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

Pradip Nath[a,*], Prabir Kumar Sarker[b]
[a] Department of Civil Engineering, Curtin University, GPO Box U1987, Perth, WA 6845, Australia.
email: pradip.nath@curtin.edu.au
[b] Department of Civil Engineering, Curtin University, GPO Box U1987, Perth, WA 6845, Australia.
email: p.sarker@curtin.edu.au
[*]Corresponding author: Tel +61 8 9266 7568; Fax +61 8 9266 2681;
email: pradip.nath@curtin.edu.au

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^{o}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.

Keywords: Ambient curing; flexural strength; fly ash; geopolymer concrete, modulus of elasticity.

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 to 30.8 GPa. In another study [23], modulus of elasticity of GPC was found to be in the range of 10.7 to 18.4 GPa falling much lower than that of OPC concrete (30.3 to 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 14M 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 8 and 11 had 6% OPC and 2% calcium hydroxide respectively along with 35% alkaline liquid. To compare with similar grade geopolymer mixtures, two OPC concrete mixtures were designed in accordance with the ACI guideline [31].

The effects of alkaline liquid and additives on workability and setting time of the mixtures were reported elsewhere [21, 32, 33]. Generally, slumps of the mixtures with 40% alkaline liquid were above 200 mm. The mixtures with 35% alkaline liquid generally showed lower workability. Hence, additional water and superplasticiser were used in order to improve workability, as shown in Table 2. Setting of low-calcium fly ash geopolymer at room temperature is generally very slow and it may take more than 24 hours to set. However, setting times of the mixtures of this study using OPC, GGBFS and calcium hydroxide were comparable to that of general purpose cement. Setting time increased with the increase of liquid content and decreased with the increase of the calcium containing additives [21, 32].

For the ease of presentation of the results, the geopolymer mixtures were designated in terms of their variable constituents in the mix as shown in Table 2. The variables are the amount of alkaline liquid (A) and the amount of additives such as GGBFS (S), OPC (P) and calcium hydroxide (C). For example, mixture 2 is designated as “A40 S10” representing a geopolymer mixture containing 40% alkaline liquid (A) and 10% GGBFS (S).

2.3 Method of casting and curing

The GPC mixtures were mixed in a laboratory pan mixer. The alkaline liquid was prepared prior to final mixing with the other ingredients and left in a water bath at room temperature to cool down. The coarse aggregate, sand and the binders were dry-mixed thoroughly in the mixing pan for two minutes before adding the alkaline solution. The premixed alkaline solution was then added gradually and mixing was continued for another 4 to 6 minutes until a consistent mixture was obtained. The fresh concrete mixture was cast in the moulds filling in two layers and each layer was compacted using a vibrating table. The moulds were then stored in a room where the temperature varied between 18 and 23 ^{o}C, and the relative humidity was 70±10%. The samples were removed from moulds after 24 hours of casting and left in the same room to cure until tested. The geopolymer mixtures without any additive (Mix 1 and 4) were de-moulded three days after casting. This is because setting of these mixtures was slow and the specimens were too soft to remove from the mould after 24 hours. The OPC concrete samples were de-moulded 24 hours after casting and cured in water for 28 days. After curing, the OPC specimens were stored in the same condition as the geopolymer samples until tested.

2.4 Test methods

All the mixtures were tested for compressive strength, flexural strength and modulus of elasticity at 28 and 90 days. Compressive strength was reported as the mean value of three cylindrical specimens (100 mm diameter and 200 mm depth) of concrete according to AS 1012.9 [34]. The dimension and weight of each specimen was measured to calculate unit weight of hardened GPC in accordance with the requirements of AS 1012.12.1 [35].

Flexural strength or modulus of rupture was determined by following AS 1012.11-2000 [36]. The average of the results from two prism specimens of dimensions 100 × 100 × 400 mm was reported.

The Young's modulus of elasticity test was conducted in accordance with ASTM C469/C469M – 10 [37]. The test was done using cylindrical specimens of 100 mm in diameter and 200 mm in depth. For each age, at least two cylinders were tested.

3 Results and discussion

3.1 Unit weight of geopolymer concrete specimens

The unit weight or density of the hardened concrete was determined for specimens of every mix before conducting the compressive strength test. Table 3 presents the density, along with the respective compressive and flexural strengths of all the mixtures. The mean density of the GPC mixtures varied in the range of 2323 to 2400 kg/m^3 at 28 days, with a standard deviation of 26.3. This is well within the typical range of normal-weight concrete, 2155 to 2560 kg/m^3, as per ACI building code [38]. The density of ambient cured GPC of this study is comparable to that of heat cured GPC which is almost close to final density due to heat treatment [39]. A slight decrease of unit weight (0.25-1.70%) of the specimens was observed at the age of 90 days. This is due to gradual evolution of the geopolymer matrix through dissipation of water.

The density of the mixtures is compared with compressive strength in Figure 1. It is evident that there is an inherent relationship between compressive strength and the density of concrete. Considering all mixtures at the age of 28 days it can be discerned that the mixtures with greater density achieved higher strength. This is similar to the usual observation in OPC concrete.

