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# Torsional behaviour of steel fibre-reinforced oil palm shell concrete beams

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ABSTRACT

The increasing demand for curved structural members has prompted an increase in the research on the torsional behaviour of concrete. Recently, oil palm shell (OPS) has received considerable attention as a material that enables the production of sustainable lightweight concrete. This work investigated the effects of steel fibre of 0.25%, 0.50%, 0.75% and 1.00% volume fractions on the mechanical properties and torsional resistance of OPS concrete (OPSC) and OPS fibre-reinforced concrete (OPSFRC) beams. The experimental results showed that the increase in fibre content resulted in better mechanical properties and torsional resistance of OPSFRC. The compressive, splitting tensile and flexural strengths of OPSFRC with 1% steel fibres were found to be 40%, 110% and 150%, respectively, higher than the control mix. The crack bridging effect also improved the pre-cracking and post-cracking torsional behaviour of OPSFRC. The highest cracking torque, ultimate torque, twist at failure and torsional toughness of 8.3 kNm, 8.5 kNm and 1.31 kNm/m were obtained for the mix with 1% steel fibre. Moreover, the crack arrest ability of the steel fibre reduced the primary torsional crack widths and formed multiple fine cracks. Further, a simplified torsional model is proposed to predict the torsional behaviour of OPSC and OPSFRC.



## 1. Introduction

The advantages of using lightweight concrete (LWC) in structures contributed to rapid growth in developed countries and its impact has encouraged many researchers to utilize local materials in the development of LWC in developing countries including Malaysia. One of the most significant advantages of LWC is its density reduction relative to the normal weight concrete (NWC). The decreased density of LWC could lead to a lower self-weight of the LWC members, which, ultimately, allows for greater design flexibility and cost savings [1]. Improved fire and frost resistance, heat and sound insulation and earthquake damping properties are also among the benefits of LWC [2]. In the production of green and sustainable concrete, lightweight aggregate originating from waste materials, such as foamed slag, pumice, expanded clay, expanded shale, sintered pulverized fuel ash and oil palm shell (OPS) played vital role [3]. The overuse of granite aggregates in construction is well documented and hence the benefit of utilizing these wastes, as partial or whole replacement for conventional crushed granite aggregate would not only lead to ecological balance but also sustainable material.

Among the above-mentioned lightweight aggregates, many researchers focussed on the usage of OPS in the development of LWC in Malaysia during the last decade including the latest trend of geopolymer concrete [1,4]. The rapid development of oil palm shell concrete (OPSC) as LWC can be attributed to the annual generation of over 4 million tons of OPS as waste from the vast palm oil plantations in Malaysia [1]. The lightweight OPS has much lower bulk density and higher impact resistance compared to the granite aggregate [3]. Published studies on OPSC have shown that the density and compressive strength of OPSC could achieve up to 48 MPa and 1600–1960 kg/m$^3$, respectively [1]. The other notable concern of OPSC is its durability due to the organic origin of OPS. However, it was reported that when OPS is cured in water, the durability performances in terms of water permeability and water absorption of the OPSC was comparable to other LWCs [5] and that there was no retrogression in the long-term compressive strength over the age of 365 days [6]. Moreover, the OPSC beams exhibited comparable flexural and shear behaviour, compared to the NWC. A larger deflection at near maximum load indicated that the ductile behaviour of the OPSC beams could provide ample warning before total collapse, and the narrower cracks in the OPSC beams showed that the good aggregate interlock of OPSC resulted in its good cracking resistance [7,8]. The performance of OPSC also demonstrated that OPS has high potential as a replacement for crushed granite aggregate in the development of LWC.

Most LWCs are brittle and weak in tensile strength compared to NWC [3,9]. In the case of OPSC, this is evident from the low splitting tensile strength of only about 2.2–2.6 MPa [2,8]. The low tensile strength of OPSC could lead to significant tensile cracking occurring at a much lower loading capacity. This might limit the application of OPSC as structural members with special applications, such as high tensile, torsion, impact, blast loaded members. Therefore, the enhancement of the

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mechanical properties becomes the prime objective in recent studies on OPSC in order to endorse OPSC as a viable concrete in structural members.

There had been few studies on the enhancements to address the low mechanical properties of OPSC include pre-treatment coating of OPS [10]; the addition of cementitious materials, such as fly ash and silica fume [11,12]; crushing of OPS [13,14]; and addition of fibre [2,3,9, 15–17]. Among these methods, the addition of fibre in OPSC outperformed the other methods by producing a remarkable improvement in the mechanical properties, toughness, ductility and impact resistance. Among the various types of fibre, steel fibre is most commonly used for structural and non-structural purposes [18,19]. Past studies have proven that the addition of steel fibre improved the performance of concrete, particularly the tensile strength, post-cracking or residual strength, toughness, spalling and abrasion resistance and durability [3,16,18,20]. Hence, the objective of this study is to investigate the effect of steel fibre on the mechanical properties and torsional performance of OPS fibre-reinforced concrete (OPSFRC).

