Engineering Structures 101 (2015) 24–33

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effect of fibre aspect ratio on the torsional behaviour of steel fibre-reinforced normal weight concrete and lightweight concrete

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ARTICLE INFO

Article history:
Received 28 September 2014
Revised 3 July 2015
Accepted 6 July 2015
Available online 18 July 2015

Keywords:
Fibre-reinforced concrete
Lightweight concrete
Normal weight aggregate
Oil palm shell
Steel fibre
Torsion

ABSTRACT

The emergence of torsion studies is attributed to the increasing demand for the aesthetic design of curved structural members; however, they are limited in respect of lightweight concrete. Oil Palm Shell Concrete (OPSC) has been researched in Malaysia, which is known to produce a sustainable lightweight concrete by using locally available oil palm shell waste. This study aims to compare the torsional behaviour between the normal weight concrete (NWC) and OPSC, and to investigate the effects of steel fibre of varying aspect ratio – 55, 65 and 80 – in both types of concrete. The results showed that OPSC is more ductile in torsion than the NWC beam, with a twist at failure 2.8 times that of NWC. The steel fibre reinforcement compensated the weak tensile strength of OPSC and enhanced the mechanical properties, torsional strength and ductility, toughness and crack resistance of the OPSFRC specimens. The effect of the aspect ratio is evident from the OPSFRC-80 mix reinforced with steel fibre of aspect ratio 80, which produced the highest ultimate torque, twist at failure and torsional toughness of 8.60 kN m, 0.179 rad/m and 1.074 kN m/m, respectively. In addition, equations are proposed to predict the cracking and ultimate torques to improve the torsion design of lightweight concrete.

1. Introduction

The recent trend of building structures has focused on the concepts of being more economical and space efficient, as well as the aesthetic design in which the structural members are designed to be irregular or curved in shape. In such circumstances, the curved members will be eccentrically loaded, which will induce torsion in the members. Examples of torsion-loaded structures include utility poles, eccentrically loaded box bridge girders, spiral staircases, spandrel beams in building frames and curved beams [1]. The torsion force normally occurs by combining with the flexure and shear forces. In structures with the combined forces, the design procedures are normally based on the force interactions, and, hence, the behaviours of the members under pure torsion need to be known and quantified [2]. There have been numerous studies concerning the torsional resistance of concrete in recent years [1–9]. The studies showed the significance of the torsion design. An under-reinforced torsion-loaded member will result in torsional cracking commencing before the flexural or shear failures, as the torsional strength is highly dependent on the tensile strength, which is the weakest component in brittle concrete [10], and, ultimately, causes an early loss of serviceability. The above-mentioned studies focused on the torsional characteristics of normal weight concrete (NWC), high strength concrete and high performance concrete; however, the investigation of the torsional strength of lightweight concrete (LWC) is limited. This is because the conventional torsional design from the ACI code is based on the skew bending theory [4], and then further theories including the Thin Tube theory, Variable Angle Truss Model and Softened Membrane Model were developed for the prediction of the torsional behaviour of concrete [2,4,11,12]. However, there are no studies available on the torsional behaviour of LWC.

This present study highlights the torsional behaviour of LWC called oil palm shell concrete (OPSC). The introduction of the idea to replace conventional granite aggregate by lightweight waste aggregates, such as slag, pulverized fuel ash, furnace clinker, expanded clay, pumice, coconut shell and oil palm shell (OPS), enables the production of sustainable lightweight concrete (LWC) [13,14]. LWC has the advantage of density reduction compared to NWC, which allows for design flexibility space and cost savings on beams, columns and foundations [15,16]. Moreover, improved fire and frost resistance, heat and sound insulation properties and earthquake damping ability are among the added benefits of LWC [17]. In addition, the utilization of agricultural waste materials, such as coconut shells and OPS as a replacement of coarse

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http://dx.doi.org/10.1016/j.engstruct.2015.07.007
0141-0296/

aggregate also contributes a positive environmental impact as it reduces the pollution issues attributed to the waste storage and extraction of granite aggregate.

In Malaysia, OPS has emerged as a potential substitute for granite aggregate in recent years. The huge palm oil industry in Malaysia generates about 4 million tonnes of OPS as waste annually [18]. The vast amount of OPS waste is dumped in open spaces, which might produce severe pollution problems. Therefore, research has been conducted to produce a LWC called OPS concrete (OPSC) with a density and compressive strength of about 1800–1960 kg/m^3 and 14–39 MPa, respectively by using OPS as full replacement for coarse aggregate [19–22]. In addition, the researchers also reported that the compressive strength of OPSC did not deteriorate over a period of up to 365 days and that OPSC possessed high impact resistance [15,19,23]. Despite the benefits of OPSC over the NWC, OPSC produced lower tensile strength than the NWC, which has limited the applications of OPSC to a wider field. The published papers on OPSC showed that the flexural strength of OPSC could achieve about 5–7 MPa, but that the values were about half of NWC [15,18,22]. LWC with high tensile strength is desirable for the structural design to arrest tensile cracking and to improve the tensile loading capacity. Hence, the enhancement of the mechanical properties, especially the tensile strength of OPSC, becomes the priority issue for the development of OPSC.