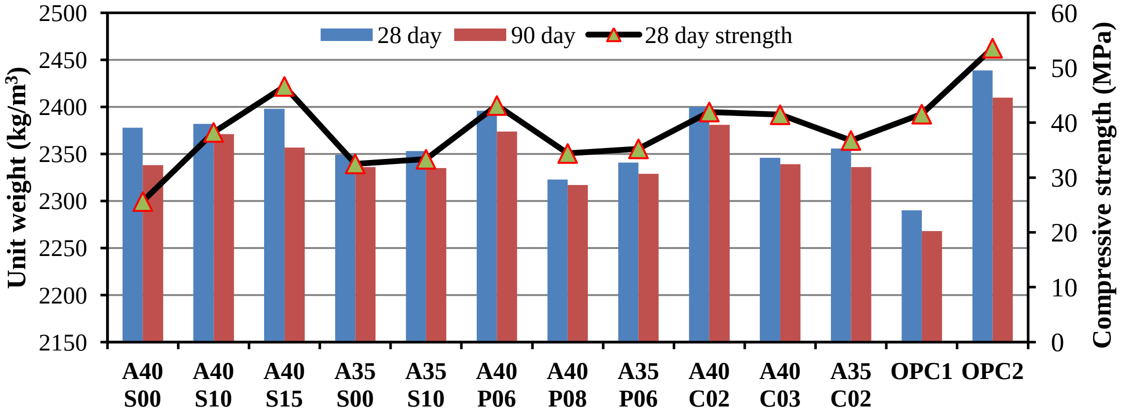

Fig. 1: Comparison of unit weight with compressive strength of GPC.

3.2 Compressive strength

As shown in Table 3, the 28-day compressive strength of the GPC mixtures varied from 25 MPa to 46 MPa. The strength further increased at 90 days in the order of 33 to 53 MPa. Thus, the ambient-cured specimens continued to develop strength beyond 28-days of age. Such continuation of strength development is not usually observed in heat-cured specimens as they develop most of the strength immediately after the heat curing. Figure 2 compares the percentage increase of 28-day compressive strengths of geopolymer concretes with respect to the control mixture A40 S00. It is clear that the 28-day compressive strength increased by the inclusion of GGBFS, OPC or CH with fly ash. Strength increased with the increase of GGBFS in the mixture. This is consistent with that reported in previous study [21]. The mixture A40 P08 having 8% OPC achieved less strength than A40 P06 having 6% OPC. This is possibly due to the additional superplasticiser that was added during mixing to overcome stiff nature of the mixture A40 P08. Although superplasticiser was used in geopolymer mixtures of previous studies, its effect on the reaction mechanism of geopolymer concrete is still not clear [22, 40]. Hardjito and Rangan [41] used naphthalene based superplasticiser as 2% of binder in their study on heat cured fly ash geopolymer concrete. A reduction in strength was noticed when the content of superplasticiser was increased.

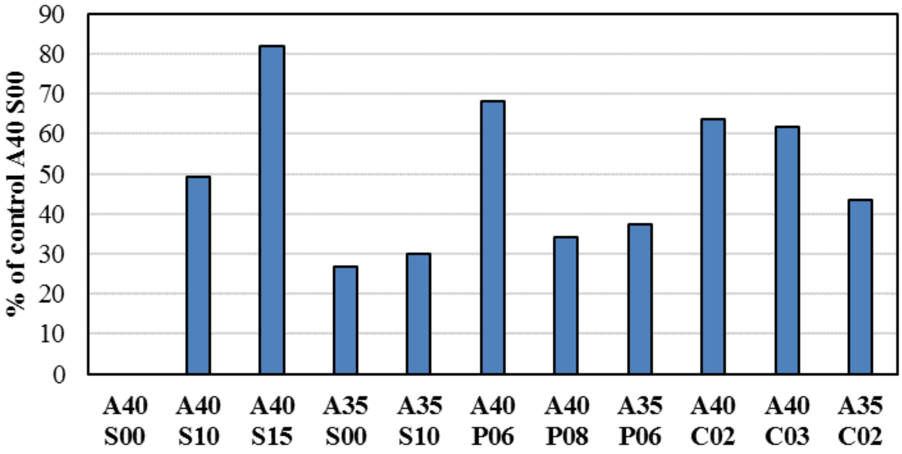

Fig. 2: Percentage increase in 28-day compressive strength of geopolymer concrete by the additives.

The increase of strength was significant when no extra water was added with alkaline activator. The mixtures containing 35% alkaline activator, except A35 S00, showed relatively lower strength than those containing 40% alkaline activator and similar additive contents (Fig. 2). This is because of the addition of extra water along with superplasticiser in the mixtures containing less activator liquid (Table 2). When additional water was included to facilitate workability of the mixtures having 35% alkaline liquid, it increased water to solid ratio (w/s) and reduced the concentration of alkaline activator solution which eventually decreased strength. Adverse effect of water on geopolymerisation is also reported elsewhere [42, 43]. However, the studied mixtures present the effect of a good range of different variable to design GPC mixtures suitable for low to medium compressive strength by curing in ambient condition.

3.3 Flexural strength

Strength of the specimens subjected to flexure can be used as tensile strength of concrete. However, the flexural strength generally shows higher value than the indirect split tensile strength. Hence it is essential to specify the type of test method used for tensile strength in the design process. The flexural strength (modulus of rupture) results of the GPC and OPC concrete specimens are presented in Table 3. Figure 3 compares the flexural strengths of the geopolymer concretes having different additives and OPC concrete with respect to compressive strength. Flexural strength of GPC cured in ambient temperature mostly followed similar development trend as that of compressive strength. It can be seen that flexural strength increased when GGBFS, OPC or calcium hydroxide was used with fly ash. However, when the amount of additives increased after certain limit, flexural strength tended to decline, although was higher than control (A40 S00). As shown in Fig. 3, for the mixtures containing 40% alkaline liquid, flexural strength increased for adding GGBFS up to 10%, OPC up to 6% and CH up to 2%. The mixture having 15% GGBFS (A40 S15), although showed highest compressive strength, has not achieved highest flexural strength, but showed lower values as compared to mix A40 S10, A40 P06 and A40 C02. According to Deb et al. [44], fly ash geopolymer concretes blended with GGBFS up to 20% indicated increased split tensile strength with the increase of GGBFS. Those mixtures used aggregate size up to 20 mm whereas this study used a maximum aggregate size of 10 mm. This implies the effect of mixture composition on the tensile strength of the mixtures having additives.

