Construction and Building Materials 111 (2016) 286–297

Contents lists available at ScienceDirect

Construction and Building Materials

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

Engineering properties and fracture behaviour of high volume palm oil fuel ash based fibre reinforced geopolymer concrete

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HIGHLIGHTS

- High volume POFA (90%) was used in development of geopolymer concrete.
- Aspect ratio of steel fibre had significant effect on tensile properties.
- Tensile properties due to steel fibres are more significant in OPSGC than NWGC.
- Bonding between matrix and aggregate influenced tensile and fracture properties.

ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form 5 February 2016
Accepted 6 February 2016

Keywords:
Palm oil fuel ash
Metakaolin
Geopolymer concrete
Fibre reinforced concrete
Aspect ratio
Fracture energy
Flexural toughness

ABSTRACT

This article reports investigation carried out using high volume palm oil fuel ash (POFA-90%) based geopolymer concrete using oil palm shell (OPS) as coarse aggregate. The tensile and fracture properties of OPS based lightweight geopolymer concrete (OPSGC) with the addition of steel fibres (SF) of two aspect ratios (AR80, AR65) and three volume fractions (0.25%, 0.50%, 0.75%) were investigated. The results were compared with that of normal weight geopolymer concrete (NWGC) with and without steel fibre of AR80 and AR65 (0.50% volume fraction). The higher values of flexural and splitting tensile strengths of OPSGC could be attributed to stronger bond between the rougher surfaces of the crushed OPS and matrix. The addition of $SF_{(AR80)}$ produced higher splitting strength, flexural strength and total fracture energy of 5%, 6% and 50–80%, respectively compared to the corresponding values of $SF_{(AR65)}$. The toughness and equivalent flexural strength ratio of OPSGC were found higher than the corresponding values of NWGC and this could be attributed to the ductility of OPS. The values of residual load and residual strength in two-deflection limits of L/600 and L/150 indicated the progressive failure, which reflected the ductility of the OPSGC with fibres.

1. Introduction

Geopolymer concrete (GC) could be an alternative of ordinary Portland cement concrete (OPC) [1]. The greenhouse effect by the emission of CO_2 from the calcination during cement production can be relegated through the application of geopolymer technology in the construction industry. The production of one tonne of cement directly generates 0.55 tonnes of chemical CO_2 and requires the combustion of carbon fuel to yield an additional 0.4 tonnes of CO_2. Conversely, there is no CO_2 production in the geopolymerisation process. The polymeric reaction between silica and alumina exploits in geopolymer through the use of alkaline activators. The alkalinity of the activator can be low to mild or high. The main contents in geopolymerisation process are the silicon and the aluminium. The binder can be produced by a polymeric synthesis of the alkali-activated material from either geological origin or any by-products consisting of silica and alumina as known as pozzolanic material. Hence, the application of geopolymer technology could also be advantageous in term of making use of waste by-product materials from industry.

Palm oil fuel ash (POFA) is one of the largest industrial pozzolanic by-products in the South-East Asia. The abundance and availability of POFA created an ideal platform for the researchers

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.022
0950-0618/

to work on this pozzolanic material as source material in the development of cleaner and sustainable material like GC. Research works on POFA-based geopolymer concrete are limited and the incorporation of metakaolin (MK) along with POFA is another avenue for research towards utilisation of local waste materials in the development of GC.

Besides the environmental pollution due to the production of cement, the consumption of large quantity of natural sand and coarse aggregates (47 billion tonnes/year [2]) has led to a decrease in ground water levels and natural disaster in many countries. In order to ensure sustainable development, researchers, from all around the world have focused their research on applying waste materials to replace the conventional materials [3–6]. Recently, one industrial by-product from the quarry industry as known as manufactured sand (M-sand) and another agro-waste material named oil palm shell (OPS) have drawn the attention of many researchers in the production of lightweight concrete and as full replacement of mining sand [7–9].

Balamurugan and Perumal [10], Ji et al. [11] and Raman et al. [12] reported the potentiality of using quarry fines as a replacement of river/mining sand. The quarry industries produce millions of tons of wastes in the form of quarry dust (QD). These wastes are dumped in the factory yards and hence reuse of QD might help in reducing the overuse of mining and quarrying. The sophisticated technology known as Vertical Shaft Impact Crusher System allows QD to be centrifuged to remove flaky and sharp edges. The end product is commonly known as manufactured sand (M-Sand) and it is popular in some of the developing countries [13].

Apart from the initiative to utilise M-sand to wholly replace conventional sand, OPS has been used to replace conventional crushed granite aggregate. Researchers [14–16] explored the suitability of OPS as lightweight aggregate and found that structural grade lightweight concrete could be produced using OPS as coarse aggregate [17,18]. During the last three decades, many research works have been carried out using OPS in OPC concrete as lightweight aggregate to replace conventional crushed granite aggregate [8,15,19–23]; Yap [14] reported the possibility of significant cost saving due to density reduction as the OPS concrete has about 17–25% lesser density compared to conventional normal weight concrete.

