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Assessment of flexural toughness and impact resistance of bundle-type polyamide fiber-reinforced concrete

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ABSTRACT

This study compares the fiber/matrix bonding strength and flexural properties of bundle-type polyamide fibers to those of hooked-end steel fibers. Their fracture behavior upon impact with a high-velocity projectile is also assessed in terms of penetration depth, crater diameter and rear-side scabbing. The results obtained demonstrate that the bundle-type polyamide fibers undergo fracture without fiber pullout because of the increased interfiber gap and specific surface area for bonding, but exhibit poorer flexural fracture behavior with a lower flexural strength and fracture energy when compared to hooked-end steel fibers. Yet despite this, concrete reinforced with bundle-type fibers is shown to more effectively suppress scabbing during high-velocity impact, which is attributed to a more efficacious dispersion of shock stress due to the increased number of individual fibers.

1. Introduction

The reinforcing of concrete with short fibers is designed to improve its dynamic loading, impact resistance and explosion resistance by increasing the tensile strength and toughness, as well as inhibiting crack formation and growth through the bridging of the fibers. Past studies have confirmed the safety advantages offered by fiber-reinforced concrete, in that it helps to prevent brittle fracture induced by impact or explosion. In the literature pertaining to the fracture mechanism of concrete structures, it is compressive strength (stiffness) that has generally been associated with projectile penetration, while flexural tensile toughness is related to scabbing.

The use of fiber-reinforced concrete in construction and repair/retrofitting applications requires a combination of high flexural toughness, tensile strength, shear strength, crack control and impact resistance. Performance therefore varies widely depending on the effectiveness of the fiber used, with Fig. 1 providing a schematic diagram of load–displacement relationship for when a fiber is pulled out of the matrix [1]. The high flexural tensile strength and crack resistance offered by steel reinforcing fibers makes them a popular choice in construction; however, the high specific gravity and stiffness of steel fibers can cause concrete pump tubes to rupture and increases the rebound volume of shotcrete, not to mention the problems associated with corrosion of the fibers [2–5]. To overcome this, the use of lightweight organic fibers with mechanical properties similar to steel, but a higher resistance to corrosion, has been explored [6,7].

1.1. Literature review

Consequently, it has been shown by Anderson et al. [8] that the penetration resistance of concrete (i.e., the penetration depth) is not greatly influenced by the type of fiber type, but only by fiber content within a limited practical range. Moreover, their results showed that greater fiber contents lead to a smaller crater volume. Ramakrishnan et al. [9] reported that reinforcement with hooked-end fibers increases the low-velocity impact resistance of shotcrete during hammer drop testing when compared to plain shotcrete. Meanwhile, Dancygier and Yankelevsky [10,11] observed that using steel fibers inhibits the brittle fracture of concrete impacted by a high-velocity projectile, while also tending to suppress crack propagation and minimize the crater area. This led to investigations by Mohamed et al. [12], O'Neil et al. [13], Zhang et al. [14], Vossoughi et al. [15], and G.Y. Kim et al. [16,17] into the fracture

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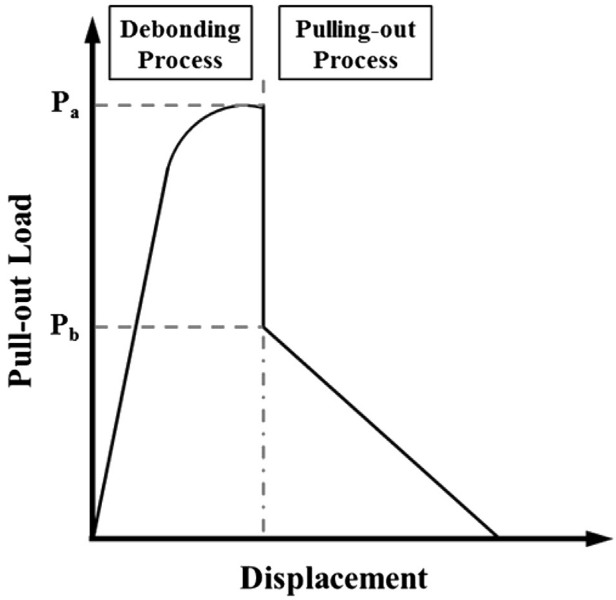

Fig. 1. Schematic diagram of load–displacement relationship for fiber pulled out of the matrix.

resistance of concrete under impact when it is reinforced with different types and shapes of fiber by looking at the change in flexural tensile strength. Many of these researchers have reported that fiber-reinforcement reduces impact-induced crack formation and scabbing, as the bridging effect of the fibers increases the flexural and tensile strength in proportion to the fiber volume fraction.

