EFFECT OF PVA FIBER RATIO ON MECHANICAL AND DIMENSIONAL STABILITY PROPERTIES OF ENGINEERED CEMENTITIOUS COMPOSITES

Hasan Erhan Yücel, Özge Küçükarslan

Nigde University, Central Campus, 51240, Nigde, Turkey

Abstract

Engineered Cementitious Composites-ECC is a type of high-performance fiber reinforced cementitious composites with high ductility and multiple micro-cracks under mechanical loadings. In literature, poly-vinyl-alcohol (PVA) fibers, %2 by volume, are used in the production of ECC. The aim of this study is to determine producibility of ECC with less PVA fiber ratios as %1.75, %1.50, %1.25 and %1.00. Mechanical (compressive and flexural strength) and dimensional stability (drying shrinkage) tests were performed on ECC samples. As a result, ECC can produce with less PVA fiber ratio for specified purposes.

Key words: *ECC, PVA fiber, compressive strength, flexural strength, drying shrinkage*

1. INTRODUCTION

Many countries in the world have been struggled with unsustainable development problems. The results of this struggle can be seen more clearly in countries that have developing and fast-growing economy. Public structures such as highways, airports, bridges, underground mass transport systems etc. are one of the most important elements of fast-growing economies to increase trade and foreign investments. Therefore, such structures can be considered as one of the keystones of economic development.

Public structures must have a minimum service life of 75 years according to European standards [1]. But, the experiences have shown that structures begin to deteriorate by the effect of mechanical loading and environmental conditions after 20 to 30 years of service lives [2]. Shortening of the service life of structures is very important because of the potential of the negative effects like repair and replacement of deteriorated structures, traffic congestion during repair/retrofit, released gases and fuel consumption. In addition, millions of dollars are needed for repair/retrofit of deteriorated structures. In recent years, the money spent for repair of existing structures has exceeded the money used for the construction of new structures [3]. For example, money spent annually for the maintenance of the bridges in Europe is over $ 1 billion [4]. In the light of this information, it is an inevitable need to develop a new high-performance construction material effective against mechanical loads and environmental conditions.

As a result of studies at the University of Michigan, a high-performance fiber reinforced cement-based composite material has been developed. It is called as Engineered Cementitious Composites (ECC). ECC resembles medium and high strength concrete in many aspects. For example, the compressive strength of ECC can be 30 to 100 MPa. However, different from other normal and high-performance composite materials, the tensile strain capacity of ECC is considerably high (about 3% to 5%) [5,6]. Since many ductile materials have tensile strain capacity as about 6% to 8%, ECC can be considered as a ductile material. Tensile strain capacity of ECC is about 300-500 times higher than tensile strain capacity of conventional concrete [5]. On the other hand, ECC shows ductile behavior under heavy flexural loads [7-9]. The main reason for the high ductility shown by ECC is strain hardening behavior after the first crack formation [7]. This behavior is possible with the micro-mechanical based design. High-performance composite materials are obtained with the control of the interaction between fiber, matrix and interface [10]. ECC uses relatively low amounts, typically 2% by volume, of short, discontinuous PVA fiber to gain strain hardening behavior.

In general, ECC have been used as repair material in reinforced concrete elements such as beam, column and shear wall to retrofit and increase their durability [7]. In addition, repair of retaining wall,

dam, bridge deck and pavement applications have been done by using ECC as overlay material in Japan, Korea, Switzerland, Australia and the U.S. [11]. Therefore, it is very important to analysis ECC according to the specifications of overlay materials.

The scientific research has been carried out in Nigde University, Construction Materials Laboratory. This research is composed of two stages. The first stage consists of the production of ECC with different PVA fiber ratios as %1.75, %1.50, %1.25 and %1.00 to determine the effect of PVA fiber ratio on compressive strength, flexural strength and dimensional stability properties. The main objective of the first stage is the production of ECC with less PVA fiber ratio to decrease production cost without compromising the material properties. Determination of overlay performances of produced ECC mixtures in the first stage is formed the second stage of the research. This article indicates the results of the first stage of the research.

2. EXPERIMENTAL PROGRAM

2.1. Materials and Mix Proportions

The cement used in all mixtures was a normal Portland cement CEM I 42.5R, similar to ASTM Type I cement. It had a specific gravity of 3.06 and Blaine fineness of 325 m^2/kg. Class-F fly ash conforming to ASTM C 618 [12] requirements with a lime content of 1.64% was used.

