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Flexural performance of green engineered cementitious composites containing high volume of palm oil fuel ash

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HIGHLIGHTS

- ▶ POFA exhibits very promising potential as a supplementary binder for ECC.
- ▶ The POFA–ECCs show acceptable first cracking strength and modulus of rupture.
- ▶ The POFA–ECCs exhibits higher flexural deflection capacity.
- ▶ Higher POFA content reduces the crack width and facilitates the formation of multiple fine cracks in the POFA–ECCs.

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ABSTRACT

The flexural performance of green engineered cementitious composites (ECCs) containing high volume of palm oil fuel ash (POFA) has been investigated. Three sets of ECC mixtures with water–binder ratios of 0.33, 0.36, and 0.38 were prepared, and for each set, the ECC mixtures were proportioned to have varying POFA contents of 0, 0.4, 0.8, and 1.2 from the mass of cement. The flexural performance was assessed after 3, 28, and 90 days of curing using the four-point bending test. The results suggest that there is a corresponding reduction in the first cracking strength and flexural strength of the ECC beams with the increase of water–binder ratios and POFA content. Nonetheless, higher water–binder ratio and higher POFA content was found to concomitantly improve the flexural deflection capacity, which indicates a superior deflection hardening behaviour. Furthermore, number of cracks was increased and crack width of the ECC was significantly reduced with an increase of POFA content. In addition, there are good correlations between flexural deflection capacity from the four-point bending test and tensile strain capacity from the uniaxial tensile test.

1. Introduction

Engineered cementitious composites (ECCs) are designed to have improved ductility and toughness [1]. ECC depends on micromechanical design, and when designed accordingly, ECC exhibits a remarkable tensile strain capacity although it uses only short fibres with a moderate volume fraction of typically around 2% or less [2]. The most important characteristic of ECC is its tensile ductility, with strain capacities ranging from 3% to 7% [3,4]. ECC also exhibits strain capacities 500–600 times higher than normal concrete [5]. Coarse aggregates are eliminated in the mixture design of ECC, resulting in the usage of greater cement content compared with normal concrete. High cement content generally introduces higher shrinkage, heat of hydration, and cost. Moreover, high cement content leads to an increase in greenhouse gases emission, which is highly relevant to global warming. Every ton of cement produced liberates about 1 ton of carbon dioxide [6], and the cement industry is responsible for almost 5% of the total global industrial energy consumption [7]. A reasonable solution for these problems is via the substitution of larger portions of the cement in ECC with industrial wastes or by-products as supplementary cementitious materials without sacrificing its mechanical properties in general, particularly its ductility. Palm oil fuel ash (POFA) is one such material that has good potential to be used as partial cement replacement for concrete.

POFA is a by-product of burning fibres, shells, and empty fruit bunches of palm trees as fuel for heating boiler to produce steam for electricity generation in palm oil mills [8–10]. Large amounts

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Table 1
Mixture proportions of ECCs.

Mix ID	C/C	S/C	w/b	POFA/C	SP/C	HPMC/C	Fibre	28-Day compressive strength (MPa)
Ma1	1	0.8	0.33	0	0.022	0.001	0.02	39.52
Ma3	1	0.8	0.33	0.4	0.022	0.001	0.02	40.55
Ma5	1	0.8	0.33	0.8	0.025	0.001	0.02	39.21
Ma6	1	0.8	0.33	1.2	0.03	0.001	0.02	37.30
Mb1	1	0.8	0.36	0	0.019	0.001	0.02	37.35
Mb3	1	0.8	0.36	0.4	0.019	0.001	0.02	39.83
Mb5	1	0.8	0.36	0.8	0.021	0.001	0.02	36.53
Mb6	1	0.8	0.36	1.2	0.027	0.001	0.02	32.82
Md1	1	0.8	0.38	0	0.015	0.001	0.02	36.65
Md3	1	0.8	0.38	0.4	0.018	0.001	0.02	35.60
Md5	1	0.8	0.38	0.8	0.02	0.001	0.02	31.91
Md6	1	0.8	0.38	1.2	0.025	0.001	0.02	30.02

of POFA are generated annually in Malaysia as well as Thailand, and the amount is expected to increase annually. POFA is not toxic in terms of heavy metal leachability [11]. In addition, since the ash does not have sufficient nutrients to be used as fertilizer, POFA is dumped in open fields near palm oil mills without any commercial gain. Several studies have found that POFA has pozzolanic properties [12–16]. The partial replacement of Portland cement (PC) with POFA can lower the production costs, as well as improve the engineering properties and durability of concrete. A recent study [17] has shown that refined POFA with smaller particle size and lower unburned carbon content could enhance the engineering and transport properties of high strength concrete even at high POFA content of 60%. Furthermore, the utilization of POFA in particular in high volume can increase the eco-friendliness and greenness of concrete, contributing to a healthier and more sustainable environment.

