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Assessing Behaviour of Fresh and Hardened Geopolymer Concrete Mixed with Class-F Fly Ash

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Abstract

Geopolymer binders have been shown to be a potential green replacement for Ordinary Portland Cement (OPC) in concrete manufacture. This paper presents an experimental study into the behaviour of geopolymer concrete in both its wet and hardened states using Class F fly ash. The experimental program included 15 mix designs to investigate the influence of water-to-binder and superplasticiser-to-binder ratios on the workability and strength of fly ash-based geopolymer concrete. The results show that the addition of naphthalene sulphonate polymer-based superplasticiser has little to no influence on workability and a detrimental effect on strength. Furthermore, the indirect tensile strength, flexural tensile strength and elastic modulus of fly ash-based geopolymer concrete were recorded in this experimental program and have been added to a database of available tests in the open literature. The experimentally determined results are subsequently compared with prediction models developed for OPC-based concrete. The comparison suggests that existing OPC models provide reasonably accurate predictions of the elastic moduli and stress-strain relationships, whereas they slightly underestimate flexural and splitting tensile strengths.

Keywords: *fly ash, geopolymer concrete, engineering properties, workability, tensile strength, elastic moduli*

1. Introduction

The global production of Ordinary Portland Cement (OPC) is nearly four billion tonnes per year. The production of cement, in fact, contributes to the emission of carbon dioxide (CO_2) through the combustion of fossil fuels and calcining of limestone. Globally, the production of one tonne of OPC generates around 0.95 tonnes of CO_2 (Eliasson *et al.*, 1999; Bosoaga *et al.*, 2009), with the total CO_2 released by manufacturing OPC estimated to be between 5% and 8% of the global anthropogenic CO_2 emissions into the atmosphere (Davidovits, 1991; Sofi *et al.*, 2007a and 2007b; Duxson *et al.*, 2007; Nowak, 2008; Vijai *et al.*, 2010; Shi *et al.*, 2011; van Deventer *et al.*, 2012). The environmental impact of global OPC manufacture has therefore provided increased impetus for research into alternative concrete binders, such as geopolymers. Geopolymer binders utilise waste materials that contain a high volume of aluminium and silicon species, typically fly ash from coal-burning power plants which are activated in a highly alkali solution, such as sodium hydroxide (NaOH).

The chemistry of geopolymer binders has been widely studied (Davidovits, 1991 and 1994; Bijen, 1995; Palomo *et al.*, 1999; Xu and van Deventer, 2000; van Jaarsveld *et al.*, 2002; Yip and van Deventer, 2003; Duxson *et al.*, 2007) and it has been shown that it is possible to use geopolymers as an alternative binder to OPC in concrete manufacture. However, due to several limitations regarding production process, such as workability, necessity of heat curing and delay in setting time (Vijai *et al.*, 2012; Naik and Kumar, 2013), more widespread applications of geopolymer concrete are needed at both concrete manufacture and structural design levels.

The properties of Geopolymer Concretes (GPC) are highly dependent on the source materials, which are generally industrial waste materials that are not subject to the strict quality control procedures used in OPC manufacture. To address the uncertainty in using specific sources of waste materials, generic models describing the wet and hardened properties of geopolymer concrete are required.

To establish new generic models for the hardened properties of geopolymer concretes, the results of this experimental program

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are added to a database of available test results in the literature (Sofi *et al.*, 2007a; Hardjito and Rangan, 2005; Raijiwala and Patil, 2010; Nguyen *et al.*, 2010; Yildirim *et al.*, 2011; Olivia and Nikraz, 2011; Ivan Diaz-Loya *et al.*, 2011). Through a regression analysis of the database, models to describe the mechanical properties of hardened geopolymer concrete as a function of the compressive strength are then developed. The results of this analysis show the variation in mechanical properties with compressive strength is similar to that seen in OPC concrete, which suggests the possibility that only minor changes to design guidelines are required to incorporate geopolymer concretes.

2. Experimental Program

A total of 15 mixes described in Table 1 were carried out to quantify the influence of naphthalene sulphonate polymer-based superplasticiser and water on workability and strength. In these tests, the superplasticiser-to-binder (sp:b) ratio and water-to-binder (w:b) ratios were varied within the started range up to where sufficient slump was obtained, so the sp:b ratio was varied between 0 and 0.115 and the w:b ratio was varied between 0 and 0.14.

2.1 Material Specifications

In this study, low-calcium Class-F (ASTM C618-08 2008) fly ash produced at Port Augusta Power Station in South Australia was used. The selection of class-F fly ash was based on several reasons (i) its abundance worldwide, and (ii) the absence of tricalcium aluminate (C_3A) reaction, which is the main reason of concrete deterioration in the presence of sulphate attack (Tosun-Felekoğlu, 2012). The chemical compositions of the fly ash were determined by x-ray fluorescence (XRF) and are presented in Table 2 together with chemical composition of OPC for comparison reason.

For all of the mixes, the alkaline solution phase consisted of a sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) 14 M pre-mixed with a Na_2SiO_3-to-NaOH ratio of 1.5, and the ratio of activator-to-binder (a:b) was kept at 0.37.

2.2 Specimen Preparation

Mixing was carried out in either a 20 kg planetary mixer or a 150 kg pan mixer, depending on the mix volume. The mixing procedure consisted of initially mixing the dry constituents for three minutes. Following this, the water and activator solution were added. Once sufficient wetting of the concrete was observed, usually after one minute, the superplasticiser was added and mixed in for seven more minutes. Immediately following mixing, the workability was measured using slump test in accordance with Australian Standards AS 1012.3.1 (1998); standard 100 mm × 200 mm cylinders were then cast in accordance with Australian Standards AS 1012.3.2 (1998). The specimens were then either covered at a constant 23°C ambient room temperature or heat-cured in an oven at 70°C for 24 hours and then placed in a fog room until the testing day.

