Effect of Elevated Temperature on Strain-Hardening Engineered Cementitious Composites

Prakash Bhat, Vivian Chang, Mo Li

Department of Civil and Environmental Engineering, University of Houston, N132 Engineering Building

1, 4800 Calhoun Road, Houston, Texas 77204, United States

Tel.: +1 713 743 2650, Email: moli@uh.edu

Abstract

Strain-hardening engineered cementitious composite materials (ECC) is proposed to substitute quasi-brittle concrete materials for building extended spent nuclear fuel (SNF) storage systems in nuclear power plants. While most of ECC properties have been established under normal temperature, the study aims at understanding ECC material behavior under elevated temperature that is expected in a SNF storage environment. On the composite level, ECC specimens were characterized at various temperature levels up to 600 °C under both uniaxial tension and compression. The elevated temperature effect on tensile strength and strain capacity, compressive strength and failure mode, moisture loss, and spalling behavior was studied. On the microstructure level, optical microscopy and scanning electron microscopy were conducted to probe the degradation of components, and the change of pore structures due to fiber melting within ECC. The results will provide crucial data and insights for future studies of re-engineering ECC with robust properties specifically desired for nuclear engineering applications.

Keywords

Engineered cementitious composites; Spent nuclear fuel storage; Uniaxial tension; Elevated temperature; Degradation; Spalling; Tensile Properties; Nuclear infrastructure

1. Introduction

Concrete is a major material component for nuclear power plants and spent nuclear fuel (SNF) storage systems, which provide radiation shielding in steel-lined concrete pools, concrete dry-storage casks, and foundation pads. The concrete is constantly subjected to aging and deterioration under combined thermo-

chemo-hygro-mechanical effects, which often cause chemical and physical alteration of the concrete and result in excessive cracking, spalling and loss of strength ^[1,2]. SNF storage concrete is also susceptible to severely elevated temperatures during accident conditions and extreme events, which can lead to catastrophic fracture failure ^[3,4]. While the long-term durability and safety of concrete structures for spent fuel pools and dry casks are key factors for extended storage of SNF ^[4,5], it is challenging to achieve this goal using conventional concrete materials.

With a quasi-brittle nature, concrete is highly susceptible to cracking and fracture failure under combined mechanical loads and environmental effects. Cracking causes strength loss and greatly impairs the transport properties of concrete. This further leads to other common deterioration mechanisms such as chemical attack, chloride diffusion and corrosion of embedded steel, moisture penetration, radioactive water leakage, and increased radiation levels ^[5,6]. The deterioration process is further accelerated when concrete is exposed to elevated temperature, causing strength loss and brittle fracture failure modes such as spalling ^[7].

Engineered cementitious composites, or ECC, is a class of fiber reinforced cementitious composite materials that provide great potential for application in SNF storage systems. ECC features large tensile ductility and intrinsic crack width control capacity ^[8]. While containing similar ingredients as concrete or normal fiber reinforced concrete (FRC), the microstructure of ECC can be deliberately tailored through the use of micromechanical models to achieve tensile strain-hardening behavior and ductility levels approximately 200 to 600 times that of concrete or FRC under tension, thereby leading to delayed fracture localization ^[9]. The fiber/matrix interface is engineered to allow ECC to dissipate energy through multiple micro-cracking with crack widths less than 100 μm . The tensile strain-hardening behavior of ECC differentiates it from FRCs that exhibit tension-softening behavior. ECC's high tensile ductility, deformation compatibility with existing concrete, and self-controlled micro-crack width lead to its superior resistance to restrained shrinkage cracking, freeze-thaw, water permeation and chloride diffusion ^[10,11,12,13,14].

