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Experimental study of the reinforcement effect of macro-type high strength polypropylene on the flexural capacity of concrete

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HIGHLIGHTS

- Flexural capacity of concrete reinforced with high strength PP fibers was evaluated.
- Stress-deflection curves, residual strength, and energy absorption were discussed.
- Residual strength was defined using average stresses for a period of deflection.
- Effect of high strength PP fiber content on the flexural performance was evaluated.
- Effect of high strength PP fiber on normal and high strength concrete was evaluated.

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ABSTRACT

In this paper, an experimental study was performed to examine the flexural capacity of concrete reinforced with macro-type high strength polypropylene fiber. Four fiber volume fractions, 0.25, 0.5, 0.75, and 1.0%, and three concrete compressive strengths, 30, 40, and 60 MPa, were involved to determine the effects of the high strength polypropylene fiber on the flexural capacity of fiber-reinforced concrete. The stress and deflection curves, residual strength, and energy absorption capacity obtained from the experiment were used to investigate the flexural capacity of high strength polypropylene fiber-reinforced concrete, particularly in high strength concrete. High strength concrete reinforced with a 0.25% volume fraction of high strength polypropylene fiber showed a flexural capacity lower than normal strength concrete reinforced with the same volume fraction. The reinforcing effect of the high strength polypropylene fiber in the flexural capacity of high strength concrete was excellent at volume fractions more than 0.50%.

1. Introduction

Concrete exhibits excellent compressive performance but has a very low tensile strength. The tensile strength of concrete is only approximately 10% of the compressive strength [1], and cracks quickly initiate and develop when concrete is subjected to tensile force [2]. Therefore, in the design of concrete structures, the tensile capacity of concrete is neglected, and steel bars are used to support the tensile forces generated in the concrete. When using the steel bars, it is crucial to prevent corrosion of the rebars to maintain the performance of the concrete structures. In addition, careful attention should be paid to the placement, the development and adhesion, and the anchorage of the steel bars. Therefore, instead of using steel bars to support the tension force generated in the concrete, a small quantity of fibers, such as steel, plastic, and carbon fibers, is mixed with the concrete to enhance the ability to resist the tensile cracks and improve the energy absorption of concrete [3–5], and [6].

Research on fiber-reinforced concrete (FRC), particularly steel fiber-reinforced concrete (SFRC), has been actively performed to improve its performance. For the steel fiber-reinforced concrete, many studies [7–9], and [10] have evaluated and improved the strength and toughness of concrete. Currently, SFRC concrete has many applications in tunnels [11–13], and [14], such as tunnel shotcrete and lining in the New Austrian Tunneling Method (NATM), precast tunnel segment in the Tunnel Boring Machine

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(TBM), and slabs supported on the ground and columns [15–19], and [20].

The polypropylene (PP) fibers have low strength and modulus of elasticity compared to steel fibers. On the other hand, PP fibers would help restrain the plastic cracks with their good properties of ductility, fineness, and dispersion [21]. Kakooei et al. [22] reported that PP fiber has the advantages of low specific weight and chemical resistance over the other reinforcing fibers. Patel et al. [23] also reported that PP fiber-reinforced concrete showed no significant improvement in compressive strength but significant improvement in flexural strength. In addition, Nurdian and Jalan [24] suggested that a proper quantity of PP fibers in concrete could be effective in improving the tensile performance of concrete. Therefore, the PP fiber can be used to enhance the durability of concrete and improve its resistance to shock, abrasion, and fatigue. Cho et al. [25] compared the post-cracking behavior of concrete reinforced with PP fibers with that reinforced with steel fibers. The PP fiber delayed the decrease in stress after concrete cracking, which indicates that an appropriate PP fiber content can improve the flexural performance of concrete. Bayasi and Zeng [26] also investigated the relationship between the length (13 and 19 mm long) and volume fractions (0.1, 0.3, and 0.5%) of the PP fibers in concrete. For fiber content volumes of 0.3% or less, long PP fibers were more effective than short fibers, whereas short fibers were more effective with a 0.5% fiber volume fraction.

