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Effects of the geometry of recycled PET fiber reinforcement on shrinkage cracking of cement-based composites

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Abstract

In this study, the reinforcing fibers were constructed with three different geometries, *i.e.*, embossed, straight, and crimped, from waste polyethylene terephthalate (PET) bottles and used them to control plastic shrinkage cracking in cement-based composites. Pullout tests evaluated how the fiber geometry and fraction by volume (0.1–1.00%) affected the rate of moisture loss and controlled the plastic shrinkage cracking characteristics. The fiber geometry and fraction by volume did not affect the total moisture loss or moisture loss per hour; the moisture loss per hour exceeded 0.5 $kg/m^2/h$ in 5 h after casting, causing plastic shrinkage cracking. However, increased fractions of recycled PET fiber resulted in improved control of the plastic shrinkage cracking. At a fraction of 0.25%, the plastic shrinkage was reduced, but no further improvements were observed when the fraction of fiber was increased to 0.5%. Fiber geometry also affected the control of plastic shrinkage cracking up to a fiber fraction of 0.25%.

Keywords: A. Fibres; A. Recycling; B. Mechanical properties; Shrinkage

1. Introduction

Plastic shrinkage cracking is a primary cause of reduced performance in cement-based composites [1–3]. In particular, wide surfaces such as bridge slabs or paving and parking lot floors are affected by restraint, high rates of evaporation, and high temperatures during the initial placing of cement-based composites, which can cause plastic shrinkage cracking before the cement-based composite has hardened completely [4–7]. Cracking can also occur after casting and before hardening if the temperature of the cement-based composite differs from the outside temperature [6,7]. If a cement-based composite were not restrained, no cracking would result from shrinkage due to moisture evaporation, but cement-based composite structures are usually restrained by a foundation or other structural factors such as steel reinforcements [8–10]. With shrinkage, the restraints cause tensile stress within the cement-based composite, and cracks appear when this tensile stress exceeds the tensile strength of the cement-based composite [11–14]. Randomly dispersed steel, synthetic, or natural fibers within a cement-based composite can be effective in controlling plastic shrinkage cracking [1–3,15,16]. These fibers produce a bridging force across the width of a crack and prevent its propagation [1,2]. Namaan [17] found that the addition of a minimum of 0.2% (V_f) polyvinyl alcohol (PVA) fiber to the mixture was effective at reducing plastic shrinkage cracking; Qi [15] found that 0.3% (V_f) monopolypropylene was effective at reducing settlement and the amount of moisture evaporation and controlling plastic shrinkage cracking. Najm and Balaguru [16] found that adding polyolefin fiber to cement-based composites was more effective at controlling cracks than adding steel fiber, whereas Wang [4] showed that adding 0.1% (V_f) PVA fiber to cement-based composite reduced plastic shrinkage cracking. In addition, Najm and Balaguru [16]

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found that polyolefin fibers with thicker diameters were more effective at controlling plastic shrinkage cracking than polypropylene fibers with microscopic diameters. Thus, the addition of reinforcing fibers to cement-based composites is a very effective way to control plastic shrinkage cracking.

Polyethylene terephthalate (PET) is a plastic material widely used in beverage containers and other products. However, PET can cause environmental damage if it is not disposed of properly, and research on the recycling of PET bottles has indicated that the process can cause considerable environmental and economic problems [18]. Constructing reinforcing fibers from waste PET bottles to control plastic shrinkage cracking in cement-based composites is an effective way to reuse the bottles. Because the bottles are plastic, they have many limitations and disadvantages. The characteristics and low surface energy of plastic materials result in a poor mechanical bond with the cement-based composite [19]. Low mechanical bond strengths may not provide sufficient bridging force to control crack development [19–23]. Poor mechanical bond strength may also cause internal micro-cracks in the interfacial mechanical bond area between a fiber and the cement matrix [22,23]. One effective way to increase the mechanical bond strength of fibers with low surface energy is to change the fiber geometry and surface [19]. Therefore, this study evaluated the mechanical bond behavior and characteristics of plastic shrinkage cracking control for a variety of surface geometries of reinforcing fibers made from waste PET bottles. Fibers were formed into three geometric patterns and added to cement-based composite in five different fractions by volume.

2. Experiment

2.1. Manufacturing of fibers from waste PET bottles

Reinforcing fibers were constructed from waste PET bottles that were melted and formed into a roll-type sheet. This sheet was then slit into pieces 0.5 mm thick and 1 mm wide, and a deforming machine was used to change the geometry of each piece (Fig. 1). Finally, the fibers were cut into 50-mm strips. Three fiber geometries were evaluated with the goal of improving the mechanical bond strength of the reinforcing fibers: straight, crimped, and embossed (Fig. 2).

