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DUCTILE SPRAY-APPLIED FIRE-RESISTIVE MATERIAL FOR ENHANCED FIRE SAFETY

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Abstract. *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 impacts caused by maintenance work. Such loss of fire protection material puts the steel structure in great danger under fire loading, especially under multi hazards (post-earthquake or post-impact fires). 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 loading. In this paper, a new spray-applied fire-resistive material that combines the desirable thermal insulation property, ease of construction (facilitated by sprayability), light-weightness of SFRM and the enhanced ductility of ECC is developed as an alternative material to current SFRM. The newly developed spray-applied fire-resistive ECC (SFR-ECC) exhibits density as low as 550 kg/m^3 yet with tensile strength of 1.1 MPa and tensile strain capacity of 3.0%, significantly higher than those of conventional SFRM with tensile strength of less than 0.1MPa and no inelastic tensile strain. The thermal conductivity and sprayability of SFR-ECC are measured to be comparable to conventional SFRM, which ensures the proper functionality of SFR-ECC. SFR-ECC with enhanced mechanical performance is expected to improve the overall fire safety of steel structure under both service and extreme loads.*

1 INTRODUCTION

Spray-applied fire-resistive material (SFRM) is the most widely-used passive fire protection for steel structures in North America. SFRM offers many advantages, such as low thermal conductivity, cost-effectiveness, ease of construction (facilitated by sprayability) and low self-weight, over other fire protection methods. Apart from the functionality properties (thermal insulating properties and sprayability), the performance of SFRM also naturally depends on its durability characteristics (mainly refers to the ability to stay on the steel). However, due to the brittle nature, very low strength and poor bond (to steel) of SFRM, the durability of SFRM is often called into questions. Studies have shown that SFRM could easily delaminate or get damaged during earthquakes or impacts, [1, 2] as well as vibration caused by regular maintenance work. Loss or damage of insulation significantly reduces the fire resistance of the steel structures. [3, 4] This puts the steel structures in great danger, particularly under multi hazards, such as post-earthquake/post-impact fires.

Adhesion and cohesion are two major durability characteristics 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 and ductility (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) is a special family of ultra-ductile high performance fiber reinforced cementitious composites. ECC has been developed based on micromechanics principles [5,6] 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. The high tensile ductility and damage tolerance of ECC lend itself to significantly improved cohesive properties.

Recent study [7] demonstrated the feasibility of using lightweight ECC as a passive fire-resistive material. The fire-resistive ECC (FR-ECC) uses hollow glass microspheres as lightweight aggregates and successfully combines the thermal insulating property and high tensile ductility in one material. It has also been experimentally demonstrated that FR-ECC can be tailored to possess high adhesion to steel by incorporating acrylic latex into the mixture. [8] Therefore, with intrinsic high cohesion and tailored high adhesion, FR-ECC exhibits significantly enhanced durability characteristics over conventional SFRM.

FR-ECC studied in the previous researches, however, consists high cost and energy consumption materials: glass microspheres and PVA fibers, which leads to possible increase of material cost. In addition, the previous version of FR-ECC is not sprayable. Without the sprayability, the construction cost of FR-ECC is also expected to increase. These may impede the broader adoption of such material in the construction industry and lessen the advantage of FR-ECC over some other alternatives, such as intumescent.

In an attempt to address these deficiencies, this study aims at developing a version of sprayable fire-resistive ECC (SFR-ECC) with more accessible and low cost materials including vermiculite and polypropylene (PP) fiber. In this study, SFR-ECC containing vermiculite and high tenacity polypropylene (HTPP) fibers has been successfully designed following a parallel design process. Characterizations of both functionality and durability performance of the newly developed SFR-ECC have been conducted and are reported in this paper.

2 SFR-ECC MIXTURE DESIGN

SFR-ECC material development involves designing the material for multiple performance targets (high tensile ductility, low thermal conductivity, sprayability) simultaneously in one mixture. There are many interrelating design parameters involved in this process. Designing for low thermal conductivity is essentially designing the microstructure of the material to possess high air void content and small air void size. This can be achieved by using porous or hollow lightweight aggregates in the mixture. Designing for tensile ductility requires tailoring the micromechanical parameter of the mixture, including keeping the matrix toughness low and tailoring the interfacial bond property between fiber and matrix. This often requires using small-sized smooth-shaped aggregates that have less resistance to crack propagation, and carefully selecting the fiber type, geometry and content. Designing for the sprayability involves controlling the rheology of the mixture. This is often achieved by controlling the water content, chemical admixtures, aggregate absorption and geometry, using non-abrasive aggregates, and properly selecting the fiber content and geometry. To simultaneously attain the desired properties of SFR-ECC, the design process for one target needs to be conducted in parallel to the design process for other target performance, recognizing all the interdependencies and potential conflicts.