The behavior of ECC materials at elevated temperature is of great interest to safe operation of structural components and systems in nuclear power plants and SNF systems. For SNF pools, the temperatures are typically maintained below 50 °C. For abnormal and severe environmental conditions, temperature of local hot spots can reach 191 °C; for extreme conditions, the temperature may go from 140 °C to 260 °C; and for accident conditions, temperatures may reach or exceed 600 °C (e.g., a large sodium spill in the inert and air-filled equipment cells of a liquid-metal fast breeder reactor) ^[7,15]. Elevated temperatures can cause two forms of degradation in concrete ^[38,16,17,18,19,20,21]. One is the degradation in mechanical properties of concrete, such as strength and Young's modulus. This is due to the physical-chemical changes of the cement paste and aggregates, change of pore structure, and the thermal incompatibility between the aggregate and the cement paste which causes internal micro-cracking. The other form of damage is spalling, which results from the internal tensile stress induced by the vapor pressure. Spalling can be explosive, or be a gradual reduction of concrete cross section. Experimental results have shown that spalling can occur in concrete under rapid heating in the temperature range of 200 °C to 350 °C ^[7].

Sahmaran et al. ^[22,23] studied the effect of elevated temperature up to 800 °C on the compressive behavior of ECC, i.e. compressive strength, stiffness, and compressive stress-strain relation. These studies found that the compressive strength of ECC dropped by 40-50% after one hour exposure to 600 °C. The tensile behavior of ECC under elevated temperature, however, has not been studied. The knowledge is important because cracking and spalling are failure modes under tension. Given that ECC's large tensile ductility and self-controlled tight crack width are essential for ensuring structural durability, a question that could naturally be raised is whether ECC can still maintain these tensile properties under elevated temperature.

This paper first summarizes previous studies on high temperature effect on cementitious materials. To bridge the knowledge gap, this paper studied the elevated temperature effects on ECC material properties and microstructure, especially under uniaxial tension. The results help understand ECC material behavior under a high temperature environment, and lay out the groundwork for future research to develop new and robust strain-hardening ECC materials for high temperature applications.

2. Elevated Temperature Effect on Cementitious Materials

Published literature on high temperature effect on cementitious materials has focused on concrete, high performance concrete, high strength concrete, and fiber reinforced concrete. The results vary, depending on the material ingredient and composition, curing conditions, heating rate and time, and specimen types. It has been shown that under high temperature environments, such as a fire, concrete starts to deteriorate and lose its mechanical properties. After 400 °C, concrete typically experiences a 30–60 % drop in compressive strength at 600 °C and a 60–90 % drop at 800 °C^[24,25,26]. By 800 °C, many cracks are visible with a change in color of the concrete, and only 5–18 % of the original compressive strength is retained^[24,26,27]. Cracks continue to appear and enlarge until spalling occurs at 1200 °C. At this point, only 0.9% of the compressive strength is retained^[24]. Such a reduction in strength can be attributed to the dehydration of the concrete, and the cracks and voids created by the degradation and decomposition of aggregates and C-S-H gels^[7,16,17,18,19,20,21,24]. The heating and cooling rates played important roles on the reduction of compressive strength and elastic modulus^[26,29], while the heating durations did not show a significant impact.

High performance concrete (HPC) features high compressive strength and a dense microstructure. While the compressive strength is higher, the temperature threshold for spalling is much lower. Some HPC spalled between 300 °C to 600 °C^[28,29] after one hour heating duration, while normal strength concrete (NSC) only showed a reduction in compressive strength without spalling. The spalling is often explosive and can be attributed to the combined effect of two factors: (i) the increased brittleness of HPC compared to NSC, and (ii) an increase in the vapor pressure from the addition of silica fume in making HPC^[28,29]. Since silica fume leads to low permeability and low porosity in concrete, the vapors from the evaporation of water cannot escape and will increase the pressure and tensile stress inside the concrete, causing spalling. It was also found that siliceous aggregates generate higher thermal conductivity and expansions than carbonate aggregates in a concrete mixture^[30]. Consequently, HPC subjected to high temperature is more susceptible to spalling and strength loss, despite its higher compressive strength than NSC.