2.2. Pullout test methods

Dumbbell-shaped specimens were used to evaluate the mechanical bond performance resulting from changes in the geometry of the recycled PET fibers. The cement-based composite mix proportions by weight of cement was 0.5:1:1.7 (water:cement:sand). Bond test specimens were prepared using the JCI SF-8 standard (Fig. 3). The test specimens were placed in a universal testing machine (Instron model No. 3369) for the bond test (Fig. 4). The bond tests were carried out under displacement control at a crosshead speed of 0.5 mm/min. The mechanical bond strength of the reinforcing fibers was calculated using the following equation:

$$\tau_{\max} = \frac{P_{\max}}{2(b+h)l} \tag{1}$$

where $\tau_{\max}$ is the maximum mechanical bond strength, $P_{\max}$ is the maximum pullout load, b is the fiber width, h is the fiber thickness, and l is the embedded fiber length.

2.3. Plastic shrinkage cracking test plan and method

Plastic shrinkage cracking tests were conducted for the various fiber geometries and fiber fractions by volume. The mix proportion by weight of cement was 0.55:1:2 (water:cement:sand). Table 1 indicates the mix ratios of the cement-based composites used in the plastic shrinkage cracking tests.

Cracks occur in a cement-based composite as it shrinks with moisture evaporation, so moisture evaporation is a very important factor in construction [1,2,24,25]. The first 24 h after casting are especially important, and many stud-

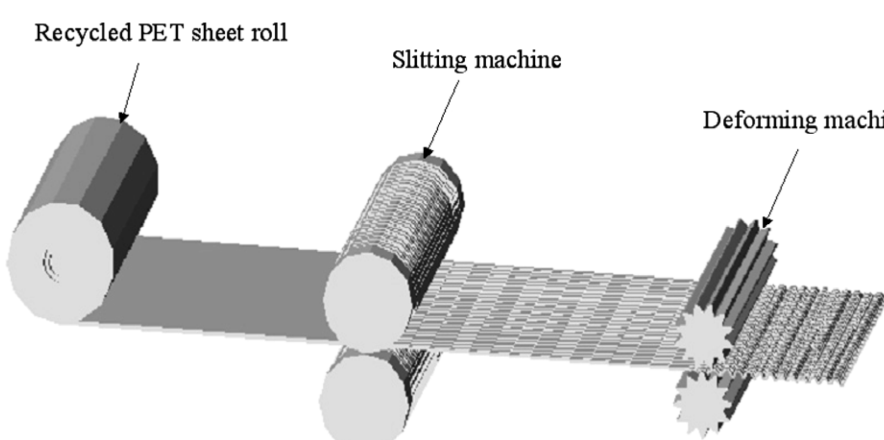


Fig. 1. Process used to manufacturing fibers from recycled PET bottles.

