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Development of Engineered Cementitious Composites with Dune Sand

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Abstract

In the last few decades, different studies have been conducted to develop high-performance fibre reinforced cementitious composites (HPFRCCs) exhibiting very high tensile strain. This type of material is designed based on micromechanics principles and is different from conventional concrete as it contains only very fine sand, usually silica sand with maximum aggregate size about 250µm. However, other types and sizes of aggregates have been successfully used to produce HPFRCCs. This study aims to develop ECC, which is a class of HPFRCCs, produced with a replacement of silica sand with dune sand at 0, 50 and 100% by weight. The presence of dune sand was seen to improve the strength of ECC by up to 50% at both early and later ages. The tensile strain at early age also was seen to improve in comparison to the control mix.

Keywords: ECC, Dune sand, Compressive strength, Tensile strength, Ductility.

1. INTRODUCTION

Engineered cementitious composite (ECC) is a group of high-performance fibre reinforced cementitious composites characterised by high ductility in the order of several hundred compared with that of normal concrete. This tensile property exhibited by ECC give it superior energy absorption capacity and impact resistance than ordinary concrete and fibre reinforced concrete (FRC). Unlike other high-performance fibre reinforced cementitious composites, the fibre volume content in ECC is normally not more than 2% Kanda et al (2000) and Li et al (2001). The composites are designed based on micromechanics principle by tailoring the interaction between fibres and cementitious matrix to produce desired tensile properties. In order to achieve good tensile properties, very fine silica sand with average size of 110µm and maximum size of 250 µm is often used Yang et al (2007). So far, the most popular fibre used in the production of ECC is polyvinyl alcohol (PVA) fibre, with length between 6-12mm and a diameter of 39 µm. Although aggregates play a key role in ensuring dimensional stability of cement composites, however, aggregates having a grain size bigger than the average fibre spacing may hinder the dispersion of fibre in the matrix Soroushian et al (1992) and Sahmaran et al (2009) and therefore result in poor fresh and hardened properties of the composites.

In order to produce sustainable ECCs, attempts have been made by different researchers using different types of supplementary cementitious materials Yang et al (2007) and Zhou et al (2010) and also using sand from different sources Sahmaran, et al (2009). This effort has led to the production of greener ECC with more robust tensile properties. For example, it was revealed that increasing the amount of fly ash in ECC led to reduced drying shrinkage, tighter crack width and more robust tensile strain ductility. Dune sand is a resource of very fine natural sand which is formed when blown sand is trapped by non-moving objects such as beach grass. It is one of the most untapped local materials in the construction industry, especially in Australia. The use of dune sand as an alternative to silica sand or river sand will bring benefits to the environment because of the various issues attributed to the mining of river sand and a lot of energy involved in the manufacture of silica sand. Studies have shown that very fine particles of dune sand have two major effects on cement hydration, which include heterogeneous nucleation and Pozzolanic effect. Luo et al (2013) amongst other studies have investigated the effect of dune sand particles on the properties of concrete. They found that dune sand can be beneficial in concrete production provided that sand-cementitious material ratio is less than 1.41. They further revealed that dune sand with a particle size less than 175 μm could affect cement hydration. Regarding the use of dune sand in the production of strain hardening cementitious material, Huang and Zhang (2016) developed a high-performance fibre reinforced cementitious composite with 7-day and 42-day average compressive strengths of 34.9 and 66.4 MPa, respectively. The average tensile strain capacities at 7 and 14 days were 1.96% and 1.22%, respectively.

This study proposes the use of dune sand particles in the development of ECC containing a high volume of fly ash. The strength and ductility properties of the developed ECC are investigated. The utilisation of dune sand, which is a locally sourced material abundant in Australia, will improve the material greenness of the composites.

