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The effect of steel fibres on the enhancement of flexural and compressive toughness and fracture characteristics of oil palm shell concrete

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HIGHLIGHTS

- Addition of 1.0% steel fibre enhanced the flexural toughness of OPSC by up to 16 times.
- Compressive toughness improved by 6 times with 0.75% of steel fibre in SFOPSC.
- Fracture toughness and fracture energy increased with the addition of steel fibres.
- Direct tensile strength increased up to 41% with the addition of 1.0% steel fibre.

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ABSTRACT

This effect of steel fibre on the toughness characteristics such as flexural toughness, fracture parameters and compressive toughness of steel fibre oil palm shell concrete (SFOPSC) is described in this paper. In the post-peak regions of the bending specimens, the addition of steel fibres significantly increased both the fracture energy and flexural toughness of the SFOPSC up to 16 times. The compressive toughness of SFOPSC specimens with 0.75% steel fibre of about 864 kN mm was 6 times higher than the specimens without fibres. The pre-peak response through the mechanical property tests shows an increase of up to 178%, 88% and 41% for splitting tensile, flexural and direct tensile strengths, respectively.

1. Introduction

Oil palm shell (OPS) is considered as a waste material produced from the extraction of palm oil in South East Asian countries, such as Indonesia, Malaysia, and Thailand. Most of the wastes that emanate from the production of palm oil are dumped in the vicinity of the factories. The excessive dumping of these wastes including OPS leads to pollution in the surrounding environment. Research works on utilizing the oil palm wastes such as OPS, palm oil fuel ash (POFA) and palm oil clinker paved way to develop sustainable materials. The utilization of OPS as lightweight coarse aggregates resulted the development of structural grade lightweight oil palm shell concrete (OPSC) with a reduction in the density of about 15–33% [1–3] compared to the normal weight concrete (NWC) of density of about 2400 kg/m^3. Thus the reduction of concrete density significantly increases the strength to density ratio of the concrete; this allows the design flexibility of structural members and further reduces transportation and fabrication costs.

The cube compressive strength of the OPSC varies in the range of 15–45 MPa; however, one of the shortcomings of the OPSC is the low tensile strength. As known, most of the lightweight aggregate concrete is inferior in the tensile strength [4] as well as higher brittleness compared to NWC of the same strength [5–7]. Recently, Shafigh et al. [8] have researched on enhancing the compressive strength of OPSC by varying the size of the OPS and developed high strength OPSC with a cement content of 550 kg/m^3. The increase in the compressive strength, however, will be offset by the increased brittleness of the concrete [6–10]. The brittleness of concrete is more prone towards catastrophic failure that occurs without much warning, and could be hazardous to the surroundings. In addition, the OPSC has a relatively low modulus of elasticity [4,9,11] compared to NWC which might lead to acceleration of crack development [12]. The cracks in concrete provide easy routes for deleterious agent and that could lead to durability issues. The

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addition of fibres in the concrete enhances both the tensile strength and the ductility of the concrete.

It has been reported that the addition of specified quantity of steel fibres is known to increase the tensile capacity of the fibre reinforced concrete (FRC) along with its post-failure ductility [13–15]. The post-failure ductility is extremely useful in cases where tensile strength is not adequate to characterize the mechanical response of concrete [16]. After the cracking of matrix, the steel fibres function as a crack bridging mechanism, in which the fibres undergo fibre pull-out, thus delaying the crack formation and limit the crack propagation [17,18]. De-bonding and pulling out of fibres from FRC require higher amount of energy, resulting in the increased toughness and ductility of concrete. Since the toughness characteristic is essential for FRC, codes of practice in some countries incorporated this aspect to measure this property. The commonly used codes of practice for the measurement of flexural toughness tests of FRC are ASTM C1018-92 and JCI SF-4 and these are widely reported in literatures [5,19–21]. However, the toughness indices as proposed in these standards have been questioned as these are not material properties [22].

On the other hand, the fracture behaviour of concrete is the fundamental to understand the basics of reinforced concrete structures through the application of fracture mechanics. One of the vital fracture properties for the design of concrete structures is the fracture energy (G_f) and this is the most accepted and commonly used in numerical models [23]. Another characteristic namely, fracture toughness (K_{ic}) has also been found to be a fracture mechanics parameter to describe the resisting property of concrete to cracking [24].

There have been many research works carried out on the mechanical, thermal, durability and structural behaviour of OPSC [9,25]. In addition, a low cost house along with a foot bridge constructed using OPS as a lightweight aggregate in Malaysia is being monitored for structural performance [26]. A low aggregate impact value (AIV) implies high resistance to impact. Thus, owing to its high impact resistance, OPS could be used in road blocks, crash barriers, etc. In addition, pavement blocks, drain culverts, etc. are some other possible applications. Research works on potential structural application of OPSC in reinforced concrete beams and impact-resistant panels had been carried out. Alengaram et al. [27] reported that the ductility of reinforced OPSC beam was about 2 times higher than the corresponding reinforced NWC beam; Mo et al. [28] investigated the impact resistance of OPSC panels due to the improved AIV of OPS compared to conventional granite aggregates; the AIV of the OPS was found 2 times lower than the crushed granite aggregate. In order to promote the potential application of the OPSC, the structural behaviour with respect to fracture behaviour needs to be investigated. Thus the study on the influence of steel fibre in OPSC (SFOPSC) would pave way in understanding the material properties, toughness and fracture energy of the concrete for further application.

