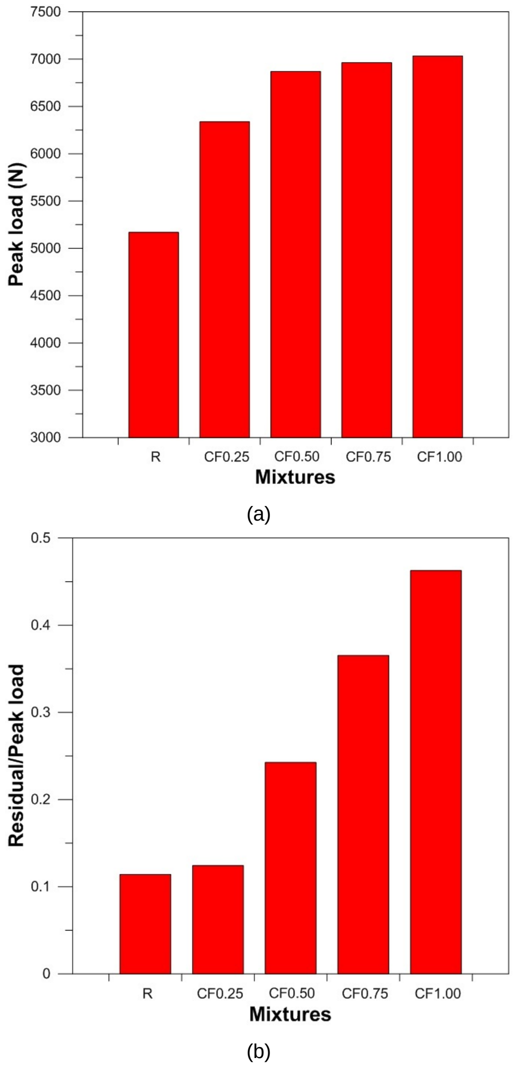

Fig. 7. Peak and residual loads of R and CF samples

In this study, fracture energy denoted as G_f is used to quantify the toughness. Fracture energy is the energy required to create one unit area of crack surface. G_f was calculated by RILEM proposal as followed in [20]. The total energy utilized in breaking the specimens completely is measured using the load–deflection curves of the fracture test. The G_f is calculated using:

$$G_f = \frac{W_0 + mg\delta}{A} \tag{4}$$

where W_0 is the area under the load–deflection curve, m is the mass of the specimen, g is the gravity, A is the crack path area, and δ is the deflection at a final load carrying capacity limit of 100 N.

The fracture energy obtained on reference and CF added samples are presented in Fig. 8. Although the fracture energy enhancement was more significant after 0.5 percent dosage but it can be generally commented that the fracture energy of the samples increased with the increasing carbon fibre addition. CF reinforcement exhibited 12%, 86%, 135% and 164% improvement in fracture energy with 0.25%, 0.50%, 0.75% and 1.0% addition respectively. The increase in fracture energy was attributed to the increase in the maximum, residual and equivalent tensile strengths brought by fibres. Similar findings was reported by Pajak and Ponikiewski [21] as they observed that the fracture energy depends almost linearly on the fibre content for given fibre type. Moreover matrix and fibre strengths are effective parameters for the mechanical properties especially fracture energy of fibre reinforced concretes [22].

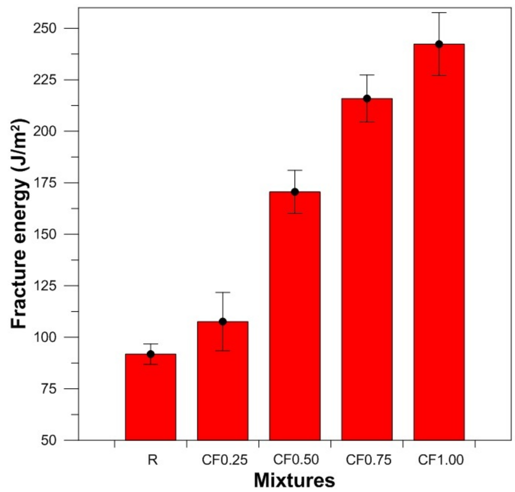

Fig. 8. Fracture energy of the reference and reinforced concrete

For TPFM, the propagating crack length (a) corresponding to each point in the load Load-CMOD relationship can be calculated by using the below equation:

$$a_{eff} = \frac{2}{\pi}(h + H_0)\, arctan \sqrt{\frac{bE(CMOD)}{32.6P} - 0.1135} - H_0 \tag{5}$$

Here, h and b are depth and thickness of the beam respectively, and H_0 is the thickness of knife edge that holds the clip gage. The crack extension (Δa) determined using equation (Eq.(6)):

$$\Delta a = a_{eff} - a_0 \tag{6}$$

where a_{eff} is the effective crack length and a is the initial notch length (30 mm).

