27 LIGHTWEIGHT ENGINEERED CEMENTITIOUS COMPOSITES (ECC)

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Abstract

Lightweight concrete with densities between 900 and 1600 kg/m^3 has been used in various structural and non-structural applications, offering considerable weight saving. By adding ductility, lightweight ECC can further broaden the applicability. Four approaches to achieving lightweightedness for a Polyvinyl Alcohol (PVA) fiber ECC are explored in this paper, including uses of air-entrainment admixture, polymeric micro-hollow-bubble, natural lightweight aggregates perlite and glass micro-bubbles. Density, uniaxial tensile behavior, and compressive strength of 15 mix designs are examined. The experimental results show that multiple cracking and strain hardening can be achieved by all these approaches; however, tensile and compressive strengths and robustness of strain capacity significantly vary with content and type of lightweight "filler" used. Mixes by adding glass micro-bubbles with controlled size distribution exhibit more superior mechanical performances than other approaches. For example, tensile strength of 4 MPa with strain capacity above 4% is achieved in a lightweight PVA-ECC with 2% fiber volume fraction at a density of 1450 kg/m^3, along with a compressive strength of 40 MPa.

1. Introduction

Engineered Cementitious Composites (ECC) is a special type of high performance fiber reinforced cementitious composites (HPFRCC) featuring significant tensile ductility and moderate fiber volume fraction (typically 2%). The design of ECC is guided by micromechanics models, which provide quantitative links between composite mechanical behavior and the properties of the individual phases, e.g. fiber, matrix and interface [1]. Utilizing the models, the desired high tensile ductility, which is achieved by strain hardening and multiple cracking, is converted to a set of constraints on individual component properties. These components, i.e. the fiber, the matrix and the interface, are then synergistically tailored either at raw material manufacturing stage or through mix design to meet the constraints [2].

With the advantage of high ductility and flexible processing, ECC materials are finding themselves in a broad range of applications, from repair and retrofit to seismic resistant structural elements [3]. In some situations, such as precast ECC wall panel for seismic retrofit of building and ECC seismic energy damper, lightweight is greatly favored, as it means reduced gravity load and seismic internal mass, and in turn smaller member sizes and foundation forces.

For concrete, lightweightedness has traditionally been made by using lightweight aggregates, such as pyroprocessed shales, clays, slates, expanded slags, expanded fly ash, and those mined from natural porous volcanic sources [4]. The air-dried unit weight of lightweight concrete is usually in the range of 1400 to 1900 kg/m^3. Further reduction in weight can be achieved by adding foams into mixes, wherein the entrapped air takes the form of small and spherically shaped bubbles uniformly dispersed in the concrete matrix [5]. Similar methods also include the use of expanded polystyrene or polyurethane beads [6].

As the lightweight aggregates are usually weaker than cement matrix and provides little resistance to crack propagation, the lightweight concrete typically exhibits more brittle behavior than normal concrete with similar compressive strength. Zhang and Gjorv reported that the tensile/compressive strength ratio for high strength lightweight concrete is lower than that for high strength normal weight concrete [7]. For lightweight foamed concrete, the fracture energy is only a fraction of that of the normal weight concrete [8]. To impart ductility into lightweight concrete, various fibers, including steel, carbon, glass, nylon and propylene (PP) fibers, have been introduced into the mixes [6, 9-13]. While improvements in tensile strength, flexural strength and particularly flexural toughness are observed, the behavior of these fiber reinforced lightweight concrete are no more than conventional fiber reinforced concrete characterized by tension softening behavior.

The object of the present study is to develop a lightweight version of ECC material, i.e. a lightweight fiber reinforced cementitious composite having high strain capacity in tension with strain hardening behavior and high strength in both tension and compression. While weight reduction approaches similar to those used in lightweight concrete may also be applicable to the ECC material, cautions have to be taken on the influences of the lightweight fillers upon the workability, interface bond properties, fiber dispersion and composite strength.

In the present study, four types lightweight fillers, including air bubbles generated by air entrainment admixture, expanded perlite sand, glass bubbles and polymeric microform, were experimental investigated. The composite densities, strengths, and tensile strain capacities are reported.

