Ductile Fire-resistive Material for Enhanced Fire Safety Under Multi-hazards – A Feasibility Study

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ABSTRACT

Multi-hazards, such as earthquake and/or impact followed by fire, represent a major challenge on fire protection of steel structures. Spray-applied fire-resistive material (SFRM) is one of the most widely used passive fire protection material in North America. However, SFRM is inherently brittle and tends to dislodge or delaminate under extreme loading conditions (earthquakes or impacts) and even under normal service conditions such as wind induced building movement. Such loss of fire protection material puts the steel structure in great danger under fire loading. As an alternative to conventional brittle cementitious material, engineered cementitious composites (ECC) is a family of high performance fiber reinforced cementitious composites. ECC typically exhibits strain hardening behavior with very high tensile ductility (3-5%) under static and high rate loading. In this paper, a new type of fire-resistive material that combines the desirable thermal insulation property of SFRM and the enhanced ductility of ECC is proposed as an alternative material to current SFRM. Two preliminary mixture designs are presented. The thermal conductivity of the new fire-resistive ECC are measured in accordance with ASTM E2584 and are shown to be similar or lower than a conventional SFRM within the same density range. The proposed material achieves tensile strength up to 3 MPa and tensile strain capacity as high as 2.9%, significantly higher than those of conventional SFRM. Fire-resistive ECC with enhanced mechanical performance is expected to improve the overall fire safety of steel structure under multi-hazards.

INTRODUCTION

Behaviors and design of seismic resistance, impact resistance and fire resistance of structures have received wide attentions. However, most structures are not designed for more severe multi hazard scenarios, such as earthquakes or impacts followed by fires. These scenarios are not rare in reality, and represent a major challenge for civil engineers. One of the challenges is associated with the poor performance of cementitious spray-applied fire-resistive materials (SFRM) for steel structures under such conditions.

Spray-applied fire-resistive materials (SFRM) is a class of widely-used passive fire protection for steel structures in North America. SFRM have very low thermal conductivity that delays temperature rise in steel structure under fire hazards. Apart from the thermal properties, the performance of SFRM coated on steel members also heavily depends on its resistance to cracking and delamination. The mechanical performance of SFRM is often called into questions even under normal service loads. This problem is further exacerbated under earthquakes or impacts (Braxtan & Pessiki 2011, Carino et al., 2005). In such events, the spray-on fireproofing material may detach or delaminate from the steel members. The loss of insulation significantly reduces the effectiveness of the fire protection during postearthquake/post-impact fires (Keller & Pessiki, 2012; Li et al. 2012; Tomecek & Milke, 1993; Ryder et al., 2002). Adhesion and cohesion are two important components for the delamination and cracking resistance of SFRM. While adhesion is interfacial property, and sometimes could be enhanced by applying external bonding agent on the interface, cohesion is an intrinsic material property closely associated with the strength and deformation capacity of the material. SFRM are inherently brittle and has very low tensile strength (e.g. medium density SFRM have typical tensile strength less than 0.1MPa and tensile strain capacity less than 0.01%). Therefore, poor cohesive property is the major bottleneck of conventional SFRM and leads to limited functional performance of protecting steel structures.

Engineered Cementitious Composites (ECC), a special family of ultra-ductile high performance fiber reinforced cementitious composites, is a plausible solution for the problem described above. ECC has been developed based on micromechanics principles (Li & Leung, 1992; Kanda & Li, 1999) over the last decade as a ductile construction material alternative to conventional concrete. Its tensile strain capacity under uniaxial tension reaches 3-5%, about 300-500 times that of normal concrete. Under tensile load, ECC develops multiple micro-cracks instead of one large crack, and the load carrying capacity continues to increase after first crack thus achieving pseudo strain-hardening behavior. This damage tolerant feature and large deformation capacity of ECC can be beneficial for deformation compatibility with the steel substrate under mechanical loads induced by earthquakes or other accidents. It was also demonstrated that by micromechanics based tailoring of fiber, matrix, and particularly the fiber/matrix interface, tensile ductility of ECC can be maintained even under high rate loads, resulting in high impact resistance of ECC compared to other cementitious material. An added benefit is that the micro-sized cracks in ECC (typically 30-50 µm wide), compared with millimeter size cracks in SFRM and other brittle cement-based materials, can potentially cause less heat transfer through radiation via crack openings under high temperature. Due to the desirable properties of tensile ductility, damage tolerance, and small crack widths, ECC can be potentially developed as a safer insulation alternative to SFRM for protecting steel structures from heat related failures especially when multi hazards situation is of concern.

