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Flexural behavior of precast reinforced concrete composite members reinforced with structural nano-synthetic and steel fibers

Su-Jin Lee, Jong-Pil Won *

Department of Civil & Environmental System Engineering, Konkuk University, Seoul 143-701, Republic of Korea

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ABSTRACT

In this study, structural nano-synthetic and steel fibers were used to reduce the amount of steel rebar distributed in precast reinforced concrete composite members. The flexural performance of the members was evaluated using longitudinal steel ratios of 1.65 and 1.20 and a transverse steel ratio of 0.20. Hybrid fiber mixtures consisting of various amounts of structural nano-synthetic and hooked-end steel fibers were used as reinforcing materials along with the steel rebar. The nano-synthetic fiber volume fractions were 0.4, 0.5, and 0.6 vol.%, and the steel fiber contents were 5, 10, and 20 kg/m^3. Flexural performance tests were carried out for the resulting hybrid fiber-reinforced cement composites. The test results demonstrated that the hybrid fiber-reinforced cement composites satisfied the necessary conditions to replace the general reinforcing bars according to the RILEM standard when the mixture contained 0.4 vol.% of nano-synthetic fiber and 20 kg/m^3 of steel fiber. The flexural behavior of a 350 × 180 × 1500-mm precast composite member reinforced by such a hybrid fiber mixture and steel rebar was evaluated; its maximum load was 30% greater than the designed ultimate load and 3.5% greater than that of a steel fiber-reinforced composite member.

1. Introduction

Plain concrete is a brittle material with low tensile strength and low tensile strain and hence requires reinforcing material to be used as a structural member. Currently, continuous steel rebar distributed appropriately has been used as the reinforcing material to improve tensile strength.

Fibers are not only discontinuous, but they also end up distributed irregularly in the cement matrix. Therefore, fiber reinforcements do not effectively resist tensile stress. However, fibers are effective at controlling cracking because the distance between fibers is less than the distance between the steel rebar sections.

Therefore, if both fiber and steel rebar are used as reinforcing materials, the steel rebar will enhance the load-bearing capacity of the concrete, and the fiber will effectively control cracking [1].

Steel, synthetic, glass, and natural fibers have all been used as reinforcing materials. Among these, steel and natural fibers are used as structural reinforcing materials [2]. Structural synthetic fiber has recently been studied as a substitute reinforcing material for steel fiber. Structural synthetic fiber is known to exhibit similar features to steel fiber, such as good tensile strength, flexural strength, flexural toughness, and impact resistance. It has good chemical resistance and no possibility of corrosion, and it is easily movable due to its low specific gravity. Additionally, it is not dangerous to workers and is economically advantageous compared with steel fiber. For these reasons, its use is increasing [1,3–7]. However, structural synthetic fibers experience dramatic stress reduction and deformation after the application of the maximum load, which is typical of polymeric fibers [1,8–10]. Along with this, they have poor adhesion to cementitious composites due to their hydrophobic nature resulting from their raw material properties.

Nonetheless, structural synthetic fibers are often used because the fiber ends are fixed in the cement matrix and elongate simultaneously during pull-out to induce ductile behavior, unlike steel fibers, which resist cracking with high stiffness when pulled [9–11]. This property of polymer fibers, known as elongation, provides increased toughness. Many research results have shown that concrete with 1.0 vol.% of synthetic fiber has performance equivalent to concrete with 0.5 vol.% steel fiber, which is suitable for structural use [11–14]. However, the elongation of structural synthetic fiber, which allows it to resist pull-out, makes the fiber unable to effectively resist the stress reduction after cracking, which leads to safety concerns when the fiber is used as a reinforcing material in real structures. Additionally, fibers tend to stick together (known as balling) when 1.0 vol.% synthetic fiber is used as a structural reinforcing material; since the number of fibers per unit volume is large, this reduces the efficiency and productivity of precast reinforced concrete (RC) products [4–7,9].

* Corresponding author. Tel.: +82 2 450 3750; fax: +82 2 2201 0907.
E-mail address: jpwon@konkuk.ac.kr (J.-P. Won).

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To resolve these problems, structural nano-synthetic fiber was developed and used a nano-material to improve the properties of standard structural synthetic fiber [15,16]. Structural nano-synthetic fiber has a tensile strength of 674 MPa, an elastic modulus of 6500 MPa, and a specific gravity of 0.91; the tensile strength and elastic modulus are both approximately 35% greater than these values for conventional structural synthetic fiber.

This study was carried out to improve the flexural performance and economic benefits of precast RC composite members. A hybrid reinforcing material was considered, consisting of structural nano-synthetic fiber and high-stiffness steel fiber, to manage the dramatic stress reduction after cracking. Workability was obtained by reducing the fiber volume fraction compared with the requirements for structural synthetic fiber.

2. Materials and mix proportions

Previous research results have verified that the performance of 1.0 vol.% structural synthetic fiber is equivalent to that of 0.5 vol.% steel fiber [11–14,17,18]. However, it lowers the workability of the material and cannot manage the dramatic stress reduction after application of the maximum load, which is a typical disadvantage of polymer fiber used at this unit volume. In this study, a mixture containing 1.0 vol.% of structural nano-synthetic fiber was chosen to define the required performance criterion of hybrid fiber mixtures, which was 42 MPa of compressive strength after 28 days. This is the requirement for precast RC composite members. Structural nano-synthetic and steel fibers were used together to obtain equivalent performance with good workability but without the stress reduction after the onset of cracking.

