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Mechanical and thermal properties of green lightweight engineered cementitious composites

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HIGHLIGHTS

- High-ductile GLECC developed with high volume of industrial wastes.
- The use of fly ash cenospheres as lightweight fillers to prepare GLECC.
- Physical, mechanical and thermal properties of GLECC.

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ABSTRACT

This study reports the development of green lightweight engineered cementitious composites (GLECC) with high volume of industrial wastes. Three types of industrial wastes including iron ore tailings, fly ash, and fly ash cenosphere were used as aggregates, mineral admixture, and lightweight filler, respectively, in the production of GLECC. The influences of fly ash and fly ash cenosphere contents on the physical, mechanical, and thermal properties of GLECC mixtures were experimentally investigated. Fly ash cenosphere was most advantageous in reducing the density and thermal conductivity, while improving the tensile ductility of GLECC with only a slight reduction in compressive strength. The GLECC mixtures in this study exhibit density of 1649–1820 kg/m^3, tensile strain capacity of 3.3–4.3%, tensile first cracking strength of 2.5–3.6 MPa, ultimate tensile strength of 4.8–5.9 MPa, and compressive strength of 25.0–47.6 MPa at 28 days, depending on the contents of iron ore tailings, fly ash, and fly ash cenosphere. The GLECC mixtures developed in this study utilize industrial wastes up to about 89% by volume of total solid matrix materials and weigh under 1850 kg/m^3 (limit for lightweight concrete classification); yet their mechanical properties are similar to ultra-ductile ECC with added advantage of lower thermal conductivity for energy conservation when used as a building material.

1. Introduction

Lightweight concretes with relatively low densities of (1600–1760 kg/m^3) are often used in the construction of structures requiring high strength/weight ratio such as high-rise buildings, large-span bridges and floating concrete platform [1,2]. The use of lightweight concrete instead of normal weight concrete (2400 kg/m^3) offers many benefits, such as reduction in dead loads and section dimensions, improved thermal insulation, savings in steel reinforcement, ease of handling and transportation, and lower overall cost [1]. However, lightweight concrete exhibits more brittle behavior than normal weight concrete with similar compressive strength due to higher cement content and weaker lightweight aggregates [1]. The brittle nature of lightweight concrete makes it prone to cracking and less durable, which limits its structural applications.

High tensile ductility is the unique feature of engineered cementitious composites (ECC) that exhibit tensile strain hardening behavior through the formation of multiple micro-cracks with widths typically below 100 μm [3]. Tensile strain capacity of ECC with poly-vinyl alcohol (PVA) fibers at a fiber volume fraction of 2% has been demonstrated to range from 3–5% [4]. Due to such high tensile ductility and tight crack width, ECC exhibits superior durability compared to normal concrete under various mechanical and environmental conditions [5]. The density of typical ECC M45 [6] is about 2050 kg/m^3, which is lower than that of normal weight concrete with density of 2400 kg/m^3; nevertheless, ECC cannot be classified as being lightweight according to the specification of lightweight concrete that requires density not exceeding 1850 kg/m^3 [2].

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The only notable investigation in the past to simultaneously achieve the properties of lightweight and high tensile ductility in ECC was reported in Wang and Li [7]. In that study, three lightweight fillers: expanded perlite, hollow glass bubbles, and polymeric microform, along with air bubbles generated by air entrainment admixture, were investigated for the development of lightweight ECC (LECC) [7]. Among these fillers, hollow glass bubbles, with their closed shell structure and small size, were found to be the most promising lightweight fillers in terms of fiber dispersion, mechanical performance, and lowering the density of LECC. Using hollow glass bubbles of diameter 10–60 μm, LECC achieved high tensile strain capacity over 4% with a density of 1450 kg/m^3 [7]. However, such LECC consumes high content of cement, manufactured micro-silica sand, and high temperature-processed hollow glass bubbles [7], which compromise the material carbon and energy footprints and also result in high initial material cost. To facilitate the wider application of LECC and address the global call for sustainable infrastructure development, the carbon and energy intensity of material ingredients in LECC must be significantly reduced.

Several studies on green ECC incorporating industrial wastes as constituents to reduce environmental impacts have been reported in the literature [8–10]. Pozzolanic recycled industrial wastes such as fly ash (FA) and slag have been successfully used in normal weight ECC to substantially lower the cement content [8–9]. Furthermore, iron ore tailings with appropriate size were proven suitable for completely replacing manufactured micro-silica sand as aggregates in ECC [10]. Building on the knowledge gained in the past studies, the simultaneous use of iron ore tailings as aggregates and high volume of fly ash as mineral admixture is explored in the matrix design of GLECC to lower the material environmental footprint in this study.