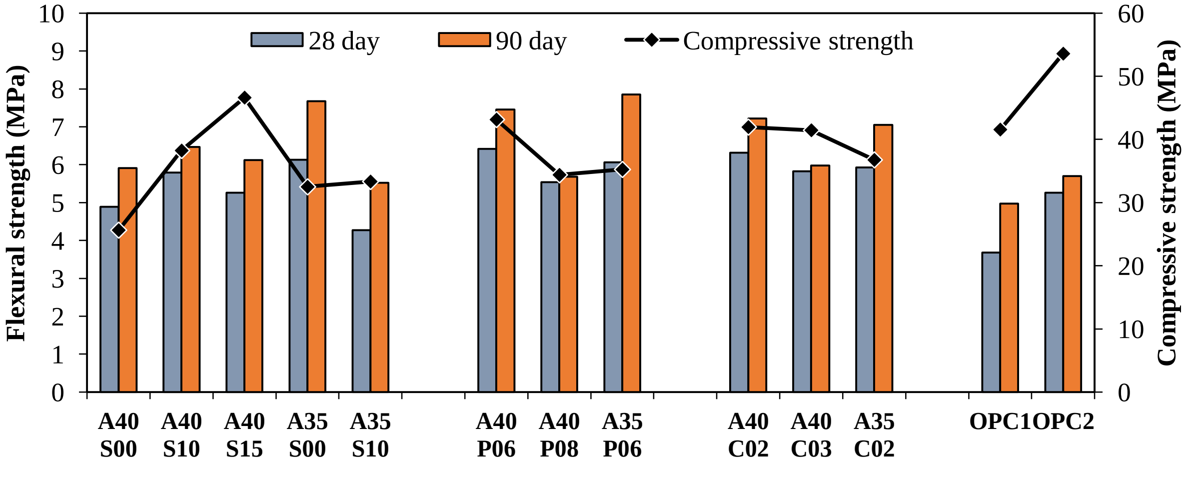

Fig 3: Flexural strength of GPC and OPC concrete compared with 28-day compressive strength.

When compared with OPC concrete (OPC1), geopolymer concretes of similar grade exhibited higher flexural strength than OPC1. This is consistent for both heat cured [5, 22, 39] and ambient cured geopolymer concretes [44].

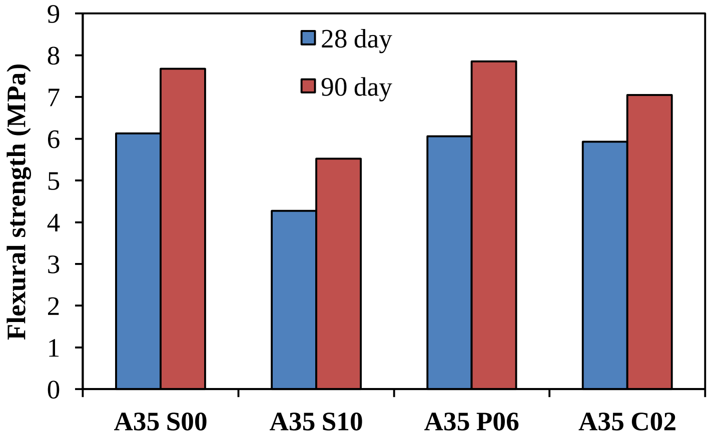

Fig. 4: Comparison of flexural strength of GPC mixed with 35% alkaline activator and different additives.

Mixtures having 35% alkaline activator and different additives are compared in Fig. 4. It can be seen that, all mixtures having 6% OPC and 2% CH, and extra water in the mixtures achieved slightly less flexural strength than the control geopolymer (A35 S00) which had no extra water. Mixture A35 S10 showed about 30% less flexural strength than mixture A35 S00. This indicates that the presence of extra water along with additives have adverse effect on flexural strength of geopolymer concretes cured in ambient condition.

While inclusions of additives increased the compressive strength, the inclusion of more additives after a certain limit apparently affected the rate of tensile strength development when cured in ambient temperature. The inclusion of GGBFS or, OPC introduces a small quantity of calcium silicate hydrate (CSH) gel in the geopolymer binder [21, 32]. With the increase of additives in the mixture, the percentage of CSH gel also increases to a level that modifies the tensile capacity of geopolymer binder and reduces to the value close to the OPC concrete of similar grade. It is well known that the strength of OPC concrete gradually increase over the age due to the development of CSH. Thus mixtures containing higher percentage of GGBFS and other additives is likely to behave in a similar manner to OPC concrete when cured in ambient temperature. Moreover, the presence of additional water instead of alkaline liquid tends to negate the positive effect of additives.

3.3.1 Comparison between predicted and experimental flexural strengths

Concrete design standards have recommended equations to predict the flexural strength from compressive strengths of concrete. The equations recommended in the Australian and American standards are used to predict flexural strengths of geopolymer concrete specimens and compared with the experimentally determined values.

