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Effects of ageing and storage conditions on the interfacial bond strength of steel fibers in mortars

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HIGHLIGHTS

- The bond strength of steel fibers in mortars, stored in air, increased until 120 days.
- The bond strength of steel fibers in mortar, if stored in water or seawater, decreased at 120 days.
- GGBS significantly increased the bond strength of steel fibers in mortar.

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ABSTRACT

The ageing effects on the interfacial bond strength of steel fibers in cement mortars, under different storage conditions, were investigated by performing single fiber pullout tests. The bond strength rapidly increased until the 28 days water curing. After the water curing, the bond strength still monotonically increased if specimens were stored in air whereas it decreased if they were stored in water or 3.5% sodium chloride solution at the 120 days of age. The bond strength of fiber-mortars if they were stored in 3.5% sodium chloride solution was the lowest. Moreover, the addition of ground granulated blast-furnace slag in mortars, regardless of storage conditions, notably increased the bond strength.

1. Introduction

Steel-fiber-reinforced concretes (SFRCs) have been widely used in civil infrastructures such as airport runways, tunnel shotcrete, and concrete bridge decks, even those subject to severe conditions [1]. A potential application of SFRCs would be in offshore structures such as concrete caissons, concrete deep-water structures (condeep), and offshore windmill substructures. Furthermore, water-retaining structures that are designed to be impermeable such as water tanks and major dams are expected to be suitable applications of SFRCs [1,2].

However, offshore concrete structures or water retaining structures are exposed to different conditions, e.g., in seawater, pure water, and air, according to their locations and/or the positions in the structures during their service life. The long-term effects of exposure to various conditions on the performance of SFRCs, especially under harsh marine environments, need to be understood.

The performance of SFRCs, especially crack resistance under tensile and flexural loads, strongly depends upon the interfacial bond strength between the fiber and matrix [3,4]. Many researchers have investigated the influencing factors on the interfacial bond strength of fiber-matrix: matrix composition [5–15], fiber characteristics [6–9,11,14,16,17], and interfacial transition zone (ITZ) of the matrix surrounding fiber [8,12,18,19]. However, it is still difficult to find any direct information regarding the effects of ageing and storage conditions, especially the effect of ageing in seawater storage condition on the bond strength. Chan et al. [11] investigated the effect of ageing from 0.5 to 28 days on the bond strength of polyethylene (PE) fiber in plain and silica fume matrixes under moisture curing. They reported that the friction bond strength developed with age up to 28 days and pullout out load versus slip curves gradually changed from a slip softening to a slip hardening behavior. Jewell et al. [14] reported about the effect of ageing from 1 to 56 days on the bond strength of steel, polyvinyl alcohol (PVA), and polypropylene (PP) fibers embedded in the ordinary portland

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cement (OPC) and the calcium sulfoaluminate (CSA) cement in humid and temperature controlled condition. The pullout strength of steel fibers embedded in the matrices decreased at 56 days of age. However, Gray et al. [13] reported that the interfacial bond strength increased until 90 days as the specimens were stored in water and fog room curing conditions. Beglarigale et al. [20] reported that the maximum pullout load of steel fibers-matrix increased while no corrosion was found on the surface of embedded fibers, after 600 wetting-drying cycles (each cycle included 120 min for wetting in 3.5% sodium chloride solution and 180 min for drying). Frazao et al. [21] reported that as the embedded hooked fibers was corroded, the bond strength of fibers-matrix increased because of the increase in fiber surface roughness as result of corrosion. Thus, the effect of chloride – induced corrosion of steel fibers embedded in cementitious composites under long-term storage conditions should be carefully considered as well.

In this study, we aim to investigate the effects of ageing on the interfacial bond strength of fiber-mortar under different storage conditions including air, water, and seawater after 28 days of water curing. In this study, to investigate effect of the chloride ion on the bond strength of fiber-mortar under long-term storage condition, a 3.5% sodium chloride solution was used. Since seawater contains sulfate, magnesium, calcium, and potassium in addition to chloride, additional investigation is needed to evaluate the effects of seawater later. In addition, ground granulated blast furnace slag (GGBS) was used as a 40% partial replacement of cement (determined by weight ratio) to delay chloride ion penetration [22]. The replacement of GGBS by weight of cement would cause the increase in the total volume of mortars with GGBS due to lower specific gravity of GGBS compared to cement.

2. Interfacial bond strength of steel fibers

The interfacial bond strength is a primary factor determining the performance of SFRC structures. If the bond strength is too weak, fibers would be easily detached from the matrix before they prevent crack propagation. On the other hands, if the bond strength is too strong, fibers would rupture prior to contributing to the crack bridging [14].

