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Contribution of acrylic fibre addition and ground granulated blast furnace slag on the properties of lightweight concrete

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HIGHLIGHTS

- Drying shrinkage reduced in the presence of acrylic fibres.
- Enhancement in tensile strength with the addition of 0.1% acrylic fibres.
- OPSC with 20% GGBS had superior mechanical properties compared to those with 70% GGBS.
- Lower strength loss upon heat exposure with the use of acrylic fibres and more GGBS.

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ABSTRACT

The experimental investigation concerning the mechanical performance, drying shrinkage and residual strength upon heat exposure of acrylic fibre reinforced lightweight oil palm shell concrete (OPSC) containing ground granulated blast furnace slag (GGBS) is reported. The addition of 0.1% acrylic fibres in OPSC containing 20% GGBS was found to be the most effective in enhancing the tensile strength. The addition of acrylic fibres in OPSC was also found to reduce the 60-day drying shrinkage strains by up to 10% and improve the relative residual strength by up to 23%. Generally, the OPSC containing 20% GGBS had superior performance among the investigated hardened OPSC properties, except for the residual strength upon heat exposure, in which mixes with 70% GGBS achieved lower strength loss.

1. Introduction

The utilisation of lightweight aggregate (LWA) as coarse aggregate to produce lightweight concrete (LWC) has been explored and well studied over the last five decades. Structural grade LWC has been successfully developed using a variety of LWA, such as expanded clay, shale, scoria, pumice, ceramic, coconut shell and oil palm shell (OPS). One of the main drawbacks of LWC is the higher drying shrinkage values compared to conventional normal weight concrete (NWC) [1]; the high shrinkage in LWC is due to the lower stiffness of LWA that provides a lower restraining effect on the shrinkage movement. The shrinkage of LWC could be as much as 50% higher compared to NWC [2]. Kayali et al. [3] found that LWC made with sintered fly ash aggregate exhibited about 60% higher drying shrinkage compared to NWC. In the case of OPS concrete (OPSC), after oven-drying, the drying shrinkage was reported to be five times higher compared to NWC for mixes with a similar water to cement ratio [4]. After water curing of 90 days, Mannan and Ganapathy [5] investigated the drying shrinkage of OPSC of similar mix proportions to NWC and found higher shrinkage of about 14% compared to the latter. Drying shrinkage is caused by the reduction in volume due to the loss of water from the hardened concrete. This shrinkage movement could induce tensile stress in concrete and cause the formation of cracks once the tensile capacity of the concrete is exceeded. Such a phenomenon is particularly important for LWC, such as OPSC, where the tensile strength is lower compared to the corresponding NWC with similar strength [6]. The presence of cracks due to shrinkage could affect the load bearing ability, durability and the appearance of concrete.

One of the methods to reduce the shrinkage of concrete is by adding fibres in concrete to mitigate the propagation of micro-cracks. Furthermore, the need to improve the tensile capacity for improved structural performance validates the use of fibres in OPSC. In the past, a few researchers [7–10] utilised steel fibres to improve the tensile strength of OPSC. A more economical approach through the use of low modulus synthetic fibres, such as nylon and

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polypropylene (PP) fibres was investigated and a slight improvement in the mechanical properties of OPSC was reported [11]. However, there is a major disadvantage that arises from the use of these synthetic fibres as the workability of the concrete is drastically reduced by fibre balling when a high volume of synthetic fibres is added. Hence, the use of synthetic fibres with a higher tensile strength and modulus of elasticity (MOE) is considered to provide (i) a cheaper alternative compared to steel fibres and (ii) reduce the shrinkage and enhance the tensile strength at a lower volume fraction compared to low modulus fibres, such as nylon and PP fibres.

Polyacrylonitrile (PAN), also known as acrylic fibre, is classified as one of the high modulus synthetic fibres with a MOE in the range of 14–25 GPa and is of the same order of magnitude as the MOE of a cementitious matrix [12]. Acrylic fibres are cheap as well as having high tensile strength and MOE [13]. The superior mechanical properties of acrylic fibres are due to the intermolecular forces between the polymer chains while the electrostatic forces that occur between the dipoles of adjacent $-C{\equiv}N$ groups restrict bond rotation and lead to a stiffer chain [13]. Acrylic fibres have also been found to have excellent adhesion with the cement matrix [14] due to the higher surface free energy of the fibres [15] compared to other synthetic fibres, such as PP and nylon fibres. In the past, acrylic fibres were used to replace conventional asbestos fibres in a variety of applications, such as flat roof sheets, corrugated sheets, discharge and vent pipes, as the asbestos fibres constituted a grave health concern [16,17]. These fibres have also been found to be effective in reducing shrinkage in shotcrete, which is used in tunnel lining and embankment stabilisation [16]. In the past, research using acrylic fibres include fibre reinforced cementitious composites [15,18–20], bitumen [21] and cement mortar [22]. Although limited literature is available for the shrinkage performance and tensile strength of acrylic fibre reinforced concrete, the use of acrylic fibres has been found to be effective in reducing shrinkage [23] and enhancing the flexural strength of cementitious composites [18–20]. The addition of acrylic fibres has also been found to have beneficial effects on the toughness [15,19,20] and impact performance [23–25].

