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Influence of different types of polypropylene fibre on the mechanical properties of high-strength oil palm shell lightweight concrete

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HIGHLIGHTS

- Polypropylene fibres enhanced the strength of oil palm shell lightweight concrete.
- PPTB1 of 0.5% fibre produced the highest compressive strength.
- Addition of 0.5% PPTB1 fibre achieved the highest tensile strengths.
- The highest residual compressive strength was found for 0.5% PPTB1 fibre.

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ABSTRACT

This study aims to investigate the use of various polypropylene (PP) fibres with different aspect ratio and geometry to enhance the mechanical properties of oil palm shell fibre-reinforced lightweight concrete. The volume fractions (V_f) of 0.25%, 0.375% and 0.5% were studied for each fibre. As various PP fibres were added into oil palm shell fibre reinforced concrete, the marginal density reduction was reported. The effectiveness of new types of PP fibres to increase the compressive strength at later ages was more pronounced than at early age. It is found that low volume fractions of polypropylene twisted bundle (PPTB) fibres are more effective in improving the flexural strength of OPS concrete compared to its splitting tensile strength. The average modulus of elasticity (E value) is obtained to be 13.4 GPa for all mixes, which is higher than the values reported in previous studies. An increase in the percentage third load compressive strength of 0.5% PPTB fibre of up to 11% was reported. Hence, this new types of PP fibres is a promising alternative solution to compensate lower mechanical properties for lightweight concrete.

1. Introduction

The current state of the structural lightweight aggregate concrete industry was born out of realization of sustainable construction. Development of sustainable structural lightweight concrete construction using oil palm shell (OPSLWC) is due to the density limit of 2000 kg/m^3 [1]. The utilization of industrial and agricultural waste materials can be a breakthrough to make the industry more environmentally-friendly and sustainable. It has led to green and sustainable construction to improve the environmental friendliness of concrete by reducing the cost of construction materials and waste management. The utilization of waste materials, such as natural pumice, vermiculite, shale, slate, oil palm shell (OPS), fly ash, ground granulated blast furnace slag (GGBFS), silica fume, recycled concrete, recycled tyres, and recycled plastics, have been successfully used in concrete [2–4]. Recently, a large amount of lignocellulosic wastes OPS is generated due to the increasing number of plantations of oil palm trees in Malaysia, Indonesia, and Nigeria [5]. This waste is considered as one of the potential lightweight aggregate (LWA) in the development of lightweight aggregate concrete (LWAC). It is reported that Malaysia contributed some 18.79 million tonnes of crude palm oil on approximately 5 million hectares of land [6], making it a major producer of palm oil. Calculations show that 1.1 tonnes of shells, or 5.5% of the weight of the fresh fruit bunch, is produced annually from each hectare cultivated. There are many advantages of using OPS, especially when the material cost is minimized by utilizing the waste OPS aggregate in construction. These include savings in reinforcement, scaffolding, formwork and foundation costs. Furthermore, such concrete can be used for heat insulation, sound absorption, better fire resistance, superior anti-condensation properties and increased damping [7].

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Air-dry density of oil palm shell concrete (OPSC) varies in the range of 1868–1988 kg/m^3 with a corresponding 28-day compressive strength of more than 40 MPa [8–13]. In a past studies, the enhancement of mechanical properties of OPSC is dependent on the density, aggregate content, crushed or uncrushed particle size of OPS and heat treatment on OPS aggregate [8–10]. Other factors include water-cement ratio and incorporation of cementitious materials (silica fume, fly ash and ground granulated blast furnace slag). The influence of density on the compressive strength of OPSC can be observed from previous studies [8–13]. Alengaram et al. [14] showed that with a density of about 1900 kg/m^3, a compressive strength of 37 MPa with the addition of silica fume (SF) can be produced. However, Yew et al. [10] reported that heat treatment on OPS aggregate, having a density of about 1945 kg/m^3 achieved compressive strength of 49 MPa. Furthermore, Shafigh et al. [8,9] have successfully produced compressive strength of up to 53 MPa for a density of about 2000 kg/m^3. It is generally known that, high compressive strength of LWAC results in brittleness and weak in tensile strength [15] and the density of LWAC is limited to 2000 kg/m^3 [1]. As a result of these characteristics, LWAC could not support normal stresses and impact loads, where tensile strength is approximately one tenth of its compressive strength. It can be seen from recent research that, OPSLWAC can be reinforced with discontinuous (steel, polypropylene and nylon) fibres to overcome high potential tensile stresses and shear stresses at critical location in OPSLWC member [16–19]. However, the main disadvantage of adding steel fibres into OPSLWC in fresh state is its significant reduction in slump value and increased density. Furthermore, the inclusion of polypropylene and nylon insignificantly increased the mechanical properties of OPSC, particularly for the tensile strength [17]. One innovative method to improve the mechanical properties of OPSC without reaching the density limit is an addition of a new type of non-metallic fibre namely polypropylene twisted bundle (PPTB).

This study is to access the effects of different types of PP fibre and aspect ratio at various volume fractions of 0.25%, 0.375% and 0.5% on mechanical properties of OPSC. The beneficial effects of new types of PP fibres are considered in the investigation on fibre-reinforced oil palm shell concrete (FROPSC). To the best of the authors' knowledge, so far there are no reports on the effects of the different geometries (lengths and shapes) of PP fibres on the properties of OPSC incorporating fibres. In this study, the mechanical properties of OPSFRC containing fibres at three different percentages is evaluated and reported. The primary objective of this study is to investigate the effects of PPTB fibres at various volume fractions on the compressive strength of OPSFRC. The effects of different PP fibres on the splitting tensile strength, flexural strength, modulus of elasticity and residual compressive strength (RCS) are also investigated.

