Construction and Building Materials 28 (2012) 362–371

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Pull-out behavior of prestressing strands in steel fiber reinforced concrete

Eray Baran, Tolga Akis *, Seda Yesilmen

Department of Civil Engineering, Atilim University, Incek-Ankara, Turkey

ARTICLE INFO

Article history:
Received 9 March 2009
Received in revised form 17 May 2011
Accepted 16 August 2011
Available online 20 October 2011

Keywords:
Steel fiber reinforced concrete
Prestressing strand
Pull-out
Bond

ABSTRACT

This paper presents the results of an experimental study investigating the effects of steel fibers on the mechanical properties of concrete and the enhancement of bond strength of prestressing strands in steel fiber reinforced concrete (SFRC). The first part of the experimental program consisted of compression, tension and flexural tests on SFRC. Two types of steel fibers with 30 mm and 60 mm fiber lengths were used with five different fiber contents. The second part of the study consisted of simple pull-out tests on 12.7 mm and 15.2 mm diameter seven-wire untensioned prestressing strands embedded in concrete blocks. The pull-out tests were conducted with two different fiber lengths and five different fiber contents for each strand diameter. The steel fibers were observed to improve the pull-out resistance of strands by controlling the crack growth inside concrete blocks.

1. Introduction

Recent advances in the field of construction materials have led to the development of fiber reinforced concrete, which offers, among other things, increased ductility and toughness compared to the plain concrete. Fiber reinforced concrete is a composite construction material that contains fibers of various materials added to the concrete matrix. Even though the addition of fibers leads to improvements in mechanical properties of plain concrete, the degree of such improvements usually depends on the fiber material and shape, as well as the fiber content in the mix. Fibers used in concrete are usually made of steel, glass, plastic, or natural materials.

Steel fiber reinforced concrete (SFRC) has been rapidly gaining popularity as a result of its improved mechanical properties over plain concrete. One of the examples for the use of SFRC is in prestressed concrete beams, mainly to enhance the shear resistance. Recent studies have shown that the beneficial effects of fibers can significantly reduce the shear reinforcement requirement and increase the flexural strength in prestressed concrete beams [1,2]. Despite the potential use of SFRC in prestressed concrete structural members, very little has been studied regarding the bond behavior of prestressing strands in this type of concrete. The study presented here aimed at characterizing the mechanical properties of SFRC with various fiber contents and investigating the bond behavior of 12.7 and 15.2 mm diameter seven-wire prestressing strands in these concrete mixes.

2. Literature review

Fiber reinforced concrete has improved mechanical characteristics compared to plain concrete such as flexural strength, tensile strength, ductility and flexural toughness. Remarkable increases in tensile strength were obtained when steel fiber reinforcement was used due to the crack arrest effect of the fibers [3–5]. The inclusion of steel fibers also modifies the shear performance of concrete. Beam tests showed that the steel fibers converted the brittle shear behavior of plain concrete into a ductile mechanism, for which a significant increase in the shear strength was reported [6,7]. It was observed in another study that the improvement in the tensile and flexural strengths of the SFRC members can be at least two to three times that of plain concrete members while the corresponding strains were even higher [8].

The level at which the addition of steel fibers influences the mechanical properties of the concrete was shown to be dependant on various parameters like material and aspect ratio of the fibers, their volume fraction in the mix, and loading rate [9,10]. Flexural toughness is an important parameter that is widely assessed to observe the influence of fibers on the post-cracking response of the concrete composites. Toughness indices were shown to increase with increasing fiber dosage, with an optimum value present for fiber volume fraction [10,11]. This optimum fiber dosage is dependant on various parameters like concrete type, fiber properties, and mix design.

Bond behavior of prestressing strands through pull-out tests have been studied by several researchers. Among them, Moustafa [12] performed pull-out tests on untensioned prestressing strands embedded in concrete blocks. This type of testing has been used by many researchers to evaluate the bond performance of the

* Corresponding author. Tel.: +90 312 586 8335; fax: +90 312 586 8091.
E-mail address: takis@atilim.edu.tr (T. Akis).

0950-0618/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2011.08.040

strands since the procedure is fairly simple [13–15]. Logan [14,15] performed pull-out tests to evaluate the bond performance of the strands obtained from different prestressed concrete producers using the same specimen geometry and test procedure that Moustafa had used earlier and discussed the relation between the pull-out test results and transfer and development length characteristics of the strands. A direct relation was reported to exist between the strand pull-out capacity obtained following the Moustafa test procedure and strand transfer length. Rose and Russell [16] investigated the effect of strand surface condition on the bond performance by performing pull-out tests on both tensioned and untensioned 12.7 mm diameter strand, and reported that the pull-out tests on tensioned strands are difficult to perform and produce inconsistent results for bond strength of strands. Regarding the effect of strand surface condition on bond strength, the authors indicated that a roughened strand surface (e.g. weathered strand) enhances the bond. Girgis and Tuan [17] performed pull-out tests on 15.2 mm diameter untensioned prestressing strands embedded in small prisms of $15 \times 15 \times 20$ cm dimensions and large blocks made of self-consolidating plain concrete. The pull-out load was applied to the small prism specimens using two different methods. Their results indicated that supporting the concrete blocks on their back side resulted in higher bond strength than conventional way of supporting the specimen on the same side of the tested strand. In a closely related study, Chao et al. [18] investigated the bond behavior of 12.7 mm diameter untensioned strands embedded in $15 \times 15 \times 10$ cm concrete prisms reinforced with various types of fibers. Fibers added to concrete matrix with 1% volume fraction were found to improve the pull-out behavior of strands by limiting the crack width in concrete prisms.