FRCs use short discontinuous fibers to control cracking during the post-cracking stage, and feature a tension-softening behavior. It has been shown that the addition of steel fibers into HPC increased specific heat capacity and decreased thermal expansion^[31]. For HPC, the steel fibers increased the lower bound of the spalling temperature range from 300 °C to 450 °C, but concrete still spalled between 450 °C to 800 °C^[28,32]. In contrast, the addition of polypropylene fibers into HPC did not show spalling at any temperature range tested^[28,32]. Due to melting of the fibers, more pores were created in the concrete. This caused a decrease in the compressive strength, but allowed water vapors to escape, lessening the vapor pressure and tensile stress. FRCs still experience a large reduction in their mechanical properties such as compressive strength, with the critical temperature also around 400 °C^[33,34,35]. By 650 °C, FRC of various fibers such as polypropylene, polyvinyl alcohol, carbon, glass, and aramid fibers have shown a 60 – 70 % decrease in its compressive strength with major cracks being visible^[34,35,36].

While previous studies have provided significant insights on high temperature effect on cementitious materials, the focus has been on quasi-brittle and tension-softening cementitious materials and their compressive properties. For ECC, previous work has focused on compressive properties under elevated temperature. There has been a lack of knowledge on the tensile behavior of strain-hardening ECC under elevated temperature. This information is crucial, considering that cracking and spalling under high temperature are both induced by internal tensile stresses. Understanding both tensile and compressive properties of ECC subjected to elevated temperature is the focus of this paper. Furthermore, this paper studied a special version of ECC designed to possess microcracks width below 40 µm for reduced transport properties, which is different from the most well-studied version of ECC, M45.

3. Material and Methods

In this study, the ECC mixture was designed by integrating micromechanics theory, rheology control during processing, and micro-structure tailoring. The ECC design theory requires the simultaneous satisfaction of steady state cracking criteria^[37] and maximized micro-cracking density^[38]. The ingredient particle size distribution and the combined amount of water and admixtures were first determined to

achieve a homogeneous cementitious composite material at fresh state, with plastic viscosity and yield stress tailored to an optimal level^[38] that favors uniform dispersion of micro-scale polyvinyl alcohol (PVA) fibers. Then, the micro-parameters of the hardened material, including matrix properties (e.g., fracture toughness, flaw size distribution, hydration products), the fiber/matrix interfacial properties (e.g., interfacial chemical and frictional bonds, slip-hardening coefficient, fiber debonding and pullout behavior), and fiber properties (e.g., aspect ratio, strength, Young's modulus) were tailored to ensure the strain-hardening criteria^[37] were satisfied. Furthermore, the micro-parameters were tailored so that the tensile stress vs. crack open relation (i.e. $\sigma \sim \delta$ relation) of each individual microcrack allows the steady-state microcrack to maintain a tighter crack width below 40 μm .

The designed ECC (**Table 1**) binder system contained water, a polycarboxylate-based high range water reducer, a viscosity modifying agent, Ordinary Portland Cement (OPC) Type I cement, ASTM standard Type F fly ash, and silica sand that served as fine aggregates with a 425 μm maximum grain size and a 275 μm mean grain size. The cementitious ingredients, silica sand, water and admixture together formed the ECC matrix, with tailored toughness and tensile cracking strength satisfying the strain-hardening criteria. Polyvinyl alcohol (PVA) fibers were incorporated into the composite system at a volume fraction of 1.8 %. The PVA fibers were 8 mm long and 39 μm in diameter, with nominal tensile strength of 1620 MPa and density of 1300 kg/m^3 (**Table 2**). The fiber/matrix interfacial bond was tailored so that the complementary energy (determined from fiber bridging – crack opening relation) and the maximum fiber bridging stress satisfy the strain-hardening criteria.