An elastically equivalent fracture toughness, K_{IC}, is one of the most important parameters for fracture characterization of cementitious systems along with the critical crack tip opening displacement ($CTOD_C$) which is a measure of the bridging interlock capability of the microstructure and indicates the limit beyond which unstable crack propagation begins [23, 24]. Table 4 reports these two major fracture parameters which was derived using the TPFM for all the mixtures studied here. TPFM considers that the fracture parameters are inherent material properties [25].

To determine K_{IC} and $CTOD_C$, values at 95% of the peak load are considered. K_{IC} for a notched beam in three-point bending can be determined as:

$$K_{IC} = \frac{PL}{bh^{3/2}} F\left\{\frac{a_{eff}}{d}\right\} \tag{7}$$

Tab. 4. Results of Δa, K_{IC} and $CTOD_c$ for reference and CF reinforced concrete

Fiber (%)	Δa (mm)	K_{IC} (MPa/mm^2)	$CTOD_C$ (mm)
0	13.6	13.6	0.0069
0.25	17.2	16.8	0.0090
0.50	19.2	21.8	0.0108
0.75	21.2	22.8	0.0116
1.00	29.7	23.7	0.0124

$$F\left\{\frac{a_{eff}}{h}\right\} = \left[2.9\left(\frac{a_{eff}}{h}\right)^{1/2} - 4.6\left(\frac{a_{eff}}{h}\right)^{3/2} + 21.8\left(\frac{a_{eff}}{h}\right)^{5/2} - 37.6\left(\frac{a_{eff}}{h}\right)^{7/2} + 38.7\left(\frac{a_{eff}}{h}\right)^{9/2}\right] \quad (8)$$

The value of $CTOD_C$ is calculated by following equation,

$$CTOD_C = \frac{6\,(P_{max} + 0.5W_h)\,S\,a_{eff}\,g(a_{eff}/b)}{Eb^2h} \cdot \left[(1-\beta_0)^2 + \left(1.081 - 1.049\frac{a_{eff}}{b}\right)\left(\beta_0 - \beta_0^2\right)\right]^{1/2} \quad (9)$$

where

$$g\left(\frac{a_{eff}}{b}\right) = 0.76 - 2.28\left(\frac{a_{eff}}{b}\right) + 3.87\left(\frac{a_{eff}}{b}\right)^2 - 2.04\left(\frac{a_{eff}}{b}\right)^3 + \frac{0.66}{(1 - a_{eff}/b)^2}$$

and

$$\beta = \frac{a_0}{a_{eff}}$$

It can be clearly seen from Table 4 that the values of Δa, K_{IC} and $CTOD_c$ increase with increasing quantity of carbon fibre dosage. It can be observed that Δa values increased drastically while fibre volume fraction was increased from 0 to 0.25% and from 0.75 to 1%. Also, K_{IC} values increases significantly from 0.25% to 0.50%. No further change was observed after 0.75%. The improvement in $CTOD_C$ and K_{IC} of CF0.75 was greater at 68% over plain concrete. Similar improvement in fracture parameters were reported by Stynoski et al. [26] for mortar reinforced with 0.25% of CF by volume. So it can be concluded that 0.75 is most ideal dosage of fibre in the concrete. These results confers with the point that carbon fibres help dissipation of energy which is reflected in the form of increased unstable crack propagation threshold limit as compared to reference sample.

4 Conclusions

In this paper, the mechanical properties and fracture behaviour of high strength concrete with different volume fractions of carbon fibre is presented. The following conclusions can be drawn from the experimental results.

The workability of concrete was reduced with the addition of carbon fiber. However compressive strength of concrete was increased when compared with plain concrete. Compressive strength of concrete with 0.75% carbon fiber was 8.8% higher when compared to plain concrete. Beyond this dosage limit no significant change in strength was observed.

Inclusion of fiber did not affect the modulus of elasticity of concrete significantly but strain capacity of concrete under compression increased significantly at peak load. This became more dominant after 0.50% fiber dosage.

Both splitting tensile strength and flexural tensile strength of concrete increased with the increase in carbon fiber content. The only difference is that the beneficial effect of carbon fiber was observed for flexural tensile strength even at low dosages but splitting tensile strength required significantly high dosages such as 0.75% and 1.0% to show an improvement.

Carbon fibre also improved the load bearing capacity, fracture energy and toughness of concrete. Fibre volume fraction was more prominent factor in this regard. Especially fracture energy showed better performance beyond 0.50% fibre inclusion. The other fracture parameters such as effective crack length, stress intensity factor and critical crack tip opening displacement were also improved by carbon fibre usage. This improvement was more distinct after 0.50% fibre dosage. So it can be concluded that minimum 0.50% carbon fibre dosage was required to obtain satisfied amount of enhancement in high strength concrete.

Acknowledgement

The author acknowledges the support from Yildiz Technical University Scientific Research Projects Coordinate (2014-05-01-KAP01). Author also thanks DowAksa (Turkey) for providing the carbon fibres to conduct this study.

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