MECHANICAL PERFORMANCE OF HYBRID FIBRE-REINFORCED ENGINEERED CEMENTITIOUS COMPOSITE INCORPORATING NITI-SMA SHORT FIBRES

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ABSTRACT

A new high-strength, high-tensile ductility hybrid fibre-reinforced engineered cementitious composite (HECC-SMAF) incorporating randomly dispersed nickel-titanium shape memory alloy short fibres (NiTi-SMA) has been pioneered in this study. The mechanical properties of the HECC-SMAF produced with a combination of 2% polyvinyl-alcohol (PVA) and 0.5%, 1%, and 1.5% NiTi-SMA fibres by volume fraction have been explored. The experimental results indicate that utilizing a combination of those fibres can enhance the tensile capacity of ECC by up to 39% with a slight to no increase in compressive strength. An overall reduction in workability was observed compared to that of ECC made with only 2% PVA by volume fraction, which is typical of metallic fibre-reinforced cementitious systems. Among the tested ECC mixtures, HECC-SMAF made with 2% PVA and 1% NiTi-SMA presents the best mechanical performance.

Keywords: Engineered cementitious composite, HECC-SMAF, PVA, shape memory alloy.

1. INTRODUCTION

Concrete is the most utilized construction material in the world. Although it primarily carries compressive loads, concrete is also subjected to tensile stresses. The concept of using fibres to reinforce brittle materials has been utilized for thousands of years when sunbaked bricks reinforced with straw were adopted to build the 57-m high hill of Aqar Quf near Baghdad. More recently, asbestos fibres have been used to reinforce cement products for about 120 years, cellulose fibres for at least 70 years, and metal, polypropylene, and glass fibres for the past 50 years (Hannant 1995).

Recently, two new classes of high-performance fibre-reinforced concrete (HPFRC) emerged: (1) Ductal; which has high tensile strength of up to 12 MPa with ductility of up to 0.06% (six times that of normal concrete); and (2) Engineered Cementitious Composites (ECCs), which have significantly increased ductility of more than 3% (hundreds times that of normal concrete) (Wu et al. 2012). A variety of fibres were used in the production of ECCs such as polyvinyl alcohol (PVA), polypropylene (PP), polyethylene (PE), and steel fibres. In recent years, hybrid fibres have been used to improve the performance of cement-based composites (Pan et al. 2015, Nehdi and Ladanchuk 2004). Although the use of shape memory alloys (SMAs) in civil engineering structures have been reported by many researchers, most used SMA rods (e.g. Nehdi et al. 2010) or continuous wires (Choi et al. 2015). However, information on using SMA as short fibres remains scarce.

Therefore, this paper aims to investigate the early-age mechanical performance of a hybrid PVA-ECC incorporating randomly dispersed NiTi-SMA fibres at 0.5%, 1% and 1.5% volume fraction. Flowability, compressive and splitting tensile strength are examined and discussed.

2. EXPERIMENTAL PROGRAM

2.1 Materials and Mixture Proportions

ASTM C150 ordinary portland cement (OPC) with a specific gravity of 3.15 and a surface area of 371 m^2/kg was used as the main binder. Class C fly ash (FA) according to ASTM C618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete) specifications with specific gravity of 2.6 was used as a pozzolanic additive in this study. Silica-sand (SS) with maximum nominal size of 200 µm and specific gravity of 2.65 was used as fine aggregate. Table 1 reports the cement, fly ash and silica-sand chemical compositions.

Table 1: Chemical analysis of OPC, FA, and SS

Component (%)	OPC	FA	SS
CaO	64.35	16	0.01
SiO_2	20.08	52.19	99.7
Al_2O_3	4.63	17.56	0.14
Fe_2O_3	2.84	3.66	0.016
MgO	2.07	1.57	0.01
SO_3	2.85	2.4	---
K_2O	---	0.9	0.04
Na_2O	---	0.7	0.01
Loss of ignition	2.56	1.6	---

The ECC mixture was reinforced with nickel titanium (NiTi) shape memory alloy fibres, which meet the ASTM F2063 (Standard Specification for Wrought Nickel-Titanium Shape Memory Alloys for Medical Devices and Surgical Implants) specifications, and polyvinyl-alcohol (PVA) short fibres. Table 2 summarizes the mechanical properties of the PVA and SMA fibres. The utilized SMA fibre has a martensite and austenite finish temperature of 85°C and 111°C, respectively. Figure 1 represents a typical stress-strain curve of SMA at different temperatures. The volume fraction for SMA addition was 0.5%, 1% and 1.5%, while it was 2% for PVA. Polycarboxylate high-range water reducing admixture (HRWRA) according to ASTM C494 (Standard Specification for Chemical Admixtures for Concrete) specifications was added as a percentage of cement weight to adjust and improve the workability of tested mixtures.