Table 1. Mix Designs

Mix no	w:b	sp:b	Quantity (kg/m^3)					
			Coarse aggregate	Sand	Fly ash	Activator solution	SP	Water
1	0	0.0203	1200	600	424.8	158.4	8.64	0
2	0	0.0331	1197.12	598.56	424.8	158.4	13.92	0
3	0	0.1146	1179.84	589.92	424.8	158.4	48	0
4	0.0525	0.1129	1168.8	584.4	424.8	158.4	48	22.32
5	0.0079	0.0576	1192.8	594.48	424.8	158.4	24	3.36
6	0.0169	0.0576	1192.8	587.52	424.8	158.4	24	7.2
7	0.0225	0.0576	1192.8	584.16	424.8	158.4	24	9.6
8	0.0960	0	1180.8	580.8	424.8	158.4	0	40.8
9	0.0887	0.0197	1185.6	585.6	424.8	158.4	0.84	35.28
10	0.0225	0.0745	1183.2	585.6	424.8	158.4	31.68	9.6
11	0.0225	0.0858	1183.2	585.6	424.8	158.4	36.48	9.6
12	0.0225	0.0971	1183.2	585.6	424.8	158.4	41.28	9.6
13	0.0225	0.1129	1183.2	585.6	424.8	158.4	48	9.6
14	0.1073	0	1183.2	585.6	424.8	158.4	0	45.6
15	0.1412	0	1183.2	585.6	424.8	158.4	0	60

w:b = water-to-binder ratio, sp:b = superplasticiser-to-binder ratio, sp = superplasticiser

Table 2. Chemical Composition of Fly Ash

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	SrO	Mn_2O_3	*LOI
Fly ash	49	31	2.8	5.4	3.76	1.17	2.1	2.5	0.9	0.3	>0.1	>0.1	0.3
OPC	20.2	5.8	3.2	64.1	0.3	0.7	-	2.5	-	2.66	-	-	2.5

*Loss on Ignition

Table 3. Influence of w:b and sp:b Ratios on Workability and Strength

Mix	w:b	sp:b	Slump (mm)	3 day compressive strength MPa (heat cured 24 hr)
1	0	0.020	4	53.8
2	0	0.033	6	34.8
3	0	0.115	70	29.4
4	0.052	0.113	210	36.3
5	0.008	0.058	5	74.5
6	0.017	0.058	15	67.6
7	0.026	0.058	25	64.4
8	0.096	0	125	55.6
9	0.089	0.020	200	44.4
10	0.023	0.075	65	66.9
11	0.023	0.086	85	62.4
12	0.026	0.097	125	57.1
13	0.026	0.113	165	40.9
14	0.107	0	165	46.2
15	0.141	0	230	27.2

w:b = water-to-binder ratio, sp:b = superplasticiser-to-binder ratio

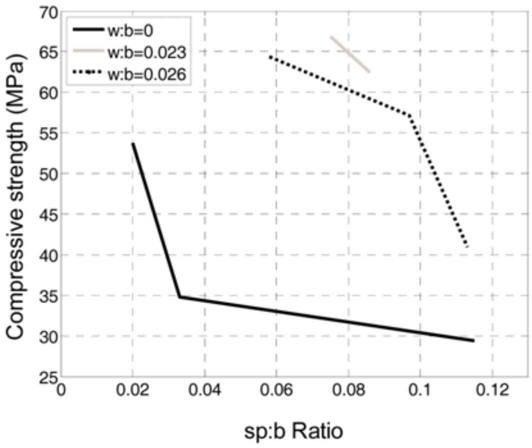

Fig. 1. Influence of sp:b Ratio on Compressive Strength

3. Results and Discussion

The results of the workability and strength tests for the mixes identified in Table 1 are presented in Table 3. The general trends of superplasticiser influence are shown in Fig. 1, where it can be seen that increasing the $sp : b$ ratio results in a reduction in the compressive strength of the geopolymer concrete.

3.1 Workability

To investigate the influence of the w:b and sp:b ratios on workability, slump tests were performed on each mix design. The results are presented in Table 3 and represented graphically in Fig. 2. It is shown that the addition of superplasticiser leads to increase concrete slump. This increase can be expressed mathematically through a linear regression of the data, as shown in Fig. 2(a), which yields:

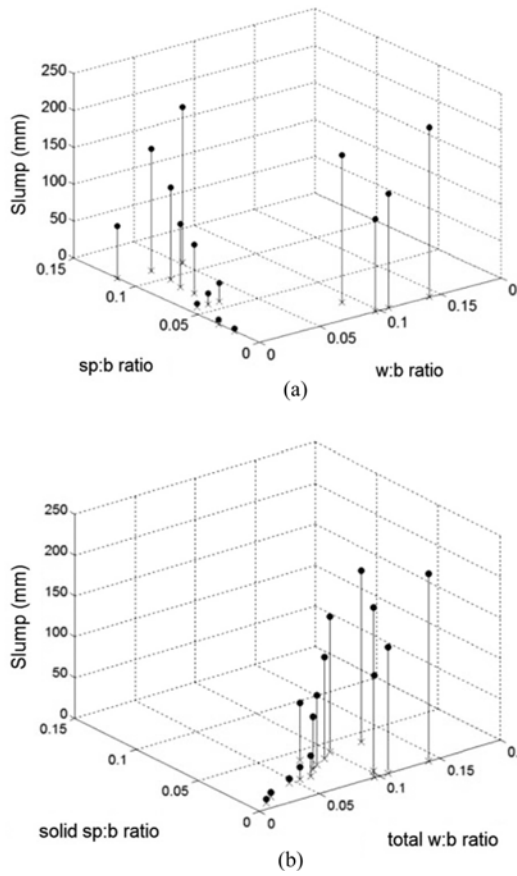

Fig. 2. (a) Superplasticiser-to-Binder Ratio vs. Water-to-Binder Ratio, (b) Solid Superplasticiser-to-Binder Ratio vs. Total Water-to-Binder Ratio

