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Compressive behaviour of lightweight oil palm shell concrete incorporating slag

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HIGHLIGHTS

- Good prediction of OPSC stress–strain curve using material parameters in Popovics model.
- Little difference in strain at peak stress for OPSC between 25 and 45 MPa strength.
- OPSC with higher compressive strength exhibit more brittle behaviour.
- Good correlation between OPSC compressive strength with UPV and rebound hammer values.

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ABSTRACT

In this paper, the investigation of the compressive behaviour of lightweight oil palm shell concrete (OPSC) containing ground granulated blast furnace slag (GGBS) was carried out. The variables studied include the compressive strength class (grade 25, 35 and 45), curing method (air and water curing) and GGBS replacement level (20% and 60%). Higher GGBS content and air curing resulted in lower mechanical properties such as compressive strength and modulus of elasticity (MOE) of the concrete. Analysis revealed that when the experimental stress–strain parameters such as the peak stress, strain at peak stress and MOE were incorporated into Popovics stress–strain model, the compressive stress–strain relationship of the lightweight concrete could be well-estimated.

1. Introduction

Concrete is a composite material consisting mainly aggregate, cement and water. Recent studies revealed that the use of waste oil palm shell (OPS) as lightweight coarse aggregate to produce structural grade lightweight concrete (LWC) is viable. The resulting OPS concrete (OPSC), was found to be satisfactory in terms of the mechanical, durability and structural performances [1]. One of the greatest benefits in re-using the waste OPS for LWC production lies with the environmental sustainability. This is because the OPS is essentially a waste material resulting from the palm oil extraction process and it is usually dumped in the surrounding of the palm oil factories, without any systematic and proper disposal system. Re-using the aggregate to produce OPSC could greatly solve the disposal problem of the OPS in addition to reduce the dependence of conventional granite aggregate. The possibility of using ground granulated blast furnace slag (GGBS)-blended cement in OPSC for additional environment benefit was also explored previously and it was found that the use of 20% GGBS as partial cement replacement could achieve similar strength properties as the concrete without GGBS [2].

Being a type of LWC, one of the most welcoming advantage in the use of OPSC for structural members is the reduction in self-weight, which could significantly reduce costs arising from the design and construction stage. Despite the usefulness of LWC for structural purposes, little research has been carried out in the past to investigate the material properties to be incorporated into new structural design guidelines for LWC. One of the most important material properties of concrete for non-linear analysis and design of reinforced concrete structures is the compressive behaviour. The knowledge on the compressive stress–strain relationship allows the assessment of the overall structural response under action of loads, which is essential for a wide range of design considerations [3]. In design practice, the stress–strain relationship for normal concrete is usually adopted. However, with the advancement in concrete technology and development of newer types of concrete such as LWC, further investigations are required to analyse their behaviour when subjected to uniaxial compressive forces so that engineers could provide a safe design for reinforced concrete structures utilising such concretes. This is because

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parameters such as water–binder (w/b) ratio, aggregate type and binder material could significantly affect the stress–strain relationship of concrete [4].

In the past, stress–strain models are proposed for LWC [5–8]. Since most of these models were empirical-based, it is unclear whether the models could be utilised with adequate degree of accuracy for other types of LWC. For instance, the LWC tested in past researches were mainly made from manufactured lightweight aggregates, such as expanded clay and shale. As such, the models derived from these tests may not be applicable to LWC such as aerated concrete or LWC prepared with lightweight aggregate of vastly different nature and stiffness such as OPSC, which is produced utilising agricultural waste OPS. Despite the continuous research on OPSC, there is a lack of attempt to evaluate the compressive stress–strain relationship and to utilise such relationship in the numerical simulation to predict and analyse the structural behaviour of reinforced OPSC members.

