Composites: Part B 45 (2013) 356–368

Contents lists available at SciVerse ScienceDirect

Composites: Part B

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

Improving the workability and rheological properties of Engineered Cementitious Composites using factorial experimental design

Mustafa Şahmaran [a,*], Zafer Bilici [a], Erdogan Ozbay [b], Tahir K. Erdem [c], Hasan E. Yucel [a], Mohamed Lachemi [d]

[a] Department of Civil Engineering, Gaziantep University, Gaziantep, Turkey
[b] Department of Civil Engineering, Mustafa Kemal University, Antakya, Turkey
[c] Department of Civil Engineering, İzmir Institute of Technology, İzmir, Turkey
[d] Department of Civil Engineering, Ryerson University, Toronto, Canada

ARTICLE INFO

Article history:
Received 8 February 2012
Received in revised form 25 August 2012
Accepted 31 August 2012
Available online 11 September 2012

Keywords:
A. Fibers
B. Rheological properties
B. Mechanical properties
A. Discontinuous reinforcement
Engineered Cementitious Composites

ABSTRACT

In the development of Engineered Cementitious Composites (ECC), micromechanics-based design theory is adopted to properly select the matrix constituents, fiber, and fiber–matrix interface properties to exhibit strain hardening and multiple cracking behaviors. Despite the micromechanics design constraints, practical applications show that the workability and rheological properties of matrix can affect the fiber dispersion uniformity, which have also direct concerns on composite mechanical properties. For this reason, in this research, parameters of micromechanics-based optimized ECC mixture design, which most possibly affecting the workability and rheological properties, are investigated. An experimental program that contains 36 different ECC mixtures was undertaken to quantitatively evaluate the combined effects of the following factors on workability and rheological properties: water-binder (w/b), sand-binder (s/b), superplasticizer-binder (SP/b) ratios and maximum aggregate size (D_{max}). A mini-slump cone, a Marsh cone and a rotational viscometer were used to evaluate the workability and rheological properties of ECC mixtures. Compressive strength and four point bending tests were used for mechanical characteristics of ECC mixtures at 28 days. The effects of studied parameters (w/b, s/b, SP/b and D_{max}) were characterized and analyzed using regression models, which can identify the primary factors and their interactions on the measured properties. Statistically significant regression models were developed for all tested parameters as function of w/b, s/b, SP/b and D_{max}. To find out the best possible ECC mixture under the range of parameters investigated for the desired workability and mechanical characteristics, a multi-objective optimization problem was defined and solved based on the developed regression models. Test results indicate that w/b, s/b and SP/b parameters affect the rheological and workability properties. On the other hand, for the range of studied aggregate sizes, D_{max} is found to be statistically insignificant on the rheological and workability properties of ECC.

1. Introduction

During the last decade concrete technology has been undergoing rapid development. The effort to modify the brittle behavior of plain cement materials such as cement pastes, mortars and concretes has resulted in modern concepts of high performance fiber reinforced cementitious composites (HPFRCCs) that exhibit ductile behavior under uniaxial tension load. HPFRCC promises to be used in a wide variety of civil engineering applications, as summarized in Japan Concrete Institute and by Kunieda and Rokugo [1,2]. One of the most promising areas of application of this material is in the repair and strengthening of concrete structures. Several investigations on the mechanical properties of HPFRCC and advantages of structures repaired/strengthened by HPFRCC have been carried out [3–10].

Engineered Cementitious Composite (ECC) is a special class of the new generation HPFRCC featuring high ductility with relatively low fiber content. Tensile strain capacity at a range of 3–5% has been demonstrated in ECC materials using polyvinyl alcohol (PVA) fibers with fiber volume fraction no greater than 2% [8–10]. Unlike ordinary concrete materials, ECC strain hardens after first cracking like a ductile metal and demonstrates approximately 300–500 times more tensile strain capacity than normal and fiber-reinforced concrete. Even at large imposed deformations under tensile loading, crack widths of ECC remain small, at less than 100 μm [11]. High fracture toughness and multiple cracks with tight crack width make ECC an ideal material to improve

* Corresponding author.
E-mail address: sahmaran@gantep.edu.tr (M. Şahmaran).

1359-8368/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2012.08.015

serviceability and durability of infrastructures. In recent years, the field application of ECCs has increased. The material has been successfully applied to dam repair, bridge deck overlays, coupling beams in high-rise buildings, and other structural elements and systems [2,12,13].

During the design of ECC, the criteria of micromechanical design theory, which is a technique to tailor the composite based on the understanding of the mechanical interactions between the matrix, fiber, and interface phases under load, has been considered [8]. In order to obtain desired high ductility, fiber should be uniformly distributed throughout the ECC's matrix, however, in some cases, because of the lack of perfect fiber dispersion or inhomogeneous distribution of fibers, mechanical properties of ECC tends to degrade as well as introduce undesirable variability into the mechanical properties [14]. Moreover, ingredients with inappropriate characteristics (type, size, and amount) as defined by micromechanical principles and ingredients from different sources and/or processing procedures lead to a change in the fresh and hardened properties of ECC. Thus, these facts restrict the widespread application and usability of this unique composite. So far, in most of the previous ECC researches, mix proportion of ECC kept constant or only the mineral admixture (generally fly ash) to cement ratio was changed, and all other parameters were kept constant [10,15,16]. However, it is very well known that the optimal design of the ECC mixture parameters committed to the micromechanical design theory criteria might be a very powerful tool to modify the workability and rheological properties of fresh cementitious mixture and mechanical properties of hardened composites.