$$slump = 2112\,(w : b) + 1275\,(sp : b) - 61 \quad (1)$$

A clear indication of the influence of the superplasticiser on the workability can be seen in Fig. 2(b) in which the solid superplasticiser-to-binder (solid sp:b) ratio and total water-to-binder (total w:b) ratio are plotted. Repeating the regression analysis for the data in Fig. 2(b) gives:

$$slump = 2112\,(total\,w : b) - 279.8\,(solid\,sp : b) - 60.1 \quad (2)$$

When the reactive component of superplasticiser is considered only to be its solid contents, which makes up 35% of the total quantity of the superplasticiser, it becomes clear that the reactive component of naphthalene sulphonate polymer-based superplasticiser has little to no effect on the workability of geopolymer concrete and the influence on the workability is raised due to the free water in the superplasticiser.

It is worth mentioning that Laskar and Bhattacharjee (2013) studied the influence of lignin-based plasticiser and polycarboxylic-ether-based superplasticiser on the rheology of fly ash-based geopolymer concrete, and found similar results. It was found that the superplasticiser additives only improved the slump of the geopolymer concrete when the alkalinity of the activator solution was lower than 4 M, and all mixtures containing

NaOH solutions with molar strength above 4 M showed a reduction in the slump with increasing the amount of super-plasticiser.

Other studies into the workability of geopolymer concrete have found similar findings and it has been suggested that the workability of geopolymer concrete is more strongly influenced by other factors, such as molarity of NaOH, Na_2SiO_3 : NaOH ratio and ambient temperature. For example, a major study by Hardjito and Rangan (2005) on the influence of the molarity of NaOH was conducted and it was observed that increasing molarity leads to a reduction in the workability. Similar results were also found by Rattanasak and Chindaprasirt (2009) in a study where different molar strengths of NaOH were used as an activator solution. Furthermore, Heah *et al.* (2012) found that the workability of the geopolymer concrete decreases with increasing the ratio of Na_2SiO_3 : NaOH. The ambient temperature was noticed to affect the workability of geopolymer concrete, as higher temperature improves the workability. This can be attributed to the polymerisation reaction mentioned by Shi *et al.* (2011).

3.2 Mechanical Properties of Hardened Concrete

Knowledge of modulus of elasticity and tensile strength of concrete are fundamental to structural concrete design. For OPC, these properties are typically defined empirically as a function of compressive strength in national design standards, such as ACI 318-08 (2008). For GPC's comparatively little experimental testing has been performed (Hardjito *et al.*, 2004; Hardjito and Rangan, 2005; Sofi *et al.*, 2007a; Ivan Diaz-Loya *et al.*, 2011); hence, tests to determine the full compression stress-strain relationships, the elastic modulus, the flexural strength and indirect tensile strength of the GPC have been undertaken on both ambient- and heat-cured specimens manufactured from mix 13. In order to enable a meaningful comparison, the obtained data have been added to a database of available test results for fly ash-based geopolymer concrete manufactured from both class-C and class-F for each engineering property, and then a regression analysis was performed to provide updated generic material models.

3.2.1 Stress-Strain Relationship

The full stress-strain relationships for both heat and ambient cured specimens are shown in Fig. 3(a), together with Hognestad (1951) and Collins *et al.* (1993)'s expressions. The axial strains have been determined based on the average of four Linear Variable Displacement Transformers (LVDTs) readings measuring the total deformation over the full height of the specimen. It is evident from Fig. 3(a) that the expressions of Hognestad (1951) and Collins *et al.* (1993) provide reasonable accuracy for fly ash-based geopolymer concrete stress-strain relationships. Fig. 3(b) shows the stress-lateral strain relationships measured by three lateral strain gauges located at the mid-height of the specimens. The readings are provided up until the point at which damage to the concrete prevented any further accurate measurements.

It can be noticed that there is significant difference in the compressive strengths of the heat- and ambient-cured specimens,

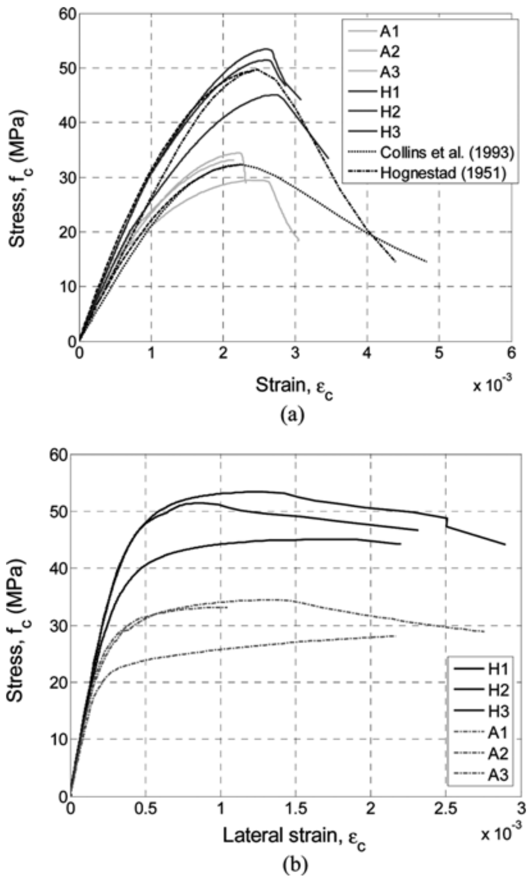

Fig. 3. Stress-Strain Relationships: (a) Axial Stress-Strain, (b) Lateral Stress-Strain

