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Development of durable spray-applied fire-resistive Engineered Cementitious Composites (SFR-ECC)

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ABSTRACT

A new spray-applied fire-resistive material (SFRM) that combines the desirable thermal insulation property, sprayability, lightweightness and enhanced mechanical property is developed adopting Engineered Cementitious Composite (ECC) technology, overcoming the lack of durability issue of conventional brittle 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 0.87 MPa and tensile strain capacity of 1% when spray-applied, significantly higher than those of conventional SFRM with tensile strength of less than 0.1 MPa and no inelastic tensile strain. The newly developed material also exhibit significantly higher adhesion to steel than conventional SFRM. The thermal conductivity and sprayability of SFR-ECC are measured to be comparable to conventional SFRM, which ensures the proper functioning 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 functional properties (thermal insulating properties and sprayability), the effective performance of SFRM depends heavily 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]. The lack of durability of SFRM could endanger the steel structures, particularly under multi hazards, such as post-earthquake/post-impact fires.

Adhesion and cohesion are two major durability characteristics of SFRM. While adhesion is an interfacial property, and sometimes could be enhanced by applying an 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 0.1 MPa and tensile strain capacity less than 0.01%). Therefore, the limited cohesive property is the major bottleneck property that leads to limited functional performance of conventional SFRM in protecting steel structures.

Engineered Cementitious Composite (ECC) has been developed over the last decade as an alternative infrastructure material to conventional concrete. ECC belongs to the family of high performance fiber reinforced cementitious composites designed for high tensile ductility and can flex under extreme bending load. Its uniaxial tensile strain capacity is 3–5%, about 300–500 times that of normal concrete. This characteristic distinguishes ECC from almost all kinds of concrete, fiber reinforced or not, that has tensile strain capacity of about 0.01% [5]. Originally developed for earthquake resistant structures, ECC has since been applied to full-scale building, transportation, water and energy infrastructures in Europe, Asia and the US for enhanced safety, durability and sustainability [6].

Recent studies demonstrated the feasibility of using lightweight ECC as a passive fire-resistive material. [7] Fire-resistive ECC (FR-ECC) has been demonstrated to possess inherent high cohesion over conventional SFRM facilitated by the high tensile ductility and damage tolerance. It has also been demonstrated that FR-ECC can be tailored to possess strong adhesion to steel. [8]

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Therefore, FR-ECC exhibits substantially enhanced durability over the conventional SFRM.

The FR-ECC studied in the previous researches, however, consists of high cost and energy consumption materials: glass microspheres and PVA fibers, which leads to substantially higher cost than conventional SFRM. In addition, the previous FR-ECC was not designed to be spray-applied. Without the proper sprayability, construction cost of FR-ECC could also be increased. The high material cost and lack of sprayability of FR-ECC 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.

As an attempt to address this problem, this study aims at developing an economical version of sprayed-applied FR-ECC (SFR-ECC) with more accessible and lower cost materials including exfoliated vermiculite, and polypropylene (PP) fiber.

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 W m^{-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 non-abrasive and water absorbing nature. However, despite all the advantages of vermiculite, it has never been used as a constituent in ECC material before. Vermiculites are generally accordion-shaped granules. According to the micromechanics underlying ECC design [9,10], such irregular shaped aggregates generally increase the matrix toughness that is undesirable for achieving strain-hardening behavior. Therefore adoption of vermiculite in ECC needs to be carefully experimented; the gradation and volume fraction of the vermiculite needs to be properly selected.

High tenacity polypropylene (HTPP) fibers have been successfully incorporated into ECC as an economical alternative to PVA fibers. In a previous study conducted by Yang [11], HTPP-ECC with ductility up to 4% and 2.5 MPa ultimate tensile strength were developed. A recent study by Felekoğlu et al. [12] further enhanced the robustness of HTPP-ECC material with controlled mixing and curing procedures. Some of the main drawbacks of HTPP fibers include lower tensile strength (800–900 MPa) and weak interfacial bond with cement, when compared with PVA fibers. In FR-ECC design, the material is intrinsically of lower strength (compared to other structural ECC material), therefore, the use of HTPP fiber for SFR-ECC could be justified.

