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Impact resistance of hybrid fibre-reinforced oil palm shell concrete

Kim Hung Mo, Soon Poh Yap, U. Johnson Alengaram *, Mohd Zamin Jumaat, Chun Hooi Bu

Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

HIGHLIGHTS

- Hybrid fibre of 0.9% steel fibre + 0.1% PP fibre produced the highest impact energy.
- Uncrushed OPSC had better impact resistance compared to crushed OPSC.
- The lowest crack width was observed in the mix with 1.0% steel fibre.
- The highest compressive strength and compressive energy were found for 1.0% steel fibre in uncrushed OPSC.

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ABSTRACT

This paper presents the results of an experimental impact test conducted using drop hammer on the plain and the fibre reinforced oil palm shell concrete (FROPSC) panels. The variables investigated are different contents of steel (0.75%, 0.9%, 1%) and polypropylene fibres (0.1%, 0.25%, 1%), with uncrushed and crushed OPS. The FROPSC with uncrushed OPS developed higher initial and final impact resistance compared to specimens with crushed OPS. The specimen with 0.9% steel + 0.1% polypropylene (PP) hybrid-FROPSC, developed excellent impact energy of about 17 kJ that was 60 times higher than the plain OPSC. Its impact ductility index (μ_i) of 42 is double the value compared to other specimens. It also showed excellent crack growth resistance due to secondary cracks formation. Final crack widths of FROPSC ranged between 0.079 and 0.507 mm. Further, the compressive energy of 785 J was found for specimen with 1% steel fibres.

1. Introduction

The application of concrete is not only limited to structural members, but it is also used in the construction of barriers and protective structures in places that are subjected to high repeated impact loads. The examples of impact loadings are vehicular and ship collisions with structure, rock falls, missile impacts, explosions, machine dynamics, wind gusts and earthquakes [1,2]. Concrete subjected to high impact loads will experience significant damage in the structural stability and integrity. The residual strength of concrete may be questionable once damage has occurred [1]. Therefore, impact resistant concrete has to be designed to sustain repeated impact loading effectively. Most impact resistant structures require the use of mass concrete or high performance concrete; which leads to higher construction costs of the structures. As such, lightweight concrete (LWC) could provide a more economic-friendly alternative for impact resistant structures.

LWC can be produced using oil palm shell (OPS) as lightweight coarse aggregates [3–6]. In Malaysia, the huge oil palm industry generates 4 million tons of oil palm shell (OPS) as waste materials annually [7]. The vast amount of shells is stockpiled in open air which might contribute to air, water and land pollutions. Conversion of OPS into potential replacement for conventional crushed granite aggregate contributes to sustainability as it might reduce both the extraction of granite stones and the environmental impact. A number of investigations had been carried out in the last decade to produce structural grade OPS concrete (OPSC) [8–11]. Recent investigations were focused on the production of high strength OPSC by using crushed OPS, with compressive strength exceeding 40 MPa being successfully developed [12–14].

The role of coarse aggregate in impact-resistant concrete is vital as it acts as a barrier to the crack propagation [15]. Published researches showed that the lightweight OPS has lower aggregate impact value (AIV) than the crushed granite aggregate, an indication of high impact resistance of OPS [4,9]. However, LWC is considered as a brittle material [16]. The higher the compressive strength of LWC, the higher is its brittleness. To compensate the brittleness of LWC, addition of fibres into concrete is desirable to improve

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* Corresponding author. Tel.: +60 379677632; fax: +60 379675318.
E-mail address: johnson@um.edu.my (U.J. Alengaram).

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both the ductility and impact strength of concrete. The inclusion of steel fibres in concrete improves ductility and energy absorption capacity under repeated impact loading as reported in published studies [17–20]. Steel fibres volume of above 0.5% was mostly used to enhance the impact resistance of concrete [21–24]. The enhancement is attributed to the crack bridging mechanism where the propagation of crack is blocked by the presence of steel fibres.

Apart from the steel fibres, there are increasing applications of synthetic fibres such as polypropylene (PP) and nylon fibres in concrete and these fibres were found to improve the impact resistance of concrete [25–28]. Although synthetic fibre reinforced concrete provides lower impact resistance than that of steel fibres, the added advantages of synthetic fibres are light and non-corrosive. Hence the idea of fibre hybridization is introduced to improve the impact resistance and crack growth resistance of concrete [20,24,29–31]. The hybrid fibres in impact resistance structures serve to preserve the impact strength of such structures over a longer period of time. This is especially important for structures that are subjected to high possibility of steel fibre corrosion, such as in coastal and marine structures and in humid condition which is common in tropical countries like Malaysia. Further, for a given volume of fibres, increasing the amount of synthetic fibres with a relatively lower density than steel fibres in the hybrid fibre system reduces the dead load of the structural members. Investigation on fibre reinforced OPSC (FROPSC) had been done by Shafigh et al. [32] and Yap et al. [33], using steel and synthetic fibres individually but work has yet to been carried out on hybrid FROPSC (h-FROPSC).

The beneficial effects of hybrid fibres in concrete contributed to the investigation of h-FROPSC in this study. The addition of hybrid fibres in the OPSC might enhance both the impact and crack growth resistances of the OPSC. The combined effect of LWC and hybrid fibres could greatly reduce the construction costs. However, there is uncertainty to what extent the fibres combination can be used to obtain the optimum impact resistance. Therefore, the focus of the present study is to investigate the effects of steel–PP hybrid fibres of different percentages on the impact behaviour of h-FROPSC. The other characteristics investigated in this study include slump, oven-dry density (ODD), compressive strength and ultrasonic pulse velocity (UPV). The effect of the crushed and uncrushed OPS in the h-FROPSC is also investigated and reported.

