Materials Science Forum Vol. 841 (2016) pp 104-110
© (2016) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.841.104

Submitted: 2015-09-30
Accepted: 2015-10-17

Flexural Strength of Low Calcium Class F Fly Ash-based Geopolymer Concrete in Long Term Performance

ARIE Wardhono[1, 2, a*], DAVID W. Law[3,b] and THOMAS C.K. Molyneaux[3,c]

[1]Universitas Negeri Surabaya, Surabaya, Indonesia

[3]RMIT University, Melbourne, Australia

[2]Konsorsium Riset Geopolimer Indonesia (KORIGI), Lab Beton dan Bahan Bangunan ITS, Surabaya, Indonesia

[a]ariewardhono@unesa.ac.id, [b]david.law@rmit.edu.au, [c]tom.molyneaux@rmit.edu.au

Keywords: Fly ash, geopolymer concrete, flexural strength, compressive strength, velocity, long term performance

Abstract. This paper reports on experimental work that has been undertaken to investigate the flexural strength performance of fly ash-based geopolymer (FG) concrete. The FG concrete was prepared using low calcium class F fly ash with high silicate content. The flexural strength properties of FG were assessed using modulus of rupture test up to the age of 360 days. Compressive strength and Ultrasonic Pulse Velocity (UPV) tests were also performed to corroborate the flexural strength test results. The results showed that the FG concrete demonstrates a comparable compressive strength and velocity to OPC concrete. Hewever, the flexural strength of FG concrete exhibited a better performance compared to that OPC concrete. The measured flexural strength of FG concrete also exhibited a higher value compared to the predicted one using ACI 318M-08 standard. The relationship between flexural strength with compressive strength demonstrated a similarity behavior to that OPC concrete. Thus, it can be concluded that the use of the ACI standard can be applied conservatively to determine the flexural strength of fly ash-based geopolymer concrete.

Introduction

The utilization of fly ash-based geopolymer (FG) as an alternative material to ordinary Portland cement (OPC) contributes sustainability to concrete material by reducing the CO_2 emission associated with cement production. The production of OPC has led to the environmental concerns over the production of CO_2 with approximately 0.7-1 ton of CO_2 per 1 ton OPC produced [1, 2]. On further development, the FG concrete has played a significant role in green technology by eliminating the use of cement and by utilizing various by-product materials such as fly ash, a waste product from the burning of coal. The major benefit of FG concrete is that the greenhouse gas emissions produced by FG is reduced compared to OPC, which depends on the limestone calcination process and produces around 5% of worldwide greenhouse emissions [3].

The properties of FG concrete have been investigated in a number of papers. In terms of mechanical properties, some researchers have demonstrated the similarity of FG concrete to traditional concrete over short periods of time. The FG concrete has been observed to have a comparable compressive strength and modulus of elasticity. It has also been found that FG concrete can develop similar flexural strength behavior to that OPC concrete [4, 5]. The correlation of mechanical properties in terms of flexural strength of FG concrete was also investigated by Diaz Loya et al. [6] using regression analysis at 28-days age. The authors found that FG concrete seems to possess a similar mechanical behavior to that of OPC concrete and that the relationship between the flexural and compressive strength can be expressed using ACI standard intended for ordinary concrete. Neupane et al. [7] investigated the applicability of the Australian Standard concluded that the flexural strength were higher than calculated by the Australian standard. Using the relevant Australian standard, the authors found that the observed flexural strength of the FG concrete was slightly higher than that of OPC concrete at 28 days. They found that observed results were 10%

All rights reserved. No part of contents of this paper may be reproduced or transmitted in any form or by any means without the written permission of Trans Tech Publications, www.ttp.net. (ID: 103.242.124.2-24/11/15,07:42:01)

higher than those predicted by this standard. Most of the studies to date, however, have focused on short term behavior of FG concrete, and only limited studies have been conducted on the long term performance.

This paper reports the details of experimental work that has been carried out to identify the flexural strength behavior of FG concrete in term of long term performance. The FG concrete was prepared using a low calcium class F fly ash with high silicate content. The flexural strength properties of FG concrete were assessed using modulus of rupture test up to the age of 360 days The compressive strength and velocity tests were also performed to corroborate the result of flexural strength test.