In this study, a version of spray-applied fire-resistive Engineered Cementitious Composite (SFR-ECC) has been developed incorporating vermiculite and HTPP fibers. The mechanical properties of the resultant mixture are evaluated by compressive test and direct uniaxial tensile test. Direct spray test is conducted to assess the sprayability of the newly developed material. The thermal, mechanical and adhesive property of the sprayed material are characterized using thermal calorimetry (in accordance to ASTM E2584 [13]), direct uniaxial tensile test and fracture energy based adhesion test [14], respectively, to fully assess the in-situ performance of the material.

2. Experimental procedures

2.1. Material design

SFR-ECC material design involves simultaneous tailoring the material for multiple performance targets (low thermal conductivity, high tensile ductility, high adhesion to steel, and sprayability) in one mixture. There are many interrelated design parameters involved in this process. Designing for low thermal conductivity requires tailoring 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 fiber, matrix, and fiber/matrix interfacial micromechanical parameter of the mixture according to micromechanics [6,9,15], including keeping the matrix toughness low and controlling the interfacial bond property between fiber and matrix for maximum bridging force but with minimum breakage. These considerations lead to using small-sized smooth-shaped aggregates that have less resistance to crack propagation, and carefully selecting the fiber type, geometry and content. Designing for high adhesion (to steel) involves modifying the cementitious material/steel interfacial transition zone and often requires adding polymeric admixtures into the mixture that might have side-effects on rheological and micromechanical characteristics. Designing for sprayability involves controlling the rheology of the mixture [16]. This is often achieved by controlling the water content, chemical admixtures, aggregate absorption and geometry, using water holding and non-abrasive aggregates, and properly selecting the fiber content and geometry. To simultaneously attain the desired fresh property and mechanical and thermal properties of SFR-ECC, the interdependencies and potential conflicts highlighted above need to be taken into account in the design procedure.

Super fine grade vermiculite was used together with a small portion of glass bubbles as aggregates in the SFR-ECC mixture design. Vermiculite has an irregular concertina shape and a very porous structure, as shown in the micrograph in Fig. 1. Superfine grade vermiculite was selected due to several considerations. The density, thermal property and water absorption of vermiculite all depend on the particle size. Smaller particle size is often associated with denser material and higher thermal conductivity which are less desirable. However, aggregate of smaller size limits the matrix toughness and, according to micromechanics underlying ECC design, is favorable for multiple cracking and strain hardening behavior. Smaller particles also have higher water absorption, which are preferred in fire-resistive materials. In addition, heat transfer theory indicates that smaller air voids are preferred to keep low radiation heat transfer at high temperature. Given the above considerations, the second finest grade vermiculite was chosen in this study. The particle distribution of the selected vermiculite is plotted in Fig. 2. The measured water absorption is 214% by weight in accordance with ASTM C128 [17].

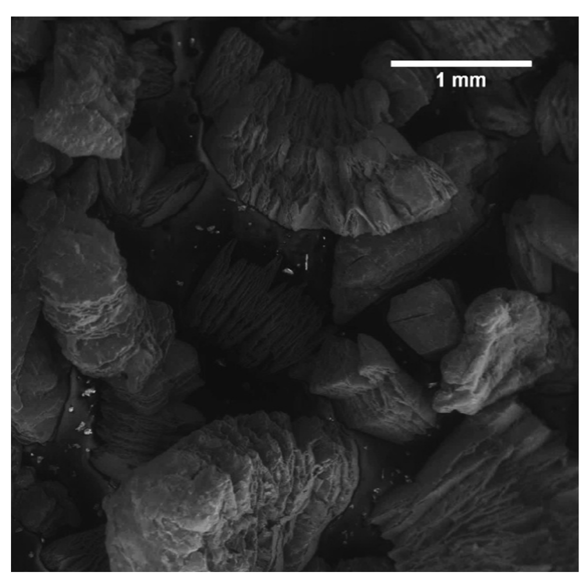

Fig. 1. Vermiculites have irregular shape and porous structure.