Previous studies showed that the performance of OPSC beams are comparable to that of NWC under flexural and shear loadings [7,8]. However, torsional loading generally occurs in combination with flexural or shear loading. When the external load has no alternative but to be resisted by torsion, the structural member is subjected to primary torsion [21]. Examples of structural members subjected to torsion are utility poles, eccentrically loaded box, bridge girders, spiral staircases and spandrel beams [22]. The increasing demand for curved members highlights the necessity to investigate the torsional characteristics of concrete members to avoid severe torsional cracking. The torsional rigidity and torsional stiffness of the members also play an important role in the three-dimensional analysis of concrete structures, especially earthquake resistant structures [21]. Furthermore, there is no literature available on the torsional resistance of the OPSC beams. Hence, the importance of investigating the torsional behaviour of the OPSC beams is evident.

In the case of OPSC, the low tensile strength of OPSC may contribute to torsional cracking before the flexural or shear strengths are achieved. It has been shown that an improvement in the reinforcement ratio including the addition of steel fibre enhanced the torsional strength, ductility and cracking resistance of the concrete [23,24]. Hence, this work aims to study the effect of various volume fractions (0–1%) of steel fibre on the mechanical properties and torsional behaviour of OPSFRC beams. The torsional behaviour investigated includes cracking, ultimate and failure torque/twist, initial and cracked torsional stiffness, torsional toughness, as well as the cracking resistance of OPSFRC beams.

## 2. Experimental programme

### 2.1. Materials

#### 2.1.1. Cement and supplementary cementitious materials

Type 1 ordinary Portland cement was used in all the concrete mixes. The Blaine specific surface area and specific gravity of the cement used in this research were 3450 $cm^2/g$ and 3.13, respectively. Silica fume (SF) of 10% cement weight was added as supplementary cementitious material to improve the mechanical properties of the OPSC mixes.

#### 2.1.2. Coarse and fine aggregates

OPS was used to fully replace conventional coarse aggregate to produce oil palm shell concrete (OPSC). The OPS was collected from a local palm oil extraction factory and OPS of different sizes and shapes are shown in Fig. 1. Table 1 reports the physical properties of the OPS used in this study. The key properties of the OPS are the low bulk density and aggregate impact value, which, eventually, results in the production of lightweight OPSC with high energy absorption capacity.

Mining sand of specific gravity and fineness modulus of 2.65 and 2.7, respectively, were used as fine aggregate in all the mixes.

**Fig. 1.** Oil palm shell (OPS) of diverse shapes and sizes.

#### 2.1.3. Water and superplasticiser

Potable water (pH = 6.2) was used in both the mixing and curing processes. The water to binder ratio of 0.30 was set constantly in all the OPSC mixes. A polycarboxylate-based superplasticiser of 0.65% cement weight was added into the fresh concrete to improve the workability.

#### 2.1.4. Steel fibre

Hooked-end steel fibre with an aspect ratio of 65 (Fig. 2) was added to the OPSC to produce OPSFRC mixes. The length and diameter of the steel fibre were 35 mm and 0.55 mm, respectively.

### 2.2. Mix proportion

The mixing proportions of all the OPSC and OPSFRC mixes are shown in Table 2. The amount of constituent materials was kept constant except the steel fibre. Different volume fractions of steel fibre of 0.25%, 0.50%, 0.75% and 1.00% were added to the OPSFRC mixes.

### 2.3. Specimen preparation and testing

For the testing of the mechanical properties of each mix proportion, 100 mm cubes, 100 $\phi \times 200$ mm cylinders, 150 $\phi \times 300$ mm cylinders, $100 \times 100 \times 500$ mm prisms and $100 \times 100 \times 300$ mm prisms were prepared for compressive strength (BS EN 12390:2009), splitting tensile strength (ASTM C496/C496M-11), flexural strength (ASTM C78-10) and modulus of elasticity/Poisson's ratio (ASTM C469-10), respectively. After the specimens were removed from the moulds, all the specimens were cured in water until testing at 28 days.

For the torsion testing, the OPSC and OPSFRC torsion beams were fabricated according to Eurocode 2. Fig. 3 shows the detailing for the torsion beams. The torsion beams were also cured and tested at the age of 28 days using the automated torsion machine. A constant loading rate of 0.5 mm/min was applied in all the beams until failure. The torsion load-deflection curves were directly measured from the torsion machine. The results were then analysed according to the following parameters: cracking torque, $T_{cr}$/twist, $Ø_{cr}$, ultimate torque $T_{ult}$/twist, $Ø_{ult}$ and failure

**Table 1**
Physical properties of OPS.

| Physical property | OPS |
|---|---|
| Maximum size (mm) | 15 |
| Moisture content (%) | 10 |
| Fineness modulus | 6.41 |
| Compacted bulk density ($kg/m^3$) | 635 |
| Specific gravity | 1.37 |
| 24-hour water absorption (%) | 24.3 |
| Aggregate impact value (%) | 2.11 |