Australian Standard: The characteristic flexural strength ($f'_{ct.f}$) at 28 days can be calculated using Equation 1 as recommended by AS 3600-2009 [45] when accurate data are not available. The mean value and upper characteristic value are calculated by multiplying the value obtained using Equation 1 by 1.4 and 1.8, respectively.

$$f'_{ct.f} = 0.6\sqrt{f'_c} \tag{1}$$

where, f'_c is the characteristic compressive strength which is taken as 90% of mean cylinder strength (f_{cm}) [44].

American Concrete Institute: The ACI Code 318-14 [38] recommends Equation 2 as the approximate relationship between the flexural strength and the compressive strength.

$$f_{ct.f} = 0.62\sqrt{f'_c} \tag{2}$$

where f'_c is the specified compressive strength. The relationships between the measured and specified compressive strengths (f'_c) are given by Equations 3-5 [46].

$$f_{cm} = f'_c + 7.0 \qquad for\ f'_c < 21\ MPa \tag{3}$$

$$f_{cm} = f'_c + 8.3 \qquad for\ 21 < f'_c \leq 35\ MPa \tag{4}$$

$$f_{cm} = 1.1f'_c + 5.0 \qquad for\ f'_c > 35\ MPa \tag{5}$$

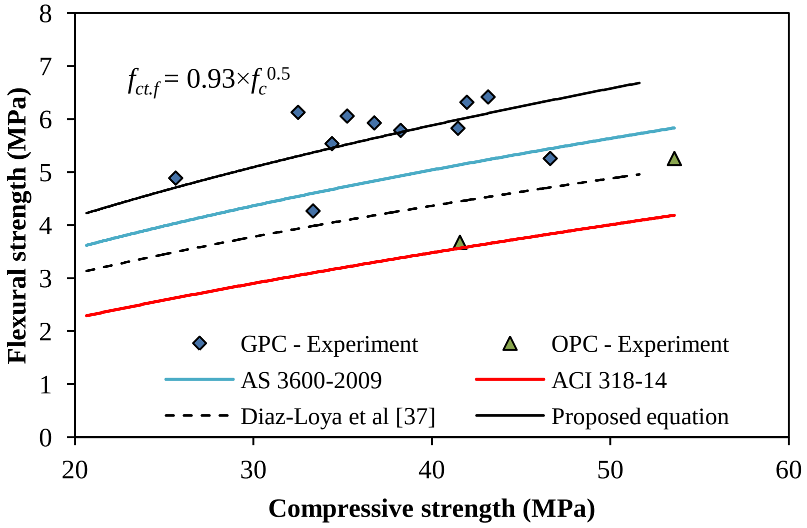

Fig. 5: Comparison of experimental and predicted flexural strengths at 28 days.

The predicted flexural strengths by these equations are given in Table 3. The ratios of the test to predicted flexural strengths are also given in the table. It can be seen that experimental values for GPC are mostly higher than the predicted values. The ratio of experimental to calculated values for GPC range from 0.93 to 1.35 for the AS 3600-2009 and from 1.38 to 2.01 for the ACI 318-14 Code. The experimental and predicted values are also plotted in Fig. 5. The comparisons show that the flexural strengths of ambient cured geopolymer concrete calculated by both the standards are mostly conservative. Nevertheless, the predicted values by the Australian standard are closer to the experimental values. Diaz-Loya et al. [39] proposed an equation to predict flexural strength of heat cured fly ash based GPC ($f_r = 0.69\sqrt{f_c}$), where f_c is 3-day compressive strength after heat curing. The predicted values by this equation are about 11% higher than those calculated by ACI 318-14 and less than those calculated by AS 3600-2009. Most of the values of this study fall in the upper prediction band of the equation proposed by Diaz-Loya et al [39]. Using the data of this study an expression was found by regression analysis using least square fit method. The following equation (Eq. 6) best fit the results as shown in Fig. 5.

$$f_{ct.f} = 0.93\sqrt{f_{cm}} \qquad (6)$$

where, f_{cm} is mean cylinder strength in MPa. The proposed equation calculates about 17% higher values than the mean characteristic flexural strength calculated as per AS 3600-2009. Considering the limited available data and variability of mixture composition of GPC, the estimation of mean value of flexural strength recommended by Australian standard for OPC concrete can be applied for ambient cured GPC with reasonable margin of factor of safety.

3.4 Modulus of elasticity

Modulus of elasticity measures the resistance of any substance against elastic deformation when a force is applied. It is a vital parameter of concrete for structural design. The mean value of the modulus of elasticity at 28 days and 90 days for both geopolymer and OPC concrete was determined from tests and the results are given in Table 4. Figure 6 shows the variation of modulus of elasticity with respect to compressive strength at 28 and 90 days. Generally, the value of elasticity varied with the compressive strength. Modulus of elasticity increased with the increase of compressive strength. It can be seen from the results that the modulus of elasticity of geopolymer concretes are relatively less than OPC concrete of similar compressive strength. While OPC1 had modulus of elasticity of 30.6 GPa for a 28-day compressive strength of about 40 MPa, similar grade geopolymer concrete (A40 S10, A40 P06, A40 C02, A40 C03) achieved values in the range of 21.6 to 23.2 GPa at 28 days. This is about 25-30% less than the value for OPC concrete. After 90 days, while OPC1 reached 50 MPa compressive strength and modulus of elasticity of 33.4 GPa, geopolymer concretes of similar strength (A40 S15, A40 P06, A35 P06 and A40 C02) achieved modulus of elasticity in the range of 23.0 to 26.2 GPa, which is 21.6 to 31.1% less than the value for OPC concrete.

