UNIAXIAL TENSILE, FLEXURAL AND FIBRE-MATRIX PULL-OUT BEHAVIOUR OF ULTRA-HIGH-TOUGHNESS CEMENTITIOUS COMPOSITES

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ABSTRACT. This paper presents the experimental investigation of uniaxial tensile and flexural properties as well as fibre-matrix pull-out resistance of ultra-high-toughness cementitious composites (UHTCC). Specimens of UHTCC containing high-volume fly ash were fabricated using polyvinyl alcohol (PVA) fibres and subjected to uniaxial tensile test and four-point bending test at third points. The uniaxial tensile and flexural response demonstrated strain hardening behaviour of the cementitious composites, which exhibited high fracture toughness and resilience. In addition, fibre pull-out tests were conducted with single PVA fibre embedded in the cementitious matrix. Special techniques of the specimen preparation necessary for the test protocol are explained, such that the obtained pull-out response was able to realistically reflect the bond behaviour of fibre.

Keywords: Flexural property, Fibre-matrix pull-out, Ultra-high-toughness cementitious composites, Uniaxial tensile property

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INTRODUCTION

Concrete is highly meritorious to be the most widely used construction material. However, conventional concrete has the major drawback of being prone to cracking and having low tensile deformability. To address these issues, ultra-high-toughness cementitious composites (UHTCC), which possesses strain hardening property and has superior tensile ductility, fracture toughness and resilience, has been developed [1,2]. UTHCC can be characterised as being: 1) reinforced with short fibres with volume fraction not more than 2.5%, 2) pseudo-ductile and possessing strain hardening behaviour with tensile strain capacity of higher than 3%, and 3) able to effectively control cracking with the crack width limited to less than 100 μm when the tensile strain reaches its maximum value [3,4]. To achieve these properties, the materials and mix proportioning of UHTCC require utilisation of fibres of appropriate types in combination with properly selected matrix design based on principles of micromechanics. Among various fibres, polyvinyl alcohol (PVA) fibres had been identified to be suitable for use in UHTCC production [5,6], for the reason that the tensile and bond stiffness and strength of PVA fibres embedded in the cementitious matrix can optimally fulfil the UHTCC design requirements in terms of fracture energy and bridging strength criteria [7].

PVA fibre is a hydrophilic fibre with hydroxyl functional groups attached to its molecule, which is able to adequately develop chemical bond and frictional interaction at the fibre-matrix interface [8,9]. It should be noted that optimisation of chemical bond and frictional interaction, which make up the fibre-to-matrix bond, is necessary. If the fibre-to-matrix bond is too strong, premature rupture of fibre and reduced ductility may occur. On the other hand, if the fibre-to-matrix bond is too weak, the full tensile strength of fibre may not be attained and the slip-hardening phenomenon due to fibre/matrix interfacial abrasion would be suppressed [10]. This would limit the tensile strain capacity as well as the strain hardening property of the fibre-reinforced cementitious composites [11]. Therefore, for optimal performance of the UHTCC, the bond stiffness and strength between fibre and matrix should be within suitable ranges. In such case, under tension load, part of the fibres would be pulled out with the ends remaining intact or partially peeled off, whereas some of the fibres would be ruptured. Under the combination of these failure modes of fibres, the UHTCC would concurrently exhibit the desired ductility and ultimate tensile strength.

In this study, UHTCC specimens were fabricated with the use of proprietary PVA fibres. The specimens were subject to uniaxial tensile test, four-point bending test at third points, and fibre pull-out test of single PVA fibre. The cracking process under uniaxial tension and flexure as well as the pull-out response of single PVA fibre were observed. As reported later in this paper, the experimental results of specimens demonstrated ample strain hardening property, high modulus of rupture, small crack spacing and fine crack widths, as well as satisfactory bond behaviour of PVA fibre embedded in cementitious matrix.

SPECIMEN PREPARATION AND EXPERIMENTAL TESTING

The UHTCC specimens were produced from ordinary Portland cement, fly ash, fine aggregate, water, superplasticizer and PVA fibres. The cement was of grade 52.5N conforming to European Standard EN 196. The fly ash was of low-calcium class conforming to European Standard EN 450. It has a silicon dioxide content of more than 65% and aluminium oxide content of more than 20% and can be regarded as a cementitious binder material. The fine aggregate was fine silica sand with particle size in the range from 0.1 mm

to 0.25 mm. The water was potable water from the municipal water supply. The superplasticizer was of polycarboxylate-based type in aqueous form. The PVA fibre was supplied from Japan. It was imported product of type Kuralon K-II REC 15 with proprietary surface coating. The fibre diameter and length were respectively 40 μm and 12 mm. The mechanical properties of the PVA fibre are as follows: the nominal strength was 1600 MPa, the elastic modulus was 40 GPa, and the elongation was 6%. Fig. 1 and Fig. 2 depict the micrograph images of the silica sand and PVA fibre, respectively.