In order to further enhance the material greenness of GLECC and meet the density target (<1850 kg/m^3 for lightweight classification [2]), the use of fly ash cenospheres (FAC) as green lightweight substitutes for hollow glass bubbles (previously used in LECC) was investigated in this study. FAC are hollow alumino-silicate spheres within fly ash waste from coal-fired power plant. Recent studies have reported the use of FAC in various materials, such as polyester composites [11], ceramics [12], concrete [13–14], and geopolymer [15]. The advantages of FAC in weight reduction, thermal insulation, and sound absorption was demonstrated in these researches. Because of their hollow structure, FAC have low density of 200–800 kg/m^3 and low thermal conductivity of about 0.065 W m^{-1} K^{-1}[15]; thus FAC hold a good potential for weight reduction and for lowering the thermal conductivity of ECC.

The reduction of energy consumption and the associated greenhouse gas emissions in the use phase of a building life cycle is critical for sustainability considerations. Space heating and cooling for buildings constitute a major portion of the total energy consumption by buildings [16]. Construction materials with low thermal conductivity can effectively reduce the heat exchange between the outside environment and inner spaces of buildings. As an indicator for the potential energy conservation capability when used in building envelops, the thermal conductivity of GLECC mixtures with different contents of FAC and FA is also examined.

In this study, the simultaneous use of FA, IOTs, and FAC as partial replacements for cement, silica sand, and hollow glass bubbles, respectively, is investigated in the design of GLECC for achieving three objectives: (1) to enhance the material greenness, (2) to reduce the material density, and (3) to reduce the material thermal conductivity. Material density, tensile performance, compressive strength, and thermal conductivity of the GLECC were determined experimentally and detailed in the following sections.

2. Experimental procedures

2.1. Materials and mix proportion

The constituent materials used for preparing ECC mixtures in this study include ASTM Type I Portland cement (C), ASTM Class F fly ash (FA), iron ore tailings (IOTs), fly ash cenospheres (FAC), polyvinyl alcohol (PVA) fibers, and water, along with a high range water reducing admixture (HRWRA) for controlling mix rheology. Chemical composition and physical properties of FA used in this study are given in Huang et al. [17]. IOTs, used as very fine aggregates, have an average size of 135 μm and nominal maximum size of 300 μm. The investigation on the use of these IOTs in the production of green ECC is reported in Huang et al. [10]. The bulk density and average size of FAC is 800 kg/m^3 and 200 μm, respectively. Particle size distribution of FAC obtained through sieve analysis is shown in Fig. 1. The chemical composition of FAC determined by X-ray fluorescence (XRF) spectrometer is given in Table 1. PVA fibers with a surface oil coating of 1.2% by weight have a diameter of 39 μm and a length of 12 mm. The nominal tensile strength, elastic modulus and maximum elongation (at break) of PVA fibers are 1620 MPa, 42.8 GPa, and 6%, respectively.

Six mixtures (including two controls) were prepared in this study to investigate the influence of FA and FAC content on various properties of GLECC (Table 2). For all mixtures, the weight ratio of water to cementitious material (C + FA) was kept constant at 0.26, and PVA fiber volume fraction was fixed at 2%. Two levels of FA content with FA/C ratios of 2.2 and 4.4 were adopted targeting different levels of material strength. The adoption of such high content of FA is designed for lowering cement content. For the two control mixtures (C1 and C4) without FAC, IOTs were used as very fine aggregates with aggregate to cementitious material ratio of 0.36 by weight. Four different GLECC mixtures (C2–3 and C5–6) were prepared by replacing 60% and 100% volume of IOTs with the same volume of FAC in the two control mixtures with different ratios of FA/C. The content of HRWRA was varied in these mixtures to maintain the viscosity of fresh matrices at a level desirable for homogenous fiber dispersions. In the design of in GLECC mixtures, the industrial wastes account for about 89% and 82% by volume of total solid matrix materials at a FA/C ratio of 4.4 (C4–C6) and 2.2 (C1–C3), respectively.

2.2. Specimen preparation and testing

The mixtures were prepared following a typical ECC mixing procedure [8]. For each mixture, three 50 mm cube specimens for compression tests, three dogbone specimens for tension tests, and three 152 × 152 × 25 mm^3 plate specimens for thermal conductivity measurement were cast. The geometry of a dogbone specimen used in this study can be found in Ranade et al. [18]. In addition to the specimens for composite testing mentioned above, four beam specimens measuring 305 × 76 × 38 mm^3 were cast without adding fiber to determine the matrix fracture toughness. A notch with depth of about 30 mm, equal to 40% of the total beam depth (76 mm), was cut prior to testing. All specimens were demolded after 24 h of casting and then cured under wet cloth in a plastic bag at a room temperature of 23 ± 3 °C until the age of 28 days.

