RESILIENT INFRASTRUCTURE

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IMPACT BEHAVIOUR OF SHAPE MEMORY ALLOY HYBRID FIBRE-REINFORCED ENGINEERED CEMENTITIOUS COMPOSITE

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ABSTRACT

An experimental study was conducted to evaluate the impact behaviour of an innovative hybrid-fibre engineered cementitious composite (ECC) incorporating randomly dispersed short shape memory alloy fibres (SMA). A modified drop weight test was conducted on specimens from various ECC mixtures with and without SMA fibres. The impact behaviour was evaluated and compared based on the ability to dissipate energy and sustain impact load without damage. Results show that the addition of SMA to ECC mixtures significantly enhanced their performance under impact loading. The amount of dissipated energy by ECC increased by about 51% as a result of SMA fibre addition. This highlights the potential benefits of incorporating SMA in composite materials exposed to impact loads, paving the way for a wider implementation in the field of fortified structures.

Keywords: Engineered cementitious composites, shape memory alloy, hybrid, fibre.

1. INTRODUCTION

The impact resistance of conventional reinforced concrete (RC) buildings depends mainly on its ability to dissipate energy upon impact events, blasts, and earthquakes. Failure to sustain such extreme loads would result in partial or total collapse of the RC building (Alemdar and Sezen 2010). In order to avoid such a hazardous failure mechanism, innovative construction materials are needed in constructing new smart buildings that are characterized by: i) enhanced deformation capacity and ductility, ii) higher damage tolerance, iii) better concrete confinement, iv) decreased or minimized residual crack sizes and, v) recovered or reduced permanent deformations (Parra-Montesinos et al. 2005).

Shape memory alloys (SMA) are promising innovative materials that can be utilized to achieve such smart buildings. For instance, SMA bars can be used in structural elements as replacement for traditional steel reinforcement. This was explored extensively by many researchers (e.g. Saiidi et al. (2007), Nehdi et al. (2010), and Choi et al. (2015)).

On the other hand, engineered cementitious composites (ECCs) are unique high performance fibre-reinforced cementitious systems featuring high ductility and damage tolerance loading. ECC is made of binder, small particle size sand, fillers, supplementary cementing materials and small amount of high modulus short random fibres. It is also categorized as a green material due to its high content of recycled by-products and mineral admixtures (Marks and Conklin 2013).

Therefore, this paper investigates the potential of producing a hybrid polyvinyl alcohol-engineered cementitious composite (PVA-ECC) incorporating randomly dispersed nickel titanium (NiTi) SMA short fibres.

2. EXPERIMENTAL PROGRAM

2.1 Materials

Ordinary portland cement (OPC) according to ASTM C150 (Standard Specification for Portland Cement) with a specific gravity of 3.15 and a surface area of 371 m^2/kg was used as the main binder. Fly ash class C 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 with maximum nominal size of 200 µm and specific gravity of 2.65 was used as fine aggregate. Table 1 shows the composition of the cement, fly ash and silica-sand chemical compositions.

Table 1: Chemical composition of ordinary portland cement, fly ash and silica-sand

Component (%)	Cement type I	Fly ash	Silica sand
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	---

Two types of fibres were added: 16 mm nickel titanium (NiTi) shape memory alloy (SMA), which meets the ASTM F2063 (Standard Specification for Wrought Nickel-Titanium Shape Memory Alloys for Medical Devices and Surgical Implants) standard and 8 mm polyvinyl-alcohol (PVA) short fibres. The volume fractions for SMA and PVA were 0.5 and 1.5%, respectively. Polycarboxylate high-range water reducing admixture (HRWRA) according to ASTM C494 (Standard Specification for Chemical Admixtures for Concrete) was added as a percentage of cement weight to adjust and improve the workability of the tested mixtures. The tested mixtures compositions are given in Table 2. The first number in the abbreviation indicates PVA fibre content, while the second number shows the SMA fibre content. For example, ECC1.5-0.5 refers to an engineered cementitious composite (ECC) incorporating 1.5% PVA fibre and 0.5% SMA fibre by volume fraction. Table 2 shows the mixture proportions for all tested mixtures. The target 28 days compressive strength was 65 MPa for all mixtures. All tests were performed after 7 and 28 days after casting.