Some researchers have also reported improved fracture-resistance through a hybrid of steel and organic fibers, with the polypropylene/steel hybrid of Almusallam et al. [18] successfully reducing impact damage and fragmentation by inhibiting impact-induced crack propagation. Beppu et al. [19–23] have reported that increasing the tensile strength of concrete improves its penetration resistance and tends to prevent scabbing, but means that any scabbing that does occur is likely to cause brittle fracture. Contrary to this, however, a *polypropylene/steel hybrid exhibits both an* enhanced compressive toughness and flexural toughness, which inhibits the propagation of diagonal tension cracks, and reduces the depth and diameter of scabbing.

1.2. The purpose of research

In this study, a bundle-type polyamide fiber very different from conventional reinforcing organic fibers was developed with a view to improving the problems of inadequate dispersion often encountered when mixing with concrete. To this end, the fiber/matrix bonding strength and flexural behavior of fiber reinforced concrete was measured, and its behavior upon impact with a high-velocity projectile was assessed by measuring the penetration depth/diameter on the front side and scabbing depth/diameter on the rear. These values are compared against those of concrete reinforced with hooked-end steel fibers of the same length that are currently widely used in construction.

2. Materials and methods

2.1. Experimental fibers

As shown in Fig. 2(a), polyamide fiber was manufactured by air injection of 544 micro nylon fibers with 19.5 m-diameter to increase the area of fiber/matrix bonding interface, as manufactured by KOLON Co. of Korea. The polyamide fiber was 30 mm in length, 0.5 mm in diameter, with an aspect ratio of 60, tensile strength of 594 MPa, and density of 1.14 g/cm^3. Fig. 2(b) and (c) shows a schematic diagram and the air nozzle for producing polyamide fibers. The production mechanism is air interlacing of multi-filaments consisting of core yarns and effect yarns under high pressure. The yarn structure of the effect yarns forming a loop around the core yarns offers the advantages of less elongation, resistance against the tension-induced swelling reduction, and improved fiber/matrix bonding strength. As shown in the magnified image of polyamide fibers in Fig. 2(d), the interfiber gaps keep the fibers from intermingling during mixing with concrete, thus increasing the likelihood of improving the fiber/matrix interface bonding. Fig. 3 shows the improve flowability by surface coating of

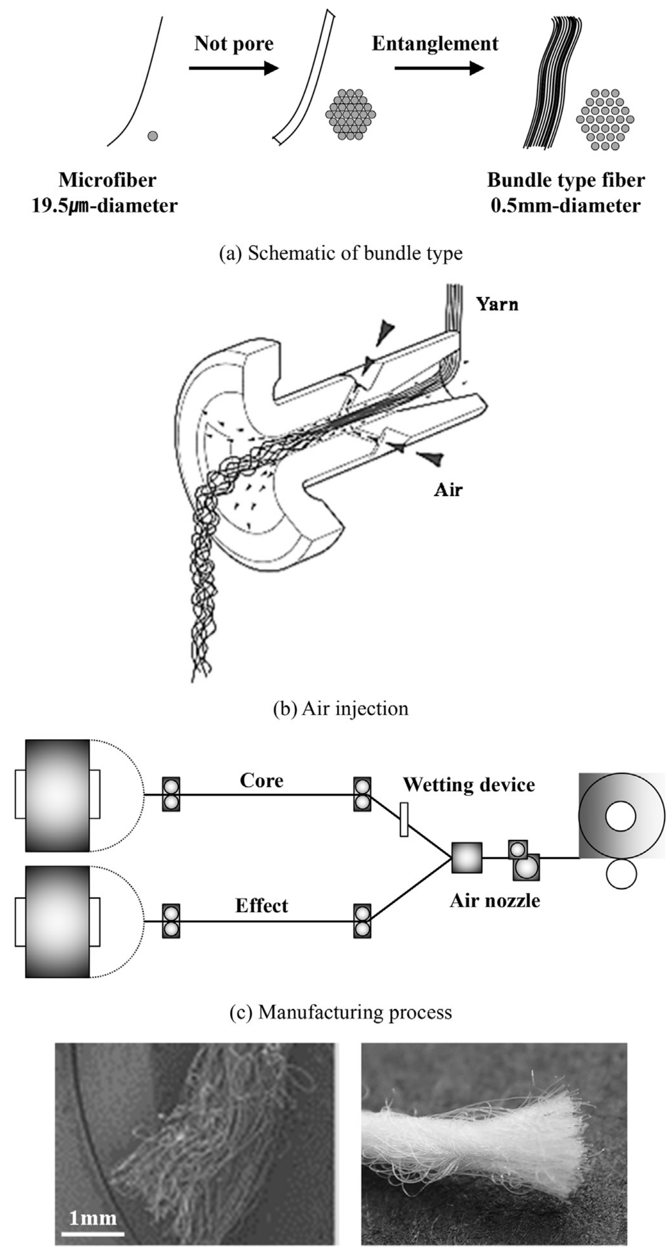

Fig. 2. Bundle type polyamide fiber.