Uniaxial tensile tests on dogbone specimens were conducted to characterize the tensile behavior of the GLECC mixtures. Tests were conducted under displacement control with a loading rate of 0.5 mm/min as recommended by the Japan Society of Civil Engineers (JSCE) for direct tension testing of high performance fiber reinforced cementitious composite [19]. 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.

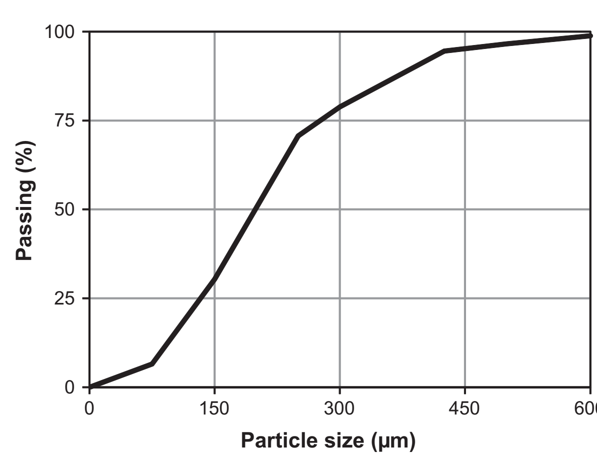

Fig. 1. Particle size distribution of FAC.

Table 1
Chemical composition of FAC.

Composition (wt%)	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O	K_2O
FAC	61.9	27.7	1.0	1.2	3.9	1.3	2.8

After the uniaxial tension tests, residual crack widths on the surface of dogbone specimens were measured using an optical microscope with 1 μm resolution, following the method recommended by JSCE [19].

The matrix fracture toughness was measured in accordance with ASTM E399 [20] using a three-point bending test setup. Although ASTM E399 is a standard for testing the fracture toughness of metals, it can be used for determining fracture toughness of brittle materials such as the GLECC matrices that show small scale yielding and, therefore, the assumptions of linear elastic fracture mechanics are valid [21]. The span length between the bottom supports for the beam was 254 mm and the notch depth (at the longitudinal center of the beam) to beam height ratio was 0.4.

Thermal conductivity measurements were conducted on plate specimens using a thermal capacitance calorimeter in accordance with ASTM E2584 [22]. The experimental setup and data processing were adopted from the reference [23]. As most infrastructures such as residential or commercial buildings are subjected to air drying, plate specimens were tested under air day state in the laboratory environment that is similar to field exposure. After being cured in the plastic bag for 28 days, plate specimens were placed in the laboratory environment of 23 ± 3 °C and 25 ± 5% RH. The air-dry state of plate specimens was achieved by daily measurements of their weight until there is no significant loss of weight after additional 30 days. These same GLECC plate specimens for thermal conductivity measurements were also used for density measurements.

3. Results and discussion

3.1. Density

Density is an important physical property for lightweight concrete. The densities of GLECC plate specimens (prepared for thermal conductivity tests) were measured at 28-days after curing under wet cloth in a plastic bag and again after an additional 30 days of air-drying in laboratory environment of 23 ± 3 °C and 25 ± 5% RH. The densities of GLECC mixtures thus measured at 28-days and at 58 days are given in Table 3. The density of GLECC mixtures (C2–3 and C5–6) at 28 days range from 1649 kg/m^3 to 1820 kg/m^3, which is 18–31% less than that of normal concrete with a typical density of 2400 kg/m^3. The 58 days air-dried density of GLECC mixtures ranges from 1483 kg/m^3 to 1684 kg/m^3. According to the ACI Committee 213, lightweight concrete at 28 days shall have an equilibrium density (cured at 50% RH) not exceeding 1850 kg/m^3 [2]. All GLECC mixtures with FAC exhibit densities lower than 1820 kg/m^3 at 28 days after curing under wet cloth in a plastic bag that is expected to have RH value (close to 100%) higher than 50%. Hence, GLECC designed in this study meet the density requirement for lightweight concrete.

The replacement of all IOTs with FAC (comparing C3 and C1; C6 and C4) causes a decrease in density by about 15% for both FA/C levels. Meanwhile, GLECC mixtures C4, C5, and C6 with a FA/C ratio of 4.4 exhibit densities of about 3% lower than that of mixtures C1, C2, and C3, with FA/C ratio of 2.2 and the same IOTs replacement as C4, C5, and C6, respectively. This can be attributed to the smaller specific gravity of FA (2.45) than that of cement (3.15). As cement was replaced with FA by mass in this study, higher FA content (FA/C) in GLECC results in lighter weight within a constant volume. Therefore, both FAC and high volume of FA are beneficial for the weight reduction of GLECC.

