Mechanical properties and 3D fractal analysis of engineered cementitious composites with shape memory alloy fibres

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ARTICLE INFO

Keywords:
Fibre reinforced concrete
Strain-hardening cementitious composites
Shape memory alloy
Mechanical properties
Microstructure
Fractal analysis

ABSTRACT

This paper presents a systematic experimental study on the effect of shape memory alloy (SMA) fibres (0.25–1% by volume) on microstructure and engineering properties, in particular mechanical properties of polyvinyl alcohol (PVA) fibre (2% by volume) reinforced engineered cementitious composites (ECC). A series of tests were performed to characterise the flowability, compressive properties and flexural and uniaxial tensile behaviour in terms of strain/deflection-hardening and multiple microcracking performance and flexural and tensile strengths, as well as the 3D fractal crack analysis and microstructural evolution of ECC. Results indicate that the presence of more SMA fibres diminished the flowability of ECC, which can be ascribed to the higher surface roughness of SMA fibres as confirmed by the atomic force microscopy analysis but did not result in any change in the self-compacting characteristics of ECC. The highest compressive strength was achieved at the ECC mix with 0.5% SMA inclusion as 62.5 and 72.1 MPa for ambient curing of 28 and 56 days. Although the presence of 1% SMA fibre reduced the compressive strength of ECC due to the increased interfacial porosity and fibre cluster, the residual flexural crack width of ECC containing 1% SMA fibre was effectively reduced by about 54.3% as compared with the reference ECC mix, consistent with its best tensile performance. Accordingly, the failure patterns of ECC changed from the tensile failure with more uniformly distributed cracks and the highest dissipated fractal fracture energy ($W_s/G_f=167.7$) to the tensile failure along with less tortuous crack path and fractal fracture energy ($W_s/G_f=80.2$).

1. Introduction

Concrete is the most widely used construction material in the world, which has low tensile strength and works with cracks at the service-level stage [1]. Fibre reinforced cementitious composites are developed to enhance the tensile strength, ductility and fracture toughness [2]. Engineered cementitious composites (ECC) fall under high-performance fibre reinforced cementitious composites designed based on micromechanics and possess high tensile strain capacity of 3% or more, along with multiple cracking with an average crack width of less than 100 µm [3,4]. Compared to conventional fibre-reinforced concrete, ECC has more advanced mechanical properties, such as strain-hardening behaviour, improved crack-resistant capacity and wishable energy absorption ability. Generally, ECC is made with cement, fly ash, silica sand, water, chemical additives and short fibres. The commonly used fibres in ECC include steel, polyethylene (PE) and polyvinyl alcohol (PVA) fibres at the total fibre volume fraction of usually up to 2% and it was

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found that micro-fibres can restrict micro-crack development, while macro-fibres inhibit the development of larger cracks [5]. Thus, an increasing number of interests have been placed on the use of hybrid fibres of two or more fibre types and sizes that could generate synergistic effects.

Engineers search for innovative materials and intelligent systems that have enhanced deformation capacity, higher damage tolerance, decreased or minimised residual crack sizes, and recovered or reduced plastic deformation. Shape memory alloys (SMAs) are metallic alloys that can remember their original shapes, experiencing large inelastic deformation and regain its undeformed shape when subjected to some stimulus such as electric heating, radiation, thermo-mechanical or magnetic variations [6]. SMAs are innovative smart materials displaying the real properties of shape memory effect and super-elasticity. The former refers to the deformation received below a critical temperature that can be recovered with heating, while the latter suffers from the recovery of nonelastic strains by removing stress. The valuable properties of SMA hinge on martensitic transformation and reverse transformation. The superelastic SMA resumable strain can reach up to 6–8%, with a similar yield strength to steel (400–500 MPa), while the ultimate strength and deformation attain 1000 MPa and 25%, respectively. Moreover, SMA materials have some advantages such as high damping, fatigue resistance, corrosion resistance, resistance sensitivity to strain and large recovery stress [7].