but in general, the strain at peak stress varied between 0.0022 and 0.0026. The relationship between compressive strength and the strain at peak stress is plotted in Fig. 4 using the results of the current study, as well as the results of Hardjito and Rangan (2005), Yost *et al.* (2013), and Fernández-Jiménez *et al.* (2006). The results were then compared with several models set for OPC-based concrete, including Chen *et al.* (2013), as given in Eq. (3), and Ahmad and Shah (1985), as given in Eq. (4):

$$\varepsilon_{co} = 4.76 \times 10^{-6} f_c' + 2.13 \times 10^{-3} \quad (3)$$

$$\varepsilon_o = 0.001648 + 1.65 \times 10^{-5} f_c' \quad (4)$$

It can be seen from Fig. 4 that the model of Chen *et al.* (2013) is in line with the trend-line of the geopolymer data of the investigated studies, which yields:

$$\varepsilon_{co} = 4 \times 10^{-6} f_c' + 2.2 \times 10^{-3} \quad (5)$$

These findings indicate that the strain behaviour of GPC is quite similar to that of OPC, and hence the same equations can be used in order to predict the stress-strain relationships, as well as the strain at peak stress.

3.2.2 Compressive Strength

The compressive strength results for all of the mixes are

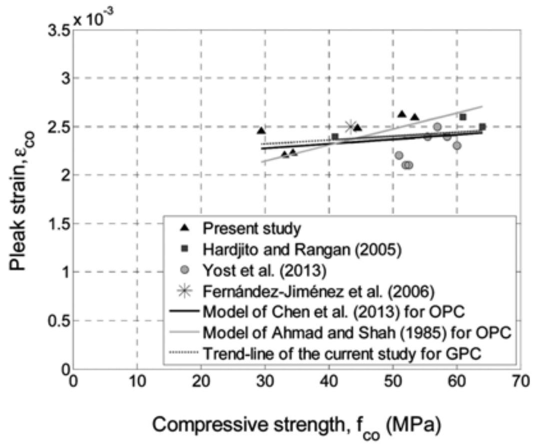

Fig. 4. Compressive Strength-Peak Strain Relationship

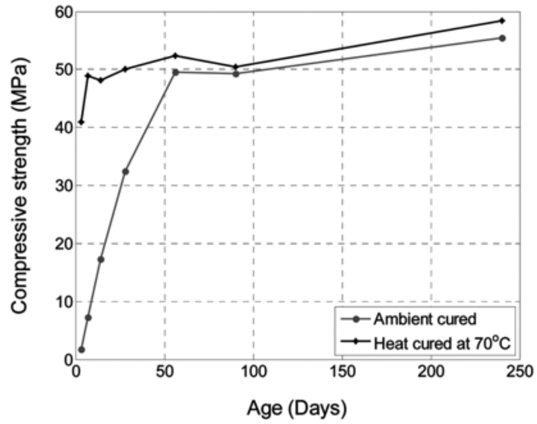

Fig. 5. Compressive Strength Developments of Ambient and Heat Cured

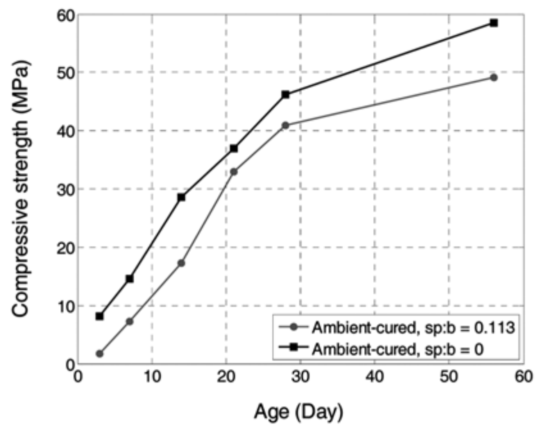

Fig. 6. Compressive Strength Developments of Mixes with and without Superplasticiser

presented in Table 3. It can be observed that the compressive strength decreases with an increase in sp:b ratio, as can be seen in Fig. 1. The compressive strength developments of heat- and ambient-cured specimens of mix 13 are shown in Fig. 5. It can be seen that the strength development of ambient-cured cylinders is slower than that of the heat-cured cylinders, reflecting the process of the polymerisation reaction, which can be accelerated with heat curing. In fact, Bijen (1995) stated that the curing sensitivity of fly ash-based geopolymer is slower than that of OPC-based concrete. Nevertheless, the compressive strength development is sensitive to the liquid in the mix design. For instance, mix 13, which contains superplasticiser, gained the strength at a slower rate than mix 14, which does not contain superplasticiser, as can be seen in Fig. 6. It was deduced that while the naphthalene sulphonate-based superplasticiser may improve the strength of the conventional concrete, it reduces the compressive strength of fly ash-based geopolymer concrete. This observation was also reported by Al Bakri *et al.* (2012).

3.2.3. Splitting Tensile and Flexural Strength

The splitting tensile and flexural strength tests for mix 13 were experimentally determined in accordance with Australian Standards AS 1012.10 (2000) and AS 1012.11 (2000), respectively. The results of the splitting tensile and flexural tests are tabulated in Table 4 and Table 5, respectively, together with other available results.

Figure 7 shows the results of splitting tensile tests of the present study, as well as available results on geopolymer concrete, including Sofi *et al.* (2007a); Hardjito and Rangan (2005); Raijiwala and Patil (2010); Nguyen *et al.* (2010); Olivia and Nikraz (2011); and Ivan Diaz-Loya *et al.* (2011), and compared with predictions models developed for OPC-based concrete and GPC, including ACI 318-08 (2008), Eurocode (2002) and Sofi *et al.* (2007a). A regression analysis was then performed, and the following expression is proposed in terms of the compressive strength:

$$f'_{ct} = 0.6\sqrt{f'_c} \text{ (MPa)} \tag{6}$$

which is in the same form as that of the ACI 318-08 (2008).

