Construction and Building Materials 69 (2014) 370–380

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of elevated temperature on strain-hardening engineered cementitious composites

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HIGHLIGHTS

- Engineered cementitious composite is proposed for spent nuclear fuel storage.
- High temperature effect on ECC uniaxial tension properties is characterized.
- ECC has high spalling resistance after 6 h of exposure to 600 °C.
- "Spider web" nano-cracks are absent in ECC at temperatures up to 600 °C.
- The change in ECC microstructure explains its mechanical properties deterioration.

ARTICLE INFO

Article history:
Received 29 May 2014
Received in revised form 18 July 2014
Accepted 18 July 2014
Available online 15 August 2014

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

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.

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

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http://dx.doi.org/10.1016/j.conbuildmat.2014.07.052
0950-0618/

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 200–600 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 [10–14].

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 [7,16–21]. 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 200–350 °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 [24–26]. 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 [7,16–21,24]. 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 and 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 and 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 [33–35]. 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 [34–36].

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.