Experimental Procedure.

Materials. Low calcium class F fly ash with high silicate content in accordance with ASTM standard [8] was used as the primary materials. The chemical composition of the fly ash is shown in Table 1.

Table 1. Chemical compositions of fly ash (mass %)

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	P_2O_5	Mn_2O_3	SO_3
Fly ash	70.28	23.12	1.41	0.17	0.54	0.89	0.32	2.61	0.23	0.01	0.22

The fineness of the fly ash materials was 67.9% (passing 45 μm) and measured using a Malvern Particle Size Analyser Instruments Mastersizer X.

Alkaline Solutions. A sodium silicate (Na_2SiO_4) with alkali modulus (AM) of approximately 2.0 ($Na_2O = \pm 0.147$ and $SiO_2 = \pm 0.294$) and a high concentration of sodium hydroxide (NaOH), 15 M NaOH, in liquid form were used to formulate alkaline activator solutions. The dossage and activator modulus (Ms) of the activator solutions were 15% (by fly ash mass in FG concrete mix) and 1.00, respectively.

Mix Proportions. The details of FG concrete mix proportions are shown in Table 2. The FG concrete mix was developed from the previous project at RMIT University with a design strength of 40 ± 10 MPa. As continuation project (Stage II Project), the mix design of OPC concrete was derived from previous project (Stage I Project) by Adam [9] as comparison data. In order to give more consistent workability on mixing process, a water solid ratio (w/s) of 0.41 was used to prepare the FG concrete mix, rather than a w/b ratio. The quantity of water in FG concrete mix was taken as the sum of water contained in the sodium silicate, sodium hydroxide and the added water, while the quantity of solid was determined by the mass of fly ash and the solid content of the alkaline activator solution.

Table 2. Mixture proportions of FG concrete (kg)

Mixture	Portland Cement	Fly ash	Aggregate			Activator		Added water
			Sand	7 mm	10 mm	Na_2SiO_3	NaOH 15M	
OPC *	467	-	784	346	693	-	-	222
FG	-	467	784	346	693	234	147	10

Note: * Adam (2009) [9]

Testing Specimens. Compressive strength was performed on a Universal Testing Machine, UH-F500 kNI, Shimadzu, under a load control regime with a loading rate of 20 MPa/min [10]. The flexural strength of FG specimen was determined by modulus of rupture in accordance with ASTM C78-02 [11]. The flexural strength measurement was carried out on a MTS machine with additional testing apparatus under a loading rate of 1 ± 0.1 MPa/min. The UPV test was carried out to determine the bulk property of FG concrete in accordance with ASTM C597-02 [12]. Three specimens were tested for each data point.

Results and Discussion

Compressive and Flexural Strength Development. Although concrete is designed to achieve a specified compressive strength, flexural strength is also plays an important role due to the occurrence of cracking in concrete caused by the overloading under flexural conditions. These cracks may cause serviceability and durability issues.The flexural tensile strength of concrete may be calculated using two different methods as follows:

1) Based on the measured flexural strength test (modulus of rupture test result), in accordance with ASTM C78-02 [11] as shown in Fig. 1.
2) Based on the compressive strength test result, in accordance with ACI 318-08 [13], the flexural strength of concrete can be calculated using the equation (1):