SMA is generally used as bar, cable or fibre in conventional concrete or high-strength composites [7–12]. However, only very limited studies are available on the utilisation of SMA as fibre in ECC [1,6]. Ali and Nehdi [6] investigated the mechanical properties of ECC containing short randomly dispersed 2% PVA and 0.5%, 1%, and 1.5% SMA fibres. They found that a combination of PVA and SMA fibres significantly enhanced the tensile and flexural capacity of ECC, in comparison with ECC reinforced with 2% PVA fibre alone. The addition of SMA and PVA fibres led to a slight drop in compressive strength at all testing ages, which can be ascribed to the increased porosity induced by the rising fibre dosage. It was reported that ECC specimens with 1% SMA fibres had higher strength and ductility than PVA fibre reinforced ECC at a fibre dosage of 1.7%, as indicated from both the ultrasonic pulse test and mechanical test results [1].

Although the above-mentioned two studies have examined some mechanical properties of ECC with SMA fibres; the 3D flexural crack analysis in terms of fractal dimension and corresponding dissipated fracture energy and micro-structural fracture behaviour of SMA reinforced ECC have not been extensively explored yet.

The main purpose of this experimental study is to investigate the feasibility of hybridisation PVA fibres with SMA fibres to produce innovative and sustainable ECC with acceptable engineering properties. First of all, a series of tests were carried out to study the influences of SMA fibre dosage (0.25%, 0.5% and 1.0% by volume) on the engineering properties of PVA fibre (2%) reinforced ECC including flowability, compressive strength, ultrasonic pulse velocity, uniaxial tensile properties. Special focus was placed on the flexural response of ECC in terms of stress-strain response, strain capacity, and fracture patterns as well as the 3D crack analysis in terms of fractal dimension and corresponding dissipated fracture energy. Then, the fibre failure and surface condition after the flexural tensile test were characterised using scanning electron microscopy (SEM) and atomic force microscopy (AFM) to get a comprehensive understanding of the mechanical behaviour and fracture mechanism of ECC. Moreover, the economic viability of the manufactured mixtures in terms of material cost was assessed and discussed. Finally, an optimal mixture of ECC was proposed considering the acceptable engineering properties, material cost and strain hardening responses.

It should be highlighted that the addition of SMA fibres can enhance the crack-closing capacity of ECC under dynamic loading. Thus, it is vital to explore the effect of SMA fibre on the crack-closing performance of ECC mixes subjected to dynamic loads with various strain rates. These are subjects of ongoing work and will be presented in near future publications.

2. Experimental programme

2.1. Raw materials

The raw materials used include CEM I 42.5 N Portland cement, fly ash, silica sand, PVA and NiTi SMA fibres, tap water, and high-range water-reducing admixture (HRWRA). Cement and fly ash were used as binders and silica sand as fillers. The specific gravity and
The specific gravity and blaine factor of the cement are 3.06 and 325 m²/kg, respectively. The specific gravity and blaine factor of the fly ash are 2.1 and 290 m²/kg, respectively. Table 1 lists the chemical compositions of cement and fly ash. The specific gravity of silica sand is 2.6. The PVA fibres of 12 mm lengths with aspect ratio of 857 were utilised. The aspect ratio and length of the SMA fibres were almost similar to that of PVA fibre. The SMA fibres were obtained from a NiTi wire, composed of 55.75% Ni and 44.25% Ti. The properties of PVA and NiTi-SMA fibres conforming to ASTM F2063 [13] are given in Table 2. Also, the SEM images of the fibres are shown in Fig. 1.

### 2.2. Mix proportions

Table 3 shows the mix proportions adopted in this study. The control mixture (0 SMA-2 PVA) is designed without any SMA fibres. High range water-reducing additives (HRWRA) were used to obtain a good dispersion of PVA and SMA fibres. The dosages of HRWRA were adjusted to keep all mixtures had the same slump distribution (230 mm ± 5 mm). SMA fibres at fibre volume fractions of 0.25%, 0.5% and 1% were added to PVA-ECC reference mix to develop hybrid ECC with PVA and SMA at a fixed volume fraction of 2%. In the use of hybrid fibre, the amount of one fibre was sometimes used by reducing the amount of the other fibre. The maximum dosage of SMA fibre was determined as 1% so that the total fibre dosage did not exceed 3%. In Table 3, the number after PVA and SMA for mix ID indicates the volume fractions of fibre added to each blend. For example, the mix of “0.5 SMA-2 PVA” contained 0.5% SMA fibre and 2% PVA fibre by volume.
2.3. Sample preparation

First, the dry ingredients (cement, fly ash and sand) were mixed in a mixer at 100 rpm for 1 min. Then, the mixture of water and HRWRA was added and mixed at 150 rpm for 1 min. The mixing process continued at 300 rpm for another 2 min to achieve the uniform condition of fresh mortar. After that, the fibres were added and the mixing process was run at 150 rpm for 3 min.