2. Experimental details

2.1. Materials

2.1.1. Cement

The cement used in this study was ASTM type I ordinary Portland cement (OPC) [20] with a specific gravity of 3.14 g/cm^3 and Blaine's specific surface area of 3510 cm^2/g. The chemical compositions and physical properties of the OPC are given in Table 1. A cement content of 520 kg/m^3 was used for all mixes.

2.1.2. Mineral admixture

Silica fume (SF) is available in dry powder form and is procured from ScancemMaterials Sdn Bhd, Kuala Lumpur. The light gray, under the product name "Scancem" is available in 20 kg bags. The SF procured by the company satisfies all the requirements of the International Standards; ASTM C1240 [21] and AS 3582 [22]. The amount of densified SF at 5% of the cement weight was added as additional mineral admixture to enhance the mechanical properties of concrete.

Table 1
Chemical composition and physical properties of OPC.

Chemical composition (%)						Physical properties		
SiO_2	Fe_2O_3	CaO	MgO	Al_2O_3	SO_3	LOI	Specific gravity	Blain specific surface area (cm^2/g)
21.28	3.36	64.64	2.06	5.60	2.14	0.64	3.14	3510

2.1.3. Water and superplasticizer (SP)

Potable water to binder (w/b) ratio of 0.30 was used for all mixes. The SP used in this study was polycarboxylic ether (PCE) supplied by BASF, and complies with the ASTM C494/C494 M [23] specifications. The amount of SP was kept constant at 1.0% of the cement weight in order to improve workability.

2.1.4. Aggregate

Local mining sand was used as the fine aggregate. The specific gravity, fineness modulus, water absorption and maximum grain size were found to be 2.68 g/cm^3, 2.72, 0.97% and 4.75 mm, respectively. A sand content of 960 kg/m^3 was used in all mixes.

Old OPS were used as the coarse aggregate in this study, indicating that they had been discarded for more than six months. The old OPS were collected from a local crude palm oil producing mill. The percentage of fibres for old OPS (less than 2%) has been selected as an aggregate, which improves contact between the mortar and OPS grains and thus increases the compressive strength of the concrete. The advantages of using this aggregate in OPS concrete were reported by Shafigh et al. [8]. The OPS were washed and sieved using a 12.5 mm-sieve. The OPS aggregates retained in the sieve were collected and subsequently crushed using a stone-crushing machine in the laboratory. The crushed OPS aggregates were sieved using a 9.5 mm-sieve to remove OPS aggregates with sizes greater than 9.5 mm. The OPS aggregates were heat-treated at 60 °C over a period of 0.5 h using a temperature-controlled laboratory oven. Once cooled to room temperature, they were weighed under dry room conditions and immersed in water for 24 h. Due to the high water absorption of OPS, it was subsequently air dried in the laboratory to attain a saturated surface dry (SSD) condition before mixing. The difference in quality of the OPS surface between heat treatment and without heat treatment condition was reported by Yew et al. [10] and shown in Fig. 1. The OPS content was set constant at 330 kg/m^3 for all mixes. The physical properties of the OPS used, are shown in Table 2.

2.1.5. Fibres

The properties of different type of PP fibres are presented in Table 3. The three types of PP fibres are (i) polypropylene twisted bundle 1 (PPTB1); (ii) polypropylene twisted bundle 2 (PPTB2) and (iii) straight polypropylene 1 (PPS1), respectively, as tabulated in Table 3.

2.2. Mix proportions

The proportions used for all mixes as described in Section 2.1. The volume fraction (V_f) of the fibres added to the concrete mix typically ranges from 0.1% to 3.0% [24]. It is noted that fibres with a high V_f tend to 'ball' in the mix and create workability problems. Therefore, low volume fractions ($\leqslant$0.5%) were used for the PP fibres in this study. The volume fraction of the PPTB fibres was set as 0%, 0.25%, 0.375% and 0.5%. The amount of water and superplasticizer was kept constant for all mixes.

2.3. Test methods

The procedure used to mix the fibre reinforced concrete is detailed as follows. Firstly, the OPS and sand were poured into a concrete mixer and dry mixed for 1 min. Following this, the cement was spread and dry mixed for 1 min. The fibres were then distributed and mixed for 3 min in the mix, based on the volume fraction specified above. Water and superplasticizer were then added with a mixing time of 5 min. Slump test was carried out prior to casting the specimens. The concrete specimens were cast onto oiled moulds and a poker vibrator was used to decrease the amount of air bubbles in the mix. For each mixture, 150 mm × 150 mm × 150 mm cubes were used to study the compressive strength and ultrasonic pulse velocity (UPV) at 1, 3, 7, 28, 56 and 90 days. Two cylinders (diameter: 150 mm, height: 300 mm) were used to examine the modulus of elasticity. Three cylinders (diameter: 100 mm, height: 200 mm) and three prisms of 100 mm × 100 mm × 500 mm were used to examine the 28-day splitting tensile strength and 28-day flexural strength, respectively. The specimens were demoulded approximately 24 ± 2 h after casting. The compression testing machine used was an ELE (Engineering Laboratory Equipment) with a load capacity of 3000 kN running of 3.0 kN/s in accordance to BS EN 12390-3:2009 [25]. Furthermore, RCS involves reloading the cube specimens for further 3 cycles after reaching maximum value, the failure in the compression test setting at 15% to ascertain the corresponding RCS.