Table 3
Density of GLECC (kg/m^3).

FA/C	Mix ID	IOTs replacement (% Vol.) with FAC	28-days density	Air-dry density
2.2	C1[a]	0	2001	1890
	C2	60	1820	1684
	C3	100	1698	1549
4.4	C4[a]	0	1967	1811
	C5	60	1771	1625
	C6	100	1649	1483

[a] Control mixes with no FAC.

3.2. Tensile performance

The uniaxial tensile stress–strain curves of GLECC mixtures C1–6 are presented in Fig. 2. The tensile test results of the control mixtures C1 and C4 were adopted from a previous research by the authors of this paper [10]. Under uniaxial tensile loading, all GLECC mixtures exhibit strain hardening behavior through multiple-cracking process.

Tensile properties in terms of first cracking strength, ultimate tensile strength, and tensile strain capacity are summarized in Figs. 3 and 4. First cracking strength and ultimate tensile strength of GLECC mixtures (C2–3, C5–6) vary from 2.5 to 3.6 MPa and from 4.8 to 5.9 MPa, respectively. Tensile strain capacity of GLECC mixtures ranges from 3.3% to 4.4%, which are two orders of magnitude higher than that of conventional brittle concrete. Thus, the development of GLECC with high volume of industrial wastes is demonstrated.

The FA/C ratio greatly influences the tensile performance of GLECC. As observed in Fig. 3, the increase in FA/C ratio from 2.2 to 4.4 causes a decrease in first cracking strength and ultimate tensile strength by an average of 30% and 20%, respectively. From Fig. 4, it can be observed that GLECC mixtures with a FA/C ratio of 4.4 exhibit an increase in tensile strain capacity by an average of 25% than those with a FA/C ratio of 2.2. The lower strength performance and higher ductility in GLECC mixtures with higher content of FA is consistent with previous research results [9]. This is due to the fact that higher FA content leads to an increase in frictional bond at the interface between PVA fibers and matrix, and a decrease in interfacial chemical bond and matrix fracture toughness [9]. According to the micromechanics design theory of ECC, all

Table 2
Mix proportions of GLECC.

FA/C	Mix ID	FAC/(FAC + IOTs) (% Vol.)	Ingredients (kg/m^3)						HRWRA/(C + FA) (%)
			C	FA	IOTs	FAC	Water	Fiber	
2.2	C1[a]	0	389.5	856.8	448.7	0	324.0	26	0.46
	C2	60	389.5	856.8	179.5	84.1	324.0	26	0.38
	C3	100	389.5	856.8	0	140.2	324.0	26	0.33
4.4	C4[a]	0	227.2	999.7	441.7	0	319.0	26	0.42
	C5	60	227.2	999.7	176.7	82.8	319.0	26	0.32
	C6	100	227.2	999.7	0	138.0	319.0	26	0.26

[a] Control mixes with no FAC.