Table 2 Mixture proportions

Mixture	Cement	Fly ash	Silica sand	w/cm	HRWRA	PVA (%V_f)	SMA (%V_f)
ECC0-0	1	1.2	0.8	0.26	0.012	0	0
ECC1.5-0	1	1.2	0.8	0.26	0.012	1.5	0
ECC1.5-0.5	1	1.2	0.8	0.26	0.012	1.5	0.5

2.2 Mixing and Curing

A 20 L concrete mixer was used to prepare all ECC mixtures. Initially, all solid ingredients including the cement, FA, and silica sand were mixed together in a 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. After 24 hrs, cast specimens were demolded and kept inside sealed bags for 7 days to avoid mixing water loss due to evaporation. Specimens were stored in the lab conditions (Temperature of 20 ± 2 °C and relative humidity 55 ± 5%) until testing.

3. TESTING METHODS

3.1 Compressive Strength

Six cubic specimens 50 mm x 50 mm x 50 mm from each ECC mixture were prepared to monitor compressive strength development 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. Three specimens from each mixture were tested at ages 7 and 28 days.

3.2 Drop-Weight Impact Test

A drop weight impact test was conducted on different ECC mixtures to evaluate its impact resistance under multiple impacts at different drop-levels (50 mm, 100 mm, and 150 mm). Freshly mixed ECC was cast in cylindrical moulds having dimensions 100 mm x 200 mm. From each cylindrical specimen, three discs of size 100 mm x 50 mm were cut using a diamond saw. The discs were then subjected to a drop weight test using an Instron impact loading testing machine (Fig. 1) with a maximum impact energy of 1603 J. More details about the test can be found elsewhere (Nehdi and Soliman 2013). Also, a series of tests was made on similar heated specimens to investigate the shape memory effect of NiTi-SMA fibres on ECC at the age of 28 days. The heating process takes place for 10 minutes, 35 mm away from front surface of specimens, using a heat gun which was able to produce up to 300°c.

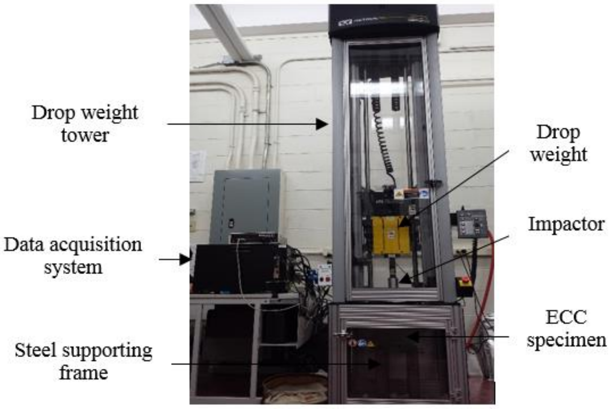

Figure 1: Illustration of the Instron impact loading testing machine.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

Figure 2 displays the variation in compressive strength for different ECC mixtures versus time. It can be observed that the SMA and/or PVA fibre addition did not show a significant effect on the achieved compressive strength at all testing ages. For instance, the compressive strength of ECC1.5-0 and ECC1.5-0.5 mixtures exhibited a slight increase of about 1% and 4.76%, respectively, at age 28 days compared to that of the ECC0-0 mixture. Regardless of the ECC mixture composition, all ECC mixtures gained about 51% higher strength at age 28 days compared to that at 7 days. This can be attributed to the progress in the hydration products formation, which in turn improves the fibre-matrix interface frictional bond resistance.

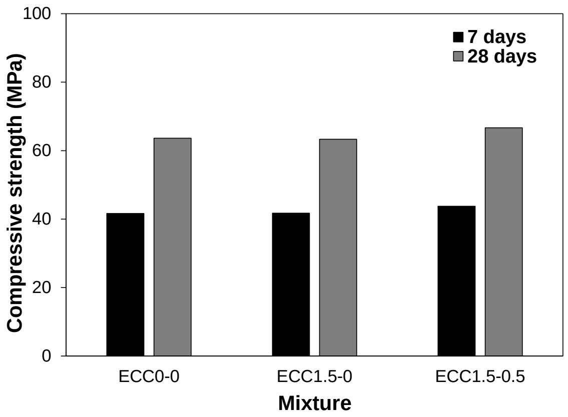

Figure 2: Compressive strength for ECC specimens.

