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Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete

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HIGHLIGHTS

- Direct tension, comp and flexural strengths with various fiber volume fractions.
- Fibers of various lengths and diameters used for various concrete strengths.
- Fiber contents and lengths caused significant effect on the mechanical properties.
- Proposed analytical model showed good agreement with the experimental results.

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ABSTRACT

Concrete has high brittleness along with low tensile strength and tensile strain capacities. Such unsatisfactory performance can be improved with the addition of steel fibers in concrete. Steel fiber reinforced concrete (SFRC) has gained popularity in the last decades because of its superior performance. Its main advantages include hindrance in macro crack propagation, prevention of growth of micro cracks to macroscopic level, improvement in ductility and residual strength after formation of the first crack, and high toughness. This study investigates the effect of adding steel fibers with different lengths and diameters on the mechanical properties of concrete for three values of concrete strength. In this study, hooked ended fibers of three lengths (40, 50, and 60 mm) and two diameters (0.62 and 0.75 mm) were used with three water-to-cement ratios (0.25, 0.35, and 0.45). Steel fibers were added with three volume fractions, 0.5%, 1.0%, and 1.5%. Thirty concrete mixes were prepared and investigated. The results indicated that the addition of different content and lengths of steel fibers with increasing water-to-cement ratios caused significant change in the mechanical properties of concrete, with an increase of about 10–25% in compressive strength and about 31–47% in direct tensile strength. The increase in the fiber content from 0.5% to 1.5% increased the flexural strength from 3% to 124% for fiber with the smaller aspect ratio of 65, whereas, for the higher aspect ratio of 80, a 140% increase in the flexural strength was observed compared to the concrete without any fibers. With the consideration of steel fibers of different lengths and diameters, an analytical model for stress strain relationship of fiber reinforced concrete under compression is proposed. There is good agreement between the proposed model and the experimental results.

1. Introduction

Construction of high-rise buildings, long span bridges, and offshore structures has made steel fibers important in improving the properties of concrete such as strength, toughness, energy absorption capacity, and durability. The addition of steel fibers in high performance concrete (HPC) can improve the brittle behavior and the energy absorption capacity [1–5]. Hence, steel fiber reinforced concrete plays a significant role in developing modern concrete technology, which represents a new class of construction concrete. In recent years, extensive research performed to explore the use of steel fiber in producing high strength fiber reinforced concrete (HSFRC). The comparison between mechanical properties of high strength fiber reinforced concrete has been presented [6]. The addition of hook end steel fiber with different aspect ratio and crimped round steel fibers in concrete has influenced the compressive and split tensile strength and it was found that both the fibers at different levels for same mix has affected both properties [7]. Split cylinder tensile and flexural strength increased up to 30%

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as compared to plain concrete for different contents of steel fibers [8]. Effect of steel fibers in combination with coarse aggregate was investigated on the compressive and flexural toughness of high strength concrete. The results indicated that the mechanical properties of high strength fiber reinforced concrete are volume fraction of aggregate and both compressive strength and flexural toughness are significantly influenced with increase in fiber content [9]. Results indicated that the HRWRA fiber reinforced lightweight aggregate concrete showed considerable improvement in compressive, splitting, flexural strengths, impact resistance, static modulus of elasticity, and Poisson's ratio at 60 and 90 d of curing, compared to the fiber reinforced lightweight aggregate concrete without HRWRA. Increase in the fiber content improves both the peak load and the post cracking behavior of concrete [10–13]. Conversely, the same parameter related to properties of fiber such as aspect ratio, shape, modulus of elasticity, and the bond between fiber and cement matrix, affects the overall mechanical behavior of the material [14,15]. High strength fibers with different contents were found to have positive effect on the mechanical properties of the high strength concrete [16]. Steel fibers with hook ends were recommended to be used for further studies for better workability and were reported to increase the ductility [16]. Experiments were conducted to investigate the effect of bond of hook end steel fibers on the different strengths of the concrete and results revealed that with the increase in strength of matrix, peak pullout load and post peak pullout load was increased [17]. The influence of adding fibers on the properties of concrete, such as compressive strength, toughness, post cracking load resistance, tensile strength, and durability, had been investigated and improvement in mechanical properties of concrete using different fibers had been reported [18–20]. The effect of the fiber aspect ratio on the mechanical properties of concrete and optimal value of the aspect ratio for strength had been reported [21]. Beyond a certain value of aspect ratio of 60, ductility increased rather than the strength of concrete with the addition of steel fibers.

