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Optimal dimension of arch-type steel fibre-reinforced cementitious composite for shotcrete

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ABSTRACT

In this study, the optimal dimension of arch-type steel fibre for cementitious shotcrete was derived based on the bond properties with a cement matrix, as a function of the length of the steel wire, the radius of curvature of the arch, and bend length at the fibre end. Our results indicated that a smaller radius of curvature of the arch-type steel fibre was able to withstand a higher maximum load, without fibre fracture or pullout. Pullout was evident for a larger radius of curvature of the fibre; however, fibre fracture was not observed. Additionally, the arch-type steel fibre end with a longer bend length showed excellent bond properties and pullout behaviour as the radius of curvature increased, due to stable anchoring within the cementitious composite. Statistical analysis of the experimental results indicated that the steel wire length had no effect on the bond properties of the fibre; also, a bend length >2.0 mm was identified as optimal for a radius of curvature of 20 mm. Our optimised fibre configuration was compared with a 35-mm hooked-end-type steel fibre, which is commonly used as reinforcing material in shotcrete.

1. Introduction

Fibre-reinforced shotcrete has been used as reinforcing material for ground stability for several years, especially for hard rock ground; however, there is no perfect substitution [1]. Recent tunnel design trends have attempted to increase the service life of structures by optimizing the ductility of fibre-reinforced shotcrete, as ductility restrains brittle fracture by load redistribution upon the occurrence of ground movement (the source of localised crack formation) [2].

Steel fibre is used in fibre-reinforced shotcrete, among other fibre materials, to enhance ductility [3,4]; the ability to improve ductility depends on the size, shape, and volume fraction of the fibre, with fibre networks providing optimal performance [3]. Studies have shown that the length of the fibre should be a minimum of 3× the size of coarse aggregate; additionally, smaller-diameter steel fibre can be used at a higher density to provide the required fibres per unit weight to improve reinforcement [3,4]. Steel fibre reinforcement applied as described provides ductility to shotcrete by transferring tensile strength, via the bridging effect, through the fibre network after crack occurrence under loading, ground disturbances, and other effects [4–6].

The quantitative expression of fibre bridging via the fibre network is toughness; toughness is determined by the pullout behaviour of fibre from the fibre-cement matrix. The pullout behaviour of fibre is defined by its bond properties with the cement matrix [5,6]. In general, the pullout behaviour of fibre can be improved by transforming the fibre shape and increasing the specific surface area in contact with the cement matrix [4,7,8], thereby enhancing the efficiency of fibre load transfer with crack occurrence by changing the fibre spacing via fibre orientation [9]. The orientation factor of fibre is a quantitative expression of the fibre dispersion level and can be different depending on the fibre's diameter, length, shape, volume fraction, and mix proportion in cementitious composite, as well as the application method [9,10]. In a previous study, transforming the steel fibre shape to an arch-type (i.e. changing the orientation factor) improved bonding 1.5-fold [7]. In addition, evaluation of the flexural properties of fibre reinforced concrete with arch-type steel fibre demonstrated an equivalent flexural strength increase of 6.8–25.8%, in a comparison to hooked-end-type steel fibre applied with the same volume fraction [11]. Accordingly, compared with hooked-end-type steel fibre, even if a lower volume fraction of arch-type steel fibre is used in shotcrete, it is expected that equivalent performance can be secured while improving fibre dispersion (i.e. fibre-balling prevention) and economic feasibility.

In this study, we attempted to optimise the dimensions of arch-type steel fibre to improve the load transfer efficiency of shotcrete.

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Our optimised fibre configuration was then compared with 35-mm hooked-end-type steel fibre, which is commonly used as a shotcrete reinforcing material.

2. Materials and mix proportion

2.1. Arch-type steel fibre

When hooked-end-type steel fibre debonds from cementitious composite, the pullout resistance load is indicated by the frictional resistance between the cementitious composite and bent fibre ends following pullout along the duct; additional anchoring behaviour is not a factor in this case. On the other hand, arch-type steel fibre enhances the bond properties with the cement matrix by simultaneously providing frictional resistance force and mechanical anchoring, as the entire fibre has an arch-shaped curvature even after the bend sections of both ends [7]. Thus, to determine the optimum dimension of arch-type steel fibre with a short length, we set the steel wire length (L) to make the fibre, the radius of curvature of the arch (R), and the anchorage part of the bend length of both ends of the fibre (l_e) as variables in this study. Pullout tests were also conducted on a conventional 35-mm hooked-end-type fibre of the same tensile strength and diameter as a comparison.