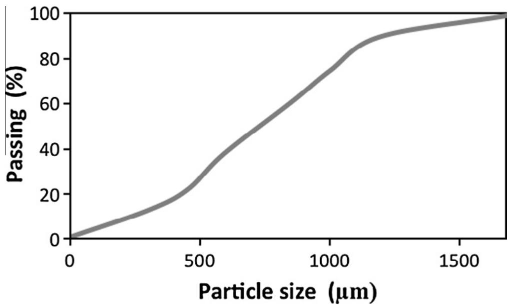

Fig. 2. Vermiculite particle size gradation.

K25 glass microspheres having a density of 0.25 g/cm^3 and isostatic crush strength of 5.1 MPa were used in this study as a replacement of the previously used S38 glass bubble in the FR-ECC mixtures for economic efficiency. K25 are considered an economical alternative to the previously used S series 3 M glass microspheres, which has the same composition and similar particle size. However, K25 has lower crush strength than S38 glass bubbles. The lower strength could be justified in nonstructural SFR-ECC application. The spherical-shaped glass bubbles are expected to improve the workability of the fresh mixture due to the ball bearing effect. They are also expected to effectively reduce the matrix toughness of designed SFR-ECC, which counterbalances the potential matrix toughness increase due to adoption of vermiculite.

Acrylic latex bonding agent, aimed at better adhesive properties to steel, was also used in the SFR-ECC mixture. Recent work [8] demonstrated that adding latex bonding agent in the previous FR-ECC mixture significantly improves the adhesive energy between FR-ECC and steel. It is worth noting that the addition of bonding agent could alter the fresh and mechanical property of the SFR-ECC material [8]. As a result, the effect of acrylic latex bonding agent in the present SFR-ECC mix design needs to be carefully examined.

Adoption of High Tenacity Polypropylene (HTPP) fibers are explored in SFR-ECC mixtures for economic reasons. HTPP fibers, compared to poly vinyl alcohol (PVA) fiber typically used in regular ECC mixes, are of significantly lower cost (over 50% lower).

Based on the above considerations, three mixtures were designed as listed in Table 1. Mix 1 has a lower glass bubble content than Mix 2 and 3, while Mix 2 has an acrylic dosage double that of Mix 3. All three mixes contain 1.5% (by volume fraction) HTPP fiber and the same amount of vermiculite (0.3 weight ratio of cement).

2.2. Specimen preparation and testing

The direct tension tests of the mixtures were conducted using the uniaxial tension test setup on a set of three dog-bone shape specimens in accordance to Recommendations for direct tension testing of High Performance Fiber Reinforced Cementitious Composites by Japan Society of Civil Engineers [18]. The dog-bone shape specimens were tested on a load frame with 20 kN capacity, under a displacement control at the rate of 0.5 mm/min. Two external linear variable differential transducers (LVDTs) were attached to the specimen edges, with a gage length of approximately 101.6 mm, to measure the tensile strain.

Compressive strength of the mixtures was measured using a set of three cube specimens of side 50.8 mm. The test was conducted using a compression load frame at a loading rate of 1300 ± 300 N/s in accordance with ASTM C109 [19].

In the above studies, the mixing procedure follows that in [12] suggested for ECC with HTPP fibers, and the mixtures were cast into the desired specimen configuration.

