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Flexural response of steel-fiber-reinforced concrete beams: Effects of strength, fiber content, and strain-rate

Doo-Yeol Yoo [a], Young-Soo Yoon [b, *], Nemkumar Banthia [a]

[a] Department of Civil Engineering, The University of British Columbia, 6250 Applied Science Lane, Vancouver BC V6T 1Z4, Canada
[b] School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 136-713, Republic of Korea

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ABSTRACT

This study aims to investigate the flexural behavior of steel-fiber-reinforced concrete (SFRC) beams under quasi-static and impact loads. For this, a number of SFRC beams with three different compressive strengths (f_c' of approximately 49, 90, and 180 MPa) and four different fiber volume contents (v_f of 0, 0.5, 1.0, and 2.0%) were fabricated and tested. The quasi-static tests were carried out according to ASTM standards, while the impact tests were performed using a drop-weight impact test machine for two different incident potential energies of 40 and 100 J. For the case of quasi-static load, enhancements in the flexural strength and deflection capacity were obtained by increasing the fiber content and strength, and higher toughness was observed with an increase in the fiber content. For the case of impact load, an increase in the load carrying capacity was obtained by increasing the potential energy and strength, and an improvement in the post-peak behavior was observed by increasing the fiber content. The increases in fiber content and strength also led to enhancements in residual flexural performance after impact damage. Finally, the flexural strength became less sensitive to the strain-rate (or stress-rate) as the strength of concrete increased.

1. Introduction

The recent disasters occurring around the world have led to the interest in the enhancement of the resistance of concrete structures to seismic, impact, and blast loadings. Unfortunately, since concrete is a brittle material, the energy absorption capacity under such high strain-rate loadings is very poor, which causes several concerns. Therefore, many researchers [1–7] have performed studies to enhance its energy absorption capacity under impact and blast by using various reinforcements, such as fibers (i.e., steel fibers, polymeric fibers, and carbon fibers), fiber-reinforced polymers, steel reinforcing bars, etc. However, because the studies on the impact response of concrete are in infancy in comparison with those for quasi-static load, much work still remains to be done.

Concrete is known as a material that is sensitive to the strain-rate [1]. The strain-rate sensitivity of concrete is apparently influenced by numerous factors including strength, moisture content, temperature, and loading configurations (i.e., compression, tension, and flexure) [1,6,8]. Ross [8] reported that tensile strength is more sensitive to the strain-rate than compressive strength, and Bindiganavile et al. [1] indicated that high-strength concrete is less sensitive to the strain-rate than low-strength concrete. Sercombe et al. [9] also mentioned that fully saturated concrete has an increased strain-rate sensitivity, compared to that of dry concrete, and Banthia et al. [10] experimentally verified that there is no effect of sub-zero temperature on the stress-rate sensitivity of concrete.

Likewise, several meaningful studies on the mechanical properties of concrete under impact loading have been reported. However, only limited research has been carried out to investigate the complex effects of strength and fiber content on the flexural performance of concrete under impact loading. Various strengths of concrete have been applied recently in the field according to the structural element types. In addition, steel fibers are one of the most widely used reinforcements to improve its tensile performance, and the quantity of steel fibers used is various. Therefore, the strain-rate effect on the flexural behavior of steel-fiber-reinforced concrete (SFRC) beams with various strengths and fiber contents is required to be estimated.

Accordingly, in this study, the flexural response of SFRC beams under both quasi-static and impact loadings is investigated. To do this, a series of SFRC specimens having various strengths (normal-,

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[*] Corresponding author. Tel.: +82 2 3290 3320, fax: +82 2 928 7656.
E-mail address: ysyoon@korea.ac.kr (Y.-S. Yoon).

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high-, and ultra-high-strengths) and steel fiber contents were fabricated and tested. The quasi-static tests were carried out according to the ASTM standards, while the impact tests were performed using a drop-weight impact test machine. The specific objectives are to investigate the effects of strength and steel fiber content on (1) the compressive strength, elastic modulus, and strain capacity under quasi-static loading, (2) flexural strength and toughness under quasi-static loading, (3) flexural behavior under impact loading and strain-rate (or stress-rate) effect on dynamic increase factor (DIF), and (4) residual capacity after impact damage.