In this research work, high volume of POFA combined with M-sand and OPS as fine and coarse aggregates, respectively were used in the development of a cleaner GC. Like OPC, GC was found good in compressive resistance and weak in tensile properties. Its weakness in tensile resistance could be overcome by using the steel fibres [24,25]. The concrete with high compressive strength shows brittleness characteristics due to the low tensile strength which affects a weak bond in the transition zone of the cement matrix [26,27]. The bond weakness due to low tensile strength of concrete could be mitigated by adding steel fibres in concrete and the use of single type of fibres could improve the tensile property of concrete [28–30]. Knight et al. [31] reported the contribution of fibres in the enhancement of strength and toughness retention. The usage of steel fibres in concrete also enhances the toughness as well as impact resistance of concretes [32]. Regardless the improvement of tensile properties of concrete using steel fibres, a weak transition zone between steel fibres and paste was observed by the researchers [33,34] and this weak bonding was caused due to a lot of porosity in the transition zone. By using appropriate material, the porosity could be reduced as well as consolidate the transition zone [35–37]. Madhkhan et al. [38] suggested the usage of pozzolanic material to reduce the porosity in concrete.

The mechanical properties of GC using conventional crushed granite aggregate were reported [39–41]. However, the use of POFA and MK as binders and OPS and M-sand as coarse and fine aggregates in GC is entirely a new area of research; The use of high volume of POFA of 90% and MK as source materials in GC would enable researchers to entirely utilise POFA as sole binder in the development of GC in future; further, the utilisation of M-sand and OPS as fine and coarse aggregates would pave way for the development of lightweight concrete as OPS is considered as lightweight aggregate [3,7,20,42]. On the other hand, the higher aggregate impact resistance of OPS would enable to test the ability of OPS to resist other engineering properties such as fracture. In addition, to overcome the brittle behaviour of GC, the effects of steel fibres with two different aspect ratios have been investigated and reported through this research work. Ten concrete mixes were prepared and tested for mechanical properties and fracture behaviour of the hardened OPS geopolymer concrete (OPSGC) and the experimental results were compared with normal weight geopolymer concrete (NWGC). The fracture behaviours investigated through four-point bending test include fracture strength, fracture toughness and peak deflection.

The novelty of this research work lies in the development of geopolymer lightweight concrete using high volume POFA, with low content of MK; the addition of two local waste materials-M-sand and OPS as fine and coarse aggregates is another aspect of novelty. This is the first time the effect of M-sand and OPS in GC was investigated. The enhancement of ductile properties of GC by replacing crushed granite aggregates by OPS and by the addition of steel fibres with two aspect ratios and different volume fractions is another innovative aspect of this research work.

2. Materials and methods

2.1. Materials

The test result based on X-ray fluorescence (XRF) analysis of both POFA and MK is shown in Table 1 and it shows that both contained more than 70% of SiO_2, Al_2O_3 & Fe_2O_3 and hence both could be categorised as Class F in accordance with ASTM C618. Fig. 1 represents the particle size distribution of POFA and MK. The physical properties of POFA and MK are shown in Table 2 and it was found that MK was finer and more uniformly graded than POFA. The percent of POFA and MK passing through 45 μm sieve were recorded as 95% and 80%, respectively (Fig. 1) which complies with the recommendation by ASTM C618-12a. M-sand of Grade C (particle size grading) was used (Fig. 2, Table 3). Lightweight crushed OPS were used as the whole replacement of conventional crushed granite aggregate. The fineness modulus, specific gravity, water absorption and aggregate impact value (AIV) of OPS and granite were determined based on ASTM C127-12, ASTM C131-06 and ASTM C136-06. The 24 h water absorption of OPS was found 25% (Table 4); since the AIV of OPS were 3 times lower than that of granite, it has been proved that OPS has good impact resistance due to natural fibres. OPS were soaked in water for 24 h in water before being used for casting. Hooked-end type steel fibres of length 60 mm and 35 mm with aspect ratio 80 and 65, respectively were used. The steel fibres had a minimum tensile strength of 1100 MPa as specified by the manufacturer. Potable water was used for all concrete casting.

2.2. Preparation of Alkaline solution and mix design

The alkaline activator using 14 M sodium hydroxide (NaOH) and liquid sodium silicate (Na_2SiO_3, ratio of $SiO_2/Na_2O = 2.5$) was prepared at least 24 h before the casting. The sodium silicate liquid was mixed with 14 M NaOH solution by weight proportion of 1:2.5.

Table 1
Chemical composition of POFA and MK (%).

Chemical compounds	CaO	SiO_2	Al_2O_3	MgO	Na_2O	SO_3	K_2O	Fe_2O_3	LoI
POFA	5.57	67.72	3.71	4.04	0.16	1.07	7.67	4.71	6.20
MK	0.04	52.68	42.42	0.12	0.07	0.05	0.34	2.02	1.40