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Fracture properties of steel fiber reinforced high strength concrete using work of fracture and size effect methods

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HIGHLIGHTS

- The effects of steel fiber volume fraction on fracture behavior of HSC were studied.
- The fracture energy obtained by work of fracture method and size effect method.
- The fracture energies measured by two methods were compared.
- Steel fibers significantly improve fracture behavior of HSC.

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ABSTRACT

This paper deals with investigation of fracture behavior of steel fiber reinforced high strength concrete (SFRHSC) and compare it to plain high strength concrete (HSC). Based on an experimental program, a series of three point bending tests were carried out on 54 notched beams, as recommended by RILEM. The fracture parameters were measured by two methods: work of fracture method (WFM) and size effect method (SEM). Then the fracture parameters obtained from these two methods were compared. The results showed that with increase of steel fibers, fracture energy of G_F in WFM and G_f in SEM increase but this increase in work of fracture method is more significant. The effective size of the process zone (c_f) and the characteristic length (L_{ch}) increase with increase of steel fibers, which indicates that the HSC becomes more ductile by introducing fibers. The accuracy of the fracture parameters obtained from the SEM for SFRHSC is acceptable for low steel fiber volume fractions. Also, G_F/G_f ratio increased from about 2.5 for the HSC to around 10.5 for the SFRHSC.

1. Introduction

Concrete is a brittle material with low tensile strength compared to its compressive strength and low deformation capacity that results in low resistance to crack initiation and propagation [1]. It is well-known that the addition of steel fibers into concrete may improve the impact strength and ductility of concrete, considerably, [2,3] but tensile strength increment is moderate. The most important advantages of steel fibers are hindrance of macrocracks' development, delay in microcracks' propagation to macroscopic level and the improved ductility after microcracks' formation [4]. Steel fibers restrict crack propagation by bridging crack faces and improve the toughness and energy absorption capacity of the composite material [5]. After the formation of cracks, the most important factors in energy dissipation are steel fiber-matrix bond strength, volume fraction and tensile strength of steel fibers.

Fracture energy of concrete is one of the most important parameter in fracture analysis of concrete. Different methods have been proposed for determining fracture parameters. The most common and simplest method to determine the fracture energy of concrete is work of fracture method (WFM) based on fictitious crack model (FCM) of Hillerborg et al. [6–8]. According to this method, the fracture energy (G_F) is expressed as the area under the load–deflection curve per unit fractured surface area. Bažant and Kazemi [9] proposed size effect method (SEM) to obtain fracture energy and other fracture parameters which are independent of the size of the specimens. Two methods listed, are recommended by RILEM standards [10,11].

It is clear that the propagation of the crack is controlled by the steel fibers along the fracture surface. Also, it is pointed out that fibers, during the crack propagation, are broken or pulled-out of the matrix due to fiber-matrix interface debonding [12].

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Sahin and Köksal [2] showed that the compatibility between the matrix and the steel fiber is so important for post-cracking behavior and fracture energy enhancement of concrete and fiber strength is a controlling factor in the performance of SFRCs. They also mentioned that for the performance and economical points of view, both water to cement ratio and fiber strength must be taken as the mix design parameters. Kazemi et al. [3] studied the effect of the volumetric fraction of fibers in SFRC on the fracture energy. Their experimental results showed that the main effects of fibers are in the amount of fracture energy and in the postpeak region, where a significant increase in ductility can be observed. It has been proved by many researchers that including steel fibers provided higher flexural strength, deflection capacity, and post-peak ductility than plain concrete, and these strength and ductility increases with the increase in the fiber content [13,14]. Pajak and Ponikiewski [15] investigated the flexural behavior of SCC reinforced with straight and hooked end steel fibers and concluded the fracture energy increases with the increase of fiber dosage and is higher for hooked end steel fibers than for straight ones. On the other hand, Köksal et al. [16] indicated that Performance of fiber reinforced concrete much depends on the properties of steel fibers in concrete, when matrix strength is high. They also reported that accordance between matrix and steel fiber strengths must be taken into consideration in design of steel fiber reinforced concrete mixes to maximize the fracture energy and minimize the cost of mix.