After pouring, the composites were stored in plastic bags to minimise moisture loss. After 24 h, the composites were removed from the moulds and moved to a curing room (50% ± 5% relative humidity and 23 °C ± 2°C) for 28 d. The mixing process and appearance of the prepared 50 × 50 × 50 mm cubic, 15 × 50 × 350 mm, and dog-bone prismatic composites are shown in Fig. 2.

2.4. Test methods

2.4.1. Flow table test

Flow table test was conducted to evaluate the flowability of the mixtures as per ASTM C230 [14]. The truncated conical mould with a height of 50 mm, a top diameter of 70 mm and a bottom diameter of 100 mm was used. Firstly, the fresh mixture was poured into the mould. Secondly, mould was lifted, and the flow table was falled 25 times. Finally, the spread diameter of each fresh mixture was measured. Relative slump values were calculated using the spread diameter (d) and base diameter of the mould (d₀).

\[ \Gamma_p = \left( \frac{d}{d_0} \right)^2 - 1 \]  \hspace{1cm} (1)

2.4.2. Ultrasonic pulse velocity test

As a non-destructive test, UPV was performed on the specimens as per BS 1881–203 [15] to assess the quality of the samples. The detector has a transmitter and a receiver. The transmitter was placed at one end and the receiver was placed on the other end. To
eliminate possible gaps between the detector and concrete surface, a gel was attached to the concrete surface. The travelling time was measured and then the ultrasonic pulse velocity was calculated.

2.4.3. Compression test

Cube specimens of $50 \times 50 \times 50$ mm were prepared from each mix to measure the compressive strength after curing of 7, 28, and 56 d. The compressive strength test was carried out as per ASTM C39 [16] using a pressing machine with a capacity of 2000 kN and a loading rate of 0.602 MPa/s.

2.4.4. Three-point bending test

Three-point bending test was conducted on ECC specimens ($15 \times 50 \times 350$ mm) at 28 d to determine the flexural strength, mid-span displacement and load-deformation curves according to ASTM C348 [17]. A closed-loop controlled universal testing equipment (Fig. 3) with a loading rate of 0.003 mm/s was employed. The deflection of the manufactured ECC samples was monitored by a high-precision electronic dial indicator and the flexural load-deformation curves were recorded by the testing machine's computer data recording system. For each mixture, three specimens were measured and the mean values were adopted for analysis and discussion.

Toughness is defined as the energy equal to the area under the load-deflection curve up to a certain deflection. The energy required to lose its load-carrying capacity for fibre reinforced concrete would rise with the increase in the area under the load-deflection curve. According to ASTM C1018 [18], toughness indices describe the material behaviour up to the selected displacement value [19]. The three-point bending test was conducted on the unnotched beam, and the energy required for the deflection at the first crack was calculated. The point determined the first crack in the load-deflection curve where the rising part of the curve deviated from linearity. Then, the energy required for deflections of several times the deflection corresponding to the first crack was determined. In this context, $I_5$, $I_{10}$, $I_{20}$ and $I_{30}$ values were calculated based on the flexural load-deflection values obtained from three-point bending test for ECC with SMA fibres.

2.4.5. Uniaxial direct tension test

Dog-bone shaped ECC specimens were prepared as per ASTM D638 [20] to examine the uniaxial tensile behaviour of ECC. The uniaxial direct tension test was performed using appropriate clamping jaws with a deformation controlled closed-loop testing machine with 100 kN capacity (Fig. 4). An extensometer was mounted on one side of the specimen to measure the displacement along the length of the narrow cross section of the manufactured cementitious composites. Each dog-bone specimen was initially clamped on both ends and then subjected to a uniaxial tension loading to failure at a loading rate of 2 mm/s. As highlighted by Ozkan and Demir [21], during the tensile testing process, the secondary bending effects should be avoided for preventing the change at the uniaxial tensile behaviour of the dog bone cementitious materials. For that purpose, the manufactured composites need to be perfectly aligned in the vertical direction and free rotation of the composites is also required. The same procedures have been followed in this study.