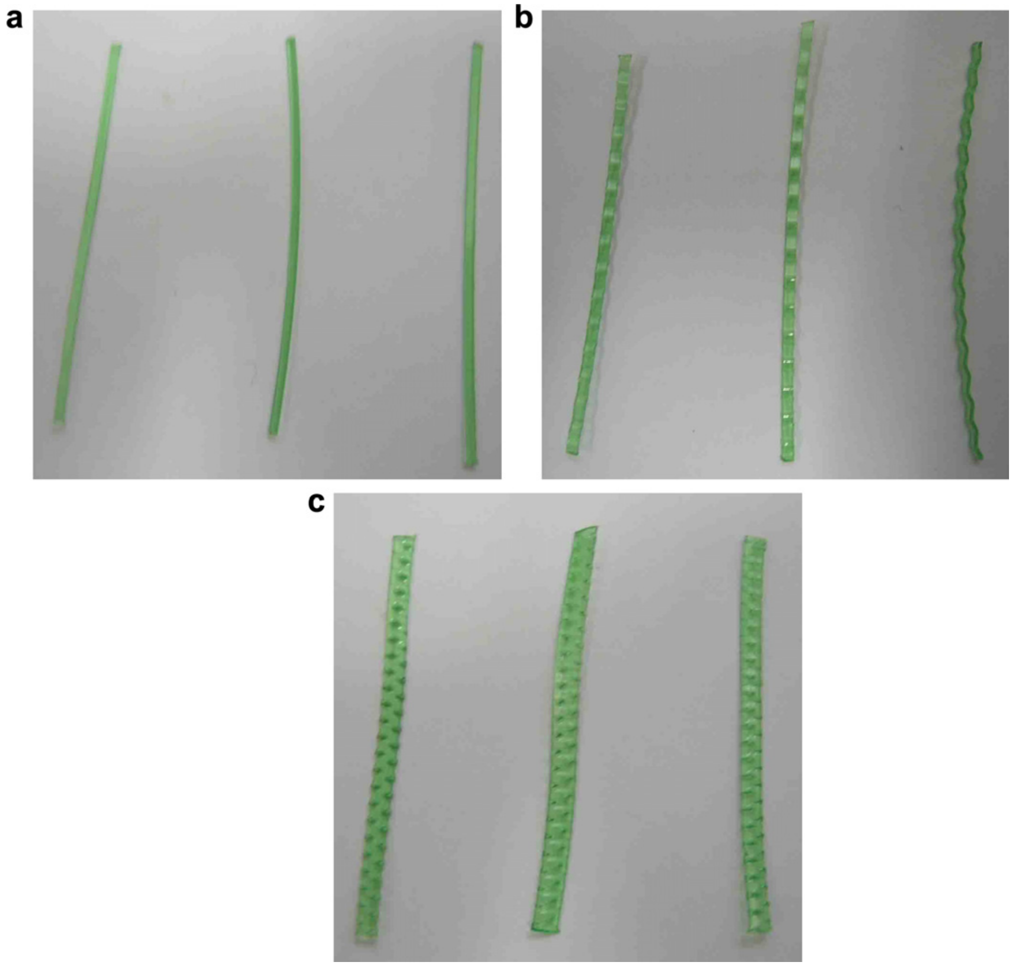


Fig. 2. Geometry of the recycled PET fibers. (a) Straight type (0.5 mm × 1 mm × 50 mm), (b) crimped type (0.3 mm × 1.2 mm × 50 mm), and (c) embossed type (0.2 mm × 1.3 mm × 50 mm).

ies have evaluated the effects of reinforcing fibers on moisture evaporation from cement-based composites during this period [1,2,10,22]. Moisture in hydrated cement paste may be classified into three types: free water, chemically combined water, and gel water [22]. Free water is held in capillary pores and is outside the range of the surface forces of solid particles. By contrast, chemically combined water is the water needed for chemical hydration. The gel water is held in various ways such as by the surface forces of gel particles (called adsorbed water) or between the surfaces of C–S–H sheets (called interlayer water) [22]. Generally, evaporable water is the free water that is neither held nor combined by chemical bonds [22]. Therefore, understanding how reinforcing fibers control plastic shrinkage cracking requires the evaluation of how the reinforcing fibers affect the evaporation of free water [22]. We used a cylinder-type evaporation mold to measure evaporation rates. The cylinder mold had a diameter of 20.3 cm and a height of 3.5 cm. It was constructed from stainless steel to prevent absorption and evaporation of moisture anywhere other than at the surface. The plastic shrinkage cracking test was carried out using the method of Kraai [6]. The mold used in the test was a 900 × 600 × 150 mm panel (Fig. 5). The test presented a restraining condition at 100-mm intervals to create tensile strength around the circumference. A mixed mortar was placed in the mold; after casting it was kept in a controlled environment at a temperature of 28 ± 2 °C, a humidity of 40 ± 3%, and wind speed of 6 m/s. It was monitored for 24 h, during which time visible cracks appeared. The total visible crack area is defined as the sum of the product of the visible crack length times the crack width [22]

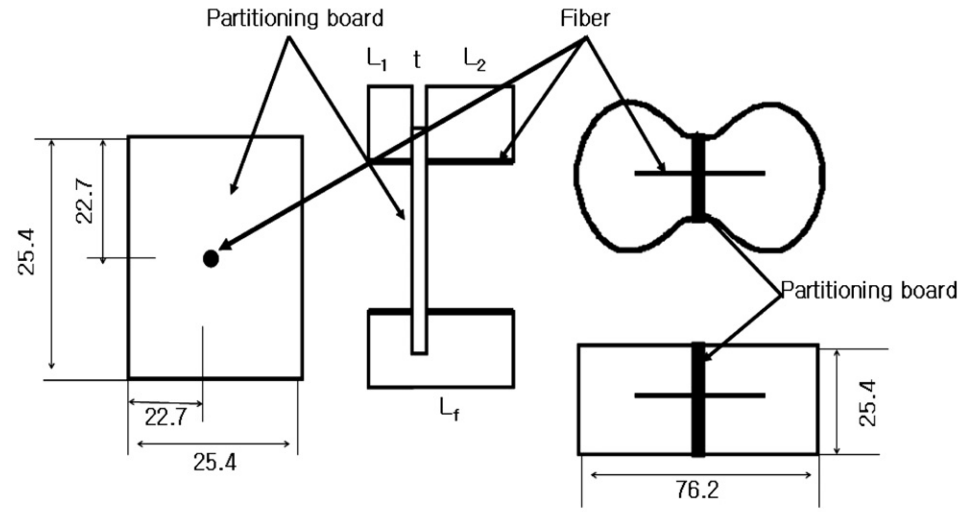
$$\text{Total crack area} = \sum_{i}^{n} (L_i W_i) \qquad (2)$$

where W_i is the width of a crack, L_i is the length of a crack, and n is the number of cracks.

