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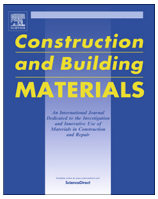

Internal heat liberation and strength development of self-cured geopolymers in ambient curing conditions

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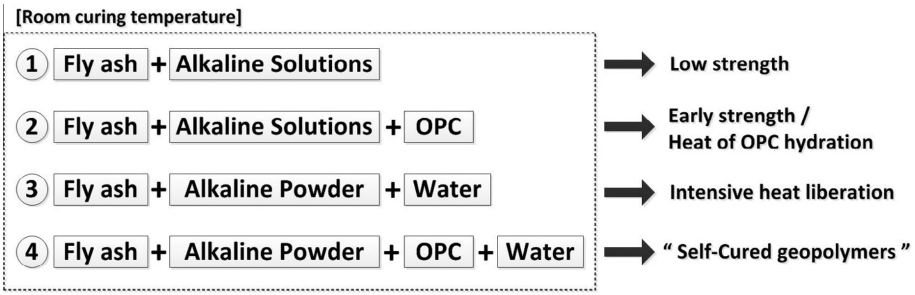
HIGHLIGHTS

- Inclusion of OPC increased early strength and shortened setting time of GeoPC system.
- Heat liberation in GeoPC system was mainly influenced by (inclusion) OPC hydration.
- Pre dry-mixing process released intensive heat when reacted with water.
- Pre dry-mixing process provided ability for practical work and in-field applications.
- GeoPC system and Pre dry-mixing could achieve the Self-cured GP production.

GRAPHICAL ABSTRACT



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ABSTRACT

Curing geopolymers with a temperature around 40–90 °C can significantly improve the mechanical properties and mechanisms of reaction. There is a challenge to develop GP with its abilities of curing in ambient temperature (22 ± 2 °C) without external source of heat supply for on-site practices. This study is extended from the previous research work on the influence of OPC inclusion and manufacturing process. The main aim is to study and evaluate the effects of additional OPC (GeoPC system) and manufacturing procedures on accumulated-internal heat liberation and strength development of low calcium fly ash-based geopolymer paste. The results showed that the GeoPC compounds and manufacturing procedures were closely related to the curing process, internal heat, microstructure development and hence properties of the end products. Both optimum GeoPC mixtures and new-introduced mixing method (pre dry-mixing) have been generated, providing clear potential and basis of the development of self-cured geopolymers to achieve the mechanical strength and for on-site construction under ambient conditions.

1. Introduction

Ordinary Portland cement (OPC) is an energy consuming product with high carbon dioxide (CO_2) emission along its production process. To reduce the amount of greenhouse gas, alternatives have been studying to partially or totally replace the consumption of OPC [1]. Many research studies have revealed that fly ash, blast furnace slag and other aluminosilicate materials can be used as prime materials to produce a cementitious binder by activating with alkaline solutions, which is known as alkaline-activated cement or geopolymer cement [2–5]. Due to the complexity of various factors affecting its reaction, the definite mechanism of the alkaline-activated cement is not yet fully understood. However, many researchers agree that its mechanism consists of three-stage model which are dissolution, gelation and polymerization/hardening

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[6,7]. Apart from that, the term "Geopolymers" (by Davidovits J., 1979) is also used and receives much more attention as an alternative binder for construction material [8,9]. The final reaction products of those systems can be C-S-H (Ca + Si), zeolite/polymers (Si + Al) or C,N-A-S-H (Ca,Na + Al + Si) which mainly depend on the characteristics of raw starting materials and alkaline activators [6,10–17].

In construction sector, Geopolymers (GP) is developed and theoretically produced by utilising industrial by-products or wastes such as fly ash, silica fume or even agro-waste ashes. Fly ash, a by-product from coal-fired power station, seems to be the most widely used prime material for the production of geopolymers because of its richness in alumina-silica composition and the considerable un-utilised quantity [18]. The most commonly used alkaline materials are a combination of sodium hydroxide or potassium hydroxide (NaOH, KOH) with sodium silicate or potassium silicate (Na_2SiO_3, K_2SiO_3) [8,19]. Curing condition is one of the major factors affecting the mechanical properties and micro-structures of geopolymers. At ambient temperature around 20–25 °C, fly ash-based geopolymers does not completely harden and could not be tested on compressive strength in the first day after synthesis [20,21]. Somehow, it has been found to achieve very high strength in both early and later stages when cured in high temperature e.g. 40–90 °C [2,3,22–24]. Furthermore, some of its properties have also been reported to be similar as or even better than those of OPC [4,18].