Direct spray test were conducted to characterize the sprayability of the developed mixtures. A wet spray procedure was used to ensure proper fiber dispersion. After mixing, the fresh mix was pumped through a peristaltic pump connected to the spraying gun, and sprayed out. It is suggested that peristaltic pump works well with fiber reinforced materials without fiber clumping as the pump is designed for pumping more viscous mixtures. A mill surface structural steel substrate of 914 mm × 305 mm × 12.7 mm was placed vertically on the ground. The substrate was cleaned with alcohol prior to the spray test in order to remove the oil and dirt on the surface. During the low pressure spraying process, fresh SFR-ECC were sprayed onto the steel substrate and gradually built up. When the material started to fall off and could not build up further, the spray test was aborted and the maximum thickness was measured as the initial built-up thickness. Allowing the applied material setting for a period of time (24 h in this study), a second spray were performed to further increase the built-up thickness. The total thickness built up after the second application was measured and recorded. The combined thicknesses of the two pass sprays were used to characterize the sprayability of the mixture.

To assess the in-situ properties of the sprayed SFR-ECC, specimens were cut from the sprayed material and tested for their thermal and tensile properties. Thermal conductivity measurements were conducted on plate specimens of 152.4 mm × 152.4 mm × 25.4 mm using a thermal capacitance calorimeter in accordance with ASTM E2584 [13]. The detailed test procedure was adopted from that described in [7] with slight modification. Instead of a pair of specimens, only one specimen was used. The other side of the slug was covered by insulation. This modification was made to eliminate the effect of unevenly distributed temperature within the small furnace. The test configuration is shown in Fig. 3. A type of commercially available medium-density Portland cement based SFRM was used as control to evaluate the thermal conductivity of SFR-ECC.

The tensile property of sprayed SFR-ECC was characterized by uniaxial direct tension test on coupon specimens of

Table 1
Mix details of SFR-ECC.

Mix ID	Cement	Water	Bonding agent	Vermiculite	Glass bubble
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

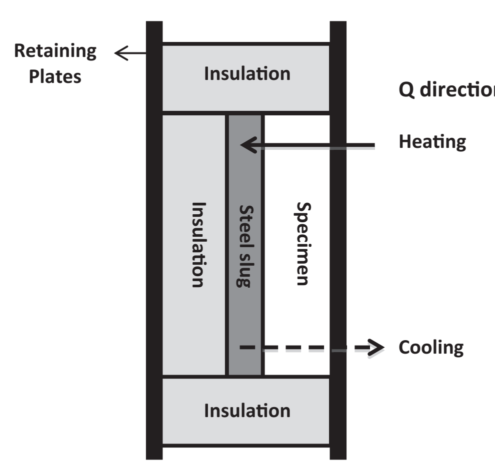

Fig. 3. Schematics of assembled single specimen for thermal conductivity test.

203.2 mm × 76.2 mm × 12.7 mm that were cut from the sprayed material. Coupon specimens were used since it was very difficult to cut dogbone shaped specimens out of the sprayed material. Other than the specimen geometry, all test parameters were kept the same as the test on cast material.

As another key durability characteristic, the adhesion between SFR-ECC and structural steel were also characterized using an energy-based adhesion test method developed at NIST [14]; the detailed test procedure was documented in [8]. In the present study, the SFR-ECC were sprayed-applied into the box molds onto the structural steel strips (approximately 13 mm wide, 1.3 mm thick and 250 mm long) placed at the bottom of the molds. During the experiment, structural steel strips that were bonded to the SFR-ECC 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. Again, the same medium-density conventional SFRM was used as control.

All specimens were tested at the age of 28 days after curing under laboratory room conditions (23 ± 3 °C; 30 ± 10% RH).

3. Results and discussion

3.1. Mechanical property of cast material

The tensile test results of all mixes are plotted in Fig. 4. Mix 2 and 3 exhibit robust strain hardening behavior with substantial tensile strain capacity (greater than 1.5%). Mix 2 has an average tensile strain capacity as high as 3.0%, which is about 300 times that of typical cement-based material. Mix 1 shows a strain softening behavior with significantly less tensile ductility. The reason behind the different behaviors is rooted in the micromechanics underlying ECC design.