One very important performance target for the proposed fire-resistive ECC (FR-ECC) is the thermal insulating properties, which is mainly due to low thermal conductivity in cementitious fire-resistive materials. Low thermal conductivity is often associated with low density and high porosity mixes, since air has significantly

lower thermal conductivity than liquid or solid component in the composites. In addition, it is desirable that the nonstructural fire-resistive material be lightweighted to reduce unnecessary dead loads on the structural members. Based upon the above considerations, previously developed lightweight ECC mix seems a good candidate material as FR-ECC. However, the thermal conductivity of such material needs to be characterized to evaluate the feasibility of being employed as a fire-resistive material.

In this study, the thermal insulation property (thermal conductivity) of two candidate FR-ECC were characterized in accordance with the test procedures of ASTM E2584. The mechanical behavior of FR-ECC was characterized by direct uniaxial tension and compression tests. The feasibility of combining ductility and low thermal conductivity in one material was demonstrated. All test results and findings are documented in this paper.

EXPERIMENTAL PROGRAM

Mixture Details

The objectives of the development of FR-ECC are to achieve good insulation property (low thermal conductivity) and ductile mechanical performance simultaneously in one material for the targeted application. Heat transfer theory and micromechanics needs to be applied in the design and selection process of FR-ECC.

Thermal conductivity is closely associated with the microstructure, particularly pore structure, of the material. It is known that the thermal conductivity decreases with increase in total porosity of the material. As the total porosity is closely related to bulk density, the thermal conductivity of concrete often decreases with decrease in bulk density. (Blanco et al., 2000; Lo-Shu et al., 1980) In addition to porosity, pore size distribution is also important for high temperature applications. (Bouguerra et al., 1998; Dos Santos, 2003) Heat transfer theory predicts that the equivalent thermal conductivity of a pore due to radiation is proportional to pore size. The apparent thermal conductivity due to radiation. Hence, to attain low thermal conductivity at high temperature, it is desirable to have high porosity and small pore size.

Strain-hardening behavior of ECC under tension is achieved by the formation of multiple microcracks after initial cracking of the matrix. For achieving multiple micro cracking, the ECC microstructure has to be tailored to satisfy certain strength and energy criteria based on micromechanical principles (Li & Leung, 1992; Li et al. 2001; Marshall & Cox, 1988). One very important factor is that the matrix toughness needs to be kept low. And this typically requires using small sized and smooth shaped aggregates.

In a previous study (Wang & Li, 2003), micron-sized hollow glass bubbles (GB) were successfully used to produce lightweight ECC material with mechanical properties (compressive strength and tensile ductility) suitable for structural applications. The average size of these micro glass bubbles is 20-40 microns. Unlike

other angular lightweight aggregates, these tiny spherical glass bubbles have less resistance to crack propagation thus lowering the matrix fracture toughness. In addition to the benefit of enhancing tensile ductility and reducing the density of ECC, glass bubbles have a hollow spherical structure with air entrapped inside and thus possess very low thermal conductivity. And glass bubbles are thermally stable up to high temperature (600 °C). Therefore the size of entrapped air voids in these bubbles will be maintained at micron size up to a high temperature when a significant fraction of the strength of steel is lost. As previously discussed, this is beneficial in maintaining low equivalent thermal conductivity (due to radiation) at high temperature. As a result, lightweight ECC made with these glass bubbles as aggregates seems a suitable candidate for FR-ECC. One of the lightweight ECC mixture (with minor modification on the fiber geometry) were selected and studied in this research.

Adopting the same philosophy, a similar mix was designed substituting the glass bubbles with fly ash cenospheres (FAC). Fly ash cenospheres are the lightweight part of fly ash, which are produced during combustion of coal. Fly ash cenospheres resembles the hollow spherical structure of glass bubbles and has even greater thermal stability under high temperature, yet they are much more economical and environmental friendly compared to glass bubbles. To keep the matrix toughness low, fly ash cenospheres of size less than 106 microns were used.

The physical properties of glass bubbles and fly ash cenospheres are listed in Table 1. And two candidate mixes for FR-ECC using glass bubbles (Mix 1) and fly ash cenospheres (Mix 2) were studied in this research and the mix details are listed in Table 2.