2.4.6. Microstructural characterisation

The microstructure of ECC was characterised using a SEM-EDS. In addition, the quantification of the porosity in the interfacial zone between the fibres and the surrounding matrix was performed on the flat polished sections of ECC by means of the technique developed by Scrivener and Pratt [22]. The images of interfacial zone and the bulk matrix were analysed using an image processing software, Scandium. Moreover, X-ray computed microtomography (XCT) scanning were carried out to detect the fibre distribution using a Phoenix Nanotom 180NF XCT system (GE Sensing and Inspection Technologies, GmbH, Wunsdorf, Germany) with a maximum electron acceleration energy of 110 kV and acquiring 1440 projection images.
2.4.7. Crack characterisation
Following the bending tests, the fractal dimensions of the surface cracks were determined. Images of the samples after the bending tests were firstly captured using a high-resolution camera. Then, these images were converted from RGB mode to an 8 bytes greyscale and scaled up to reflect the actual dimensions. The primary flexural bending moment-induced cracks at the same point for all ECC samples were digitised for thresholding using open-access digital image analysis software called Image J. These were then covered by imaginary meshes with rectangular box sizes containing the number of pixels of the crack image. Next, the number of grid squares to cover the cracks was counted for the plot of In (box count) versus In (box size), which were used to compute the average value of fractal dimension that is the slope of the line joining the logarithm of the number of grid squares encountered by the crack and the logarithm of the square grid dimension.

Afterwards, the dissipated fracture energy (Ws/Gf) of ECC was approximated at the macro scale as a function of the surface macro-cracks and the ratio of energy (Ws) produced by crack propagation to fracture energy (Gf) is shown by the value of Ws/Gf [23].

\[
\frac{W_s}{G_f} = h \cdot \left(\frac{\delta}{h}\right)^{1-D}
\]  

where \(h\) denotes the Euclidean length, \(\delta\) is the maximum size of the silica sand, and \(D\) is the fractal dimension of the crack.

3. Results and discussion

3.1. Flowability

The relative slump values of the ECC mixes were calculated based on the formula suggested by Dehghani and Aslani [24]. Fig. 5 illustrates the variation of relative slump versus SMA fibre content of hybrid ECC. As expected, the addition of SMA fibre into PVA fibre reinforced ECC reduced the slump value. Compared to the reference mix (0 SMA-2 PVA), the relative slump values were reduced by 5.2%, 9.3%, and 14.4% with the addition of 0.25% SMA (0.25 SMA-2 PVA), 0.5% SMA (0.5 SMA-2 PVA), and 1% SMA (1 SMA-2 PVA), respectively. The trend showed that the relative slump almost linearly decreased by increasing SMA fibre content in PVA fibre reinforced ECC. As reported in Ref. [24], the surface parameters of the fibres play a crucial role in the flowability of the hybrid fibre cementitious composites. The higher surface roughness of SMA fibres in comparison to PVA fibres may increase the internal friction and the contact network between the particles and the surrounding matrix, resulting in reduced slump values. It is also well-established that the higher flowability associated with high slump values generally induces from the drop in the yield stress of cementitious matrix and an increase in slump value signifies greater deformability of the composites [25,26]. The movement of the fresh mixture might be restricted by the incorporation of SMA fibres into ECC, leading to an increase in the overall yield stress.

It should be also noted that the use of SMA fibres did not result any change in the self-compacting characteristics of hybrid PVA-SMA based ECC composites and no pronounced fibre clumping or balling was observed for all mixtures at the macro-scale. Therefore, a laboratory vibrating table was not used for the placement of the produced mixtures into the moulds.

3.2. Ultrasonic pulse velocity

Fig. 6 depicts the UPV values of the samples after 28 days. Compared to the reference mix, the pulse velocity was increased by 4.7% and 5.8% with the addition of 0.25% SMA and 0.5% SMA, respectively. However, the addition of 1% SMA into the mix reduced the
UPV value by 3.1%. As per BS 1881–203 [15] specifications, the quality grading’s of the manufactured composites were good for all the mixes indicating that the hybrid dispersion of SMA and PVA fibres has not a significant effect on the compact nature of the cementitious composites.

