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Mechanical, durability and microstructure properties of lightweight concrete using aggregate made from lime-treated sewage sludge and palm oil fuel ash

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HIGHLIGHTS

- The novel Posslite LWAC produced from LWA made from lime-treated SS and POFA.
- Dense shell and rough surface of Posslite LWA enhanced the strength of LWAC.
- Presence of crystals prevents Posslite LWA from decay in concrete.
- Workability of Posslite LWAC is comparable with NWAC and yet it is 15% lighter than NWAC.
- The mechanical and durability performance of Posslite LWAC is comparable to NWAC.

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ABSTRACT

This paper reports the investigation on toxicity characteristics, microstructure, physical and mechanical properties of artificial Posslite lightweight aggregate (LWA) made from lime-treated sewage sludge (SS) and palm oil fuel ash (POFA). The presence of crystals and a dense shell of Posslite LWA enhanced its strength and the rounded shape of LWA enhanced the workability of fresh lightweight aggregate concrete (LWAC). Results showed that mechanical and durability properties of Posslite LWAC were comparable to normal weight aggregate concrete (NWAC). Posslite LWAC possesses compressive strength, VPV, sorptivity, chloride diffusion of 50.4 MPa, 8.7%, 0.0151 mm/s$^{0.5}$ and 2.12×10^{-11} m^2/s, respectively.

1. Introduction

Concrete is the most widely used construction material and its high production has led to the depletion of natural resources such as conventional normal weight aggregate (NWA) and cement. For instance, the quarrying of coarse aggregates in Kuwait had been completely stopped and is entirely dependent on imported aggregates from the neighbouring countries [1]. Several other countries such as Taiwan and Argentina also face the shortage of good quality natural aggregates to support the needs in the local construction activities [2–3]. In order to alleviate this problem, researchers have been developing a more sustainable approach in the construction industry. One such approach is the reuse of different solid waste streams to produce artificial lightweight aggregate (LWA) [4–7].

LWA can be categorised into two major types – natural LWA and artificial LWA. The primary source of natural LWA is from

Abbreviations: LWAC, Lightweight aggregate concrete; NWAC, Normal weight aggregate concrete; VPV, Volume of permeable voids; RCPT, Rapid chloride penetration test; SEM, Scanning electron microscopy; XRD, X-ray diffraction; EDX, Energy dispersive spectroscopy; SS, Sewage sludge; POFA, Palm oil fuel ash.

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volcanic origin such as pumice and scoria. Artificial LWA on the other hand can be manufactured through thermal treatment of naturally occurring materials, industrial by-products, waste materials and etc. [8]. As the industrial by-products and waste materials have been proliferating for the past decades due to industrialisation and urbanisation, researchers have been using these materials such as plastic wastes [9–11], sediments [2,12], coal residues [5–6,13] and etc. to produce artificial LWA.

Sewage sludge (SS) is an inevitable solid waste produced from wastewater treatment plant and lime has been traditionally used to stabilise the SS before applied to land [14]. In Malaysia, a local wastewater treatment plant alone produced about 3 tons lime-treated SS per day. Researchers had utilised the SS with low lime content to produce LWA [15–17] but not high lime content SS. Besides that, Malaysia being the world's second largest producer of palm oil, produces about 0.06 million tonnes of palm oil fuel ash (POFA) every year [18]. Researchers had utilised POFA to replace cement in concrete [19–20] but there is no known study that utilise POFA in LWA production. In the previous work of this research project [21], these two major waste streams (SS and POFA) was reused to produce artificial LWA. However, the resulting concrete properties of this LWA have not been investigated. In this paper, this LWA will be utilised to produce lightweight aggregate concrete (LWAC) and the mechanical, durability and microstructure properties will be investigated.

Generally, the LWA developed from low lime content SS for structural concrete has a bulk density ranged from 620 to 1036 kg/m^3 and crushing strength ranged from 5.27 to 16.5 MPa [15–17]. The compressive strength of the LWAC made from these LWAs ranged from 28 to 52 MPa at w/c of 0.3 to 0.55 [15,17]. In addition to the ratio of strength to weight of LWAC, the other aspect which is equally important is the durability of concrete when exposed to severe environment. Published research works on LWAC reported that although LWA was more porous than NWA, the LWAC have similar durability performance as the normal weight aggregate concrete (NWAC) [6,22–23]. Even though LWAC portrayed similar durability performance as NWAC, the LWAC with the same mix proportion as NWAC exhibited a drop in strength as compared to the NWAC [6,22–23]. Kockal and Ozturan [6] attributed the drop in strength of LWAC to the higher porosity and lower strength of the LWA as compared with the NWA when incorporated into the concrete.