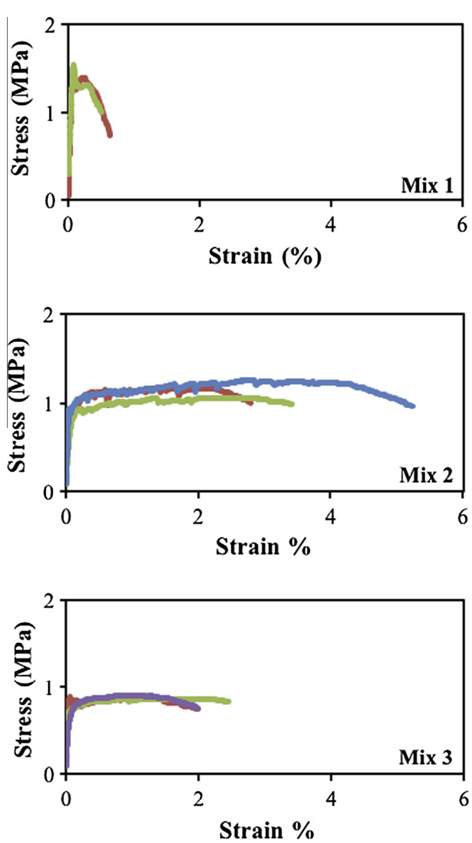

Fig. 4. Uniaxial tensile behavior of the cast mixes varies with mix compositions.

The first crack strength of the three mixes are shown in Fig. 5. First crack strength is governed by the matrix toughness and largest flaw size. Fig. 5 clearly shows the decreasing trend of first crack strength with increasing glass bubble content (from Mix 1 to Mix 2/3). Glass bubbles, with spherical shape and micron scale diameter, have less resistance to crack propagation and therefore lower the matrix toughness, resulting in lower first crack strength. This is favorable for achieving the desired multiple cracking and strain hardening behavior. Comparing Mix 2 and Mix 3, the acrylic latex bonding agent dosage does not show significant influence on the first crack strength. This could be due to the combined effect of air entrainment (which alters the flaw size) and enhanced matrix fracture toughness (associated with the formation of cement-polymer co-matrix).

The tensile ductility also depends on the fiber/matrix interfacial property. The ultimate tensile strength in ECC is closely associated with and serves as a good indicator of the interfacial property. The acrylic latex dosage greatly affects the ultimate tensile strength of the mixtures as shown in the comparison between Mix 2 and 3 in Fig. 4. The increasing acrylic latex dosage (from Mix 3 to Mix 2) noticeably increases the ultimate tensile strength (from 0.87 MPa to 1.17 MPa). The larger margin between the ultimate tensile strength and first crack strength is favorable for strain hardening behavior and leads to a higher tensile ductility. This is also confirmed with the tensile behavior of the mixtures, which shows that Mix 2 has a significantly larger tensile strain capacity than Mix 3. The crack pattern of Mix 2 is depicted in Fig. 6. The measured average residual crack width is 40 μm, much tighter than cracks found in conventional cement-based material.

Based on above discussion, Mix 2 seems to be the most promising candidate for SFR-ECC and will be investigated in the following sections for its compressive strength, sprayability and in-situ performance.

The compressive strength of Mix 2 is measured to be 3.46 ± 0.2 MPa and the dry density measured at 28 day is 550 kg/m^3. The compressive strength of Mix 2 well exceeds the requirement

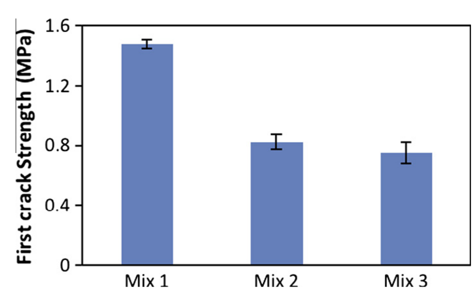

Fig. 5. Mix 2 and 3 with higher glass bubble content shows lower first crack strength.