2. Material design considerations

Successful design of a composite with desired properties is based on the understanding of the mechanical interactions between fiber, matrix and interface phases. Extensive studies on these interactions at micromechanics level have lead to the successful development of polyvinyl alcohol fiber reinforced ECC (PVA-ECC) [2, 14], which provides a base on which the lightweight functionality will be added.

To retain strain hardening and multiple cracking behaviors, the micromechanics models indicate that adequate interface bond strength has to be maintained. When the presence of high volume fraction of lightweight fillers tends to reduce the average bond strength, a hydrophilic fiber such as PVA is preferred due to its usually excessive bond both chemically and frictionally to the surrounding hydrated cement. In contrast, for other common fiber/matrix composite systems such as steel, carbon and PP fiber where the bond strengths are already considered too low to achieve strain hardening, the addition of lightweight fillers can only lead to reduced post-crack ductility.

One challenge in developing lightweight composite is to maintain high strength when reducing the weight, since the lightweight aggregates act like flaws in the matrix. From the viewpoint of fracture mechanics, for a brittle matrix such as cement the tensile strength is determined by the largest existing flaw size while the compressive strength is controlled by a group of relatively large flaws. Therefore, one approach to minimize the adverse impact of lightweight aggregates on the strengths both in tension and compression is to employ aggregate with size much smaller than the dominant pre-existing flaws. In ECC mixes, the most common pre-existing flaws are entrapped air bubbles with sizes above 1 mm. Meanwhile, small lightweight aggregate size is also desired from the workability consideration, as large aggregate deteriorates the fiber dispersion.

3. Experimental program

Four types of small size lightweight aggregates were evaluated, including glass bubbles S38 and S60, polymeric micro-hollow-bubble MHK, and an expanded perlite sand. The glass bubbles and MHK have average sizes below 100 μm while the expanded perlite sand has a larger average size of 1.5 mm. The difference between S38 and S60 lies at their different size distribution, and S38 has larger mean size than that of S60. The properties of these aggregates are listed in Table 1. In addition, an air entrainment admixture was also used to produce air bubble as lightweight filler.

Table 1: Properties of lightweight aggregates

	Density (kg/m^3)	Size Distribution (μm)	Mean Size (μm)
Glass Bubble S38	380	10-80	40
Glass Bubble S60	600	10-60	30
Micro-hollow-bubble MHK (1)	16.7	40-120	80
Expanded perlite	1400	500-2000	1500

(1) Polyvinylidenchloride-acrylnitril polymer

PVA REC15 fiber, which is specially developed for ECC materials [14], is used in this study with a fixed volume fraction of 2%. The properties of the fiber are shown in Table 2. Other ingredients include Type I OPC, fine silica sand (average size 110 μm), viscosity agent hydroxypropyl methylcellulose (HPMC) and superplasticizer (SP). The mix proportions of lightweight ECC are tabulated in Table 3, where the 15 mixes are divided into 4 groups with the glass bubble, air bubble, MHK, and expanded perlite respectively.

Table 2: Properties of REC15 PVA fiber

Nominal Strength (MPa)	Apparent Strength (MPa)	Diameter (μm)	Length (mm)	Modulus of Elasticity (GPa)
1620	1092	39	12	42.8

Table 3: Mix proportions of lightweight ECC

Mix No.	Cement	Water	Sand	Lightweight aggregates	HPMC	SP	Fiber by volume
1	1	0.45	1.0	S38 0.05	0.0015	0.030	0.02
2	1	0.47	1.0	S38 0.10	0.0015	0.030	0.02
3	1	0.47	1.0	S38 0.20	0.0015	0.030	0.02
4	1	0.45	0.6	S60 0.40	0.0015	0.035	0.02
5	1	0.48	1.0	S60 0.20	0.0015	0.040	0.02
6	1	0.45	0	S60 0.20	0.0015	0.030	0.02
7	1	0.60	0	S60 0.50	0.0015	0.040	0.02
8	1	0.75	0	S38 0.50	0.0015	0.040	0.02
9	1	0.45	1.0	AE 0.02 (1)	0.0010	0.020	0.02
10	1	0.45	1.0	AE 0.04 (1)	0.0010	0.020	0.02
11	1	0.45	1.0	AE 0.06 (1)	0.0010	0.020	0.02
12	1	0.54	1.0	AE 0.06 (1)	0.0010	0.020	0.02
13	1	0.45	1.0	MHK 0.05	0.0010	0.030	0.02
14	1	0.45	1.0	MHK 0.10	0.0010	0.020	0.02
15	1	0.50	0.6(2)	S38 0.15	0.0015	0.030	0.02