2. MATERIALS AND METHODS

2.1 Materials

Ordinary Portland cement (OPC) and Class F fly ash were used as dual binders for all mixtures. The OPC complies with the requirements for Type General Purpose cement in Australian Standard AS3972. Silica sand with a maximum particle size of 300 μm and dune sand with a maximum aggregate size of 300 μm were used. High range water reducer (HRWR), MasterGlenium SKY 8100, supplied by BASF chemical company, Australia was used to adjust the workability. All ECC mixtures had a constant water-to-binder ratio (w/b) of 0.26, and fly ash-cement ratio (FA/C) of 1.2. PVA fibres were used at 2% volume fraction for all mixes. The fibres were sourced from Kuraray Co., Ltd, Japan, which is one of the major suppliers of coated PVA fibres for the production of ECC, The ratio of sand to cementitious material was kept at 0.36. Dune sand was added at 0, 50, 100% replacement levels of silica sand to the ECC mixtures. Table 1 summarises the size distributions of dune sand and silica sand used in this study, while Tables 2 and 3 show the properties of PVA fibres and proportions of the ingredients in various mixes respectively.

Table 1. Size distribution of silica sand and dune sand

Sand Type	**<300 (μm)**	**<150 (μm)**	**<106 (μm)**	**<75 (μm)**
Dune sand	100	47	24	10
Silica sand	93.3	67	32	11

Table 2. Properties of PVA fibre

Length (mm)	Diameter (mm)	Strength (MPa)	Young's Modulus (GPa)	Density (g/cm^3)	Elongation (%)
8.00	0.04	1560.00	41.00	1.30	6.00

Table 3. Mix design

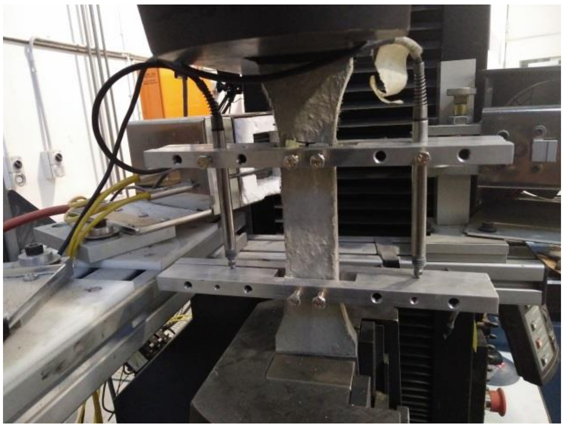
Mix	Cement (Kg/m^3)	FA (Kg/m^3)	Silica sand (Kg/m^3)	Dune Sand (Kg/m^3)	Water (Kg/m^3)	HRWR (Kg/m^3)	PVA (Kg/m^3)
S100D0	571	685	456	-	332	6.8	26
S50D50	571	685	228	228	332	6.8	26
S0D100	571	685	-	456	332	6.8	26

2.1.1 Specimen Preparation and Curing

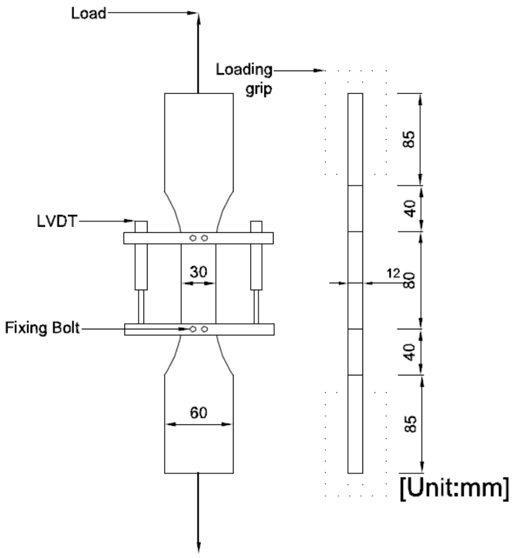
In this study, the mixing was done using a 15L mixer in the Structures Laboratory of Western Sydney University, Australia. Initially, all the solids such as cement, fly ash, silica sand and/or dune sand were mixed together at a low speed for one minute. Subsequently, water and superplasticizer were then added to the dry mix and mixed at a medium speed for one minute and at a high speed for another two minutes. The mortar was inspected to ensure that a uniform state was reached after which PVA fibres were added and mixed at a high speed for three minutes. The total time taken for the mix was seven minutes, where the mixing procedure used by Yang et al (2007) was adopted in this study. The fresh mix was then cast into various moulds and demoulded after 24 hours. After demoulding, the specimens were wrapped in plastics bags and cured under a controlled temperature of 23 ± 2oC and RH of 65 ± 5% until the testing date.

