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Use of hollow glass microspheres and hybrid fibres to improve the mechanical properties of engineered cementitious composite

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HIGHLIGHTS

- Study on producing lightweight ECC construction material was carried out.
- Effect of HGM on mono and hybrids ECC was assessed.
- Energy absorption including first crack energy absorption were measured.
- HGM is a choice to reduce gravity and flowability of ECC products.
- First crack energy absorption increased with using HGM in ECC.

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ABSTRACT

Engineered cementitious composite (ECC) is a well-known high performance cementitious composites for its superior strain-hardening properties and high impact resistance. ECC has been produced using single type of fibre (mono-fibre). However, producing ECC using hybrid-fibre and as a lightweight construction material is in need for investigation. This paper describes the mechanical properties of ECC containing hollow glass microspheres (HGM) and hybrid-fibre consisted of polyvinyl alcohol (PVA) fibre and steel fibre (SF). The variables in this study were the HGM content (0% and 10%) and the hybrid-fibre volume fraction proportions (PVA : SF of 2.0% : 0.0%, 1.75% : 0.25%, 1.50% : 0.50%, and 1.25% : 0.75%). Compressive strength, flexural behaviour, energy absorption including first crack energy absorption were measured for the proposed cementitious composites. This study aimed at developing a new class of ECC with less unit weight, high-energy dissipation and ductility compared to conventional ECC. The results showed that mono-fibre ECC (PVA : SF is 2.0% : 0.0%) had higher compressive and flexural strengths than those showed by hybrid-fibre ECC mixtures. The ratio (PVA/SF) of 3.0 displayed the highest flexural strength compared to other hybrid-fibre ECC. The compressive and flexural strength of ECC was found to decrease with using HGM, although some lightweight ECC matrixes were deemed viable. Enhancements in compressive and flexural strength with further decrease in unit weight were achieved while w/b ratio decreased from 0.56 to 0.45.

1. Introduction

Engineered cementitious composite (ECC) is a high-performance material containing cement, water, fine aggregate, fly ash, chemical admixtures, and discrete fibres. ECC is considered as a high performance fibre reinforced cementitious composite, which is well known for its superior strain-hardening properties, significant ability to absorb high energy, and resist impact shutter compared to the traditional fibre reinforced concrete (FRC) [1,2]. The mono-fibre ECC (or conventional ECC) contains single type of fibre, which is usually polyvinyl alcohol (PVA) fibre; however, hybrid-fibre ECC, is a special type of ECC where it has at least two types of fibre [2]. The performance of ECC basically depends on the fibre characteristics in which the low modulus types of fibre are used, the high interaction between the cementitious matrix and fibres and hence, multiple-cracks that delay the failure and add high ductility to the material [1,2]. The existence of low

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modulus fibres provides bridging actions that leads to prevent main cracks mode of failure and create multiple cracks instead [3].

Low modulus fibres such as PVA, PE, and PP have been recognized to be able to decrease crack width and improve the ductility of cementitious material significantly. However, high modulus fibres such as steel fibre (SF), carbon fibre, and glass fibre have been found to improve the toughness and strength of the cementitious paste, while their intrinsic fragile performance does not let for strain hardening and ductility [2]. It has been found that the application of hybrid-fibres (low modulus fibres and high modulus fibres) with a certain volume fraction can further improve the mechanical properties of the ECC material [4,5]. A simultaneous enhancement in strain and stress is anticipated by the application of hybrid-fibres; thus, it is expected the specimens will have a strong potential to absorb higher energy especially where impact resistance is fundamental in structures subjected to dynamic loading. Therefore, ECC has proven a promising construction material for defensive and protective structures where both strength and ductility are desired for impact resistance since high strength is essential for penetration resistance, and ductility is fundamental for the energy absorption capacity [2].

Limited research was carried out on hybrid-fibre ECC; previous research was conducted on the ratio of low modulus and high modulus fibres to reach an equilibrium between the strain and strength capacity [5]. The cracking behaviour and tensile strain of ECC having SF and PP fibres was investigated by Ahmed and Maalej [6]. The effect of wide range of SF and PP fibres with different lengths, as well as, various contents of sand on the ECC behaviour were studied. It was found that the ultimate tensile strength improved with using combinations of SF and PP fibres. Improvement in multiple cracking performance and increasing in tensile strain capacity were observed by increasing the length of PP fibres. It was also found that increasing the sand contents adversely influenced the multiple cracking behaviours and tensile strength of hybrid-cementitious paste.

