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Engineering properties and carbon footprint of ground granulated blast-furnace slag-palm oil fuel ash-based structural geopolymer concrete

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HIGHLIGHTS

- Normal weight and lightweight structural green concrete could be produced by using POFA and GGBS with low binder content.
- Manufactured sand could be used as an ideal replacement for conventional mining sand.
- In ambient cured conditions, 96% of the compressive strength of OPSGC could be achieved in 7 days.
- The usage of OPSGC could reduce the density by 20% compared to NWGC.

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ABSTRACT

Engineering properties of geopolymer concrete developed using palm oil fuel ash and slag as binders, manufactured sand and quarry dust as replacement materials for fine aggregate, and oil palm shell (OPS) as coarse aggregate were investigated along with carbon footprint. The use of binder content of 425 kg/m^3 with OPS based lightweight concrete produced the highest compressive strength of 33 MPa. Ultrasonic pulse velocity of normal weight geopolymer concrete (NWGC) shows it as "good quality". The development of structural grade OPS geopolymer concrete comparable to NWGC shows its potential application for structural purposes. OPS geopolymer concrete has lower carbon footprint of 50–60% compared to conventional concrete.

1. Introduction

The term *structural concrete* indicates any type of concrete that is used in structural applications, which may be plain, reinforced, pre-stressed, or partially pre-stressed concrete [1]. For structural concrete, generally, the pragmatic requirement is that any lightweight aggregate that is suitable with a crushing strength sufficient to have reasonable resistance to fragmentation while enabling concrete strengths in excess of 20 N/mm^2 [2]. The density of structural lightweight aggregate concrete can range from approximately 1200–2000 kg/m^3 compared to 2300–2500 kg/m^3 for normal weight concrete (NWC) [2]. The oven-dry density range, as specified in EN 206-1 [3] for lightweight concrete and NWC are 800–2000 kg/m^3 and 2000–2600 kg/m^3, respectively. Concrete with a density that exceeds 2600 kg/m^3 is known as heavyweight concrete. The minimum strengths for structural lightweight concrete, as identified by several codes, are shown in Table 1 [2].

As known, concrete is the most widely used construction material in the world, with the current consumption of 1 m^3 per person per year [4]. The concrete industry is said to be one of the contributors to global warming due to the use of ordinary Portland cement (OPC), which is the main component in the production of concrete and other cement based construction materials. The carbon dioxide (CO_2) emissions from the production of OPC constitute approximately 5% to 7% of global anthropogenic emissions [5,6]. It has been reported [7] that 1 tonne of cement produces about 1 tonne of CO_2.

Every year millions of tons of industrial waste are generated of which most are either unutilised or underutilised. Furthermore, these wastes cause environmental issues due to storage problems and pollution of the surrounding fields. In recent years, there has been increasing awareness concerning the quantity and diversity of hazardous solid waste generation and its impact on human health. The quarrying of natural sand has a sizeable and

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Table 1
Minimum strengths for structural lightweight concrete [2].

Code	Reinforced	Prestressed
BS 8110	20	30[a] and 40[b]
BS 5400	25	Not permitted
ACI 318	30	30
ENV 1992-1-4	12	25[a] and 30[b]
AS 3600	25	25
NS 3473	25	35
JASS 5	25	25

[a] Post-tensioned.
[b] Pre-tensioned.

irreversible environmental impact [8], as it causes a reduction in the groundwater, which affects the moisture content of the soil. Due to the drop in river water level, drinking water is badly affected, especially during the dry season, and saltwater intrusion becomes a potential problem. In addition, sand mining causes the erosion of nearby land leading to instability in the ecosystem [9].

Currently, the need for environmentally friendly construction materials for sustainable development is an important environmental issue in the construction industry. An alternative cementitious binder, termed "geopolymer", comprising alkali-activated palm oil fuel ash (POFA) and ground granulated blastfurnace slag (GGBS) binders could be considered as a substitute for OPC. Geopolymer was first described by Davidovits [10] as an inorganic material that is rich in silicon (Si) and aluminium (Al), and reacts with alkaline activators to become cementitious. Yusuf et al. [11] investigated the microstructure analysis of POFA–GGBS based geopolymer paste and found that the optimum content of GGBS was about 20% in POFA, which could produce a compressive strength of 44.57 MPa at 28 days. Geopolymer concrete is well-suited to manufacture precast concrete products that can be used in both infrastructure developments [12] and main building structures [13]. The University of Queensland's Global Change Institute (GCI), Australia, is the world's first building to successfully use slag/fly ash-based geopolymer concrete for structural purposes Fig. 1 [13].

The recent research works on the utilisation of palm oil fuel ash (POFA) as the source material opens a new avenue in the development of geopolymer concrete [14–16] as well as normal concrete [17–19]. Aldahdooh et al. [18] reported that POFA could be used to produce high strength fibre reinforced concrete of about 158 MPa at 90 days. Mijarsh et al. [14] developed geopolymer mortar using 65 wt.% of POFA and found a compressive strength of 47 MPa after 7 days of curing. It is reported [19] that the smaller size of POFA particles is more potential than that of the larger size of POFA particles due to the filler effect. Kupaei et al. [20] developed fly ash based lightweight geopolymer concrete using OPS as lightweight coarse aggregate. OPS based structural lightweight cement-concrete has also been developed [21] in the recent years. Kanadasan and Razak [22] reported that another potential waste from palm oil mill called palm oil clinker, which can be directly incorporated into concrete as replacement for natural aggregates.

(a)

(b)

Fig. 1. (a) Queensland's University GCI building with 3 suspended floors made from structural geopolymer concrete, (b) precast slag/fly ash – based geopolymer concrete floor parts, Australia [13].