The aim of this article is to investigate experimentally the fracture behavior of high strength concrete reinforced with steel fibers. Steel fibers at different contents were added to concrete and the results were compared with plain HSC. The test methods used in the experimental work are based on RILEM recommendations which include work of fracture method and size effect method. The SEM was developed to obtain fracture properties of plain concrete. However, in this article, we want to examine the efficiency of SEM for determining the fracture properties of SFRHSC at low fiber volume fractions. For this purpose, the accuracy of the results for different contents of steel fiber was examined by the predicted coefficients in this method. The three point bending test set up is carried out on 54 notched beams in a servo controlled testing system.

2. Experimental program

2.1. Material

Type-II Portland cement and ultra-fine limestone powder were used for the program. Natural sand with the specific gravity of 2.7 and fineness modulus of 2.85 was used as fine aggregate, and natural crushed gravel with the maximum size of 12.7 mm and specific gravity of 2.75 was used as coarse aggregate. Both coarse and fine aggregate were used in saturated surface dry (SSD) condition. In order to reach a desirable workability, superplasticizer based on polycarboxylic ether was added to all mixes. Steel fibers were hooked-end and had an average length of 36 mm and 0.7 mm diameter. Fibers had an average tensile strength of 2100 MPa and the apparent modulus of elasticity of 160 GPa.

2.2. Mix design and preparation

In order to investigate the effects of steel fibers on fracture parameters of HSC, a total of 6 HSC mixes containing different fiber volume fractions including a control HSC mix with zero fiber content were considered. Five different volumes of steel fibers, 0.2%, 0.3%, 0.4%, 0.8% and 1.6% were used as the percentage of total concrete volume. All other mix proportions were the same in all mixes. Also, the water/cement ratio kept constant at 0.4 for all mixes. Mix proportions are detailed in Table 1.

In order to achieve a uniform quality of concrete, coarse and fine aggregates and cement were mixed for two minutes and then mixture of water and superplasticizer was added. The amounts of superplasticizer were determined in order to obtain, practically, a constant flowability without segregation among the different mixes. After a minute the steel fibers were scattered to the mixture by hand and mixed adequately to obtain a uniform distribution of fibers. All the specimens were cast in polymer molds and compacted on vibration table less than a minute and demolded after 24 h and placed in a curing tank at 28 ± 1 °C for 28 days. A notch was created at the midspan and top side of each beam with a 3 mm thick PVC plate during the concrete casting in the tensile face of the beams. Also the casting was done in such a way that the flow of concrete below the notch would not be influenced much by the plate, although it could have some effects on the fiber crossing and orientation around the notch tip.

Table 1
Quantity of materials per cubic meter of concrete.

Materials	Weight (kg/m^3)
Cement	402.6
Coarse aggregate	727.1
Sand	817.4
Limestone powder	280.6
Water	161
Water/cement	0.4

2.3. Test methods

In order to determine fracture parameters of SFRHSC, two series of tests were carried out on notched beams according to RILEM recommendations [10,11]. Along with the determination of fracture parameters, compressive strength, splitting tensile strength and modules of elasticity were measured by using a hydraulic testing machine. Compressive strength (f_c) tests were performed on a total of eighteen cubic specimens with dimensions of 100 × 100 × 100 mm according to BS EN 12390 [17]. Also for each mix design, three cylindrical specimens with dimensions of 150 × 300 mm were used to evaluate the splitting tensile strength (f_t) and modules of elasticity (E_c) according to ASTM C496 [18] and ASTM C469 [19] respectively. All test results were reported as the average value of three tested specimens.

2.3.1. Work of fracture method (WFM)

In order to evaluate fracture parameters based on work of fracture method, three notched beams with the same dimensions of 100 × 100 × 840 mm^3 and with the effective span of 800 mm and notch depth of 25 mm (Fig. 1) were tested for each mix design, based on RILEM FMC-50 [10] recommendations, which allows the use of single size specimens. Three point bending tests were conducted using a closed loop servo electro controlled testing universal machine with a maximum load capacity of 150 kN (Fig. 2) and the load was applied at the rate of 0.4 mm/min. The load and midspan deflection were recorded and load–deflection curves were plotted graphically for each specimen during the test process. Fracture energy G_F was obtained by the following equation:

$$G_F = \frac{W_0 + 2P_0u_0}{b(d - a_0)} \tag{1}$$

where w_0 is the area under load deflection curve, u_0 is the maximum measured deflection, P_0 is the point-load, equivalent to the