Several studies of the PP fiber-reinforced concrete have mainly focused on normal strength concrete. Moreover, the tensile strength of PP fiber involved in previous studies ranged from 400 to 450 MPa. In general, fibers can be classified into macro-type and micro-type fibers. Micro fibers, which range from 5 to 100 μm in diameter and 5–30 mm in length [27], are intended to enhance pre-cracking behavior of concrete while macro fibers are used to resist the tensile load and cracks for structural and non-structural applications [28,29] and [30]. Therefore, in this study, a macro-type high strength PP fiber that can overcome the weakness of its relatively low tensile strength was used to evaluate the flexural capacity of the PP fiber-reinforced concrete and assess its applicability to construction sites. To analyze the flexural effect of high strength PP fiber in concrete, three concrete compressive strengths, 30, 40, and 60 MPa, were selected. In addition, four volume fractions of PP fibers, 0.25, 0.50, 0.75, and 1.00%, were used to evaluate the flexural capacity of the PP fiber-reinforced concrete with the variance in the fiber content ratios. To ensure the reliability of the experimental results, a total of 120 reinforced beam specimens with 10 specimens per variable were manufactured to carry out the experiments. Based on the experimental data obtained, the stress and deflection curves, residual strength, and energy absorption performance were analyzed to determine the reinforcement effect of the high strength PP fibers on normal and high strength concrete according to the fiber content.

2. Flexural tests of high strength PP fiber-reinforced concrete beams

2.1. Specimens

In this study, high strength macro-type PP fiber with a tensile strength of 650 MPa was used. The diameter and length of the fiber was 0.63 mm and 58 mm, respectively, and the aspect ratio of the fiber was calculated to be 92. Table 1 lists the geometry and material properties of the PP fiber, and Fig. 1 presents a photograph of the fiber shape.

To assess the effectiveness and applicability of the macro-type high strength PP fibers with the variance in the compressive strength of concrete, three types of concrete compressive strengths were designed; normal strength concrete (30 and 40 MPa), which is generally used in the field, and high strength concrete (60 MPa). With the same amount of the gravel and sand, the proportion of cement, water, super-plasticizer, and silica fume were adjusted to reach the designed compressive strength of the concrete. All the mix proportions were also designed to satisfy a slump value more than 12 cm commonly used in the construction field. Table 2 lists the mix proportions for each of the designed compressive strengths of concrete.

Concrete beam specimens reinforced with high strength PP fibers were manufactured according to the ASTM C 1609 standard [31]. A dry mixing of sand, gravel, and cement was first performed. Water containing a high performance super-plasticizer was then added for mixing until the PP fibers were distributed uniformly in the concrete matrix. The mixed concrete was poured in a steel mold, 150 mm high, 150 wide, and 500 mm long. The specimens were covered with a vinyl sheet and cured for twenty four hours. After that, the fiber-reinforced concrete beam specimens were cured in a water tank at 23 ± 1 °C for 26 days twenty four hours before the flexural tests.

Four fiber content volume fractions, 0.25%, 0.50%, 0.75%, and 1.00%, were used to evaluate the effects of the high strength PP fibers on the flexural capacity of the fiber-reinforced concrete. Table 3 shows the PP fiber-reinforced concrete beam specimens according to the experimental variables of the compressive strength of concrete and the content ratio of the PP fiber. To ensure the reliability of the experimental results, ten beams per type of specimen were manufactured. Therefore, a total of 120 beam tests were carried out.

2.2. Experimental method

The specimen beam with its concrete casting face toward the side of the beam was simply supported. The length between the supports was 450 mm. To distribute the supporting forces at the beam uniformly, a rubber plate was placed at the contact portion between the steel support roller and the specimen beam. A four point bending test with a distance of 150 mm between the point loads, in which the pure bending stress occurs, was performed based on the ASTM C 1609 standard [31]. A rubber plate was also placed between the loading points and the top surface of the beam to prevent local cracks of concrete and distribute the applied load along the width of the beam. The load was applied at a rate of 0.2 mm/minute and continued until the deflection of the beam at the mid-span was 3 mm, or 1/150 of the beam length. Two linear variable differential transducers (LVDTs) were installed on the front and back sides of the beam at the mid-span to measure the vertical displacement and control the eccentric displacement. According to Gopalaratnam et al. [32], the vertical deflection measured at the mid-span was approximately double that of the real deflection at the cracking strength of concrete. This is because of the additional deflection due to the elastic and inelastic behaviors of the load-applying device and the sliding of the specimen. There-

Table 1
Geometric and material properties of the macro-type high strength PP fiber.

Specific gravity	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Tensile elongation (%)
0.91	58	0.63	650	⩾6.0	⩽15