Construction and Building Materials 75 (2015) 255–265

Contents lists available at ScienceDirect

Construction and Building Materials

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

Pull-out behavior of steel fiber embedded in flowable RPC and ordinary mortar

Ahsanollah Beglarigale*, Halit Yazıcı

Department of Civil Engineering, Eng. Faculty, Dokuz Eylül University, Buca, İzmir, Turkey

HIGHLIGHTS

- Embedment length is more important for the smooth fiber than the hooked-end fiber.
- The fiber bond was improved as the W/C ratio decreased in all curing conditions.
- Congestion of hydration products in fiber–matrix interface improves bond characteristics.

ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form 4 October 2014
Accepted 12 November 2014

Keywords:
Pull-out test
Bond characteristics
Reactive powder concrete
Steel fiber

ABSTRACT

The aim of this research is to investigate some of the factors which affect the steel fiber–matrix bond characteristics by means of pull-out test. Ordinary mortar (OM) and reactive powder concrete (RPC) were used as main matrices. The effect of parameters such as end condition of fiber (smooth or hooked-end), embedment length, water/binder ratio, paste phase of RPC, steel-micro fiber, and curing conditions on fiber–matrix pull-out behavior were determined. The fiber–matrix bond characteristics improved as the embedment length of fiber increased, especially for smooth fiber. Low W/C ratio, which enhances the bond strength, reduces the importance of embedment length of the hooked-end fiber. Furthermore, the pull-out peak load and debonding toughness increased as the W/C ratio decreased in the all curing conditions. Microstructural investigation revealed that the congestion of hydration products in fiber–matrix interface improves pull-out behavior remarkably.

1. Introduction

Cement based plain mortar and concrete are known as a brittle construction material with low tensile strength which leads to crack under low levels of tensile strain. It has long been recognized that the behavior of such materials can be improved by the addition of steel or various discontinuous fibers. Mechanical properties of these composites are dramatically influenced by steel fiber–matrix bond which provides the stress transferring between the fiber–matrix phases.

The fiber–matrix interface characteristics (fiber–matrix transition zone) are the most important factor which affects the bond strength. It is well known that the transition zone in the mature traditional cementitious composites is quite porous and also filled with CH in direct contact with the fiber surface [1]. These characteristics are similar to the aggregate-matrix interfacial transition zone [2]. Depending on bulk and fiber properties, the CH layer can be 1 μm (duplex film) or much more massive [1]. The density of this zone can be increased by supplementary cementitious materials [3–8]. Generally, it can be summarized from many researches that the pull-out behavior depends on both matrix and fiber characteristics. The positive effect of increasing matrix strength on the bond strength was reported by Tuyan and Yazıcı [8], Abu-Lebdeh et al. [9], and Shannag et al. [10]. Beglarigale and Yazıcı [11] have investigated the effect of alkali silica reaction (ASR) on steel fiber–matrix bond characteristics. Test results indicate that the ASR gel congestion in the fiber–matrix interface increased the bond strength significantly during alkali exposure.

Tuyan and Yazıcı [8] showed that the pull-out peak load of the hooked-end steel fibers was significantly higher than the smooth steel fibers. The end condition of fiber was also investigated by some researchers and the very similar result was reported [9,12]. Tuyan and Yazıcı [8] reported that the pull-out peak load and the debonding toughness increased by an increasing in the embedment length of the smooth and hooked-end fibers. Similar results were observed by Shannag et al. [10] and Silva et al. [13]. Lee et al. [14] reported that the highest peak load was observed at a fiber inclination angle of 30° or 45°.

---

* Corresponding author. Tel.: +90 232 3017044; fax: +90 232 3017253.
E-mail address: ahsan.beglari@gmail.com (A. Beglarigale).

http://dx.doi.org/10.1016/j.conbuildmat.2014.11.037
0950-0618/© 2014 Elsevier Ltd. All rights reserved.

1.1. Research significance

Limited studies were realized on the effects of parameters such as water to cement ratio and curing conditions (especially autoclave curing and its effect on the microstructure of fiber–matrix interface) on the fiber–matrix characteristics. The other important investigation in this study is the effect of end condition and embedment length of steel fiber on the fiber–matrix bond characteristics in flowable reactive powder concrete and ordinary mortar. The authors believe that this detailed study will shed some light on further research.

2. Experimental

2.1. Materials

CEM I 42,5R ordinary portland cement with 371 m^2/kg Blaine fineness was used. The silica fume used in RPC mix design had 92.25% SiO_2 content and 20,000 m^2/kg nitrogen absorption fineness. Two types of aggregate were used in experimental program. Crushed lime stone (0–5 mm) was used in the ordinary mortar (OM) design and four different sizes (1–3, 0.5–1, 0–0.4, and 0–0.075 mm) of quartz aggregate were used in the RPC mix design. A polycarboxylic ether based superplasticizer was used to reach the target workability. A single type of steel fiber with 0.75 mm diameter, 60 mm length, and 80 aspect ratio was used in the pull-out tests. Furthermore, brass-coated steel-micro fiber with 0.16 mm diameter, 6 mm length, and 37.5 aspect ratio was used.

2.2. Methodology

Mix design of OM and RPC are presented in Table 1. An OM with 0.5 water/cement ratio and a RPC with 0.2 water/binder ratio were designed to examine the effect of end condition and embedment length of steel fiber on the fiber–matrix bond characteristics. The effect of these parameters was also investigated in paste phase of RPC and a high strength mortar with 0.3 W/C ratio. The mix design of these mixtures was also presented in Table 1. The steel fiber used in this study was produced as a hooked-end fiber. For evaluating the effect of end condition of fiber, a series of smooth fibers were used. The smooth and the hooked-end fibers were embedded into matrix in four different lengths (1, 2, 3, and 4 cm).

