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MATERIAL PROPERTIES AND IMPACT RESISTANCE OF A NEW LIGHTWEIGHT ENGINEERED CEMENTITIOUS COMPOSITE

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ABSTRACT

Engineered Cementitious Composite (ECC) is a unique type of cement mixture that exhibited superior tensile strain-hardening compared to normal fibre reinforced concrete (FRC). ECC contains a mix of cement/fly ash, sand, water, chemical adhesives and a relatively low volume (typically <2%) of short discrete low modulus fibres, such as polyvinyl-Alcohol (PVA) fibre. The interaction between the microfibers and other materials create flat steady state multi-cracking of concrete when under stress. In this paper, an innovative lightweight ECC material is developed by replacing a fraction volume of cement with lightweight hollow glass microsphere additives. It is expected that the material will have a lower density than the normal ECC, better energy absorption and improved compressive strength. Both static testing and impact testing using Split Hopkinson Bar (SHPB) have been conducted.

KEYWORDS

ECC, lightweight, hollow microsphere, fibre reinforced material, impact testing, SHPB.

INTRODUCTION

Concrete is a versatile construction material that is capable of being moulded into virtually any shape. This property is valuable as it allows engineering design to suit the aesthetics of modern and ever evolving architecture in addition to optimisation of material and geometries. However, the downfall of concrete is its brittle characteristic and cracks easily under mechanical and environmental loads. In the past, research has been carried out aimed at improving the concrete mixture with a good ductility and retaining a large tensile strength. Fibre Reinforced Concrete (FRC) was developed partially to fulfil this aim where the bending strength of the material was improved. However, the tensile strain capacity of FRC is typically about 1.5% or less (Li, 2003).

Recently, a new kind of fibre reinforced cementitious composite, known as Engineered Cementitious Composite (ECC) has been developed at the University of Michigan (Li, 2003). ECC is a unique type of cement mixture that exhibited superior tensile strain-hardening compared to normal FRC with strain capacity in the range of 3-7% (Li 2003). ECC contains a mix of cement, fly ash, sand, water, chemical adhesives and a relatively low volume (typically <2%) of short discrete low modulus fibres, such as polyvinyl-Alcohol (PVA) fibre. The superior mechanical properties and existence of multiple micro crackings equip the ECC material excellent capability of high energy absorption and impact shutter resistance, and it has been regarded as a very promising material for construction of protective and defensive structures (Khin et al. 2013).

For protective or seismic resistant structures, lightweight will be greatly favoured (Wang and Li 2005a). While lightweight aggregates are traditionally used to make lightweight concrete, they are normally weaker than cement matrix and provide little resistance to crack propagation (Wang and Li 2005a). In recently years, hollow sphere structures made by various materials and sizes, have been developed. Hollow spheres show a different physical behaviour compared to classical solid materials since the macroscopic behaviour is determined by the cell wall material and the cellular structure. Due to the high porosity, the material is able to compress at high strains which characterizes the ability of the structure to absorb energy at a low and constant stress level even at high strains (Öchsner et al. 2008).

In this research, an innovative lightweight ECC material is developed by replacing a fraction volume of cement with lightweight hollow glass microsphere additives. It is expected that the material will have a lower density than the normal ECC, better energy absorption and improved compressive strength. Both static testing and impact testing using Split Hopkinson Pressure Bar (SHPB) have been conducted. This research will also investigate if the smooth surface of the hollow glass microspheres will reduce the chemical bond between the PVA fibre and the matrix. Hence, there is potential to eliminate the need of surface coating the PVA fibre since the microspheres may reduce the PVA fibre chemical bond similar to that of surface coating.

SAMPLE PREPARATION AND STATIC TESTING

Material Properties and Mix Design

There are two mix designs were attempted in this paper. The first mix design (1F series) of the lightweight ECC developed in this research is based on Wang and Li (2005b) which was a typical ECC mix with 2%PVA fibre only; while for our mix, a 10% of hollow microsphere was added and only 1.5% of PVA fibre was used. A 2% volume fraction of superplasticizer was also used to maintain a good workability as no fly ash was used. Through the tailoring of micromechanics, mix designs have been created that allow for an ECC to achieve strain-hardening. Typically, these mix designs have a low water/cement ratio and a low aggregate/cement ratio. As suggested by Wang and Li (2005b), the silica sand used in the mix had a maximum grainsize of 250μm and an average size of 110μm. For the 2nd group mix design, a higher ratio of water/cement and aggregate/cement were attempted (2F series). The mix proportions are shown in Table 1. The mixing procedures suggested by Wang and Li (2005b) were adopted where 10% of water and superplasticizer were added after 2 min dry mix for another 2 min before the remaining water was added. Fibres and microspheres were then added gradually to ensure a good dispersion. All ingredients were further mixed in a motorised drum mixer for 5 min.