$$f_r = 0.62 \sqrt{f'_c} \qquad (1)$$

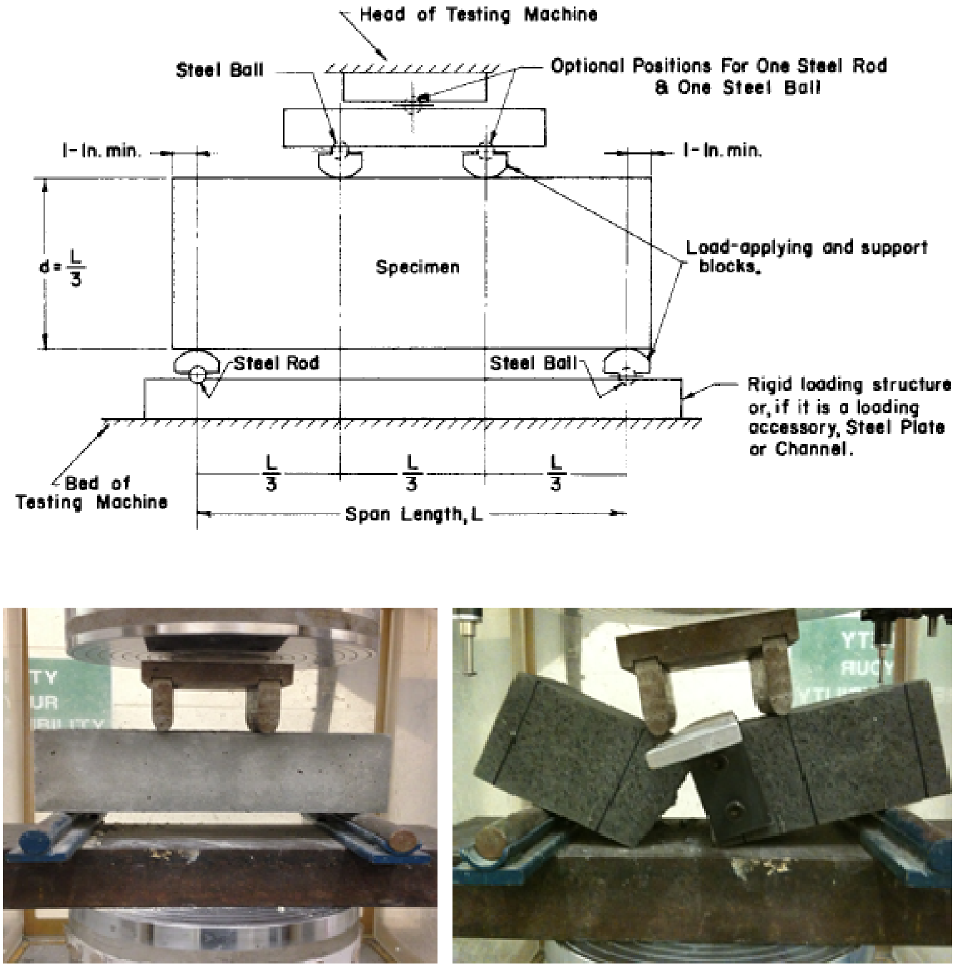


Fig. 1. The apparatus for flexure test of concrete by third-point loading method (ASTM C78-02)

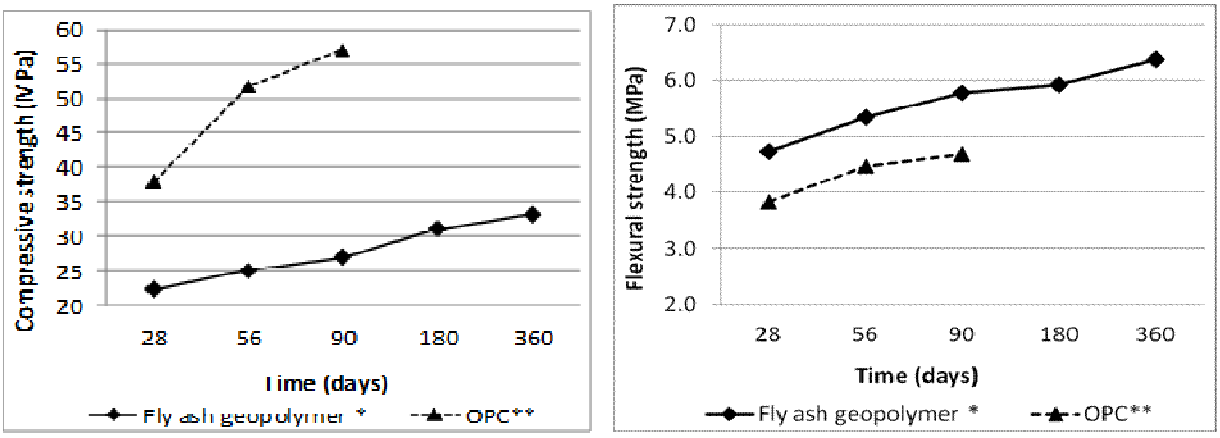
The flexural strength test based on the measured modulus of rupture test result, the compressive strength and the velocity test results of the FG concrete are shown in Table 3. The FG concrete exhibited a lower strength at 28 days compared to the OPC concrete which has been investigated by other researcher [9]. Indeed at 28 days the FG concrete has only achieved a compressive strength of 22.37 MPa. However, the FG concrete showed a significant increase in strength with further time, achieving 31.09 MPa at 180 days and increasing to 33.23 MPa at 360 days as shown in Figure 2. This would indicate that the reaction process was not complete at 28 days. Overall an increase in strength of 48.55% was observed between 28 and 360 days. In general, class F fly ash-based geopolymer concretes exhibit a slower setting and strength development at room temperature and higher strength can be achieved by adopting a heat curing treatment [14]. As such it is interesting to note that even with heat curing, strength development continues with time, indicating that the geoploymeric reaction is on-going with time despite the heat curing.

