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EFFECT OF FIRE EXPOSURE ON IMPACT RESISTANCE OF HYBRID FIBER-REINFORCED ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract: In this study, the effect of fire on the impact resistance of a novel hybrid fiber-reinforced engineered cementitious composite incorporating short randomly dispersed shape memory alloy and polyvinyl alcohol fibres (HECC-SMAF) was investigated. A two-parameter Weibull distribution was used to analyze variations in experimental results in terms of reliability function. Results showed that the impact resistance of HECC-SMAF was generally degraded due to fire exposure. However, among the tested specimens, the composite incorporating 2% PVA and 1% SMA fibres achieved highest impact resistance. Adding more fibres beyond a threshold level led to fibre clustering, compromising impact resistance. The Weibull distribution was proofed to be an adequate tool that can be used by engineers to predict the impact failure strength of the composite, allowing to preclude additional costly experiments.

Keywords: Fire; impact loading; shape memory alloy; engineered cementitious composite; Weibull distribution.

1 INTRODUCTION

Fire is believed to be the main factor in bringing down the world trade center tower during the catastrophic event in September 2001, New York, USA (Ali et al., 2004). Hence, researchers became more proactive towards developing advanced fire-resistive materials for structural applications. Fire resistance is a major requirement for buildings since it could be the last line of defense when all other sources of restraining a fire fail (Kodur, 1999). Concrete has been the world's most widely used construction material. It is a complex material consisting of different constituents having different properties. Such properties can vary significantly when exposed to high temperatures. Concrete behaviour under fire stimuli depends mainly on its constituents (e.g. moisture content, aggregates and cement type), size of concrete element and its geometry, load intensity, and fire duration and temperature profile (Husem, 2006).

The principal effects of fire on concrete are compressive strength degradation and spalling. Spalling is described as the explosive ejection of concrete chunks from its surface due to breakdown in surface tensile strength (Khoury, 2000). As concrete gets exposed to fire, the water within its internal voids transfers to the gaseous state, thus resulting in an increase in internal pressure in the concrete pore structure. If concrete prevents water vapor from escaping, high pressure will be induced in the internal concrete structure, leading to brittle failure, which could be explosive, leading to catastrophic consequences (Husem, 2006). To avoid such events, several investigations have been conducted worldwide for the development of concrete with improved fire resistance.

Over the past decade, a new type of concrete has emerged and is known as engineered cementitious composites (ECC). ECC has the same ingredients to that of conventional concrete, except for coarse aggregates. Many research works have been conducted to establish its mechanical properties. However, its performance under fire has not yet been duly studied. Zhang et al. (2014) developed a spray-applied fire resistive material using ECC technology (SFR-ECC). It was observed that the essential high ductility of

ECC enhanced the overall durability and fire protection compared to that of conventional concrete and brittle spray-applied fire-resistive materials (SFRM). Similarly, Zhang and Li (2015) found that the SFR-ECC material showed superior tensile characteristics, ductility and better adhesion to steel compared to the brittle performance and poor tensile properties of conventional SFRM. Consequently, the superior characteristics of SFR-ECC could improve the fire protection performance. Furthermore, Byung-Chan et al. (2007) studied the applicability of utilizing ECC as a fire-resistive material in tunnel lining applications. They found that the ECC achieved better fire resistance in such applications compared to that of conventional concrete. Although, the CSA Standard A23.3-14 (Design of Concrete Structures) and National Building Code of Canada 2015 (NBC) provide detailed guidelines for the design of structural concrete elements, there is lack of information regarding the evaluation of fire performance of ECC members in such standards. Recently, smart materials have found various applications in civil engineering. One of the most important classes of smart materials is known as shape memory alloys (SMAs). SMAs are metallic alloys that have the ability to memorize their original shape. Investigating the effect of such a material in structural applications have been reported by many researchers, mostly utilizing SMA rods (e.g. Nehdi et al., 2010) or continuous wires (e.g. Li et al., 2015). However, data regarding utilizing SMA short fibres in structural elements is still scarce.

According to the aforementioned discussion, this study aims to develop important data on the impact resistance of mono- and hybrid-fiber-reinforced ECC composites exposed to fire. In this investigation, the impact resistance was evaluated after air cooling, subsequent to fire exposure. Threefold objectives were the main focus in this study; (i) To present a series of fire tests on mono- and hybrid-fiber-reinforced ECC composites; (ii) To explore the effects of fire on impact resistance of ECC composites incorporating different dosages of shape memory alloy (SMA) fibres; and (iii) To analyze variations in impact test results in terms of a reliability function.