	Glass bubble	Fly ash cenosphere
Specific gravity	0.38	0.85-0.95
Composition	Soda-lime-borosilicate glass	Silica/Alumina/Iron
Average diameter (µm)	40	75
Effective maximum diameter (µm)	85	106
Isostatic crush strength (MPa)	27.6	22.1
Melting temperature (°C)	600	1200-1400

Table 1. Physical property of glass bubbles and fly ash cenospheres

	Cement	GB/FAC	Water	Fiber*
Mix 1	1	0.5 (GB)	0.75	2% by Volume
Mix 2	1	0.8 (FAC)	0.75	2% by Volume

Fable 2. Mix design	of FR-ECC	candidates
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* Polyvinyl alcohol fibers of 8mm length and 0.5% oil (by weight) coating were used

Test procedures

Compressive strength of FR-ECC was measured using a set of three cube specimens measured 50.8 mm on each side. The test was conducted using a compression test system at a loading rate of 1300 ± 300 N/sec in accordance with ASTM C109.

The uniaxial direct tension tests were conducted under displacement control with a loading rate of 0.5mm/min on dogbone shaped specimens as recommended by the Japan Society of Civil Engineers (JSCE) for high performance fiber reinforced cementitious composite (JSCE, 2008). Two linear variable displacement transducers (LVDTs) were attached diametrically opposite to each other on each dogbone specimen (with gauge length of approximately 100 mm) to measure the specimen extension. After the uniaxial tension tests, residual crack widths on the surface of dogbone specimens were measured using an optical microscope with 1 micron resolution, following the method recommended by JSCE.

To assess the insulation property of FR-ECC, apparent thermal conductivity of the material was measured using a thermal capacitance calorimeter in accordance with ASTM E2584. A high density SFRM (with density of 704-768 kg/m³) commonly used in the US was adopted as control to evaluate the performance of FR-ECC. The setup requires two plate specimens of fire-resistive material with dimension of 152.4mm x 152.4 mm x 25.4mm sandwiching a stainless steel slug. Additional insulation material with very low thermal conductivity was used to insulate all four edges of the specimen to enforce a one dimensional heat transfer within the specimen. The assembled specimen was then placed in a small-scale furnace with maximum heating capacity up to 1000 °C, and heated up from room temperature to a critical temperature where the corresponding steel slug temperature reaches 537°C (the temperature at which steel experiences substantial strength loss) at the rate of 5°C/min. The temperature of the slug and outer surface of the specimen were measured and recorded at a constant time interval of 1 minute using K-type thermocouples. After reaching the critical point, the test was aborted by shutting down the furnace and the specimen was allowed to naturally cool down to room temperature. Two heating and cooling cycles were adopted for more reliable data. The apparent thermal conductivity is calculated based on one-dimensional heat transfer analysis using the temperature data obtained from the test.

RESULT AND DISCUSSION

Mechanical properties

Compressive strength of FR-ECC candidate mixes at 28 days is measured to be 22.3 ± 3.3 MPa and 20.5 ± 0.5 MPa for Mix 1 and 2, respectively. These compressive strengths surpass the minimum strength specifications (ICC-ES; USACE & UFGS) for fire-proofing materials by an order of magnitude. The dry density of Mix 1 and 2 at 28 days are 857 kg/m³ and 960 kg/m³ respectively, which are comparable with conventional high density SFRM typically within the range of 640-1280 kg/m³. Although FR-ECC is not supposed to carry load, the substantially higher compressive strengths compared to SFRM improve the material's ability to withstand occasional direct load, such as abrasion or direct impact caused by maintenance work.

The direct tensile stress-strain relationships of FR-ECC Mix 1 and 2 are shown in Figure 1. Robust strain-hardening behavior with average tensile strain capacities exceeding 1.5% and tensile strength over 2 MPa are observed for both mixes. In particular, Mix 1 exhibits a tensile strain capacity as high as 2.9% on average. These values are about one or two orders of magnitude larger than those of SFRM. The high tensile strength and tensile ductility enables FR-ECC to withstand stress induced by vibration and accommodate large deformation without delamination or substantial cracking. This will be critical under multi hazards scenarios. Under impact, the induced acceleration could impose tensile stress in the fire-resistive material. Under earthquake loading, structural steel is likely to go through large deformation and even yield at certain locations and such deformation poses large strain on the fire-resistive material covering the steel. The higher tensile strength and strain capacity of FR-ECC are expected to reduce the tendency of delamination and cracking under such loading conditions. In addition, the average residual crack width after unloading is approximately 15 µm for both Mix 1 and 2. The micro-sized cracks have minimal effect on the thermal insulation property of FR-ECC compared with large crack openings. Therefore, FR-ECC with high strength and ductility as well as tight crack width, is expect to maintain its integrity and functionality and protect steel structures against fire even under extreme loading conditions, particularly under multi hazards.