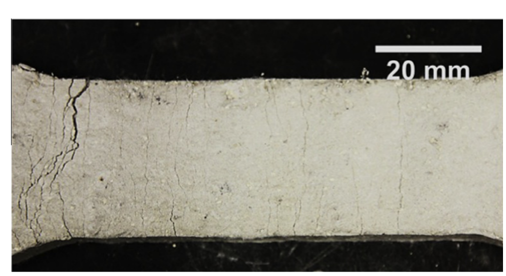

Fig. 6. Cast SFR-ECC (Mix 2) shows fine multiple cracks under uniaxial tension.

for SFRM of medium density (352–640 kg/m^3) in various specifications [20,21].

3.2. Sprayability characterization

Sprayability is an important functionality associated with the construction phase of SFRM type of material. Sufficient build-up thickness for each pass is critical to ensure a feasible construction schedule. The direct spray test shows that a maximum built-up thickness of 10–15 mm can be achieved in a first spray application. Another 30 mm can be built up in a consecutive spray application after the first layer has been dried (after 24 h in this study). The final maximum build-up thickness after two sprays adds up to 40–45 mm as shown in Fig. 7. The typical thickness of SFRM used for steel structures is 10–50 mm which is often achieved by multiple sprays. The built up thickness of SFR-ECC is therefore acceptable for field application; SFR-ECC offers ease of construction similarly to conventional SFRM.

3.3. Performance of sprayed material

Although cast SFR-ECC exhibits satisfactory mechanical performance, how the material is applied (cast versus sprayed) might affect the performance of the in-situ SFR-ECC. SFR-ECC is designed for low pressure spray application. The spray process could alter the microstructure of the material and how the fiber disperses within the mixture. Two key characteristics: tensile ductility and thermal conductivity are particularly sensitive to changes in material microstructure. As a result, the SFR-ECC needs to be characterized using spray-applied specimens to ensure meeting the performance targets.

The tensile stress–strain curve of sprayed SFR-ECC is plotted in Fig. 8. As shown in the figure, the sprayed SFR-ECC maintained significant tensile ductility. However, the tensile strain capacity of this sprayed version is noticeably lower than that of the cast version of the same mix (Mix 2). The difference between the tensile behavior of cast and sprayed specimens could be associated with the differences in fiber orientation and fiber dispersion between the two methods of placing the material.

Comparing Figs. 8 and 4, it is clear that the ultimate tensile strength of sprayed SFR-ECC is lower than that of the cast version, while the first crack strengths are quite similar. The first crack strength is closely associated with the matrix properties, including the matrix toughness and flaw size distribution. The consistent first crack strength indicates that the spray process has limited influence on the matrix property.

The reduced tensile ductility in SFR-ECC is closely associated with the reduced ultimate tensile strength. These reductions are most likely due to the change in fiber orientation in sprayed specimens compared to cast specimens. In cast specimens, due to the restraint of the mold edges, the fiber tends to orient towards the longitudinal directions, which could result in a higher fiber bridging capacity in this direction. However, due to the nature of low pressure spray, the fibers in SFR-ECC is expected to have a 2-D random distribution. This could lead to a reduced fiber bridging capacity in the loading direction compared to that of cast specimens. The reduced ultimate tensile strength leads to a reduced margin between first crack strength and ultimate tensile strength, which is associated with the noticeably less multiple cracking (Fig. 9) and reduced tensile ductility. Potential modifications to further improve the strain capacity include increasing the fiber content, for example, from 1.5% to 2%, or increasing the acrylic latex dosage. Nevertheless, the average tensile strain capacity of sprayed Mix 2 still reaches 1.0%, which is about 100 times larger than conventional SFRM.