2 ECC COMPOSITION, PREPARATION, CASTING AND CURING

Type I ordinary Portland cement (OPC), class-C fly ash (FA), micro-silica sand (SS) with average particle size of 150 µm were used in the production of the ECC mixtures. Nickel-Titanium (NiTi-SMA) and polyvinyl alcohol (PVA) short fibres were utilized in reinforcing the ECC mixtures. Table 1 illustrates the mechanical characteristics of the PVA and SMA fibres. A polycarboxylate high-range water-reducing admixture (HRWRA) was added to control the workability of the mixtures.

Table 1: Properties of PVA and SMA fibres

Mechanical properties	Ultimate tensile strength (MPa)	Diameter (mm)	Length (mm)	Young's modulus (GPa)	Elongation (%)	Density (kg/m^3)
PVA	1620	0.039	8	43	6	1300
SMA	869	0.635	16	41	38	6450

Table 2 shows the mixture proportions of different ECC mixtures. The first number in the abbreviation denotes the PVA fibre content, while the latter relates to the SMA fibre content. First, OPC, FA and SS were dry mixed for one minute. Thereafter, water and HRWRA were gradually added to the dry constituents until homogeneity was achieved. Finally, SMA and PVA fibres were gradually added to the wet mixture and mixed for another three minutes until uniform dispersion of fibres was observed. This was followed by direct pouring of mixtures into 100 mm x 200 mm cylindrical molds. After 24 hours, all ECC cylinders were demolded and cured inside sealed plastic bags for 7 days, then removed from bags and left in the laboratory environment (T=21 ± 2 °C and RH=55%) without external moisture supply until the testing age of 90 days. Then the cylinders were cut into three identical discs 100 mm x 50 mm for the drop weight impact test.

Table 2: ECC Mixture proportions

Mixture ID	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

3 TEST PROCEDURE

A series of drop weight impact tests were carried out at the age of 90 days on different ECC specimens as per the guidelines recommended by the American Concrete Institute (ACI) Committee 544 (Measurement of properties of fiber reinforced concrete). The impact load was applied using a 4.5-kg steel hammer dropped from 457 mm height above the ECC discs. More details about the test setup could be found elsewhere (e.g. Gupta et al., 2015). Equation 1 was used to calculate the impact energy per hit according to the ASTM standard D5628 (Standard test method for impact resistance of flat, rigid plastic specimens by means of a falling dart (tup or falling mass)) as follows:

$$[1]\ IE = N_i.h.w.f$$

Where IE is the impact energy in Joule, Ni is the number of blows, h is the falling height of the steel hammer in mm, w is the mass of the steel hammer in kg, and f is a constant with a value of 9.806 x 10-3. The number of impacts that caused the first visible crack (N1) and failure (N2) were recorded. All reported results represent the average value obtained on identical triplicate specimens.

According to Canisius et al. (2003), concrete spalling could be observed at early stages of a fire. Likewise, Both et al. (1999) found that this phenomenon could occur at temperatures as low as 200°C. In addition, Chen and Liu (2004) recognized that spalling could happen for high strength concrete at a temperature of about 400°C. Therefore, in this study, in order to evaluate the effect of fire on the impact resistance of ECC mixtures, specimens were first cracked under impact loading, then subjected to fire stimuli inside a heating chamber, which was able to heat the specimens up to 400°C temperature for an hour. Thereafter, the specimens were left to cool down to room temperature, and then reloaded using the drop weight test up to failure.

4 RESULTS

4.1 Under normal condition

Table 3 summarizes the impact test results up to first crack and failure of ECC specimens. Generally, the impact resistance of ECC specimens was improved due to SMA fibre addition. For instance, the number of impacts to first crack and failure of the ECC composite was increased by about 284% and 1423%, respectively, due to 0.5% SMA fibre addition by volume fraction compared to that of the control ECC2-0 specimens. Similarly, 1% and 1.5% SMA fibre addition increased the impact resistance to first crack and failure of the hybrid ECC specimens. For example, the impact resistance to first crack and failure of ECC2-1 and ECC2-1.5 specimens increased by about 477% and 1687%, and 384% and 1628%, respectively, compared to that of ECC2-0. It was observed that exceeding 1% SMA fibre addition (e.g. ECC2-1.5) decreased the impact resistance compared to that of ECC2-1. This can be attributed to the increased porosity and fibre clustering induced in the ECC mixture containing higher than 2% PVA and 1% SMA fibres by volume fraction.