Comparing the tensile results of FR-ECC Mix 1 and 2, Mix 1 shows better tensile behavior, with slightly higher tensile strength and doubled strain capacity compared to those of Mix 2. It should be noticed that the volume fraction of lightweight aggregate (GB or FAC) in Mix 1 is higher than that of Mix 2, yet Mix 1 shows higher first cracking strength and ultimate tensile strength. It is observed that the workability of Mix 1 is better than that of Mix 2. Possible reasons of the difference in workability are that fly ash cenospheres have higher water absorption than glass bubbles and the shape of fly ash cenospheres are not perfectly smooth and spherical (due to the nature of industrial waste). And the poorer workability could affect the homogeneity of the matrix and lead to non-uniform fiber dispersion. It is also likely that the fiber/matrix interfacial bonding properties are affected by the fresh property. These effects may result in lower strength and larger variability in the strain capacity of Mix 2. The overall mechanical performance of FR-ECC Mix 1 (with glass



Figure 1 High tensile strength and ductility attained in two FR-ECC mixes

Thermal properties

As an important input to derive the apparent thermal conductivity from the measured data, the specific heat capacities of FR-ECC and SFRM were determined using DSC in accordance with ASTM E 1269. Instead of treating the specific heat capacity as a temperature-dependent variable, the specific heat capacity measured at room temperature for all materials was assumed constant throughout the entire temperature range under investigation. This assumption is justified by previous research (Bentz, 2007). The measured specific heat capacities are 929 J/(kg·K), 757 J/(kg·K) and 947 J/(kg·K) for Mix 1, Mix 2 and SFRM (control), respectively.

The measured apparent thermal conductivities for FR-ECC and control SFRM are plotted in Figure 2. Each curve represents an average of three specimens. It is observed that apart from a slightly higher averaged thermal conductivity of FR-ECC compared to SFRM between 180°C and 240°C, FR-ECC exhibits a lower thermal conductivity compared to the control (SFRM) specimen over much of the temperature range investigated in this paper. The reduction in apparent thermal conductivity between 100 ~ 400°C for all materials tested is associated with endothermic reactions including evaporation of free moisture, and decomposition of physically and chemically bonded water, that delay the temperature rise. The generally higher water content in SFRM compared to FR-ECC may be the reason behind the observed lower apparent thermal conductivity data, it is expected that the FR-ECC would offer similar, if not better, fire resistance for steel structures when compared with the control SFRM; however, this still requires full-scale fire-resistance test and numerical simulation for verification.

It is also observed that FR-ECC Mix 1 exhibits a lower thermal conductivity than FR-ECC Mix 2. This is due to a lower density (and higher air content) in Mix 1

than that in Mix 2, associated with higher volume fraction of lightweight aggregates. Further, glass bubbles have a lower thermal conductivity than fly ash cenospheres.



FR-ECC is similar to that of conventional SFRM

Figure 3 shows the apparent thermal conductivity of FR-ECC measured during two consecutive heating cycles. Except for the big drop around 200 °C in the first heating cycle associated with endothermic reactions, the two curves show good consistency without degradation (increase in apparent thermal conductivity) over two consecutive heating cycles. Since the apparent thermal conductivity is related to the pore structures of the material, the observed consistency suggest minimum degradation of the pore structure, especially porosity over two heating cycles.



Figure 3 Consistency in thermal conductivity of FR-ECC suggests minimum pore structure degradation between two consecutive heating cycles

CONCLUSION

In this study, FR-ECC material using micro-sized hollow glass bubbles and fly ash cenospheres were investigated for their thermal and mechanical performance. Based on the results of this experimental investigation, the following conclusions are drawn:

- 1. The feasibility of developing fire-resistive Engineered Cementitious Composites (FR-ECC), which exhibit high tensile strength, ductility and thermal insulation property, were experimentally demonstrated. The measured apparent thermal conductivity of FR-ECC are similar or lower than that of SFRM; yet FR-ECC possess tensile strength over 2 MPa and strain capacity as high as 2.9%, significantly higher than those of conventional SFRM. These properties are expected to enhance the cohesive behavior of FR-ECC when applied as fire protection coating on structural steel members.
- 2. FR-ECC mix developed with glass bubbles shows better mechanical and thermal properties than the mix developed with fly ash cenospheres. However, the latter mix has a lower economic and environmental cost.
- 3. The measured apparent thermal conductivity of FR-ECC shows good consistency, indicating no major damage of the porosity and pore structure of FR-ECC, over heating cycles. This suggests a stable insulating behavior even without the chemical and physical reactions that occur in the first heating cycle.

The significantly higher tensile strength and tensile ductility of FR-ECC are expected to prevent premature failures due to steel deformation/vibration and improve the overall fire safety of steel structures under multi-hazards.

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