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Mechanical behaviour of a polyvinyl alcohol fibre reinforced engineered cementitious composite (PVA-ECC) using local ingredients

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HIGHLIGHTS

- A new PVA-ECC with reduced cost and strain capability matching that of steel rebar.
- Extensive tests on the mechanical behaviour including large number of tensile test.
- A statistical analysis for the study of the probability distribution.
- A new finite element model for modelling of flexural behaviour of PVA-ECC beams.
- Development of a relationship on tensile strength between 2D and 3D specimen.

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ABSTRACT

A polyvinyl alcohol fibre reinforced engineered cementitious composite (PVA-ECC) using local ingredients is developed, aiming for a reduced cost and a tensile strain capacity matching that of steel reinforcement for commonly used reinforced concrete structures. Experiments are conducted to determine mechanical behaviour of the composite. In addition, a finite element model is developed to simulate the flexural behaviour of PVA-ECC beams, and experimental results are used to calibrate the model. The material models of the PVA-ECC under compression and tension are calibrated using experimental results of uniaxial compression and tension tests. Furthermore, a theoretical relationship on the tensile strength between specimens with two-dimensional and three-dimensional fibre distribution is derived, and accuracy of the simulation is improved by using the theoretical ratio. Agreement between the computed results and the experimental data demonstrates the effectiveness of the finite element model.

1. Introduction

High performance fibre reinforced cement composites (HPFRCC) are considered promising construction materials due to their superior mechanical properties. Engineered Cementitious Composite (ECC) belongs to HPFRCCs and is known for its significantly improved tensile strain hardening behaviour and multiple microcrackings [1]. ECC contains a mix of cement, fly ash, sand, water, chemical additive and randomly distributed fibres. The type, geometry and volume fraction of constituents used in the mix, in particular the characteristics of the fibre, play an important role in tailoring the material properties of the composites [2].

Fibres such as polypropylene (PP), polyethylene (PE) and polyvinyl alcohol (PVA) fibres have been used in ECCs. A variety of ECCs reinforced with these fibres have been developed. Among these, PVA fibre has a higher tensile strength than PP fibre, and ECC mixed with PVA fibre shows higher toughness and flexural strength than that reinforced with PP fibre [3]. Furthermore, compared to PE fibre, PVA fibre is eight times cheaper [4]. Hitherto research on PVA-ECC has been the main focus of ECC design. For a typical PVA-ECC with a fibre volume fraction of 2%, a tensile strain capacity up to 4% and an ultimate strength of 4.5 MPa can be achieved [4].

Because of the high ductility of PVA-ECC, it has been proposed for use in steel reinforced structural elements to improve component strength and ductility capacity. Recent research shows that there is room to employ an ECC with a slightly lower tensile strain capacity in ECC structural members [5]. It should be noted that with the recent trend of using reinforcement bars with high yield strength (e.g. 600 MPa or even higher) in reinforced concrete (RC) structures, a minimum tensile strain of 0.5% of the ECC matrix is essential to ensure that the ECC will not fail before the yielding of the reinforcement bars. However, tensile strain capacity beyond

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1%, which far exceeds the yield strain of even high strength steel (≈0.5%), will only lead to performance improvement at the material or local level (e.g. control of crack size and numbers) but generally will not improve much on the structural performance of the RC structures in most normal structural engineering applications. Thus, an ECC matrix with a slightly lower tensile strain is required for optimal design and to take full advantage of the ECC material.

The aggregate type and grain size have been found to significantly affect the tensile ductility and mechanical properties of ECC [6,7]. Most of the reported PVA-ECCs have used microsilica sand with a maximum size of 200 μm [4]. Sahmaran et al. [6] indicated that the increase in aggregate size might have a negative effect on the ductility. Local sand, which has coarser particle size than microsilica sand, can be used to obtain a slightly lower tensile strain capacity. Moreover, using local sand can reduce both material cost and manufacturing cost since microsilica sand is relatively expensive and difficult to obtain. In many situations, using local sand as the main construction material is not only a cost saving option but also a good solution for the complex social and environmental problems caused by the production of construction material. A quite notable situation is the import/export of fine sand as the main ingredient for concrete production in the Southeast Asia region. Many countries imposed export restriction (or even ban) on river/sea fine sand due to the substantial social and environment problems generated during extraction. Therefore, the use of local ingredients would be preferred for broader adoption of PVA-ECC in large-scale applications by considering economic reasons, availability as well as environment sustainability [8].

