Prediction of Flexural Behavior of Fiber-Reinforced High-Performance Concrete

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Abstract The availability of ultra-fine materials, mineral, and chemical admixtures have made an easy design of concrete mix of high and ultra-high strength. Many investigators have developed methods to predict the flexural strength of fiber-reinforced concrete composites assuming different stress distribution over the crosssection. However, it has been observed that the use of fibers throughout the crosssection is structurally inadvisable and economically wasteful, as the tensile stresses are developed in one portion of the crosssection, depending on loading and end conditions. The beams having fiber reinforcement in only tension region are found to possess higher flexural load capacity and higher initial stiffness in comparison to the corresponding beams with fibers throughout the section. Based on this approach of tension reinforcement, the concept of partial depth fiber-reinforced high-performance concrete beams has been established by incorporating fibers in tension zone only. The typical results obtained experimentally are analyzed in the light of load–deflection behavior, failure pattern, cracking and ultimate moment capacity, and ductility associated parameters have demonstrated that Fiber-Reinforced High-Performance Concrete (FRHPC) is extensively used as a construction material because of fact that the composite provides better mechanical, rheological, and durability properties.

Keywords Load–deflection behavior · Ultimate moment capacity · Failure pattern · Toughness

1 Introduction

High-performance concrete (HPC) is designed to give performance characteristics satisfying comprehensive list of requirements based on hardened properties Kumar Bharat et al. (2001), high strength is made possible by reducing porosity, non-homogeneity, and microcracks in concrete, whereas HPC mix proportioning relies on the concept of densified system with ultra-fine particles, effective combination

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of mineral additives, and chemical admixtures in addition to the use of very low water–cement ratio. Therefore, reduction in total concrete volume due to slenderness of structural member and improvement in material and structural durability by the use of high-strength high-performance concrete is evident. Su and Miao (2003) and Lim et al. (2004). Research conducted on high-performance concrete concluded that the inclusion of steel fibers in concrete increases ductility, toughness, and strength of flexural members. The concrete that needs special performance and uniformity requirements that cannot always be achieved routinely by using conventional material, normal mixing, placing, and curing is termed as high-performance concrete.

2 Published Work

Several researchers have studied the behavior of steel fiber-reinforced high-strength concrete (SFRHPC) in flexure, predicting flexural strength of full depth fiber-reinforced concrete composites assuming different stress distribution over the section. Hannant (1978), Narayanan and Green (1981), Ghalib (1980), Rajagopalan et al. (1974), Snyder and Lankard (1972), Shah (1991) and others have developed models to predict the flexural strength of FRHPC. Gunasekaran (1975), however have demonstrated that the use of fibers throughout the section is structurally inadvisable and economically wasteful in all of the cases of the beams tested, as tensile stresses are normally developed in the lower half of the beam only. The beams that had fiber reinforcement in the lower half (tension region) were found to possess higher flexural load values and higher initial stiffness than the corresponding beams with fibers throughout the section. Padmarajaiah and Ramaswamy (2002) have studied the full and partial depth steel fiber high-strength concrete beams and showed that for partial depth concrete beam for a specified fiber volume showed similar load––deflection behavior corresponds to full depth steel fiber-reinforced concrete beams. Dwarkanath and Nagaraj (1992) have studied conventionally reinforced concrete beams tested under pure bending condition and they have shown that the half depth fiber inclusion is equally effective in improving the behavior of beam in flexure, and found half depth fiber inclusion as economical.

The review of the published literature has demonstrated that significant research has been conducted on conventional, normal, and high-strength concrete with full depth of fiber inclusion and partial depth inclusion, to investigate flexural behavior and load–deflection pattern of beams. Several investigators have attempted the problem by considering the stress distribution in compression and tension as triangular and rectangular in nature. The influence of the tensile strain enhancement factor, which is the ratio between the ultimate tensile strength of FRC and the ultimate flexural tensile strain of concrete without fiber have also been studied. Most of the investigators have used circular steel fibers in fiber volume content varies from 0.5 to 3%. However, the influence of inclusion of steel fibers on high-performance concrete of higher grades has not been studied by any researcher. The variation of fiber content in SFRHPC has also not been investigated. In the present study, therefore, experimental investigations have been conducted by incorporating circular crimped steel fibers of 0.5 mm diameter and 30 mm length with aspect ratio of 60 in SFRHPC beams to full depth, half depth, and quarter depth of the beam crosssection, to investigate flexural characteristics, load–deflection behavior, and ductility associated parameters of such SFRHPC beams, in an attempt to optimize application of fiber in the beam crosssection.

Extensive experimental investigations have been conducted in the present study to investigate the behavior of high-performance concrete for M90 grade in flexure using circular crimped steel fibers of aspect ratio 60. The experimental work consists of determining the basic mix proportioning of constituent materials, casting, curing, and preparing the specimens including instrumentation and testing of these specimens.

3 Analytical Study

Steel fiber-reinforced high-performance concrete beams with fibers up to different depths have been studied in flexure. Several investigators have studied the problem analytically, considering different variables and assumptions. Some derivations were based on strain compatibility and equilibrium conditions for fully and partially SFRHPC sections with suitable idealized tension and compression stress blocks.