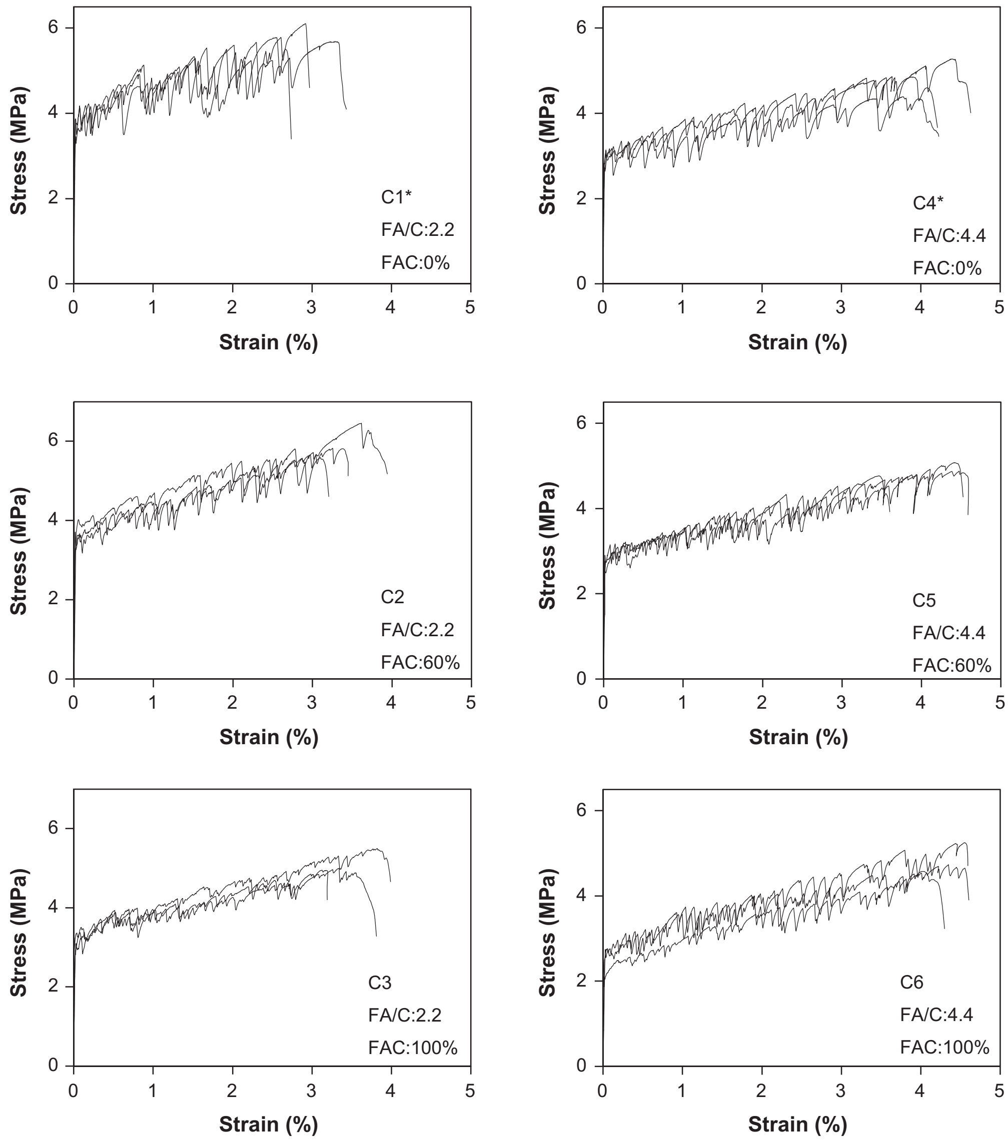

Fig. 2. Uniaxial tensile stress–strain curves of GLECC mixtures at 28 days. (*Test results of control mixtures C1 and C4 adopted from Huang et al. [10]).

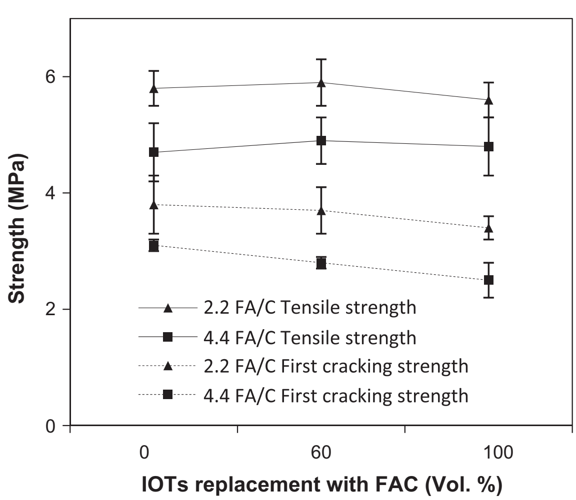

Fig. 3. First cracking strength and ultimate tensile strength under direct tension of GLECC mixtures at 28 days.

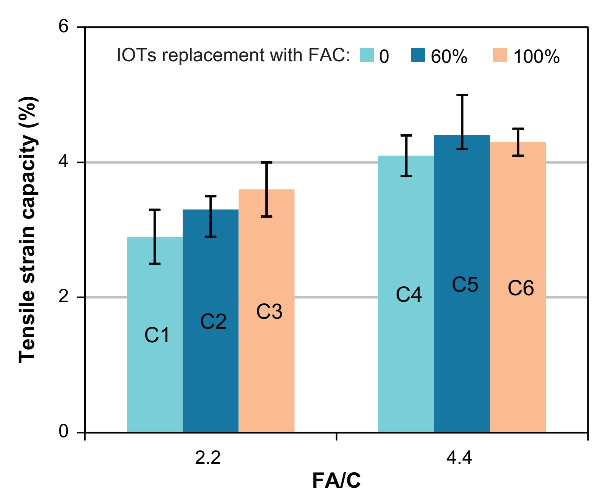

Fig. 4. Tensile strain capacity of GLECC mixtures at 28 days.