Table 2: Properties of SMA and PVA fibres

	Ultimate tensile strength (MPa)	Diameter (mm)	Length (mm)	Young's modulus (GPa)	Elongation (%)	Density (kg/m^3)
SMA	869.43	0.635	16	41	38	6450
PVA	1620	0.039	8	42.8	6	1300

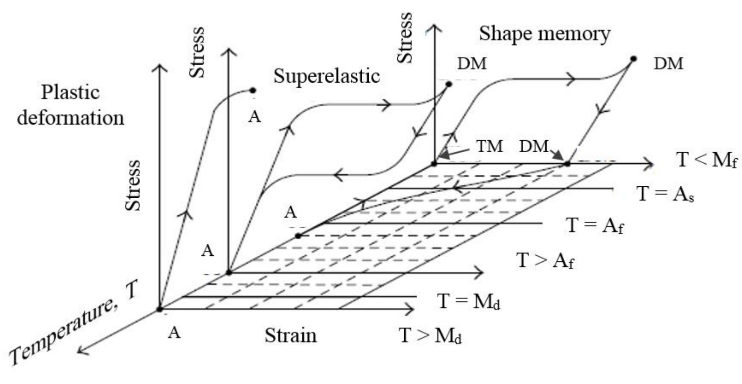

Figure 1: Typical stress-strain curve of superelastic SMA at different temperatures (after Desroches & Smith 2004).

The tested mixtures compositions are given in Table 3. The first number in the abbreviation indicates the PVA fibre content, while the second number shows the SMA fibre content. For example, ECC2-1 refers to engineered cementitious composite (ECC) incorporating 2% PVA fibre and 1% SMA fibre by volume fraction. Table 3 shows the mixture proportions for all tested mixtures.

Table 3: Mixture proportions

Mixture	Cement	Fly ash	Silica sand	w/cm	HRWRA	PVA (%V_f)	SMA (%V_f)
ECC2-0	1	1.2	0.8	0.26	0.012	2	0
ECC2-0.5	1	1.2	0.8	0.26	0.012	2	0.5
ECC2-1	1	1.2	0.8	0.26	0.012	2	1
ECC2-1.5	1	1.2	0.8	0.26	0.012	2	1.5

2.2 Specimen Preparation and Curing

Initially, all solid ingredients including the cement, FA, and silica sand were mixed together in dry condition for one minute. Then, water and HRWRA were added to the dry mixture over another three minutes until a homogeneous mixture was produced. This was followed by PVA and SMA fibres addition gradually and mixing continued for another three minutes until all fibres were uniformly distributed. A 20 L concrete mixer was used to prepare all ECC mixtures. All cast specimens were demolded after 24 hrs and kept inside sealed bags for 2 days to avoid mixing water loss due to evaporation until testing.

3. TESTING METHODS

3.1 Workability

Flow table test was conducted on freshly mixed ECC mixtures as per the guidelines of ASTM C230 (Standard Specification for Flow Table for Use in Tests of Hydraulic Cement) to explore the effect of SMA fibre addition on workability.

3.2 Compressive Strength

Six cubic specimens 50 mm x 50 mm x 50 mm from each ECC mixture were tested at the ages of 3 and 28 days for the determination of the compressive strength for the different ECC mixtures as per ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) using a standard testing machine with a capacity of 2000 kN.

3.3 Splitting Tensile Strength

From each mixture, six cylindrical specimens of 75 mm in diameter by 150 mm in height were prepared for the determination of the splitting tensile strength at the ages of 3 and 28 days as per ASTM C496 (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens).