3. Results

3.1. Pullout performance of recycled PET fiber according to geometry

The mechanical bond strength between a fiber and the matrix plays an important role in the control of plastic



L_1: embeddment length (20 mm)

L_2: anchored length (20 mm)

L_f: fiber length (50 mm)

t: thickness of the partitioning board (0.5 mm)

Fig. 3. Arrangement of the partitioning board and fibers, and setting in the mold (unit: mm).

shrinkage cracking in cement-based composites. In the mechanical bond test for the various geometries of recycled PET fiber (Fig. 6), the strength of the embossed fiber was vastly superior to the other types; its mechanical bond strength was about 5 MPa, whereas those of the crimped and straight types were 3.9 and 1.7 MPa, respectively. This was because of the greatly increased surface energy of the fiber due to the friction resistance during pullout of the embossed area bonded to the cement-based composite. In addition, with the crimped fiber, the crimped part of the fiber surface was observed to stretch fully during the pullout test. The stretching of the crimped fiber leads to a rapid increase in displacement. Therefore, the initial stiffness of the crimped fiber was lower than that of the other fibers.

The fiber surface was examined after the pullout test to analyze the frictional resistant force according to fiber shape during the pullout process using recycled PET fiber. Electron microscopy at a magnification of 1000× was used for the observations. Compared to the other PET fiber shapes before the pullout test (Fig. 7a), the straight fiber had no significant difference in scratching, other than the presence of small amounts of cement matrix (Fig. 7b).

Fig. 4. Pullout test set-up.

Table 1
Mix proportions of the mortar used for the plastic shrinkage test

Fiber geometry	Water/cement ratio	Cement:fine aggregate	Fiber volume fraction (%)
Plain	0.55	1:2	0.00
Straight			0.10
			0.25
			0.50
			0.75
			1.00
Crimped			0.10
			0.25
			0.50
			0.75
			1.00
Embossed			0.10
			0.25
			0.50
			0.75
			1.00

Fig. 5. Apparatus used for the mortar plastic shrinkage test.

The straight fiber had almost no scratching on the surface because of its low surface area and low friction resistance.

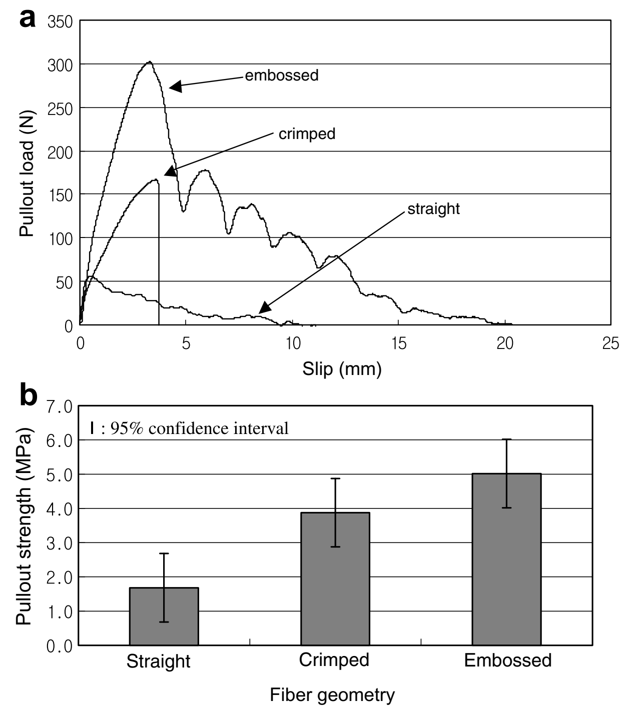


Fig. 6. Mechanical bond performance of the recycled PET fibers according to geometry. (a) Pullout behavior and (b) mechanical bond strength.