2.2 Methods

Compressive strength tests were conducted using Ø50x100 mm cylinders to determine 3, 7, 28-day compressive strengths using an Instron universal testing machine of 1000 kN capacity. On the testing date, the ends of the cylinders were grinded to ensure both surfaces are flat. The tensile coupon specimens were tested using a servo-hydraulic testing system under uni-axial tension with two external linear variable displacement transducers (LVDTs) attached on both sides of the specimen to measure the specimen deformation as shown in Figure 1(a). The coupon specimen was fixed to the machine with plates glued at both sides of the grip in order to avoid pre-mature failure of the specimen at the grip point. The gauge length used was 80 mm and the testing was done at a displacement control mode at a rate of 0.0025 mm/s to simulate quasi-static loading condition. Coupon dimensions are shown in Figure 1(b), where are recommended by the Japanese Society of Civil Engineers for high-performance fibre reinforced cementitious composites with multiple cracks.



(a)



(b)

Figure 1. Uni-axial tensile test setup (a) and specimen details (b)

3. Results and Discussion

3.1 Tensile Properties

Prior to testing, the tensile coupons were sanded with sandpaper to ensure that the thickness was as uniform as possible. Figure 2 shows the representative 3-day tensile stress-strain curves for the three mixes. In the initial loading stage, all the specimens were seen to experience elastic straining up to the first cracking strength. After that, multiple micro cracks occurred as a result of bridging effects of the fibres with controlled crack width. In contrast, normal fibre reinforced concrete exhibits a localised crack when subjected to axial tension due to their brittle nature. The first crack strength of ECC as shown in Table 4 is predominantly the property of the matrix, which represents the matrix tensile strength. It is found that the first crack strength increases with increasing replacement level of dune sand, proving that the dune sand particles influence the fracture toughness of the matrix. Meanwhile, mix S50D50 with a dune sand replacement of 50% exhibited the highest ultimate strength and strain capacity. This mix has an ultimate tensile strength (σ_{tu}) to first cracking strength (σ_{fc}) ratio of 1.69, which is higher than the corresponding values of S100D0 (1.35) and S0D100 (1.36). The ratio of σ_{tu}/σ_{fc} is one of the critical parameters, determining the saturation of multiple-cracking of ECC. Accordingly, more multiple cracks were observed in mix S50D50, as shown in Figure 3. This is in line with the ECC theory that a specimen exhibits more cracks as the ratio of σ_{tu} /σ_{fc} increases. Figure 3 also shows the crack patterns of the three mixes. As the applied tensile load increased, the number of micro-cracks increased with decreasing distance between adjacent cracks until localised fracture occurred. The local failure was induced when the fibre bridging capability had been exceeded and the distance between neighbouring micro-cracks no longer reduced. The ultimate strain values are consistent with the values reported by Yang et al (2007). But the strain capacity exhibited by the control specimen, S100D0 is 2.4%, which is lower than 3.3-4.6% reported by Yang et al (2007). The reason for this discrepancy could be attributed to the different size distributions of silica sand or the difference in the properties of ingredients used in the two studies. The early age tensile strength was not reported in the same study for comparison.

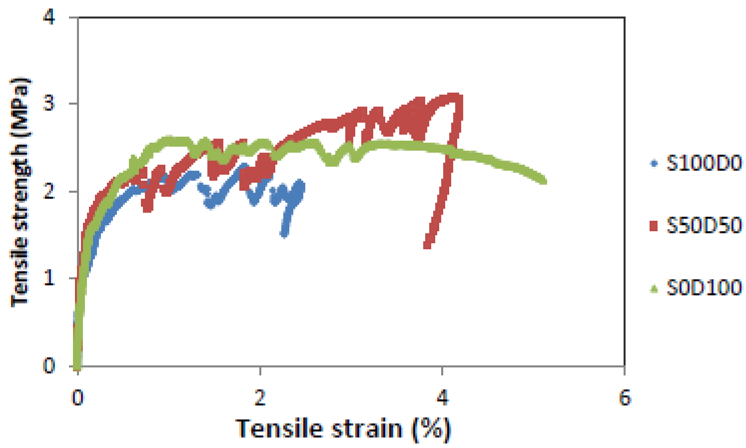


Figure 2. 3-day tensile stress-strain curve for all mixes

Figure 3. Crack patterns of the specimens

3.2 Compressive Strength

Table 5 shows the compressive strength of all the three mixes at different ages. Each representative value of compressive strength is an average of three cylinder tests with a respective standard deviation.