3.3. Compressive strength

Fig. 7 presents the compressive strengths of the reference ECC composite (zero percent of SMA fibre) and hybrid ECC reinforced with 0.25%, 0.50% and 1.0% inclusions of SMA fibres at different curing days (7, 28, and 56 d). The strength of the control ECC mix (0 SMA-2PVA) was generally enhanced at early and later ages with the SMA fibre addition. The compressive strength of ECC with 0.25% SMA fibre (0.25 SMA-2 PVA) reached 59.4 and 69.7 MPa at 28 and 56 d. The maximum strength was obtained at the ECC composite with 0.5% SMA inclusion (0.5 SMA-2 PVA), which reached 62.5 and 72.1 MPa at 28 and 56 d. However, the addition of 0.50% SMA fibre seems to be an inflection point as increasing SMA fibre to 1% resulted in a dropping trend in terms of compressive strength, which is consistent with the finding by Ali and Nehdi [6]. However, they have also observed a decrease in the compressive strength of ECC after adding 0.5% SMA fibre. A higher porosity of the interfacial transition zone (ITZ) between the fibres and ECC matrix after a certain level of fibre dosage would weaken the microstructure, leading to a less amount of deposited matrix around each fibre and thus reduce the compressive strength of the composite [24].

To quantify and compare the porosity of ITZ, three micrographs were selected for each sample type, and the porosity was measured within ITZ at a distance of \( d = 50 \) µm. The same thresholding algorithm was applied and the average of nine values for each sample was.
Fig. 8. Interfacial porosity of 0 SMA-2 PVA and 1 SMA-2 PVA mixes.

Fig. 9. Fibre cluster in ECC specimen.

Fig. 10. Flexural stress-deformation curves of SMA and PVA fibre reinforced ECC.
recorded. Fig. 8 illustrates the porosity of ITZ obtained from the image analysis of the micrographs as a function of the distance from
the fibre surfaces. The porosity of ITZ clearly revealed that the volume of the pores in ITZ reduces with the increase in distance from
the fibres. The porosity of the matrix in the reference mix (0 SMA-2 PVA) at all distances was clearly smaller than that of the matrix located
around the PVA fibres. By contrast, the 1 SMA-2 PVA specimen at all distances had distinctively the largest interfacial porosity
compared to 0 SMA-2 PVA.

Overall, the results indicated that there is an optimum content of fibres for the improvement of compressive strength. Specifically,
the compressive strength went up with the incorporation of SMA fibres up to 0.5% by volume and then dropped as more SMA fibres
were introduced into the composite. Another equally plausible explanation for the lower compressive strength is that the fibre cluster
may produce weak points for the load transfer from the matrix to the fibres, eventually allowing the composite to fail at a relatively
lower strength level, as confirmed by XCT image shown in Fig. 9 that indicates the fibre clusters in the composite.

3.4. Flexural behaviour

The effect of hybrid PVA-SMA fibres was also manifested in the flexural performance of the composite and the relations between
flexural response and cracking behaviour and, between surface characteristics of the fibres and bond behaviour will be analysed and
discussed below.

3.4.1. Flexural strength and toughness

Fig. 10 shows that the flexural stress-deformation curves of ECC at 28 d. Three specimens were made for each mixture and the
deflection capacity of ECC was determined as the deflection corresponding to the maximum flexural load. The flexural strength test
results are summarised in Table 4.

The highest flexural strength (12.97 MPa) was obtained for the 1 SMA-2 PVA mix. The 28 d flexural strength went up by 46%, 62%
and 97% for 0.25 SMA-2 PVA, 0.5 SMA-2 PVA and 1 SMA-2 PVA mixes, respectively, compared to the reference mix (0 SMA-2 PVA).
Although the displacement dropped with the addition of 0.25% and 0.5% SMA fibres, the specimen with the highest mid-span
displacement (10.02 mm) was the 1 SMA-2 PVA mix.

It is also interesting to highlight that the cracking strength corresponding to the strength at the end of the initial linear part of the
flexural stress-deflection curve was also found to increase with the rising SMA fibre content in ECC. Meanwhile, the addition of SMA
fibres could considerably improve the maximum flexural stress. As seen in Fig. 10, increasing the SMA fibre content in ECC resulted in a
larger improvement in the flexural strength, suggesting that SMA fibre could successfully bridge the cracks tended to localise enabling
the stress transfer and thus, postpone the crack localisation. This, in turn, produced a strain-hardening composite with higher flexural
strength. These findings are consistent with the findings in the literature [6, 24].