According to micro-mechanic based design of ECC, exhibiting ductile and showing a large crack number, but small in width, of cementitious composites, a low toughness of the matrix is required. However, with the increasing of maximum grain size of aggregate, an increase in toughness of the matrix appears and as a result, to obtain suitable ECC, aggregate grain size is limited [13]. Therefore, so far, ECC has been produced successfully with an average grain size of about 110 μm and maximum grain size of about 200 μm [13]. Using high volumes of industrial by-product in the production of ECC decreases matrix toughness and provides freedom of changing aggregate size. It is very important to produce ECC from normal size local sources of aggregate regarding widespread application. For this purpose, in the production of ECC, fine quartz with maximum aggregate size of 400 μm was obtained from local sources. Water absorption capacity and specific gravity of quartz aggregate used are 0.3% and 2.60, respectively.

To develop the workability of ECC mixtures, a high range water reducing admixture (HRWR – polycarboxylate ether as an active ingredient with 1.1 specific gravity and 40% solid content) was used.

PVA fiber was used in this study, although several kinds of fibers have been used in the production of ECC. The use of PVA fiber was decided based on micromechanical principals and PVA-ECC represents the most practical ECC used in the field [6, 14] at the present. PVA fibers have attracted most attention due to the outstanding composite performance and economics consideration. The dimensions of the PVA fiber are 8 mm in length and 39 μm in diameter. The density of the fiber is 1300 kg/m^3 and the nominal tensile strength of the fiber is 1620 MPa. In order to decrease the fiber/matrix interfacial bond strength, the surface of PVA fiber is coated by hydrophobic oil (1.2% by weight).

A fiber content of 2% by volume in excess of the calculated critical fiber content according to previous studies [6, 15] was typically used in the control mix design. Material quantities of all ECC mixtures were same except for PVA fiber content. Different fiber ratios of the control mix as %1.75, %1.50, %1.25 and %1.00 by volume were used for production of ECC to determine the effect of PVA fiber on mechanical and dimensional stability properties of ECC. The Mix IDs were determined as ECC-2.00 (control mix), ECC-1.75, ECC-1.50, ECC-1.25, ECC-1.00 according to PVA fiber content. The numbers written after ECC referred to PVA fiber content of each mix. The proportions of all ECC mixtures can be seen in Table 1.

Materials (kg/m^3)	**ECC-2.00 (Control Mix)**	**ECC-1.75**	**ECC-1.50**	**ECC-1.25**	**ECC-1.00**
Portland Cement	566	566	566	566	566
Fly Ash	680	680	680	680	680
Water	331	331	331	331	331
Quartz Sand	453	453	453	453	453
HRWR	5.0	5.0	5.0	5.0	5.0
PVA	26.00	22.75	19.50	16.25	13.00
Water/Binder	0.27	0.27	0.27	0.27	0.27

Table 1. Proportions of ECC Mixtures

2.2. Test Methods

2.2.1. Compressive Strength

Twelve cubic samples (6 specimens for each of age) of 50 mm were cast from each ECC mixture. The samples were demolded after 24 hours, and moisture cured in plastic bags at 95±5 % relative humidity, 23±2 ºC for 7 days. The samples were then air cured at 50±5 % relative humidity (RH), 23±2 ºC until the day of testing. In accordance with ASTM C39 [16], the compression test was performed on the cubic samples by using a 3000 kN capacity testing machine (Fig. 1-a). ECC cubic specimens were tested for compressive strength measurement at the age of 7 and 28 days.

2.2.2. Flexural Strength

To measure the flexural performance of ECC mixture, twelve prismatic samples (6 specimens for each testing age) having dimensions of 360x75x50 mm were cast from each produced ECC mixture. ECC prisms were first cleaned, and then flexural strength under four-point test was performed by using universal testing system. Four point bending test was performed on a closed-loop controlled material testing system at a loading rate of 0.005 mm/s. The capacity of the loading frame was 100 kN (Fig. 1-b). To eliminate extraneous deformations like sample rotations and support settlements, a four point bending loading fixture was improved. The span length of flexural loading was 304 mm with a 101 mm center span length. During the flexural tests, the load and mid-span deflection were written down on data recording system in a computer. Linear variable displacement transducer (LVDT) was fixed on the test set-up to measure the flexural deflection of the specimen. In this study, flexural deflection capacity of ECC prismatic specimens is also determined.