(1) Air entrainment admixture, the proportion is weight ratio to cement

(2) Replaced by expanded perlite lightweight sand

The mixture was prepared by conventional fiber reinforced concrete preparation procedure. Coupon specimen measuring 304.8 mm x 76.2 mm x 12.7 mm for tension test and cylinder specimen having a diameter of 75 mm and a height of 150 mm for compression test were cast and cured in water for 28 days before test. The tensile behaviors of the composites were characterized by uniaxial tensile test under displacement control. The loading rate was 0.15 mm/min throughout the test. Two external LVDTs (Linear Variable Displacement Transducer) were attached to specimen surface with a gage length of about 180 mm to measure the displacement.

4. Results and discussion

The test results are summarized in Table 4, including density, tensile first and ultimate strengths, tensile strain capacity, and compressive strength. Complete tensile stress-strain curves of these composites are illustrated in Figs. 1, 5 and 6. All of them exhibit strain hardening and multiple cracking behavior.

Table 4: Properties of hardened lightweight ECC

Mix No.	Density (g/cm^3)	Tensile first cracking strength (MPa)	Tensile ultimate strength (MPa)	Tensile strain capacity (%)	Compressive strength (MPa)
1	1.78	3.28	4.25	3.68	46.4
2	1.61	3.20	3.94	3.62	42.3
3	1.46	3.12	4.02	3.71	39.2
4	1.42	2.95	3.80	3.71	36.7
5	1.67	3.90	4.56	3.42	43.2
6	1.45	2.74	4.31	4.24	41.7
7	1.10	2.18	3.17	3.41	26.2
8	0.93	2.01	2.85	3.70	21.8
9	1.80	2.66	3.27	1.40	28.7
10	1.48	2.60	3.34	1.39	22.4
11	1.38	2.42	2.89	2.37	18.3
12	1.22	1.93	2.38	1.26	14.2
13	1.78	3.12	3.73	1.63	28.4
14	1.36	1.64	1.91	1.49	11.8
15	1.47	3.11	3.50	0.35	39.0

Mix 1, 2 and 3 have the same weight ratio of sand to cement but different content of glass bubble S38 for achieving different densities. The test results show that even though the density is reduced to 1.46 g/cm^3 with the increase of S38 content, the tensile first cracking strength and ultimate strength, and strain capacity are little changed (Fig. 1a-1c). The average tensile strain capacity reaches about 3.6%. The compressive strength decreases with the density; however, at a density of 1.46 g/cm^3 the strength 39.2 MPa (Mix 3) is still higher than most normal strength concrete typically with density around 2.40 g/ cm^3.