The influence of steel fibers on pull-out behavior of prestressing strands still remains to be a subject that needs further research. The study explained in this paper aims at addressing this need by investigating the bond behavior of untensioned prestressing strands in steel fiber reinforced concrete blocks. Different from studies referenced above, the effects of strand diameter and fiber aspect ratio were studied with five different fiber contents.

3. Background

The force transfer between prestressing strands and the surrounding concrete through bond is a fundamental mechanism that directly affects the service performance of the prestressed concrete members. This mechanism is required at two conditions: (1) when the prestressing force is transferred from the strands to the concrete at strand release and (2) when the additional stresses due to service loads (or an overload) is transferred between the strands and the concrete (i.e., to provide strain compatibility). Based on these two conditions, two design parameters, namely prestressing transfer length and strand development length, are usually used to define the required length of prestressing strands to have certain level of force transfer between the strands and the concrete. The transfer length is the distance over which the prestress in a strand is transferred to the concrete, while the development length is the distance required to develop the full strength of the strand.

There are several parameters that affect the transfer length and the development length of prestressing strands. The most important of these are strand diameter, surface condition of the strand, stress level in the strand, concrete strength, and reinforcement detail around the strand. Various studies have been conducted on bond behavior of prestressing strands in concrete to quantify the effect of these parameters on the transfer and development length of strands. Even though several formulas that can be used to predict the transfer and development lengths for prestressing strands have been developed as a result of these studies, the test results have shown the highly variable nature of the transfer and development lengths. The current study aims at investigating the variation in bond strength of prestressing strands when used in plain concrete and in concrete reinforced with various concentrations of steel fibers. This way, the applicability of the available transfer length and development length formulas for prestressing strands embedded in SFRC could be determined.

4. Experimental studies

The experimental program consisted of two phases. In the first phase, tests were conducted on concrete cylinders and flexural beams to characterize the mechanical behavior SFRC with different fiber contents and fiber geometries. The second phase of the experimental program included pull-out tests on prestressing strands embedded in SFRC blocks. The specimens for both the material tests and the pull-out tests were fabricated and tested at Atilim University Structural Mechanics Laboratory.

Two types of hooked steel fibers, Dramix ZP-305 and RC-80/60, with the geometries shown in Fig. 1, were used in both phases of the experimental program. As indicated on the figure, the fibers were 30 mm and 60 mm long with diameters of 0.55 mm and 0.75 mm, respectively. The fibers were conforming to ASTM A820 Standards and the manufacturer specified minimum tensile strength values were 1100 MPa for the 30 mm long fibers and 1050 MPa for the 60 mm long fibers. The material tests and strand pull-out tests on SFRC were repeated for four different fiber contents: 15 kg/m^3, 30 kg/m^3, 45 kg/m^3, and 60 kg/m^3 (corresponding volumetric ratios of fibers are approximately 0.2%, 0.4%, 0.6%, and 0.8%). Control specimens were also tested with plain concrete with no steel fibers. The concrete mix proportions used in the experimental studies are given in Table 1. The mix had a target 28-day compressive strength of 40 MPa. Identical mixes were used for SFRC and the concrete with no fibers, except for the addition of steel fibers in SFRC mixes.

The fibers were initially mixed with cement and aggregates inside a drum-type mixer and the mixing operation was continued after adding water and super plasticizer until a uniform distribution was obtained. Workability of the concrete mix was observed to decrease with increasing fiber content and fiber length. Compaction of concrete for cylinder and beam samples was done with a vibration table, while a stick-type internal vibrator was used in strand pull-out specimens for this purpose. Visual observations performed after flexural toughness testing of beam samples indicated a relatively uniform distribution of steel fibers inside the beam cross section. Such an observation could not be performed for cylinder samples and strand pull-out specimens as it was not possible to break these samples following the load tests to observe the fiber distribution.

4.1. Material tests

The tests that were conducted to characterize the mechanical properties of SFRC included compressive strength tests, split tension tests, and flexural toughness tests. The compressive strength and split tension tests were conducted on concrete cylinders with 150 mm diameter and 300 mm height, while $150 \times 150 \times 600$ mm concrete beams were used for the flexural toughness tests. Following the fabrication, the cylinder and beam specimens were kept inside a curing tank until they were tested at 28-day age. All tests were performed according to the corresponding ASTM Standards. For each type of test, three specimens were tested for each fiber content (no fiber, 15 kg/m^3, 30 kg/m^3, 45 kg/m^3, and 60 kg/m^3).

The test setup used for the flexural toughness tests is shown in Fig. 2. The beam specimens were tested under four-point loading with a clear span of 450 mm and the loading applied at third-points of the clear span. The loading was applied with a 1500-kN capacity universal testing machine at a rate of 0.1 mm/min. During the tests, the total load applied on the beam specimens was monitored with a load cell attached to the head of the testing machine and the beam midspan deflection relative to the testing machine was monitored with a dial gage.

4.1.1. Material test results

4.1.1.1. Compressive strength. The measured concrete compressive strength (f_{comp}) values are presented in Table 2. The values shown are the average of results from three repeat tests. The results indicate that for both fiber lengths studied, the addition of steel fibers caused a small decrease in the measured concrete compressive

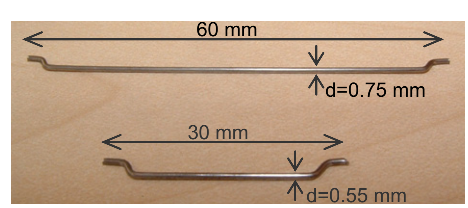

Fig. 1. Fiber geometries used in experimental studies.