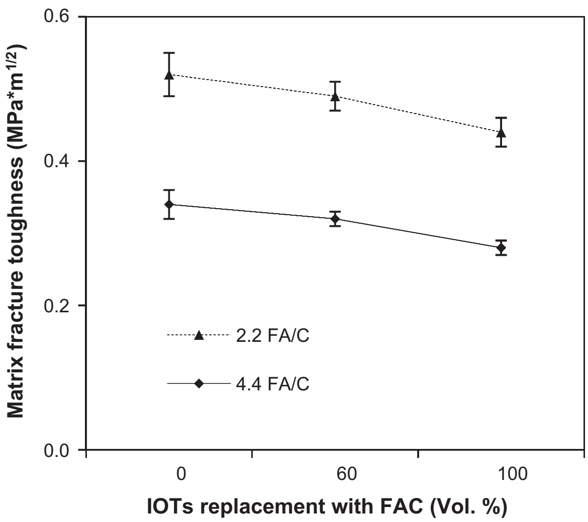

Fig. 5. Matrix fracture toughness of GLECC at 28 days.

these effects due to high content of FA are beneficial for obtaining high tensile ductility [3].

For each level of FA/C ratio, the replacement of IOTs aggregate with FAC results in a reduction in first cracking strength (Fig. 3). As shown in Fig. 5, at each level of FA/C ratio, matrix fracture toughness decreases with the increase in FAC content, which causes the reduction in first cracking strength. The ratio of first crack strength for C3 to that of C1 is consistent with the ratio of matrix fracture toughness for C3 to that of C1, further supporting the influence of IOT replacement with FAC on first crack strength via matrix fracture toughness. FAC was found stable in alkaline solution at ambient temperature [15,24]. So both FAC and IOTs can be regarded as inert fillers in the GLECC mixtures examined in this study. The decrease in matrix fracture toughness is likely due to the difference in particle shape of IOTs and FAC. Fig. 6 shows an environmental scanning electron microscope (ESEM) image of a polished surface of dogbone specimens of mixtures C1 and C3. As shown in Fig. 6, the replacement of irregularly shaped IOTs with spherical FAC reduces the tortuosity of fracture path along the interface between aggregates and cement paste, which is expected to facilitate crack propagation and, therefore, result in lower fracture toughness and first cracking strength.

For each level of FA/C ratio, the replacement of IOTs aggregate with FAC has little influence on ultimate tensile strength (Fig. 3). Ultimate tensile strength is determined by fiber bridging capacity which is further influenced by the properties of fiber and fiber/matrix interface. At each level of FA/C ratio, FAC was used to replace IOTs without changing the amount of cement, FA and water. Therefore, the interfacial properties between fiber and surrounding cement paste are expected to be independent of the FAC content, and as a result, the influence of FAC on the ultimate tensile strength of GLECC mixtures is insignificant.

For each level of FA/C ratio, tensile strain capacity of GLECC mixtures increases with the replacement of IOTs with FAC (Fig. 4). For example, the tensile strain capacity of GLECC increases from 2.9% for mixture C1 to 3.3% for mixture C2, when 60% volume of IOTs in the control mixture C1 are replaced with FAC in mixture C2 (with FA/C ratio of 2.2). The increase in tensile strain capacity can be attributed to the decrease in matrix fracture toughness and slight change in fiber bridging capacity as reflected by ultimate tensile strength. According to the micromechanics based design theory of ECC, two complementary criteria, energy criterion and strength criterion, must be satisfied to obtain multiple cracking behaviors [3]. The energy criterion requires that crack tip toughness J_{tip} must be less than the complementary energy J'_b. The strength criterion requires that first cracking strength σ_{cr} must be smaller than the fiber bridging capacity σ_0. Hence, ratios of J'_b/J_{tip} and σ_0/σ_{cr} greater than 1, and preferably greater than 3, are favorable for obtaining robust tensile ductility in ECC [25]. Therefore, lower matrix fracture toughness (which reduces J_{tip}) and lower first cracking strength (σ_{cr}) due to the replacement of IOTs with FAC lead to an increase in the ratios of J'_b/J_{tip} and σ_0/σ_{cr}, which result in improved tensile strain capacity.