Thermal property is the core functionality characteristic for SFR-ECC. Low thermal conductivity is the core requirement of these lightweight cementitious fire-resistive materials. The measured apparent thermal conductivity of sprayed SFR-ECC as a function of temperature is plotted in Fig. 10. As a comparison, a

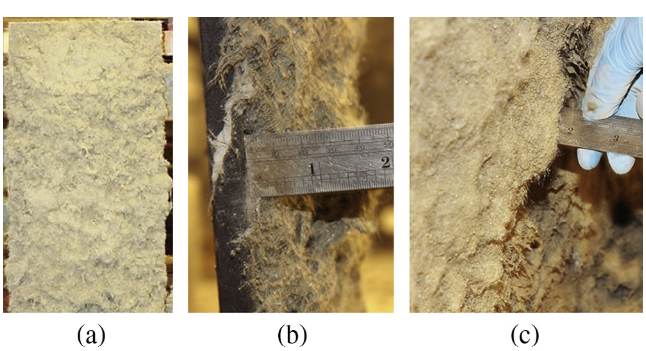

Fig. 7. SFR-ECC can build up to 40–45 mm in 2 sprays (a) front view; (b) side view; (c) maximum built-up thickness before falling off.

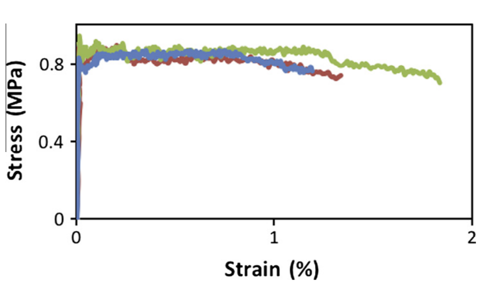

Fig. 8. Sprayed SFR-ECC maintains substantial ductility.

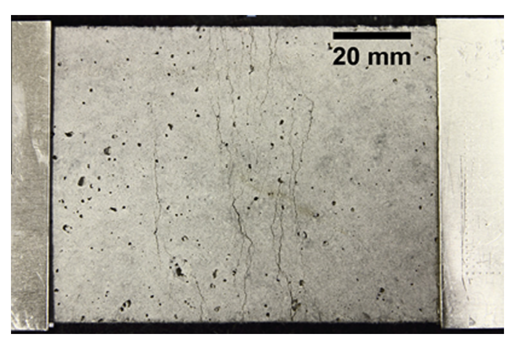

Fig. 9. Multiple cracking on the sprayed specimen.

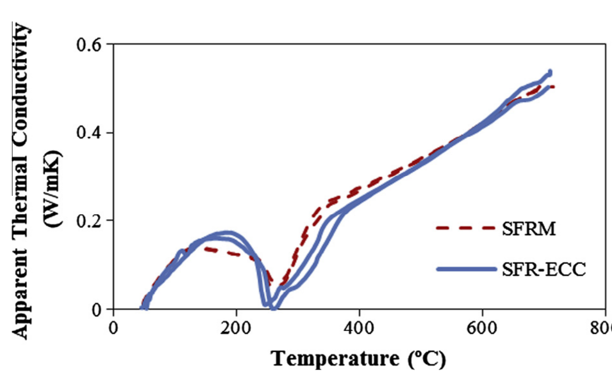

Fig. 10. Comparable apparent thermal conductivity of SFR-ECC to SFRM.

Fig. 11. Fibers bridge across the interfacial crack between steel and SFR-ECC.

medium-density conventional SFRM was also characterized as control specimens. The thermal conductivity of SFR-ECC is comparable to conventional SFRM over the investigated temperature range. The fire resistance of cementitious fire resistive materials mainly comes from their low thermal conductivity that delays the temperature rise in the steel structures. The comparable thermal conductivity of SFR-ECC and control SFRM suggests that the two materials have similar fire resistance (for the same thickness). In this small-scale test that simulates large-scale fire resistance test, the measured time for the steel slug to reach critical point (537 °C) from room temperature (23°) was 180–182 min for SFR-ECC and 178–181 min for control specimen. This also confirms that SFR-ECC and control SFRM possess similar effectiveness in delaying temperature rise in steel.