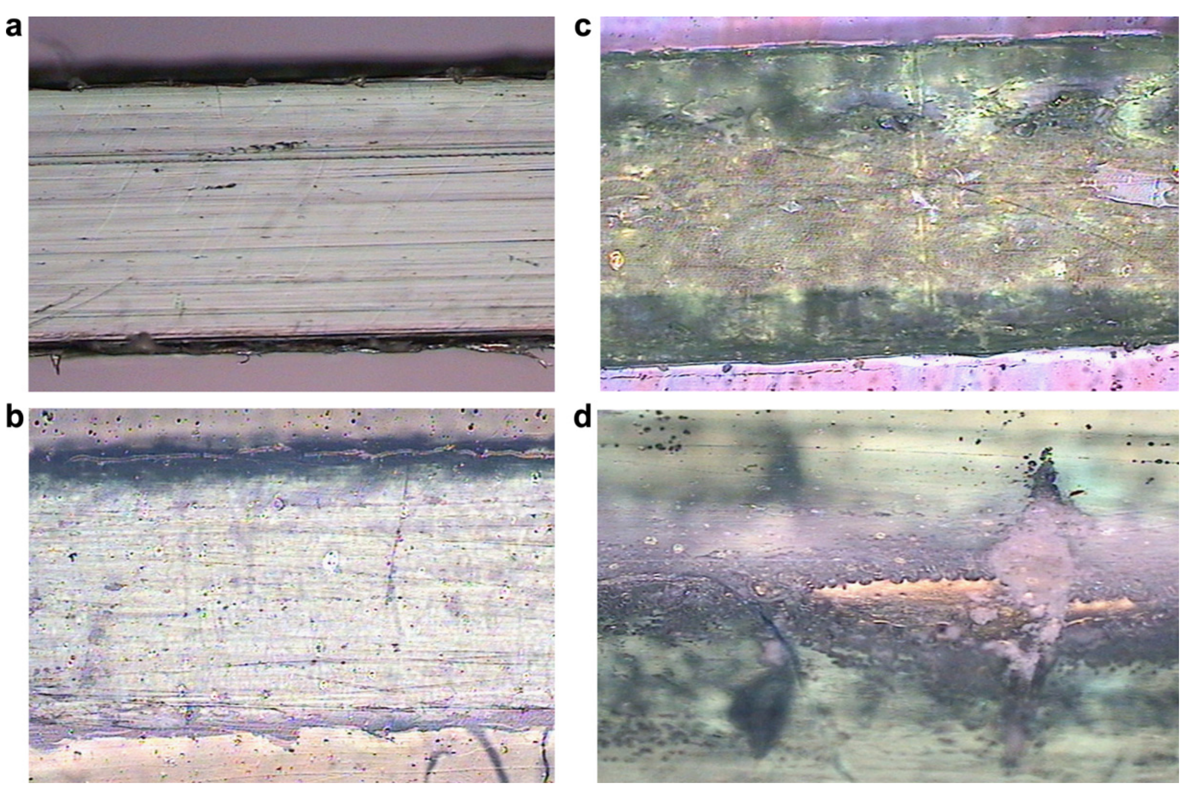


Fig. 7. Surface pattern of the PET fibers after the pullout test. (a) Control, (b) straight, (c) crimped type and (d) embossed type.