Following the parallel design methodology, super fine grade vermiculite was chosen as the main lightweight aggregates in the SFR-ECC based on several considerations. Vermiculite is one of the most commonly used lightweight aggregates in conventional SFRM due to its low density (64-160 kg/m^3), high water absorption (200%-325% by weight and 20%-50% by volume), low thermal conductivity (0.05-0.071 Wm^{-1}K^{-1}), high thermal stability, abundance in nature and low cost. In addition, SFRM use vermiculite to facilitate the application (typically low pressure spray) due to its water holding and non-abrasive nature. Despite all the advantages of vermiculite, it has never been used as a constituent in ECC material before. Vermiculites are generally accordion-shaped granule. According to the micromechanics underlying ECC design, such irregular-shaped aggregates generally increase the matrix toughness, which is undesirable for achieving strain-hardening behavior. Therefore, in the design of SFR-ECC, super fine grade vermiculite of particle size less than 1.5 mm was used in conjunction with a small volume fraction of 3M K25 glass microspheres (economical alternative to S38 glass microspheres that were used in previous FR-ECC) to counter balance the potential increase of matrix toughness.

Acrylic latex bonding agent was also used in the SFR-ECC mixture aiming at better adhesive property to steel. Recent work demonstrated that adding latex bonding agent in the previous FR-ECC mixture significantly improves the adhesive energy between FR-ECC and steel. In addition, adding latex into the mixture is expected to increase the viscosity of the fresh mix, which is favorable for dispersing the fibers uniformly. It is worth noting that acrylic latex could also increase the matrix toughness and fiber/matrix interfacial bond, which could influence the mechanical property of the hardened material.

Low content of High Tenacity Polypropylene (HTPP) fibers were used in SFR-ECC mixtures. HTPP fibers are more than 50% cheaper than PVA fibers that are typically used in ECC material including the previous FR-ECC. HTPP fibers have lower strength and lower bond to the matrix. However, since SFR-ECC is a nonstructural material and has relatively low strength requirement, the use of HTPP fibers could be justified. The fiber content was kept under 2% by volume fraction to avoid difficulty in pumping and spraying process.

Three mixtures were designed as listed in Table 1. All mixtures are composed of 1.5% (by volume fraction) HTPP fiber.

Table 1. Mix details of SFR-ECC.

Mix ID	Cement	Water	Acrylic Latex Bonding Agent	Vermiculite	Glass Microspheres
1	1	1.08	0.12	0.3	0.125
2	1	1.08	0.12	0.3	0.2
3	1	1.14	0.06	0.3	0.2

3 CHARACTERIZATION OF DURABILITY PROPERTIES

The major durability characteristics of SFR-ECC include cohesion and adhesion. Both properties are critical in keeping SFRM in place on the steel under multiple loading conditions.

The tensile strength and ductility of SFR-ECC were characterized using direct uniaxial tension test recommended by JSCE [9]. The tensile stress strain curves for SFR-ECC Mix 1-3 are plotted in Figure 1. Among all three mixes, Mix 2 exhibits the highest tensile ductility, with tensile strength of 1.1 MPa and an average strain capacity of 3.0%. Mix 3 also shows robust tensile strain hardening behavior, however, with less strain capacity. The decrease in ductility from Mix 2 to Mix 3 is associated with the decrease in the margin between ultimate tensile strength and first crack strength. Micromechanics design theory indicates that a sufficient margin between the ultimate tensile strength and first crack strength is required for robust multiple cracking. The lower acrylic latex dosage in Mix 3 leads to lower first crack strength and lower ultimate tensile strength, however, lower margin between them that is undesirable. Mix 1 behaves similarly to conventional fiber reinforced cementitious composites with localized crack and strain softening behavior. Comparing Mix 1 and Mix 2, the higher glass microsphere content in Mix 2 effectively lowers the matrix toughness that governs the first crack strength and leads to robust strain-hardening behavior. Considering the tensile performance, Mix 2 is the most promising candidate for SFR-ECC and is thus studied for other durability and functionality characteristics. The dry-density of Mix 2 is 550 kg/m^3 at 28 day, which falls into the medium density SFRM range. The compressive strength at 28 day is measured to be 3.5 ± 0.2 MPa. The strength and ductility values are one or two orders of magnitude larger than conventional SFRM of the same density range.

