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Innovative crack-healing hybrid fiber reinforced engineered cementitious composite

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HIGHLIGHTS

- Innovative SMA-PVA engineered cementitious composite was pioneered.
- The composited is endowed with strain recovery owing to SMA fibers.
- The new composite offers superior tensile, flexural and toughness behavior.
- Structural safety could be enhanced using the new composite.

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ABSTRACT

An innovative hybrid engineered cementitious composite with crack-healing capability is pioneered in this study. The mechanical properties of this composite, which incorporates short randomly dispersed polyvinyl alcohol (PVA) and shape memory alloy (SMA) fibers were investigated. Results show that a combination of PVA and SMA fibers significantly enhanced the tensile and flexural capacity of the ECC by 59% and 97%, respectively compared to that of a conventional ECC made with 2% PVA fiber alone. No further improvement in mechanical behavior was achieved beyond a certain fiber dosage due to increased porosity and fiber clustering. In spite of the damage incurred by coexisting PVA fibers due to heat treatment, cracked SMA-ECC specimens were self-healed upon heat treatment owing to the self-centering capability of SMA fibers. The findings of this research highlight the prospect to engineer novel cementitious composites with eminent mechanical behavior to mitigate damage mechanisms and enhance safety of infrastructure critical for national security importance.

1. Introduction

The concept of using fibers to reinforce brittle materials has been utilized for thousands of years, for instance when sunbaked bricks reinforced with straw were used to build the 57-m high hill of Aqar-Quf near Baghdad [1]. Cement products have also been reinforced with asbestos and cellulose fibers for about 90 years [2]. Glass, polypropylene and steel fibers have also been used in reinforcing cement-based matrices over the past 70 years [1]. Concrete, which is the world's most utilized construction material, is often subjected to various combinations of compressive, tensile and shear stresses via gravity, seismic and wind loads, explosive forces, shrinkage, thermal contraction, etc. Recently, high-performance fiber-reinforced concrete (HPFRC) has been utilized in structural applications owing to its superior tensile load resistance and enhanced durability. Two new classes of HPFRC have emerged: (i) Ultra-High Performance Concrete, which has exceptionally high mechanical strength and superior ductility; and (ii) Engineered Cementitious Composites (ECCs); which have superior ductility hundreds of times higher than that of normal concrete [3].

ECC was developed in the early 1990s [4]. Cement, fine sand, supplementary cementitious materials and high-modulus short fibers are the main components of this special type of HPFRC. The fibers used in ECC are micro-mechanically designed to achieve high damage tolerance under severe loading with high durability under normal service conditions [5]. Polyvinyl alcohol, polypropylene, polyethylene, and steel fibers have been utilized in the production of ECCs. Conventional concrete normally fractures in a brittle manner under flexural loading. Conversely, ECC displays a metal-like performance after first cracking and exhibits superior strain capacity of about 500 times higher than that of normal concrete [6]. The ductility of ECC beams can be evaluated through estimating fracture toughness, which is a quantitative value expressing the ability to dissipate energy and resist brittle fracture

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under flexural loading. Ductile ECC beams can achieve high fracture toughness [7], which is usually expressed in terms of relative values called "toughness indices". These indices are used as indicators for the deflection ability of beam specimens under flexural loading and its energy absorption capacity [8].

Past research has primarily focused on the mechanical performance of mono-fiber-reinforced-cement-based materials [9,10]. Since micro-fibers can restraint the growth of micro-cracks, while large fibers inhibit the growth of larger cracks, there is growing interest in using hybrid fibers involving two or more fiber types and sizes that could create synergistic effects through their different elastic properties and/or various sizes and shapes [11–13]. Said et al. [8] investigated the flexural behavior of mono-fiber ECC slabs reinforced with 1%, 2% and 3% PVA fiber under four-point bending. Results indicated the potential of PVA fibers in reinforcing ECC slabs. Increasing the reinforcing index (product of fiber content by its aspect ratio) led to improving the deflection at failure (corresponding deflection at 25% of ultimate load in the descending part of load-deflection curve), flexural capacity, ductility and energy absorption capacity. However, this decreased the compressive strength of the ECC composite by up to 15% at 7 days. Moreover, Yuan et al. [14] explored the mechanical performance of steel-fiber-reinforced ECC beams subjected to reversed cycling loading. It was revealed that ECC beams exhibited 46% higher load carrying capacity and 400% larger energy dissipation ability compared to that of traditional concrete beams. Furthermore, Huang et al. [15] showed that incorporating recycled tire rubber in the production of ECC composites significantly enhanced the cracking resistance, while it generally decreased the tensile and compressive strengths of the ECC composite, thus compromising potential structural applications. Soe et al. [16] observed that the young's modulus of hybrid fiber-reinforced ECC composites is lower than that of conventional concrete having comparable compressive strength at all testing ages. Similar observation was reported by Huang et al. [15] for mono-fiber-reinforced ECC.