All mixtures were prepared under controlled room temperature 20 ± 1 °C and relative humidity conditions 50 ± 5 % RH. To prepare tensile specimens, the mixtures were casted into tensile coupon molds in a direction that is perpendicular to the length (305 mm) and width (76.2 mm) of each specimen. The specimen thickness is 12.7 mm. No external vibration was applied. To prepare compressive specimens, the mixtures were casted into 76.2 mm (diameter) by 152.4 mm (height) cylinder molds. The tensile coupon and compressive cylinder molds were then covered with plastic sheets and demolded after 24

hours. Finally, the specimens were moisture-cured in plastic bags at 95 ± 5 % RH and 25 ± 1 °C for 7 days, and air cured at 65 ± 5 % RH and 25 ± 1 °C for 21 days until the age of 28 days. Control mortar specimens were prepared in the same way, with the same mix design except that they do not contain any PVA fibers.

At the age of 28 days, the specimens were heated in an electric furnace with a heating rate of 23.5 °C/min, up to different maximum temperatures of 100 °C, 200 °C, 300 °C, 400 °C, and 600 °C. Some control specimens were stored at 20 °C and were not subjected to heating. When the target temperature was achieved, the specimens were maintained at this temperature in the furnace for 2 hours (for the tensile specimens) and 6 hours (for the compressive specimens) to ensure a steady-state thermal condition. The specimens were then tested in direct uniaxial tension and uniaxial compression at room temperature. It should be noted that the direct uniaxial tensile test (**Figure 1**) is considered the most convincing method for validating strain-hardening behavior of ECC, because some tension-softening materials can show “pseudo deflection hardening behavior” under bending^[39,40]. The specimen dimensions were 229 x 76.2 x 12.7 mm, with the middle gage length of 102 mm. Both ends of the specimen were strengthened so that multiple cracking only occurred within the gage length, allowing for more accurate measurement of strain. Tests were conducted under a displacement control rate of 0.0025 mm/s to simulate a quasi-static loading condition. Two external linear variable differential transformers (LVDTs) were attached to the specimen surface at a gage length of 102 mm to measure displacement, which was used to calculate strain. Three specimens were tested for each temperature exposure scenario. The uniaxial compression test was conducted on sulfur-capped cylinder specimens to measure the load-displacement curves, under displacement-control rate of 0.0025 mm/s. The test procedure followed ASTM C39^[41]. Three specimens were tested for each temperature exposure scenario. The microstructure of ECC after exposure to elevated temperature was studied through optical microscopy and scanning electron microscopy.

4. Results and Discussion

4.1. Elevated temperature effect on tensile properties

The ECC tensile specimen details and moisture loss after heating are summarized in **Table 3** and **Figure 2**. Test results revealed 2.69 %, 7.34 %, 8.92 %, 12.68 % and 13.35 % of moisture loss of the ECC specimen at 100 °C, 200 °C, 300 °C, 400 °C, and 600 °C, respectively. The moisture loss was faster between 20 – 400 °C, and approached a plateau between 400 – 600 °C. The moisture loss is associated with the liberation of free water in large pores as well as small capillary pores, followed by the loss of water adsorbed on the surface of C-S-H and physically bound water from the decomposition of calcium hydrates and other formed cement hydrates. During this process, the high vapor pressure within the cementitious material can lead to surface cracking or spalling. However, despite a high amount of moisture loss, no spalling was observed in the ECC tensile specimens, including those subjected to a maximum temperature of 600 °C. The specimens without heating were compared to the specimens subjected to 2 hours of heating at different temperatures (**Figure 3**). No spalling or degradation was observed from the specimen surface.