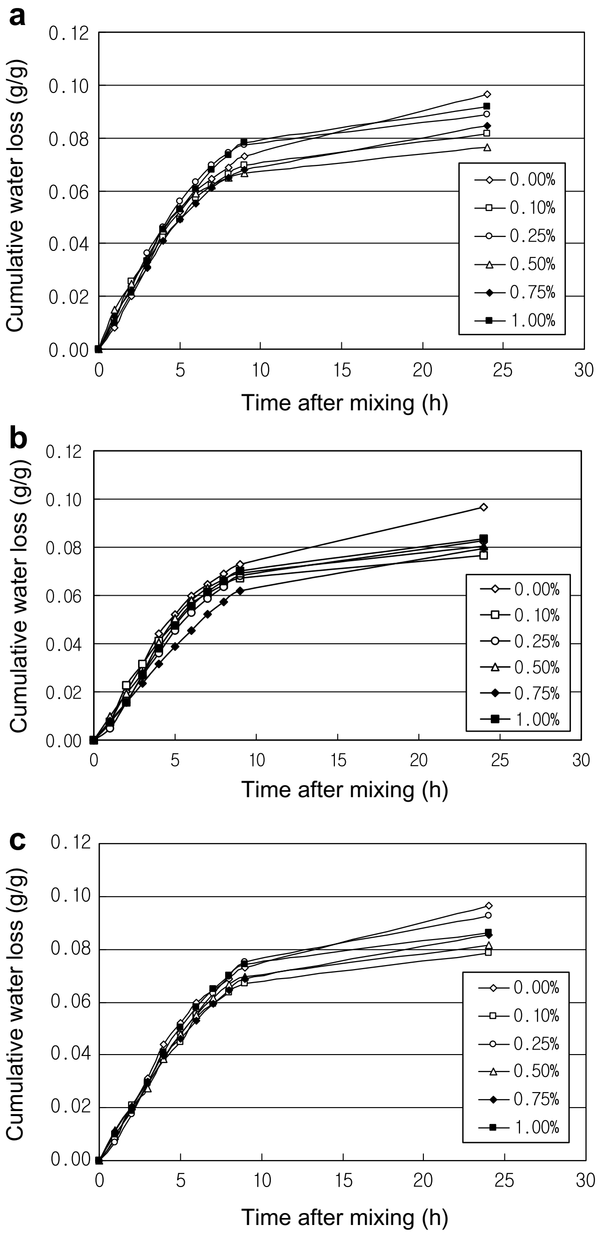


Fig. 8. Comparison of the cumulative water loss due to evaporation with fiber geometry and fraction by volume. (a) Straight type, (b) crimped type and (c) embossed type.

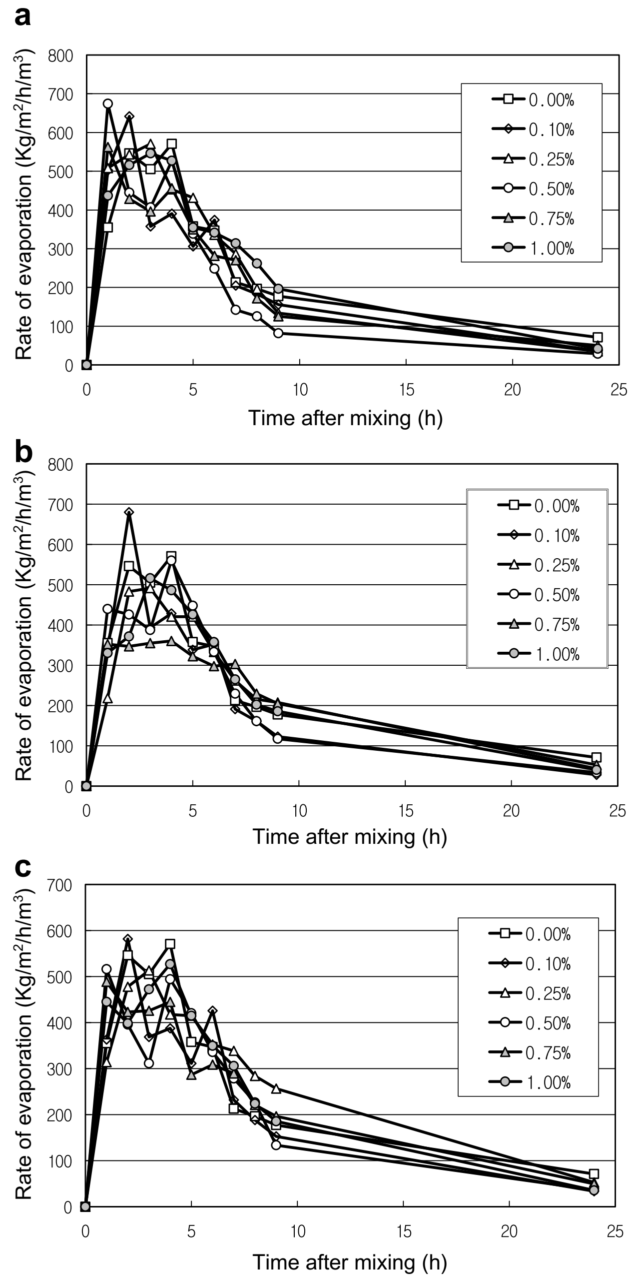


Fig. 9. Rate of evaporation of cement-based composites according to fiber geometry and fraction by volume. (a) Straight type, (b) crimped type and (c) embossed type.

The surface of the embossed fiber was scratched, and the embossed area was ripped out (Fig. 7d). The crimped area of the crimped fiber was laid open (Fig. 7c). In this fiber, the bond was strengthened as a result of a mechanical anchorage effect in the crimped area, but the fact that the crimped area was laid open indicates that the strength was insufficient. Therefore, its mechanical bond strength was lower than that of the embossed type; its mechanical bond strength increased continuously as the crimp was opened, but stopped once it was completely opened. Moreover, the crimped area was relatively weaker than the other areas because of production procedures and was partially destroyed during testing. The addition of a reinforcing fiber to cement-based composites prevents crack development because the fibers are positioned across the cracks. That is, the increased bonds in fiber-reinforced cement-based composite are effective at controlling plastic shrinkage cracking. Therefore, the superior mechanical bond of the embossed fiber likely makes it more effective at controlling cracks than other fiber structures.