Table 3. Flexural and compressive strengths of FG concrete

Age of concrete (days)	Compressive strength f'c (MPa)	Velocity from UPV measurement (km/s)	Measured flexural strength $f_{r.1}$ (Actual) (MPa)	Flexural strength from ACI $f_{r.2} = 0.62\sqrt{f'c}$ (Predicted) (MPa)	Flexural strength ratio (actual / predicted)
28	22.37 ± 0.56	2.81 ± 0.14	4.73 ± 0.33	2.93	1.614
56	25.13 ± 0.66	2.90 ± 0.33	5.33 ± 0.45	3.11	1.714
90	27.01 ± 0.71	3.06 ± 0.20	5.78 ± 0.69	3.22	1.795
180	31.09 ± 1.15	3.10 ± 0.23	5.92 ± 0.16	3.46	1.711
360	33.23 ± 1.50	3.38 ± 0.21	6.37 ± 0.18	3.57	1.784

Table 4. Predicted flexural and compressive strengths of OPC concrete by Adam (2009) [9]

Age of concrete (days)	Compressive strength f'c (MPa)	Flexural strength from ACI $f_{r.2} = 0.62\sqrt{f'c}$ (Predicted) (MPa)
28	38.0	3.82
56	51.8	4.46
90	57.0	4.68



Note: * Actual, based on laboratory results (Project Stage II)
** Adam (2009) [9], previous project (Project Stage I) conducted at RMIT University

Fig. 2. The flexural and compressive strength development of FG concrete

In term of flexural strength, the relationship between the flexural strength and the compressive strength of OPC concrete follows a positive linear relationship. An increase in the compressive strength of OPC concrete leads to an increase in the flexural tensile strength. The behavior of the flexural strength of the FG concrete was seen to be similar to that of OPC concrete (Fig. 2). Both compressive and flexural stregths of FG concrete showed a significant increase over periods of time. The 28 days of FG concrete achieved a flexural strength of 4.73 MPa and increasing significantly to 6.37 MPa at 360 days.

Further, these results were also corroborated with the increase of velocity test results as shown in Table 3. The velocity test depends on the density and the elastic properties which are related to the quality and strength of the concrete. The velocity of FG concrete was seen increase from 2.81 km/s at 28 days to 3.10 km/s at 360 days with an overall increase of 10.32%. This indicated that the bulk properties and the quality of FG concrete are getting better over time. Compared to OPC concrete, FG concrete demonstrated a lower performance in terms of velocity measurment. Although the velocity measurement showed the highest value at 360 days with the velocity of 3.10 km/s, the velocity of FG concrete is still slightly lower than the standard velocity of OPC concrete, 4.47 km/s [15].

Despite the FG concrete demonstrated a low compressive strength, it exhibited a better flexural strength compared to OPC concrete as shown in Fig.2. This might attributed to the micro-structural characteristic of FG concrete. According to Fernandez-Jimenez [16], the 3D skeleton produced in the geopolymeric reaction affords exceptional physical solidity which is responsible for the mechanical behavior observed. Based on EDX analysis (Fig. 3), it was showed that the matrix of FG concrete mainly comprised of silicate (Si) and aluminate (Al). As the ratio of Si/Al was 3.32, the main geopolymeric gel of FG concrete was inferred to be (Si)-poly sialate-disiloxo.

