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Splitting tensile and pullout behavior of synthetic wastes as fiber-reinforced concrete

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HIGHLIGHTS

- The ring-shaped PET fibers performed better as they are mainly designed to activate fiber yielding instead of fiber pullout compared to the irregularly shaped PET and waste wire fibers in concrete.
- The R-10 fibers, which have a width of 10 mm, present higher maximum pullout load compared to the R-5 and irregularly shaped PET fibers.
- The R-10 fibers exhibit an impressive pullout strength compared with those of the R-5 and waste wire fibers.
- A large surface contact area, the load energy required to debond the fiber from the concrete matrix is high.
- The surface contact area of fibers with concrete matrix allows good frictional resistance against pullout or tensile load.

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ABSTRACT

Plastic bottles and waste wires are the most commonly discarded synthetic wastes that contribute to environmental pollution. Polyethylene terephthalate (PET) bottles act as one of the contributors to environmental pollution. One solution to environmental pollution includes recycling plastic bottle wastes as synthetic fibers and incorporating them into concrete. Therefore, pullout strengths of synthetic fibers in a concrete matrix should be investigated by conducting splitting tensile and pullout tests. Experiments of the present study used fibers from ring-shaped PET bottles with widths of 5 and 10 mm. Irregularly shaped PET bottles with 10–15 mm size, waste wires measuring 55 mm in length, and manufactured synthetic macro-fibers were also used in comparative analysis. Results indicate that an increase in fiber volume improves tensile strength of concrete. Incorporation of high-volume fiber with concrete results in a substantial amount of fibers bridging and crossing fractured sections, thereby activating failure resistance mechanisms. In comparison with irregularly shaped PET and waste wire fibers, ring-shaped fibers performed better as they are mainly designed to activate fiber yielding instead of fiber pullout. The load energy required to debond fibers and the concrete matrix was high when the surface contact area was large in comparison with that when a small surface contact area was considered. Fibers with small surface contact area easily slip under tensile stress. Thus, the surface contact area of fibers with concrete matrix allows good frictional resistance against pullout or tensile load.

1. Introduction

The amount of synthetic plastic consumed annually have increased steadily. The intensifying synthetic plastic consumption can be ascribed to practical synthetic plastic features, namely, light plastic product and low production cost [1,2]. Synthetic plastic has been extensively used in food cases and water bottles, industrial applications, and communication materials and housing. Although several methods have been employed for disposal of synthetic wastes, most treatments are inadequate due to excessive synthetic waste generation. One of the solutions to this growing problem involves recycling synthetic wastes as fiber reinforcement for concrete. Synthetic fibers are popularly used in lightweight precast concrete elements, such as double wall, pipes, and sleepers [3–5]. These applications can effectively control and arrest crack growth and improve toughness [6] and dry shrinkage cracks of concrete [7]. Synthetic fibers improve brittle concretes to become tough materials with enhanced crack resistance and ductility [8]. Foti [9] studied the feasibility by using polyethylene terephthalate

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(PET) bottles as fibers to improve concrete ductility and observed that the average tensile strength of ring-shaped fibers with 5 mm width measured 180 MPa, which is sufficiently high and comparable with those of other fibers used to reinforce concrete.

Wan et al. [10] stated that fibers from different materials with similar embedded lengths and widths exhibit different behavior in pullout pattern strength. Juhász et al. [11] claimed that the length of the fiber has a major effect on its performance in fiber reinforced concrete. The length of the fiber was optimized with the help of the critical length (l_c), which is the maximum length where fibers are pulled-out from the matrix instead of rupturing. Juhász et al. [11] claimed that the length of the embossed surface, logically the longer the synthetic fibers the higher post-crack capacity. Therefore, pullout strength increases as embedded length of fibers increases [12,13]. Richardson et al. [14] noted that average pullout strength increased from 39% to 48% at embedded length range of 45 mm to 55 mm. Different embedded lengths of fibers present different behavior in forming pullout strength pattern. These differences are related to the surface fibers over the concrete surface and determined as surface friction and interfacial bond energy [15,16].

