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MECHANICAL PROPERTIES OF A PVA FIBER REINFORCED ENGINEERED CEMENTITIOUS COMPOSITE

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High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) are promising construction materials characterized by tensile strain hardening behavior. Engineered Cementitious Composite (ECC) is a special type of HPFRCC developed with enhanced ductility and durability. Coarse aggregates are usually excluded from the ECC matrix, and the reported ECCs are typically produced with microsilica sand having a maximum grain size of 200 µm. In this paper, a PVA-ECC mixture containing local dune sand with a maximum grain size of 300 µm was developed, and its compressive and tensile properties were experimentally investigated. A dog-bone-shaped specimen and a rectangular-coupon-shaped specimen were both used in the tensile test, and it was found after extensive research that the dog-bone specimen was more suitable than the rectangular coupon specimen. The experimental results from the dog-bone specimens indicated that the newly-developed composite possessed good tensile strain-hardening behavior, with a high ultimate tensile strength, and the compressive strength was comparable to that of existing PVA-ECCs.

Keywords: HPFRCC, PVA-ECC, Aggregate, Grain size, Compression, Tension.

1 INTRODUCTION

High Performance Fiber Reinforced Cementitious Composites (HPFRCCs), with their superior resistance to tensile loads and various environmental conditions, have been promoted as promising construction materials to overcome the shortcomings of conventional concrete, such as poor durability and serviceability. Engineered Cementitious Composite (ECC) is a special type of HPFRCC featuring enhanced ductility and tight crack width. Unlike ordinary cementitious materials, ECC is designed based on micromechanical principles and fracture mechanics, with the mechanical interactions between matrix, fiber, and interface taken into account, which results in optimized mechanical performance for the composite. One of the most significant characteristics of ECC is the excellent tensile strain-hardening behavior. For example, the strain capacity for polyethylene fiber or polyvinyl alcohol (PVA) fiber-reinforced ECC was in the range of 2% to 5%, with fiber content no more than 2% by volume (Kanda *et al.* 2000, Li *et al.* 2001).

For ECC, the mix proportions, the geometrical and mechanical properties of fiber, as well as the type and size of matrix ingredients are defined by the micromechanical principles in order to achieve desired high ductility and self-controlled crack width.

Ingredients with inappropriate characteristics and/or ingredients from a different source may lead to a decrease in ductility and even absence of strain-hardening behavior. Aggregates (coarse aggregates in particular) are considered to play a major role in controlling the dimensional stability of the cementitious materials. In the presence of fibers, however, the introduction of aggregates having a grain size larger than the average fiber spacing may lead to balling of the fibers (Soroushian *et al*. 1992, Sahmaran *et al.* 2009), hindering uniform dispersion of fibers in the matrix. Moreover, the inclusion of coarse aggregates in the mix tends to increase the matrix toughness, which will negatively affect the tensile strain-hardening behavior of the composite. Therefore, in spite of positive effect of coarse aggregates in terms of economy, strength and dimensional stability, ECC in most of the previous researches have been designed with coarse aggregates deliberately eliminated, and fine aggregates restricted to microsilica sand with a maximum grain size of 200 µm so far (Li *et al.* 2001).

Recently, the influence of aggregate type and grain size on the tensile ductility and mechanical properties of ECC has been investigated (Sahmaran *et al.* 2009, Şahmaran *et al.* 2012, Şahmaran *et al.* 2013). Their studies indicated that apart from microsilica sand, crushed sand and gravel sand with relatively larger grain size can also be successfully used to produce ECC. Further, the negative effect of the increase in matrix toughness due to the increase of aggregate size could be alleviated by using a high volume mineral admixture, such as fly ash (FA).

The aim of this research is to develop a PVA-ECC composite with moderately high compressive strength while maintaining the tensile ductility using local ingredients, including local dune sand having a maximum grain size of 300 µm and an average grain size of 200 µm. Mechanical properties, including compressive strength, tensile strength and strain capacity of the PVA-ECC, were experimentally tested and analyzed in this paper. The developed PVA-ECC in this research was comparable with the PVA-ECC developed by Li and his associates (Li *et al.* 2002, Sahmaran *et al.* 2009) in terms of compressive and ultimate tensile strength, while suffering from loss of ductility.

2 EXPERIMENTAL PROGRAM

2.1 Materials and Mix Proportions

The basic matrix ingredients in the newly developed PVA-ECC were Portland cement, fly ash, fine aggregates and superplasticizer. The cement used was AS3972 Type General Purpose cement (C) from Cement Australia Pty Ltd and the fly ash (FA) used was from Boral Ltd with a lime content of 1.59%. The fine aggregates used were local dune sand with a maximum grain size of 300 µm and an average grain size of 200 µm. In terms of superplasticizer, a polycarboxylic-ether-based high-range water reducer (HRWR) ADVA® 142 from W.R. Grace & Co. was used. The PVA fibers used in this study were 12 mm KURALON K-II REC15 supplied by Kuraray Co., Ltd., which were extensively used in previous ECC studies (Li *et al.* 2001, Li *et al.* 2002). The geometrical and mechanical properties of the PVA fibers are listed in Table 1.