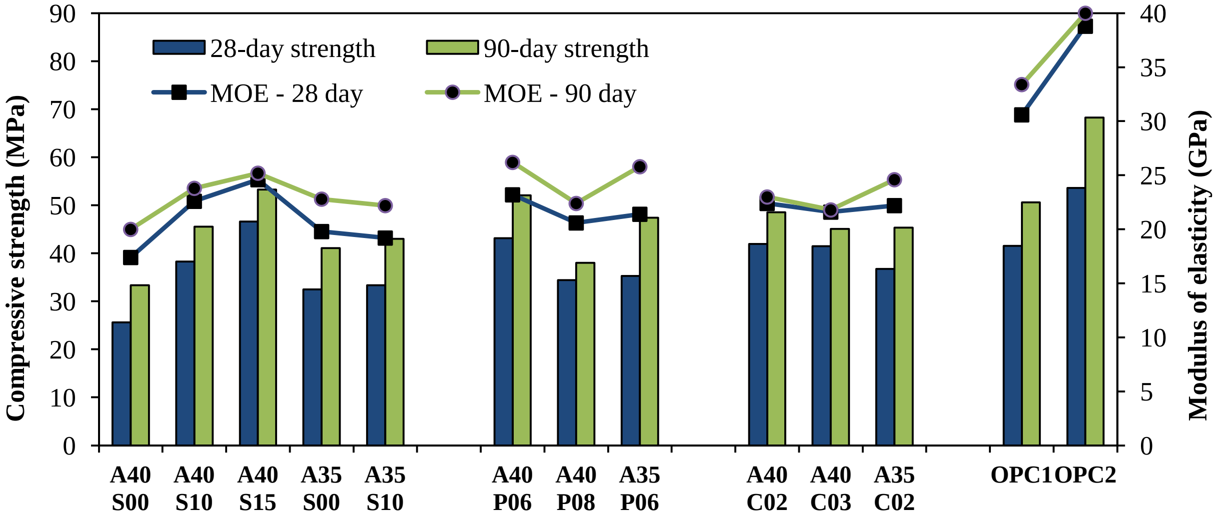

Fig. 6: Variation of modulus of elasticity of geopolymer and OPC concrete with respect to compressive strength at 28 and 90 days.

Geopolymer concretes cured at elevated temperature are generally reported to have less modulus of elasticity as compared to OPC concrete [23, 24]. According to the study of Olivia and Nikraz [47], heat cured fly ash based geopolymer concretes of about 55 MPa compressive strength showed moduli of elasticity 14.9–28.8% lower than those of the OPC concrete. Hardjito et al. [48] observed the elastic modulus of heat cured fly ash geopolymer to be about 10% less than that of OPC concrete of similar compressive strength. Yost et al. [49] found 11-16% less elastic modulus of fly ash based geopolymer concrete than the theoretical value predicted using ACI 318. The results of this study on ambient cured fly ash geopolymer concrete compare well with the values reported for heat cured geopolymer concrete. Thus, it can be stated that the curing at normal temperature, although cause delay in strength development of fly ash geopolymer, produce concrete of similar modulus of elasticity to that of the GPC cured in elevated temperature.

Comparing the modulus of elasticity values of GPCs, no significant difference is observed due to variation of the mixture proportions. However, no adverse effect on elasticity is seen for the presence of GGBFS, OPC and calcium hydroxide with fly ash in the mixture. Generally, the value of modulus of elasticity increased with the increase of compressive strength caused by inclusion of additives. This is true for any age either 28 days or 90 days as shown in Fig. 6. As the strength increased after 90 days so did the modulus of elasticity.

3.4.1 Comparison between predicted and experimental modulus of elasticity

The test results are compared with the modulus of elasticity predicted by the equations given in different standards and that proposed by previous researchers, as described below.

Australian Standard: AS 3600-2009 [45] recommends Equations 7 to 8 for the mean modulus of elasticity (in order of ±20%) at appropriate age.

$$E_{cj} = (\rho^{1.5}) \times \left(0.043\sqrt{f_{cmi}}\right) \quad when\ f_{cmi} \leq 40\ MPa \tag{7}$$

$$E_{cj} = (\rho^{1.5}) \times \left(0.024\sqrt{f_{cmi}} + 0.12\right) \quad when\ f_{cmi} > 40\ MPa \tag{8}$$

where E_{cj} = mean modulus of elasticity (MPa), ρ = the density of concrete (kg/m^3), f_{cmi} = mean in-situ compressive strength which is taken as 90% of mean cylinder strength (f_{cm}).

American Concrete Institute: According to the ACI Building Code ACI 318-14 [38], elastic modulus of OPC concrete with density ranging from 1442 to 2483 kg/m^3 can be calculated by Equation 9.

$$E_c = 0.043 \times \rho^{1.5} \times \sqrt{f_c'} \tag{9}$$

where E_c is modulus of elasticity (MPa) and f'_c is the specified compressive strength (MPa) of OPC concrete after 28 days of curing (Eq. 3-5).

CEB-FIP Model Code: The modulus of elasticity of normal weight concrete can be estimated by the CEB-FIP model code [50] using Equation 10.

$$E_c = 0.85 \times 2.15 \times 10^4 \times \left(\frac{f_c}{10}\right)^{1/3} \tag{10}$$

where E_c is the modulus of elasticity of concrete (MPa) and f_c is the average compressive strength (MPa).