3.4 Flexural Behaviour

From each ECC mixture, six 40 mm x 80 mm x 360 mm prisms were used for the determination of the flexural capacity (modulus of rupture) and crack propagation as per the guidelines of ASTM C1609 (Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete (Using Beam with Third-Point Loading)) at testing ages of 3 and 28 days using an MTS machine under a loading rate of 0.05 mm/min. The number of cracks and their width were measured using optical microscope.

The modulus of rupture (MOR) was calculated using Eq. 1:

[1] $$\mathrm{MOR} = \frac{P*L}{b*d^2}$$

Where P is the applied load in Newton. L, b, and d, are the beam span, width and depth in mm, respectively. After testing the specimens, they were heated up by about 300°C for 3 minutes using a heat gun, which was fixed at 3.5 cm away from the tensile (cracked) side of the specimens. The heat treatment process was used to activate the SMA fibres, which were in the martensite phase before heating, to investigate its strain recovery capability and how that affects the overall performance of the composite.

4. RESULTS AND DISCUSSION

4.1 Workability

It was observed that the ECC mixture that incorporates only 2% PVA fibres by volume fraction (control) had the ability to flow under its own weight, while an overall reduction in workability was observed due to SMA fibre addition compared to that of the ECC control mixture. For instance, the workability decreased by 15.6%, 33.33% and 43.1% due to SMA fibre addition by 0.5%, 1% and 1.5%, respectively. Figure 2 demonstrates the relative reduction in flow diameter of ECC mixtures compared to that of control specimen.

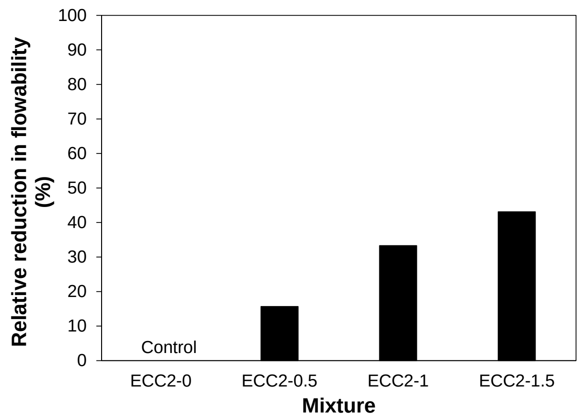

Figure 2: Relative reduction in flow diameter due to SMA fibre addition.

4.2 Compressive Strength

Figure 3 illustrates the variation in the compressive strength for different ECC mixtures at testing age of 3 and 28 days. It can be observed that the SMA fibre addition did not have a significant effect on the compressive strength of the composite. For instance, at early age testing, the compressive strength of ECC2-0.5 and ECC2-1 mixtures exhibited a slight increase of about 0.67% and 2.82%, respectively, compared to that of the ECC2-0 mixture. On the other hand, the compressive strength of ECC2-1.5 slightly decreased by about 2.87% at the same testing age. This may be attributed to increasing the porosity due to over-reinforcing the composite by 3.5% by volume fraction fibres (2% PVA and 1.5% SMA) which led to strength degradation. The same performance was observed at 28 days but with different percentages. For instance, the compressive strength of ECC2-0.5, ECC2-1 and ECC2-1.5 mixtures exhibited a slight decrease by about 5.2%, 4.8% and 2.99%, respectively. The achieved compressive strength of ECC specimens at 3 and 28 days was 39 to 41 and 65 to 69 MPa, respectively, depending on SMA fibre content.

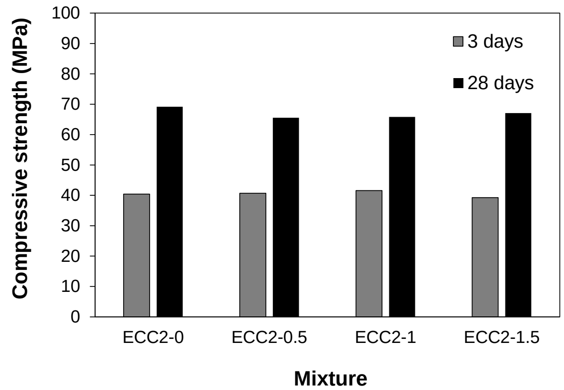

Figure 3: Compressive strength of ECC specimens.