Ochi et al. [17] studied the tensile strength of manufactured polyvinyl alcohol (PVA), PET, and PP fibers (fiber length was fixed at 30 mm) with widths of 0.71, 0.75, and 1.21 mm, respectively. The concrete with PVA fibers possessed the highest tensile strength, whereas that with PET fibers yielded the lowest values [17]. Ochi et al. [17] claimed that PP fibers form a weak connection with concrete because of the smooth surface of fibers, such that sufficient friction between concrete and fibers is hindered [18]. Ochi et al. [17] also observed that the embedded length of fibers in concrete positively affected pullout behavior. Pullout strength of embedded length fibers from 19 mm to 38 mm increased from 39% to 68%. Compared with commercial plastic fibers, PET fibers exhibit adequate tensile strength. The surface contact area between fibers and concrete influences both pullout energy and interfacial energy [6,15]. Ochi et al. [17] claimed that large surface contact area between fiber and concrete areas result in high pullout energy. A study has been conducted with 0.4% content of PP fibers with lengths of 15, 20, and 24 mm [19]. Vikrant et al. [19] observed that average strength ranged from 1.1% to 4.2% for 15 mm to 24 mm embedded fiber lengths. Different fiber lengths lead to different strength values of fiber-reinforced concrete (FRC). A long fiber possesses a large surface area that is connected to the concrete matrix. Therefore, long-fiber concretes possess higher friction energy and interfacial bond strength than short-fiber ones. Thus, fiber surface area, which depends on fiber length, significantly influences strength. The increase in PET fiber content also increases strength. Irwan et al. [20] observed that concrete with 0.5% fiber content is stronger compared with normal concrete. Irwan et al. [20] also claimed that volume content of fiber is not the main primary parameter that improves the compressive strength of FRC. Instead, the shape and size of fibers serve as the primary parameters in FRC [6,21]. Ramadevi et al. reported that the compressive strength of concrete containing 2% waste PET as replacement and as fine aggregate materials increased compared with that of normal concrete [22]. Compared with normal concrete, concretes with 0.5% and 1% fiber contents exhibited 4.0% and 15.4% increase in strength, respectively. In durability resistance of fiber, most researchers stated that PP and HDPE fibers present high resistance to alkaline environment. Synthetic fibers are superior alternatives to steel fibers for preventing the negative effects of corrosion, alkaline reactions, acidic water, salt, chlorine, chemicals, and micro-organisms [23]. Synthetic fibers show no adverse effects on concrete containing PET fibers [23,24]. Alavi et al. [25] investigated the impact resistance of FRC by using PP fibers. Alavi et al. [25] discovered that an increase in fiber content increased the compressive strength of FRC. Long fibers feature high surface contact area and can function as fiber bridges during compression and tensile strength tests. Therefore, long fibers present high friction energy against pullout stress because of fiber-bridging mechanism. Foti [9] used waste PET bottles as recycled fiber materials and claimed that concrete strength rises with increasing fiber content. The lamellar fiber in concrete with 0.75% fiber content exhibited an increased compressive strength of 3% compared with the normal concrete with 0.5% fiber content. On the other hand, the concrete with 0.75% ring PET fiber content showed an increased compressive strength of 5% compared with the concrete containing 0.5% ring PET fibers [9]. Pelisser et al. [26] investigated recycled PET fibers with volume fractions of 0.18% and 0.3% in FRC and lengths of 10, 15, and 20 mm. These authors noted that adding recycled PET fibers incorporated with concrete resulted in improved toughness and better energy absorption of FRC under flexural load compared with normal concrete. Pelisser et al. [26] also claimed that an increase in fiber length increases the surface contact area in concrete matrix. Afterward, this increase will contribute to high flexural toughness indices of concrete, particularly in I_{10} and I_{20}. An investigation was conducted to demonstrate the pattern in flexural toughness with 0.5%, 1%, and 1.5% of fiber content [20]. Pereira [20] showed that the concrete with 1.5% fiber content increased flexural toughness I_{20} index by 22.4% and 5.7% compared with concretes with 0.5% and 1.0% fiber contents, respectively.

The study of Hasan et al. used three fiber content percentages (0.33%, 0.42%, and 0.51%) [27]. Strength of concretes with 0.42% and 0.51% fiber contents showed gradual improvements of 6.5% and 6.9%, respectively. On the other hand, the concrete with 0.33% fiber content showed an improvement of 4% compared with the normal concrete. In tensile strength, compared with the normal concrete, strength of concretes with 0.33% and 0.41% fiber contents increased by 10% and 15%, respectively. Hasan et al. [27] claimed that such increases are attributed to the fiber-bridging mechanism in concrete. Fibers in concrete consequently acted as load bridge during transfer when the concrete cracked. The concrete with 0.51% fiber content presented a decreased tensile strength because of poor concrete workability during mixing. Hasan et al. [27] discovered that high fiber content becomes a fiber balling problem and fails to achieve full compaction. Nili et al. reported that the concrete with 0.2% PP fiber showed a 3% increase in compressive strength, whereas that with 0.5% fiber content incurred a 14% increase [28]. Wan et al. [10] observed that concretes with 0.2%, 0.3%, and 0.5% fiber contents exhibited 15%, 20%, and 27% increases in tensile strength, respectively. The fibers in concrete effectively reduced the brittleness of specimens.

Wan et al. [10] claimed that adding fiber to concrete causes failure crack patterns to change from a single large crack to a group of narrow cracks. Cracks can be substituted by micro-cracks due to fiber-bridging in the concrete [29]. Therefore, synthetic fibers are always popularly used in lightweight concrete constructions, such as in pedestrians walk [23], lightweight wall precast [30], and shotcrete [31]. This study aimed to determine the performance of synthetic wastes, such as PET bottles and waste wires, in terms of tensile concrete strength and pullout strength. This study also considered manufactured synthetic macro-fibers (PP fiber) in comparative analysis and discussion.

2. Materials and methods

In this study, ordinary Portland cement Type I and class F fly ash were used. The superplasticizer used was Darex Super 20, which conforms to ASTM D638 [32]. Size of coarse aggregates reached 14 mm, whereas fine aggregates measured 5 mm. Water–binder ratio was 0.55. Waste PET bottles (Fig. 1) were also used in this