Hardjito et al. [25] proposed Equation 11 based on test results on heat cured fly ash based GPC.

$$E_c = 2707\sqrt{f_c'} + 5300 \tag{11}$$

Diaz-Loya *et al.* [39] analysed data from a variety of heat cured fly ash geopolymer concrete made of Class C and Class F fly ash and proposed Equation 12 which predicts modulus of elasticity values about 14% less than ACI prediction (Equation 9).

$$E_c = 0.037 \times \rho^{1.5} \times \sqrt{f_c} \tag{12}$$

where E_c is modulus of elasticity (MPa) and f_c is the compressive strength of geopolymer concrete after 3 days curing in elevated temperature. Since the mixtures cured at high temperature gain strength close to ultimate strength just after curing, the value of f_c in Eq. 12 represents approximately the ultimate strength of the concrete. Fly ash geopolymer mixtures cured in ambient condition develop strength gradually over the age [21, 32]. Hence the strength at any particular age has been considered as the value of f_c while calculating modulus of elasticity using Equation 12.

Lee and Lee [51] proposed the following prediction equation for the elastic modulus of geopolymer concrete.

$$E_c = 5300 \times \sqrt[3]{f_c} \tag{13}$$

The values of modulus of elasticity are plotted in Fig. 7 and compared with the value predicted by the above equations. It is clear that, the experimental values of modulus of elasticity of ambient cured GPC are lower than those calculated according to recommended equations of AS 3600-2009, ACI 318-14 and CEB-FIP model code. All of these prediction formulas are intended for OPC concrete, hence these evidently overestimate modulus of elasticity for geopolymer concretes. Experimental values of GPCs are 73-79% and 70-83% of the calculated values as per AS 3600-2009 at 28 days and 90 days respectively (Table 4). Comparing with the model equations for GPC, it can be seen that the model provided by Hardjito et al. [25] fits most with the results of this study, whereas the model by Diaz-Loya et al. [39] predicts higher and that by Lee and Lee [51] predicts lower values than experimental values. This is possibly due to the variation of the mixture compositions and curing condition used in those respective studies.

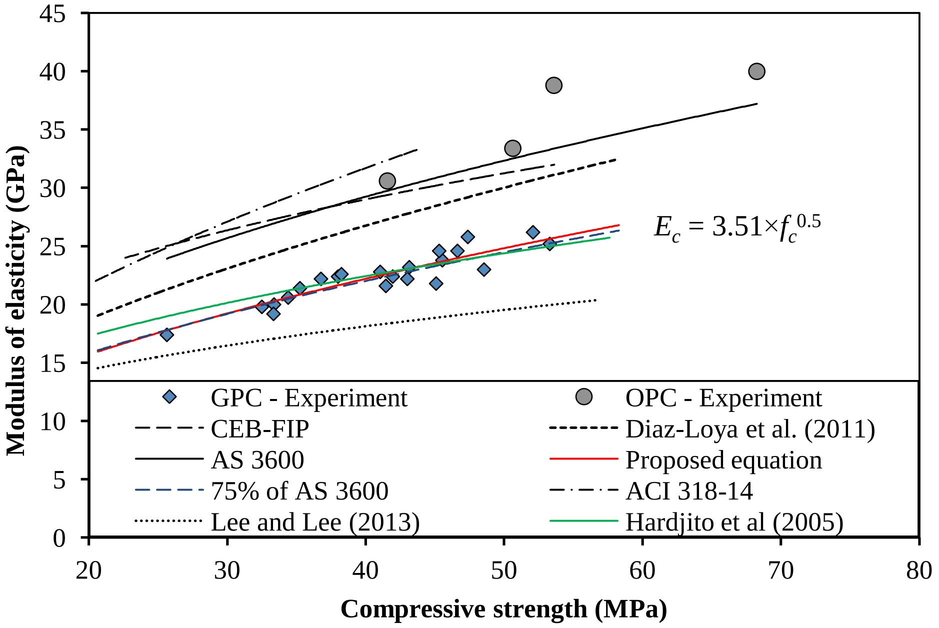

Fig. 7: Relationship of modulus of elasticity with compressive strength using existing and proposed equation**.**

It can be seen from Fig. 7 that the rate of increase of modulus of elasticity with compressive strength is almost equal to that followed by the equation of AS 3600-2009. Based on this observation, a factor of 0.75, which is about the same as the mean of the ratio of experimental values to the calculated values by AS 3600-2009, has been introduced (in Eq. 14) for predicting the modulus of elasticity of fly ash based GPC cured in ambient condition.

$$E_{cj.a} = 0.75 \times E_{cj} \qquad (14)$$

where $E_{cj.a}$ is modulus of elasticity of ambient cured fly ash geopolymer concrete and E_{cj} is mean modulus of elasticity as calculated by Equations 7-8 with a variation of ±20%. The values calculated by Equation 14 are plotted in Fig. 7. It clearly represents the experimental values of this study which are well within the applicable range of ±20%.

The experimental values have been analysed to fit in a general equation using commonly used term, square root of compressive strength ($\sqrt{f_c}$). A regression analysis by the method of least square was performed to fit the data in a given equation. The analysis proposed the final equation as follows:

$$E_{cj.a} = 3510\sqrt{f_c} \tag{15}$$

where f_c = compressive strength of geopolymer concrete (MPa). Values calculated with Equation 15 are also plotted in Fig. 7. It can be seen that Equation 15 from regression analysis matches very well with the Equation 14. Hence Equation 15 is proposed for predicting the modulus of elasticity of fly ash geopolymer concrete cured in ambient condition.

Table 5 shows some results of modulus of elasticity of different grade geopolymer concrete from previous works and those of this study. It should be noted that, all previous data are on samples cured in elevated temperature, whereas this study presents the results of the ambient cured samples. Fig. 8 compares the results presented in Table 5 in three grades of strength: 32 MPa, 40 MPa and 50 MPa. The proposed Equation (Eq. 15) was also plotted to facilitate a comparison with the reported values of heat cured geopolymer concrete. Generally, both heat cured and ambient cured samples demonstrated the usual trend of increasing modulus of elasticity for increasing concrete compressive strength. The circles shown in Fig. 8 represent the values for any particular grade of concrete.