Uniaxial tensile test on ECC specimens without heating (20 °C) was the sole method to validate that strain-hardening ECC, instead of tension-softening FRC, was produced (**Figure 4(a)**). Despite the variation in the experimental data among specimens, the tensile stress-strain curve followed the same pattern that contained three stages: (1) The initial elastic stage, characterized by Young's modulus. (2) The strain-hardening stage, accompanied by multiple micro-cracking formations. During this stage, the width of each micro-crack remained nearly constant after formation, while the increasing applied strain increased the number of the micro-cracks. This stage is characterized by first cracking strength (i.e. the stress when the first micro-crack occurs), ultimate tensile strength (i.e. the peak stress), and the strain capacity of the material (i.e. the strain corresponding to peak stress). As this test was conducted under displacement control, each tiny load “drop” on the curve corresponded to the released energy during the formation of each micro-crack. (3) The tension-softening stage, accompanied by the formation of a localized fracture at one of the micro-cracks and the continuous drop of the ambient load. At this stage,

the ECC material behaves the same as tension-softening FRC materials. The results showed that at 20 °C the ECC specimens exhibited strain-hardening behavior with tensile strain capacity 2.3% in average, which is approximately 230 times that of concrete adopted in current SNF systems. Such strain-hardening behavior will lead to greatly higher fracture energy for providing damage tolerance to safely store SNF.

The specimens exposed to various temperature levels were then subjected to direct uniaxial tension test. The effect of elevated temperature on ECC tensile stress-strain relation is plotted in **Figure 4**. There was an obvious trend of reduction in tensile strain capacity of ECC. At 20 °C, all three specimens showed tensile strain-hardening behavior with strain capacity between 2 – 2.5 %. At 100 °C, the specimens still exhibited strain-hardening behavior; however, the tensile strain capacity was reduced to 0.5 – 2.0 %, with large variation indicating the change in matrix flaw distribution and fiber bridging capacity. At 200 °C, strain-hardening behavior still existed in ECC. The specimens tensile strain capacity was further reduced to 0.5 – 0.8 %, 50-80 times that of concrete;. At 300 °C, 400 °C and 600 °C, the specimens lost strain-hardening behavior; they did not exhibit tension-softening behavior as normal fiber reinforced concrete either, but a brittle behavior just as concrete.

The effect of elevated temperature on ECC tensile strength is shown in **Figure 5**. From 20 °C to 200 °C, ECC tensile strength increased by 10 % on average. As the ECC mixture contained a large amount of fly ash, the hydration process and pozzolanic reaction continued after 28 days, and was accelerated due to the high temperature curing effect up to 200 °C. At 300 °C, 400 °C and 600 °C compared to 20 °C, tensile strength decreased by 54 %, 29 % and 41 % respectively. This was explained by the rapid decomposition and pyrolysis of PVA fibers followed by loss of all fibers, the increased amount of pores after fiber melting, as well as the degradation of the cement paste and aggregates.

The final failure section of each tensile specimen was studied under a high-resolution optical microscope (**Figure 6 and 7**). It was clearly shown that the PVA fibers were present after exposure up to 200 °C, but were melted and lost after 6 hours of heating at 400 °C or 600 °C. The melting of the fibers created a large quantity of 40 – 50 µm micro-pores in the cementitious matrix, which changed the material's pore

structure and consequently influenced material mechanical and transport properties. This explains the reduction in tensile strength and the loss of strain-hardening behavior of ECC at temperatures of 300 – 600 °C. The elevated temperature up to 200 °C did not seem to have an effect on PVA fibers. This can be further evidenced by the un-decreased ultimate tensile strength of ECC (**Figure 5**), which was dominated by fiber bridging capacity. However, the decrease of tensile strain capacity from 20 °C to 200 °C indicated that there was a combined effect of increase in matrix toughness and degradation of fiber/matrix interfacial properties due to elevated temperature up to 200 °C, which negatively impacted on the strain-hardening criteria described in Section 3.