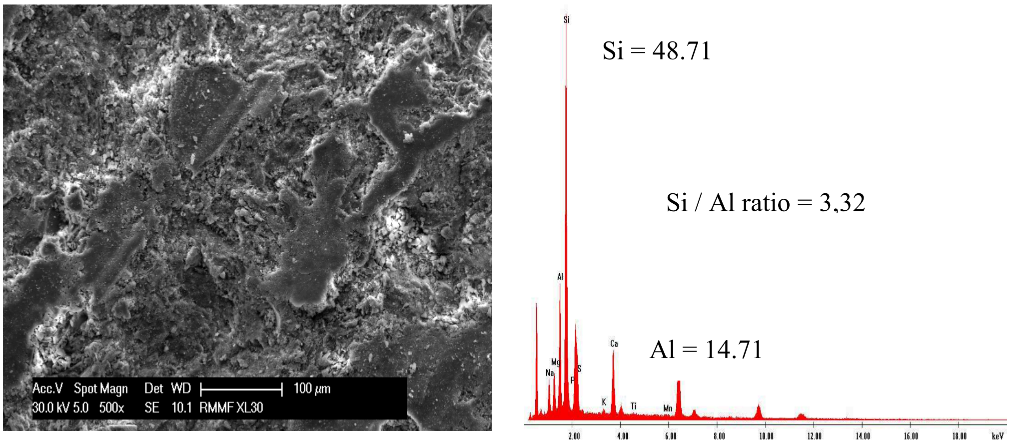
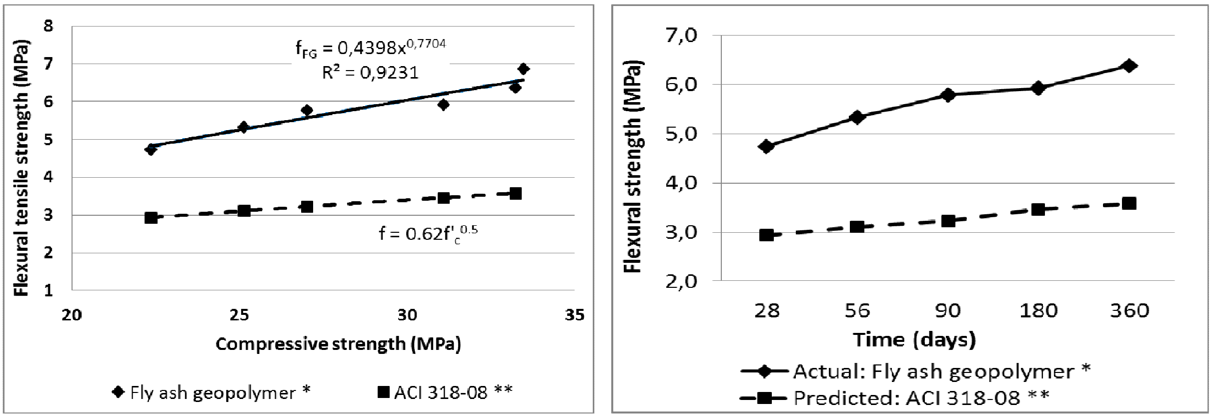


Fig. 3. Microscopy analysis of FG concrete

Measured and Predicted Flexural Strength. The development of actual and predicted flexural strengths are shown in Table 3 and Figure 4. The actual flexural strength ($f_{r.1}$) was measured based on the modulus of rupture (MOR) test in accordance with ASTM C78-02 [11]. The predicted flexural strength ($f_{r.2}$) was derived from the compressive strength test result using a formula of: $f_r = 0.62 \sqrt{f'_c}$ as in accordance with ACI 318-08 [13].