A numerous researchers have studied on the improvement of setting and strength properties of fly ash-based geopolymers without high temperature curing. The considered challenge is to step over the limitation of heat curing process: precast components, and to be more convenient in practical works or in field applications. Some additives such as ground granulated blast furnace slag, gypsum, Portland cement or even high calcium fly ash are studied in order to enhance the reasonable strength development in ambient curing conditions [14,18,25–28]. The use of OPC as an additive in geopolymers is widespread due to its uniformity complied with any standard and its global availability as a commercial construction material. This hybrid cementitious system is generally classified as an alkali-activated Portland blended cements or alkali-activated Portland fly ash cement [29] or, sometimes, called Geopolymer-Portland cement (GeoPC) [21]. Incorporating Portland cement to the system leads to significant effects on the setting behaviour and early strength development. The extra heat liberated by exothermic reaction of OPC and water could also provide a positive effect enhancing its mechanical properties and microstructures [10].

Another latent factor influencing the properties of geopolymers is mixing order. It is confirmed that the optimum/proper mixing order leads to better results, especially for any alkaline-activated binder [19,30]. For general mixing, alkaline solutions (e.g. NaOH and Na_2SiO_3) are firstly prepared and left over-night to confirm a complete dissolution. Prime materials and those alkaline solutions are incorporated and mixed together at the same time [31–34]. Apart from that, the separate mixing is also studied. Hydroxide soluble (e.g. NaOH) is initially mixed with prime materials, and subsequently added by silicate soluble (e.g. Na_2SiO_3) [17,25,34,35]. Those two aforementioned procedures, general mixing and separate mixing, provided a satisfactory result as fully dissolved alkaline activators are used. However, the separate mixing process seemed to get slightly higher strength than that of normal mixing. As the initial mixing with NaOH solution led to a high rate of leaching, more silica, alumina and other ions from prime materials are therefore obtained, leading to more degree of geopolymerization [31,34,36,37]. In addition, pre-dry mixed process (working with solid activators instead of alkaline solutions) was proposed to be developed by just mix with water [29]. The attempts to simplify geopolymers mixing process, by crushing fully-activated final product into powder, and adding water to re-activate the reaction again as called "one-part geopolymers" or "just adding water geopolymers", were also studied [38–40]. With the pre dry-mixed process, extra water in the system might be required in order to sufficiently activate all solid materials, therefore, low mechanical strength may be obtained by the increase of water-to-solid (w/s) ratio. However, the main aims of the development of this dry-mixed process should be primarily focused on its advantages in term of practical work in field applications, and properties.

The previous work, from our intensive study on self-curing geopolymers, concluded that the self-cured geopolymers could be developed with the setting time and early strength being affected by the OPC replacement and the manufacturing procedures [21]. The main aim of this paper is to study and evaluate the effects of additional OPC (GeoPC system) and potential manufacturing procedures (pre dry-mixing process) on accumulated-internal heat liberation and strength development of low calcium fly ash geopolymer paste as "Self-cured geopolymers".

2. Materials

Coal-fired fly ash was supplied by the Drax power station, North Yorkshire, UK. Its properties comply with BS EN 450-1:2012, fineness category S and loss on ignition category B (similar to low calcium fly ash class F specified by ASTM: C618). OPC was commercial CEM II/A-L under the brand name of Cemex. The chemical compositions of fly ash and OPC were examined by using the Energy dispersive X-ray Analysis (EDXA) technique and are summarised in Table 1. Alkaline materials used in this study were sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The sodium hydroxide pearl was purchased from the Fisher Scientific, UK and prepared as a solution with the concentration of 15 M (M). Sodium silicate powder was also purchased from the Fisher Scientific, UK with a SiO_2 to Na_2O ratio (M_s Modulus) of 2.0. The sodium silicate solution with 48.20% w/w was used in the experimental work. To prepare sodium silicate solution, solid powder was weighted in the container and filled with the designated amount of purified water (e.g. 48.20 g of sodium silicate powder and 51.80 g of purified water).

3. Experimental details

3.1. Mixture designation of OPC, geopolymers and GeoPC pastes

OPC paste was made of cement powder and the purified water with the water-to- cement ratio (w/c) at its standard consistency of 0.25. Geopolymer paste was manufactured with general mixing process (process B, see Section 3.2) and composed of fly ash, sodium hydroxide and sodium silicate. The sodium hydroxide and sodium silicate solutions were prepared and left overnight before uses to ensure a thorough solution achieved. The sodium silicate solution-to-sodium hydroxide solution (SS/SH) ratio by mass was 1.50 and the constant alkaline liquid-to-fly ash (A/FA) ratio by mass was 0.40. A series of Geopolymer-Portland cement paste (GeoPC) was made from the designation mass of GP and OPC paste in general mixing process (process B, see Section 3.2). The mass of each material used, including alkaline solution and water, was calculated individually from the designed GP and OPC pastes (e.g. GeoPC30 is composed of 70% GP-paste and 30% OPC-paste). The mass of each material used in GeoPC system, including alkaline solution and water, was calculated individually from the designed GP and OPC pastes). A standard mortar mixer with speed of 140 ± 5 rpm was used to synthesize each mixture in ambient temperature of 18–22 °C. It is noted that the GeoPC mixtures which have OPC replacement from GeoPC30 to GeoPC90 were synthesized with 4% added-water in order to obtain the workability in practical work.