This study on h-FROPSC could enhance the understanding on the effect of hybrid fibres in OPSC. The enhancement of the impact and crack growth resistance would enable the possibility of FROPSC to be used as sacrificial protective barriers such as highway crush cushions, mountain rock fall barriers, heavy industry walls or floors, and dykes.

2. Experimental program

The main objective of the experimental study was to evaluate the impact resistance of steel fibre reinforced OPSC and hybrid steel-polypropylene fibre reinforced OPSC. The other tests include compressive strength and modulus of elasticity.

2.1. Materials

2.1.1. Cement

ASTM Type I Ordinary Portland Cement with Blaine specific surface area and specific gravity of 335 m^2/kg and 3.10, respectively was used in this investigation. The cement content was kept constant at 550 kg/m^3 for all the mixtures. Silica fume (SF) of 10% by weight of cement was used as a supplementary cementitious material with a specific gravity of 2.10.

2.1.2. Coarse and fine aggregate

The coarse aggregate used in this study was OPS collected from local palm oil factory, in both uncrushed and crushed conditions, with maximum sizes of 14 mm and 9 mm, respectively (Fig. 1). The uncrushed OPS has concave and convex shape with smooth surface on the outer convex side. The crushed OPS has more spiky edges than the uncrushed OPS (Fig. 1b). The physical properties of the uncrushed and crushed OPS are given in Table 1. Both the crushed and the uncrushed OPS have lower aggregate impact value (AIV) and bulk density than the crushed granite aggregate. The OPS content in all the mixes was kept constant at 360 kg/m^3.

Mining sand with specific gravity and fineness modulus of 2.67 and 2.70 respectively was used as fine aggregate. The fine aggregate content was kept constant at 780 kg/m^3 for all mixes.

2.1.3. Water and superplasticizer

Potable water with pH value of 6 was used in all the mixes. In order to improve the workability of the concrete mixes, a polycarboxylate ether-based superplasticizer of 1.2% of cement weight was used. The water to binder ratio of 0.30 was used for all the mixes.

2.1.4. Fibres

The hybrid fibres in this study include (i) hooked-end steel fibre (aspect ratio = 65 and length = 35 mm) and (ii) fibrillated PP fibre (length = 12 mm). The specific gravity of steel fibre and PP fibre are 7.9 and 0.9, respectively.

2.2. Mixing procedure

A total of 10 mixes were prepared. The mix proportions of all the concrete mixes are shown in Table 2 with different steel and PP fibres combinations. Initially the coarse and fine aggregates were mixed in the rotary mixer followed by cement and silica fume for about 5 min. This was followed by the addition of water and SP and the mixing continued for another 6 min. Finally, the fibres were added and mixed for a further 2 min.

2.3. Specimen moulding and testing

The concrete was cast in 100 mm cubes, 150 $\phi \times 300$ mm cylinders and $600 \times 600 \times 50$ mm panels for testing the compressive strength, modulus of elasticity/compressive energy and drop hammer impact test, respectively. The demoulding was done after 24 h and the concrete specimens were cured in water till the age of testing. The compressive strength and modulus of elasticity tests were done in accordance to British Standard (BS) 1881: Part 118. The cube compressive test was tested at 1-, 3-, 7-, 28-, 56-, 90- and 180-day, while the modulus of elasticity was tested at the age of 28-day.

2.3.1. Compressive energy

The compressive energy of concrete was taken as the area under the load–deflection curve obtained by subjecting the concrete cylinder under compressive loading. The rate of loading was kept at 4.42 kN/s similar to that of the modulus of elasticity test.

2.3.2. Drop hammer impact test

The drop hammer impact test was done based on modification of the recommendations by ACI Committee 544 in which an impact specimen is subjected to repeated blows on the same spot. In this modified impact test, a 10 kg drop hammer was released from a height of 600 mm on the panel specimen (Fig. 2). The number of blows to cause the first visible crack and failure was observed and used to calculate the first crack and failure impact energy of the concrete, respectively. The impact energy is given in the following equation:

$$E_{\text{impact}} = mgh \times N \tag{1}$$

where E_{impact} = impact energy in Joule (J); m = mass of drop hammer = 10 kg; $g = 9.81\ m/s^2$; h = releasing height of drop hammer = 600 mm; N = number of blows.

The ratio of the number of blows to cause failure, N_f to the number of blows to cause the first crack, N_c is defined as impact ductile index, $\mu_i = N_f/N_c$ [29]. The crack widths were also measured using a high magnification crack microscope. Fig. 3 shows one of the crack width measurements observed using the microscope. Further, the microscope could provide clear illustrations on the pull out of fibres within the crack as shown in the Section 3.6.4.

3. Results and discussion

3.1. Workability

3.1.1. Slump values

The slump values of the OPSC mixes are given in Table 3. In general, the addition of fibres in concrete caused significant loss in the workability of the concrete. The large surface area of fibres adsorbed more cement mortar around the fibres and hence the viscosity of the concrete increased, resulting in low slump values [16]. The slump values of FROPSC in the range of 20–50 mm was found 60–70% and 40–60% lower than control mixes for uncrushed