The impact performance of hybrid-ECC panels reinforced with 1.5% PE and 0.5% SF was investigated by Maalej et al. [5]. It was found that the strain capacity and scabbing resistance improved with a significant reduction in both damage zone and shutter fragmentation. Hybrid-fibre ECC reinforced with 1.25% PVA fibres and 0.75% SF was used to study the behaviour of the ECC panel under impact load by Bell [7], where gas-gun with the velocity of about 800 m/s was used. The results showed that the hybrid-fibre ECC materials were not as good as the FRC with regard to the impact load, but the enhancement of the energy absorption of hybrid-fibre ECC allowed the specimens to endure intact, while the FRC specimens became unserviceable. Soe et al. [8] recommended that ECC panels with 1.75% PVA and 0.58% SF are promising in restating the high-velocity impact. It was also recommended that PVA and SF with volume proportions of 1.5% and 0.5% respectively can have better behaviour under impact load [1]. From the investigation conducted by Wang et al. [9] on impact performance of concrete reinforced with SF fibre, it was found that the range of SF from 0.5% to 0.75% was the best range for impact resistance whereas fibre content below 0.5% volume showed rupture failure and above 0.75% resulted in fibre pull-out failure. It was also recommended that PVA with a volume fraction of 2% was approved to be able to improve the strain capacity for mono-fibre ECC. The pull-out test was conducted for the ECC material reinforced with 1.5% PVA and 0.5% SF as suggested by Victor et al. [10], and the same proportions of fibres were also recommended to resist dynamic actions [1]. The combination of 1.5% PVA and 0.5% SF has proved excellent to achieve good strength, desirable strain, and molecular bond during the process of the dehydration in the cementitious paste, leading to a dramatic improvement in shutter resistance and ductility of ECC with reduced zone damage, spalling, scaping and fragmentation; such performances are essential in structures subjected to dynamic loading [11,12]. Therefore, PVA was considered as one of the best polymeric fibres and was recommended for the ECC material [13].

Due to the lack of coarse aggregate in ECC material, lower modulus of elasticity is expected; however, a suppression of the most desirable performance (strain-hardening) and accompanying ECC ductility are inevitable when excessive using of fine aggregate. This finding is compatible with conclusions of micromechanical analyses, which found that a critical volume fraction of fibre is related to matrix toughness and interfacial properties [14,15]. A cementitious matrix has elastic modulus and fracture toughness that can be controlled, while fibre has strength, diameter, and elastic modulus. Interfacial zone has frictional and chemical bond and slip-hardening performance. The tailoring process is guided by the theoretical analyses based on micromechanics that quantitatively accounts for interactions between interface, matrix and fibre [16].

Due to the high tensile strain (about 3%) and micro-crack performance with controlled crack width of about 80 μm, ECC offers considerable prospects for durable structures in civil construction fields. ECC material is well known for phenomenon of what called, self-healing of cracked-ECC. In an experimental study [17], coupon specimens of ECC were pre-loaded under tension to certain strain level, and after being exposed to an alkaline environment at a temperature of 38 °C, the specimens were then reloaded under axial tension up to failure. The results showed the reloaded ECC specimens can retain its micro-cracking performance and also considerable tensile strain with a value of 2%, which is 200 times more than that of normal concrete or concrete reinforced with fibre, indicating strong evidence that cracked-ECC can restore its origin stiffness and still provide considerable strain and strength under axial tension. The study brought to light strong evidence of the phenomenon of self-healing that can close the micro-cracks of ECC even when exposed to alkaline for 30 days. In the same study [17], bars of ECC were soaked in alkaline solution; after one month immersing at 80 °C, the ECC bars did not show any length change indicating that pre-cracked and virgin ECC both were durable in spite of high alkaline exposure. Moreover, due to the high-volume content of fly ash in ECC, the alkali silica reaction (ASR) cannot be expected to cause a deleterious expansion. Furthermore, based on a study on long term durability behaviour, ECC proved high ability to resist hot-cold and freeze thaw exposure as well as protect steel reinforcement bars from corrosion. It demonstrated ability to maintain mechanical behaviour over long term and resist fatigue loading [18].

The hollow glass microsphere (HGM) is a controlled dimension hollow space glass material that contains air encapsulated by a thin glass enclosure of sphere [19]. These microspheres look like powder to the naked eye but resemble a ping pong ball when viewed under a microscope, as shown in Fig. 1. The small lid thickness compared to bubbles' diameters is resulting in a lightweight material with an ability to provide advantages for many products. These microspheres are available with different particle sizes and densities, and are also available with the surface coated to be compatible with a wide range of materials such as concrete and construction materials. The material (HGM) with board range densities are also available, and the dominant density ranges from 120 kg/m^3 to 490 kg/m^3, the practical distribution is dependent on the products and the size distribution of 81 μm and less is widely available.

Although the commercial execution of implementing lightweight concrete has long been known, it has been less known that ECC material can be produced as a lightweight construction material while maintaining the unique mechanical properties of ECC. Lightweight construction materials are produced by some widely known procedures such as creating air bubbles into concrete or using lightweight aggregate resulting in density reduced from 2200-2400 kg/