The predicted flexural strength ($f_{r.2}$) of FG concrete, which measured using ACI 318-08 standard, was predicted to be 2.84 MPa at 28 days and increased to 3.46 MPa at 360 days. However, the actual measured flexural strength (test result, measured using ASTM C78-02) was found to be higher than the characteristic flexural strength predicted (Table 3 and Fig. 4). Hence ACI standard was found to under-value the flexural strength development of FG concrete, indicating that the use of ACI standard would be conservative to calculate the flexural strength. This also indicated that the long term behavior of FG concrete was significantly better than the ACI 318-08 standard prediction.



Note: * Actual, based on laboratory results, ASTM C78-02 [11]
** Predicted, based on ACI 318-08 [13]

Fig. 4. Flexural strength development of fly ash-based geopolymer concrete

A general regression model for FG concrete based on the correlation between flexural tensile strength and compressive strength (Fig. 4) can be made as follows:

$$f_{FG} = 0.4398.(fc')^{0.7704} \tag{2}$$

where ‘f_{FG}’ is the flexural tensile strength of FG concrete and fc’ is the compressive strength. The regression model shows that the model fitted the data with the coefficient of determination of 92.31%. It should be noted that the model is based on a limited number of data.

Similar results have been found by other researchers [6, 7, 16]. They showed that the measured flexural strengths of geopolymer concrete are higher than values predicted from as ACI standard [13]. The flexural strength ratio, which is determined based on the ratio of the measured flexural strength to the predicted ACI value, shows that the measured flexural strength is approximately 20% – 60% higher than that predicted by ACI standard.

Summary

The following conclusions may be drawn based on this study:

1. The increase of flexural strength of FG concrete was followed by the increase of compressive strength and velocity results which indicating that the quality of FG concrete are getting better with time.
2. The FG concrete demonstrated a lower compressive strength and velocity results compared to that OPC concrete.
3. The modulus of rupture of FG concrete performed a better performance than OPC concrete indicating that FG concrete has a better flexural strength compared to OPC concrete.
4. The relationship between the flexural tensile strength with compressive strength is similar to that for OPC concrete.
5. The ACI standard was under-value the flexural strength of FG concrete, indicating that the use of ACI standard would be conservative to calculate the flexural strength.
6. The use of the existing standard can be applied conservatively to determine flexural tensile strength of fly ash geopolymer concrete.
7. The improved performance of fly ash concrete with time suggests that the structural use of fly ash concrete is feasible.

Acknowledgements

The authors would like to acknowledge the materials support from the PQ Australia for carrying out this research project.

References

[1] Davidovits, J.: World Resource Review Vol. 6 (2) (1994), p. 263-278.

[2] Berry, M., D. Cross, and J. Stephens, in: World of Coal Ash (WOCA), Lexington, KY, USA (2009).

[3] Gartner, E.: Cement and Concrete Research Vol. 34 (2004), p. 1489-1498.

[4] Hardjito, D., et al.: ACI Materials Journal Vol. November - December (2004), p. 467-472.

[5] Rangan, B.V., et al.: Materials Forum Vol. 30 (2006), p. 170-175.

[6] Diaz-Loya, E.I., E.N. Allouche, and S. Vaidya: ACI Materials Journal Vol. May - June (2011), p. 300-306.

[7] Neupane, K., et al., in: Concrete in Australia magazine, edited by Concrete Institute of Australia, Australia (2014), p.50-56.

[8] ASTM International: ASTM C618-03 (2003).

[9] Adam, A.A.: Dissertation, School of Civil, Environment and Chemical Engineering, RMIT University, Melbourne, Australia (2009).

[10] ASTM International: ASTM C109/C109M-07 (2008).

[11] ASTM International: ASTM C78-02 (2003).

[12] ASTM International: ASTM C597-02 (2003).

[13] American Concrete Institute: ACI 318M-08 (2011).

[14] Bakharev, T.: Cement and Concrete Research Vol. 35 (2005), p. 1224-1232.

[15] Yaman, I.O., et al.: ACI Materials Journal Vol. November - December (2001), p. 450-457.

[16] Fernandez-Jimenez, A., A. Palomo, and C. Lopez-Hombrados: ACI Materials Journal Vol. March - April (2006), p. 106-112.