Composites: Part B 56 (2014) 536–545

Contents lists available at ScienceDirect

Composites: Part B

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

The role of flaw size and fiber distribution on tensile ductility of PVA-ECC

Kamile Tosun-Felekoğlu [a,*], Burak Felekoğlu [a], Ravi Ranade [b], Bang Y. Lee [c], Victor C. Li [b]

[a] Department of Civil Eng., Dokuz Eylul University, İzmir, Turkey
[b] Department of Civil and Environmental Eng., University of Michigan, Ann Arbor, MI, USA
[c] School of Architecture, Chonnam National University, Republic of Korea

ARTICLE INFO

Article history:
Received 15 June 2013
Received in revised form 13 August 2013
Accepted 26 August 2013
Available online 5 September 2013

Keywords:
A. Fiber
B. Mechanical properties
D. Optical microscopy
D. Physical methods of analysis
Tensile ductility

ABSTRACT

Polyvinyl Alcohol-Engineered Cementitious Composites (PVA-ECC) designed based on micromechanics exhibit high tensile ductility (above 1%) and limited crack widths (below 100 μm). The tensile performance of ECC is dependent on the fiber and flaw size distributions. These parameters are known to be influenced by the matrix flowability and mix processing; however, a comprehensive quantitative analysis framework linking fiber and flaw size distributions to the tensile performance of PVA-ECC is needed to supplement theoretical understanding of the relationship between micromechanical parameters and composite macro-properties. In the present work, fiber distribution (dispersion and orientation) of two different ECCs in terms of matrix flowability was investigated using fluorescence microscopy and advanced digital image analysis. The maximum flaw size distribution along the specimens was also analyzed by cross-sectional image analysis. The influences of fiber and flaw size distributions on the composite behavior of PVA-ECCs were experimentally established.

1. Introduction

In recent years, Engineered Cementitious Composites (ECC) with significantly high tensile ductility and limited crack widths have emerged as a promising alternative to normal concrete and fiber reinforced concrete for improving structural performance. Micromechanically designed ECC has tensile ductility at least 100 times higher than concrete, and it utilizes moderate fiber content of 2% or less by total mix volume [1]. The design of ECC is based on micromechanics-derived scale-linking models to predict the composite behavior, which is closely dependent on the fiber and flaw size distributions along with fiber/matrix interfacial bond properties [2]. For instance, the bridging efficiency of fibers drops by up to 50%, when the fiber distribution is changed from 1D uniform alignment to 3D random distribution [3], and the ductility of ECC can be improved by more than 100% through incorporation of artificial flaws of appropriate size range [4]. The design of ECC with robust mechanical performance requires detailed knowledge of how tensile properties are governed by fiber and flaw size distributions.

Recent studies showed that the fiber and flaw size distributions in ECC are dependent on the matrix flowability and mix processing [5,6]. In a typical ECC mixing procedure, fibers are added after a plastic matrix state is achieved. An ECC matrix usually consists of cementitious materials, fine aggregate, water, and admixtures. The processing details such as mixer type, mixing speed, time and sequence, and mixing personnel's experience level can influence the homogeneity of the ECC matrix. Li and Li [5] studied the relationships between matrix rheology, fiber dispersion uniformity and composite strain capacity. The role of flaw size was not a focus on that study. Li and Wang [2] recognized the influences of both fiber dispersion uniformity and flaw size distribution on composite properties, but only quantified experimentally the flaw size distribution. A quantitative research combining the roles of fiber distribution (both dispersion and orientation) and flaw size distribution on composite tensile properties has not been reported. This paper aims to fill this knowledge gap.

The objective of this study is to systematically correlate the tensile strength and ductility of ECCs by considering the effects of three different processing parameters (largest flaw size, fiber dispersion coefficient, and fiber orientation distribution), simultaneously. It provides an effective approach to investigate the variation of ECC ductility with respect to ECC microstructure and specimen processing. For this purpose, PVA-ECC mixtures with the same mix ingredients were deliberately prepared with two different contents of HRWR admixtures. Their flowability was measured indirectly using Marsh cone flow times. The uniaxial tensile stress–strain properties were determined by using dogbone shaped specimens. After the tension tests, each dogbone specimen was sectioned at a number of locations within the gauge length. Maximum flaw size distribution, fiber dispersion coefficients, and fiber orientation distributions were measured at each cross-section. Tensile ductility differences between the specimens of each

* Corresponding author. Tel.: +90 2323017059.
E-mail address: kamile.tosun@deu.edu.tr (K. Tosun-Felekoğlu).

1359-8368/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2013.08.089

ECC mixture are discussed based on this cross-sectional data analysis.

2. Research significance

To design ECC with consistent mechanical properties, it is necessary to gain a comprehensive understanding of the roles of the variability of flaw size and fiber distribution on composite tensile behavior. This paper develops quantitative linkages between the material microstructure and composite macro behavior. For this purpose different experimental techniques were applied simultaneously for the first time to determine the fiber and flaw distribution in ECC, and correlate with tensile properties. The findings of this research enhance the fundamental knowledge of the factors governing the tensile ductility of ECC. With broadening use of ECC in field applications, this fundamental knowledge becomes increasingly significant in constructing structures with reliable performance.