The PVA fibre used is called NYCON-PVA RECS15 which was specifically designed for use in concrete products. The PVA fibre had a diameter of 38μm, a length of 8mm and a tensile strength of 1600MPa. The hollow microspheres utilised in this study are Sphericel 110P8 and Q-Cel 5070S which were supplied by Potters Industries. Table 2 tabulates the properties of the microsphere products. Only the testing results using 110P8 were presented in this paper.

For each mix design, cylindrical specimens of 100mm diameter x 200mm high were used for compressive testing; rectangular cross sectioned beams of 350mm long x 100mm wide x 50mm deep were used for 4 point bending test. After casting, the samples were covered by the lids and were demoulded after 24 hours, labelled and weighted for various testing. The samples were then placed in a curing chamber at 23±2 ℃ and 100% relative humidity until the day of testing according to AS 1012.8.1-2000.

Table 1. PVA-ECC mix proportions

Sample No.	Cement	75μm-250μm sand	Water	HRWR Superplasti-cizer (%)	PVA fibre fraction Vol. (%)	Sphericel 110P8 (%)
1F0S0	1	0.363	0.25	2.0	0	0
1F1S0	1	0.363	0.25	2.0	1.5	0
1F1S1	1	0.467	0.308	2.0	1.5	10
2F0S0	1	1	0.437	2.0	0	0
2F1S0	1	1	0.437	2.0	2.0	0
2F1S1	1	1	0.456	2.0	2.0	10

Table 2. Specification of hollow microspheres

Names	Density (kg/m^3)	Particle size distribution (μm)	Particle mean size (μm)	Max working pressure (MPa)
Sphericel 110P8	490	5-25	15	68.95
Q-Cel 5070S	430	5-90	35	27.58

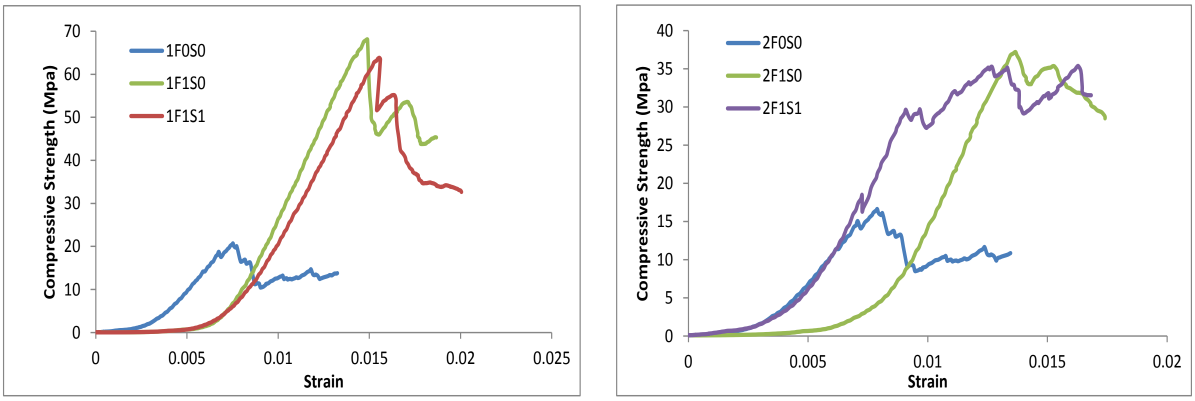
Compressive Testing Setup

Uniaxial compression test for the cylindrical specimens was performed using a universal concrete compression testing machine under a controlled loading rate of 20 ± 2 kN per minute as shown in Figure 1. All specimens were tested until they failed and the results were recorded using a data logging system.

Figure 1. Uniaxial compressive test

Compressive Testing Results

The compressive stress-strain relationship obtained from the compressive testing at 28 days of the two mix designs is shown in Figure 2. In general, 1F series mix design produced a higher compressive strength than 2F series mix design which indicates that a higher ratio of water/cement and aggregate/cement should not be adopted in the mix design for ECC. Although a 0.5% more PVA fibres were added to 2F series, the compressive strength was around 50% lower. The testing results also clearly indicated the significant improvement of compressive strength when only 1.5% of PVA fibres were added to the mix, the compressive strength increased more than 3 times to the normal concrete mix. However, the results also shown that adding 10% of hollow microspheres didn't improve the compressive strength of ECC although the density was reduced around 6%. A scanning electron micrograph (SEM) study of the specimens is undertaken at the moment to investigate if the hollow microspheres were broken during the mixing process.