To produce a more sustainable concrete, there is a need to utilise supplementary cementitious material to partially replace the cement, particularly in the case of LWC, such as OPSC, whereby the cement content used is high, ranging between 480 and 550 kg/m^3 [26]. The emission of a large amount of greenhouse gases that could detrimentally affect the environment is commonly associated with the use of cement. Hence, the use of supplementary cementitious materials, such as fly ash [27], ground granulated blast furnace slag (GGBS) [28] and rice husk ash [29] in OPSC, has previously been investigated. In fact, the use of high volume GGBS up to 60% could still produce structural grade lightweight OPSC with a compressive strength exceeding 25 MPa [30]. Further, the use of GGBS offers a higher environmental value since the carbon dioxide (CO_2) emissions for the production of GGBS are about five times lower compared to that of cement.

Previously, Mo et al. [9] studied the effect of steel fibres on the mechanical and toughness properties of OPSC containing GGBS; however, work has yet to be carried out to study the combined effects of fibres and GGBS in OPSC. Further, no previous literature was found concerning the effects of the addition of fibre on the shrinkage performance of OPSC. Therefore, in the present investigation, the effects of adding acrylic fibres and GGBS as partial cement replacement material on the shrinkage and mechanical properties of OPSC were explored. In terms of the economic and workability considerations, a low amount of acrylic fibres was used (up to 0.2%); in view of the environmental impact, the effects of low (20%) and high (70%) amounts of GGBS as partial cement replacement were investigated.

2. Experimental programme

2.1. Materials

2.1.1. Binder

Ordinary Portland cement (OPC) with a specific gravity and specific surface area of 3.10 and 352 m^2/kg, respectively, was used in this study, together with GGBS, with a specific gravity of around 2.90 and specific surface area of 405 m^2/kg, as partial cement replacement. The oxide compositions of OPC and GGBS are listed in Table 1.

2.1.2. Aggregate

Manufactured sand (M-sand), which is a waste material from the quarrying of granite aggregate with sizes of between 300 µm and 5 mm, was used as fine aggregate, while crushed OPS with sizes between 2.36 and 14 mm was used as coarse aggregate. The particle size distributions of the M-sand and crushed OPS are presented in Fig. 1. The specific gravities of manufactured sand and OPS were 2.56 and 1.35, respectively. The OPS had a compacted bulk density, loose bulk density and 24 h water absorption of 658 kg/m^3, 590 kg/m^3 and 25%, respectively. Prior to casting, the OPS were pre-soaked in water for 24 h and then air dried to achieve a saturated surface dry (SSD) condition.

2.1.3. Water and superplasticiser

Potable water, free from contaminants and impurities, was used for the concrete mixes. A polycarboxylic-ether based superplasticiser (SP), with the commercial name of Masterglenium Ace 8388 was used to ensure sufficient workability.

2.1.4. Acrylic fibres

The monofilament acrylic fibres (Fig. 2) used had a filament diameter of 9 microns and a length of 12 mm. The physical properties of the acrylic fibres used in the investigation and locally available PP fibres [11] are compared in Table 2.

2.2. Mix proportion and procedure

A total of six concrete mixes were prepared for this investigation, with a constant binder, sand and OPS content of 510, 950 and 410 kg/m^3, respectively. The water-to-binder ratio and SP content used for all mixes was fixed at 0.31% and 1.0%, respectively. The variables used in the investigation include GGBS volume (20% and 70%) and the volume fraction of acrylic fibres (0%, 0.1% and 0.2%). The mix designation is shown in Table 3.

In the mixing process, OPS and manufactured sand were dry mixed for about 3 min, followed by the addition of OPC and GGBS for another 3 min. Wet mixing was done with the addition of the mixing water and SP for a further 6 min. Then,

Table 1
Oxide composition of OPC and GGBS (%).

Oxide composition	OPC	GGBS
SiO_2	19.8	33.8
Fe_2O_3	3.10	0.52
CaO	63.4	43.9
Na_2O	0.19	0.20
MgO	2.50	5.40
Al_2O_3	5.10	13.40
SO_3	2.40	0.10
K_2O	1.00	0.31
TiO_2	–	0.55
Mn_2O_3	–	0.30
LOI	1.80	1.00

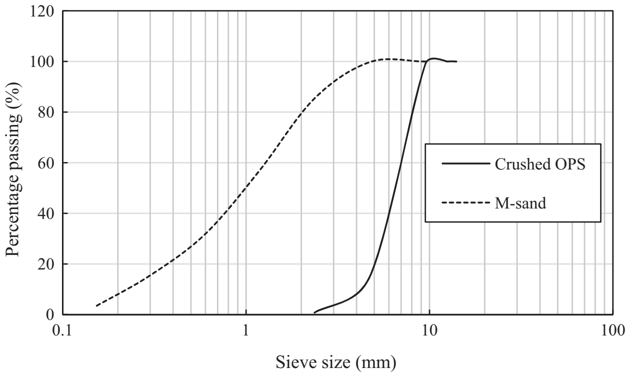

Fig. 1. Particle size distribution of crushed OPS and M-sand.