3. Experimental studies

3.1. Materials and mix proportions

Type I ordinary Portland cement (OPC) compliant with ASTM C150 [7] was used in all mixtures. The physical properties and chemical composition of class F fly ash used in this study are listed in Table 1. This fly ash contains significant amount of Calcium Oxide (CaO). Approximately 83% (by weight) of fly ash particles are finer than 44 μm which indicates high reactivity with the secondary hydration products. Silica sand with a maximum grain size of 250 μm and a mean size of 110 μm was utilized as fine aggregate. A polycarboxylate-based high range water reducing admixture (HRWRA) was used for the purpose of changing the matrix flowability.

PVA fibers with 39 μm diameter and 12 mm length were used. The density, nominal tensile strength, Young's modulus, elongation at rupture of PVA fibers are 1.3 g/cm^3, 1620 MPa, 42.8 GPa and 6%, respectively. In order to reduce the excessive chemical bond between fiber and matrix, the surface of the PVA fiber is oil coated (1.2% by weight) at the manufacturing stage.

ECC mixtures were prepared using a Hobart mixer with a capacity of 5 l. All solid ingredients were premixed without water for 2 min. Water and HRWRA were then added. The resulting mixture was mixed for 1 min at low speed and for 2 min at high speed, respectively. Two PVA fiber reinforced ECC mixtures were prepared with identical fiber volume fraction (2%) and matrix proportions (adopted from [8]), except that the HRWRA dosage was deliberately varied to adjust matrix flowability (see Table 2). The matrix flowability was indirectly measured using a modified Marsh cone (orifice diameter was increased to 20 mm) flow time, as described in Li and Li [5] who reported a strong linear correlation between the modified Marsh cone flow time and plastic viscosity. The flow time of ECC-I and ECC-II mixes exhibiting different flowability were 15 s and 36 s, respectively. Relatively high flow time (between 24 and 37 s) is recommended by Li [9] for achieving better PVA fiber dispersion. HRWRA induced flow difference is expected to alter the pore structure and related maximum flaw size of ECC-I and ECC-II mixes.

Table 1
Analysis results of class F fly ash from Headwaters DTE Monroe.

Chemical analysis (%)		Physical analysis	
SiO_2	44.09	Fineness (retained on 44 μm) (%)	16.85
Al_2O_3	23.21	Strength activity index 7d (%)	83
Fe_2O_3	8.39	Strength activity index 28d (%)	92
SO_3	1.46	Water requirement (% of control)	97
CaO	14.04	Autoclave soundness (%)	0
LOI	0.56	Density	2.45

3.2. Specimen preparation and mechanical tests

Fresh ECC mixtures were cast into dogbone shaped molds on a vibration table at a moderate vibration rate. The geometry of dogbone specimens conforms to JSCE [10]. Three $50 \times 50 \times 50$ mm^3 cube specimens were also prepared with the same casting procedure for compression strength tests. Specimens were demolded after 24 h. After demolding, specimens were cured in sealed plastic bags at room temperature (23 ± 3 °C) for 7 days and then stored at room temperature until the age of 28 days.

At 28 days, uniaxial tensile tests were performed with a servo-hydraulic testing frame, under displacement control (0.5 mm/min). Two external linear variable displacement transducers (LVDT) were attached to the specimen with a gauge length of 100 mm for strain measurement. The uniaxial tensile test setup is shown in Fig. 1. The uniaxial compression tests were performed in accordance with ASTM C109 [11].

3.3. Methodology of cross-section analysis

After performing the uniaxial tensile tests, the gauge length region of each dogbone specimen was sectioned into five equal pieces perpendicular to the loading direction. Ten cross-sections with surface area of 30×12.7 mm^2 were exposed in this way (Fig. 2). The saw caused a loss of approximately 3 mm of specimen thickness at each cut. Due to this reason, cross-sections facing each other exhibited different flaw and fiber distribution characteristics. For example, bottom of piece #1, section (2), is different from the top of piece #2, section (3). All cross-sections were ground with #600 and #1000 SiC paper (2 min at 200 rpm for each paper) to create a smooth surface.

3.3.1. Determination of maximum flaw size distribution

Maximum flaw size at a given cross-section determines the cracking stress of the matrix at that section in accordance with Irwin's fracture criterion. Each cross-section was photographed with a high resolution camera. Binary images were processed using thresholding in the Image-J software of the National Institute of Health (NIH), and the maximum flaw size at each cross-section was determined (Fig. 3). In some cases light colored grinding dust filled the flaws and slightly reduced the observed flaw size. Overall, the maximum flaw sizes at all cross-sections were satisfactorily determined with this technique.

3.3.2. Determination of fiber dispersion coefficient

While flaw size distributions can be determined using basic optical microscopy, more advanced techniques are needed to determine the fiber distribution, such as fluorescence microscopy combined with digital image analysis, transmission X-ray photography, and AC-impedance spectroscopy [12–16]. Fluorescence microscopy combined with digital image analysis is particularly useful for detecting Poly-vinyl Alcohol (PVA) fibers in ECC [12], and is employed in this study for quantifying fiber distribution.

Among the cross-sections obtained above for flaw size analysis, the cross-section nearest to the final failure crack was first analyzed in order to determine fiber dispersion coefficient. This cross-section is considered to be the "weakest section", where fiber bridging strength is the lowest and, therefore, determines the ultimate tensile strength of the dogbone specimen. Additionally, three more cross-sections in the vicinity of this selected section were