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Evaluation of thermal conductivity, mechanical and transport properties of lightweight aggregate foamed geopolymer concrete

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ABSTRACT

Energy efficiency is the predominant criterion in green building indices, which, in turn, contributes to sustainable development. One of the materials commonly used in the insulation of buildings is foamed concrete. This investigation presents the main objective of the experimental results concerning the thermal conductivity of oil palm shell foamed geopolymer concrete (OPSFGC), utilizing waste materials such as low-calcium fly ash (FA) and palm oil fuel ash (POFA) as cementitious materials, and oil palm shell (OPS) as lightweight coarse aggregate (LWA). Three OPSFGC mixtures with densities of 1300, 1500 and 1700 kg/m^3 were prepared using an artificial foaming agent; a control mix without foam and conventional materials – block and brick – were used for comparison. The test results on the mechanical and transport properties are also discussed. The thermal conductivity of OPSFGC13 of about 0.47 W/mK was 22% and 48% lower than the conventional wall materials, block and brick, respectively. OPSFGC, with a density of 1300 and 1500 kg/m^3, could be categorized as structural and insulating concrete, Class-II, whereas OPSFGC with a density of 1700 kg/m^3 is classified as Class-I structural grade concrete with a compressive strength and thermal conductivity of about 30 MPa and 0.58 W/mK, respectively.

1. Introduction

The concept of sustainable development is not a passing fad but rather a policy that will last and has become more relevant because the great ones of this world are breathing the same polluted air as the rest of us [1]. The need to optimize the energy behaviour of buildings' has been enforced by the scientific and government policies. The public debates are focused on the quality of the urban environment, as more energy efficient buildings could reduce the quantities of fossil fuels consumed and thereby reduce the amount of carbon dioxide and sulphur dioxide emitted into the atmosphere, particularly on a micro- and mesoscale [2]. According to Mahlia et al. [3], a proper insulation material with the capacity to achieve acceptable comfort for the building occupants while reducing the cooling load is necessary as it would generate huge energy and cost savings as well as reduce environmental emissions from the power plants.

As the construction industry is considered to be one of the fastest growing industries, reducing the heat loss in buildings by increasing its thermal insulation properties is important, as it would enable energy efficient buildings and improve environmental sustainability. In addition, the usage of industrial waste would be an added advantage. Ng and Low [4] discovered that sandwiched newspaper, which could be used as the wall envelope for energy efficient building construction, has a significant impact on the thermal conductivity performance of aerated lightweight concrete panels with a reduction of thermal conductivity of up to 22% compared to the control panels. Incorporation of 0.5–1.0% of the air-entraining agent in lightweight aggregate cellular concrete has shown an excellent characteristic as an architectural member due to its high acoustic shielding and thermal insulation properties [5]. Moreover, Alengaram et al. [6] reported that structural grade oil palm shell foamed concrete (OPSFC) has 39% reduced thermal conductivity compared to conventional brick. However, the spacing of cracks in the OPSFC beams was found to be closer than those found in normal weight concrete (NWC) beams; thus, OPSFC beams produced a higher modulus of elasticity (MOE) with smaller crack widths [7]. Furthermore, Ramírez et al. [8] determined that recycled coarse aggregate (RCA) concrete used in the construction of bio-digesters delivers significant savings in energy consumption with its good thermal behaviour and mechanical performance. Stalite aggregate has been presented as the most effective insulating RCA when 20–30% of glass bubbles are added, compared with normal concrete [9].

Although modern concretes are composite materials, cement is still an indispensable material in concrete production [1]. The production of cement is one of the main contributors towards global warming caused by the emission of carbon dioxide (CO_2). Davidovits [10] was the pioneer in introducing binders other than cement that could be produced by the reaction between alkaline

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liquids and source materials that are rich in silica and alumina, commonly known as geopolymerization. The material has been termed 'geopolymer'. The geopolymerization process is aided by heat curing and drying [11]. The use of geopolymer technology not only substantially reduces the CO_2 emissions by the cement industry, but also utilizes waste materials, such as FA [11]. Low-calcium (ASTM Class-F) FA is preferred as a source material to high calcium (ASTM Class-C) F since the presence of a high amount of calcium interferes with the polymerization process and alters the microstructure [12].

Malaysia is the second largest palm oil producer through which it contributes large quantities of waste, such as empty fruit bunches, palm oil clinker, oil palm shells (OPS) and palm oil fuel ash (POFA). These waste materials are unutilized and cause land and air pollution in the vicinity of the palm oil factories. Many researchers have taken the initiative to utilize some of these palm oil industry wastes, such as OPS and POFA, to develop sustainable construction materials [13–17]. Tangchirapat et al. [16] reported that a 20% replacement in ordinary Portland cement (OPC) concrete with medium size POFA as the pozzolanic material produced 90% of the compressive strength of the control concrete at the age of 90 days. Similarly, Ahmad et al. [17] investigated the optimum cement replacement of POFA and found that a replacement of 15% produced comparable strength to that of the control concrete. Shafigh et al. [14] used crushed OPS to produce high strength oil palm shell concrete (OPSC) with a compressive strength of up to 53 MPa with a density of 2000 kg/m^3. The addition of polypropylene and nylon fibres in the OPSC enhanced the post-failure compressive strength [15]. Further, it was shown that the use of a sand to cement ratio of 1.6 in the OPSC enhanced the MOE up to 11 kN/mm^2 [13]. Kupaei et al. [18] developed an optimum mix proportion for the 50-mm oil palm shell geopolymer concrete (OPSGC) with a compressive strength and density of 33 MPa and 1800 kg/m^3, respectively.