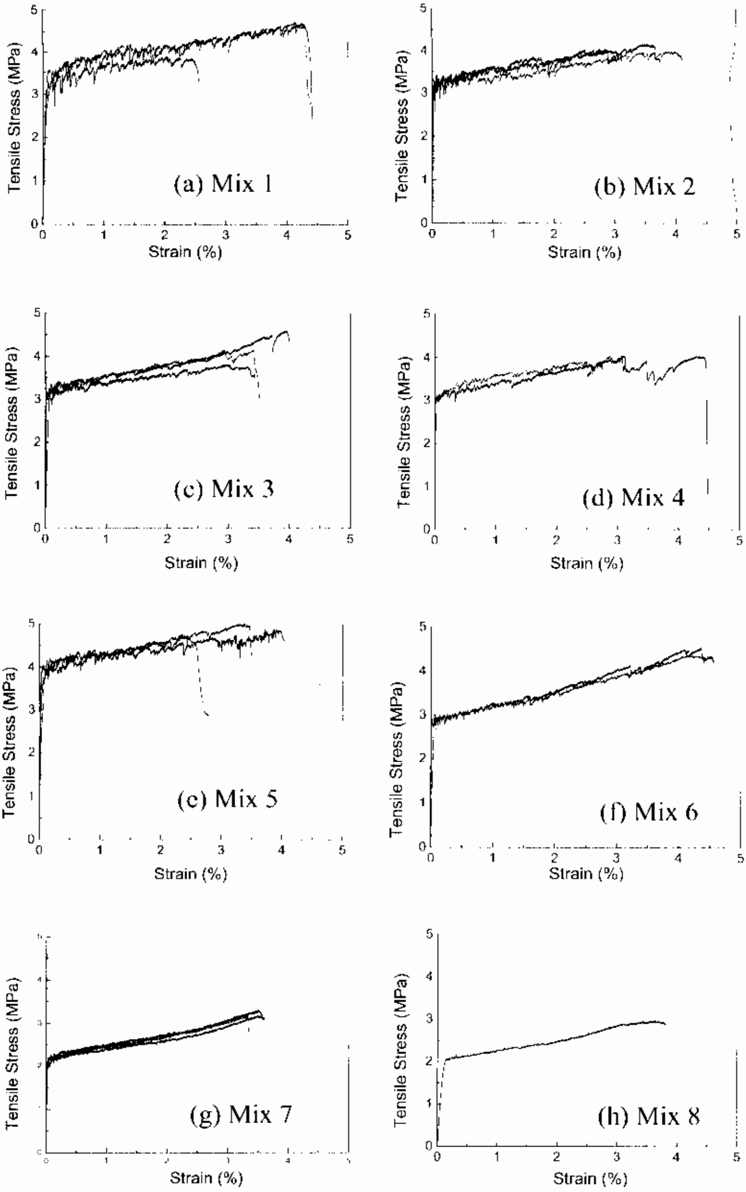

Fig. 1: Tensile behaviors of lightweight ECC with Glass bubbles

Mix 4 and 5 also contain sand but use glass bubble S60 instead, which has smaller particle size than S38. Mix 2 and 5 show similar density, suggesting that the volume fraction of voids is similar in these two composites though the size distribution of voids is different. Composites made from Mix 5 have finer void system than the composites made from Mix 2. A comparison between Fig. 1b and Fig. 1e indicates that smaller void size may lead to a higher first cracking strength.

Mix 6, 7 and 8 are a set of composites targeting very low density. Test results show that the further increase of glass bubble content has little influence on the composite strain capacity but significantly reduces the strength both in tension and compression. However, even at a density lighter than water, i.e. Mix 8, the tensile strength 2.85 MPa and compressive strength 21.8 MPa satisfy requirements of some structural applications such as seismic dampers.