The measured adhesive fracture energy of SFR-ECC (to structural steel) at 28 day is $104.3 \pm 15.4\ J/m^2$, about an order of magnitude higher than that of conventional medium-density SFRM used as control specimen in this study ($11.1 \pm 1.4\ J/m^2$). For both SFR-ECC and control SFRM, fracture occurs within the cementitious material adjacent to the interface, thus a cohesive type of failure. For SFR-ECC, the HTPP fibers actually bridge across the delaminating crack (as shown in Fig. 11) 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 with a flat R-curve. 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) was not reached; the adhesion energy was conservatively calculated as an average value measured between 150 and 200 mm crack length instead of the true plateau value for conservative and realistic considerations.

The high adhesive property of SFR-ECC comes from both enhanced adhesion due to polymeric latex addition and enhanced cohesion due to fiber bridging. Considering that the delaminating crack self-selects the plane requiring minimum energy for propagation, the cohesive type of fracture within the SFR-ECC suggests that SFR-ECC possesses sufficient adhesion (right at the interface) to the steel substrate, possibly due to its polymeric latex modification. In addition to the high interfacial adhesion, the fibers bridging across the fracture surface also greatly increases the energy required to drive the crack propagation. This is also reflected in the adhesion measurement. The significantly higher adhesive property of SFR-ECC compared to conventional SFRM helps to resist delamination of fire insulation under various loading conditions and contributes to enhanced durability of SFR-ECC fire protection system.

In the present research, SFR-ECC is developed aiming at enhanced durability under ambient temperature. Under elevated temperature, it is expected that the adhesive and cohesive properties of SFR-ECC might degrade, since acrylic latex and polymer fibers (with low thermal stability) are used in the mixture design. However, as previously discussed, the main challenge of conventional SFRM is that their poor durability leads to delamination and detachment under extreme events as well as service loads. In most cases, these events (earthquakes, impacts, maintenance work, etc.) occur at ambient temperature. The damage or total loss of fire protection at ambient temperature renders the steel structure unprotected in the actual fire events. This undesirable situation can be prevented by using SFR-ECC with enhanced durability characteristics (mechanical and adhesive properties) at ambient temperature. During a fire event, SFR-ECC is expected to perform at least similar to conventional SFRM material and provides the required thermal insulating effect to the structural steel. The overall fire safety of steel structure, especially under multi-hazards, is therefore greatly enhanced with SFR-ECC.

4. Conclusion

Based on above findings, it is concluded that SFR-ECC should contribute to enhanced fire safety of steel structures due to enhanced durability over SFRM. Specifically the following conclusions are drawn:

1. Cast SFR-ECC with dry density of $550\ kg/m^3$, and tensile strength of 1.1 MPa and strain capacity of 3.0% that are one to two orders of magnitude higher than those of SFRM, has been developed incorporating vermiculite and HTPP fibers.
2. Spray-applied SFR-ECC exhibits reduced tensile ductility compared to cast specimens due to reduced fiber bridging capacity. Nevertheless, the sprayed SFR-ECC still exhibits ultimate tensile strength of 0.87 MPa and tensile strain capacity of 1.0%, significantly higher than those (<0.1 MPa tensile strength and 0.01% strain capacity) of conventional SFRM.
3. SFR-ECC has apparent thermal conductivity and sprayability comparable to conventional SFRM, which ensures proper functionality of SFR-ECC as fireproofing material.
4. The measured adhesive fracture energy of SFR-ECC (with structural steel) is $104.3\ J/m^2$, significantly higher than that of conventional SFRM ($11.1\ J/m^2$). The SFR-ECC/steel interface exhibits a ductile fracture behavior associated with fibers bridging across the crack.

SFR-ECC with enhanced durability (mechanical and adhesive properties) and comparable functionality (low thermal conductivity and sprayability) relative to conventional SFRM, is promising as a durable alternative to current SFRM.

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