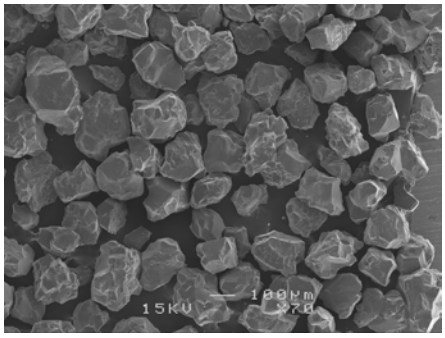

Figure 1 Micrograph image of the silica sand

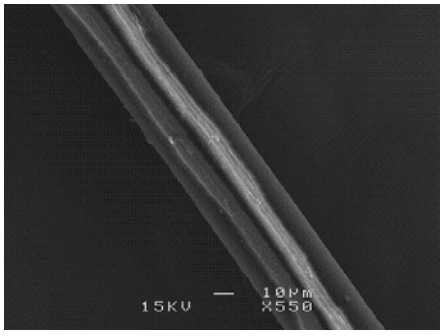

Figure 2 Micrograph image of the PVA fibre

To reduce the cement consumption and enhance the eco-friendliness of the UHTCC [12], high-volume fly ash was adopted in the mix design, such that the fly ash comprised more than 60% by mass of the binder content. The water/binder ratio was less than 0.24 by mass to achieve good mechanical performance in terms of strength and stiffness. The fibre volume fraction was set at 2% of total volume of materials. This adopted fibre content was from a balanced consideration of structural performance, cost and ease of production [13]. The mixing was conducted by employing the Hobart A200 type mixer with planetary rotating blade. During the mixing process, the binder materials and fine sand were first mixed in dry state for 1.5 to 2 minutes, then water and superplasticizer were added to the mixture sequentially and thoroughly mixed for more than 5 to 6 minutes. While the mixing was continuing, PVA fibres were added into the mixer eventually over a duration of approximately 1 minute. After adding the required amount of fibres, the mixing was further continued for 4 to 5 minutes. Through the whole mixing process which took about 15 minutes, the mixing speed was kept constant. The resulting fresh UHTCC was consistent and the PVA fibres were uniformly dispersed without formation of fibre balls.

Rectilinear specimens of 15 mm thickness were fabricated for undergoing uniaxial tensile test and four-point bending test. The planar dimensions of uniaxial tensile and bending test specimens were 350 mm by 50 mm and 400 mm by 100 mm, respectively. The rectilinear specimens were cast in single layer, and were covered with plastic sheets after casting and

surface finishing. They were demoulded at 24-hour age and cured in mist curing chamber under standard temperature and humidity conditions. The specimens were tested at the age of either 14 days or 28 days. Cuboid specimens of 15 mm planar dimensions and thickness were fabricated for undergoing fibre pull-out test. To avoid fibre-break and ensure pull-out of PVA fibre from the cementitious matrix, the embedment length of the PVA fibre must not be excessive. In this study, an embedded length of 0.8 mm was adopted.

For undergoing the uniaxial tensile test, the specimen surface was first smoothed by grinding, followed by drying in air, and then both end zones of 100 mm length were adhered with carbon fibre sheets, upon which aluminium plates of 70 mm length were glued at both ends using epoxy resin adhesive. The specimen was clamped by hydraulic wedge grips against the aluminium plates. The load was exerted by MTS testing machine under displacement control mode at a loading rate of 0.1 mm/min. The elongation of specimen was measured using a pair of linear variable displacement transducers (LVDTs), whose installation followed the steps of adhering LVDT holders to both lateral sides of the specimen using fast-setting cyanoacrylate adhesive, then fixing the LVDTs against the holders, and finally adjusting the verticality of the LVDTs. The tensile strain of specimen was obtained from the gauge length of 150 mm, and the tension force was measured by the load cell of the testing machine. Fig. 3 illustrates the test arrangement. During testing, the tension load and deformation were measured and the cracking behaviour was observed and recorded.