Although many researchers have attempted to utilize waste materials in geopolymer concrete, there has not been much research on the development of aerated or foamed geopolymer concrete. Raden and Hamidah [19] made an effort to utilize waste paper sludge ash as a source material to develop foamed geopolymer concrete (FGC). The density and the compressive strength of FGC were found to be approximately 1800 kg/m^3 and 3 MPa, respectively. OPSFC with a density of 1100 kg/m^3 is able to reduce 56% of the thermal conductivity when matched with the conventional brick in Malaysia [6]. However, there is no literature available on the thermal insulation characteristic of FGC. Furthermore, no research has been conducted on utilizing industrial waste such as OPS and POFA to replace the coarse aggregate and the binder in geopolymer concrete.

As a further research, artificially generated foam is introduced to produce both structural and non-structural grade FGC in which OPS was used as the coarse aggregate. POFA and FA were used as cementitious materials (CM). The oven-dry density (ODD), porosity, sorptivity and compressive strength up to the age of 28 days were reported. This study focused on a comparison of the thermal conductivity effect of oil palm shell foamed geopolymer concrete (OPSFGC) for various ODDs with the conventional materials used for building walls in Malaysia, such as block and brick. The reported ODDs of OPSFGC ranged from 1300 to 1700 kg/m^3, which were classified as lightweight concrete.

2. Experimental programme

2.1. Materials

The binders used in this experimental work are Class-F FA and POFA. Class-F FA was supplied by Lafarge Cements, Malaysia, whereas POFA was collected from local palm oil mills. The chemical composition of FA and POFA conforming to ASTM C618-12a are shown in Table 1. The POFA collected from the mill was dried in an oven at 105 ± 5 °C for 24 h, followed by sieving through 300 μm to remove any coarse foreign particles. Then, the POFA was ground in a Los Angeles abrasion machine for 30,000 cycles to a mean particle size of 45 μm to improve reactivity. For all mixtures, the binder consists of 20% POFA and 80% of FA.

Table 1
Chemical composition of Class-F FA and POFA.

Chemical composition (%)	Class-F FA	POFA	ASTM C618
Silica (SiO_2)	57.6	63.4	–
Ferric oxide (Fe_2O_3)	5.8	4.2	–
Calcium oxide (CaO)	0.2	4.3	–
Magnesium oxide (MgO)	0.9	3.7	–
Potassium oxide (K_2O)	0.9	6.3	–
Sulphuric anhydride (SO_3)	0.2	0.9	≤ 4.0
Alumina (Al_2O_3)	28.9	5.5	–
Loss of ignition (LOI)	3.6	6.0	≤ 10.0
$SiO_2 + Al_2O_3 + Fe_2O_3$	92.3	73.1	≥ 70.0

Crushed OPS of sizes between 2.36 and 9.5 mm was used as the coarse lightweight aggregate in this study. Table 2 shows the physical properties of the OPS. The OPS was washed and kept in a saturated surface dry (SSD) condition for about 24 h before being used. Mining sand with a specific gravity of 2.67, passing through 2.36 mm and retained on 300 μm was used as fine aggregate for the OPSFGC; however, mining sand passing through 5 mm and retained on 300 μm was used as the fine aggregate for the oil palm shell non-foamed geopolymer concrete (OPSNFGC).

A combination of sodium hydroxide in flake form and sodium silicate solution was used as the alkaline activator. The solution was prepared at least 1 day prior to its use to allow the exothermically heated liquid to cool to ambient temperature. The ratios of the sodium silicate solution to sodium hydroxide solution and the alkaline solution to CM were 2.5 and 0.55 by mass, respectively. The molarity of the sodium hydroxide was 14 M. In addition, a polycarboxylate ether (PCE) based superplasticizer (SP) was used at a dosage of 1.5% by mass of CM. Potable water was used in all the mixes. The commercially available foaming agent, Sika AER-50/50 was used in this investigation by using a foam generator. The air pressure of the foam generator was maintained at 75 psi or 517 kN/mm^2 and the generated foam was then added during the mixing of OPSFGC.

2.2. Specimen preparation

In this investigation, the OPSFGC was cast based on the target ODD; namely, 1300, 1500 and 1700 kg/m^3. The control OPSNFGC specimen was cast for the purpose of comparison. The total CM used was 489 kg/m^3, which consists of 20% of POFA and 80% of FA. The ratios of coarse aggregate to CM and fine aggregate to CM were kept at 0.6 and 1.7, respectively. The additional water to binder (w/b) ratio was kept constant at 0.1, whilst the SP was used at a dosage of 1.5% by mass of CM for all mixtures. The dosage of foam varied with the target densities of the OPSFGC. Table 3 showed the details of the mixture proportions of the OPSFGC and OPSNFGC.

Table 2
Physical properties of OPS.

Physical property	OPS
Specific gravity (saturated surface dry)	1.36
Bulk density (loose) (kg/m^3)	589
Bulk density (compacted) (kg/m^3)	652
Fineness modulus	5.90
Water absorption (24 h) (%)	24.39