4.2 Impact behaviour

The impact force was measured during each impact as derived from the accelerometer measurements. The impact load-penetration depth curves are shown in Figures 3a, 4a and 5a. Typical impact failure was observed in the ECC mixture without fibre after the second hit (100 mm drop-height), while all the other ECC specimens did not fail or crack under the effect of multi-impacts up to 44000 N. The peak impact load increased accordingly to the testing age and SMA and/or PVA fibre addition rate. The peak impact force for mixtures incorporating 1.5% mono PVA fibre addition increased by about 19.8% and 2.3% compared to that of the ECC mixture without fibre at ages 7 and 28 days, respectively. Furthermore, ECC1.5-0.5 exhibited greater peak impact forces of about 12.5% and 22.6% than that of the ECC1.5-0 at the age of 7 and 28 days, respectively. This highlights the significant improvement in the impact strength due to SMA addition.

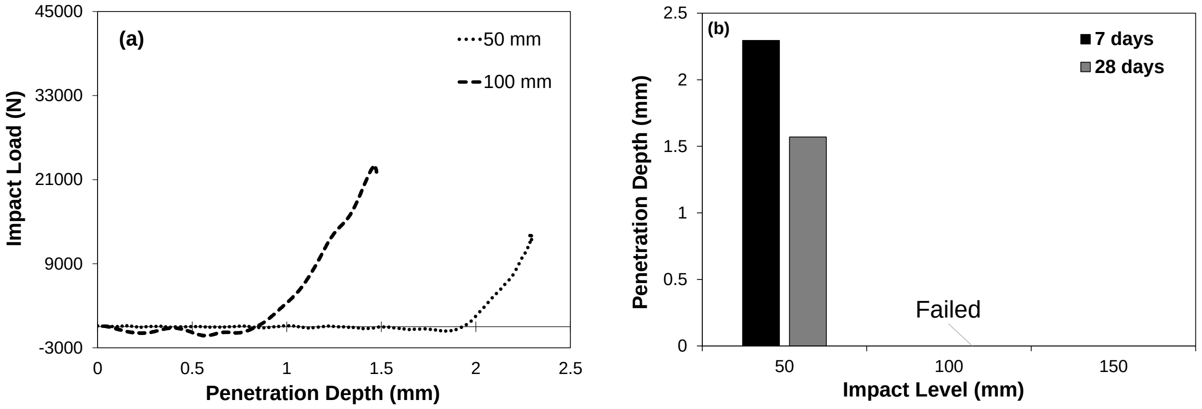

Figure 3**:** Impact load-penetration depth performance of ECC0-0 a) at age 7 days and, b) 7 and 28 days.

The difference in the ability of mono and hybrid fibre ECC specimens to resist impact load mainly depends on the fibre type and content. The material's response under impact load depends on its interactive behaviour under compressive and shear stresses (Li et al. 2000). Since all ECC mixtures have a slight difference in compressive strength, therefore, it can be concluded that stronger bond between SMA and/or PVA fibres and matrix better resists shear stresses induced by the impact load leading to achieve higher impact resistance.