As observed from the values, it can be seen in Figure 4 that the strength increased with age for all the mixes. In addition, specimens with dune sand exhibited higher compressive strength both at early and later ages compared with the control sample S100D0 without dune sand. While S50D50 gained up to 10 MPa in compressive strength between 3 and 7 days, S100D0 only gained 5 MPa. It seems that the presence of dune sand in adequate proportion can catalyse the formation of cement hydration products, thereby improving the strength of the composites The values of compressive strength however were found to be comparable to those reported by Huang and Zhang (2016) for their developed dune sand HPFRCCs, which attained a 7 days and 42 days strength of 34.9MPa and 66.4MPa, respectively. Additional analysis of the strength development in Table 5 reveal that at 3 days, S50D50 and S0D100 attained up to 56.5% and 64.2% respectively of their 28-day compressive strength, whereas the corresponding value for the control sample is only 54.8%. Meanwhile, the 7-day strengths of S50D50 and S0D100 represent 77.3% and 75.9% of the 28-day strengths respectively. Once again, the percentages are higher than the corresponding percentage of 71.9% for the control sample. Thus, it might be concluded that the presence of dune sand influences the early formation of hydration products which leads to higher bonding and compressive strength. Further microstructure analysis is required to confirm this finding. From this investigation, 50% replacement of silica sand by dune sand gave the highest compressive strength at all ages. The 28-day compressive strength is 47.6 MPa for mix S50D50 whilst the corresponding compressive strength is only 29.2 MPa for the control sample S100D0.

Table 4. Compressive strength, MPa of Dune sand ECC with age

Mix	Compressive strength (days)			Strength ratio (%)	
	3	7	28	3/28	7/28
S100D0	15.96±1.35	21.01±1.86	29.2±1.2	54.8	71.9
S50D50	26.93±1.30	36.75±0.62	47.6±3.4	56.5	77.3
S0D100	24.21±1.00	28.62±2.01	37.7±3.8	64.2	75.9

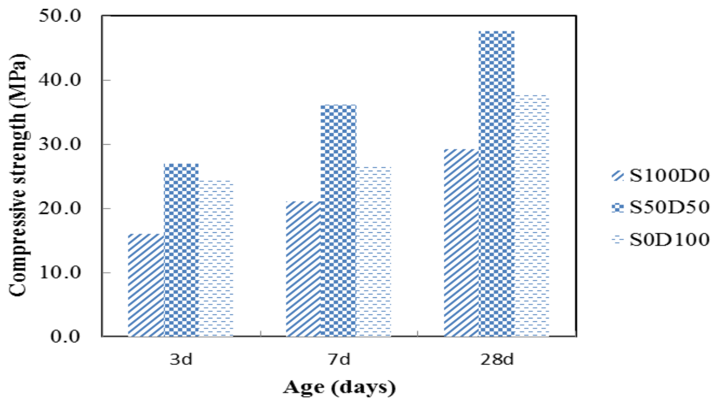


Figure 4. Comparative strength of ECC with age

4. CONCLUSION

Three ECC mixes with different replacement ratios of silica sand with dune sand were developed in this study to demonstrate the feasibility of using dune sand particles to produce ECC. The most common ECCM45 mix was used in this study. Tensile and compressive tests were conducted in order to determine the compressive strength and tensile properties of the developed dune sand composites. It was found that replacement of silica sand with dune sand particles by up to 50% gave better compressive and tensile properties compared to the control sample. This shows that dune sand particles in appropriate proportion could facilitate the formation of cement hydration products and improve the fibre matrix interfacial properties in ECC mixes. However, further research is required to find out the optimised replacement ratio of dune sand, and a microstructure analysis is also required to clarify the influence of dune sand on the mechanical behaviour of ECC.

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