(a) 1F series (b) 2F series

Figure 2. Compressive stress-strain curve

IMPACT TESTING SETUP AND TESTING RESULTS

As one of the objectives of this research is to investigate if the lightweight ECC developed by the authors will exhibit excellent impact resistance to low and high velocity impacts, the samples made from 1F series mix design were also tested by SHPB. The details are discussed in the following sections.

Split Hopkinson Pressure Bar (SHPB) Testing Setup

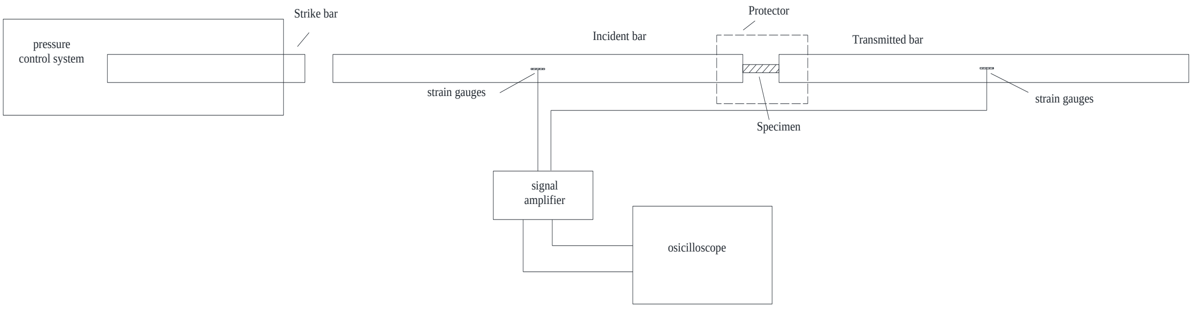


Figure 3. Setup of the Split Hopkinson Bar test

Figure 3 shows the setup of the SHPB test, including pressure control system, strike bar, incident pressure bar, and transmitted pressure bar. The specimen is placed between the incident and transmitted bars. The dimension of the incident and transmitted bars are the same. The length of the bar is 2m long and the diameter is 37mm. The material is steel. By adjust the input pressure, different impact velocities are obtained, varying from 1m/s - 18m/s. Two strain gauges are attached on the opposite side of the bar at the middle of the incident and transmitted bars (1 meter from the end). Then, the strain signals from incident and transmitted bar are collected by using a signal amplifier and oscilloscope. Figure 4 shows the strain signals in the SHPB test. The impact in the SHPB test could induces three elastic stress waves, including incident wave, ε_i, reflected wave, ε_r and transmitted wave, ε_t. The strain gauges on the incident bar can capture the incident and reflected waves while the transmitted wave is collected from the signal at the transmitted bar.

Before the experiment, preparation works are necessary to be carried out, including the alignment of the bars, polish the surface of the bar surfaces to be perpendicular to the loading direction, clean the surface of the bars and check the functional of the strain gauges by conducting bar calibration: bar apart and bar together tests.

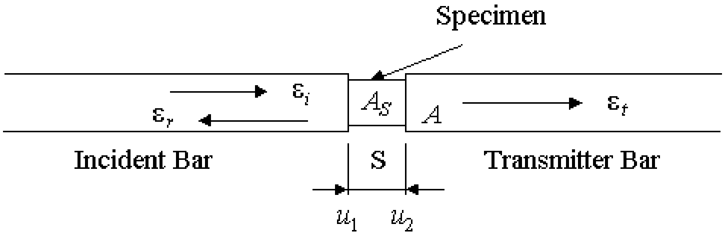


Figure 4. Stress propagation in the SHPB test

Figure 5a shows the strain signals from the incident bar from the bar apart test and Figure 5b shows the strain signals from the incident and transmitted bars from the bar together test.