4.2. Elevated temperature effect on compressive properties

The moisture loss of ECC compressive specimens compared with control mortar specimens, were summarized in **Table 4 and 5**. The results revealed 0.3 %, 5.48 %, 9.96 %, 12.42 % and 14.43% of moisture loss of the ECC compressive specimens after 6 hours of exposure to 100 °C, 200 °C, 300 °C, 400 °C, and 600 °C. The moisture loss trend and level were also similar for control mortar specimens. The slightly higher moisture loss of ECC compared to control mortar was attributed to the higher initial porosity of ECC, which resulted from the higher plastic viscosity at fresh state during processing. Consequently, more air pores were entrapped during mixing.

Spalling of the three mortar control specimens occurred after 30-75 minutes of exposure to the maximum temperature of 600 °C. The spalling was explosive, as shown in **Figure 9**. In contrast, the ECC specimen did not exhibit any spalling or visible degradation observed from the surface, despite the fact that moisture loss of ECC was higher than mortar. The spalling resistance of ECC under high temperature can be attributed to two mechanisms: First, the melting of fibers created a large amount of micro-pores to reduce the internal thermal stress and vapor pressure; Second, the tensile strain capacity of the ECC material suppressed brittle failure mode commonplace in cementitious materials, thus preventing spalling caused by internal tensile stress.

The compressive failure modes are shown in **Figure 10**. For specimens that had been subjected to 6

hours heating at 100 °C and 200 °C, and for specimens stored at 20 °C, different compressive failure modes were observed in ECC compared to control mortar (**Figure 12**). The ECC specimens exhibited a ductile failure mode with an approximately 45-degree final fracture plane. The control mortar specimens had a sudden and loud failure with large splitting cracks and large pieces of specimens spalled off. Obviously, the ductile strain-hardening behavior of ECC when the exposure temperature was up to 200 °C, in contrast to the brittle behavior of the control mortar, led to the different compressive failure modes in the two materials. Furthermore, after 6 hours of exposure to 300 °C or 400 °C, the ECC compressive specimens exhibited the same failure mode as control mortar, with splitting cracks and brittle failure. When the maximum temperature was further increased to 600 °C, the ECC compressive specimens failed with splitting cracks under uniaxial compression, while the control mortar specimens already experienced severe spalling before compressive testing.

Compressive strength of ECC compared to control specimens is shown in **Figure 11**. In contrast to the significant reduction in tensile strength, the compressive strength of ECC was not significantly affected by elevated temperature. Interestingly, the compressive strength for the control mortar specimens increased with increasing temperature up to 400 °C, and spalling suddenly occurred in all three specimens subjected to 600 °C. For mortar, the results are different with the findings in previous research in literature that showed reduction in concrete compressive strength at high temperatures. The discrepancy can be due to two reasons: (1) the high amount of fly ash in the mortar mix design, and (2) the absence of coarse aggregates; only fine aggregates with 275 µm mean size was used. ECC compressive strength was affected by elevated temperature in a similar trend as control mortar, except that ECC compressive strength was higher than mortar at 400 °C. This is due to the less internal nano-cracking damage in ECC, which was later validated by SEM results. Furthermore, ECC did not experience spalling at 600 °C as mortar did. The results further indicated that compressive strength and tensile strength of ECC are influenced by elevated temperature in different manners, which will be studied as an interesting fracture mechanics problem in details in future studies.

Scanning electron microscopy (SEM) was adopted to probe the microstructure degradation of ECC and mortar composite materials. The lower-magnification SEM of ECC subjected to different temperatures is shown in **Figure 12**. It was observed that the fibers have melted when the temperature was 400 °C and 600 °C, creating micro-pores and channels within the ECC microstructure. The higher-magnification SEM of ECC subjected to 400 °C, compared with control mortar, was shown in **Figure 13**. A large amount of cracks with width ranging from 200 nm to 500 nm was found in control mortar (**Figure 13 (b)**). These nano-cracks have a “spider web” pattern, similar as the concrete micro-cracks caused by alkali silica reaction (ASR), suggesting that the nano-cracks were formed due to the expansion of fine aggregates as well as internal vapor pressure. In contrast, few nano-cracks were found in ECC subjected to 6 hours of exposure to temperatures up to 600 °C (**Figure 13 (a)**), despite the fact that ECC has lost its tensile strain-capacity at this temperature level. This evidence strongly supports the hypothesis that the melting of PVA fibers within ECC matrix created more pores and channels for abating the vapor pressure and the tensile stress caused by aggregate expansion, leading to a much less microstructure degradation within ECC than normal mortar or concrete materials.