3.1 Flexural Analysis of Conventionally Reinforced High-Performance Concrete Beams Without Fibers

The ultimate moment capacity of the singly reinforced HPC is based on the stress–strain distribution for the crosssection of singly reinforced plain concrete beam as given in ACI 318M-11 (2011). The equation for nominal moment of a singly reinforced HPC beam is given as

$$M_n = A_s f_y (d - a/2) \tag{1}$$

$$\text{and } a = A_s f_y \big/ (\lambda f_C' b) \tag{2}$$

where

- A_s Area of tensile steel bars (mm^2),
- f_y Yield strength of tensile reinforcement bar (MPa),
- c Neutral axis depth (mm),
- b Width of beam crosssection (mm),
- h Height of beam crosssection (mm),
- λ Concrete stress block parameter, (equal to 0.86 for $f_c{}' \geq 55$ MPa),
- $f_C{}'$ Compressive strength of plain concrete, (MPa),
- β_1 Concrete stress block parameter, (equal to 0.65 for $f_c{}' \geq 55$ (MPa),
- a Depth of the equivalent compressive block (mm).

3.2 Flexural Analysis of Full Depth Steel Fiber-Reinforced High-Performance Concrete Beams

The ultimate moment capacity of the SFRHPC beams has been calculated using the empirical formulae derived by Hwan Oh (1992) for the full depth fiber inclusion in the beam crosssection for singly reinforced beam. The value of ultimate moment (M_n) for full depth SFRHPC beams is given by the equation as

$$M_n = A_s f_y (d - a/2) + \sigma_t b (h - c)(h + c - a)/2 \tag{3}$$

$$\text{and } a = \left(A_f f_y + \sigma_t bh\right) / (\lambda f_{cf} b + \sigma_t b) \tag{4}$$

where

f_{cf} compressive stress of fibrous concrete.

3.3 Flexural Analysis of Half Depth Steel Fiber-Reinforced High-Performance Concrete Beams

The ultimate moment is derived from the simplified stress distribution in which the compressive and the tensile stress blocks are simplified as rectangular blocks. The value of the stress block is assumed as $0.85 f_c{}'$. The depth of the tension zone stress block is *h*/2. The ultimate moment capacity (M_n) is given as Hwan Oh (1992),

$$M_n = A_s f_y (d - a/2) + \sigma_t bh(3h - 2c)/8 \tag{5}$$

$$\text{and, } a = \left(A_f f_y + \sigma_t bh/2\right) / \left(\lambda f_c' b\right) \tag{6}$$

3.4 Flexural Analysis of Quarter Depth Steel Fiber-Reinforced High-Performance Concrete Beams

Since none of the researchers has analyzed SFRHPC beams with quarter depth fibers in beam crosssection, the ultimate moment capacity for such cases has been derived based on stress distribution pattern considered for full and half depth fibers. Accordingly, the ultimate moment (M_n) for the quarter depth SFRHPC beams has been obtained on the basis of assumed stress distribution. The depth of tension block is taken as *h*/4. The ultimate moment capacity (M_n) is given as Hwan Oh (1992)

$$M_n = A_s f_y (d - a/2) + \sigma_t bh(7h - 4a)/8 \tag{7}$$

$$\text{where, } a = \left(A_f f_y + \sigma_t bh/4\right) / \left(\lambda f_c' b\right) \quad (8)$$

3.5 Flexural Analysis of Normal Strength Fiber-Reinforced Concrete to Full Depth

The ultimate moment capacity of the full depth normal strength fiber-reinforced concrete (NSFRC) beam can be calculated according to the method given by the ACI 318-11C (2011). The equation for the ultimate moment capacity (M_n) of the steel fiber-reinforced normal strength concrete beam is given as

$$M_n = A_s f_y(d - a/2) + \sigma_t b(h - e)(h + e - a)/2 \quad (9)$$

$$\text{where, } e = (\varepsilon_f + 0.0035)C/0.0035 \quad (10)$$

$$\text{and } \sigma_t = 0.772 V_f \left(l_f / d_f\right) F_{be} \quad (11)$$

F_{be} bond efficiency factor, taken as 1.2 for hooked and crimped steel fibers.
e the distance from the extreme compression fiber to the top of the tensile stress block of fiber concrete.

The expressions obtained above in analytical investigations may conveniently be used to obtain moment capacity of fiber-reinforced high-performance concrete beams without fibers and with fibers up to different depths.

4 Conclusion

On the basis of analytical and experimental study conducted on beam specimens, the following conclusions can be drawn.

1. The addition of fibers in HPC does not significantly improve first crack load, as fibers play role in resisting tensile stresses in post-cracking region only.
2. The fiber content in full depth has been found most effective as first crack load, ultimate load, resilience, ductility, and toughness values are found to be maximum at this value.
3. In case of partial depth SFRHPC beams, specified fiber volume fraction having an appropriate thickness of the fiber zone, load–deflection patterns have been found to be practically similar to those of corresponding full depth SFRHPC beams. Fibers in half depth of beam crosssection, in many situation are found to be more effective and at par with the corresponding value of fiber in full depth of beam cross-section.

4. Full depth SFRHPC beams is more effective in concrete elements subjected to high strain rate, repeated loadings, stress reversal, and in support regions of continuous members.
5. The ultimate moment capacity of most of SFRHPC specimens (half depth and quarter depth dispersion) are generally lower than those corresponding to full depth SFRHPC beams.

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