In this investigation, the relationship of steel fibre content and post crack toughness as well as the mechanical properties of SFOPSC is investigated and reported. In addition, the post-crack response of SFOPSC with varying steel fibre content (0–1.0%) was also compared through flexural toughness test; the fracture parameters of SFOPSC are quantified via a fracture energy test. Another aim of this investigation on the emphasis of a greener and sustainable concrete through 50% replacement of ordinary Portland cement (OPC) using ground granulated blast furnace slag (GGBS) as binder for all the SFOPSC mixes. The comparison of the mechanical properties between the OPSC with 100% OPC and OPSC with a replacement of 50% OPC replacement through GGBS is also analysed and reported.

Table 1
Physical properties of OPS.

Physical properties	OPS
Specific gravity (saturated surface dry)	1.30
Bulk density (compacted) (kg/m^3)	635
Bulk density (loose) (kg/m^3)	538
Water absorption (24 h) (%)	24.4

2. Experimental program

2.1. Materials

2.1.1. Binder

Ordinary Portland Cement (OPC) with specific gravity and specific surface area of 3.10 and 352 m^2/kg, respectively was used in all mixes. The ground granulated blast furnace slag (GGBS) supplied by YTL Cement Sdn Bhd was used as partial cement replacement; the specific gravity and specific surface area of the GGBS used was 2.90 and 405 m^2/kg, respectively.

2.1.2. Aggregates

Manufactured sand passing through 5 mm and retained on 300 μm was used as fine aggregate. OPS with specific gravity of 1.30 were used as coarse aggregates, with size ranging between 2.36 and 14 mm. The OPS collected from a local crude palm oil mill were washed, air-dried and used in saturated surface dry (SSD) condition. Physical properties of OPS are listed in Table 1.

2.1.3. Superplasticizer and water

A polycarboxylic-ether (PCE) based superplasticizer (SP), commercially known as Glenium Ace 388 and supplied by BASF (Malaysia) Sdn Bhd was used to reduce the water and enhance the workability of the mixes. Potable water, free from contaminants and impurities was used for mixing.

2.1.4. Steel fibre

Hooked-end type steel fibres of length 60 mm with aspect ratio of 80 were used as steel fibres with high aspect ratio were reported to have better flexural performance [29]. The steel fibres used had minimum tensile strength of 1100 MPa as specified by the manufacturer.

2.2. Mix proportion and procedure

A total of five mixes were prepared with binder: water: sand: aggregate ratio of 1:0.33:0.65:1.70 for all mixes. The binder content was fixed at 550 kg/m^3 with 50% GGBS replacement (by mass) used for K series mixes (K1, K2, K3 and K4) while 100% OPC was used for mix N1. The steel fibre content was varied at 0% (K1), 0.5% (K2), 0.75% (K3) and 1.0% (K4) volume fractions. The SP used in all the mixes was kept constant at 1.0% by mass of binder.

The OPS and manufactured sand were mixed in the rotary drum mixer for about 3 min, followed by the addition of OPC and GGBS for another 6 min. After the addition of mixing water along with the SP, the mixing was continued for another 8 min. Finally, steel fibres were evenly distributed into the mixture and mixed. The concrete was then poured into moulds and compacted. All the specimens were demoulded after 24 h and moist cured until the day of testing. The testing plan was presented in Table 2.

2.3. Test methods

2.3.1. Mechanical properties

The mechanical properties tests on compressive strength (BS EN 12390-3: 2002), splitting tensile (BS EN 12390-6: 2009) and flexural strength (BS EN 12390-5: 2009) tests were performed on 100 mm cube, 100 mm ϕ × 200 mm height cylinder and 100 mm × 100 mm × 500 mm prism at the age of 28-day respectively. The static modulus of elasticity test was conducted on 150 mm ϕ × 300 mm height cylinders at the age of 28-day based on ASTM C469-10. In addition, the compressive strength test results performed at the ages of 1-, and 7-day are reported.

2.3.2. Direct tensile test

The direct tensile test was performed based on RILEM TC 162-TDF. In this modified test, notched specimen with 100 mm ϕ and 200 mm height cylinder was used (Fig. 1). The depth of the notch was sawn to 7.5 mm in order to ensure the failure occurred in the mid-section of the specimen. The effective cross-sectional area was therefore reduced from 7854 to 5675 mm^2. In the report by Barragan et al. [30], no significant influence of geometry characteristics of the test specimen was noticed in the direct tensile test.