2.2.3. Drying Shrinkage

In accordance with ASTM C157 [17], the drying shrinkage of bar specimens was measured up to 112 days after an initial curing of one day in the mould and 27 days in lime saturated water by using three 285×25×25 mm prismatic specimens for all ECC mixtures (Fig. 1-c). Gauge studs were inserted in the bar moulds coaxial with the bar before the ECC mixtures were poured into the moulds. The drying shrinkage specimens were stored in the laboratory at 23±2 ºC, and 50±5% RH.



(a) (b) (c)

Fig. 1. (a) Compressive Strength, (b) Flexural Strength and (c) Drying Shrinkage Tests Set-ups

3. RESULTS AND DISCUSSIONS

The first aim of this scientific research is to produce ECC with different PVA fiber ratios and compare them with ECC which is known as 'standard ECC mixture' according to the literature [18] produced with 2% PVA fiber ratio by volume. Compressive strength, flexural strength and drying shrinkage properties of ECC mixtures were used for the comparison.

3.1. Compressive Strength

Compressive strength test results of ECC mixtures for the age of 7 and 28 days are summarized in Table 2. According to the test results, slight differences of compressive strength values were observed because of the low differences of PVA fiber contents of ECC mixtures. The compressive strength of ECC mixtures slightly increased with the reduction of PVA fiber content. Compressive strength values increased about 8.65% and 4.84% from ECC-2.00 to ECC-1.00 at 7 and 28 days, respectively.

It is known that the addition of fiber in cement-based composites increases the amount of entrapped air voids in the matrix [19] and decreases compressive strength of the mix [20-22]. Another study about PVA fibers also shows that increase of PVA fiber ratio decreases the compressive strength values [23]. Therefore, the compression test results of this study match up with previous studies in the literature. In addition, when viewed in terms of compressive strength, all ECC mixtures can use instead of ECC-2.00 (control mix) because of the higher compressive strength.

Mix ID	**Compressive Strength, MPa**		**Flexural Strength, MPa**	
	7 Days	**28 Days**	**7 Days**	**28 Days**
ECC-2.00	39.3	66.1	8.15	10.51
ECC-1.75	39.9	67.5	8.01	9.18
ECC-1.50	40.5	68.0	7.39	8.79
ECC-1.25	41.5	68.7	6.56	7.30
ECC-1.00	42.7	69.3	5.49	6.30

Table 2. Compressive Strength and Flexural Strength Tests Results of ECC Mixtures

3.2. Flexural Strength

Flexural strength values of ECC mixtures are shown in Table 2 for the age of 7 and 28 days. Flexural strength of ECC mixtures increased with the increase of PVA fiber ratio. As seen from Table 2, flexural strength values varied from 8.15 MPa to 5.49 MPa for 7 days and from 10.51 MPa to 6.30 MPa for 28 days. ECC-2.00 mixture had the highest flexural strength value for both 7 and 28 days because of the highest PVA fiber content and the values decreased by reduction of PVA fiber content. The previous studies [21, 24] also showed this similar trend between fiber content and flexural strength of the mixture.

3.3. Drying Shrinkage

Drying shrinkage measurements of all ECC mixtures are summarized in Fig. 2. According to drying shrinkage test results, similar shrinkage data were observed for all ECC mixtures. The range of drying shrinkage values from 1185 μm to 1060 μm at 112 days. Although drying shrinkage values were similar, the data slightly decreased with the reduction of PVA fiber content at 112 days as seen in Fig. 2. As a result, it is suitable to use all ECC mixtures instead of ECC-2.00 because of the lower drying shrinkage values.