Figure 8 shows the results of the flexural tensile tests conducted in the present study, as well as available results on class-F fly ash-based geopolymer concrete (Sofi *et al.*, 2007a; Raijiwala and Patil, 2010; Olivia and Nikraz, 2011; Ivan Diaz-Loya *et al.*, 2011) and compared with predictions models developed for OPC-based concrete and GPC, including ACI 318-08 (2008); Sofi *et al.* (2007a); Ivan Diaz-Loya *et al.* (2011). In addition, results on class-C fly ash (Ivan Diaz-Loya *et al.*, 2011) were also included for comparison purpose. A regression analysis was then performed to propose the following expression in terms of the compressive strength:

$$f'_{cf} = 0.75\sqrt{f'_c} \text{ (MPa)} \tag{7}$$

which is again in the same form of the ACI 318-08 (2008).

It should be noted that the expressions set for conventional OPC concrete, such as ACI (2008), under-estimate the values of class-F fly ash-based geopolymer concrete, yet they accurately enough estimate the values of class-C fly ash-based geopolymer

Table 4. Summary of Splitting Tensile Strength and Models

Experimentally determined		Models			
f'_c	f'_{ct}	ACI 318-08 (2008)	Eurocode (2002)	Sofi *et al.* (2007a)	Proposed
Present study - Class-F					
18.66	2.04	2.29	2.11	2.07	2.59
33.17	3.08	3.05	3.10	2.76	3.46
34.41	3.14	3.11	3.17	2.82	3.52
29.45	2.96	2.88	2.86	2.60	3.26
51.42	4.23	3.80	3.85	3.44	4.30
53.42	5.55	3.87	3.92	3.51	4.39
44.58	5.51	3.54	3.77	3.20	4.01
Hardjito & Rangan (2005) - Class-F					
89.00	7.43	5.00	4.86	4.53	5.66
68.00	5.52	4.37	4.35	3.96	4.95
55.00	5.45	3.93	3.97	3.56	4.45
44.00	4.43	3.52	3.74	3.18	3.98
Sofi et al. (2007a) - Class-F					
55.40	3.40	3.94	3.98	3.57	4.47
54.00	2.80	3.89	3.94	3.53	4.41
48.60	2.80	3.69	4.00	3.35	4.18
56.50	4.10	3.98	4.02	3.61	4.51
47.00	3.90	3.63	3.91	3.29	4.11
52.80	3.30	3.85	3.90	3.49	4.36
35.20	3.20	3.14	3.22	2.85	3.56
44.40	2.90	3.53	3.76	3.20	4.00
37.60	2.40	3.25	3.37	2.94	3.68
41.80	3.60	3.43	3.61	3.10	3.88
42.00	3.50	3.43	3.62	3.11	3.89
38.30	2.70	3.28	3.41	2.97	3.71
Nguyen et al. (2010) - Class-F					
35.00	3.90	3.14	3.21	2.84	3.55
42.80	4.90	3.47	3.67	3.14	3.93
Raijiwala and Patil (2010) - Class-F					
20.18	2.24	2.38	2.22	2.16	2.70
23.10	2.38	2.55	2.43	2.31	2.88
24.12	2.54	2.60	2.50	2.36	2.95
25.02	3.02	2.65	2.57	2.40	3.00
28.33	2.60	2.82	2.79	2.55	3.19
30.14	3.06	2.91	2.91	2.64	3.29
33.16	3.50	3.05	3.10	2.76	3.46
34.28	3.80	3.10	3.17	2.81	3.51
35.10	4.16	3.14	3.22	2.84	3.55
34.22	3.22	3.10	3.16	2.81	3.51
35.24	3.48	3.15	3.22	2.85	3.56
39.12	4.48	3.31	3.46	3.00	3.75
40.18	4.64	3.36	3.52	3.04	3.80
41.18	5.18	3.40	3.58	3.08	3.85
37.36	4.00	3.24	3.35	2.93	3.67
40.29	4.20	3.36	3.53	3.05	3.81
42.44	4.80	3.45	3.65	3.13	3.91
43.00	5.00	3.48	3.68	3.15	3.93
44.14	5.24	3.52	3.75	3.19	3.99
Olivia and Nikraz (2011) - Class-F					
56.49	4.13	3.98	4.02	3.61	4.51
56.51	4.18	3.98	4.02	3.61	4.51
56.24	3.96	3.97	4.01	3.60	4.50
58.85	4.10	4.07	4.09	3.68	4.60
60.20	4.29	4.11	4.13	3.72	4.66
63.29	4.79	4.22	4.22	3.82	4.77