Shape memory alloys are a class of metallic alloys that "remember" their original shapes. The properties of SMAs were discovered by accident when researchers found that the alloy had a unique ability to undergo large inelastic deformation and regain its undeformed shape when subjected to certain stimulus such as radiation, electric heating, thermo-mechanical, or magnetic variations [17]. The main types of SMAs include copper-zinc-aluminum, copper-aluminum-nickel, iron-manganese-silicon and nickel titanium (NiTi) alloys.

Engineers are actively seeking innovative materials for designing structural members and smart systems that possess enhanced deformation capacity and ductility, higher damage tolerance, decreased or minimized residual crack sizes and recovered or reduced permanent deformation. If such reinforced concrete (RC) elements can be created, the design of structures having enhanced ductility and exhibiting little damage can become a possible endeavor, thus minimizing concrete repair. This could be achieved for instance using SMA bars in structural elements as replacement for traditional steel reinforcement. This was explored for instance by Xiaopeng et al. [18] and Choi et al. [19]. It is also possible to use SMA bars in joints of RC frames, while the other structural elements could be reinforced with regular steel [20].

The main drawback of using large-diameter SMA bars is that it reduces the hysteretic area of the SMA, thus compromising its ability to dissipate energy compared to that of small-diameter wires. This is caused by the accumulation of distorted martensite crystalline structure and inherent deficiencies that exist in larger-diameter SMA rods compared to smaller-diameter wires. From a technical standpoint, the larger the diameter of SMA rods, the more distortion and inconsistency are observed at the microstructural level, which hinders the hysteretic behavior of the SMA [21]. Moreover, utilizing hybrid ECCs incorporating both randomly dispersed PVA and nickel titanium (NiTi) SMA short fibers as a replacement for traditional RC is yet to be explored. Short fibers have advantages over continuous wires in that the distribution of fibers is more uniform, thus enabling more effective local crack closing in any direction. Also, if SMA fibers could be used instead of straight tendons or continuous wires, then thin or curved shaped SMA-reinforced structural members could be constructed. Therefore, in the present study, the mechanical performance of novel hybrid fiber-reinforced ECC mixtures incorporating a combination of randomly dispersed polyvinyl alcohol (PVA) and nickel titanium shape memory alloy (NiTi-SMA) short fibers was investigated. The study aims at ultimately developing a composite with eminent mechanical properties and possibly crack-healing capability, thus minimizing concrete repair.

2. Experimental program

2.1. Materials and mixture proportions

ASTM C150 (Standard Specification for Portland Cement) Type I portland cement was used in the production of the ECC mixtures. It has a specific gravity and surface area of 3.15 g/cm^3 and 371 m^2/kg, respectively. Class-C fly ash (FA) meeting the requirements of ASTM C618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete) with a CaO content of 16% was also used. The chemical compositions of the cement and fly ash are given in Table 1. Micro-silica sand (SS) with a maximum particle size of 200 μm and specific gravity of 2.65 was also utilized. The laser diffraction particle size distribution curves for the OPC, FA and SS are displayed in Fig. 1. The ECC mixture was reinforced with NiTi-SMA fibers conforming to ASTM F2063 (Standard Specification for Wrought Nickel-Titanium Shape Memory Alloys for Medical Devices and Surgical Implants), along with PVA short fibers. Table 2 summarizes the mechanical properties of the PVA and SMA fibers. To control the workability of the different ECC mixtures, a polycarboxylate high-range water reducing admixture (HRWRA) according to ASTM specifications C494 (Standard Specification for Chemical Admixtures for Concrete) was added by percentage of cement weight. Table 3 displays the proportions of the tested ECC mixtures with a target 28-days compressive strength of 65 MPa. The first number in the mixture label shows the PVA fiber content, while the second indicates the SMA fiber content. For example, ECC2-0.5 refers to an engineered cementitious composite incorporating 2% PVA and 0.5% SMA fiber by volume fraction.

2.2. Mixture Preparation, Casting and curing

First, a 20-L rotary mixer was used to dry mix the solid ingredients including the cement, FA, and silica sand for one minute. Then, the mixing water and HRWRA were gradually added to the dry mixture over three minutes until a homogeneous mixture was produced. This was followed by the gradual addition of PVA and SMA fibers and mixing continued for another three minutes until fibers were uniformly dispersed. Finally, the specimens for testing mechanical properties were prepared by direct pouring of the mixture into molds without compaction. All specimens were demolded after 24 h and cured inside sealed plastic bags for 7-days at laboratory temperature (21 ± 2 °C) without external moisture supply, which is a common curing method for ECC. All reported test results represent average values obtained on identical triplicate specimens.

2.3. Test procedures

Flow table tests were conducted on freshly mixed ECC mixtures to evaluate the effect of SMA and/or PVA fiber addition on the workability of freshly mixed ECC mixtures as per the guidelines of ASTM C230 (Standard Specification for Flow

Table 1
Chemical analysis of cement, fly ash, and silica sand.

Component (%)	Cement	Fly ash	Silica sand
CaO	64.35	16.00	0.01
SiO_2	20.08	52.19	99.70
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	2.40	–
K_2O	–	0.90	0.04
Na_2O	–	0.70	0.01
Loss of ignition	2.56	1.60	–