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Experimental investigation on the flexural behavior of steel-polypropylene hybrid fiber reinforced concrete

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HIGHLIGHTS

- The effect of steel-polypropylene hybrid fiber on the flexural behavior of concrete was investigated.
- Favorable improvements in failure modes, flexural loads, toughness and ductility of HFRC were observed.
- The synergy of hybrid fibers with various fiber parameters was analyzed.

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ABSTRACT

This paper presents an experimental study on the flexural behavior of steel-polypropylene hybrid fiber reinforced concrete (HFRC) using four-point bending tests on 51 samples. Three types of steel fibers, i.e., straight, hooked-end and corrugated fiber, and a type of monofilament polypropylene fiber are considered. The flexural behavior in terms of load-deflection curves, load and deflection characteristics, toughness, cracking properties as well as the synergetic effect of hybrid fibers is studied. The results show that synergetic effect is observed for all the three types of steel fiber with the combination of polypropylene fiber on improving the flexural behavior of HFRC. Specimens with hooked-end fibers show the best flexural performance. However, the combination of straight steel and polypropylene fibers presents the most obvious synergy. Moreover, an increase in volume fractions of both steel and polypropylene fibers leads to an increase in the compressive, splitting tensile and flexural strengths of concrete. The post-peak ductility of concrete is improved and the strength degradation is alleviated with increasing fiber volume fraction and steel fiber aspect ratio. In addition, specimens with corrugated and hooked-end fibers exhibit a better failure behavior than specimens with straight fibers, with multiply micro-cracks induced by mechanical interlocks of deformed steel fibers observed at the main cracks. Finally, based on a comprehensive fiber reinforcing index, analytical equations for flexural loads, deflections, and toughness of HFRC are developed with varying fiber parameters taken into consideration.

1. Introduction

It is well acknowledged that concrete has been a universal construction material with wide-spread suitability for relatively different applications because of its low cost, excellent strength and durability. However, plain concrete is brittle, with a very low tensile strength, limited deflection capacity and poor post-cracking ductility [1]. Over the past two centuries, steel bars or pre-stressing strands are normally used in the design of concrete structures to support the tensile forces generated in concrete. However, when using steel bars, it is crucial to prevent corrosion of the bars and ensure sufficient bond strength between bars and concrete to maintain the performance of concrete structures. In addition, careful attention should be paid to the placement and anchorage of the steel bars. Accordingly, it is difficult to apply these reinforced concrete (RC) and pre-stressing strand concrete (PSC) elements for thin claddings, skin facades and curved panels in buildings, or for thin bridge decks for pedestrian and long suspension bridges [2,3].

Over decades, in an attempt to overcome the inherent drawbacks of plain concrete, fibers are introduced into the concrete mix, commonly known as fiber reinforced concrete (FRC), to enhance the mechanical properties of concrete, especially for its tensile and post-cracking behavior. The flexural behavior of FRC has been sufficiently investigated by many researchers [4–18]. The results showed that the addition of fiber significantly improves the flexural strength and toughness of concrete [4,5]. Fibers mainly affect the post-cracking properties of concrete, i.e. residual

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strengths and ductility, but have a little effect on the first cracking properties of concrete [6–8]. Moreover, the flexural properties of concrete are affected by many fiber factors, such as fiber type, geometry, volume fraction, length, interfacial bond properties between fiber and matrix, and so on [3,6,8–13]. The enhancement of different types of fibers on the flexural strengths and toughness is mainly attributed to the fiber crack-bridging and load-carrying capacities [14–16]. It is also noted from the literature that the fracture process in concrete is multi-scale, i.e., material scale and structural scale [12,17]. Large fibers such as long steel fiber, macro polypropylene fiber, polyvinyl alcohol fiber etc., can bridge macro cracks and then prevent their further propagation in a large scale, and further induces an improvement in the flexural behavior of concrete. In the meantime, micro fibers, i.e., carbon fiber, polypropylene fiber, short steel fiber, etc., can bridge micro cracks and restraint their formation and propagation in a small scale. In addition, based on test results and using the concept of inverse analysis, analytical equations for the flexural deflection-softening responses of FRC were also developed [18–22].