<table>
<thead>
<tr>
<th>Mixture ID</th>
<th>0 SMA-2 PVA</th>
<th>0.25 SMA-2 PVA</th>
<th>0.5 SMA-2 PVA</th>
<th>1 SMA-2 PVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural strength (MPa)</td>
<td>6.50</td>
<td>9.62</td>
<td>10.63</td>
<td>12.97</td>
</tr>
<tr>
<td>Mid-span displacement (mm)</td>
<td>6.20</td>
<td>4.36</td>
<td>5.41</td>
<td>10.02</td>
</tr>
<tr>
<td>Strain (%)</td>
<td>0.62</td>
<td>0.44</td>
<td>0.54</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Fig. 11. Toughness indices for SMA and PVA fibre reinforced ECC.
Toughness indices were calculated from the flexural test results for all specimens. A low toughness index indicates that the loss in the strength after cracking is large and the energy absorption ability is low. A comparison of toughness indices for all ECC specimens with and without SMA fibres indicated that the values of $I_{5}$, $I_{10}$, and $I_{30}$ were greater than 5, 10 and 30, suggesting that the produced ECC composites exhibited ductile behaviour (Fig. 11).

3.4.2. Failure patterns

Fig. 12 displays the typical flexural failure patterns of all ECC mixes. Only the cracks that appeared in the region of maximum moment were considered, and the dimension of the region for the crack analysis was $35 \text{ mm} \times 80 \text{ mm}$. As seen in Fig. 12, the cracking patterns of ECC were consistent with the flexural stress-deflection curves presented in Fig. 10. Moreover, multiple cracks associated with strain-hardening features can be clearly observed for all the mixes. It is also worth mentioning that more uniformly distributed cracks can be detected in the 1 SMA-2 PVA mix, which is consistent with its best flexural performance, as discussed in Section 3.4.1.

Table 5 summarises the residual crack width of the composites after the removal of flexural load. Many micro-cracks are usually closed upon the removal of the flexural load and thus, the actual crack widths should be smaller than the recorded residual crack width.

<table>
<thead>
<tr>
<th>Crack analysis results.</th>
<th>0 SMA-2 PVA</th>
<th>0.25 SMA-2 PVA</th>
<th>0.5 SMA-2 PVA</th>
<th>1 SMA-2 PVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack width ($\mu m$)</td>
<td>350.8 (4.32)</td>
<td>330.2 (7.93)</td>
<td>292.6 (13.15)</td>
<td>160.3 (9.74)</td>
</tr>
</tbody>
</table>

Note: The values are standard deviations in parentheses.

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Fig. 13. Fibre conditions across the flexural tensile fracture surfaces of (a) 0 SMA-2 PVA mix and (b) 1 SMA-2 PVA mix.

Fig. 14. Uniaxial tensile stress-strain curves of SMA and PVA fibre reinforced ECC.

Fig. 15. SEM images of the tensile fracture surfaces in ECC.
The performance of 0 SMA-2PVA ECC specimens was more stable as confirmed by the coefficient of variation of the residual crack number that was only 4.32%. On the other hand, the residual crack width of the composite was smaller when more SMA fibres were added to the mix, where the crack-bridging capacity was affected by the characteristics of fibre-matrix interface. The morphology of the fractured surfaces of ECC (Fig. 13) revealed that most of the fibres were pulled out, implying that the bond strength between fibres and matrix was adequate to prevent fibre rupture. Such fibre-matrix interfacial behaviour was important for enhancing

**Fig. 16.** Fracture behaviour of (a) 0 SMA-2 PVA, (b) 0.25 SMA-2 PVA, (c) 0.5 SMA-2 PVA, and (d) 1 SMA-2 PVA under uniaxial direct tension.

**Fig. 17.** Fractal size graphs of (a) 0 SMA-2 PVA, (b) 0.25 SMA-2 PVA, (c) 0.5 SMA-2 PVA, and (d) 1 SMA-2 PVA.
the tensile behaviour which would, in turn, enable transfer of stress and restrict the crack growth [26]. Although SMA fibres also experienced pull-out behaviour during the testing, their crack-controlling performance was not very high, particularly at the low dosage of fibre, which can be attributed to the low tensile strength of SMA fibres compared to that of PVA fibres.