The addition of fibre of various materials into the concrete is one of the widely established methods to improve the tensile strength of concrete. The extensive improvement through the use of fibre in concrete can be seen from the improved mechanical properties, toughness, ductility, crack resistance, impact resistance, blast resistance, and shrinkage control [24–27]. The addition of fibre into the cement matrix substantially converts the brittle concrete into a ductile material [3,15,24]. Among all the types of fibre, steel fibre outperforms other types through the significant improvements achieved [28,29]. Therefore, the studies on the addition of fibres to OPSC to produce OPS fibre-reinforced concrete (OPSFRC) are increasing [15,17,23,28,29]. The past literature on OPSFRC reported that OPSFRC produced better mechanical properties, flexural behaviour, toughness and impact resistance than OPSC. The enhanced tensile strength in OPSFRC relative to OPSC allows OPSFRC to be applied as structural members, including torsion-resistant structures.

This study presents the works on the comparison between the torsional behaviour of OPSC and NWC, as well as the effect of hooked-end steel fibres of different aspect ratios in both types of concrete. Previous literature has shown that the addition of steel fibres enhanced the ultimate torsional strength and post-cracking torsional behaviour of concrete including OPSC [3,5,6,30]. Previous study on the OPSC and OPSFRC un-reinforced concrete prisms showed that the use of steel fibre with aspect ratio 65 produced significant improved torsional strength and cracking resistance [30]. However, no study is available on the effect of fibres on the torsional characteristics of OPSC reinforced concrete beams. Hence, this investigation compares the effect that the aspect ratio of steel fibre has in order to optimize the selection of steel fibre, and provide the highest improvement to the torsional strength. Steel fibre of varying aspect ratios – 55, 65 and 80 – was added to OPSC and NWC to produce OPSFRC and normal weight fibre-reinforced concrete (NWFRC), respectively.

2. Research significance

Design codes, such as ACI, Eurocode and BS, do not provide the design provisions for the torsional design of LWC, particularly OPSC, which deviates from NWC with higher ductility but lower mechanical properties. Recently, LWC has gained increasing attention, which is attributed to its space and cost efficiency. The use of LWC reduces the dead load of the structure and it permits the design of members with smaller cross section. Hence the structures made from LWC possess the advantages of smaller member size and reduced cost of the structural members and foundations [15,30]. Therefore, this study presents the comparison between the torsional behaviour of NWC and OPSC to improve the understanding of the performance of LWC under pure torsion, which, ultimately, paves the way for the torsional design of LWC. The present study widens the application of the OPSC as lightweight structural members. In addition, this paper investigates the effect of the aspect ratio of steel on the torsional characteristics of OPSFRC, which has yet to be studied.

3. Materials and experimental procedure

3.1. Materials

3.1.1. Cement and supplementary cementitious materials

Type 1 ordinary Portland cement with a Blaine specific surface area and specific gravity of 3450 cm^2/g and 3.13, respectively, was used in all the mixes. In addition, silica fume of 10% cement weight was added into the OPSC and OPSFRC mixes to enhance the mechanical properties.

3.1.2. Aggregate

OPS and crushed granite aggregate were used as coarse aggregate to produce lightweight OPSC and NWC, respectively. As seen from Fig. 1, the OPS has concave and convex smooth surfaces with spiky edges while crushed granite aggregates are more rounded. Table 1 shows the physical properties of both types of aggregate. It should be noted that the OPS has low bulk density and aggregate impact value compared to the crushed granite aggregate. The aggregate impact value was determined by the aggregate impact testing (BS 812 Part 112) which gives a relative measure of the

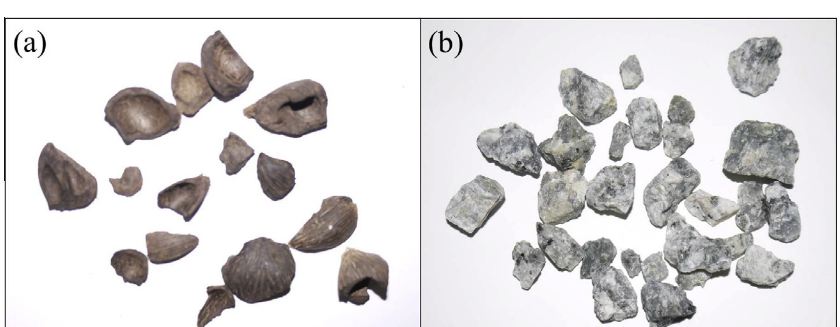

Fig. 1. (a) OPS and (b) crushed granite aggregate as coarse aggregate.