The formation of multiple micro-cracks under tensile load is one of the most distinctive characteristics of ECC. The crack patterns observed in representative GLECC specimens of all mixtures after unloading are shown in Fig. 7; dilute carbon black solution was used to enhance the microcrack images. The average residual (after load removal) crack widths observed in these crack patterns are summarized in Table 4. As seen from Fig. 7 and Table 4, both higher ratio of FA/C and higher content of FAC in GLECC mixtures increase the number of micro-cracks, which contributes towards increasing the tensile strain capacity. The average residual crack width (Table 4) for GLECC ranges from 23 to 51 μm, depending on the FAC content and FA/C ratio. For each level of FA/C ratio, the replacement of IOTs with FAC leads to a decrease in crack width. This may be due to the lower cracking strengths as a result of reduction in fracture toughness (Fig. 5) with the introduction of FAC. In addition, possible improvement in fiber dispersion, caused by the difference in particle shape of FAC (smooth sphere) and IOTs (irregular shape), may lead to stiffer crack-bridging curve, which may reduce the observed crack widths. Due to the reduction of

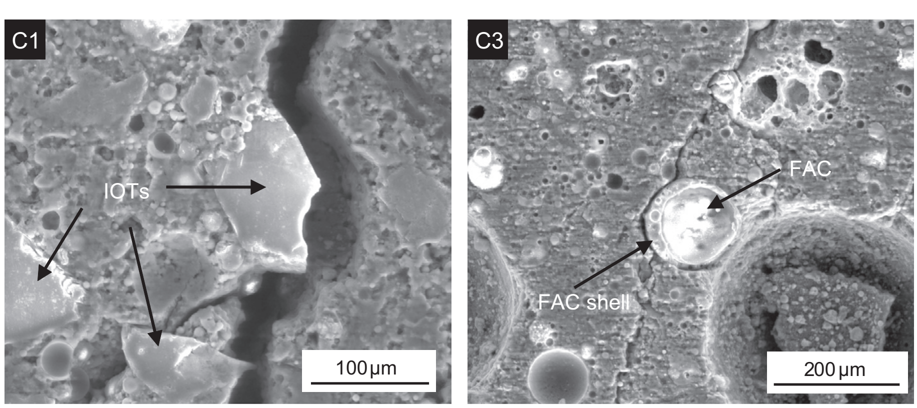

Fig. 6. ESEM images of mixtures C1 and C3 (polished surface of dogbone specimens after tension test).

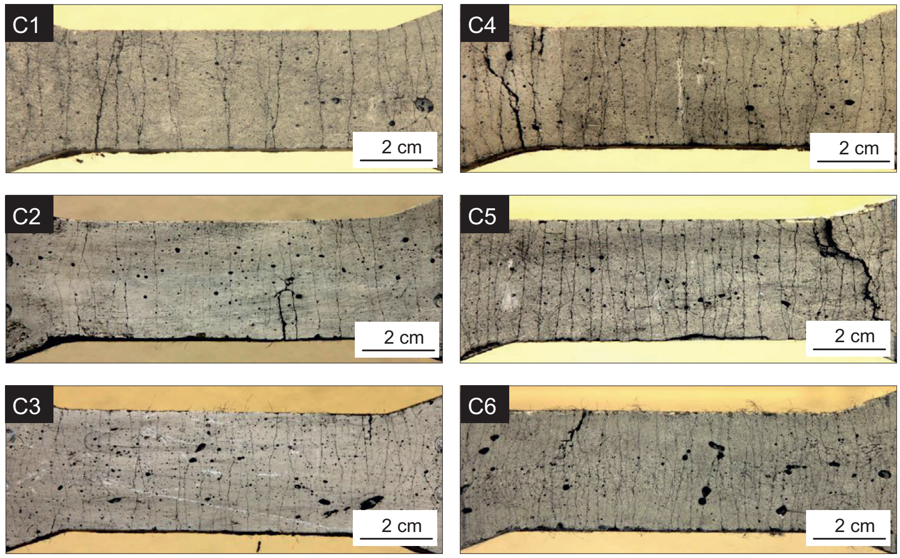

Fig. 7. Observed crack patterns in GLECC specimens after tensile testing.

Table 4
Observed average residual crack widths (after tension load) in GLECC specimens of various mixtures C1–6 (μm).

FA/C → FAC ↓ (%)	2.2	4.4
0	55 (C1)	67 (C4)
60	34 (C2)	51 (C5)
100	23 (C3)	35 (C6)

crack widths, use of FAC in GLECC can potentially assist in reducing the permeability of cracked GLECC, thus promoting the material durability.

3.3. Compressive strength

The average 28-day compressive strength test results of GLECC mixtures with different FA/C ratios and IOTs replacement (with FAC) levels are summarized in Fig. 8. As seen in Fig. 8, the compressive strengths of GLECC mixtures decrease with increase in FA/C ratio for all levels of IOTs replacement with FAC, which can be attributed to the reduction in strong primary hydration products at 28 days due to the reduced amount of cement. For each level of FA/C ratio, the increase in FAC content by increasing IOTs replacement results only in marginal (at most 10%) decrease in compressive strength. With total IOTs aggregate replaced by FAC, the 28-day compressive strength of GLECC mixtures with FA/C ratio of 2.2 and 4.4 decreases from 48.1 to 44.3 MPa and from 27.9 to 25.0 MPa, respectively. Thus, all the GLECCs developed with high volumes of fly ash and fly ash cenospheres in this study meet the strength requirement of 17.5 MPa [2] for structural lightweight concrete.

