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Effects of fly ash characteristics and alkaline activator components on compressive strength of fly ash-based geopolymer mortar

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HIGHLIGHTS

- A total of 180 geopolymer mortar mixes were prepared by activating fly ashes from five sources.
- Different proportions of NaOH and Na_2SiO_3 were used in activating the fly ashes.
- Characteristics of the fly ash govern the mix proportion of the alkaline activator.

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ABSTRACT

The compressive strength of fly ash-based geopolymer mortar (FBGM) made from five different sources of fly ash was examined. The weight ratio of alkaline activator to fly ash content (AL/FA), the weight ratio of sodium silicate to sodium hydroxide (Na_2SiO_3/NaOH) and concentration of the NaOH were considered the main parameters. A total of 180 FBGM mixes were prepared and tested for compressive strength. The results indicated that the optimum AL/FA ratio for activating fly ashes was in the range of 0.5 and 0.6. The compressive strength of the FBGM that were mixed with different fly ashes exhibited different response to the increase of the Na_2SiO_3/NaOH ratio and NaOH concentration. Fly ashes with a high content of fine particles and amorphous components such as SiO_2 and Al_2O_3 activated at a low dosage of Na_2SiO_3/NaOH ratio and NaOH. While the activation of fly ashes with a low content of fine particles and amorphous components required a high dosage of Na_2SiO_3/NaOH ratio and NaOH. An artificial neural network was developed and the analytical results showed high performance in predicting the compressive strengths of the FBGM.

1. Introduction

Geopolymer is emerging as an eco-friendly alternative to the Portland cement. The geopolymer is synthesized from the chemical reaction (geopolymerization) between the aluminosilicate materials (industrial by-product, such as fly ash or blast furnace slag) and alkaline activators [1]. Recently, fly ash is gaining more attraction to be used in producing geopolymers. This is because fly ash is considered a cheap and a widely available material [2]. Also, using fly ash in producing geopolymers contributes in decreasing the environmental impacts due to the disposal of the fly ash in landfills [3]. Fly ash is broadly produced in Australia from the combustion of the coal in power plants. Different power plants usually use different types of coal (bituminous and lignite coal), different methods of burning the coal and different ways in collecting the fly ash. Consequently, power plants usually produce different types of fly ashes having different characteristics [4,5]. Hence, the use of fly ash in producing geopolymers faces obstacles related to controlling the fly ash characteristics.

Different parameters influence the extent of the geopolymerization between fly ash and alkaline activator. The parameters include chemical and physical characteristics of the fly ash as well as properties of the alkaline activator [6]. In general, silicon oxide (SiO_2), aluminium oxide (Al_2O_3), calcium oxide (CaO) and iron oxide (Fe_2O_3) are considered the major constituents of the fly ash. According to the Ash Development Association of Australia [2], the SiO_2 and Al_2O_3 are considered the main oxides of the Australian fly ashes where they represent about 80% by weight of the fly ash. The contents of components including CaO and the Fe_2O_3 are less than 20% by weight of the fly ash. The total weight of oxides such as Na_2O, K_2O, MgO and SO_3 is less than 5% by weight of the fly ash. The particle size distribution of the fly ash is considered the main physical characteristics of the fly ash. The distribution of these oxides in the fly ash determines the extent of the geopolymerization with the alkaline activator [7].

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The SiO_2 exists in different microstructural forms (phases): crystal and amorphous forms. The amorphous SiO_2 is dissolvable (reactive) in alkaline activator more than the crystal SiO_2 [8–10]. The percentage of the amorphous SiO_2 relies on the temperature used in burning the original coal and cooling the fly ash [11,12]. Thus, the role of the SiO_2 in the geopolymerization with alkaline activator depends on the percentage of the reactive SiO_2 in the fly ash. The Al_2O_3 significantly affects the geopolymerization between the fly ash and the alkaline activator. As in the SiO_2, the amorphous Al_2O_3 represents the reactive phase of the Al_2O_3 to react with the alkaline activator. At the early stages of the geopolymerization, the Al_2O_3 acts as an auxiliary factor in dissolving the SiO_2 in an alkaline activator forming aluminosilicate gel [9,13,14]. Fernández-Jiménez et al. [10] stated that the reactivity of the fly ash with alkaline activator relies on the balance between the amount of the reactive SiO_2 and the reactive Al_2O_3. The presence of the CaO in the fly ash is considered as the promoting factor in the early compressive strength of the geopolymers [12,15–17].

On the other hand, the particle size distribution of the fly ash has a significant impact on the geopolymerization with alkaline activator. It was reported that the increase in the percentage of fine particles increases the reactivity of the fly ash [8,18,19]. The increase in the reactivity of the fly ash is attributed to the increase of the exposure area between the fly ash particles and the alkali activator [5,9,12]. As a result, the interaction effect due to the chemical and physical characteristics of fly ash leads to a considerable variation in the geopolymerization with alkaline activator.

Different types of the alkaline activators are used in activating the fly ash in order to produce geopolymers. A mix of hydroxide (NaOH and KOH) and liquid silicate (Na_2SiO_3 and Ca_2SiO_3) are commonly used in activating fly ash in the geopolymers. The properties of the alkaline activator are dependent on the types and concentrations of the components used in preparing the alkaline activator [20–23]. The selection of the alkaline activator properties is dominated by the fly ash characteristics.