The experimental variables applied to the evaluation of the bond properties of arch-type steel fibre in this study are listed in Table 1. Test specimens were identified by length of the steel wire (L), steel fibre type (A: arch-type; H: hooked-end-type), radius of curvature (R), and bend length (l_e) in sequence. For example, 30A10_1.5 refers to a 30-mm-long arch-type steel fibre, with a 10-mm radius of curvature and bend length of 1.5 mm. The arch-type wire lengths tested were 30 and 35 mm; the radius of curvature values tested for these wire lengths were as follows: 10, 15, 20, 30, and 35 mm, with bend lengths of 0, 1.5, 2.0, and 2.5 mm.

2.2. Mix proportion

For the pullout test, cementitious composites were made to a target compressive strength of 30 MPa. Type I cement (specific gravity: 3.15) was used. Crushed sand (specific gravity: 2.62; fineness modulus: 3.07) was used as the fine aggregate in this study. The mix proportion was as follows for the cement, sand, and water: C:S:W = 1:2.5:0.6; this proportion was based on the cement weight.

3. Experimental

3.1. Compressive strength of the cementitious composites

Three specimens (dimensions: 50 × 50 × 50 mm) were tested in duplicate. The specimens were cured at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5%, and then demoulded. The compressive strength was measured after curing for 28 days in a water tank maintained at 23 ± 2 °C.

3.2. Bond properties

The bond properties of arch-type steel fibre were evaluated according to JCI SF-8 ("Method of Test for Bond of Fibres") [12]. Steel fibre was centrally anchored after dividing a dog-bone-shaped specimen into two parts, as shown in Fig. 1. The specimens were cured at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5% and then demoulded. The pullout test was performed in duplicate after the specimens were cured for 28 days in a water tank maintained at 23 ± 2 °C. The specimens were tested under a 0.5 mm/min load using a universal testing machine (UTM) (model 3369, Instron®, Norwood, MA, USA), with 5-kN capacity by displacement control.

Pullout tests were conducted to determine the maximum pullout load and interfacial toughness with variations in the dimensions and configuration of steel fibre embedded in shotcrete. The interfacial toughness, which indicates the energy absorption capacity under tensile forces applied to the cementitious composite, can be determined from the area under the pullout load–slip curve. For the arch-type steel fibre used in this study, 30-mm and 35-mm wire lengths were used to make the fibre. Thus, the fibre length differs depending on the radius of curvature of the arch part and bend length of both ends. We fixed the gap between the two sides of the dog-bone-shaped specimen as 5 mm. Interfacial toughness was calculated for up to 5 and 10 mm of embedded arch-type steel fibre slip.

4. Results and discussion

4.1. Compressive strength of the cementitious composites

The cementitious composites had an average compressive strength of 34.2 MPa at an age of 28 days. This fulfilled the compressive strength requirement.

4.2. Pullout load-slip behaviour of arch-type steel fibre

Figs. 2 and 3 show the pullout load–slip curve of arch-type steel fibre as a function of the radius of curvature and bend length, for the 30-mm and 35-mm steel fibre lengths, respectively. First, for arch-type steel fibre using a 30-mm steel wire length (30AR_l_e), pullout without fibre fracture was indicated in all specimens. For the rest of the steel fibres, excluding those with a radius of curvature (R) of 10 mm, the maximum pullout load increased further with the bend length (l_e). Additionally, the pullout behaviour was stable, in that as the radius of curvature increased, the slip approaching maximum pullout load increased as well. However, for the 30A35_l_e arch-type steel fibre, the radius of curvature was larger than the fibre length; thus, the fibre shape was nearly a straight line. Accordingly, the fracture mode (Fig. 2(f)) was pullout, but as the frictional resistance of the arch part is not valid after the bend length, the lower limit of the maximum pullout load was assigned.

For arch-type steel fibre using a steel wire length 35 mm (35AR_l_e), specific tendencies of fibre behaviour with respect to the bend length could not be resolved, unlike that for the 30-mm-long arch-type steel fibre (30AR_l_e); also, fibre fracture was observed in the 35A10_1.5 and 35A10_2.0 samples, which had the smallest radius of curvature. However, the rest of the 35-mm-samples exhibited stable pullout behaviour compared with the 30-mm arch-type steel fibre (30AR_l_e). In particular, for a

Table 1
Pullout test variables.

Steel fibre type	Tensile strength (MPa)	Fibre length (L, mm)	Radius of curvature (R, mm)	Bend length, (l_e, mm)
Arch-type (A)	1300	30 35	10, 15, 20, 30, 35	0, 1.5, 2.0, 2.5
Hooked-end-type (H)		35	–	–