5. Conclusions

Strain-hardening cementitious composite materials, ECC, was proposed for extended storage of SNF systems such as fuel pools and dry casks. The ECC mixture investigated in this study exhibited strain-hardening behavior under direct uniaxial tension at normal temperature conditions of 20 °C, as well as self-controlled micro-crack width below 40 µm (which is different from ECC M45). Such behavior offers great advantage over normal concrete materials, in terms of improved damage tolerance and reduced transport properties for SNF storage.

This study found that the tensile strength and strain capacity of ECC deteriorated under elevated temperatures. At temperatures below or equal to 200 °C, the increase in matrix toughness as well as the degradation in fiber/matrix interfacial properties led to the reduced tensile strain capacity by one order,

while the tensile strength slightly increased by around 1%. At temperatures above 200 °C, ECC lost its tensile strain-hardening behavior, while its tensile strength was reduced by 40% approximately.

Interestingly, our work showed no reduction in ECC compressive strength even after 6 hours of exposure to temperatures up to 600 °C, which differs from the observations of previous studies^[23,24]. However, when the temperature was above 200 °C, ECC compressive failure mode changed from ductile 45 degree plane failure to brittle splitting crack failure.

No spalling was observed in both ECC tensile and compressive specimens, even after 6 hours of constant exposure to 600 °C. In contrast, the control mortar specimens experienced severe explosive spalling after 30-75 minutes of exposure to 600 °C. The spalling resistance of ECC was attributed to its tensile strain capacity as well as the increase in porosity due to fiber melting. Scanning electron microscopy of ECC microstructure clearly revealed the increased amount of micro-pores at temperatures above 200 °C, and the absence of “spider web” nano-cracks that are common within control mortar material at high temperatures.

The experimental results will guide future studies to re-engineering ECC materials with robust properties at elevated temperatures for SNF storage applications.

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Table 1: ECC and control mortar mixing proportion

Material	Cement	Silica Sand	Fly Ash	Water	Fiber, (V _f)	SP	VMA (%)
ECC	1.0	1.0	2.2	0.66	2.0%	0.002%	0.001%
Control Mortar	1.0	1.0	2.2	0.66	-	0.002%	0.001%

Table 2: Properties of PVA fiber

Fiber Type	Nominal Strength (MPa)	Apparent Strength (MPa)	Diameter (μm)	Length (mm)	Young's Modulus (GPa)	Elongation (%)
Poly-Vinyl Alcohol	1620	1092	39	12	42.8	6.0

Table 3: ECC tensile specimen details and moisture loss

Sample Label #	Temperature (°C) for 2 hrs	Specific Gravity	Moisture Loss (%)	Avg. Moisture Loss (%)
1	20	2.09	0.00	0.00
2		2.12	0.00	
3		2.11	0.00	
4	100	1.97	2.54	2.69
5		1.98	3.19	
6		2.05	2.33	
7	200	1.96	7.10	7.34
8		1.95	7.57	
9		1.95	7.34	
10	300	1.87	9.75	8.92
11		1.82	8.39	
12		1.84	8.62	
13	400	1.84	12.38	12.68
14		1.82	13.33	
15		1.85	12.34	
16	600	1.82	13.48	13.35
17		1.82	13.62	
18		1.83	12.96	