Table 5. Summary of Flexural Strength and Models

Experimentally determined		Predictive Models (MPa)			
f'_c MPa	f'_{cf} MPa	ACI 318-08 (2008)	Sofi *et al.* (2007a)	Ivan Diaz-Loya *et al.* (2011)	Proposed Model
Present study - Class-F					
18.66	3.56	2.68	3.02	2.98	3.24
18.66	3.56	2.68	3.02	2.98	3.24
33.17	4.12	3.57	4.03	3.97	4.32
34.41	4.35	3.64	4.11	4.05	4.40
51.42	5.30	4.45	5.02	4.95	5.38
53.42	5.25	4.53	5.12	5.04	5.48
Sofi *et al.* (2007a) - Class-F					
35.20	4.90	3.68	4.15	4.09	4.45
44.40	4.80	4.13	4.66	4.60	5.00
37.60	4.50	3.80	4.29	4.23	4.60
41.80	5.30	4.01	4.53	4.46	4.85
42.00	5.30	4.02	4.54	4.47	4.86
38.30	4.20	3.84	4.33	4.27	4.64
55.40	6.10	4.61	5.21	5.14	5.58
54.00	4.90	4.56	5.14	5.07	5.51
48.60	5.40	4.32	4.88	4.81	5.23
56.50	6.20	4.66	5.26	5.19	5.64
47.00	5.90	4.25	4.80	4.73	5.14
52.80	5.30	4.51	5.09	5.01	5.45
Raijiwala and Patil (2010) - Class-F					
16.42	2.28	2.51	2.84	2.80	3.04
20.18	3.44	2.79	3.14	3.10	3.37
23.10	3.50	2.98	3.36	3.32	3.60
24.12	3.55	3.04	3.44	3.39	3.68
25.02	3.72	3.10	3.50	3.45	3.75
28.33	3.52	3.30	3.73	3.67	3.99
30.14	3.98	3.40	3.84	3.79	4.12
33.16	4.30	3.57	4.03	3.97	4.32
34.28	4.34	3.63	4.10	4.04	4.39
35.10	4.68	3.67	4.15	4.09	4.44
34.22	4.21	3.63	4.09	4.04	4.39
35.24	5.50	3.68	4.16	4.10	4.45
39.12	5.76	3.88	4.38	4.32	4.69
40.18	5.82	3.93	4.44	4.37	4.75
41.18	6.04	3.98	4.49	4.43	4.81
37.36	5.20	3.79	4.28	4.22	4.58
40.29	6.00	3.94	4.44	4.38	4.76
42.44	6.60	4.04	4.56	4.50	4.89
43.00	6.66	4.07	4.59	4.52	4.92
44.14	7.18	4.12	4.65	4.58	4.98
Olivia and Nikraz (2011) - Class-F					
56.49	7.39	4.66	5.26	5.19	5.64
56.51	9.21	4.66	5.26	5.19	5.64
56.24	8.99	4.65	5.25	5.17	5.62
58.85	9.36	4.76	5.37	5.29	5.75
60.20	8.38	4.81	5.43	5.35	5.82
63.29	9.85	4.93	5.57	5.49	5.97

Table 5. (continued)

Experimentally determined		Predictive Models (MPa)			
f'_c MPa	f'_{cf} MPa	ACI 318-08 (2008)	Sofi *et al.* (2007a)	Ivan Diaz-Loya *et al.* (2011)	Proposed Model
Ivan Diaz-Loya *et al.* (2011) - Class-F					
40.30	4.10	3.94	4.44	4.38	4.76
47.50	5.50	4.27	4.82	4.76	5.17
46.69	5.30	4.24	4.78	4.71	5.12
46.79	4.60	4.24	4.79	4.72	5.13
46.11	4.70	4.21	4.75	4.69	5.09
47.44	5.10	4.27	4.82	4.75	5.17
12.20	2.20	2.17	2.44	2.41	2.62
12.80	2.30	2.22	2.50	2.47	2.68
20.60	3.50	2.81	3.18	3.13	3.40
10.30	2.70	1.99	2.25	2.21	2.41
46.50	6.30	4.23	4.77	4.71	5.11
49.20	4.66	4.35	4.91	4.84	5.26
43.38	4.24	4.08	4.61	4.54	4.94
Ivan Diaz-Loya *et al.* (2011) - Class-C					
59.50	4.48	4.78	5.40	5.32	5.79
52.20	4.70	4.48	5.06	4.99	5.42
55.80	4.30	4.63	5.23	5.15	5.60
80.37	5.27	5.56	6.28	6.19	6.72
61.30	6.23	4.85	5.48	5.40	5.87
39.10	4.19	3.88	4.38	4.31	4.69
53.70	4.43	4.54	5.13	5.06	5.50
36.54	3.58	3.75	4.23	4.17	4.53
57.18	5.27	4.69	5.29	5.22	5.67
42.81	5.18	4.06	4.58	4.51	4.91
62.10	4.83	4.89	5.52	5.44	5.91
2.70	0.62	1.02	1.15	1.13	1.23

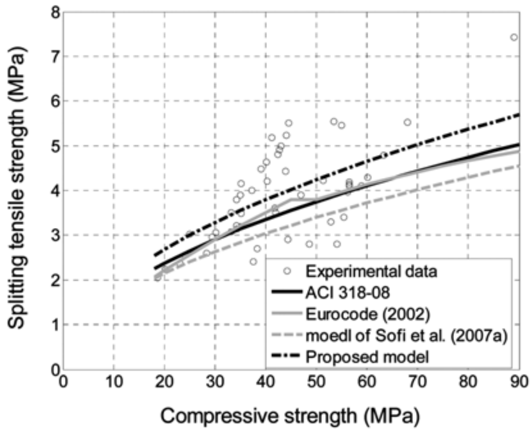

Fig. 7. Splitting Tensile Strength versus Compressive Strength

concrete, as can be seen in Fig. 8. This indicates that the mechanical properties of class-C fly ash-based geopolymer concrete are similar to those of conventional OPC-based concrete.

3.2.4 Modulus of Elasticity

The modulus of elasticity (E_c) was determined from the linear

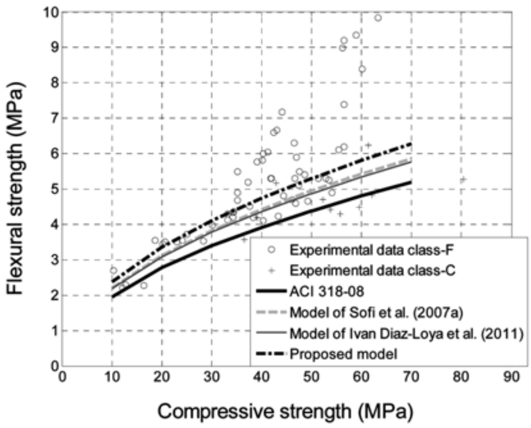

Fig. 8. Flexural Strength versus Compressive Strength

elastic portion of the stress-strain curves. The results are tabulated in Table 6, together with other available results.