The interfacial bond strength between fiber and matrix could be determined from a single fiber pullout tests [5,7–9,14] or multiple fiber pullout tests [23,24]. In this study, the single fiber test was used. The pullout resistance of fiber is based on the physio-chemical adhesion, friction, and mechanical resistance [19]. Fig. 1 shows the typical pullout load versus slip curves, of smooth steel fiber, including the elastic stage, the partial debonding stage, and the frictional stage [8,12,19,25]. There is a linear elastic bond between the fibers and the matrix in the elastic stage. After linear elastic region, the adhesion at the interface between the steel fibers and mortar matrix started to be separate in the partial debonding stage. After the complete debonding of fiber, the pullout resistance is governed by the friction in the final stage.To evaluate the interfacial bond strength at the interface between the fiber and matrix, the equivalent bond strength (τ_{eq}) is calculated using Eq. (1) based on pullout load versus slip curves [3]:

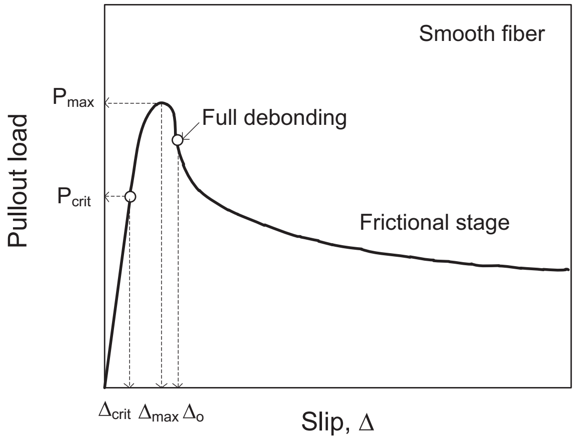

Fig. 1. The typical pullout load versus slip curve of smooth steel fiber [16].

$$\tau_{eq} = \frac{2.PE}{\pi.d_f.L_{em}^2} \tag{1}$$

where d_f is the equivalent diameter of the fiber, L_{em} is the embedded length of the fiber, and PE is the pullout energy, which is the area under the pullout load versus slip curve. The equivalent bond strength was assumed constant over the entire embedment length and calculated using the area under pullout load versus slip curve (pullout energy) [3]. Besides, the maximum bond strength ($\tau_{\max}$) was obtained from the maximum pullout load (P_{max}) in the curve according to Eq. (2).

$$\tau_{\max} = \frac{P_{\max}}{\pi.d_f l_{em}} \tag{2}$$

The maximum bond strength of steel fibers is known to be closely correlated with the post cracking tensile strength of steel fiber reinforced cementitious composites whereas the equivalent bond strength is known to be influencing on the ductility and multiple cracking behavior.

The adhesive bond (chemical and physical bonds) between fiber and matrix is weak for steel fiber. The interfacial bond strength of smooth steel fiber is particularly influenced by friction between the fiber and matrix during fiber pullout [16,26]. The frictional bond strength itself is notably affected by the properties of fiber, matrix and interfacial transition zone (ITZ) [18,19]. The parameters regarding the matrix include the strength, stiffness, and composition of the matrix [5,6,9,12,14]. The parameters about the ITZ are the local stiffness, porosity, packing density, and local strength, which are influenced by different processes [7,8,18,19]. In addition, Stang [15] reported that the shrinkage – induced clamping pressure could be one of the most important factors determining the frictional bond strength.

The frictional bond strength can be improved by enhancing the properties of ITZ between fiber and matrix [12]. The ITZ is the area surrounding a fiber with a thickness of 40–50 µm. The ITZ has highly porous structures and large flat calcium hydroxide (CH) crystals in the cement paste [27,28]. The ITZ has a significant effect on the mechanical and long-term characteristics of fiber reinforced cement composites [18]. To densify the microstructure of both the ITZ as well as the matrix, fine grains or additives (fly ash and/or silica fume) are frequently added [12,29]. In this study, to enhance interfacial bond strength, GGBS was used as a partial replacement of cement, instead of fly ash or silica fume.

3. Experiments

This experimental program was designed to investigate the effects of ageing and the use of GGBS (40% replacement of cement by weight ratio) on the pullout resistance of smooth steel fibers embedded in mortars under different storage conditions, as can be seen in Fig. 2. In the notations for the test series shown in Fig. 2, the first letter (C or G) indicates the mortar composition: C is the mortar without GGBS and G is the mortar with GGBS. The second letter (W, A, and S) designates the storage condition: W is pure water, A is air, and S is 3.5% sodium chloride solution. The