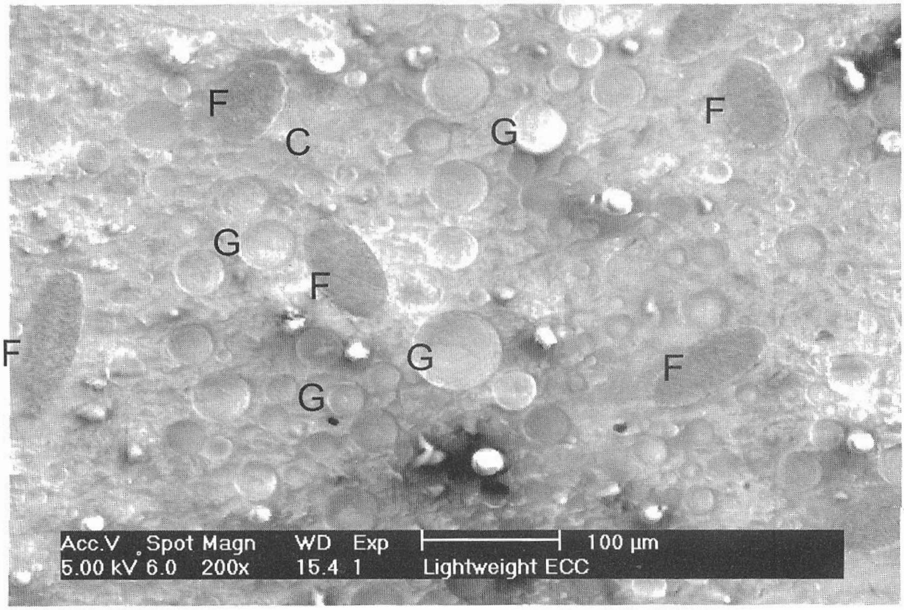

Fig. 2: SEM picture of the cross-section of Mix 6, showing uniformly distributed PVA fibers (F) and a fine cellular structure constructed by glass bubbles (G) and cement hydrates (C)

Fig. 2 is a scanning electron micrograph (SEM) at 200X magnification of the cross-section surface of the Mix 6, showing a fine cellular microstructure comprised of glass bubbles S60 and cement hydrates, along with randomly distributed PVA reinforcing fiber. A dense interface between PVA fiber and the matrix can be seen. Since the glass bubble has a spherical shape and comparative size to PVA fiber, at the content used in Mix 1-6 (up to 38% by volume) it seems that the presence of the glass bubble has little influence on the bond strength where the interface is filled with cement hydrates. This may explain why the mixes 1-6 show similar ultimate tensile strength. However, further increase in glass bubble content may eventually weaken the interfacial bond and lead to a lower peak bridging stress, as indicated in Fig. 1g and Fig. 1h.

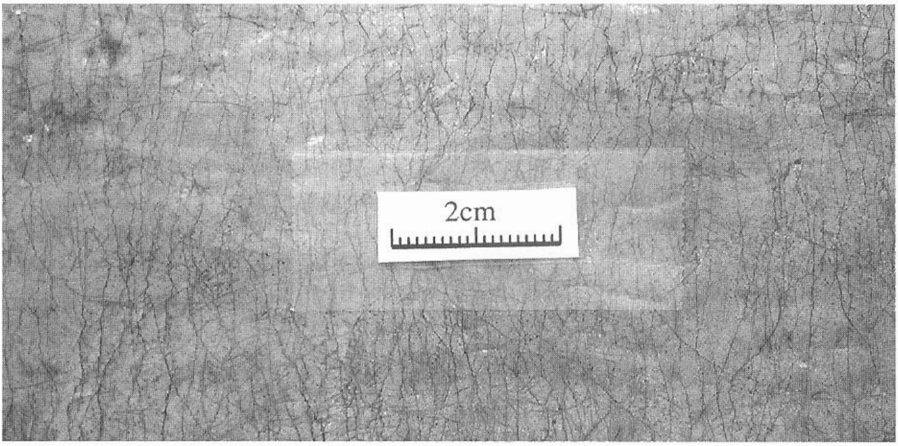

Fig. 3: Saturated crack pattern of Mix 6 after strained to 4% in tension

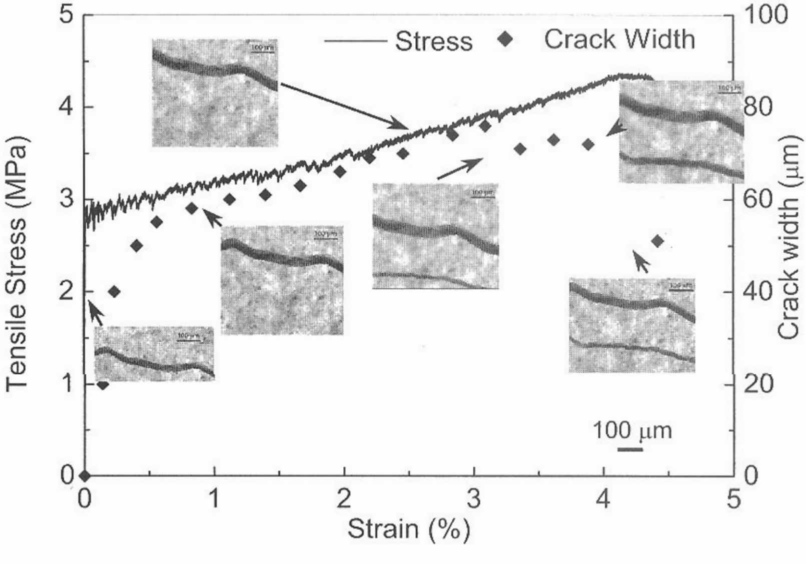

Fig. 4: Tensile stress and crack width vs. strain relationship of Mix 6, showing a stabilized crack width below 80 μm when strained to 4% in tension