2. Experimental program

2.1. Materials and specimen preparation

The mixture proportions for normal-strength concrete (NC), high-strength concrete (HSC) and ultra-high-strength concrete (UHSC) investigated in this study are summarized in Table 1. In the case of NC and HSC, type 1 Portland cement, washed sea sand (fine aggregate), and crushed gravel (coarse aggregate) with a maximum size of 19 mm were used. To increase the compressive strength of HSC, 15% (by cement mass) of silica fume with a specific surface area of 200,000 cm^2/g was also included. On the other hand, for the case of UHSC, silica sand was adopted instead of washed sea sand and coarse aggregate was excluded from the mixture. 25% (by cement mass) of silica fume and 30% (by cement mass) of silica flour were also added to improve the homogeneity. The mixture proportions and components used for UHSC are identical to those used by a previous study [11].

To investigate the effects of steel fiber content on the quasi-static and impact flexural behaviors, four different volume fractions ($v_f = 0$, 0.5, 1, and 2%) for NC and HSC and two different volume fractions ($v_f = 0$ and 2%) for UHSC were adopted by using hooked-end bundled and low carbon steel fibers with a diameter of 0.5 mm and a length of 30 mm, as shown in Fig. 1. The geometrical and mechanical properties of the hooked steel fibers are summarized in Table 2.

2.2. Test setup and procedure

2.2.1. Quasi-static tests

Compression tests were performed as per ASTM C 39 [12] using at least three cylinders (φ100 × 200 mm) each of variables concerned. A uniaxial compressive load was monotonically applied using a universal testing machine (UTM) with a maximum load capacity of 3000 kN. For measuring the average compressive strain and elastic modulus, a compressometer with three linear variable differential transducers (LVDTs) was installed [11].

Three prismatic specimens (100 × 100 × 400 mm) each of variables concerned were fabricated and tested in four-point flexure according to ASTM C 1609 [13] over a span of 300 mm. In order to measure the net deflection of beams excluding the support settlement, a steel frame with two LVDTs attached were installed at the middle of the beam height to obtain the average mid-span deflection, as shown in Fig. 2. A load was monotonically applied using a closed-loop, servo-controlled, UTM with a maximum load capacity of 250 kN. All SFRCs used in this study showed higher load carrying capacity and toughness even at large deflections. In addition, to investigate the effect of strength on the toughness of SFRC with an increase in the deflection, flexural tests were performed until a net deflection of $L/75$ (= 4 mm which is two times higher than the stipulated end point of ASTM C 1609).

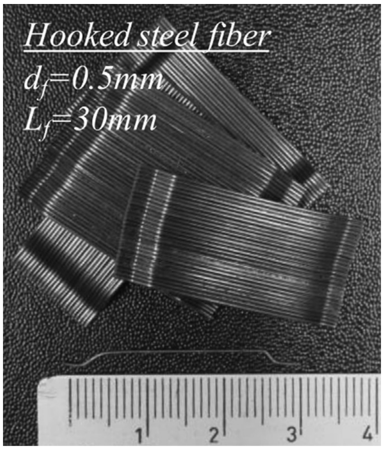

Fig. 1. Picture of hooked steel fibers.

2.2.2. Impact tests

For the impact tests, an instrumented drop-weight impact test machine was used, as shown in Fig. 3. An impact load was applied to the mid-length of the beams by dropping a 34.735 kg mass. Two different drop-heights of 120 and 300 mm were used to investigate the effects of strain-rate (or stress-rate) on flexural behaviors. These drop-heights lead to incident potential energies of 40 and 100 J and incident impact velocities of 1.47 and 2.41 m/s, respectively. In most cases three specimens were tested but in some very rare cases one specimen produced invalid response due to the detachment of the accelerometer before the impact load dropped to the zero value, which causes inadequate measurement of the mid-span deflection. Thus, this invalid response was not considered in the analysis. Simple support condition was adopted for all test beams identical to those of the quasi-static test.

A drop weight hammer having a spherical striking face with a radius of 25 mm was used, as in Fig. 3, and the impact load was measured from a load cell affixed to the drop weight tup. Because the impact load measured at the drop weight tup includes inertial load, two load cells were installed at both supports for measuring pure bending load excluding inertial load. To measure mid-span deflection, both a potentiometer and accelerometer with a

Table 1
Mix proportions.

	W/B (%)	s/a (%)	Unit weight (kg/m^3)							
			Water	Cement	Silica fume	Fine agg.	Coarse agg.	Silica flour	Silica sand	SP (%)
NC	50	40	180	360	–	738	1108	–	–	0.5
HSC	23	40	180	680	102	582	872	–	–	1.5
UHSC	20	–	160	789	197	–	–	237	867	2.0

[Note] NC = normal-strength concrete, HSC = high-strength concrete, UHSC = ultra-high-strength concrete, s/a = weight ratio of fine aggregate to total aggregate, SP = superplasticizer.