Table 3: Impact test results of ECC specimens with and without fire exposure (N1/N2)

Specimen ID	ECC2-0			ECC2-0.5			ECC2-1			ECC2-1.5		
	N_1	N_2	*N_2F	N_1	N_2	*N_2F	N_1	N_2	*N_2F	N_1	N_2	*N_2F
Mean	13	39	20	50	594	349	75	697	579	63	674	441
Standard deviation	1	2	2	2	4	9	2	7	9	4	6	8

Note: *N2F is the number of impacts up to failure of ECC specimens exposed to fire.

4.2 Behaviour subsequent to fire exposure

Figure 1 displays the impact test results of ECC specimens with and without fire exposure. It was observed that the impact resistance of the ECC composite was generally degraded due to fire exposure. For instance, the impact energy at failure of ECC specimens incorporating 2% PVA fibre decreased by about 48.7% due to fire compared to that of its counterpart at normal temperature. Similarly, the impact failure energy of ECC2-0.5, ECC2-1 and ECC2-1.5 decreased by about 41.1%, 16.8% and 34.7%, respectively, compared to their counterparts which were tested at normal conditions. The general impact resistance degradation of the ECC composite can be attributed to the melting of PVA fibres due to fire, leading to higher porosity in the composite. This is consistent with findings of a previous study (Sahmaran et al., 2010). Moreover, it was observed that SMA fibres restrained the strength degradation three times more than that occurring in PVA-ECC specimens owing to the shape memory effect. Among all tested specimens, the ECC specimens incorporating 2% PVA and 1% SMA fibres still achieved the highest impact resistance, even after fire exposure. Furthermore, no explosive spalling during or after fire tests was observed in any of these specimens. This can be attributed to the formation of a network of pathways in the ECC specimens, which served as channels for water vapor escaping outside the specimens, leading to reduced tensile stresses propagated due to thermal expansions.

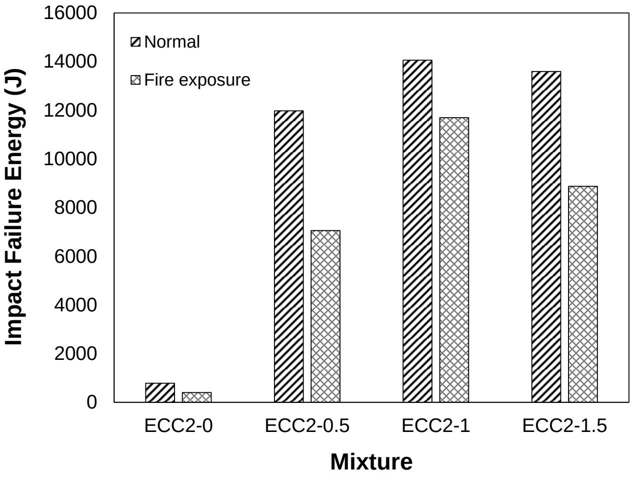

Figure 1: Impact failure energy of ECC specimens with and without fire exposure.

Generally, all hybrid ECC specimens incorporating SMA and PVA fibres exhibited a degradation in impact resistance subsequent to fire exposure. Nonetheless, they achieved impact higher than that acquired by mono-PVA-ECC specimens even at normal temperature. This is attributed to the superior capability of SMA fibres to restrain crack propagation under impact loading in ECC specimens, thus leading to enhanced post-cracking behaviour of ECC specimens, even after exposure to high temperatures due to fire. Similar observations were reported by others (e.g. Sahmaran et al., 2010; Chen and Liu, 2004; Kodur et al., 2003) who used steel-fiber-reinforced concrete (SFRC).

5 STATICAL ANALYSIS OF TEST RESULTS

Over the last few decades, different probabilistic models have been employed to statistically analyze the fatigue and impact test data of concrete. In particular, the two-parameter Weibull distribution was widely utilized in many research works for determining the fatigue and impact behaviour of concrete (Chen et al., 2011; Raman and Rakesh, 2009). More details about the Weibull distribution functions could be found elsewhere (Gupta et al., 2015; Bedi and Chandra, 2009). Figure 2 portrays a linear trend established by drawing the best fit line between data points using the method of least squares in order to determine the coefficient of determination (R2) for impact test results of ECC specimens after fire exposure.

