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Flexural and shear behaviours of plain and reinforced polyvinyl alcohol-engineered cementitious composite beams

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In this paper, the results of an experimental investigation on the flexural and shear behaviours of plain and reinforced polyvinyl alcohol-engineered cementitious composite (PVA-ECC) beams are presented. The PVA-ECC employed in this study, which has a tensile strain capability up to 1%, has been recently developed by the authors using local sand to reduce cost. The aim of this study is to investigate the effects of PVA-ECC matrix, transverse reinforcement (stirrups) and longitudinal reinforcement bars on the flexural and shear structural performances of reinforced PVA-ECC beams. Four-point bending tests were conducted and normal steel reinforced concrete beams were tested for comparison. Digital Image Correlation technique was used to monitor single crack development and was validated by LVDT measurements. Experimental results show that PVA-ECC beams present significantly improved flexural behaviour compared with normal concrete beams. Furthermore, PVA-ECC beams without stirrups eventually fail in flexure rather than in shear, and exhibit similar load-deflection, moment-curvature relationships and crack development history when compared with PVA-ECC beams with stirrups.

1. Introduction

Conventional concrete has been widely used in various infrastructures. However, it has many inherent weaknesses, such as low tensile strength, poor ductility and extensive cracking under tension [1]. In addition, conventional concrete has low shear resistance due to its low tensile strength, poor ductility and deformability. Furthermore, shear failure in reinforced concrete (RC) structures is often brittle [2]. Engineered Cementitious Composite (ECC) is a special type of High Performance Fibre Reinforced Cementitious Composite (HPFRCC) which shows excellent tensile strain hardening behaviour with a tensile strain capacity exceeding 4% and an ultimate tensile strength typically ranging from 4 MPa to 6 MPa [3]. The superior tensile properties of ECC are of great value in enhancing the structural performance in terms of structural load and deformation capacity as well as energy absorption [4]. If ECC is employed to replace conventional concrete as the main construction material for building and structures, it is expected that the ECC matrix will lead to better flexural and shear structural performances when compared with normal RC structures.

A number of flexural tests on steel reinforced ECC beams have been conducted. Yuan et al. [5] investigated the flexural behaviour of steel reinforced PVA-ECC beams under monotonic four-point loading. The experimental results showed that the ultimate deflection of steel reinforced PVA-ECC beams was increased by 2.4 times compared with normal steel RC beams. Bandelt and Billington [6] investigated the effects of longitudinal reinforcement ratio and loading type on the deformation capacity of steel reinforced PVA-ECC beams. PVA-ECC specimens with four longitudinal reinforcement ratios ranging from 0.54% to 2.0% were tested. It was found that, unlike traditional RC beams, the deformation capacity of PVA-ECC beams tended to increase with the increasing of the longitudinal reinforcement ratio. It was also suggested that a longitudinal reinforcement ratio above 0.70% would provide adequate deformation capacity for most ECC structural components with drifts of 3–4%. Drift was calculated using the midspan deflection divided by the shear span length of the specimen [6]. In these studies, detailed flexural behaviour in terms of the crack width development was not studied. Cracking behaviour has been extensively studied in fibre reinforced concrete structures [7], and it is an important indicator of durability performance especially for structures with strict requirements on crack width [8]. Therefore, the crack width development of reinforced ECC structures needs to be evaluated.

In addition to enhancing flexural performance, the use of ECC has also been found to improve the shear resistance. This implies a high potential to reduce or even eliminate the need of shear

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reinforcement bars in structural members [9]. Li and Wang [10] found that the glass fibre-reinforced polymer (GFRP) reinforced ECC beams without shear reinforcement bars exhibited an equal peak load capacity and an increase of nearly 100% in deflection capacity when compared with their counterpart concrete beams with closely spaced steel stirrups. Compared with their flexural behaviour, the shear behaviour of the steel reinforced ECC beams has received relatively little attention [11]. A possible reason is that in the traditional shear tests, simply supported beams are subjected to three-point bending or four-point bending in which the shear span is under the influence of constant shear and linearly varying moments [12]. Therefore, it is difficult to predict the behaviour under pure shear. The Ohno shear beam method [13], which ensures a state of pure shear stress at the centre of the beam, has been frequently employed to investigate the shear behaviour of reinforced ECC beams [14,15]. However, the Ohno shear beam is different from the beam members employed in practical engineering structures [16].