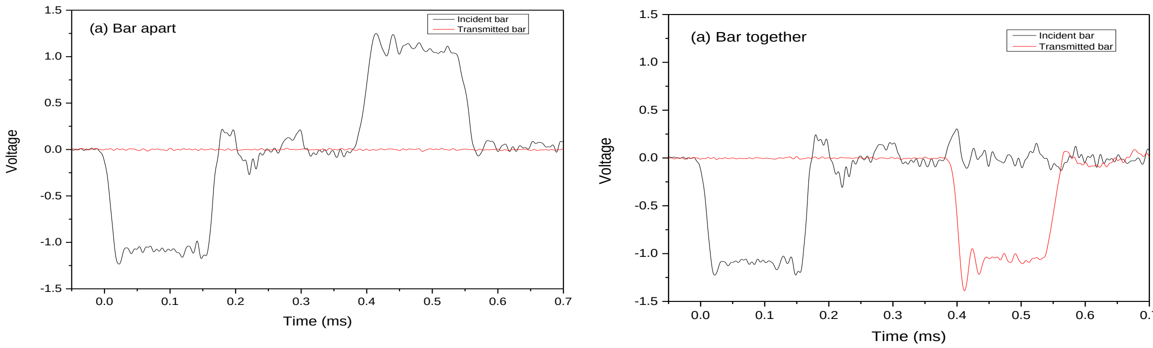


Figure 5. Preparation SHPB test: (a) bar apart test (b) bar together test

Experimental Results

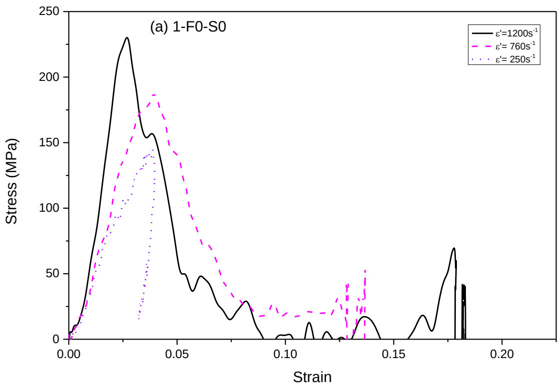
This study employs three different impact velocities 6m/s, 13m/s and 18m/s to investigate the strain rate effect of the concrete material. The diameter of the specimen is the same, 30mm and the length of each specimen varies from 9.6mm to 14.7mm. The strain rate ranged from 250 to 1200 s^{-1}.

Figure 6 shows the stress-strain relationships of the specimens under three different strain rates. In general, the dynamic compressive strength increases with the increase of strain rate. Figure 6a indicates the strain rate influences the normal concrete significantly (i.e. the peak pressure is 150MPa at $\dot{\varepsilon} = 250\text{s}^{-1}$ and it increases to 230MPa at $\dot{\varepsilon} = 1200\text{s}^{-1}$). However, the effect of strain rate is not significant for ECC specimens with 1.5% of PVA fiber (Fig. 6b) and the compressive strength was improved at the low strain rate. Figure 6c shows the stress-strain relationship for the concrete with 1.5% PVA fiber and 10% hollow microsphere. It is found that the strength is almost the same as the normal concrete for low strain rate. The strain rate effect is also very significant. The peak pressure increases to 185MPa when the strain rate increases to 630s^{-1}.

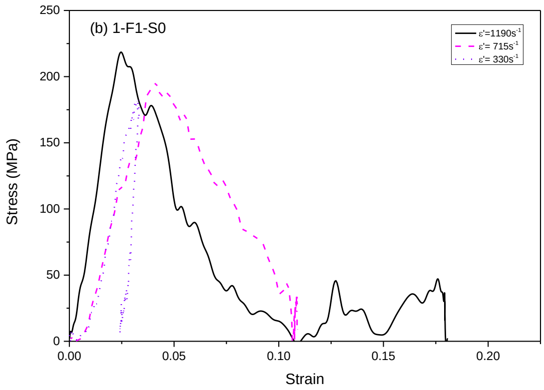
The testing result also shown that the compressive strength was not improved by adding 1.5% of PVA fibre at high strain rate which is similar to previous research on fibre reinforced concrete (Zhang et al. 2007). This may be due to the poor consolidation of concrete when incorporation of fibres.

CONCLUSIONS

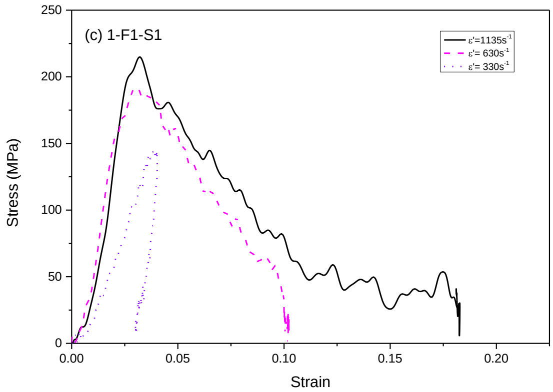
This paper presented the experimental investigation of a newly developed lightweight ECC material by replacing a fraction volume of cement with lightweight hollow microsphere additives. Both uniaxial compressive test and impact test using SHPB were conducted. It is found that the compressive strength increased 3 times for ECC samples with and without hollow microspheres compared to the control mix without PVA fibre under static testing. However, the compressive strength of the samples with microspheres was slightly decreased compared to those without microspheres. The impact test shows that the dynamic compressive strength increases with the increase of strain rate for all samples. However, the compressive strength was not improved for ECC sample which is different to the results of static testing. Further testing is being conducted to investigate the dynamic compressive properties of lightweight ECC.



(a) 1F0S0 (normal concrete)



(b) 1F1S0 (ECC without hollow microspheres)



(c) 1F1S1 (ECC with hollow microspheres)

Figure 6. Stress-strain relationships for SHPB test

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