4.3 Splitting Tensile Strength

The splitting tensile test results at testing ages of 3 and 28 days are displayed in Figure 4. It can be observed that the tensile capacity of the composite was generally improved due to SMA fibre addition. For instance, the tensile capacity of ECC2-0.5, ECC2-1 and ECC2-1.5 specimens was increased by about 30.1%, 39.09% and 31.5% at testing age of 3 days, respectively, and 20.4%, 27.16% and 24.6% at 28 days, respectively, due to SMA fibre addition compared to that of ECC2-0 at the same testing ages. However, the high reinforcement ratio of fibres in ECC2-1.5 specimens tended to decrease the tensile capacity by about 5.7% and 2.03% at 3 and 28 days, respectively, compared to that of-ECC2-1 due to the high porosity in this mixture which led to strength degradation, however, it still achieved tensile capacity higher than that of the ECC mixture incorporating only 2% PVA. The ultimate tensile strength of HECC-SMAF specimens ranged from 5.43 to 12.08 MPa depending on the SMA fibre content and maturity of specimens.

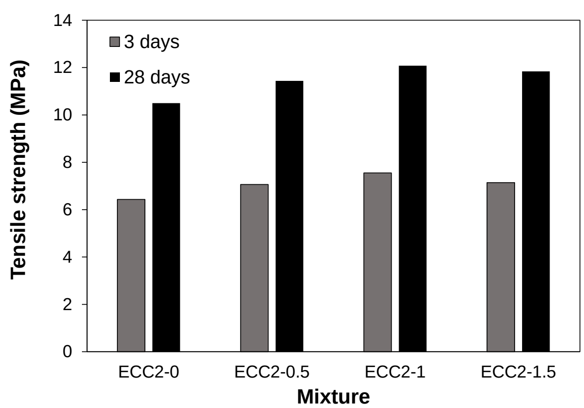

Figure 4: Splitting tensile strength of ECC specimens at different testing ages.

4.4 Flexural Behaviour

4.4.1 Flexural Strength (MOR)

Figure 5 illustrates typical load-deflection curves of specimens from different ECC mixtures tested under four-point bending at the ages of 3 and 28 days. The peak load sustained and the crack pattern were the main parameters explored in this study. It was observed that the ultimate flexural strength of ECC specimens varied from 5.3 to 12.2 MPa, depending on the curing age and fibre content. Generally, the flexural strength of ECC specimens at 3 days increased with increasing SMA fibre addition at all testing ages. For instance, the ultimate flexural strength of the ECC2-0.5, ECC2-1 and ECC2-1.5 specimens was about 2.4%, 51.9% and 44.7% higher than that of ECC2-0, respectively. Similar performance was observed when the curing age was prolonged, but with different percentages. For instance, at 28 days, the ECC2-0.5, ECC2-1 and ECC2-1.5 specimens achieved flexural capacity of 4.9%, 97.5% and 70.4% higher than that of ECC2-0 at the same testing age, respectively. This may be attributed to increasing the fibre-matrix interface frictional area due to increasing fibre content, consequently, improving the overall load carrying capacity of the composite.