In most of the reported studies on ECCs, microsilica sand was employed and a tensile strain capacity up to 4% could be achieved. However, microsilica sand is relatively expensive and difficult to obtain compared with local sand. Recent research shows that there is room to employ an ECC with a slightly lower tensile strain capacity in ECC structural members [17]. In this research [17], the minimum required tensile strain capacity of ECC for a link slab application was calculated to be 0.8% and it would be 1.6% with a safety factor of two. Furthermore, a numerical study on the flexural behaviour of steel reinforced ECC beams indicated that the increase of the ultimate tensile strain capacity (from 1% to 4%) had almost no effect on the ultimate moment capacity [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 RC structures, a minimum tensile strain of 0.5% of the ECC matrix is essential in order to ensure that the ECC will not fail before the reinforcement bars yield. However, tensile strain capacity beyond 1%, which far exceeds the yield strain of even high strength steel (approximately 0.5%), will only lead to performance improvement at the material or local level (e.g. control of crack size and their numbers) but generally will not improve much on the structural performance of RC structures in most normal structural engineering applications. Therefore, an ECC with a slightly lower tensile strain is desired for optimal design in terms of cost reduction and to take full advantage of the ECC material.

Recently, a new low cost PVA-ECC using local dune sand has been developed by the authors to achieve a tensile strain capability typically ranging from 0.5% to 1.0% [18]. In many situations, using local sand as the main construction material is a good solution to alleviate social and environmental problems caused by the production of construction materials. Therefore, local sand would be preferred in the broader adoption of PVA-ECC in large-scale applications as it is cost-effective, readily available and environmentally sustainable. Despite that the tensile strain of the ECC is usually reduced when local sand with larger grain size than the microsilica sand is used, it is acceptable if the strain is controlled within the range of 0.5–1% for RC structure applications.

This study presents the experimental results of the flexural and shear behaviours of plain and steel reinforced beams using the developed PVA-ECC. Steel reinforced normal concrete beams were also tested to study the effect of the PVA-ECC matrix on the flexural and shear behaviours of reinforced beams. The effects of the transverse and longitudinal reinforcement bars on the structural behaviour of PVA-ECC beams were also investigated. Ten rectangular beams, including five different beam types with a duplication for each, were tested using four-point bending tests. The five beam types investigated are (i) steel reinforced normal concrete beams with stirrups (RC beam) and (ii) without stirrups (RC-NS beam), (iii) steel reinforced PVA-ECC beams with stirrups (RECC beam) and (iv) without stirrups (RECC-NS beam), and (v) plain PVA-ECC beams without any steel reinforcement bars (PECC beam). The test results including load-deformation behaviour, failure mode, ductility ratio, moment-curvature relationship and strain distribution are reported. The Digital Image Correlation (DIC) technique was employed to monitor crack development during testing to complement the results obtained from LVDT measurement. Furthermore, the bond-slip behaviour of the steel reinforcement bars embedded in PVA-ECC beams was studied.

Table 1
Mix proportion of the PVA-ECC.

Cement	Fly ash	Sand/binder	Water/binder	HRWR	Fibre (vol.%)
1.0	1.2	0.36	0.3	0.01	2.2

2. Experimental program

2.1. Materials

2.1.1. The newly developed PVA-ECC

The ingredients of the newly developed PVA-ECC were Portland cement, fly ash, local dune sand, PVA fibres, High-Range Water Reducer (HRWR) and water. General purpose cement and ASTM Class F fly ash were applied. The local dune sand employed in this study had an average grain size of 200 μm with a maximum grain size of 300 μm. The PVA fibres had a length of 12 mm, a diameter of 39 μm and nominal strength of 1620 MPa. A polymer-based HRWR was used. The mix proportion of the PVA-ECC is shown in Table 1. The content of fibre is by volume fraction, while all other components are by mass.

The mechanical properties of the PVA-ECC including Young's modulus as well as stress-strain relationships under uniaxial compression and tension were tested. Uniaxial compression tests were conducted to study the compressive properties of the PVA-ECC. Five cylinders ($\varnothing 100 \times 200$ mm) were cast from the same batch of each beam type. Three were tested to obtain compressive stress-strain relationship, while the other two cylinders were tested to determine the Young's modulus. In order to obtain the stress-strain relationship, uniaxial compression tests were conducted based on ASTM C469 [19] and a previous study [18] under deformation control with a displacement rate of 0.05 mm/min. The detailed test setup can be found in the study [18]. Tests for the Young's modulus were conducted separately according to ASTM C469 [19], in which cylinders were loaded to 40% of the expected ultimate load. The overall compressive stress-strain relationships of the PVA-ECC are shown in Fig. 1. Based on the average result of nine PVA-ECC cylinders, the compressive strength and corresponding strain are 48.4 MPa and 0.55%, respectively. Compressive strength is defined as the maximum compressive stress that the PVA-ECC (or concrete) cylinder can sustain under the uniaxial compression test. It is also found that the average result of the Young's modulus of the PVA-ECC is 18.1 GPa.

Uniaxial tension tests were carried out to study the tensile behaviour of the PVA-ECC. 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. 2 were employed. Three dog-bone specimens were cast from the same batch of the reinforced PVA-ECC beam types. Details of the test setup were discussed and validated in previous studies [18,20,21]. The obtained tensile stress-strain relationship of the PVA-ECC from the tests is shown in Fig. 3. The instantaneous stress drops indicated in Fig. 3 are caused by the formation of cracks. After initial cracking occurs, the stress continues to increase with the formation of multiple