Fig. 3 shows the saturated crack pattern of Mix. 6, wherein the crack spacing is less than 2 mm. Similar patterns are also observed in other mixes with glass bubbles. Since the saturation of multiple cracking, which is determined by the interface and matrix properties, has been reached, it is not surprising to see Mix 1-8 exhibit similar strain capacity. Fig. 4 shows the opening development of a typical crack with the increase of strain (Mix 6). Shortly after the first cracking, the crack width grows rapidly and then tends to flatten after about 1% strain. The increase of strain is accommodated by newly developed microcracks, as illustrated in the inserts. Finally the crack width stabilizes at about 80 μm, while for typical FRC the crack width almost increases linearly with the deformation of the composite while the load drops. Such small crack width implies great enhancement in structural durability, as the transport of harmful ingredients via water movement through cracks is virtually stopped when the crack width is below 100 μm [15].

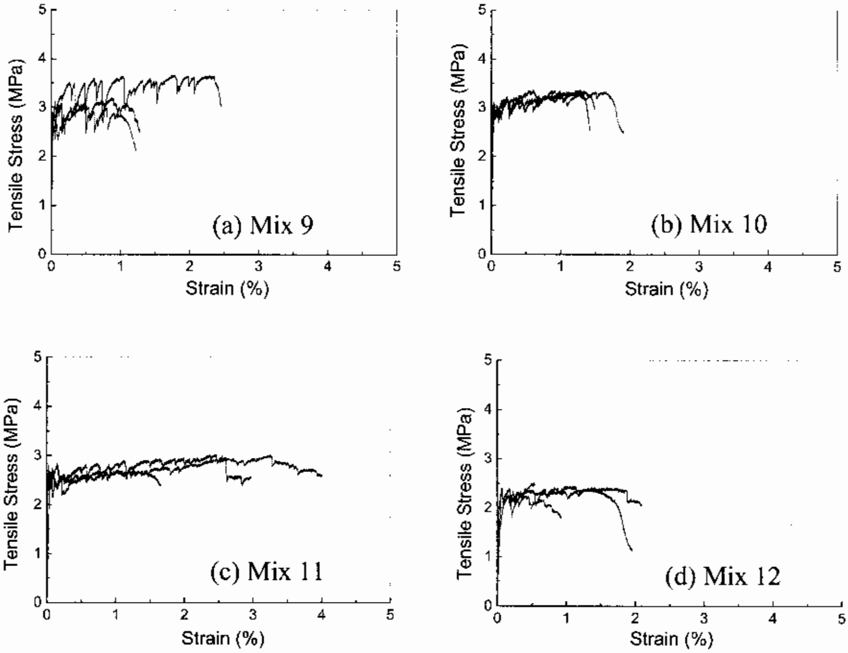

Fig. 5: Tensile behaviors of lightweight ECC with air bubbles

Fig. 5 shows the tensile behaviors of Mix 9-12 using air bubble as lightweight filler. The air bubbles were produced by air entrainment admixture. With the increase of the admixture dosage, the composite density decreases accordingly, as well as the tensile first cracking strength, tensile ultimate strength and compressive strength. In particular, the drop of compressive strength shows a faster rate than the decrease of density. Microscopic analysis reveals that the size distribution of air voids becomes wider and more large air bubbles appear at high content of air entrainment admixture. This is due to the fact that the bubble size is not stable during the mixing and handling process. Mechanical force and time both will change the size distribution of air bubbles and form large voids. When 6 wt% to cement of air entrainment admixture is used (Mix 11), a large number of bubble at size of about 2 mm can be seen. Even more large bubbles are formed when higher water content is used (Mix 12). Consequently, the compressive strengths of Mix 9-12 are significantly lower than those with similar densities but using glass bubbles. Meanwhile, since the bond is lost when the fiber contacts air bubbles, as opposed to the case of glass bubble where hydrates fill the gap between the fiber and the shell of the bubble, a significant reduction in bond strength is expected at high air bubble content. For the REC15 PVA fiber where the bond strength has been deliberately lowered during manufacturing process, the presence of large amount of air bubble can only undermine the strain hardening potential and leads to limited strain capacity.

