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Effect of matrix shrinkage on rate sensitivity of the pullout response of smooth steel fibers in ultra-high-performance concrete

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ABSTRACT

The present study investigates the effects of matrix shrinkage on the rate-sensitive pullout resistance of smooth steel fibers in ultra-high-performance concrete (UHPC) by adding a shrinkage reducing agent (SRA) to the UHPC and varying the fiber inclination angle from 0° to 30°. The pullout resistance is sensitive to the loading rate, and this sensitivity is attributed to both matrix shrinkage and the fiber inclination angle. The addition of the SRA reduces the enhancements in both peak and equivalent bond strengths at higher loading rates. Moreover, the rate sensitivity of the equivalent bond strength increases as the fiber inclination angle increased.

1. Introduction

Over the last decade, ultra-high-performance fiber-reinforced concretes (UHPFRCs) haves been used in the construction of important buildings as well as in civil and military infrastructure [1–4]. UHPFRCs have shown superior resistance to high rate loads, including earthquakes, impacts, and blasts, owing to their high tensile strength, strain capacity, and energy absorption capacity when compared with normal concrete [5–8]. Furthermore, under tension, UHPFRCs were found to be constructively sensitive to the applied strain rates [9–11]. The rate sensitive tensile response of UHPFRCs originates from the rate sensitivity of the interfacial bond characteristics between high-strength steel fibers and the ultra-high-performance concrete (UHPC) matrix [12,13].

Nevertheless, despite the superior performance of UHPFRCs even at high strain rates, the very high matrix shrinkage of UHPCs has hindered their widespread use [2]. Significant research efforts have been devoted to reducing the extent of matrix shrinkage [14–16]. As a remedy for reducing the high shrinkage of UHPC, Ryu et al. [14] reported UHPC prepared using a mixture of a shrinkage reducing agent (SRA) and an expansive agent. Park et al. [17] in 2014 reported that the addition of an SRA decreased the interfacial bond strength between the high-strength steel fibers and UHPC at a static rate. However, they did not investigated the loading rate effects on the pullout resistance of steel fibers embedded in UHPC matrices corresponding the addition of an SRA. Likewise, the effects of loading rate on the interfacial bond characteristics of high-strength steel fibers embedded in UHPC have not been fully investigated. In fact, only a few studies have examined the rate sensitivity of the pullout resistance of steel fibers in UHPC [13,18–22]. Tai et al. [13] reported recently highly rate sensitive pullout resistance of straight steel fibers embedded in UHPC, which differ from those embedded in normal strength mortar or concrete matrices. The high rate sensitivity of the pullout resistance was attributed to the large amount of silica powder in the UHPC, which was used to increase the packing density of the matrix [13]. However, with the exception of the use of silica powder, other factors that could influence the rate sensitivity of the pullout resistance of high-strength steel fibers embedded in UHPC remain poorly understood.

This study aims to develop our understanding about the loading rate effects on the pullout resistance of high-strength steel fibers embedded in UHPC by correlating the matrix shrinkage and the rate sensitive pullout resistances. Specific objectives are (1) to investigate the loading rate effects on the pullout resistance of smooth steel fibers embedded in UHPC corresponding to the addition of an SRA, (2) to investigate the effects of the fiber inclination angle on the rate sensitive pullout resistance, and (3) to correlate the rate sensitive pullout resistance of steel fibers embedded in UHPC and the rate sensitive tensile response of UHPFRCs.

Abbreviations: DIF, dynamic increase factor; LVDT, linear variable differential transformer; SRA, shrinkage reducing agent; UHPC, ultra-high-performance concrete; UHPFRC, ultra-high-performance fiber-reinforced concrete

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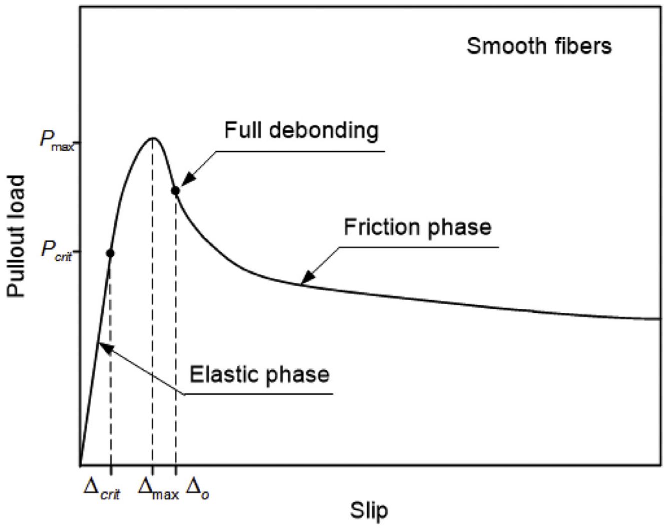

Fig. 1. Typical pullout load versus slip curve of smooth fibers [23].

2. Pullout response of steel fibers

Fig. 1 shows the typical pullout load versus slip response of smooth steel fibers embedded in a normal mortar. An analytical model for the pullout behavior of smooth steel fibers was proposed by Naaman et al. [23]. The pullout load versus slip response prior to the critical pullout load (P_{crit}), at which point fiber debonding initiates, would be influenced by the elastic moduli and Poisson's ratios of both the fiber and the matrix. Beyond this critical point, the pullout response of the smooth steel fiber is non-linear, as shown in Fig. 1.