The flexural properties of cement-based materials are dependent on their tensile characteristics [18,19]. In particular, the flexural response of ECC reflects its tensile ductility [19,20]. Under bending moment, multiple cracking forms at the moment zone of the beam, allowing it to undergo a large curvature development [21,22]. Thus, higher flexural strength (modulus of rupture, MOR) of ECC is achievable and it occurs to a large extent in the deflection hardening regime. Deflection hardening is an essential property of ECC and it does not rely on geometry [2]. Hence, flexural characteristic is an important part of the overall performance of ECC.

In the present study, a four-point bending test (flexural test) was performed on ECCs containing different proportions of treated POFA with water–binder ratios (w/b) of 0.33, 0.36, and 0.38 to assess the flexural performance of the POFA–ECCs. The investigation focused on the effects of the treated POFA contents and water–binder ratios on the first cracking strength, MOR, flexural deflection capacity, and quantity as well as width of cracks. Furthermore, the study also explored the potential relationship between flexural deflection capacity and tensile strain capacity.

2. Experimental program

2.1. Materials

The mix proportions of the ECCs with three different water–binder ratios are given in Table 1, together with the average 28-day compressive strength. The cement used was ASTM Type I cement with a specific gravity of 3.14 and Blaine surface area of 340 m^2/kg. Silica sand was used as fine aggregates with an average and maximum grain sizes of 110 μm and 200 μm, respectively. POFA was collected from a near-by palm oil mill and it was first dried in an oven at 100 °C for 24 h and then sieved using a set of sieves (3 mm, 600 μm, and 300 μm) to remove unburned fibres or shells that are coarser than 300 μm. The ash was then ground using a ball mill to reduce the particle size in order to improve its reactivity; the resulting POFA is designated as ground POFA. Chandara et al. [23] found that glassy phase crystallization and agglomeration of ground POFA particles did not occur during heat treatment at 500 °C. Thus, the POFA was heated at 450 °C for 1.5 h to remove unburned carbon and at the same time to prevent glassy phase crystallization as well as particle agglomeration which could affect its pozzolanic properties. The median particle sizes of the untreated and treated POFA were approximately 2.87 μm and 2.99 μm, respectively. This condition proves that the heat treatment did not result in unnecessary agglomeration of particles (Fig. 1). The specific surface area of the treated POFA was approximately 620 m^2/kg. The chemical compositions of the Type I cement, silica sand, and treated POFA are tabulated in Table 2. An ASTM C494 Type F high-range water-reducing admixture and a dry viscosity enhancing agent, hydroxypropylmethylcellulose (HPMC) were used to modify the workability and to achieve consistent rheological properties in the fresh matrix for better fibre distribution. Polyvinyl alcohol (PVA) fibre was used at a moderate volume fraction of 2%. The physical and mechanical properties of the PVA fibre; REC15 × 8 (Kuraray Co. Ltd., Japan) are listed in Table 3. The fibre was surface-coated with oil (1.2% by weight) to reduce the fibre/matrix interfacial bond strength [24].

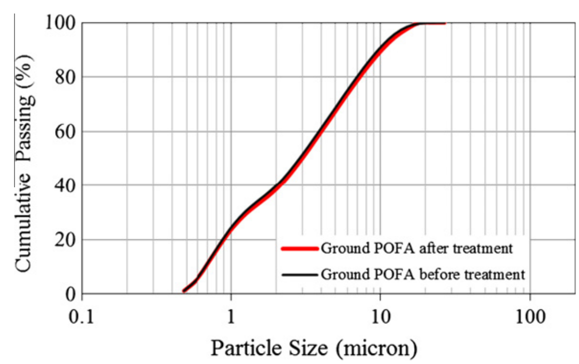

Fig. 1. Particle size distribution curves of ground POFA, before and after treatment.

2.2. Test methods

2.2.1. Four-point bending test

In order to investigate the influence of POFA inclusion and water–binder ratio on the flexural performance of the ECCs, four-point bending tests were carried out on a number of beams. The beam specimens were cast in Plexiglas moulds. After casting, they were allowed to harden at room temperature (27 ± 3 °C) for 24 h prior to demoulding, and then cured in sealed plastic bags at room temperature for an-

Table 2
Chemical compositions of type I cement, silica sand, and treated POFA.

Chemical constituents (%)	Type I cement	Silica sand	Treated POFA
Silicon dioxide (SiO_2)	20.90	99.2	66.91
Aluminium oxide (Al_2O_3)	5.27	0.02	6.44
Ferric oxide (Fe_2O_3)	3.10	0.01	5.72
Calcium oxide (CaO)	62.80	–	5.56
Magnesium oxide (MgO)	1.52	–	3.13
Sodium oxide (Na_2O)	0.16	–	0.19
Potassium oxide (K_2O)	0.63	–	5.20
Sulphur oxide (SO_3)	2.73	–	0.33
Phosphorus oxide (P_2O_2)	0.13	–	3.72
LOI	0.87	–	2.30