For undergoing the four-point bending test, the specimen was placed on steel roller supports with a span length of 300 mm, the flexural load was exerted from MTS testing machine via a load spreading steel beam mounted with steel rollers at contact points with the specimen. The spacing of steel rollers of the load spreading beam was 100 mm, such that the load was applied at third points of the specimen. Displacement control mode was adopted, and the loading rate was constant at 0.3 mm/min throughout the test. The applied force was measured by the load cell of the testing machine. At mid-span location, a LVDT holding frame was installed, and the deflection was measured by a pair of LVDTs at both sides of the specimen. The supports and LVDT holding frame were all mounted on the same steel rigid base. A photograph of the test arrangement with the deformed specimen is shown in Fig. 4. During testing, both the applied load and the mid-span deflection were recorded.

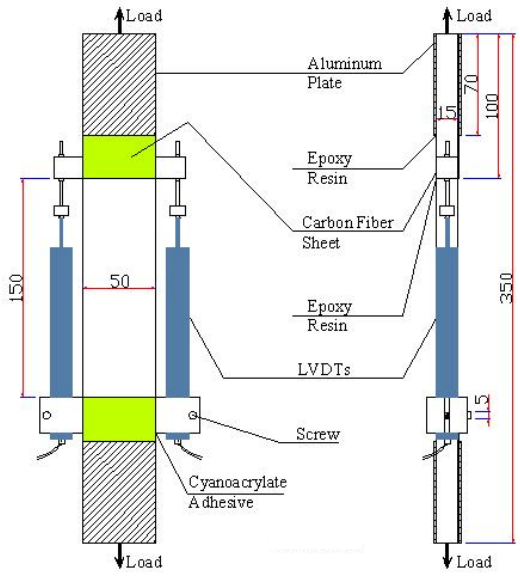

Figure 3 Arrangement of uniaxial tensile test (dimensions in mm)

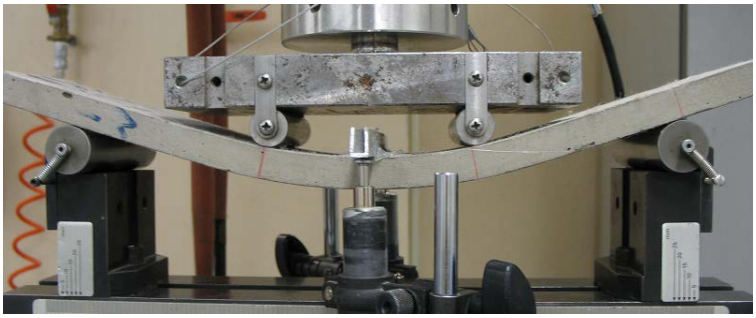

Figure 4 Arrangement of four-point bending test

For undergoing the pull-out test, an experimental set-up and protocol for pull-out test of single fibre has been designed. A bespoke mould was innovated as shown in Fig. 5 for casting the specimens each embedded with single PVA fibre. Before casting, the PVA fibre segments were fixed in position with the verticality ensured by using a special tailored pad in the mould. By placing steel separating sheets along the mould, multiple specimens could be cast from the same batch of UHTCC at the same time. Such design of the mould and arrangement of specimen preparation enabled the pull-out test to realistically reflect the bond behaviour of single fibre. After the specimens hardened, they were carefully removed from the mould, cured and stored to avoid damage until the required age of pull-out test. During testing, the pull-out force was measured by the load cell and the pull-out displacement was measured by LVDT. Fig. 6 depicts a photograph of pull-out test of single PVA fibre.

Figure 5 Mould for fibre pull-out test specimen

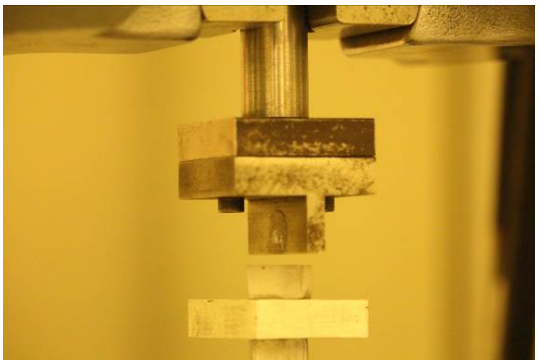

Figure 6 Arrangement of fibre pull-out test

RESULTS AND DISCUSSIONS

Uniaxial Tensile Properties

The uniaxial tensile stress-strain curves for specimens at 28 days of age are presented in Fig. 7. The results revealed that the specimens all achieved saturated multiple cracking. From the tensile stress-strain curves and observation of cracking process, it is seen that at the beginning, the stress increased linearly with the strain until the first crack appeared. Then, the stiffness dropped and the stress-strain relationship became nonlinear exhibiting strain hardening with slight fluctuations in company with appearance of steady multiple cracking until the crack distribution reached saturation. Further increase in deformation caused widening of existing cracks with the absence of new crack formation, and led to an increased rate of strain hardening. When the stress reached the peak value, crack localisation took place, where a single crack widened continuously with simultaneous strain softening of the UHTCC.

