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Flexural capacity of fiber reinforced concrete with a consideration of concrete strength and fiber content

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HIGHLIGHTS

- Flexural capacity of SFRC with variance in concrete strength and fiber content were evaluated.
- First peak and post-cracking strength, and energy absorption capacity were discussed.
- Effects of concrete strength and fiber content in equivalent strength ratio were evaluated.
- Ultimate capacity of floor slabs was evaluated considering concrete strength and fiber content.

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ABSTRACT

An experimental study was performed to examine the effects of concrete strength and fiber content ratio on the flexural capacity of steel fiber-reinforced concrete. Three fiber volume fractions, 0.25, 0.375, and 0.5%, and three concrete compressive strengths, 25, 35, and 45 MPa, were designed for the experiments. The stress and deflection relationship, first peak and post-cracking strength, and energy absorption capacity were evaluated with respect to the variance in the fiber volume fraction and concrete strength. The results showed that the equivalent flexural strength ratio, which is determined from the first peak strength and energy absorption capacity, increased with the increase in the fiber volume fraction but decreased with the increase in the concrete strength. Furthermore, the effects of the concrete strength and fiber content ratio are discussed in a steel fiber-reinforced concrete floor slab. The ultimate flexural capacity also required a consideration of the influence of the content ratio of steel fiber as well as the strength of cement composite matrix.

1. Introduction

Cement is an essential material for construction, but it is very vulnerable to tensile forces. Therefore, cement-based materials undergo cracking when subjected to a tensile load. The application of short-length fibers can enhance the ability to resist tensile cracks and improve the energy absorption of concrete. With the ability to enhance the ductility of concrete, steel fiber-reinforced concrete (SFRC) has been developed since the 1960s [1]. Studies of SFRC have mainly focused on the effects of the geometric types, volume fraction, and strength of steel fibers on the flexural behavior of cementitious composites [2–10]. The use of steel fibers in concrete was expanded to the application of various fibers, such as synthetic fibers, glass and carbon fibers, and natural fibers. In particular, steel and synthetic fibers were used to assess the properties and performance of concrete [11–14]. The influence of the combination of steel and synthetic fibers on the flexural load-carrying capacity and toughness of concrete were also investigated with respect to the shape, length, and dosage of the steel and synthetic fibers. In addition, several studies [15–17] examined the influence of steel fibers in combination with steel bar reinforced concrete beams. Most studies attempted to evaluate the amount of steel bar reinforcement in FRC members as well as the enhancement of flexural capacity associated with the types and contents of steel fibers.

SFRC are used most widely and reliably in the practical fields, particularly for tunnel shotcrete and precast tunnel segments [4,15,17–19], as well as in industrial pavements and slabs [20–22]. In the design of these structures, an equivalent flexural strength ratio is used to account for the improvement of flexural

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tensile performance of SFRC. The equivalent flexural strength ratio, which is determined from the energy absorption capacity and the first peak strength measured from the beam tests, is strongly dependent on the content ratio of fibers in concrete. Therefore, as described previously, most of the previous studies evaluated the effect of the fiber geometric types and content on the flexural strength and toughness of fiber-reinforced concrete. That is, given a type of fiber, the equivalent flexural strength ratio is determined according to the fiber content. On the other hand, the equivalent flexural strength ratio can be affected by the strength of the cementitious composite matrix. A few researchers [6,11,23] conducted experimental studies to assess the influence of fibers on the flexural performance of high-strength SFRC. Kim and Naaman [6] examined the effects of the geometric types of steel fibers in high-strength fiber-reinforced cementitious materials, and Banthia and Gupta [11] assessed the properties and performance of fiber-reinforced concrete in a high strength matrix. Mansur et al. [23] derived the stress and strain curve for high-strength fiber-reinforced concrete. These studies focused on the effects of the types and geometries of steel fibers in high-strength concrete. However, few studies have shown the effect of the strength of the cementitious composite matrix in combination with the fiber contents on the both the flexural strength and energy absorption of fiber-reinforced concrete.