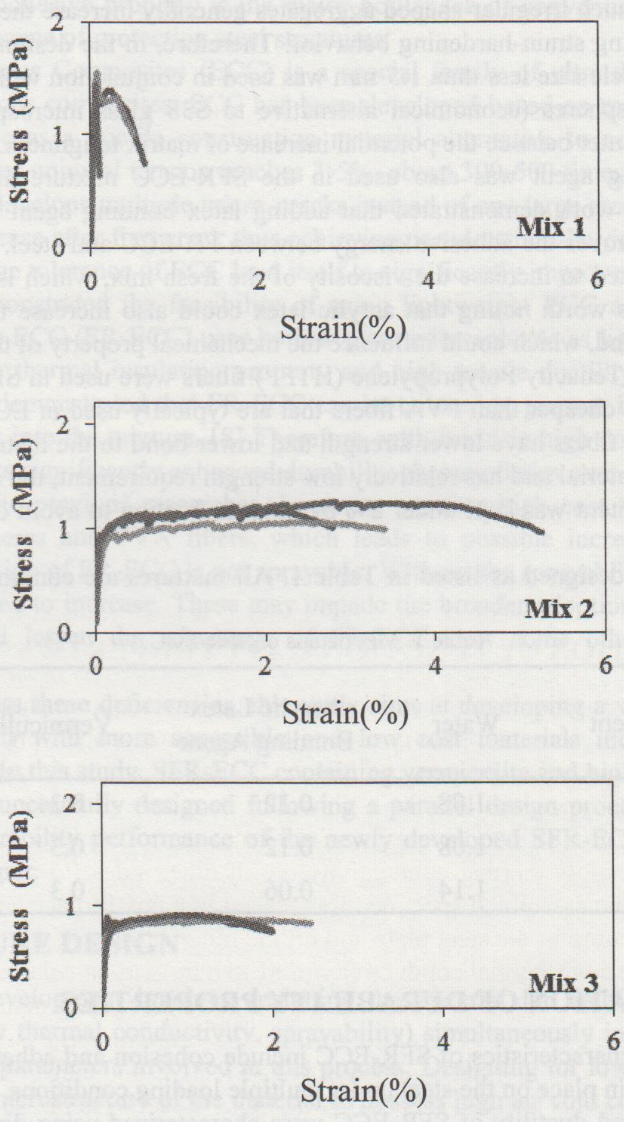

Figure 1. Ductile behavior of SFR-ECC under tension can be attained with appropriate mix design.

The adhesion property of SFR-ECC was characterized using a recently developed fracture energy based test method [10]. A medium density Portland cement based conventional SFRM was used as control in this study. During the experiment, structural steel strips of approximately 13 mm wide, 1.3 mm thick and 250 mm long that were bonded to the SFR-ECC/SFRM were peeled off by lifting one end. The load and corresponding interfacial crack length were recorded. Fracture resistance R-curves were then constructed. The adhesion is characterized by the steady-state critical energy release rate of the interfacial fracture, which is the plateau value of the R-curve.

The measured adhesion fracture energy of SFR-ECC (to structural steel) at 28 day is 104.3 ± 15.4 J/m^2, about an order of magnitude higher than that of conventional medium density SFRM used as control specimen in this study (11.1 ± 1.4 J/m^2). For both SFR-ECC and control SFRM, fracture occurs within the cementitious material adjacent to the interface. For SFR-ECC, the HTPP fibers actually bridge across the interfacial crack (as shown in Figure 2) and SFR-ECC/steel interface exhibits a ductile fracture behavior with a rising R-curve. While SFRM/steel interface exhibits a typical brittle fracture behavior. For SFR-ECC, due to the large process zone and dimension limit of the specimen, the true steady-state critical energy release rate (plateau value of R-curve) were not reached; the adhesion energy was calculated as an average value measured between 150-200 mm crack length instead of the true plateau value for conservative and realistic considerations. The significantly higher adhesion of SFR-ECC compared to conventional SFRM helps to resist delamination of fire insulation under various loading conditions.

The enhanced cohesion and adhesion properties are expected to dramatically improve the durability of SFR-ECC fire protection over conventional SFRM.

Figure 2. Fibers bridge across the delamination crack between steel and SFR-ECC.

4 CHARACTERIZATION OF FUNCTIONALITY PROPERTIES

As spray-applied fire-resistive material, apart from durability requirements, the thermal insulation property and sprayability represent important characteristics to ensure proper functionality of SFR-ECC.