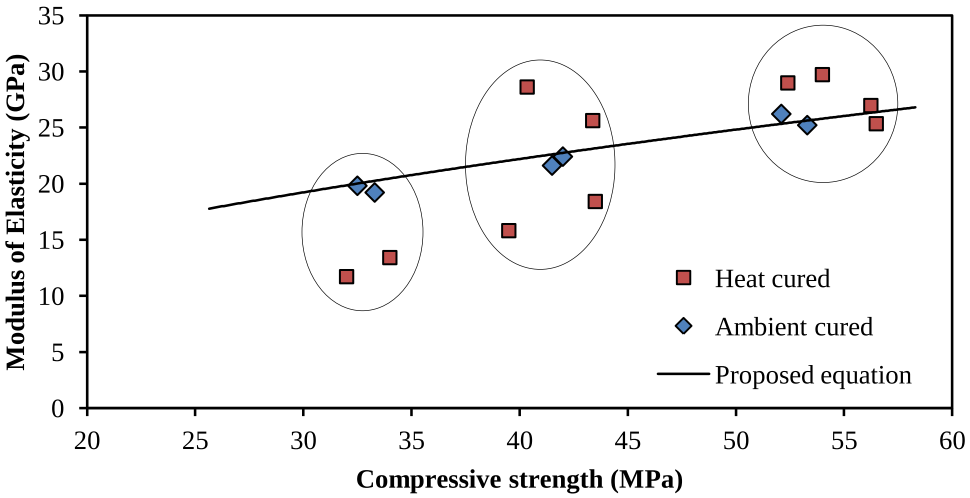

Fig. 8: Comparison of heat cured and ambient cured fly ash based geopolymer of different grades (Table 5).

It can be seen that there is less scatter in the modulus of elasticity data for the concretes of 50 MPa grade regardless of the curing condition. On the other hand, more scatter could be seen in the elasticity values of lower grade concretes. Most of the reported values were within the applicable range of ±20% of those predicted by the proposed equation. Although values taken from the literature are for geopolymers cured in elevated temperature, they fall reasonably close to the values observed for ambient cured geopolymers. The mixture proportions and activator types varied for different reports which might influence the properties of the final product. For instance, Fernández-Jiménez et al. [23] prepared geopolymer concretes with a high activator solution to fly ash ratio of 0.40 - 0.55 and two different activator solution (8M NaOH and a combination of Na_2SiO_3 and 12.5M NaOH), which resulted in different strength and modulus of elasticity. Diaz-Loya et al. [39] used gravel as coarse aggregate whereas Olivia and Nikraz [47] used crushed granite sized up to 20 mm. The curing temperature and time also varied for different mixtures reported in the literature, which influences the properties of the final product. Hence comparing the results from a wide variety of mixtures necessitates careful approximation. Nevertheless, the geopolymer samples of this study, which were cured in normal room temperature (ambient condition), have shown equivalent modulus of elasticity to that reported for heat cured fly ash based geopolymer concretes.

4 Conclusions

The effect of ambient curing on strength and elastic modulus of geopolymer concrete were studied. Low-calcium fly ash was blended with GGBFS up to 15%, OPC up to 8% and calcium hydroxide (CH) up to 3% in order to accelerate setting at ambient condition. The results of the study are summarized below:

- The mean density of the GPC specimens varied in the range of 2323 to 2400 kg/m^3 at 28 days which is similar to the typical range of normal-weight OPC concrete. The density of ambient cured GPC of this study is equivalent to that of heat cured GPC. The compressive strength increased with the increase of density of hardened concrete.

- Compressive strength increased by the inclusion of GGBFS, OPC and CH in addition to fly ash. The increase of strength was significant when no extra water was added with the alkaline liquid.
- Flexural strength of GPC cured in ambient temperature mostly followed similar development trend as compressive strength. Inclusion of up to 10% GGBFS, 6% OPC and 2% CH enhanced flexural strength as compared to the mixture without any additive. Geopolymer concretes exhibited higher flexural strength than OPC concrete of similar compressive strength. The equation recommended by AS 3600-2009 can be used for conservative prediction of flexural strength of ambient cured GPC.
- For similar compressive strength, modulus of elasticity of GPC is found to be about 25 to 30% less than that of the OPC concrete at 28 days. Modulus of elasticity increased with the increase of compressive strength. Curing in normal room temperature produced concrete of similar modulus of elasticity to that of the GPC cured in elevated temperature.
- The equations provided by AS 3600-2009, ACI 318-14 and CEB-FIP model code overestimated the value of elastic modulus for GPC. Therefore, Equation 15 is proposed to predict the modulus of elasticity of GPC cured in ambient condition.