To evaluate the effect of water/binder (W/B) ratio on pull-out behavior of steel fiber–matrix, the mix design of the OM and RPC were redesigned. The cement content (500 kg/m^3) of the OM design was fixed, but the W/C ratio was increased once to 0.6 and once more decreased to 0.4 and 0.3. Furthermore, the mix design of the RPC was redesigned. The water/binder ratio was increased to 0.3, 0.4, 0.5, and 0.6 ratios. The 0–0.4 and 0–0.075 mm sizes of quartz aggregate and silica fume dosage of mixtures were fixed, while the cement dosage was decreased as the W/B ratio increased. It is obvious that the redesigned mixtures with high W/B ratio cannot be categorized as a RPC; however, this modification was applied for analyzing the effect of W/B ratio on the fiber–matrix bond characteristics. Additionally, a series of the redesigned RPC mixtures were reinforced by 2% steel-micro fibers. The mix designs of all mixtures are presented in Table 1. It must be noted that hooked-end fiber with 30 mm embedment length were used to evaluate the effect of W/B ratio on bond characteristics.

The effect of the W/B ratio was carried out in four different curing conditions. After casting, specimens were kept for 24 h in 20 ± 2 °C and after that, were demolded and then, were cured in water for seven days and others were cured for 28 days. The temperature of curing water was fixed in 20 ± 2 °C. Another series of specimens were put in autoclave cabin. The temperature was adjusted to 210 °C and steam pressure was adjusted to 2 MPa. The specimens were cured for 12 h in autoclave cabin. The steam curing regime was different from other curing conditions. 6 h after casting the molds were put in steam curing cabin. After 6 h, the temperature of the cabin was reached to 100 °C and, the specimens were kept in this condition for 12 h.

2.3. Specimens

Mixtures were mixed by a Hobart mixer. Dry ingredients of OM mixture were premixed for 2 min and RPC for 5 min. Then, half of the mixing water was added to the dry mixture, while the remaining water was being mixed with the required amount of superplasticizer and then, poured into the mixer. After normal speed for about 1 min for OM and 5 min for RPC, mixing continued for another 3 min for OM and 10 min for RPC in high speed and the workability of each mixture was controlled with mini-flow table test. The required amount of superplasticizer was used to achieve 150 ± 10 mm flow table values for OM mixture and 220 ± 10 mm for RPC mixture. The mixtures that were prepared for the pull-out test were poured into 50 × 50 × 50 mm cubic molds in two layers with 30 s applying vibration for each layer. After placing final layer, single steel fiber was centrally embedded into the fresh mixture by an apparatus which allowed the fiber becomes perpendicular to the surface of the specimen and adjusts the desired embedment length into the matrix and then, vibration was applied for 30 s. In addition, the flexural and compressive strength of the matrices were determined in 40 × 40 × 160 mm prismatic specimens.

2.4. Test procedures

The fiber–matrix bond characteristics were determined by applying single-fiber pull-out test that is a common method used and analyzed by many researchers [8–11,14–24]. The Schematic diagram of pull-out test setup used in this study is presented in Fig. 1. Capacity of the load-cell was 6 kN. The pull-out test specimen was fixed to the frame on the bottom platen while the free end of the fiber was held by the fiber mounting plate. The matrix remained rigid while, the fiber mounting plate moved upward with a rate of 1 mm/min under closed loop control test. During the slip of fiber from the matrix, corresponding load values were recorded by the load-cell that was connected to a computer. Some important parameters such as peak pull-out load, displacement at the peak load and, debonding toughness (slip energy) were found out by analyzing the pull-out load versus end displacement curves plotted using the data from the test.

Each one of the data presented here is the average test result of three specimens for the three point flexural strength and the average test result of four specimens for the pull-out test values. Compressive strength results are the average of six samples that were left from bending test. After flexural tests, the broken half-prisms were tested in uniaxial compression (loading area is 40 × 40 mm). In addition, the specimens and mixtures were abbreviated as follow: (1) ordinary mortar (0.5 W/C ratio) = OM; (2) RPC = R; (3) the mixture which were prepared by decreasing W/C ratio of OM mixture from 0.5 to 0.3 = 0.3OM; (4) paste phase of RPC = PPR; (5) micro fiber reinforced RPC = RF; (6) smooth fiber = S; (7) hooked-end fiber = H; (8) 0.6 W/B ratio = 0.6; (9) 0.5 W/B ratio = 0.5; (10) 0.4 W/B ratio = 0.4; (11) 0.3 W/B ratio = 0.3; (12) 0.2 W/B ratio = 0.2.

3. Results and discussion

3.1. Mechanical properties of mixtures

Flexural and compressive strength of OM (0.5 W/C), redesigned OM mixtures, RPC (0.2 W/B), and redesigned RPC mixtures in

Table 1
Mix design of mixtures (kg/m^3).

Mixtures	Water	Cement	Silica fume	Aggregate					SP/C (%)[a]
				Lime stone 0–5 mm	Quartz (mm)				
					1–3	0.5–1	0–0.4	0–0.075	
0.3OM	150	500	–	1687	–	–	–	–	4.2
0.4OM	202	500	–	1588	–	–	–	–	1.4
0.5OM	250	500	–	1473	–	–	–	–	0.8
0.6OM	300	500	–	1352	–	–	–	–	0
0.2R	184	824	107	–	609	348	174	87	2.2
0.3R	249	724	107	–	570	310	174	87	1.1
0.4R	294	624	107	–	556	296	174	87	0.55
0.5R	315	524	107	–	575	314	174	87	0.01
0.6R	318	424	107	–	609	348	174	87	–
PPR	355	1590	207	–	–	–	–	–	1.3

[a] Superplasticizer/cement.