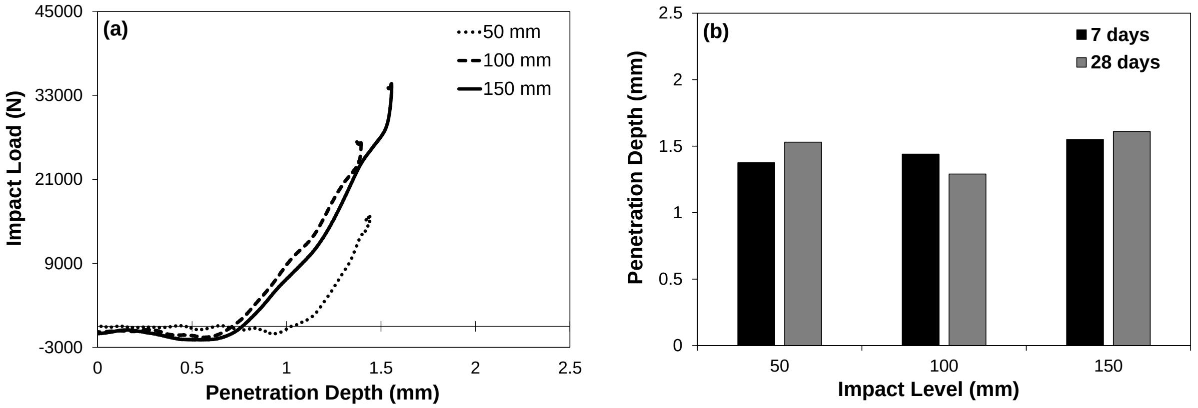

Figure 4: Impact load-penetration depth performance of ECC1.5-0 a) at age 7 days and, b) 7 and 28 days.

The impact load applied to ECC specimens and the corresponding penetration depth at testing ages of 7 and 28 days are shown in Figures 3b, 4b and 5b. Each specimen was subjected to multiple impacts at different drop-levels as follows; i) first hit at 50 mm, ii) second hit 100 mm and, iii) third hit at 150 mm. It can be observed that only a small penetration took place due to impact loading for all dropping heights. The total penetration depth tended to decrease with SMA and/or PVA fibre addition at all testing ages except for the ECC matrix without fibre. Mixture ECC0-0 cracked due to the application of the first impact load and failed after the second one due to its brittleness. This performance reflects the fibre-matrix ability to save the composite from cracking or damaging under the effect of impact loading (up to 44000 N). For instance, at first hit, the ECC1.5-0.5 specimen had a penetration depth less than that of the ECC1.5-0 and ECC0-0 by about 16.36% and 49.89% at the age of 7 days, respectively. The same performance was observed for all impact levels regardless the age.

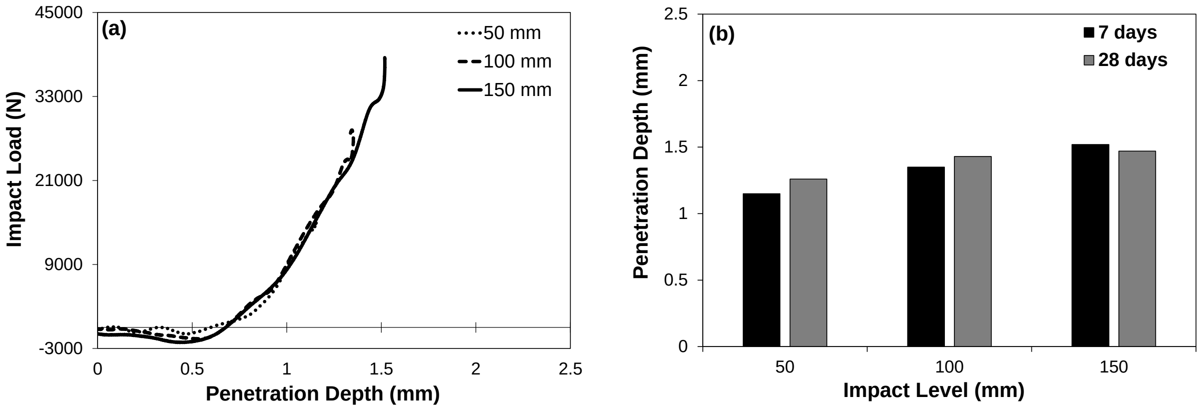

Figure 5: Impact load-penetration depth performance of ECC1.5-0.5 a) at age 7 days and, b) 7 and 28 days.

Figure 6 illustrates the energy absorption capacity of specimens produced from different ECC mixtures. The computerized system, which was used in the data measurements during impact, was programmed to calculate the energy absorption capacity of the specimens which is equal to the difference between the applied energy and that remained in the system after impact. The overall energy absorption capacity of ECC improved with the addition of SMA and/or PVA fibres. For example, ECC1.5-0.5 and ECC1.5-0 dissipated energy of around 1237% and 1080% at testing age of 7 days and 1277% and 953% at 28 days more than that of the control ECC0-0, respectively. Furthermore, the energy dissipation ability for ECC was enhanced by about 14.3% and 33.96% at the testing ages of 7 and 28 days due to 0.5% SMA fibre addition compared to that of the ECC incorporating PVA fibre alone.