Mix 13 and 14 are the mixes using polymeric micro-bubbles as the lightweight filler (Fig. 6). The micro-hollow-bubble MHK used here has desired size distribution; however, since this polymeric bubble has weaker bond to cement hydrates and PVA fiber than glass bubble, the tensile strain capacity of Mix 13 is significantly lower than Mix 1, which has similar density. Further increase of MHK content results in considerable reduction in tensile strengths.

An attempt to replace the fine silica sand with expanded perlite lightweight aggregates was made in Mix. 15. As shown in Fig. 7, poor strain hardening was observed. The reason is that the introduction of relatively large expanded perlite sand (0.5 – 2 mm) causes big change in rheology and impairs the fiber dispersion. Moreover, since the expanded perlite has a porous microstructure, higher water content is needed to compensate the absorption.

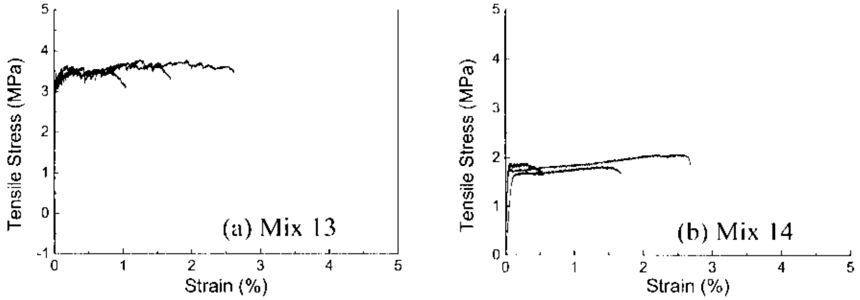

Fig. 6: Tensile behavior of lightweight ECC with polymeric micro-hollow-bubble MHK

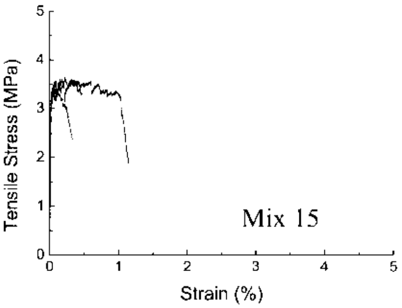

Fig. 7: Tensile behavior of lightweight ECC with expanded perlite

5. Conclusions

Lightweight ECC materials exhibiting high tensile ductility and desirable tensile and compressive strengths were successfully developed. Experimental investigations on four types of lightweight fillers, including glass micro-bubbles, polymeric micro-bubbles, expanded perlite sand and air bubbles produced by air entrainment admixture, have led to the following conclusions:

(1) Strain hardening and multiple cracking are easily achievable for all these lightweight fillers when used with the conventional PVA-ECC mix. However, lightweight aggregates with controlled small sizes, e.g. below 100 μm, are preferred as it minimizes the adverse impact on both tensile and compressive strength and retains good workability.

(2) Fillers with prescribed sizes are favored over air voids, while the size distribution of the latter is difficult to control and maintain. Moreover, a closed shell structure is more desirable as it ensures the separation of voids and does not absorb water.

(3) With the use of glass micro-bubbles, lightweight ECC materials exhibit tensile strain capacity above 3% in the density range from 0.93 to 1.78 g/cm^3. In particular, ultimate tensile strength above 4 MPa and tensile strain capacity exceeding 4% are demonstrated at a density of 1.45 g/cm^3 along with a compressive strength above 40 MPa. At a density of 0.93 g/cm^3, ultimate tensile strength above 2.5 MPa and compressive strength above 20 MPa are obtained.

6. References

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