Table 4. ECC compressive specimen details and moisture loss

Sample Label #	Temperature (°C) for 6 hrs	Specific Gravity	Moisture Loss (%)	Avg. Moisture Loss (%)
1	20	2.00	0.00	0.00
2		2.00	0.00	
3		1.99	0.00	
4	100	1.95	0.19	0.30
5		1.98	0.18	
6		1.99	0.54	
7	200	1.90	4.71	5.48
8		1.89	5.62	
9		1.87	6.10	
10	300	1.79	9.97	9.96
11		1.77	9.49	
12		1.79	10.42	
13	400	1.73	12.24	12.42
14		1.72	12.36	
15		1.72	12.66	
16	600	1.70	14.41	14.43
17		1.69	14.47	
18		1.68	14.40	

Table 5. Control compressive specimen details and moisture loss

Sample Label #	Temperature (°C) for 6 hrs	Specific Gravity	Moisture Loss (%)	Avg. Moisture Loss (%)
1	20	2.04	0.00	0.00
2		2.07	0.00	
3		2.05	0.00	
4	100	1.96	0.16	0.13
5		1.99	0.11	
6		1.98	0.13	
7	200	1.89	5.14	4.32
8		1.86	5.33	
9		1.91	2.48	
10	300	1.86	9.71	9.58
11		1.84	9.89	
12		1.85	9.13	
13	400	1.80	11.61	11.64
14		1.80	11.62	
15		1.80	11.70	
16	600	-	-	Spalling
17		-	-	
18		-	-	

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Figure 1: Direct uniaxial tension test setup

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Figure 2: Effect of temperature on moisture loss in ECC tensile specimens

(a) 20 °C

(b) 200 °C

(c) 400 °C

(d) 600 °C

Figure 3: Effect of temperature on ECC tensile specimens before testing – no degradation was observed from the surface.

(a) 20 °C

(b) 100 °C

(c) 200 °C

(d) 300 °C

(e) 400 °C

(f) 600 °C

Figure 4: Tensile stress-strain response of ECC after 2-hour of exposure at different temperatures

Figure 5: Effect of elevated temperature on ECC tensile strength

(a) ECC, 20 °C

(b) ECC, 200 °C for 2 hours

(c) ECC, 400 °C for 2 hours

(d) ECC, 600 °C for 2 hours

Figure 6: Cross section view of ECC tensile specimens subjected to (a) 20 °C, (b) 200 °C, (c) 400 °C and (d) 600 °C for 2 hours. At 400 °C and 600 °C, the micro-pores were created after fiber melting.

(a) ECC, 20 °C

(b) ECC, 200 °C for 2 hours

(c) ECC, 400 °C for 2 hours

(d) ECC, 600 °C for 2 hours

Figure 7: Side view of final failure cross section of ECC tensile specimens subjected to (a) 20 °C, (b) 200 °C, (c) 400 °C and (d) 600 °C for 2 hours. No fibers were observed at 400 °C and 600 °C

(a) ECC

(b) Control mortar

Figure 8: Effect of elevated temperature on moisture loss of (a) ECC and (b) control mortar compressive specimens

(a) ECC

(b) Control mortar

Figure 9: ECC vs. control mortar compressive specimens after 6-hour exposure at 600 °C

ECC, 20 °C

Control Mortar, 20 °C

ECC, 100 °C for 6 hours

Control Mortar, 100 °C for 6 hours

ECC, 200 °C for 6 hours

Control Mortar, 200 °C for 6 hours

ECC, 400 °C for 6 hours

Control Mortar, 400 °C for 6 hours

Figure 10: Elevated temperature effect on compressive failure mode of ECC and control mortar specimens

Figure 11: Effect of elevated temperature on compressive strength of (a) ECC and (b) control mortar specimens

(a) ECC, 20 °C

(b) ECC, 200 °C

(c) ECC, 400 °C

(d) ECC, 600 °C

Figure 12: Lower-magnification scanning electron microscopy of ECC

(a) ECC, 400 °C

(b) Control mortar, 400 °C

Figure 13: Higher-magnification scanning electron microscopy of ECC vs. Control Mortar at 400 °C