As mentioned above, the fracture and tension in concrete is a gradual and multi-scale process, occurring at both micro and macro levels. Therefore, it is very limiting when only using one type and dimension of fibers as the reinforcements, because they clearly restrict the crack growth at their own scale and have a little or no effects on the fracture process at other scales [23]. Given this, it is logical to employ the combination of fibers with different sizes, functions and mechanical properties for an optimal behavior of concrete. In this sense, hybrid fiber reinforced concrete (HFRC) has gained increasing recognition for the superior performance and then becomes a promising material [23–28]. The hybridization in HFRC means the combination of two or more fibers with different properties in an appropriate manner to take full advantages of each product. The fiber properties considered are fiber type, length, diameter, strength, elastic modulus, and so on [24–26]. Considerable efforts have been devoted to investigating the flexural behavior of HFRC with the combination of different types of fibers or one type of fibers with various fiber lengths [23,29–35]. Yoo et al. [23,29] and Kim et al. [30] studied the flexural behavior of ultra-high performance fiber reinforced concrete (UHPFRC) using hybrid steel fibers with various scales, and reported that the hybrid use of steel fibers at multi scales can effectively improve the post-cracking strength, flexural toughness and cracking process of concrete in comparison with the use of single steel fibers. Similar observations are also reported in Ref. [29,31–33]. Moreover, some researchers focused on the flexural behavior of FRC with steel and polyester fibers, and found there is a positive synergy [34–37]. Besides, Pajak et al. [38,39] conducted a research on the flexural properties of steel-polypropylene HFRC. They claimed that steel fibers play the most important role in the enhancement of mechanical properties, and polypropylene fibers only slightly improve the toughness of concrete. Yap et al. [40] studied the flexural toughness of steel-polypropylene hybrid fiber reinforced oil palm shell concrete, and found that in the hybrid system, the dominance of steel fibers on the first crack deflection and toughness of concrete is evident. In addition, investigations on the fracture behavior of HFRC were also conducted by Almusallam et al. [41] with using three types of fibers namely steel, Kevlar and polypropylene fiber. Based on the results, analytical models were developed using an inverse analysis to predict the tension softening diagram of HFRC.

From the above literature review, it is recognized that although some crucial investigations on the flexural behavior of HFRC have been conducted, the conclusions made from respective study have not come to a unanimous agreement, which consequently leads to hesitancy in the design of structural elements within civil infrastructure. The arguments by individual scenario remain to be further evidenced due to the limited experimental results. Furthermore, for each researcher's study, only one type of steel fiber and polypropylene fiber are hybridized, and no study is devoted to the comparison of the mechanical responses of concrete using different types of steel fibers in the combination with polypropylene fibers at the same condition. Additionally, limited available analysis and studies are concentrated on the fiber reinforcing mechanism in HFRC, which is insufficient to explain the distinct difference in the load-deflection response of HFRC under flexure. Therefore, flexural behavior of HFRC as well as hybrid fiber reinforcing mechanism still needs a systematical and comprehensive investigation.

The objective of this paper is to investigate the flexural behavior of HFRC with hybrid steel and polypropylene fibers. Three types of steel fiber, i.e. straight, hooked-end and corrugated fiber, and a type of monofilament polypropylene fiber were considered. Four fiber volume fractions of 0.5%, 1.0%, 1.5% and 2.0%, aspect ratios of 40, 60 and 80 for corrugated steel fiber, and three volume fractions of 0.1%, 0.15% and 0.2% for polypropylene fiber were respectively selected and adopted. The load-deflection curves, load and deflection characteristic, energy absorption capacity and cracking behavior were studied. Moreover, the synergetic effect of hybrid fiber on the flexural properties of concrete and the corresponding fiber reinforcing mechanism were analyzed and discussed. Finally, based on a new comprehensive fiber reinforcing index, analytical equations were developed to predict the flexural loads, deflections and toughness of HFRC with varying hybrid fiber parameters.

2. Experimental program

2.1. Materials, mixtures and specimens preparation

Portland cement P.O 42.5 was used as the binder. Crushed gravel stones with sizes of 5–20 mm and natural river sands of sizes of 0–5 mm were respectively employed as the coarse aggregates and fine aggregates. The grading curves of them are shown in Fig. 1. A commercially available high rang water reducing admixture derived from a polycarboxylate ether was adopted to achieve adequate workability. The mix proportions of plain concrete designed according to the Chinese Code JGJ 55-2011 [43] are given in Table 1.

Three types of steel fibers, i.e. straight, hooked-end and corrugated fiber, and a type of monofilament polypropylene fiber were considered in this study. The physical and mechanical properties of them are summarized in Table 2. For corrugated steel fibers, three fiber lengths corresponding to aspect ratios of 40, 60 and 80 were selected. The straight and hooked-end steel fibers have a circular section, and the corrugated steel fiber owns a rectangular section. The straight, hooked-end and corrugated fibers are denoted as S, H, and C. Subsequently, the letters A, B and C are used to indicate the aspect ratios of 40, 60 and 80. In order to avoid the fiber clumping, four volume fractions of 0.5%, 1.0%, 1.5% and 2.0% for corrugated steel fiber, and

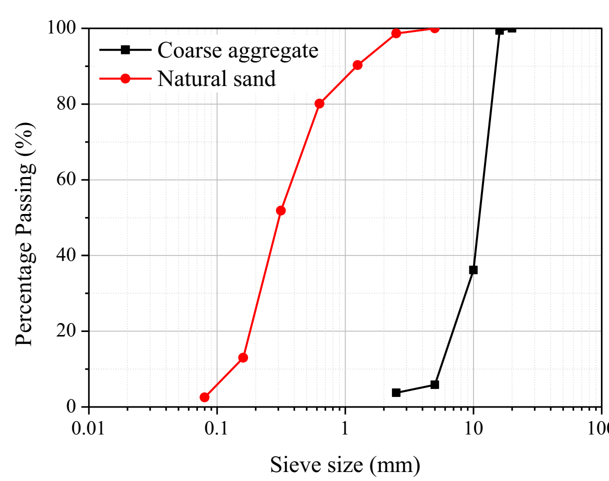

Fig. 1. Grading curves for fine and coarse aggregates.