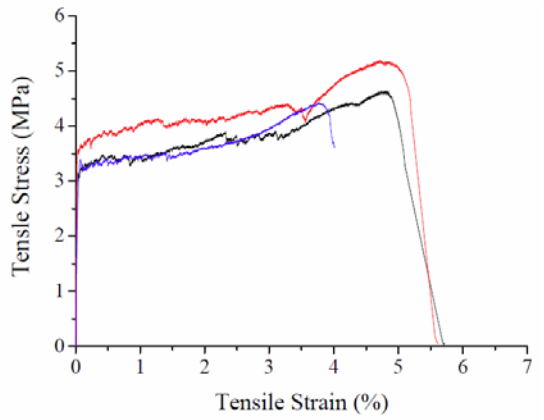

Figure 7 Uniaxial tensile stress-strain curves of UHTCC

Table 1 listed the test results of specimens at 14 and 28 days of age. It is noted that the tensile stress at first cracking increased with age while the tensile strain at first cracking decreased with age. This is reasonable due to the strength and stiffness development of UHTCC. At age of 28 days, the tensile strain at first cracking was 0.019%, which is comparable to the cracking strain of concrete normally in the range of 0.01% to 0.02%. The results reflected that the steady multiple cracking reached saturation at tensile strain beyond 3%, while the average crack width was as fine as 0.033 mm for specimens at 28-day age. The specimens demonstrated prominent strain hardening behaviour. The peak tensile stress at 28-day age had a mean value of 4.75 MPa, and the corresponding mean value of tensile strain was 4.41%, which was more than 230 times the tensile strain at first cracking. At peak tensile stress, the average crack width was as fine as 0.048 mm, and the crack distribution was very dense with an average crack spacing of approximately 1 mm for specimens at 28-day age.

Table 1 Results of uniaxial tensile test and four-point bending test

Properties	Age of specimens	
	14 days	28 days
Uniaxial tensile test		
Tensile stress at first cracking (MPa)	2.86	3.10
Tensile strain at first cracking (%)	0.025	0.019
Tensile stress at crack saturation (MPa)	4.12±0.09	4.09±0.34
Tensile strain at crack saturation (%)	3.76±0.85	3.34±0.44
Average crack width at saturation (mm)	0.023	0.033
Tensile stress at peak load (MPa)	4.90±0.37	4.75±0.39
Tensile strain at peak load (%)	5.12±1.15	4.41±0.56
Average crack width at peak load (mm)	0.033	0.048
Average crack spacing at peak load (mm)	0.83	0.99
Four-point bending test		
Flexural stress at first cracking (MPa)	5.47±0.38	5.99±0.28
Modulus of rupture (MPa)	14.93±0.08	16.03±0.50
Mid-span deflection at peak load (mm)	30.78±4.56	32.57±5.11

Flexural Properties

From the four-point bending test, the curves of flexural stress versus mid-span deflection of specimens at 28 days of age are presented in Fig. 8. From the figure and the observed cracking process, in similarity with the cracking behaviour under uniaxial tension, the flexural stress increased with the mid-span deflection linearly at the beginning until appearance of the first crack. Then multiple cracks formed steadily at the tension face of specimen within the constant bending moment region and accompanied with strain hardening until crack saturation. When the deflection was further increased, the existing cracks widened to accommodate the increasing curvature with the absence of new cracks formation, and the rate of strain hardening became higher. Subsequently, crack localisation took place when the flexural stress attained the modulus of rupture. This was followed by rapid drop of flexural load, and a number of fine cracks also appeared outside the constant moment region.

The flexural test results of specimens at 14 and 28 days of age are summarised in Table 1. From the results, the flexural stress at first cracking had a mean value of 5.99 MPa, whereas the modulus of rupture had a mean value of 16.03 MPa for specimens at 28-day age. According to previous research, the ductility performance of fibre-reinforced cementitious composites could be characterised by the ratio of modulus of rupture to the uniaxial tensile stress at first cracking [14,15]. The composites could be considered as a perfectly elastic-plastic material if the ratio attains 3 [14]. Taking the mean values for evaluating, the UHTCC specimen in this study had ratios of 5.22 and 5.17 on average at age of 14 days and 28 days, respectively. This illustrates the pronounced strain hardening property of the UHTCC. The specimens sustained very high levels of deflection at the peak load. The cracking behaviour

as well as the large deformability illustrated the high fracture toughness and resilience of the UHTCC.

