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Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete

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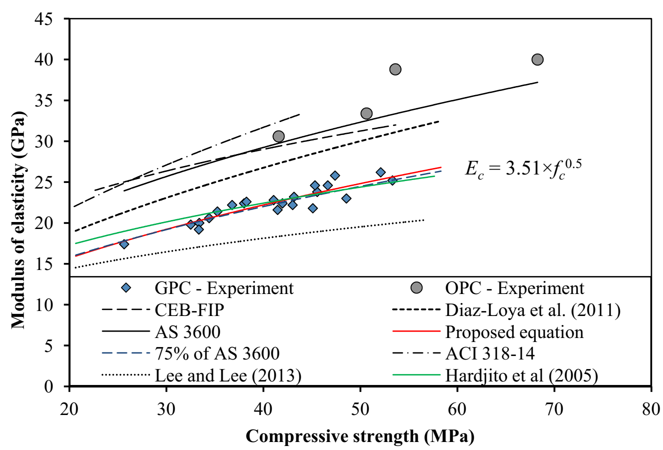
HIGHLIGHTS

- Fly ash was blended with additives to enable ambient curing of geopolymers.
- Geopolymer concretes (GPC) exhibited higher flexural strength than OPC concrete.
- Elastic modulus of GPC is 25–30% less than that of OPC concrete of same strength.
- An equation is proposed to predict the modulus of elasticity of ambient cured GPC.

GRAPHICAL ABSTRACT

Relationship of modulus of elasticity with compressive strength using existing and proposed equation.



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ABSTRACT

Fly ash geopolymer is an emerging alternative binder with low environmental impact and potential to enhance sustainability of concrete construction. Most previous works examined the properties of fly ash-based geopolymer concrete (GPC) subjected to curing at elevated temperature. To extend the use of GPC in cast-in-situ applications, this paper investigated the properties of blended low-calcium fly ash geopolymer concrete cured in ambient condition. Geopolymer concretes were produced using low-calcium fly ash with a small percentage of additive such as ground granulated blast furnace slag (GGBFS), ordinary Portland cement (OPC) or hydrated lime to enhance early age properties. Samples were cured in room environment (18–23 °C and 70 ± 10% relative humidity) until tested. The results show that, density of hardened GPC mixtures is similar to that of normal-weight OPC concrete. Inclusion of additives enhanced the mechanical strengths significantly as compared to control concrete. For similar compressive strength, flexural strength of ambient cured GPC was higher than that of OPC concrete. Modulus of elasticity of ambient cured GPC tend to be lower than that of OPC concrete of similar grade. Prediction of elastic modulus by Standards and empirical equations for OPC concrete were found not conservative for GPC. Thus, an equation for conservative prediction of elastic modulus of GPC is proposed.

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1. Introduction

Fly ash based geopolymer is earning noteworthy attention in the recent years due to its potential application as a low-emission alternative binder to ordinary Portland cement (OPC) in production of concrete [1]. Numerous studies have been conducted on the development and mechanism of geopolymers originating from different aluminosilicate sources [2–6]. Geopolymer binders are principally produced by the reaction of various alumino-silicate materials such as fly ash, blast furnace slag and metakaolin with an alkali [2,7]. By utilising by-product materials, geopolymer binders can contribute major reduction of green-house gas emission caused by OPC production [8].

Geopolymer is a synthesized inorganic polymer which develops as a three dimensional polymeric chain during the chemical reaction under alkaline condition. Chemical compositions of the source materials and the alkaline liquid govern the microstructural development and mechanical properties of the final product of geopolymerisation [6,9,10]. While OPC and other pozzolanic cements mainly forms calcium silicate hydrate (CSH), geopolymer binders consist of mainly an amorphous alumino-silicate gel with the characteristic of a zeolite precursor [3,7,11]. This microstructural difference results in notable merits of geopolymers over the conventional OPC binder. Geopolymers have been reported to achieve good mechanical and durability properties in both short and long term tests. Geopolymer binders outperform or remain comparable to the OPC in many cases of structural performances [12–16]. Previous studies also recognised the superiority of geopolymer binder in durability perspectives especially in resistances to sulphate, acid and fire exposures [17–19].