In this paper, the artificial LWA produced from the previous work [21] using lime-treated SS and POFA, also known as Posslite LWA is utilised to fully replace the normal weight limestone crushed aggregate in concretes. The performance characteristics of the LWAC and NWAC were investigated through compressive strength, tensile splitting strength, flexural strength and modulus of elasticity representing the mechanical behaviour; the volume of permeable voids (VPV), sorptivity, short-term rapid chloride penetration test and long-term salt ponding test representing the durability of concrete as well as the prediction of service life when exposed to chloride environment.

2. Experimental details

2.1. Materials used

ASTM Type 1 normal Portland cement was used in this study. The artificial Posslite LWA used in this study was made from lime-treated sewage sludge (SS) and palm oil fuel ash (POFA) via sintering, as discussed in a previous work [21]. Limestone aggregate was used as the conventional NWA. According to Flügel [24], limestone contains more than 50% by mass of CaO. As the NWA used in this study contains 55.3% by mass CaO, it can be classified as limestone.

The Posslite LWA and NWA with a maximum size of 25 mm were used to make the lightweight concrete (LWAC) and normal weight concrete (NWAC), respectively. No superplasticiser was incorporated into the concrete mixes. Natural river sand was used as fine aggregate. The particle densities of the Posslite LWA, NWA and natural river sand were 1911 kg/m^3, 2651 kg/m^3 and 2592 kg/m^3, respectively. The fineness modulus of the river sand was 1.75. The sieve analysis of the Posslite LWA and NWA is shown in Fig. 1. The Posslite LWA and NWA were within the grading requirements of ASTM C 33 [25]. However, the Posslite LWA used in this study was coarser than NWA, as indicated by the grading curve of Posslite LWA which was just on the lower limit of the ASTM C 33 [25] grading curve, as shown in Fig. 1.

2.2. Preparation of concrete samples

The concrete mix proportions of NWAC was first designed with the targeted strength of 50 MPa, in accordance with the design of normal concrete mixes [26] as shown in Table 1. All concretes mixes contained the same weight per cubic meters of water, cement, coarse and fine aggregates. The NWA was replaced by Posslite LWA by volume to produce Posslite LWAC. For each concrete mixture, the concrete samples presented in Table 2 were cast. According to BS EN 206: Part 1 [27], the oven-dried density of LWAC must exceed 800 kg/m^3 but not more than 2000 kg/m^3. From Table 1, the oven dried density of the concrete produced using the Posslite LWA was 1981 kg/m^3 and thus, it can be categorised as LWAC. The Posslite LWAC possessed 15% lower density (Table 1) as compared to NWAC produced using the same mix proportion, which signifies that this Posslite LWAC can reduce the dead-load of building and eventually reduce the required size of footings.

The slumps of the concretes were determined in accordance to BS 1881: Part 102 [28]. The Posslite LWA and NWA were pre-soaked in water for 24 ± 1 h before mixing, in order to maintain the same saturated surface dry (SSD) condition for both types of coarse aggregates. Immediately after mixing, the fresh concrete samples were poured into the respective moulds and then allowed to set for 24 ± 4 h before being demoulded. The demoulded concrete samples were then cured in water at a temperature of 26 ± 2 °C until the age for testing.

2.3. Test methods for Posslite LWA

The Posslite LWA was examined using the X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray (EDX), toxicity characteristics leaching procedure (TCLP), which was described in the following subsections.

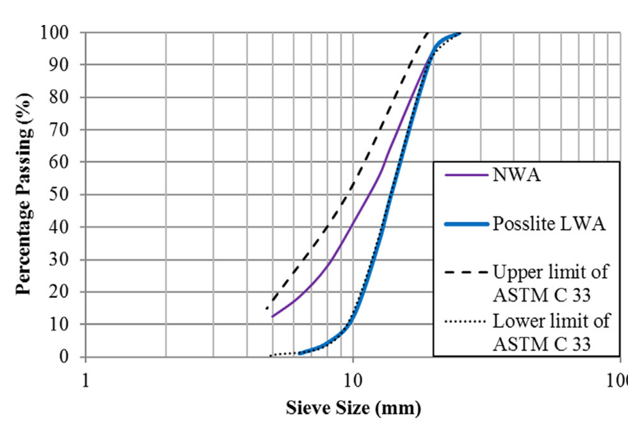

Fig. 1. Sieve analysis of NWA and Posslite LWA.