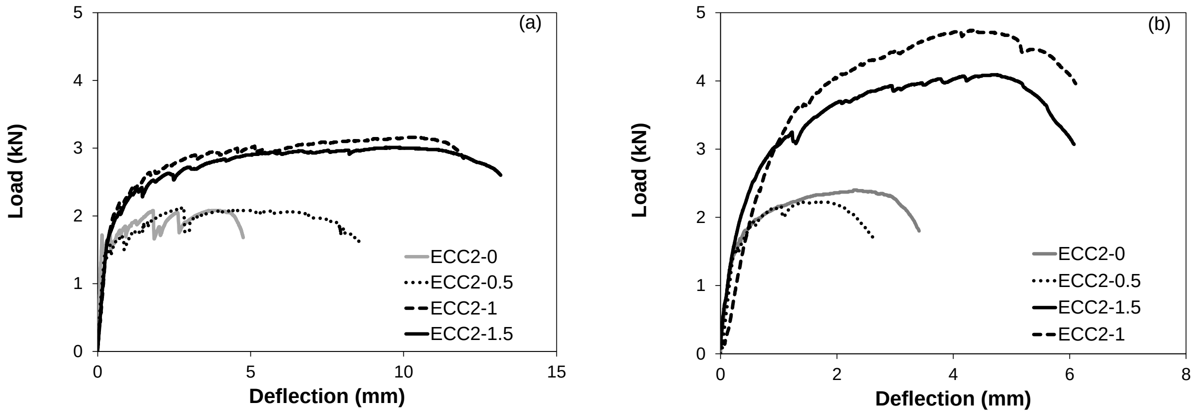

Figure 5: Typical load-deflection curves of ECC mixtures at different ages a) 3 days, and b) 28 days.

The flexural strength of the ECC specimens increased by about 36% at 28 days compared to that at 3 days. This may be attributed to the high volume of fly ash that represents more than half of the total cementitious materials, which gained more strength at later ages, thus enhancing the fibre-matrix frictional bond. The number of cracks that formed on the tension side of specimens subsequent to four-point bending was evaluated at 3 and 28 days. It was observed that all ECC specimens had multi-fine cracks on the tension face of the specimens. The average crack width measured for all ECC specimens was lower than 100 µm at all testing ages.

4.4.2 Self-Healing Performance

The SMA fibres were mobilized by heating the specimens to explore its strain recovery performance. Although, this process was accompanied with a grid of multiple fine cracks (less than 10 µm) at the tension face of the specimens, the cracks were self-healed by up to 36%, depending on the fibre type and content, as displayed in Fig. 6. For instance, the average crack width at the tension face of the ECC2-0, ECC2-0.5, ECC2-1 and ECC2-1.5 specimens decreased by about 0%, 20.8%, 29.1% and 35.9%, respectively, due to heating process compared to that of non-heated specimens. This may be attributed to the fact that the shape memory characteristic of NiTi-fibres led to strain recovery and consequently self-healing of cracks. This phenomenon demonstrates the uniqueness of SMA fibres compared to other types of fibres.

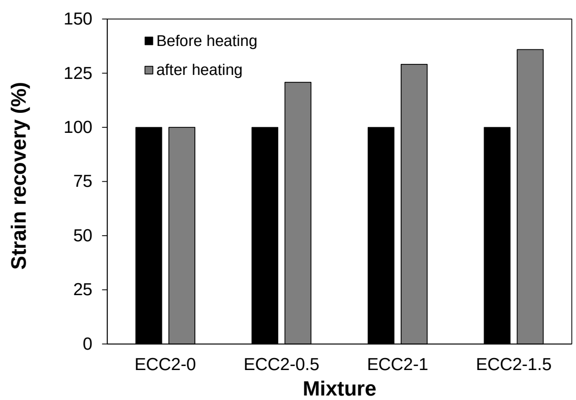

Figure 6: Strain recovery of cracked ECC specimens.

5. CONCLUSIONS

This paper aims to experimentally evaluate the mechanical properties of mono and hybrid fibre ECC mixtures, which incorporate 0%, 0.5%, 1% and 1.5% SMA fibres and 2% PVA short fibres by volume fraction. The different mixtures were tested at 3 days and the main findings are summarized as follows:

- An overall reduction in workability was observed due to SMA fibre addition compared to that of the ECC mixture that incorporates only 2% PVA fibres by volume fraction.
- Generally, SMA fibre addition led to a slight to no increase in compressive strength of the composite at testing ages of 3 and 28 days.
- ECC specimens that incorporate 2% PVA and 1% SMA fibres achieved the highest tensile capacity compared to that of the ECC control specimen at the same testing ages.
- The ECC2-1.5 specimens had decreased tensile capacity due to its relatively higher porosity compared to that of ECC2-1 specimens, however, it still acquired tensile capacity higher than that of the ECC control specimen which incorporates only 2% PVA fibre.
- Generally, the flexural capacity of the composite was improved due to SMA fibre addition and when the curing age was prolonged.
- Mobilizing the SMA fibres by heating led to strain recovery by up to 36% due to the shape memory effect.
- This study demonstrates the beneficial effects of using NiTi-SMA fibres in structural applications.

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