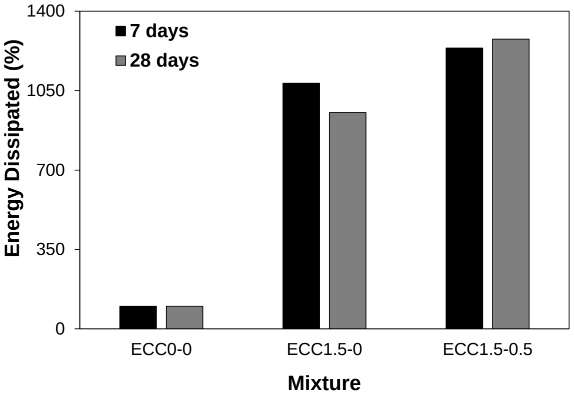

Figure 6: Cumulative energy dissipated by ECC specimens at different testing ages.

4.3 Shape memory effect

Heating up the specimens by about 300°C led to the formation of a grid of multiple fine cracks (less than 10 μm) at the front surface of the specimens. The ECC0-0 mixture and that incorporating the mono-PVA fibre were deteriorated due to degradation of the cracked matrix and losing of the PVA mechanical properties due to the heating process. However, the performance of the hybrid fibre specimens made with SMA fibres was not similar. For instance, as displayed in Fig. 7, the energy dissipation capability of the heated ECC0-0 and ECC1.5-0 specimens decreased by about 49.7% and 11.1% at the age of 28 days, respectively, while it increased by about 15.7% for the ECC1.5-0.5 specimens compared to that of similar specimens tested at the same age without heating. This may be attributed to the shape memory effect of the heated SMA fibres, which led to pre-stressing the specimens, consequently improving its energy dissipation ability. This reflects the SMA fibres capability to provide a crack arresting mechanism in concrete structures, even when affected by high temperatures.

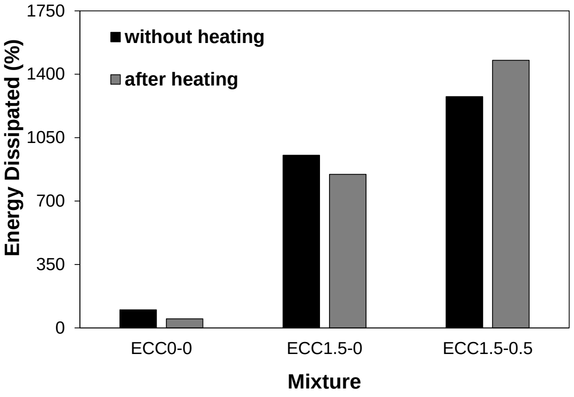

Figure 7: Cumulative energy dissipated by ECC specimens with and without heating treatment at 28 days.

5. CONCLUSIONS

This paper represents an experimental investigation on the effects of mono and hybrid fibre addition on the impact behaviour of different ECC mixtures incorporating SMA and/or PVA short fibres. The main findings are summarized as follows:

1. SMA and/or PVA fibre addition did not significantly affect the compressive strength of the composite.
2. ECC specimens that incorporate 1.5% PVA and 0.5% SMA fibres achieved the highest peak impact force at all impact levels and testing ages compared to that of the ECC specimens that contained 1.5% PVA fibres alone.

3. SMA fibre addition led to a reduction in the impact penetration depth in the ECC specimens compared to that of mixtures incorporating only the mono-PVA fibre.
4. The energy absorption ability of ECC specimens that incorporate 1.5% PVA fibres alone and that containing 1.5% PVA and 0.5% SMA fibres by volume fraction is about 10 and 12 times higher than that of the ECC matrix, respectively, at a testing age of 7 days. The same performance was observed at 28 days, but with about 9 and 13 times that of the ECC matrix, respectively.
5. Heating the ECC matrix specimen and that made with PVA fibres only led to strength degradation. Conversely, the heating mobilized the SMA fibres to pre-stress the composite due to shape memory effect, thus improving its energy dissipation ability by about 15% at the age of 28 days.

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