5 Acknowledgement

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Table 1: Chemical composition of fly ash and additives.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	TiO_2	LOI*
Fly ash (%)	53.71	27.2	11.7	1.9	-	0.36	0.54	0.3	0.71	1.62	0.68
GGBFS (%)	29.96	12.25	0.52	45.45	-	0.31	0.38	3.62	0.04	0.46	2.39
OPC (%)	21.10	4.70	2.70	63.60	2.60	0.50	-	2.50	-	-	2.00

* Loss on ignition

Table 2: Mixture proportions of geopolymer and OPC concretes (kg/m^3)

Mixtures		**Aggregate**		**Binders**		**Alkaline solutions**		**Water**	**Super-plasticizer**	**Water/ solid (*w/s*)[d]**
Mix no.	**Label**	**Coarse**	**Sand**	**Fly ash**	**Additive**	**Na_2SiO_3**	**NaOH**			
1	A40 S00	1209	651	400	0	114.3	45.7	0	0	0.202
2	A40 S10	1209	651	360	40[a]	114.3	45.7	0	0	0.202
3	A40 S15	1209	651	340	60[a]	114.3	45.7	0	0	0.202
4	A35 S00	1218	655.9	400	0	100	40	0	6	0.180
5	A35 S10	1218	655.9	360	40[a]	100	40	6	6	0.193
6	A40 P06	1209	651	376	24[b]	114.3	45.7	0	0	0.202
7	A40 P08	1209	651	368	32[b]	114.3	45.7	0	3.92	0.202
8	A35 P06	1218	655.9	376	24[b]	100	40	6	6	0.193
9	A40 C02	1209	651	392	8[c]	114.3	45.7	0	0	0.202
10	A40 C03	1209	651	388	12[c]	114.3	45.7	0	0	0.202
11	A35 C02	1218	655.9	392	8[c]	100	40	6	6	0.193
12	OPC1	799	921.4	-	387.9[b]	-	-	213.4	0	0.550
13	OPC2	1136	612.3	-	428.3[b]	-	-	157.2	0	0.367

[a]GGBFS; [b]OPC; [c]CH; [d]Water/cement (*w/c*) ratio for OPC concrete.

Table 3: Compressive and flexural strengths

Mix ID	Density (kg/m^3)		Compressive strength, f_{cm} (MPa)		Flexural Strength $f_{ct.f}$ (MPa)					
	28 day	90 day	28 day	90 day	Test- 28 day	AS 360	Test/ AS 3600	ACI 318-14	Test/ ACI 318-14	Test - 90 day
A40 S00	2378	2338	25.6	33.4	4.89	4.04	1.21	2.58	1.89	5.91
A40 S10	2382	2371	38.3	45.5	5.79	4.93	1.17	3.41	1.70	6.47
A40 S15	2398	2357	46.6	53.3	5.26	5.44	0.97	3.81	1.38	6.12
A35 S00	2349	2336	32.5	41.1	6.13	4.54	1.35	3.05	2.01	7.68
A35 S10	2353	2335	33.3	43.0	4.27	4.60	0.93	3.10	1.38	5.52
A40 P06	2396	2374	43.2	52.1	6.42	5.23	1.23	3.65	1.76	7.46
A40 P08	2323	2317	34.4	38.0	5.54	4.67	1.19	3.17	1.75	5.68
A35 P06	2341	2329	35.3	47.4	6.06	4.73	1.28	3.25	1.86	7.85
A40 C02	2400	2381	42.0	48.6	6.32	5.16	1.22	3.59	1.76	7.22
A40 C03	2346	2339	41.5	45.1	5.83	5.13	1.14	3.57	1.63	5.98
A35 C02	2356	2336	36.8	45.3	5.93	4.83	1.23	3.33	1.78	7.05
OPC1	2290	2268	41.6	50.6	3.68	5.14	0.72	3.57	1.03	4.97
OPC2	2439	2410	53.6	68.3	5.26	5.83	0.90	4.12	1.28	5.70

Table 4: Modulus of elasticity of different mixtures

Mix ID	Mean E_{cj} (GPa) 28 day			Mean E_{cj} (GPa) 90 day		
	Test	AS 3600	Test / AS 3600	Test	AS 3600	Test / AS 3600
A40 S00	17.4	24.0	0.73	20.0	26.6	0.75
A40 S10	22.6	29.4	0.77	23.8	31.6	0.75
A40 S15	24.6	32.4	0.76	25.2	32.8	0.77
A35 S00	19.8	26.4	0.75	22.8	29.6	0.77
A35 S10	19.2	26.8	0.72	22.2	30.2	0.74
A40 P06	23.2	31.4	0.74	26.2	33.0	0.79
A40 P08	20.6	26.8	0.77	22.4	28.0	0.80
A35 P06	21.4	27.4	0.78	25.8	31.2	0.83
A40 C02	22.4	31.0	0.72	23.0	32.4	0.71
A40 C03	21.6	29.8	0.72	21.8	31.0	0.70
A35 C02	22.2	28.2	0.79	24.6	31.0	0.79
OPC1	30.6	28.8	1.06	33.4	30.4	1.10
OPC2	38.8	34.6	1.12	40.0	36.4	1.10

Table 5: Modulus of elasticity of fly ash based GPC from previous works and current study.

Author	**Sample**	**f_c (MPa)**	**E_{cj} (GPa)**	**Curing**
Fernández-Jiménez et al. [23]	AAFA-N	32.0	11.7	85 ^{o}C for 20 h
	AAFA-N	34.0	13.4	
	AAFA-W	43.5	18.4	
	AAFA-W	39.5	15.8	
Diaz-Loya et al. [39]	4	40.35	28.599	60 ^{o}C for 72 h
	19	43.38	25.607	
Olivia and Nikraz [47]	T7	56.49	25.33	70 ^{o}C for 12 h
	T4	56.24	26.95	75 ^{o}C for 24 h
Yost et al. [49]	U1-4	54.0	29.704	60 ^{o}C for 24 h
	U1-6	52.4	28.964	
This study	A35 S00	32.5	19.8	18-23 ^{o}C after casting to test date
	A35 S10	33.3	19.2	
	A40 C02	42.0	22.4	
	A40 C03	41.5	21.6	
	A40 S15	53.3	25.2	
	A40 P06	52.1	26.2	