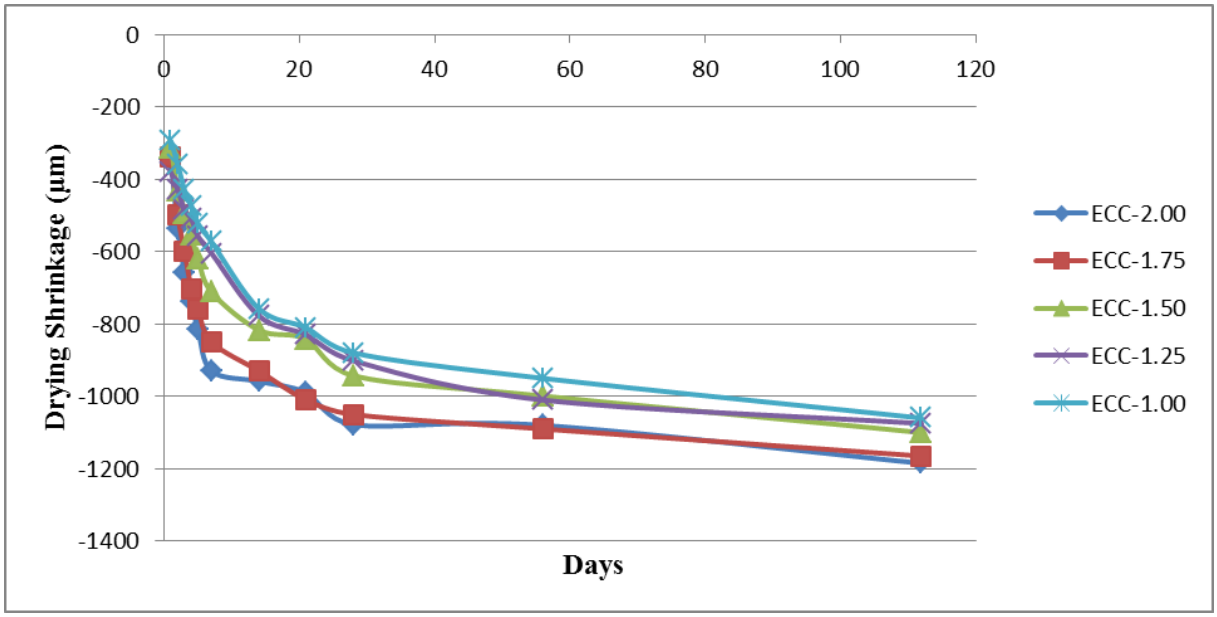

Fig. 2. Drying Shrinkage Test Results

4. CONCLUSIONS

In this study different PVA fiber content of ECC mixtures as %1.75, %1.50, %1.25 and %1.00 were produced and compared with standard ECC mixture produced with 2% PVA fiber ratio by volume. According to the test results:

- All ECC mixtures were successfully produced with high compressive and flexural strength and low drying shrinkage values.
- The compressive strength of ECC mixtures slightly increased with the reduction of PVA fiber content.
- Flexural strength of ECC mixtures increased with the increase of PVA fiber ratio.
- Drying shrinkage values slightly decreased with the reduction of PVA fiber content.

As a result, for compressive strength and drying shrinkage point of view, all ECC mixtures were acceptable for structures or applications where ECC-2.00 is used. However, when considering flexural strength, 6.30 MPa limit was observed for ECC-1.00 at 28 days, which was the lowest flexural strength value for all ECC mixtures. Therefore, it is important to note that all ECC mixtures can be used in the applications required lower than 6.30 MPa flexural strength at 28 days. In conclusion, all ECC mixtures produced in this study can be easily used according to the specified limits of the applications.

REFERENCES

[1] Alexander, MG & Stanish, K 2005, 'Durability design and specification of reinforced concrete structures using a multi-factored approach', CONMAT'05, pp. 10.

[2] Mehta, PK & Burrows, RW 2001, 'Building durable structures in the 21st century', *Conc Int*, vol. 23, no. 3, pp. 57-63.

[3] Vecchio, F & Bucci, F 1999, 'Analysis of repaired reinforced concrete structures', *ASCE Str Eng*, vol. 125, no. 6, pp. 644-652.

[4] Raupach, M 2006, 'Concrete repair according to the new European standard EN-1504', RWTH Aachen.

[5] Li, VC 1998, 'Engineered cementitious composites – tailored composites through micromechanical modelling, in fiber reinforced concrete: present and the future', Eds. N. Banthia et. A., CSCE, Montreal, pp.64-97.

[6] Li, VC, Wang, S & Wu, C 2001, 'Tensile strain-hardening behaviour of PVA-ECC', *ACI Materials Journal*, vol. 98, no. 6, pp. 483-492.