Low-calcium fly ash is the most widely used material to produce geopolymer binder. Curing conditions have a great influence on the microstructural and strength development of fly ash based geopolymer. Low-calcium fly ash based geopolymer cured at room temperature takes significantly longer time to set and it gains lower strength in the early ages as compared to the geopolymers cured by heat of elevated temperature [20,21]. Hence, low-calcium fly ash geopolymers are mostly subjected to heat curing at temperatures higher than ambient in order to accelerate the strength development. Depending on the extent of curing and temperature, it is possible to reach close to ultimate strength within short period of time. Compressive strength of heat cured geopolymer concrete increases with the increase of concentration and amount of alkaline liquid, and increase of curing temperature and curing time [5,22]. The value of Young's modulus of elasticity of GPC was shown about 90% of that OPC concrete of same compressive strength and stress-strain relation in compression was similar to that of OPC concrete using the same aggregate type. Fernandez-Jimenez et al. [23] tested some engineering properties of heat cured fly ash geopolymer concrete activated with different activators. According to their study, silicate ions present in the activator solutions improved strength and modulus of elasticity substantially, but caused a slight adverse effect on bond and shrinkage properties. Sofi et al. [24] observed that for a concrete density similar to OPC concretes, the average compressive strengths of geopolymers were close to the design strength. The splitting tensile and flexural strengths of the geopolymer concretes compared favourably with the predictions by the standards for OPC concretes. They also noted that, mechanical properties of IPC mixes depend upon mix design and curing method.

The modulus of elasticity of concrete is an important parameter to assess structural performance at service. Hardjito et al. [5,25] observed elastic modulus results for fly ash geopolymer concrete samples as 23.0–30.8 GPa. In another study [23], modulus of elasticity of GPC was found to be in the range of 10.7–18.4 GPa falling much lower than that of OPC concrete (30.3–34.5 GPa). Puertas et al. [26] compared elastic modulus of pulverized fuel ash (PFA) mortars with OPC mortars and found that alkali activated PFA mortar gained lower elastic modulus than OPC mortar. However, Bondar et al. [27] observed that, although alkali activated natural pozzolan (AANP) mixes gained lower values of static modulus of elasticity than OPC mixtures during first 14 days, the values were about 5–20% higher than OPC mixes in long-term tests. Thus a wide variation in the modulus of elasticity of geopolymer concrete was observed in the previous studies.

Most of these results were obtained from tests of heat cured geopolymer concrete specimens. The heat curing process is considered as a limitation for wide application of fly ash based geopolymer in normal cast-in-situ concreting. However, very little information is currently available for ambient cured GPC that can be used for structural design. Hence, it is essential to investigate in more details the properties of GPC cured in ambient condition. This study investigated some of the mechanical properties of the fly ash based GPC cured in room temperature. The amount and source of calcium in the fly ash was found to have significant effect on the properties of the resulting geopolymer both in fresh and hardened state [10,21,28]. Therefore, some calcium bearing additives were blended with low-calcium fly ash in order to enhance the setting of geopolymer concrete at room temperature. Results of mechanical strengths and modulus of elasticity have been analysed using existing standards and codes for design with reference to heat cured concretes and OPC concrete.

2. Experimental program

2.1. Materials

Geopolymer concrete was prepared using a locally available Class F fly ash [29] as the primary aluminosilicate source. Commercially available ground granulated blast furnace slag (GGBFS), ordinary Portland cement (OPC) or calcium hydroxide (CH) [$Ca(OH)_2$, hydrated lime] was used as additive to improve setting properties of the mixtures. The chemical compositions of fly ash, GGBFS and OPC are shown in Table 1. General laboratory reagent grade calcium hydroxide was used. Alkaline activator was a mixture of 14 M sodium hydroxide (SH) solution and sodium silicate (SS) solution at a SS/SH ratio of 2.5. Sodium silicate solution was constituted of SiO_2 to Na_2O ratio by mass of 2.61 (SiO_2 = 30.0%, Na_2O = 11.5% and water = 58.5%). Locally available natural sand was used as fine aggregate and coarse aggregates were a combination of crushed granite with nominal maximum sizes of 7 and 10 mm meeting Australian Standard specifications [30]. A superplasticiser (Rheobuild 1000) was used to improve workability when required.

2.2. Mixture proportions

Eleven geopolymer concrete (GPC) and two OPC concrete mixtures were prepared. The mixture proportions are shown in Table 2. The mixture variables include the percentage of additive such as GGBFS, OPC and calcium hydroxide, and the amount of alkaline liquid. Mixture 1 was the control mixture containing fly ash only. Mixtures 2 and 3 contained 10% and 15% GGBFS respectively. Mixtures 6 and 7 contained 6% and 8% OPC respectively. There were 2% and 3% calcium hydroxide in mixtures 9 and 10 respectively. All of these mixtures contained 40% alkaline activator with SS/SH ratio of 2.5.

Another series of mixtures were designed with a lower amount of alkaline liquid (35% of total binder) to compare the effect of the amount of alkaline liquid on the properties. Mixtures 4 and 5 were designed with fly ash alone and 10% GGBFS, respectively. Mixtures