The mix proportions of the developed PVA-ECC are summarized in Table 2. The mineral admixture replacement level, with an FA/C ratio of 1.2 by mass, was considered. The volume of sand with respect to the volume of binder (C+FA) was designed with a value of 0.36. The water-to-binder ratio (W/B) was determined at 0.3 through a previous study done by the authors (Huang *et al.* 2014). This value was chosen as it provided a point of balance between the matrix toughness requirement for strain-hardening behavior and the rheological requirement for good fiber dispersion, both of which contribute to successful production of ECC. The fiber-volume fraction was set to be 2.2%.

Table 1. Geometrical and mechanical properties of PVA fiber.

Length (mm)	**Diameter (μm)**	**Nominal strength (MPa)**	**Young's modulus (GPa)**	**Elongation (%)**
12	8	1620	42.8	6

Table 2. Mix proportions of the developed PVA-ECC.

Cement	**Fly ash**	**Sand/Binder**	**Water/Binder**	**HRWR**	**Fiber (vol. %)**
1.0	1.2	0.36	0.3	0.01	2.2

2.2 Specimen Preparation

For the tensile test, the rectangular-coupon specimen was used by Li and his associates (Li *et al.* 2001, Li *et al.* 2002, Sahmaran *et al.* 2009), and the dog-bone specimen by other researchers (Kim *et al.* 2007, Soe *et al.* 2013) in previous studies. In this research, these two categories of specimen were used so as to determine which one is more appropriate for the tensile test. The rectangular coupon specimen is measured as 350 x 65 x 20 mm, with a gauge length of approximately 145 mm (see Figure 1). The dog-bone specimen is completely similar to the rectangular-coupon specimen, except that it has a reduced section of 80 x 35 x 20 mm in the middle and a gauge length of 80 mm (see Figure 2). The 50-mm cubic specimen was used for the compressive test.

A mortar mixer with a rotating blade was used in preparing the ECC mixture. At first, all solid ingredients except fibers were dry mixed for one minute. During this time, the HRWR was fully added in the measured water to form a liquid solution. After the dry contents were thoroughly mixed, the HRWR solution was added in and mixed for a couple of minutes. Finally, the fibers were manually added in small amounts until all the fibers were dispersed into the cementitious matrix. Shortly afterwards, the mixture was completed and was then cast into the greased molds. From each PVA-ECC mixture, a total of ten tensile specimens and nine compressive specimens were prepared. Five tensile specimens and three compressive specimens were tested at the age of 7 and 14 days, respectively. And the other three compressive specimens were tested at the age of 42 days. All specimens were covered with plastic sheets until demolded after 24 hours. The specimens were then moisture-cured at 100% humidity and 23°C until the day of testing.

It should be noted that one day before the tensile testing, the tensile specimens were taken out of the curing room, and aluminum plates were glued onto both sides at each end of the specimen, in order to facilitate gripping and to distribute force (see Figure 1 and 2). International® Epiglue high-performance epoxy resin glue was used, and one day was allowed for the curing of the glue. A Shimadzu® Autograph AG-X machine of a 100 KN capacity was used to conduct the direct tensile tests. The Shimadzu® TRViewX non-contact digital video extensometer was used to measure the deformation. For a more detailed experimental set-up and testing procedure for the tensile test, refer to Soe *et al.*'s work (2013).

It was observed that most rectangular coupon specimens failed next to the grip (see Figure 3), indicating that the grip area suffered from high-stress concentration. This may have resulted in premature failure. The dog-bone specimens, on the other hand, mostly failed within the reduced section, which was entirely covered by the gauge length (see Figure 4). Thus, the dog-bone specimen was found to be more suitable for the tensile test. In this paper, the tensile properties of the developed PVA-ECC were measured from the dog-bone specimens.

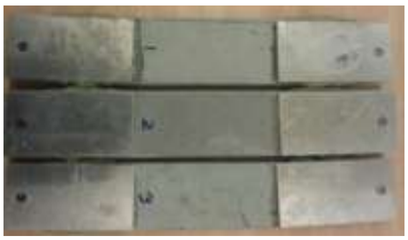

Figure 1. Rectangular-coupon tensile specimen.

Figure 2. Dog-bone tensile specimen.

Figure 3. Grip end failure in rectangular-coupon tensile specimens.

Figure 4. Failure in dog-bone tensile specimens.

3 RESULTS AND DISCUSSION

3.1 Direct Tensile Behavior

The direct tensile test results in terms of a stress-strain relationship at the age of 7 days and 14 days are displayed in Figure 5 and Figure 6, respectively. The stress-strain curves indicate that the developed cementitious composite showed tensile strain-hardening behavior, with the load continuing to increase beyond the first matrix cracking. The tensile strength and strain capacity are summarized in Table 3.