The significant differences in the fly ash characteristics influence proposing a standard method for the selection of the geopolymers mix proportions, particularly, the dosage of the alkaline activator. Several research studies examined different mix proportions of fly ash-based geopolymers using different synthesis conditions. The use of different synthesis conditions complicated the analysis of the controlling factors in the selection of the mix proportion [3,24–29]. A few researchers have attempted to propose methods of selecting the mix proportions of geopolymers [30–34]. Junaid et al. [34] proposed a mix design method for fly ash-based geopolymer concrete. However, the method proposed in Junaid et al. [34] was limited to selecting the mix proportion of the geopolymer concrete using a specific source of fly ash (Eraring fly ash). Pavithra et al. [30] used the same method of selection of the water/cement ratio (w/c) for normal concrete in selecting the amount of the alkaline activator for fly ash-based geopolymer concrete. However, the method of selecting of the water/cement ratio (w/c) might not be suitable for geopolymers as this method was originally designed for estimating the amount of water required to hydrate Portland cement [35]. This is because the nature of the reaction (geopolymerization) between the alkaline activator and the fly ash is significantly different from the reaction (hydration) between the water and Portland cement [36,37]. In general, the proposed methods in Azreen et al. [32], Olivia and Nikraz [31], Kupaei et al. [33], Junaid et al. [34] and Pavithra et al. [30] have not adopted as a standard procedure for selecting of the mix proportions of the geopolymers due to the limitations of these methods. Consequently, more investigations are required to extend the current knowledge about the relationship between different fly ash characteristics and different alkali activators, which can contribute in proposing a standard method of selection of the mix proportion of geopolymers.

The relationship between fly ash characteristics and properties of the alkaline activator in geopolymer is considered as a complex system. Thus, a robust method is required to model the relationship between the primary variables to understand the effect of each parameter on the geopolymer matrix. The artificial neural network (ANN) is a powerful method used in modelling complex systems. The ANN is used for modelling the properties of the normal concrete [38–46]. Thus, the ANN can be used for modelling the fly ash-based geopolymer mortar to understand the effect of the fly ash characteristics on the selection of the alkaline activator component.

In this paper, a comprehensive study on the effect of different fly ash characteristics on the optimum proportions of the alkaline activator components was conducted. The relationship between fly ash characteristics and properties of the alkaline activator was used in developing an ANN model. The result of the ANN model can assist in proposing a mix design method for the fly ash based geopolymer concrete.

2. Experimental methodology

In this study, fly ash Type F, supplied from five different sources, were activated using different proportions of alkali activator to produce geopolymer mortar. The alkali activator was prepared by mixing sodium hydroxide (NaOH) with sodium silicate (Na_2SiO_3) having different proportions. The sections below discuss the materials and the methods that were used in preparing of the mixes, curing and testing of the specimens in details.

2.1. Materials

2.1.1. Fly ash

In this study, fly ash Type F supplied by Ash Development Association of Australia (ADAA) [47] from five different Australian power stations: Eraring (ER), Mt Piper (MP), Bayswater (BW), Gladstone (GL), and Collie (CL) was used in producing geopolymer mortar. The X-ray diffraction (XRD), X-ray Fluorescent (XRF) and the particle size distribution analysis of the fly ash were conducted at the laboratories of the School of Earth & Environmental Sciences, University of Wollongong, Australia. The results of the XRD and XRF of the major elements and minerals of the fly ash are shown in Fig. 1, Tables 1 and 2, respectively. The particle size distribution analysis of fly ash samples is shown in Fig. 2.

The results of the analysis of the major elements and minerals of the fly ash revealed that all fly ash samples are classified as Type F according to the ASTM-C618 [48]. The summation of SiO_2, Al_2O and Fe_2O_3 content for all fly ashes were higher than 70%, and the CaO content was less than 8%. Also, the percentages of unburned particles in terms of the Loss On Ignition (LOI) for all fly ashes were ranging from 0.7% to 1.7%. The results of the particle size distribution test showed that the fineness modulus (percentage of the particles retained on sieve 45 μm (No. 325)) of fly ashes ER, MP, BW, GL and CL were 30%, 23%, 15%, 11% and 14%, respectively. Moreover, the median particle size (particles diameter of 50% the passing particles) of fly ashes ER, MP, BW, GL and CL were 24.8, 20.5, 17.0, 3.5 and 9.0 μm, respectively.

For most studies, the fineness modulus is commonly used to express the particle size distribution. However, in this study, the median particle size of the fly ash was used in expressing the particle size distribution. The use of median particle size was due to the significant variance in the median particle size between the fly ashes compared to the variance in the fineness modulus, as shown in Fig. 1. For example, the variance in the fineness modulus between BW and CL was about 6%, while the difference in the median particle size was 52%. Thus, the use of median particle size gave a realistic expression to the particle size distribution of the fly ash.

2.1.2. Alkaline activator

The alkaline activator used in this study was prepared by mixing of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) in different proportions. The NaOH solution was prepared by dissolving the caustic soda, which contained about 98% by weight NaOH, in distilled water to the required concentrations of the NaOH (12, 14 and 16 mol/L). The solution was prepared 24 h prior mixing with the FBGM mix. The Na_2SiO_3 was provided from PQ Australia Pty., Ltd in liquid form [49]. The Na_2SiO_3 contained about 29.4%, 14.7% and 55.9% by weight SiO_2, Na_2O and water, respectively. The Na_2SiO_3 was blended with NaOH into three Na_2SiO_3/NaOH weight ratios of 1.5, 2.0 and 2.5 according to the studies conducted by Joseph and Mathew [50] and Olivia and Nikraz [31]. The alkaline activator was blended with fly ash into four weight ratios (AL/FA) which are 0.4, 0.5, 0.6 and 0.7. The ranges of the AL/FA