The objective of this study is to investigate the effect of basic ECC design parameters such as water-binder (w/b), sand-binder (s/b), superplasticizer-binder (SP/b) ratios and maximum aggregate size (D_{max}) on the workability, rheological and mechanical properties of ECC and try to find out the optimal ECC mixture design for the maximization of the different performances. For this purpose, a factorial experimental design program was performed by considering the w/b, s/b, SP/b and D_{max} parameters to carry out their effectiveness on realizing the desired fresh (mini-slump flow and Marsh cone flow time, yield stress and plastic viscosity) and mechanical (crack size and density, mid-span beam deflection capacity, flexural and compressive strengths) properties. Then, the influences of each parameter and their interactions were characterized and statistically analyzed. After that, regression models were developed for the tested ECC parameters as function of w/b, s/b, SP/b and D_{max}. Finally, for the desired workability, rheological and mechanical characteristics, best possible ECC mixture under the constraints of this research was defined to meet the multiple objectives at the same time.

2. Experimental studies

2.1. Studied parameters and mixture proportions

As mentioned earlier, the design of ECC has been performed based on the micro-mechanical design theory constraining the alteration of ingredients' type and amount. Water-binder ratio, fiber (type, dimension and content) and sand-binder ratio can be considered as mixture constraints of ECC design. In order to get the desired tensile ductility, crack size and density after mechanical loading, ECC must be produced in accordance with the micromechanical design theory and production process. Otherwise, improper design and processing may lead to non-uniform fiber dispersion, inappropriate flaw size and distribution, or other microstructures not conducive to multiple cracking [14]. Suitable processing control is necessary to realize composite materials with expected optimal properties. In this study, the effect of four parameters, which are w/b, s/b, SP/b and D_{max}, were studied by committed to the micromechanical design theory. Before deciding the range of parameters given below, a number of trial mixtures varying in w/b, s/b, SP/b and D_{max} are proportioned and cast to meet a sufficient fresh and hardened properties for ECC [14]. All of these parameters were constrained or loosely constrained in ECC mixture design so the decided ranges of studied parameters as a result of trial mixtures were kept in a narrow interval. It is aimed to find out the effect of some fine tuning on the important design parameters governing the fresh, rheological and mechanical properties of ECC in the present study:

- w/b ratio (by mass), often used to adjust the workability of cementitious materials and it was studied as 0.27 (ratio for standard ECC – M45 design [10]) and 0.30;
- SP/b (%), reflecting the amount of superplasticizer (SP), a commonly used admixture to enhance the fluidity of cementitious materials; and studied as the percent of (0.200%, 0.225%, 0.250%, 0.275%, 0.300% and 0.325%) binder content;
- s/b (by mass), defined as the ratio of the amount of sand to total binder (Portland cement + fly ash), is used to find out the effect of sand content increment and it was studied as 0.36 (ratio for standard ECC – M45 design [10]) and 0.45;
- D_{max}, is used to clarify how the change of maximum aggregate size (D_{max}) will affect the properties of ECC. Two different sizes of D_{max} were studied, 400 μm and 1000 μm. In standard ECC – M45 design, D_{max} is 200 μm [10].

The increase in aggregate size and amount leads to an increase in the matrix toughness, which deteriorates the composite toughness in accordance with the micromechanical-based design calculations. Recently, fly ash (FA) has become what some consider a necessary component of ECC [10,15,16]. Increasing the FA content in ECC mixtures tends to improve the ductility of composites. The improvement in the tensile strain with the increase in the FA content can be attributed to the fact that the increase in the FA content tends to reduce the fiber/matrix interface chemical bond and matrix toughness, while increasing the interface frictional bond, in favor of attaining high tensile strain capacity [10]. In this study, in each mixture, about 70% of the Portland cement (FA/Portland cement ratio of 2.2, by mass) was replaced by fly ash in the production of ECC mixtures to compensate the increase in matrix fracture toughness caused by the increase in aggregate size and amount.

The four parameters listed above are chosen as the parameters of experimental design of this research and totally 36 ECC mixtures were developed and tested. Table 1 gives the details of the ECC mixtures.

2.2. Materials

CEM I 42.5 R Portland cement (PC), Class F fly ash (FA) conforming to ASTM C 618 requirements with a lime content of 1.64%, fine quartz with two different maximum aggregate size, polycarboxylate ether type high range water reducing admixture (HRWR) and polyvinyl alcohol (PVA) fiber were used in the production of ECC mixtures. Chemical composition and physical properties of PC and FA are presented in Table 2. The particle size distributions of PC and FA obtained by a laser scattering technique, is given in Fig. 1. So far, ECC has been successfully produced with an average grain size of about 110 μm silica sand [8] to obtain high ductility, tight crack width and high crack density. However, in order to improve the usability and applicability of ECC, it is very important to produce ECC with aggregates having more common sizes. For this purpose, in this research, ECC was produced by using the fine quartz with two maximum aggregate sizes (D_{max}) of 400 μm and 1000 μm. Water absorption capacity and specific gravity of quartz