As seen from Table 3, the tensile strength of the developed PVA-ECC is 5.17 MPa at the age of 14 days, which is greater than that of the PVA-ECCs containing either microsilica sand, crushed sand, or gravel sand. Specifically, the tensile strength of the PVA-ECC with microsilica sand is 4.41 MPa at the age of 14 days (Li *et al*. 2002). The tensile strength of the PVA-ECC with crushed sand or gravel sand ranges from 4.46 MPa to 5.02 MPa, depending on the aggregate type and size at the age of 28 days (Sahmaran *et al*. 2009). However, the newly-developed PVA-ECC is less ductile than other PVA-ECCs, with the strain capacity at the age of 7 days ranging from 1.7% to 2.4%. The PVA-ECC with microsilica sand exhibits an average strain capacity of

3.48% at the same age (Sahmaran *et al.* 2008). It is estimated that the diminished ductility might be the result of poor fiber dispersion, which is indicated by the high variation of the strain capacity. The strain capacity measured at 14 days is slightly lower than that of 7 days, which coincides with the phenomenon observed in previous studies (Sahmaran *et al*. 2008). In contrast to the strain capacity, the tensile strength increases from 4.47 MPa at the age of 7 days to 5.17 MPa at the age of 14 days.

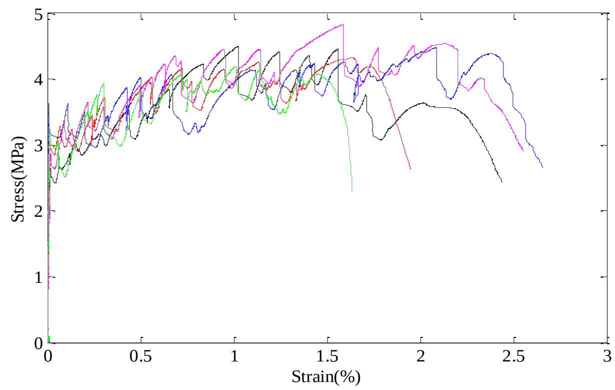

Figure 5. Tensile stress-strain curves of the PVA-ECC at the age of 7 days.

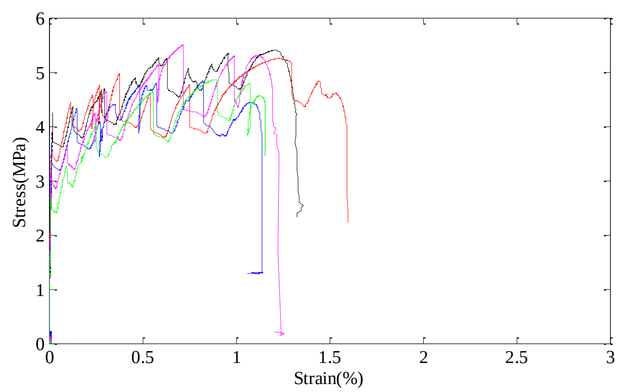

Figure 6. Tensile stress-strain curves of the PVA-ECC at the age of 14 days.

Table 3. Uniaxial tensile properties of the PVA-ECC.

Age (days)	**Ultimate tensile strength (MPa)**	**Tensile strain capacity (%)**
7	4.47(0.21)	1.96(0.33)
14	5.17(0.27)	1.22(0.16)

*Number in brackets is standard deviation.

3.2 Compressive Strength

The compressive strength of the developed PVA-ECC at the age of 7 days, 14 days, and 42 days are summarized in Table 4. Each is the average of three test results.

It can be expected that the compressive strength of the developed PVA-ECC is comparable to that of the previous PVA-ECCs of a different aggregate type and size, which were of a compressive strength ranging from 57.8 MPa to 62.5 MPa at 28 days (Sahmaran et al. 2009). This is despite the fact that the W/B ratio was deliberately increased from 0.27 to 0.3 to decrease the matrix toughness, in order to compensate for the increase in matrix toughness due to the increase in aggregate size. The compressive strength of the developed composite can meet most applications in civil engineering.

Table 4. Compressive strength of the developed HPFRCC.

Age (days)	7	14	42
Compressive strength (MPa)	34.9	48.2	66.4

4 CONCLUSIONS

A PVA fiber-reinforced ECC was developed using local dune sand instead of microsilica sand. A series of tests were carried out to study the compressive and tensile properties of this composite. The test results indicated that the composite exhibited good tensile strain-hardening behavior, with the tensile strain capacity ranging from 1.7% to 2.4% at the age of 7 days, and 1.1% to 1.6% at the age of 14 days. The ultimate tensile strength of the newly developed PVA-ECC exceeds that of the previous PVA-ECCs, while the compressive strength is similar.

From this investigation, it is also found that the specimen of the configuration of a dog-bone is more appropriate than the rectangular coupon specimen for the tensile test.

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