Cement & Concrete Composites 49 (2014) 59–69

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Effect of shrinkage reducing agent on pullout resistance of high-strength steel fibers embedded in ultra-high-performance concrete

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ARTICLE INFO

Article history:
Received 14 September 2012
Received in revised form 23 July 2013
Accepted 31 December 2013
Available online 8 January 2014

Keywords:
Interfacial bond strength
Ultra-high-performance concrete
High-strength steel fiber
Shrinkage-reducing agent
Microfiber

ABSTRACT

The interfacial bond strength of long high-strength steel fibers embedded in ultra-high-performance concrete (UHPC) reinforced with short steel microfibers was investigated by conducting single-fiber pullout tests. In particular, the influence of the addition of a shrinkage-reducing to a UHPC matrix on the pullout resistance of high-strength steel fibers was investigated. The addition of a shrinkage-reducing agent produced a noticeable reduction in the fiber pullout resistance owing to the lower matrix shrinkage, although the reduction of pullout resistance differed according to the type of fiber. Long smooth and twisted steel fibers were highly sensitive to the addition of the shrinkage-reducing agent whereas hooked fibers were not. Among the various high-strength steel fibers tested, twisted steel macrofibers showed the highest interfacial bond resistance, although twisted fibers embedded in UHPC showed slip softening pullout behavior rather than the typical slip hardening behavior observed in mortar.

1. Introduction

Ultra-high-performance concretes (UHPCs) provide very high compressive strength and are potentially highly durable. However, their brittle behavior and tendency for high shrinkage have considerably limited their practical application. UHPCs have been reinforced using high-strength steel fibers to improve resistance to cracking and increase toughness. Furthermore, a shrinkage-reducing agent (SRA) or expansive agent has been added to UHPCs to compensate for the high amount of matrix shrinkage.

Various ultra-high-performance fiber-reinforced concretes (UHPFRCs) such as DUCTAL®, BSI®/CERACEM, CARDIFRC®, multi-scale cement composites (MSCC), CEMTEC multiscale®, and ultra-high-performance hybrid-fiber reinforced concrete (UHP-HFRC) have been developed [1–8]. In some concretes, two or three types of fibers are employed in combination. In particular, the blending of long and short fibers in a cement-based matrix can provide synergistic effects on both tensile strength and ductility. Fibers play different roles in a matrix according to their size and length: longer (macro) fibers are more effective in increasing toughness by resisting crack opening at the macro level, and shorter (micro) fibers are effective for enhancing tensile strength by delaying the initiation and coalescence of microcracks within a matrix [4,7,8]. Park et al. [8] recently reported on the tensile behavior of UHP-HFRCs blending long macrofibers and short microfibers. They realized a tensile strength of 18.6 MPa and a strain capacity of 0.64% by blending 1.0% twisted steel macrofibers and 1.5% short smooth steel microfibers.

As mentioned above, an expansive agent or SRA can be added to reduce the high amount of matrix shrinkage [9]; however, the effect of adding these agents on the mechanical properties of UHPFRCs has not yet been determined. The high shrinkage of UHPCs limits their application to large-sized structural members owing to important issues such as the volume stability of structures. In addition, it is unclear whether the addition of SRA can influence the superior tensile behavior of UHPFRCs. The post-cracking mechanical resistance of fiber-reinforced concretes or cementitious composites mostly depends upon the pullout resistance of fibers bridging the cracks. Furthermore, the fiber pullout resistance is strongly influenced by the shrinkage-induced clamping pressure [10]. However, few studies have focused on the pullout load versus slip response of high-strength deformed steel fibers, especially in a UHPC matrix with high shrinkage.

This study provides useful information about the interfacial bond strength of high-strength steel fibers in UHPC to aid the realization of higher tensile strength and ductility. Specifically, this study aims to (1) investigate the pullout load versus slip response of high-strength steel fibers in UHPC, (2) reveal whether the slip hardening behavior of deformed steel fibers embedded in mortars with 24–84 MPa compressive strength (Fig. 1) is also observable in UHPC [11], and (3) study the effect of adding SRA on the interfacial bond properties of macrofibers.