3.2. Water loss from evaporation based on fiber geometry and fraction by volume

Because the recycled PET fiber is a hydrophobic polymer that absorbs very little water, any water absorption by the

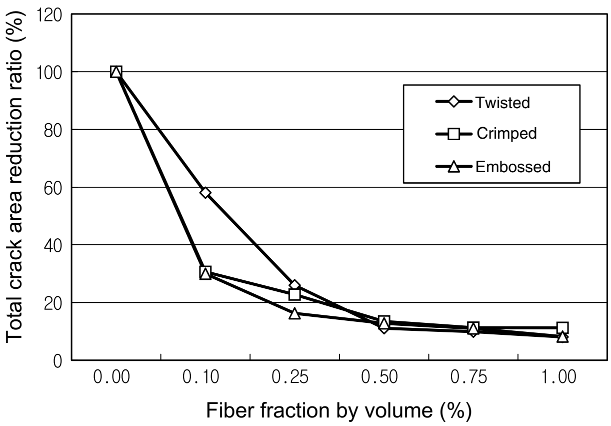


Fig. 10. Total reduction in the area cracked according to fiber geometry and fraction by volume.

Table 2
Total area cracked (units: mm^2)

Fiber geometry	Fiber volume fraction (%)					
	0.00	0.10	0.25	0.50	0.75	1.00
Control	3525					
Straight	–	2047	916.5	390	350	285
Crimped	–	1079	803	475	397.5	395
Embossed	–	1056	573	451.5	388	289

recycled PET fiber was ignored. In addition, all moisture loss was assumed to result from evaporation from the recycled PET fiber-reinforced cement-based composites. The loss of moisture via evaporation is quite rapid during the first 6 or 7 h after casting a cement-based composite, but slows greatly afterwards. There were no clear effects of fiber