Therefore, this study evaluated the effects of the concrete strength and fiber content ratio on the flexural strength, energy absorption, and equivalent flexural strength ratio of concrete reinforced with steel fiber. For this purpose, this study conducted flexural tests on SFRC beams with three concrete strengths, 25, 35, and 45 MPa, and three fiber volume fractions, 0.25, 0.375, and 0.50%. According to the stress and deflection relationship obtained from the flexural tests, the cracking and post-cracking strengths and energy absorption capacity were evaluated with respect to the concrete strength and fiber volume fraction. In the design of SFRC structures, the tensile performance is commonly measured using the equivalent flexural strength ratio. Therefore, this study analyzed the correlations of the flexural strength, energy absorption, and equivalent flexural strength ratio with the concrete strength and fiber content ratio. Furthermore, this study examined the effects of the concrete strength and fiber content ratio on the flexural capacity of SFRC floor slab, which is one of the most widely applied structures in practice.

2. Experimental program

2.1. Test variables

To assess the effects of the strength of concrete combined with the content of steel fibers on the flexural strength of SFRC, three different concrete strengths, 25, 35, and 45 MPa, and three different fiber volume fractions, 0.25, 0.375, and 0.50%, were designed. Table 1 lists the SFRC specimens according to the experimental variables of the concrete strength and fiber volume fraction. The steel fiber involved in this study was a hooked-end type that is commonly used in the field. Table 2 presents the geometry and material properties of the steel fiber.

Table 1
Test variables and specimens.

Name of the specimens	Compressive strength of concrete (MPa)	Fiber volume fraction (%)
C25-250	25	0.250
C25-375		0.375
C25-500		0.500
C35-250	35	0.250
C35-375		0.375
C35-500		0.500
C45-250	45	0.250
C45-375		0.375
C45-500		0.500

2.2. Manufacturing of specimen

To evaluate the flexural tensile performance, SFRC beams were manufactured according to ASTM C 1609 [24]. Cement was first mixed with sand, gravel, silica fume, and steel fibers, and then water containing high performance super-plasticizer were added to mix until the steel fibers were uniformly distributed in the concrete matrix. The design strength of the concrete was controlled by adjusting the proportion of cement, water, and super-plasticizer with constant amount of gravel and sand. All the mix proportions were also designed to satisfy a slump value more than 12 cm, which is commonly used in the construction field. Table 3 lists the mix proportions for each of the designed concrete strength. The SFRC mixture was poured into a steel mold of 150 mm high, 150 mm wide, and 500 mm long. The specimens were covered with a vinyl sheet and cured for twenty-four hours. Subsequently, the fiber-reinforced concrete beam specimens were cured in a water tank at 23 ± 1 °C before the flexural tests. A total of 54 SFRC beam specimens, six beams per type of variable, were manufactured to ensure the reliability of the experimental results.

Three cylinders per test variable were manufactured to evaluate the influence of the fiber-reinforced concrete strength. That is, three cylinder tests were carried out for the test variable of C25-250. Thus, the compressive strength for the C25-250 was determined as the mean of the three cylinder tests. Table 4 summarizes the compressive strengths of the SFRC measured from the cylinder tests. For the designed compressive strength of 25, 35, and 45 MPa, the measured compressive strength, which is the mean of a total of nine cylinder tests per design strength, was 26.4, 36.4, and 47.9 MPa, respectively. Therefore, the measured compressive strength of the SFRC agrees well with the designed values.

2.3. Test set-up and measurement

The beam specimen was installed as a simply-supported condition with a length of 450 mm between the supports. To generate the pure flexural moment in the beam, two-point loads, 150 mm apart, were simultaneously applied to the specimen. To prevent local cracking at the loading points and distribute the applied load along the width of the beam, rubber strips were used at each loading point. In addition, another rubber strip was used at the supports to induce a uniform distribution of reaction forces at the supports. Fig. 1 presents the four point flexural test of a SFRC beam specimen based on the ASTM C 1609 standard [24]. The vertical load was applied at a rate of 0.2 mm/min. and continued until the deflection of the beam at mid-span was 3 mm, or 1/150 of the beam span. The vertical displacement was measured using two linear variable differential transducers (LVDTs) installed on the front and back sides of the beam at the mid-span. According to Gopalaratnam et al. [25], the vertical deflection measured at the mid-span can be approximately double that of the real deflection at the cracking strength of concrete. This is because additional deflection occurs due to the elastic and inelastic behaviors of the load-applying device and the sliding of the specimen. Therefore, to exclude the influence of the additional deflection in this measurement, a deflection measurement device proposed by ASTM C 1609 [24] was manufactured and instrumented, as shown in Fig. 1.