2.1. Cement and aggregates

Type I Portland cement, which has a specific gravity of 3.15, was used in this study. Crushed stones with a specific gravity of 2.63 and a maximum size of 25 mm were used as the coarse aggregate, and river sand with a specific gravity of 2.65 and a fineness modulus of 2.49 was used as the fine aggregate.

2.2. Fibers

A hybrid material consisting of structural nano-synthetic and steel fibers was used for reinforcement and compared with steel rebar. The steel fiber had hooked ends and was 0.75 mm in diameter and 60 mm in length. The structural nano-synthetic fiber was straight and was 0.60 mm in diameter and 50 mm in length. The structural nano-synthetic fiber was developed by adding nano clay with a polymer matrix [16]. Fig. 1 shows the shape of the fibers used in this study. The material properties are listed in Table 1.

2.3. Mix proportions

The material performance was evaluated based on the mix proportions required to give 42 MPa design strength using fiber composition and volume fractions as variables. This study was performed based on the results of previous research findings showing that the performance of 1.0 vol.% of structural synthetic fiber is equivalent to that of 40 kg/m^3 of steel fiber [11–14,17,18]. Hence, the tested specimens were required to perform at least equivalently to a mix of 1.0 vol.% of structural nano-synthetic fiber, using the hybrid fiber volume fraction as a variable. The structural nano-synthetic fiber volume fractions were 0.4, 0.5, and 0.6 vol.%, and the steel fiber contents were 5, 10, and 20 kg/m^3. Table 2 lists the experimental variables and mix proportions. The test mixtures were identified according to the amount of nano-synthetic and steel fibers they contained, e.g., NSyn05St20.

3. Experimental

3.1. Compressive strength

To measure the compressive strength of the hybrid fiber-reinforced cement composites, three cylinder specimens of ϕ 150 × 300 mm were tested for each mixture. Each test was repeated twice. The fabricated specimens were initially cured for 1 day in room with a constant 23 ± 2 °C temperature and 50% relative humidity. Then, they were placed in 23 ± 2 °C water for moist curing. The compressive strength tests were performed on the cured hybrid fiber-reinforced concrete specimens according to the ASTM C39 standard [19].

3.2. Flexural strength and toughness

To evaluate the flexural performance of the hybrid fiber-reinforced cement composites, flexural tests were performed on notched beams according to the JCI-S-001 and RILEM TC 162-TDF standards [20,21]. The load-crack mouth opening displacement (CMOD) curves were measured. A notched beam has stable behavior after cracking when the location of the first crack is controlled. The resulting toughness obtained from the load–CMOD curve is known to have much less error than the toughness obtained from a load–displacement curve [22–24]. The specimens were 150 × 150 × 500-mm prisms, as shown in Fig. 2, that were cured for 28 days. A notch was cut to 30% of the cross-section height at the center of each specimen. A displacement-control universal testing machine (UTM. Shimadzu, Japan) was used to apply a load of 250 kN, and the crack-opening speed was 0.1 mm/min. The CMOD was measured to an accuracy of 1/1000 mm using a clip gauge (Tokyo Sokki, Japan) with 5-mm capacity. The post-crack strength (PCS) and flexural toughness were calculated from the load–CMOD curve. The PCS was obtained from [25]

$$PCS = [A_{post}L]/[(D - D_p)b(w - a)^2], \quad (1)$$

where L: length of the span, D: deflection at a specific point (L/1350, L/450, L/225), D_p: deflection at the peak load, b, w: size of the specimen, a: depth of the notch.

The residual flexural strength was obtained from the load–CMOD curve when the CMOD was 0.5, 2.5 mm, and at the proportional limit. The specimen could be used as a typical reinforcement if it satisfied the following conditions proposed by RILEM based on the CEB-FIP standard [21]:

$$\frac{f_{R1}}{f_L} > 0.4 \quad \text{and} \quad \frac{f_{R3}}{f_{R1}} > 0.5 \quad (2)$$

where f_{R1}: residual flexural strength at CMOD$_{0.5}$, f_{R3}: residual flexural strength at CMOD$_{2.5}$, f_L: residual flexural strength at the limit of proportionality.

3.3. Flexural behavior of precast composite members

Precast RC composite members 350 mm wide, 180 mm high, and 1500 mm long were fabricated to verify their behavior with hybrid reinforcing fiber. The longitudinal steel ratios of the precast RC composite member were 1.65 and 1.20; 1.20 is the minimum steel ratio according to the RILEM standard. The transverse steel ratio was fixed at 0.20 [21]. The steel ratios and fiber volume fractions of the precast RC composite members are listed in Table 3, and the details of the steel rebar arrangements are shown in Fig. 3. A baseline case, indicated by St05, which used 0.5 vol.% of steel fiber, was included for comparison. The considered specimens satisfied the requirements for typical reinforcements, as determined by evaluating the material properties of the resulting fiber-reinforced cement composites. The composite members were