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http://dx.doi.org/10.1016/j.cemconcomp.2013.12.012

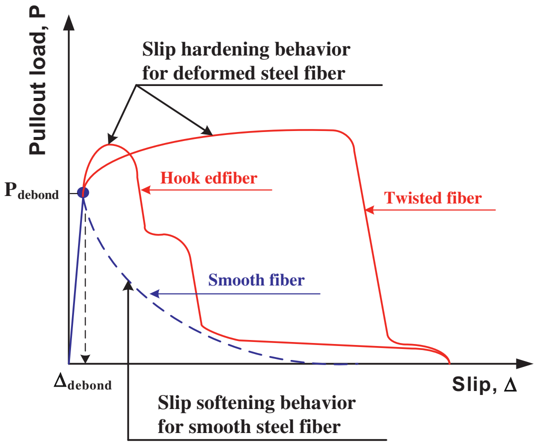


Fig. 1. Typical pullout behavior of high-strength steel fibers [11].

2. Interfacial bond strength of steel fibers embedded in UHPC

The interfacial bond strength has been enhanced by densifying the ITZ of UHPC by applying silica fume or through a special surface treatment of steel fibers by increasing their roughness in chemical or physical manners. Orange et al. [12] noted that the fiber–matrix adhesion mechanism is mainly due to the compressive hydrostatic pressure developed around the fiber by matrix shrinkage. Furthermore, they reported that surface treatment of a 0.2-mm-diameter short smooth steel fiber embedded in DUCTAL significantly improved its bond strength from 10 to 18 MPa. Chan and Chu [13] performed fiber pullout tests by using pullout specimens with nine high-strength (>2600 MPa) short smooth

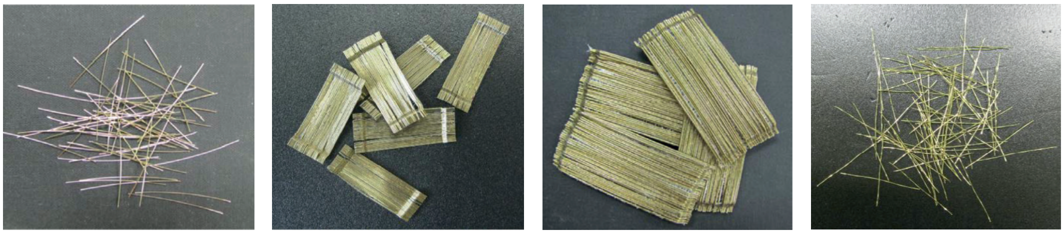
Table 2
Matrix of single-fiber pullout tests.

Macrofiber type	Microfiber volume content (%)	Contents of shrinkage reducing agent by weight ratio to cement	
		0%	1%
LS	0.0	LS00S0	LS00S1
	1.5	LS15S0	LS15S1
HA	0.0	HA00S0	HA00S1
	1.5	HA15S0	HA15S1
HB	0.0	HB00S0	HB00S1
	1.5	HB15S0	HB15S1
T	0.0	T00S0	T00S1
	1.5	T15S0	T15S1

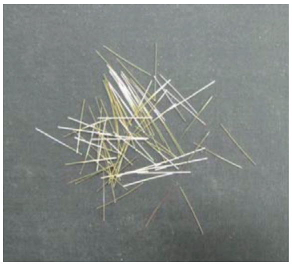
Table 1
Properties of fibers.

Fiber type	Name (Notation)	Diameter mm (in.)	Length mm (in.)	Density (g/cc)	Tensile strength MPa (ksi)	Elastic modulus Pa (ksi)
Macro	Long smooth (LS)	0.3 (0.12)	30 (1.181)	7.9	2580 (373.9)	200 (29,000)
	Hooked A (HA)	0.375 (0.015)	30 (1.181)	7.9	2311 (334.9)	200 (29,000)
	Hooked B (HB)	0.775 (0.031)	62 (2.441)	7.9	1891 (274.1)	200 (29,000)
	Twisted (T)	0.3[a] (0.015)[a]	30 (1.181)	7.9	2428[b] (351.8)[b]	200 (29,000)
Micro	Short smooth (SS)	0.2 (0.008)	13 (0.512)	7.9	2788 (404.0)	200 (29,000)

[a] Equivalent diameter.
[b] Tensile strength of the fiber after twisting.



(a) LS- fiber (b) HA- fiber (c) HB- fiber (d) T- fiber



(e) SS- fiber

Fig. 2. Photos of fibers.