In this paper, a PVA-ECC that has a reduced cost achieved by using local sand is developed. With the use of local sand, it is expected that the tensile strain will be reduced but it is acceptable if the tensile strain is controlled within the "*optimal*" range of 0.5–1% for RC structure applications. The mechanical properties of the PVA-ECC including Young's modulus, stress-strain relationship under uniaxial compression and tension, and flexural behaviour are investigated experimentally. Statistical analysis is conducted on the mechanical properties of the PVA-ECC, based on which, the 95% confidence interval of the population mean is calculated. Since the number of tested specimens is relatively small, Student's t distribution is employed for statistical analysis. Since PVA-ECC has a promising future in flexural members in civil structures, the flexural performance and cracking behaviour of the PVA-ECC beam should be fully investigated before its practical application. To date, limited numerical studies have been conducted on the structural behaviour of ECC members [9], although numerical method has been regarded an accurate and effective methods in predicting structural behaviour with varying parameters saving time and cost from experiment. In this paper, a finite element model is also developed to simulate the flexural behaviour of PVA-ECC beams with material models under compression and tension calibrated from experiments. Furthermore, a theoretical relationship on the tensile strength between specimens with two-dimensional and three-dimensional fibre distribution is derived. The developed finite element model and the proposed relationship are validated by comparing the experimental results of four point bending tests with the results obtained from the finite element analysis.

2. Experimental part

2.1. Materials

The materials used in the developed PVA-ECC were Portland cement, fly ash, local dune sand, water, high-range water reducing agent (HRWR) and PVA fibres. General purpose cement from Cement Australia Pty. Ltd. and ASTM class F fly ash were applied. The local dune sand employed in this research had an average grain size of 200 μm with a maximum grain size of 300 μm. The PVA fibres used in this study were KURALON K-II REC15 fibres supplied by Kuraray Co., Ltd, and their specifications are shown in Table 1.

2.2. Specimen preparation

The proportions of the PVA-ECC mix are summarized in Table 2. The PVA-ECC was mixed using a mortar mixer with a rotating blade. First, the solid ingredients, including cement, fly ash and sand, were fully mixed for two minutes. Meanwhile, the HRWR was added into the measured water to form a liquid solution. Then, the HRWR solution was slowly added into the mix. After the mixture became uniform and consistent, the fibres were slowly and manually added to achieve an even dispersion. Finally, all the ingredients were blended for 5–10 min until thoroughly mixed.

This mix design was obtained based on trial tests done in a previous study [10]. The fly ash to cement ratio was set at 1.2 by mass. The volume of sand with respect to the volume of binder (cement + fly ash) was set at 0.36. The water to binder ratio was determined at 0.3 as it provided a point of balance between the matrix toughness requirement for strain-hardening behaviour and the rheological requirement for good fibre dispersion. A high-range water reducing agent from Grace Australia Pty. Ltd. was used with a ratio of 0.01 to cement, and a 2.2% by volume fraction of PVA fibres was employed.

When the mixing process was complete, the fresh mixture was poured into greased moulds which were then vibrated on a vibrating table for a few minutes. After casting, the specimens were covered with lids and demoulded after 24 h. The specimens were then cured at a constant temperature of 23 °C and relative humidity of 100% until the day of testing. All the tests reported in this paper were performed at the age of 28 days.

Five cylinder specimens of 200 mm in height and 100 mm in diameter were cast for the uniaxial compression test. After grinding the top surface of the cylinders, the average value and standard deviations of the height and diameter were 195.64 (0.88) mm and 100.11 (0.23) mm, respectively. A Mitutoyo absolute digimatic caliper with a resolution of 0.01 mm was used for measurement. Two cylinder specimens were applied for the Young's modulus test, with an average height of 196.91 (0.11) mm and diameter of 100.16 (0.04) mm. Eighteen dog-bone specimens with a reduced section of 80 mm × 36 mm × 20 mm in the middle and a gauge length of 80 mm, as shown in Fig. 1, were used for the uniaxial tension test [10]. The average value and standard deviations of the length, width and thickness are 80.12 (0.30) mm, 37.54 (0.97) mm, 20.41 (0.24) mm, respectively. For the four-point bending test, six beam specimens with dimensions of 350 mm × 100 mm × 100 mm were employed (see Fig. 2). The average length, width and height of the six beams were 349.86 (0.74) mm, 98.01 (0.68) mm, 97.36 (0.36) mm, respectively.

One day before the uniaxial tension test, the dog-bone specimens were taken out of the curing room and aluminium plates were glued on the ends of specimens for transferring of the load from the machine to the specimen. To ensure that valid results were obtained from the uniaxial tension test, the specimen had to be perfectly aligned longitudinally before testing. Great care was taken to attach the aluminium plates to the ends of the specimen. Toward this end, centre lines of aluminium plates and dog-bone specimens were marked to keep the alignment between aluminium plates and specimens. Furthermore, the same amount of glue was used for each contact surface. After the glue was applied, clips were used to help bond the aluminium plates and specimens together. Two clamps were used so as to prevent any movement of