[7] Li, VC & Kanda, T 1998, 'Engineered cementitious composites for structural applications', *ASCE J. Materials in Civil Engineering*, vol. 10, no. 2, pp. 66-69.

[8] Li, VC, Mishra, DK, Naaman, AE, Wight, JK, LaFave, JM, Wu, HC & Inada, Y 1994, 'On the shear behavior of engineered cementitious composites', *J. of Advanced Cement Based Materials*, vol. 1, no. 3, pp. 142-149.

[9] Li, VC 1997, 'Damage tolerance of engineered cementitious composites', in Advances in Fracture Research, Proc. 9th ICF Conference on Fracture, Sydney, Australia, Ed. B.L.Karihaloo, Y.W. Mai, M.I. Ripley and R.O. Ritchie, Pub. Pergamon, UK, pp. 619-630.

[10] Li, VC 2003, 'On engineered cementitious composites (ECC) – a review of the material and its applications', *J. Advanced Concrete Technology*, vol. 1, no. 3, pp.215-230.

[11] Srinivasa, CH & Venkatesh, D 2014, 'A literature review on engineered cementitious composites for structural applications', *International Journal of Engineering Research & Technology*, vol. 3, issue 12, pp. 531-537.

[12] ASTM C618 2003, 'Standard specification for coal fly ash and raw or calcined natural pozzolan for the use of mineral admixtures in portland cement concrete' *American Society for Testing and Materials*, Philadelphia, USA.

[13] Li, VC, Mishra, DK & Wu, HC 1995, 'Matrix design for pseudo strain- hardening fiber reinforced cementitious composites', *RILEM Journal of Materials and Structures*, vol. 28, pp. 586-595.

[14] Kunieda, M & Rokugo, K 2006, 'Recent progress on HPFRCC in Japan', *Journal of Advanced Concrete Technology*, vol. 4, no. 1, pp. 19-33.

[15] Kong, HJ, Bike, S & Li, VC 2003, 'Development of a self-consolidating engineered cementitious composite employing electrosteric dispersion / stabilization', *Journal of Cement and Concrete Composites*, vol. 25, pp. 301-309.

[16] ASTM C39 2003, 'Standard test method for compressive strength of cylindrical concrete specimens', *American Society for Testing and Materials*, Philadelphia, USA.

[17] ASTM C157 2004, 'Standard test method for length change of hardened hydraulic-cement mortar and concrete', *American Society for Testing and Materials*, Philadelphia, USA.

[18] Özbay, E, Şahmaran, M, Lachemi, M & Yücel, HE 2013, 'Effect of microcracking on the frost durability of high volume fly ash and slag incorporated ECC', *ACI Materials Journal*, vol. 110, no. 3, pp. 259-268.

[19] Şahmaran, M, Özbay, E, Yücel, HE, Lachemi, M & Li, VC 2012, 'Frost resistance and microstructure of engineered cementitious composites: influence of fly ash and micro poly-vinyl-alcohol fiber', *Cement and Concrete Composites*, vol. 34, no. 2, pp. 156-165.

[20] Abu-Lebdeh, TM, Fini, E & Lumpkin, M 2012, 'Flexural and tensile characteristics of micro fiber-reinforced very high strength concrete thin panels', *American Journal of Engineering and Applied Sciences*, vol. 5, no. 2, pp. 184-197.

[21] Iqbal, S, Ali, A, Holschemachera K & Bier, TA 2015, 'Effect of change in micro steel fiber content on properties of high strength steel fiber reinforced lightweight self-compacting concrete (HSLSCC)', *Procedia Engineering*, vol. 122, pp. 88 – 94.

[22] Jen, G, Trono, W & Ostertag, CP 2016, 'Self-consolidating hybrid fiber reinforced concrete: Development, properties and composite behavior', *Construction and Building Materials*, vol. 104, pp. 63–71.

[23] Noushini, A, Samali, B & Vessalas, K 2013, 'Influence of polyvinyl alcohol fibre addition on fresh and hardened properties of concrete', *Hokkaido University Collection of Scholarly and Academic Papers: HUSCAP*, pp. 1-8.

[24] Arisoy, B & Wu, HC 2008, 'Material characteristics of high performance lightweight concrete reinforced with PVA', *Construction and Building Materials*, vol. 22, pp. 635–645.