The pullout resistance (P) can be divided into two parts, referred to as the bonded and the debonded zone, as illustrated in Eq. (1).

$$P = P_b + P_d \tag{1}$$

In Eq. (1), P_{b} is the pullout resistance of the bonded zone and P_{d} is the pullout resistance of the debonded zone.

Eq. (2) for the pullout resistance of the bonded zone (P_{b}) was proposed by Naaman et al. [23] by considering the bond characteristics as well as the properties of the fiber and matrix, as follows:

Table 1
Properties of high-strength smooth steel fibers.

Diameter (mm)	Length (mm)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)
0.3	30	7.9	2447	200

$$P_b = \frac{t_{\max}}{\lambda}\frac{1 - e^{-2\lambda(1-u)}}{\frac{2}{Q}e^{-\lambda(1-u)} + \left(1 - \frac{1}{Q}\right)[1 + e^{-2\lambda(1-u)}]}, \tag{2}$$

where $t_{\max}$ is the maximum allowable interfacial shear flow ($\tau_{\max}\phi$); λ is $\sqrt{KQ}$; K is $\frac{\varphi\kappa}{A_m E_m}$; ϕ is the perimeter of the fiber; K is the modulus of the bond; Q is calculated as $1 + \frac{A_m E_m}{A_f E_f}$; A_{m} and E_{m} are the area and elastic modulus of the matrix; A_{f} and E_{f} are the area and elastic modulus of the fiber; u is the debonded length.

Eq. (3) for the pullout resistance of the debonded zone (P_{d}) was also proposed by Naaman et al. [23] by considering the interfacial friction between the fiber and the matrix, as follows.

$$P_d = \tau_f \varphi\, u, \tag{3}$$

where τ_f is the frictional bond strength at the interface between the fiber and the matrix.

Parameter τ_f in Eq. (3) is affected strongly by the extent of matrix shrinkage as well as by the elastic moduli of the matrix and the fiber, as described by the shrinkage misfit theory [24–26].

Although many studies have investigated the pullout resistance or interfacial bond characteristics of steel fibers, the source of rate dependency of the pullout response has not yet been fully understood. The pullout resistance (or interfacial bond strength) of smooth steel fibers embedded in a normal mortar is generally insensitive to the applied loading rate, whereas the pullout resistance of deformed steel fibers is sensitive as a result of the frictional bond strength, which is well-known to be insensitive to loading rate [18,19].

Kim et al. [20] investigated the rate sensitive pullout resistance of deformed (hooked and twisted) steel fibers embedded in mortar matrices with compressive strength > 84 MPa. The pullout resistance of the twisted steel fibers exhibited very high rate sensitivity as the loading rate increased from 0.018 to 18 mm/s, whereas the pullout resistance of the hooked fibers displayed little sensitivity. Recently, Xu

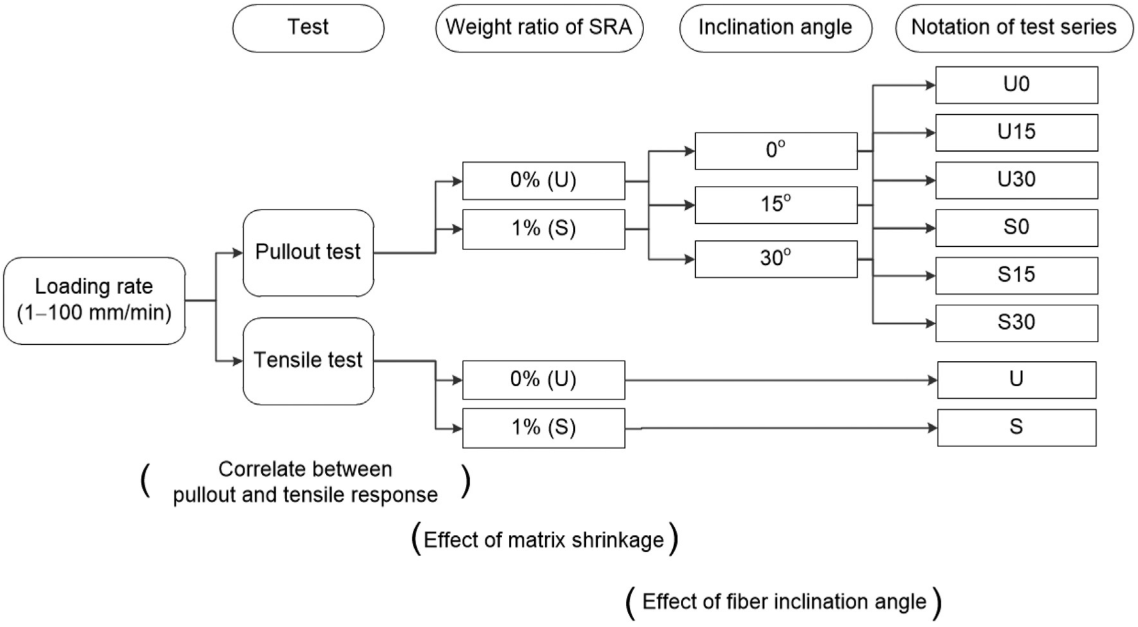

Fig. 2. Test series.