Figure 9 shows the results of the present study, together with results from database of available test data for comparison purpose, including class-C (Yildirim *et al.*, 2011; Ivan Diaz-Loya *et al.*, 2011) and class-F (Hardjito and Rangan, 2005; Nguyen *et al.*, 2010; Yildirim *et al.*, 2011; Olivia and Nikraz, 2011; Ivan Diaz-Loya *et al.*, 2011) fly ash-based geopolymer concrete. As seen in Fig. 9, while there is a large scatter of experimental results, the expression of the ACI 318-08 (2008) shown in Eq. (8) for OPC provides a reasonable estimate of the mean test results:

$$E_c = 3320\sqrt{f'_c} + 6900 \quad \text{(MPa)} \tag{8}$$

Moreover, the upper and lower bounds of Australian Standards AS 3600 (2001) shown in Eq. (9) capture the scatter of the results:

$$E_c = 0.043\rho^{1.5}\sqrt{f_{cm}} \pm 20\% \quad \text{(MPa)} \tag{9}$$

where, f_{cm} is the mean value of concrete cylinder compressive strength.

The results reported by Hardjeto and Rangan (2005) are found to be beneath the lower limit of AS 3600 (2001). This can be attributed to the size of the coarse aggregates used in the experimental program. The effective elastic modulus of concrete can be increased by increasing the maximum aggregate size, as well as by reducing the water/cement ratio, which will lead to increasing the elastic modulus of the cement paste (Neville, 2000; Shah and Ribakov, 2011).

3.2.5 Poisson's Ratio

Poisson's ratios were calculated in accordance with Australian Standard AS 1012.17 (1997). The values of the longitudinal and lateral strains were recorded simultaneously on the same samples using strain gauges and LVDTs. For each specimen, Poisson's ratio was calculated from the average strain from the second and successive loadings according to the following equation:

$$\upsilon = (\varepsilon_4 - \varepsilon_3)/(\varepsilon_1 - 0.00005) \tag{10}$$

Table 6. Summary of Modulus of Elasticity

Experimentally determined		Predictive Models (Models)			
f'_c MPa	E_c MPa	ACI 318-08 (2008)	AS 3600 (2001)	Carrasquillio *et al.* (1981)	Ahmad and Shah (1985)
Present study - Class-F					
56.97	30.2	31.959	36.97	32.581	33.664
45.52	41.6	29.300	33.05	29.870	31.297
47.3	28.4	29.733	33.69	30.312	31.690
46.58	29.2	29.559	33.43	30.134	31.532
33.17	28.07	26.021	28.21	26.527	28.238
34.41	25.05	26.375	28.74	26.888	28.576
29.45	27.81	24.917	26.58	25.402	27.167
51.42	30.88	30.707	35.13	31.305	32.561
53.42	31.02	31.166	35.80	31.772	32.968
44.58	28.55	29.067	32.71	29.633	31.085
Nguyen *et al.* (2010) - Class-F					
30	35.04	25.084	26.83	25.573	27.331
35	31.31	26.541	28.98	27.058	28.735
35.4	32.9	26.653	29.15	27.172	28.841
40.9	30.93	28.132	31.33	28.680	30.227
44	27.8	28.922	32.49	29.485	30.953
40.3	37.5	27.976	31.10	28.521	30.082
Hardjito & Rangan (2005) - Class-F					
89	30.8	38.221	46.21	38.965	38.917
68	27.3	34.277	40.39	34.944	35.658
55	26.1	31.522	36.33	32.135	33.282
44	23	28.922	32.49	29.485	30.953
Yildirim *et al.* (2011) - Class-F					
40.2	35.97	27.950	31.06	28.494	30.058
38.75	34.89	27.567	30.49	28.103	29.701
40.25	35.65	27.963	31.08	28.507	30.070
39.25	34.95	27.700	30.69	28.239	29.825
36.49	32.79	26.955	29.59	27.480	29.127
38.14	33.06	27.404	30.25	27.937	29.548
40.06	34.96	27.913	31.00	28.456	30.024
47.81	37.82	29.856	33.87	30.437	31.800
46.81	36.85	29.615	33.52	30.191	31.582
47.93	38.12	29.885	33.91	30.466	31.826
46.96	37.95	29.651	33.57	30.228	31.615
45.9	37.31	29.393	33.19	29.965	31.382
46.23	37.84	29.474	33.31	30.047	31.455
47.52	38.11	29.786	33.77	30.366	31.737
60.49	42.64	32.721	38.10	33.358	34.327
57.76	41.89	32.132	37.23	32.757	33.815
61.1	43.64	32.851	38.29	33.491	34.439
63.31	42.65	33.316	38.98	33.965	34.839
55.27	36.22	31.582	36.42	32.197	33.335
58.44	40.45	32.280	37.45	32.908	33.944
61.12	43.63	32.856	38.30	33.495	34.443

where υ is the Poisson's ratio, ε_4 is the average transverse strain at test load, ε_3 is the average of transverse strain coincident with average longitudinal strain of 50×10^{-6} m/m, and ε_1 is the average of longitudinal strain at test load.