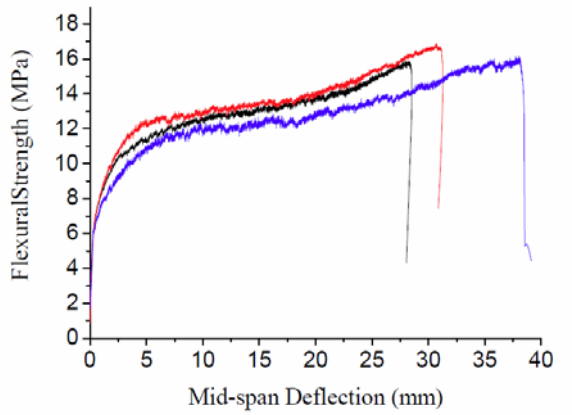

Figure 8 Flexural stress-deflection curves of UHTCC

Fibre Pull-out Properties

The pull-out force versus pull-out displacement curves of single PVA fibres are depicted in Fig. 9. The pull-out response can be broadly divided into two stages. From the start to a pull-out displacement of approximately 0.2 mm, the fibre underwent the debonding stage, which was mainly caused by the undermining of chemical bond and stretching of fibre segment along the debonded region [10]. The debonding stage was followed by an abrupt drop of load caused by crack instability at the fibre/matrix interfacial zone. Denote ΔP as the drop of load to a load level of P. From this point (P) onwards, the fibre underwent the pull-out stage, which was mainly caused by the frictional resistance with continual reduction of the embedment length. The curves in Fig. 9 demonstrate clear slip-hardening behaviour before attaining the peak pull-out force. This was due to the interfacial abrasion and jamming of the PVA fibre during its progressive sliding out of the matrix tunnel [10].

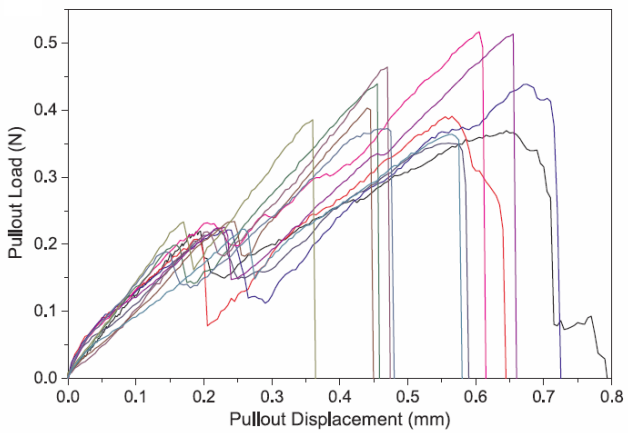

Figure 9 Pull-out force-displacement curves of single PVA fibre

Denote the tensile elastic modulus of fibre by E_f, diameter of fibre by d_f, and embedment length by l_e. According to Lin and Li [10], the chemical bond (in J/m^2) can be assessed by the equation: $G_d = 2(\Delta P)^2/(\pi^2 E_f d_f^3)$, whereas the frictional interaction (in MPa) can be assessed by the equation: $\tau_0 = P/(\pi^2 d_f l_e)$. From the experimental results, the chemical bond is evaluated to

be 1.1 J/m^2, and the frictional interaction is evaluated to be 1.52 MPa. These values fall in the appropriate ranges for strain hardening cementitious composites [16].

CONCLUDING REMARKS

In this research, the uniaxial tensile, flexural and fibre-matrix pull-out properties of ultra-high-toughness cementitious composites (UHTCC) have been experimentally investigated. UHTCC specimens containing high-volume fly ash and polyvinyl alcohol (PVA) fibres were fabricated. From the uniaxial tensile test, the UHTCC demonstrated extremely high ductility, with the tensile strain at peak load reaching approximately 4.4%. The large elongation was accommodated by closely spaced and very fine cracks. The respective average crack width and crack spacing were approximately 0.05 mm and 1 mm. From the four-point bending test at third points, the flexural strength of UHTCC was as high as 16 MPa, which was in company with pronounced strain hardening and extremely high flexural ductility. From the pull-out test of single PVA fibre, prominent slip-hardening behaviour could be observed, and the chemical bond and frictional interaction have been determined to be appropriate. This study has confirmed the satisfactory mechanical properties of the UHTCC.

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