### 3.5. Uniaxial tensile behaviour

Fig. 14 illustrates the representative tensile stress-strain curves of ECC obtained from direct tension tests. The dosage and properties of the PVA and SMA fibres and the chemical bond between the fibre and the surrounding matrix [28] are the key parameters that would affect the shape of the curves.

As seen in Fig. 14, the 0.25 SMA-2 PVA mix did not satisfy the requirements for a saturated strain-hardening behaviour, which can be ascribed to the low ratio of energy based indices (the maximum complementary fracture energy/crack tip toughness) [29]. ECC with 0.5% SMA fibres had a lower tensile strength than the reference specimen, suggesting that this fibre ratio was also not a favourable ratio. ECC with 1% SMA not only showed tensile strain-hardening behaviour, but also had a higher tensile strength than the reference specimen. Therefore, with the appropriate SMA fibre content (1%), PVA and SMA fibres can produce a synergistic effect to improve the crack-controlling behaviour of ECC under direct tensile test. It is also believed that the high dosage of fly ash adopted in this study...
would contribute to the improvement of fibre bridging effect.

Fig. 15 presents the SEM images of fibre morphology at the tensile fracture surfaces in the 1 SMA-2 PVA specimen, indicating the pronounced matrix fragments attached to SMA fibres which prevented the easy facilitation of pull-out process. This, in turn, resulted in higher tensile properties and more uniformly distributed cracks in the 1 SMA-2 PVA mix as seen in Fig. 16. Under uniaxial tensile test, the fracture of all samples was found to occur in the narrow cross-section region.

3.6. 3D Fractal crack analysis

In order to correlate the micro- with macro-scale flexural/fracture behaviour, the surface cracks of the samples were captured. The fractal analysis was then performed and the fractal dimension values of the composites were calculated using Image J, as shown in Fig. 17. Moreover, the 3D digitised images of the cracks were also obtained (Fig. 18). The average of three cracked samples from the analysis was taken. A comparison of the dissipated fracture energy (Ws/Gf) values of surface cracks under the flexural load indicated that the Ws/Gf value went up with the addition of SMA fibre compared to that of the reference mix (Fig. 19). In comparison with the Ws/Gf value of the reference ECC mix, the fracture energy (Ws/Gf) increased by 9%, 109% and 16% with the addition of 0.25%, 0.5% and 1% SMA fibres, respectively. The highest fracture energy is recorded as the composite reinforced with 0.5% SMA fibres. The fractal dimension and fracture energy findings were consistent with the flexural performance at the macro-scale.

The higher fractal dimension and subsequently the dissipated surface crack fracture energy with the increase of SMA fibre content can be attributed to the rise in the surface roughness induced by hybridisation of PVA and SMA fibres. An increase in the surface roughness would lead to an elongation of the crack path by increased tortuosity [30]. Thus, it may be concluded that the addition of more SMA fibres to PVA fibre reinforced ECC could cause the elongation of the crack path that developed around the cement matrix adhered to the fibre surface. This might, in turn, provide the strain relaxation under flexural loading. Fig. 20 shows the surface roughness of the fibres obtained from an AFM analysis and explained the differences observed on the fractal dimensions and 3D digitised crack surface profiles.

3.7. Cost analysis and multi-scale evaluation of the mixtures

Table 6 lists the market price of all ingredients needed for producing engineered cementitious composites made with PVA and SMA fibres. Based on this data, the estimated total material cost of all ECC mixtures in USD/m$^3$ has been illustrated in Fig. 21, as compared with the standard ECC M45 mixture [31].

The figure shows that the cost of PVA fibres constituted a significant portion of the total material cost of mono-PVA fibre reinforced ECC mix (0 SMA-2 PVA) and it was about 85% of the total cost. Adding a certain content of SMA fibres (0.25%, 0.50% and 1.0%) with PVA fibres in ECC increased the total cost by 68.7%, 96% and 198%, respectively. This large increase can be attributed to the high cost of SMA fibres, which is almost equal, that of PVA fibres.