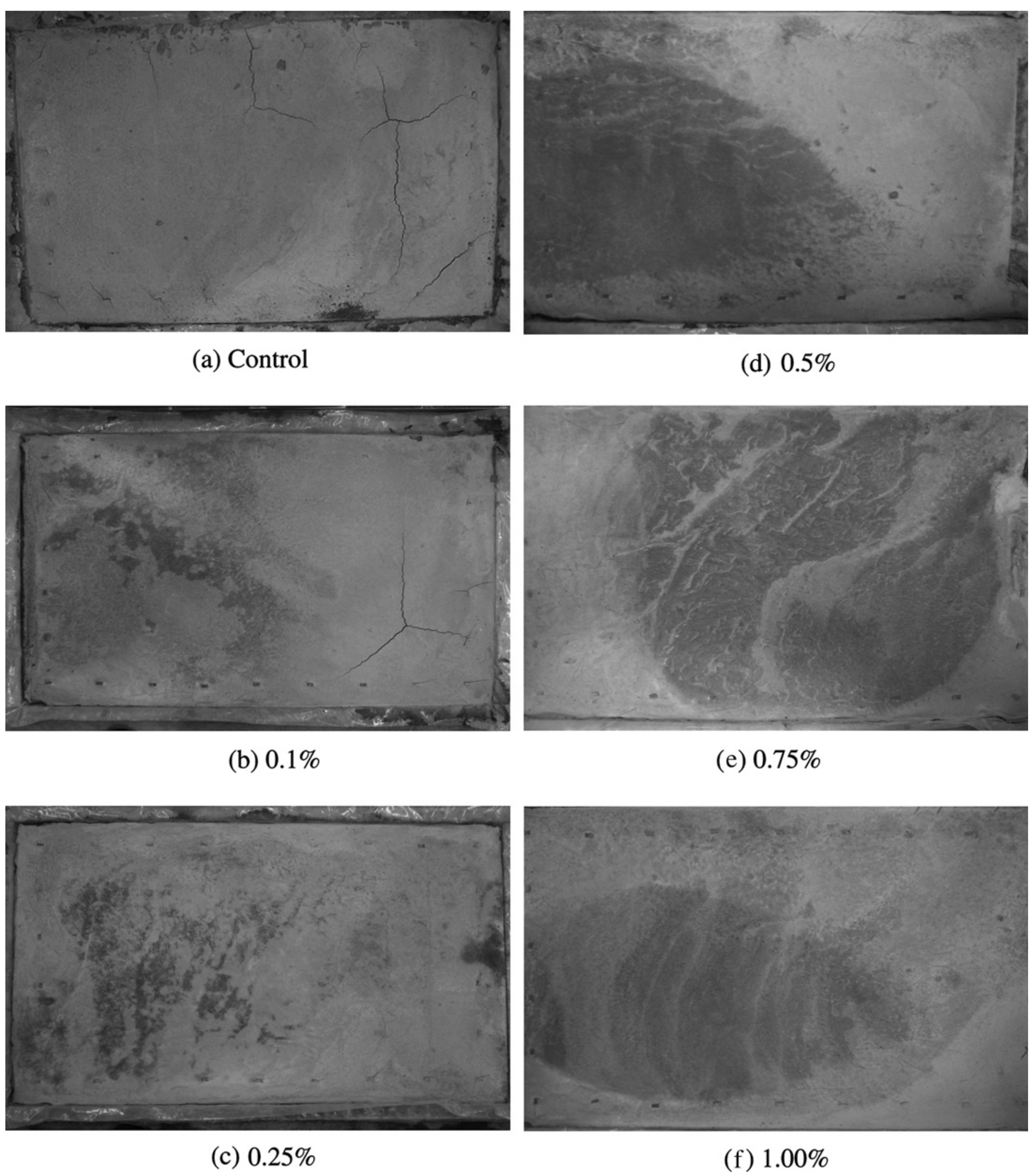


Fig. 11. Crack pattern of the embossed fiber-reinforced cement composites according to the fiber fraction by volume. (a) Control, (b) 0.1%, (c) 0.25%, (d) 0.5%, (e) 0.75% and (f) 1.00%.

geometry or fraction by volume on the evaporation rate (Fig. 8). Generally, if the moisture evaporation rate exceeds 0.5 kg/m^2/h, it causes negative capillary pressure inside the cement-based composite, resulting in internal compressive strain [13]. If the cement-based composite is restrained, this compressive strain can result in tensile strength sufficient to cause cracks during the initial stages, when adequate strength has not yet developed. Therefore, if the rate of moisture evaporation exceeds 0.5 kg/m^2/h, it results in a high possibility of plastic shrinkage cracking [13,22]. In all tests, the moisture evaporation exceeded 0.5 kg/m^2/h within 5 h of casting, regardless of the fiber geometry or fraction by volume (Fig. 9). Therefore, plastic shrinkage cracking is likely to occur within 5 h of casting. The different fiber geometries and fractions by volume had no clear effects on the rate of moisture evaporation.

3.3. Plastic shrinkage cracking

We examined the characteristics of plastic shrinkage crack control according to fiber geometry and fraction by volume (Fig. 10 and Table 2). Plastic shrinkage cracking occurred in all the testing programs because the hourly rate of moisture evaporation exceeded the limits for its occurrence. When fibers comprised 0.5% of the mix, all the fiber geometries had a significant ability to control plastic shrinkage cracking, but little improvement was observed beyond this level. In contrast to the moisture evaporation rates, the fiber geometry and fractions by volume up to 0.25% affected plastic shrinkage cracking. The embossed fiber, which had the greatest mechanical bond strength, had the best ability to control plastic shrinkage cracking. Therefore, it appears that when all other variables are equal (e.g., fiber quantity, length, aspect ratio), the fiber geometry, *i.e.*, the mechanical bond strength, affects plastic shrinkage cracking in cement-based composites. However, once the fraction of fiber volume exceeds 0.5%, a sufficient number of fibers are incorporated to control plastic shrinkage cracking, so the fiber geometry had no further effect. The plastic shrinkage cracking pattern occurred during all of the testing programs until the fiber volume fraction exceeded 0.5%; however, when it exceeded 0.5%, the occurrence was limited to areas where the composite was restrained (Fig. 11). This tendency applied to all fiber geometries.

4. Conclusions

This study examined how plastic shrinkage cracking depends on fiber geometry and fraction by volume to investigate the use of waste PET bottles as reinforcing fibers to control plastic shrinkage cracking in cement-based composites. The test results yielded four major conclusions. First, the fiber geometry and fraction by volume did not significantly affect the rate of moisture evaporation during the initial stages of casting, when the control of plastic shrinkage has the greatest effect. Rapid moisture loss occurred within 6–7 h after pouring, but was subsequently much slower. Second, the fraction of fiber volume affected the control of plastic shrinkage cracking regardless of the fiber geometry. In particular, relatively low fiber fractions of up to 0.25% by volume had a significant ability to control plastic shrinkage cracking, whereas fiber fractions greater than 0.5% had almost identical characteristics regardless of fiber geometry. Third, the fiber geometry, *i.e.*, the mechanical bond strength, affected the control of plastic shrinkage cracking at relatively low fiber fractions by volume, up to 0.25%. Therefore, the embossed type fiber, which had superior mechanical bond strength, also conferred the best resistance to plastic shrinkage cracking. Fourth, the occurrence pattern of plastic shrinkage cracking revealed that a 0.1% fraction of fiber by volume resulted in cracks throughout the surface, but when the fraction exceeded 0.25%, plastic shrinkage cracking was concentrated in areas that were restrained.

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