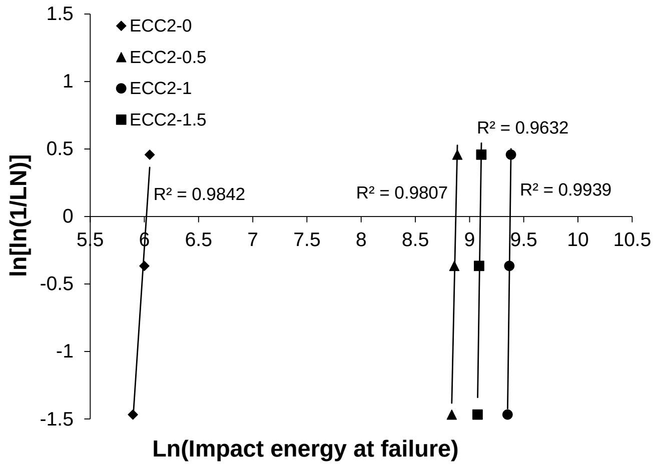

Figure 2: Weibull distribution for impact energy of ECC specimens at failure after fire exposure.

Table 4 illustrates the impact energy corresponding to failure of ECC specimens after fire exposure established using reliability analysis. The impact energy at failure of ECC2-0, ECC2-0.5, ECC2-1, and ECC2-1.5 was approximately equal to or higher than 242.94, 5885.55, 10978.30, and 6800.09 J, respectively. According to Rahmani et al. (2012), an R2 equal to or higher than 0.7 is sufficient for a reasonable reliability model. As shown in Fig. 2, since all impact test results had R2 values equal to or higher than 0.9632, a two-parameter Weibull distribution can be utilized to determine the statistical analysis of impact test results for mono- and hybrid-fiber-reinforced ECC. In addition, this reliability curve for ECC can be utilized to predict the impact energy at failure of ECC specimens after fire exposure in order to save the time and cost required for additional testing. Murali et al. (2014) and Chen et al. (2011) among others, have drawn similar conclusions for SFRC.

Table 4: Weibull distribution for impact energy of ECC specimens at failure

Reliability Level	ECC2-0	ECC2-0.5	ECC2-1	ECC2-1.5
0.99	242.94	5885.55	10978.30	6800.09
0.90	293.23	6266.94	11402.20	7088.71
0.80	311.39	6393.87	11541.00	7183.44
0.70	323.31	6474.50	11628.60	7243.29
0.60	332.74	6536.95	11696.10	7289.46
0.50	340.98	6590.48	11753.80	7328.92
0.40	348.68	6639.81	11806.80	7365.19
0.30	356.39	6688.43	11858.90	7400.86
0.20	364.77	6740.51	11914.50	7438.96
0.10	375.38	6805.32	11983.50	7486.24
0.01	396.80	6932.54	12118.20	7578.59

6 CONCLUSIONS

The behaviour of mono- and hybrid-fiber-reinforced ECC specimens incorporating SMA and/or PVA fibres under impact loading was investigated in this study by conducting a series of drop weight impact tests before and after fire exposure. The following conclusions can be drawn based on the experimental results:

- The impact resistance of ECC specimens was improved due to SMA fibre addition. ECC2-1 which incorporates 2% PVA and 1% SMA fibres by volume fraction acquired the highest impact resistance compared to all other specimens.
- Fibre addition beyond the aforementioned dosage led to fibre clustering and increased the porosity, which resulted in decreasing the resistance of the composite under impact loading.
- PVA fibres melt upon exposure to fire, which resulted in reduced performance under impact loading. However, the presence of SMA fibres seemed to restrain strength degradation and crack propagation owing to the shape memory effect.
- Melting of PVA fibres due to fire created pathways for water vapor removal through the composite and led to spalling free specimens during and after fire exposure.
- Although the hybrid ECC specimens exposed to fire showed strength degradation under impact loading compared to their counterparts tested without fire exposure, they still acquired impact resistance better than that of the control mono-PVA-ECC specimens tested under normal conditions.

The Weibull distribution function can be considered as a useful tool to determine the impact resistance at failure of ECC, without applying costly and time-consuming additional experiments.

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