Table 6. (continued)

Experimentally determined		Predictive Models (Models)			
f'_c MPa	E_c MPa	ACI 318-08 (2008)	AS 3600 (2001)	Carrasquillio *et al.* (1981)	Ahmad and Shah (1985)
Yildirim *et al.* (2011) - Class-C					
40.2	35.97	27.950	31.06	28.494	30.058
40.5	36.31	28.028	31.17	28.574	30.131
41.3	36.91	28.236	31.48	28.785	30.323
42.5	37.66	28.544	31.93	29.099	30.606
38.7	33.03	27.553	30.47	28.090	29.689
39.8	34.01	27.845	30.90	28.387	29.960
41.2	36.01	28.210	31.44	28.759	30.299
47.8	37.82	29.854	33.87	30.435	31.798
48.6	37.25	30.045	34.15	30.630	31.970
50.8	37.92	30.563	34.91	31.158	32.433
50.5	36.89	30.493	34.81	31.086	32.371
48.2	38.11	29.950	34.01	30.532	31.884
50.5	39.7	30.493	34.81	31.086	32.371
51.2	40.62	30.656	35.05	31.253	32.516
60.5	42.64	32.724	38.10	33.360	34.329
57.9	42.59	32.163	37.27	32.788	33.842
60.8	42.01	32.787	38.20	33.426	34.384
63.2	42.89	33.293	38.94	33.941	34.819
58.8	40.49	32.358	37.56	32.988	34.012
60.1	42.5	32.638	37.98	33.273	34.255
62.9	43.62	33.231	38.85	33.877	34.765
Olivia and Nikraz (2011) - Class-F					
56.49	25.33	31.853	36.82	32.473	33.572
56.51	27.18	31.857	36.82	32.477	33.576
56.24	26.95	31.798	36.74	32.417	33.524
58.85	28.03	32.369	37.58	32.999	34.022
60.2	29.05	32.659	38.01	33.295	34.273
63.29	26.8	33.312	38.97	33.960	34.835
Ivan Diaz-Loya *et al.* (2011) - Class-F					
40.300	28.599	27.976	31.10	28.521	30.082
47.500	29.475	29.782	33.76	30.361	31.733
46.690	29.358	29.586	33.47	30.161	31.556
46.790	28.517	29.610	33.51	30.186	31.578
46.110	26.455	29.444	33.26	30.017	31.428
47.440	25.635	29.767	33.74	30.346	31.720
46.500	28.744	29.539	33.40	30.114	31.514
43.380	25.607	28.767	32.26	29.326	30.811
Ivan Diaz-Loya *et al.* (2011) - Class-C					
59.500	33.633	32.509	37.79	33.142	34.143
52.200	34.377	30.887	35.39	31.488	32.721
55.800	37.108	31.700	36.59	32.317	33.438
80.370	42.878	36.664	43.92	37.377	37.648
61.300	31.447	32.894	38.35	33.534	34.476
53.700	28.91	31.229	35.90	31.837	33.024
36.540	26.972	26.969	29.61	27.494	29.140
57.180	29.448	32.005	37.04	32.628	33.705
42.810	22.567	28.623	32.05	29.180	30.679
62.100	29.896	33.063	38.60	33.706	34.621

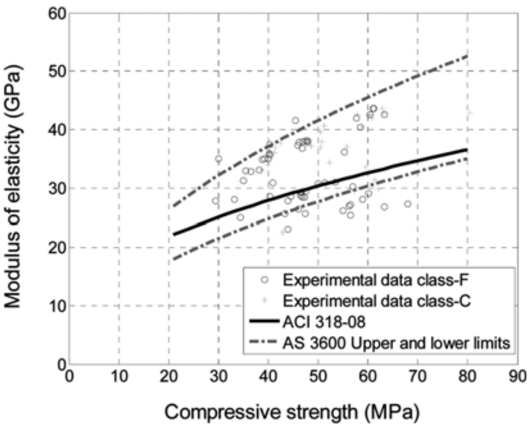

Fig. 9. Modulus of Elasticity of Fly Ash (Class-F and Class-C)

Table 7. Summary of Poisson's Ratios

Compressive strength	Poisson's ratio
Present study	
32.3	0.12
49.8	0.14
Hardjito and Rangan (2005)	
89	0.16
68	0.12
55	0.14
44	0.13
Ivan Diaz-Loya *et al.* (2011)	
40.3	0.14
47.5	0.16
46.7	0.14
46.8	0.13
46.1	0.12
47.4	0.14
12.2	0.17
12.8	0.10
20.6	0.08
10.3	0.10
46.5	0.15
49.2	0.15
43.3	0.13

Table 7 presents the experimental values obtained in the present study, as well as other studies including, Hardjito and Rangan (2005); Ivan Diaz-Loya *et al.* (2011).

The majority of experimentally determined Poisson's ratio of geopolymer concrete ranged between 0.12 and 0.16 (Table 7) with an average value of 0.13. For Portland cement concrete, the Poisson's ratio is usually ranged between 0.11 and 0.21, with an average value of 0.15 (Warner *et al.*, 1998). Thus, it can be concluded that the Poisson's ratio of fly ash-based geopolymer concrete is similar to that of conventional OPC-based concrete.

4. Conclusions

This paper presented the results of an experimental study that was conducted to obtain a greater understanding of the behaviour of typical Class-F fly ash-based geopolymer concrete. The results from the current study augmented the existing database of geopolymer concrete, as it involved compressive strength development, flexural strength, tensile strength, elastic modulus and the stress-strain relationship. The following conclusions can be drawn based on the results and discussions reported in this paper.

1. The polymerisation reaction can be accelerated with heat curing, as the compressive strength can be developed at an early age.
2. Naphthalene sulphonate polymer-based superplasticiser has little to no effect on the slump and an adverse effect on the strength of fly ash-based geopolymer concrete where high molarity NaOH is used.
3. The experimentally determined values of splitting tensile and flexural strength were higher than those in the expressions prescribed by national standards for OPC-based concrete, indicating that class-F fly ash-based geopolymer concrete exhibits higher tensile strength than the OPC-based concrete.
4. Elastic modulus and Poisson's ratio of class-F fly ash-based geopolymer concrete were found to be similar of those of conventional OPC-based concrete.
5. Stress-strain expressions developed for conventional OPC-based concrete can be applied with reasonable accuracy for determination of fly ash-based geopolymer concrete stress-strain relationships.

The results have shown that geopolymer-based concrete using Class-F fly ash has a great potential for utilisation in construction industries as a replacement for OPC-based concrete, as it has comparable structural properties.

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