To comprehensively evaluate the feasibility of SMA fibres in PVA based ECC, the overall engineering performance and the total material cost between mono-fibre reinforced ECC (0 SMA-2 PVA) and hybrid fibre reinforced ECC were compared. The overall assessment confirm that the addition of SMA fibres in PVA based ECC is beneficial for compressive strength and especially the flexural tensile strength, the residual crack width, tensile strain capacity and 3D fractal fracture energy whereas the material cost is significantly increased.

As stated by Qian et al. [37], the SMA is corrosion-resistant material. Its super elastic and shape memory characteristics and corrosion resistance can enhance the post-hazard functionality (i.e. earthquake) of the structures made with the SMA fibre-based
Fig. 20. Surface roughness profiles of (a) SMA and (b) PVA fibres.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost (USD/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement [32]</td>
<td>0.087</td>
</tr>
<tr>
<td>Fly ash [33]</td>
<td>0.0363</td>
</tr>
<tr>
<td>Silica sand [34]</td>
<td>0.025</td>
</tr>
<tr>
<td>Water [35]</td>
<td>0.001</td>
</tr>
<tr>
<td>Super plasticizer [34]</td>
<td>1.443</td>
</tr>
<tr>
<td>PVA [26]</td>
<td>30.92</td>
</tr>
<tr>
<td>SMA [36]</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 6
Cost analysis data of all components in the manufactured ECC.
engineered cementitious composites. Taking into account these key properties for the multi-scale evaluation of the mixtures, 0.5 SMA-2 PVA mix can be regarded as the most cost-effective mixture as it processed adequate mechanical properties, a moderately higher cost and better durability as compared with ECC M45. In addition, 1 SMA-2 PVA mix with a greatest tensile strength and tensile strain capacity of larger than 2.0% and the improved cracking resistance is also promising for certain structural applications, such as repairing and retrofitting of existing structures.

4. Conclusions

In this study, a series of experiments were performed to investigate the effect of SMA fibre addition on engineering properties, flexural response and damage behaviour as well as the microstructure of PVA fibre reinforced ECC. Based on the results obtained, the following conclusions can be drawn:

- The presence of SMA fibres in the PVA fibre reinforced ECC subjected to bending can effectively reduce the residual crack width by 54.3% compared to that of ECC with 2% PVA fibre, although the lower compressive strength was observed in ECC when more than 0.5% SMA fibre was added with PVA fibres.
- The flexural properties of ECC including cracking strength, mid-span displacement, ultimate strain were considerably improved with the increase of SMA fibre dosage. ECC mixtures with hybrid fibres (2% PVA and 1% SMA) exhibited robust tensile strain-hardening behaviour along with saturated multiple cracking features, although the 0.25% SMA-2% PVA mix did not satisfy the requirements for a saturated strain-hardening behaviour.
- As the SMA fibre dosage went up from 0.25% to 1%, the surface crack characteristics in terms of fractal dimension and dissipated surface fracture energy of ECC exhibited a rising trend due to the surface roughness. The dissipated fracture energy of hybrid fibre reinforced ECC with 1% SMA fibre was 2.09 times higher than that of ECC with 2% PVA fibre, which can be ascribed to the elongation of crack path developing around the cement matrix adhered to the fibre surface.
- SEM micrographs indicated that less pull-out SMA fibres took place at the fracture surface of ECC particularly at a low dosage of fibre addition, which was not favourable for the improvement of stress transfer between adjacent fibres, while the pronounced matrix fragments can be observed at the interface in ECC with hybrid fibres (1% SMA + 2% PVA), resulting in better tensile properties of ECC.

This paper reveals a great potential of producing an innovative and sustainable high dosage of fly ash-slag based ECC via the hybridisation of PVA and SMA fibres. Satisfactory engineering properties (e.g. robust strain hardening behaviour) are achievable when 0.25% and more SMA fibres are added to the PVA fibre reinforced ECC, which can be useful for certain practical applications. Besides, it is expected that the addition of SMA fibres can enhance the crack-closing capacity of ECC under loading. Thus, it is vital to explore the effect of SMA fibre on the crack-closing performance of ECC mixes subjected to dynamic loads with various strain rates. Moreover, the drying shrinkage of hybrid fibre reinforced ECC is still a concern, and thus it is important to find an effective strategy to further reduce the drying shrinkage of hybrid fibre reinforced ECC. These are subjects of ongoing work and will be presented in future publications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Data availability

No data was used for the research described in the article.

References