Steel fiber high reinforced concrete had been reported for the improved ductile response of structural members [19]. Steel fibers in high strength concrete had been used to limit the development of macro cracks in concrete elements. The addition of fibers had also affected the high residual concrete strength after the appearance of first crack and had increased the toughness [22]. Results indicated that the strain capacity and the post peak ductility of concrete improved after using steel fibers, with the fiber content of 1% found to be the minimum limiting value for significant improvement in the flexural response of concrete. Higher compressive strength led to lower ductility under flexural loading [23]. Experimental work had been carried out to investigate the effect of the fiber volume content on the mechanical properties of HPC [24]. The post peak behavior of HPC significantly improved by the inclusion of the steel fibers. In addition, increase in the fiber volume content had significant effect on the properties of HPC [24]. Investigation had been reported on the mechanical properties of concrete with different grades using different content of fibers [25]. The increase in the fiber volume content had increased the mechanical properties of the concrete. In addition, predictive models were presented for the mechanical properties of fiber reinforced concrete using different fiber volume contents [25].

As discussed above, the mechanical properties of SFRC are mainly dependent upon fiber parameter, fiber content, matrix strength, and fiber matrix interaction. Although extensive research is being conducted on steel fiber reinforced concrete, however, limited work has been done regarding different strengths of concrete and the use of different sizes of fibers with various aspect ratios, lengths, and contents. The research work available in the literature mostly deals either with small fiber lengths or with a single fiber aspect ratio. In addition, most of the published studies are related to either normal strength concrete or high strength concrete and show the relationship between the compressive strength and the split tensile strength of SFRC, without any data on the direct tensile strength. However, there is still contradiction in such relationships [25–29]. Perumal [29] and Xu and Shi [26] have reported that the flexural strength and the indirect tensile strength have nonlinear relationship, whereas Nataraja et al. [28] has suggested that flexural strength and indirect tensile strength are linearly correlated. Therefore, the correlations reported in the literature for large sets of data for the SFRC and HSFRC are not clear. Hence, an investigation of the relationships of the flexural strength, the tensile strength, and the compressive strength of SFRC and HSFRC by collecting a large set of data is required.

An effort has been made in this research to investigate the effects of different fiber parameters, which can vary simultaneously, on the mechanical properties of concrete with different strengths. This paper presents the effects of adding steel fibers with different contents, lengths, and diameters on the mechanical properties of concrete with different water-cement. The main aim of this research was to provide comprehensive information on the mechanical properties of steel fiber reinforced concrete by considering significant parameters of both concrete and fibers. The relationships among different basic mechanical properties of fiber reinforced concrete are developed and compared with the findings from other researchers. In addition, an analytical model for the stress-strain relationship of the fiber reinforced concrete under compression is proposed.

2. Materials and methods

2.1. Materials

2.1.1. Cement

ASTM Type I ordinary Portland cement (OPC) from a local cement plant was used. The chemical composition of the cement used in this study is presented in Table 1.

2.1.2. Admixture

High-range water-reducing (HRWR) modified poly-carboxylate based super plasticizer conforming to the requirements of the ASTM C494 type F was used.

2.1.3. Fine and coarse aggregates

Two types of sands, namely the crushed sand and the fine sand, with different particle sizes were used for the preparation of mixes. The fineness moduli are 1.47 and 4.66 for the fine and the crushed sand, respectively. The fine and the crushed sand were combined to achieve the fineness modulus of 2.54. Coarse aggregate with a maximum size of 10 mm was used for the preparation of the mix.

2.1.4. Fibers

Three different hooked ended steel fibers were used for the SFRC in this study. Three different lengths of steel fibers with various diameters were proposed for this work. The tensile strength and the Young's modulus of the used steel fibers were 1250 MPa and 210 GPa, respectively. Other properties of the used steel fibers are summarized in Table 2. The physical property of the hook end fiber is shown in Fig. 1. Three different mixes were prepared with different water/cementitious ratios (0.25, 0.35, and 0.45). The proportions and the contents of the three mixes including the content of the steel fibers are presented in Table 3. In total, thirty different concrete mixes were prepared as shown in Table 4. In the mix design, water/cementitious ratios of 0.25, 0.35, and 0.45 and the slump of 100 ± 25 mm were chosen for the concrete without fibers. Fibers with three different lengths (40, 50, and 60 mm) and with