



Effects of elevated temperatures on the thermal behavior and mechanical performance of fly ash geopolymer paste, mortar and lightweight concrete



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HIGHLIGHTS

- Preparation of structural lightweight building geopolymer concretes (LWAGC).
- Studying the effect of high temperatures on the thermal behavior of LWAGC.
- Addressing the macro/microstructural changes for the heated geopolymeric products.

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ABSTRACT

This paper reports a comparative study of the influence of elevated temperature on geopolymer paste, mortars and lightweight aggregate geopolymer concrete (LWAGC) systems made by using fly ash (FA) as only source material. The mechanical, thermo-physical and macro/micro-structural properties of the geopolymers before and after the exposure to elevated temperatures of 400, 600 and 800 °C have been investigated. The sequential changes in the geopolymeric gel structure upon the exposure to the elevated temperature and their reflections on the geopolymers thermal behavior have been also explored. The physical properties of the unexposed geopolymers to elevated temperatures show that the LWAGC possesses lower density and water absorption than the geopolymer paste and mortar. The mechanical strength of the geopolymer materials prior firing shows that the geopolymer paste and mortar possesses significantly high strength compared to the LWAGC, due to the lightweight aggregate (LWA) low strength and porous microstructure. It is found that the relatively high activator content used to activate the raw material, FA, results in excellent mechanical and microstructural properties for the unexposed geopolymers to elevated temperatures. While, it is significantly participating in the deterioration of the geopolymers mechanical and physical properties after exposed to the elevated temperatures especially at 800 °C by producing high unreacted silicate species. Introducing the LWAs to the geopolymeric structure considerably enhances the mechanical and microstructural properties of the geopolymers at elevated temperatures. This is attributed to the low thermal conductivity characteristics of the LWAs which inhibited the heat diffusion through the structure. The reported excellent thermal performance of LWAGCs at the elevated temperatures would increase the suggested application for this novel environmentally-friendly material.

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1. Introduction

Worldwide, It is well-known that the lightweight concrete (LWC) has more advantageous than the normal weight concrete (NWC) by the reduction of the dead-weight of the structure, better thermal insulation for buildings and less cost for transportation.

Lightweight concretes (LWC) are commonly used in the construction of buildings, bridge deck pavements, and in more limited role, for entire bridge superstructures [1–3]. The usage of lightweight aggregates (LWAs) is one of the most common methods used to produce lightweight building materials. The lightweight aggregate concrete (LWAC) has obvious advantages of high strength-to-weight ratio, good tensile strength, low coefficient of thermal expansion, and superior thermal and acoustic insulation characteristics due to the air voids within its structure [4].

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In early 1980s, professor Joseph Davidovits introduced the geopolymerization technology as an ideal and novel environmentally-friendly process for producing supplementary materials to the ordinary Portland cement (OPC) that possessing higher mechanical and durability properties. The geopolymers synthesizing technology is based on the relatively simple alkaline activation of a source material which is rich in silicon (Si) and aluminum (Al) in amorphous form at relatively low temperature [5]. The resultant geopolymer material can be used as a binder instead of the OPC binder to bind different types of aggregates to produce geopolymer mortars and concretes. The geopolymer materials are reported to be capable to reduce the CO₂ emission by 80–90% comparing to the OPC [6]. Other studies reported that the geopolymers have early strength, low permeability, excellent resistance to chemical attacks, good freezing–thawing cycles and a tendency to immobilize the heavy metal ions in their structure [7–9]. The typical source materials used for making geopolymers are metakaolin or industrial waste materials like fly ash (FA), slag and rice husk ash [10,11]. However, it is obvious that the utilization of industrial waste precursor like FA in the synthesizing of geopolymer materials will enhance the environmental and economic credentials of the final product [12].

Nevertheless, paucity in the published studies and researches regarded to the utilization of the LWAs in production of lightweight aggregate geopolymer concrete (LWAGC) has been noticed [13]. In the method of making LWC known as “no-fines concrete”, Wu and Sun [14] reported a no-fine LWC based on the activation of FA and MK as source materials using a mixture of sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) solutions. They used two types of LWAs, namely, Cenospheres and expanded polystyrene (EPS) in making of two LWCs. The concretes were cured at 0-different curing conditions of 80 °C (for 6, 12 and 24 h) and 22 °C. The optimum EPS concrete possessed a compressive strength of 22.6 MPa and an Oven-dry (OD) density of 1010 kg/m³ at age of 28 days, while the optimum Cenospheres concrete had a compressive strength of 12.8 MPa and an OD-density of 1020 kg/m³ at the same aging period.

Furthermore, Hu et al. [15] studied the fire resistance of lightweight geopolymer mortar prepared by the alkali-activation of MK via liquid alkaline activator consisting of Na₂SiO₃ and NaOH solutions and the resulted geopolymer used to bind the lightweight fine aggregate of crushed shale haydite sand. The resulted lightweight geopolymer mortars cured at 20 °C for 28 days showed a strength loss percentage up to 63% of the initial strength after exposed to elevated temperature of 950 °C for 30 min. Whereas, Yang et al. [16] reported the usage of lightweight expanded clay aggregates (LECA) and normal-weight sand in preparation of a lightweight alkaline activated mortars and concretes, based on the alkali activation of ground granulated blast-furnace slag (GGBS) with sodium silicate powder and tap water. The cured mortars and concretes at room temperature showed a bulk density range of 775–1615 kg/m³ and a compressive strength range of 3.3–19.1 MPa at age of 28 days.