To assess the thermal insulation property of SFR-ECC, the apparent thermal conductivity of SFR-ECC was measured in accordance with ASTM E2584 [11]. A square steel plate of 152 mm × 152 mm × 13 mm was covered by the SFR-ECC specimen (152 mm × 152 mm × 25 mm) on one side and insulation material of super low thermal conductivity on all other sides (to prevent heat transfer in all other directions) and then the assembled specimen was placed in a box furnace and heated up at 5 °C/min. During the test, the temperature in the steel plate and on the outer surface of the specimen was monitored and recorded. Then the apparent thermal conductivity of SFR-ECC was calculated based on a classic one-dimensional heat transfer model. The fire resistance of SFRM / steel system mainly comes from the very low thermal conductivity of SFRM. Therefore, instead of running large scale fire resistance test, comparing the measured apparent thermal conductivity of SFR-ECC and conventional SFRM could be an alternative way of assessing the fire resistance of SFR-ECC / steel system. The same medium-density conventional SFRM was used for thermal property comparison.

The measured apparent thermal conductivity is shown in Figure 3. The thermal conductivity of SFR-ECC is comparable to the conventional SFRM over the investigated temperature range. The dip in the curve indicates that endothermic reactions occur, such as evaporation of moisture, and delay the temperature rise. This is represented as very low apparent thermal conductivity over the corresponding temperature range. In this small-scale test that simulates large-scale fire resistance test, the time for the steel slug to reach critical point (537°C) from room temperature (23°) is 180-182 min for SFR-ECC and 178-181 min for control specimen. This also indicates that SFR-ECC and control SFRM possess similar effectiveness in delaying temperature rise.

Sprayability is another important functionality associated with the construction stage. Sufficient build-up thickness is critical for the construction phase of SFR-ECC. Direct spray test was conducted to evaluate the sprayability of SFR-ECC. SFR-ECC were mixed according to a typical ECC mixing procedure as detailed in the reference [12], and then the fresh mixture were transferred to a peristaltic pump before pumped and sprayed horizontally onto the structural steel panel placed vertically on the ground. The maximum built-up thickness were measured when the fresh mix were about to fall off the steel panel. The direct spray test shows that built-up thickness of 10-15 mm can be achieved in first spray application. And in a consecutive spray application after the first layer has been dried, another 30 mm can be further built up. The final build-up thickness after two sprays adds up to 40-45 mm as shown in Figure 4. Typical thickness of SFRM used for steel structures is 10-50 mm often achieved by multiple sprays. The built up thicknesses of SFR-ECC are therefore acceptable for field application.

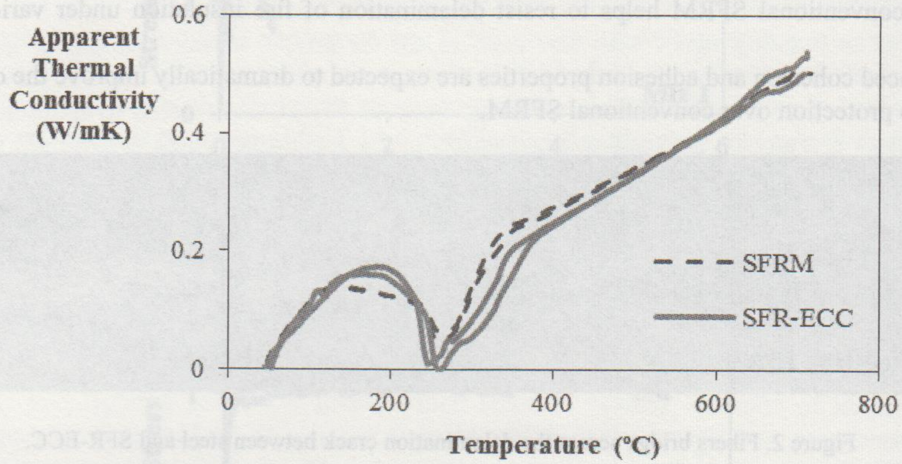

Figure 3. Comparable apparent thermal conductivity of SFR-ECC to SFRM.

(a) (b)

Figure 4. SFR-ECC can build up to 40-45mm in 2 sprays (a) front view, and (b) side view.

5 CONCLUSIONS

Based on above findings, the following conclusions are drawn:

(1) Ductile SFR-ECC with tensile strength of 1.1 MPa, strain capacity of 3.0% and interfacial adhesive energy (with steel) of 104.3J/m^2, which are 1~2 orders of magnitude higher than those of SFRM, has been developed and characterized.

(2) SFR-ECC has apparent thermal conductivity and sprayability comparable to conventional SFRM, which ensures proper functionality of SFR-ECC as fireproofing material.

SFR-ECC with enhanced durability properties and proper functionality is promising as a durable alternative to the current SFRM and contributes to enhanced fire safety of steel structures.

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