3.4. Thermal conductivity

The thermal conductivities of GLECC mixtures at ambient temperature (23 °C) normalized by the thermal conductivity of mixture C1 (0.370 W m^{-1} K^{-1}) at the same temperature are shown in Fig. 9. As observed in Fig. 9, for each level of FA/C ratio, increase in FAC content reduces thermal conductivity. With 100% IOTs replaced by FAC, thermal conductivity of GLECC mixtures is lowered by an average of 21% for both levels of FA/C ratios. The reduction in thermal conductivity due to the incorporation of FAC is caused by the lower thermal conductivity of FAC than that of IOTs. The

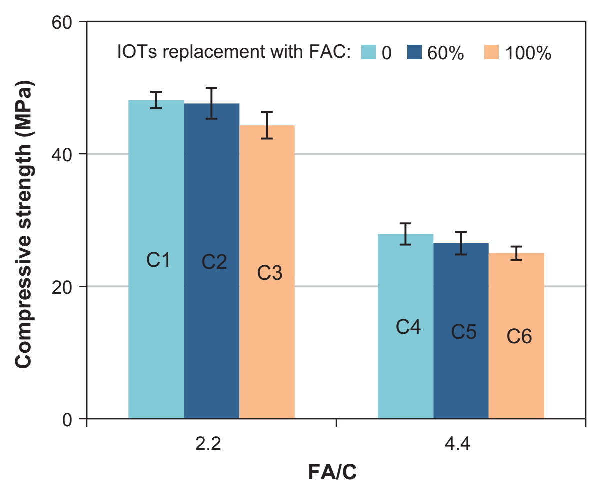

Fig. 8. Compressive strength of GLECC at 28 days.

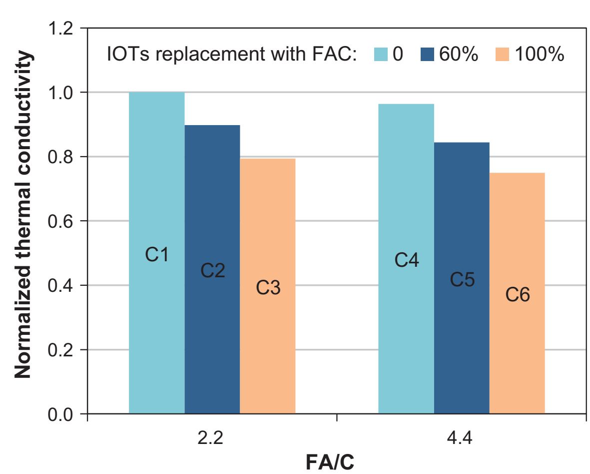

Fig. 9. Normalized (by C1) thermal conductivities of GLECC mixtures.

thermal conductivity of FAC is 0.065 W m^{-1} K^{-1} [15] compared to 3.826 W m^{-1} K^{-1} [26] of quartz, which is a major component of IOTs. The low thermal conductivity of FAC is due to their hollow structure with entrapped air. In addition to decrease in thermal conductivity with FAC content, higher ratio of FA/C ratio also decreases thermal conductivity (Fig. 9). For each replacement level of IOTs by FAC, the thermal conductivity of GLECC mixtures decreases by 4–6% as FA/C ratio is increased from 2.2 to 4.4. Such effect of FA content on the thermal conductivity of cementitious materials is consistent with data in the existing literature [27]. It is concluded that the incorporation of FAC can effectively reduce thermal conductivity of GLECC, and such effect is enhanced by the use of high volumes of FA.

4. Conclusions

In this study, GLECC exhibiting tensile ductility greater than 3.4% at densities of 1649–1820 kg/m^3 was successfully developed with high content of industrial wastes constituting 82–89% of the total solid matrix materials by volume. The tensile first cracking strength, ultimate tensile strength, and compressive strength of the developed GLECC at 28 days are 2.5–3.6 MPa, 4.9–5.8 MPa and 25.0–47.6 MPa, respectively. Replacing irregular IOTs aggregates with spherical FAC in GLECC improves tensile ductility and reduces crack width at the expense of marginal reductions in compressive strength. In addition, the use of hollow FAC as lightweight filler in GLECC can effectively reduce the materials thermal conductivity, which can potentially benefit energy conservation in buildings constructed with GLECC.

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