To our knowledge, there is no published work yet has been utilized the FA individually as a source material in production of LWAGC consisting from LWA and normal-weight sand, despite the high attention paid to the advantages of these materials. Thus, the first contribution of the current study is to highlight the LWAGC preparation using the alkali activation of a locally FA as the only source materials.

The previous studies that investigated the thermal properties of the FA geopolymers have reported that these materials possessed low thermal shrinkage and good strength maintenance after exposed to high temperatures [17–20]. The FA geopolymers in these papers were directly heated from room temperature up to the elevated temperature of 800 °C or further up to 1200 °C, without

studying the changes in the geopolymer phase composition and microstructure occurred at temperatures ranged from about 600–800 °C. Recently, these changes have been highlighted via dilatometric analysis [12,21], however, these studies were focused substantially on the effect of the silicate phase concentration exist in the FAs sources and/or geopolymers which lacks to the microstructural and mechanical analysis.

The main objective of the current study is to address the mechanical and the macro/micro- structural changes that the FA geopolymer products experience during heating at temperatures up to 800 °C. The current paper reports the mechanical, microstructural and thermo-physical performance of LWAGC system after exposing to different elevated temperatures of 400, 600 and 800 °C to enhance the understanding about this new type of building materials.

2. Experimental procedure

2.1. Source materials

The FA used in this work was provided by the Manjung Power Station, Lumut, Perak, Malaysia. The chemical composition of the FA was determined by X-ray fluorescence (XRF) as listed in Table 1. It can be observed that the calcium oxide content is more than 10%; hence it can be classified as Class-C fly ash according to ASTM C618-08 [22]. Fig. 1 illustrates the FA particle size analysis showing that the majority of FA particles size is smaller than 40 μm. The FA particles have specific surface area of 0.463 m²/g. Fig. 2a and b shows the normal scale as well as SEM micrograph of the FA used in FA geopolymer paste, mortar and LWAGC preparation. The SEM micrograph (Fig. 2b) shows that the FA consists mostly of hollow microspherical particles with the appearance of bright crystals. The FA was activated with alkaline activator prepared by mixing a technical grade sodium silicate (Na₂SiO₃) and sodium hydroxide solution (NaOH). The chemical composition of the Na₂SiO₃ was SiO₂ = 30.1%, Na₂O = 9.4%, H₂O = 60.5% and the modulus ratio (M_s) equal to 2 (where $M_s = \text{SiO}_2/\text{Na}_2\text{O}$). The NaOH of 12 M was prepared by mixing sodium hydroxide pellets of 97–99% purity with distilled water. The alkaline activator prepared by mixing the Na₂SiO₃ and 12 M NaOH solution at a constant mass ratio of 1:1.

The LWA used for the LWAGC preparation was a commercially lightweight expanded clay aggregate (LECA) illustrated in Fig. 3a. The LWA granules were spherical in shape with closed surface having slightly rough porous texture. Fig. 3b shows the bulk characteristics of the adopted LWA used in the preparation of the LWAGC as seen under the optical microscopy. It can be observed the multi-fine micro-pores and voids exist consistently within the interior structure of the LWA. Furthermore, Table 2 shows the physical properties of the LWA.

The fine aggregate was locally available river sand having water absorption of 1.6% and specific gravity of 2.50. The sieve analysis for the LWA and sand is shown in Table 3. The aggregate particle distribution for the LWA ranges from 4 to 8 mm and the maximum size of the sand is 2.38 mm having fineness modulus of 2.83.

2.2. Specimens preparation

2.2.1. Mixing of the geopolymer paste

The geopolymer paste specimens were prepared by mixing the FA with the advanced prepared alkaline activator liquid in a 5 L capacity mixer for about 5 min. After that, the mixture was poured into 100 mm × 100 mm × 100 mm cubic plastic molds, which is the sample's dimension. The specimens were then vibrated using a vibrating table for 2 min to release any residual air bubbles. Subsequently, the molded specimens were wrapped using a thin plastic sheet to prevent water evaporation.

2.2.2. Mixing of the geopolymer mortar and LWAGC

The mix proportioning of the LWAGC was made according to ACI 211.2 standard [23]. The term of water/cement ratio used in the standard was modified to Activator/FA ratio in order to fit the terms used in the geopolymeric technology. In our previous work, it has been suggested that the adoption of the proposed Activator/FA ratio by ACI 211.2 standard, produced the optimum preparation and mechanical properties for the LWAGC [13]. The LWAs were prepared in oven-dry condition (OD) by pre-dried at 105 °C for 24 h in order to remove any residual moisture prior to mixing due to the highly moisture absorption capability of the LWA. While the fine aggregate was prepared in air-dry condition (AD) by first being washed with a tap water and then dried in shade for 24 h prior mixing. The absorbed water by the LWAs and fine sand was constrained during mixing by adding extra water equivalent to the quantity of the water absorption of each aggregate type. In practice, the FA and aggregates (LWA and/or sand) were mixed in a pan mixer for 3 min. Then, the prepared alkaline activator liquid and the extra water dosages were gradually added to the solid constituents. The wet mixing continued for further 5 min until the mixture homogenized. Then, the mixtures were poured into

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