Markeset and Hillerborg [9] reported that localisation not only occurs on concrete in tension, the descending branch of the concrete compressive stress–strain curve is also subjected to localisation and is size-dependent. Recently, a mechanics-based moment-rotation approach was introduced to simulate the structural behaviour of reinforced concrete [10] and Chen et al. [11] proposed the use of a size-dependent compressive stress–strain relationship to be incorporated into the approach. As part of the study to utilise such approach to predict the behaviour of reinforced OPSC structural members, this study focuses on the investigation on the stress–strain behaviour of OPSC. The variables considered include the compressive strength class (grade 25, 35 and 45 MPa) and the amount of cement replacement with ground granulated blast furnace slag (GGBS) (20% and 60%) in OPSC. Their effect on the stress–strain parameters such as peak stress, strain at peak stress and the modulus of elasticity (MOE) is also investigated. The experimental results obtained were then compared with the stress–strain models proposed in the past for verification.

2. Experimental programme

2.1. Mix proportions

The mix proportions for all mixes are presented in Table 1. There are four parameters that were investigated, namely the compressive strength class, GGBS content, steel fibre addition and curing regime. Trial mixes were done prior to determine the mix proportions for targeted cube compressive strength level of 25, 35 and 45 MPa and these mixes were denoted by the symbols C1, C2 and C3, respectively. For these mixes, the GGBS content was fixed at 20% cement replacement level and the effect of curing regime were also studied using these mixes. The mix proportion used for mix C4 was similar to that of mix C1, but with a higher cement replacement level of 60% using GGBS.

Table 1
Mix proportions.

Mix	Content (kg/m^3)						Curing	
	Cement	GGBS	OPS	Sand	Water	SP	Water	Air
C1	375	95	425	850	200	0	/	/
C2	415	105	415	910	170	1.04	/	/
C3	455	115	330	1025	170	2.57	/	/
C4	188	282	425	850	200	0	/	–

2.2. Materials

Ordinary Portland Cement (OPC) and GGBS were used to form the binder of OPSC in this study. The specific gravities of cement and GGBS were 3.10 and 2.90, respectively and their chemical compositions are listed in Table 2.

OPS (specific gravity: 1.35) and manufactured sand (specific gravity: 2.56) were used as coarse and fine aggregate, respectively. The size of OPS used was 2.36–9 mm whereas the size of manufactured sand was between 0.3 and 5 mm. Due to high water absorption of the OPS aggregate, the OPS were soaked in water for 24 h prior to casting and used in saturated surface dry condition.

Laboratory pipeline water was used as mixing water in this study while polycarboxylate ether-based superplasticizer (SP) was used at varying content as shown in Table 1 facilitate workability.

All the specimens were de-moulded 24 h after concrete casting and subjected to continuous water curing. For mixes C1, C2 and C3, the specimens were also subjected to air curing at laboratory conditions. All specimens were tested after a curing period of 28 days.

2.3. Test method

The compressive strength of concrete was determined based on BS EN 12390-3: 2002 using both 100 mm cube and 100 mm $\phi \times$ 200 mm height cylindrical specimens. A total of three specimens were tested for each case and the average value was taken.

Cylindrical specimens with 150 mm ϕ and 300 mm height were tested using compression extensometer to obtain the compression stress–strain curve. The modulus of elasticity (MOE) of concrete was determined from the initial linear portion of the stress–strain graph. The test was carried out until the load decreased to about 30% of the maximum load attained as the compression extensometer readings obtained beyond this point were found to be erratic.

3. Results and discussion

3.1. Compressive strength

The 28-day compressive strength results for the cube and cylinder specimens obtained in this study is summarised in Table 3. As shown by the cube compressive strength results of the OPSC specimens subjected to water curing, the mix design used in this study managed to produce OPSC of the required cube compressive strength class of 25, 35 and 45 MPa.

All of the OPSC cylinder specimens subjected to water curing attained the minimum compressive strength requirement of 17 MPa and therefore could be classified as structural LWC as stipulated in ACI 213-R. In this study, only the cylinder specimens from mix C1 which were subjected to air curing did not attain the minimum compressive strength of 17 MPa required for structural purpose.

Table 2
Chemical composition of OPC and GGBS.

Chemical composition (%)	SiO_2	Fe_2O_3	CaO	Na_2O	Al_2O_3	SO_3	K_2O	MgO	LOI
OPC	19.80	3.10	63.40	0.19	5.10	2.40	1.00	2.50	1.80
GGBS	33.80	0.52	43.90	0.20	13.40	0.10	0.31	5.40	1.00