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Fly ash-based geopolymer concrete: study of slender reinforced columns

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Abstract The objectives of this paper are to present the results of experimental study and analysis on the behaviour and the strength of reinforced geopolymer concrete slender columns. The experimental work involved testing of twelve columns under axial load and uniaxial bending in single curvature mode. The compressive strength of concrete for the first group of six columns was about 40 MPa, whereas concrete with a compressive strength of about 60 MPa was used in the other six columns. The other variables of the test program were longitudinal reinforcement ratio and load eccentricity. The test results gathered included the load carrying capacity, the load-deflection characteristics, and the failure modes of the columns. The analytical work involved the calculation of ultimate strength of test columns using the methods currently available in the literature. A simplified stability analysis is used to calculate the strength of columns. In addition, the design provisions contained in the Australian Standard AS3600 and the American Concrete Institute Building Code ACI318-02 are used to calculate the strength of geopolymer concrete columns. This paper demonstrates that the design provisions contained in the current standards and codes can be used to design reinforced fly ash-based geopolymer concrete columns.

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Introduction

Concrete, an essential building material is widely used in the construction of infrastructures such as buildings, bridges, highways, dams, and many other facilities. One of the ingredients usually used as a binder in the manufacture of concrete is the Ordinary Portland Cement (OPC). The increasing worldwide production of OPC to meet infrastructure developments indicates that concrete will continue to be a chosen material of construction in the future [1]. However, it is well known that the production of OPC not only consumes significant amount of natural resources and energy but also releases substantial quantity of carbon dioxide (CO_2) to the atmosphere [2]. Currently, the cement industries produce 1.5 billion tons of OPC each year. This adds about 1.5 billion tons of CO_2 into the atmosphere [3, 4].

To address the aforementioned issues, it is essential to find alternative binders to make concrete. One of the efforts to produce more environmentally friendly concrete is to replace the amount of OPC in concrete with by-product materials such as fly ash [2]. An important achievement in this regard is the development of high volume fly ash (HVFA) concrete that utilizes up to 60 percent of fly ash, and yet possesses excellent mechanical properties with enhanced durability performance.

Another effort to make environmentally friendly concrete is the development of inorganic alumino-silicate polymer, called Geopolymer, synthesized from materials of geological origin or by-product materials such as fly ash that are rich in silicon and aluminium [5]. According to Davidovits [6], geopolymerization is a geosynthesis that chemically integrates materials containing silicon and aluminium. During the process, silicon and aluminium atoms are combined to form the building blocks that are chemically and structurally comparable to those binding the natural rocks.

Fly ash is available abundantly worldwide, and so far its utilization is limited. In 1998 estimation, the global coal ash production was more than 390 million tons annually, but its utilization was less than 15% [1]. In the USA, the production of fly ash is approximately 63 million tons annually, but only about 20% of that total is used by the concrete industries [7]. Accordingly, efforts to utilize this by-product material in concrete manufacture are important to make concrete more environmentally friendly. For instance, every million tons of fly ash that replaces OPC helps to conserve one million tons of limestone, 0.25 million ton of coal and over 80 million units of power; not withstanding the abatement of 1.5 million tons of CO_2 to atmosphere [8].

Geopolymer material

Geopolymer paste

Work on geopolymer concrete at Curtin University of Technology was triggered by several studies on geopolymer paste previously conducted by others. Davidovits and Sawyer [9] used ground blast furnace slag to produce geopolymer binders. This type of binders patented in the USA under the title Early High-Strength Mineral Polymer was used as a supplementary cementing material in the production of precast concrete products. In addition, a ready-made mortar package that required only the addition of mixing water to produce a durable and very rapid strength-gaining material was produced and utilised in rapid restoration of concrete airport runways, aprons and taxiways, highway and bridge decks, and for several new constructions when high early strength was needed. Geopolymer has also been used to replace organic polymer as an adhesive in strengthening structural members. Geopolymers were found to be fire resistant and durable under UV light [10]. It was also found [11] that the compressive strength after 14 days was in the range of 5 – 50 MPa. The factors affecting the compressive strength were the mixing process and the chemical composition of the fly ash. A higher CaO content decreased the microstructure porosity and, in turn, increased the compressive strength. Besides, the water-to-fly ash ratio also influenced the strength. It was found that as water-to-fly ash ratio decreased the compressive strength of the binder increased.

It was reported [12] that both the curing temperature and the curing time influenced the compressive strength. The utilization of sodium hydroxide (NaOH) solution combined with sodium silicate ($Na_2O.SiO_2$) solution produced the highest strength. Compressive strength up to 60 MPa was obtained for curing at 85°C for 5 hours. Swanepoel and Strydom [13] conducted a study on geopolymers produced by mixing fly ash, kaolinite, sodium silica solution, NaOH, and water. Both the curing time and the curing temperature affected the compressive strength, and the optimum strength occurred when specimens were cured at 60°C for a period of 48 h.

The interrelationship of certain parameters that affected the properties of fly ash-based geopolymer has been investigated [14]. It was reported that the properties of geopolymer were influenced by the incomplete dissolution of the materials involved in geopolymerization. The water content, curing time and curing temperature affected the properties of geopolymer; specifically, the curing condition and calcining temperature influenced the compressive strength. When the samples were cured at 70°C for 24 h a substantial increase in the compressive strength was observed. Curing for a longer period of time reduced the compressive strength.

Fly ash-based geopolymer concrete

In this study, geopolymer concrete was produced by utilising low-calcium (ASTM Class F) fly ash as the base material. A combination of sodium hydroxide solution and sodium silicate solution was used to react with the silicon and the aluminium in the fly ash to form the paste that bound the aggregates and other un-reacted materials in the mixture to produce the geopolymer concrete. The manufacture of geopolymer concrete was carried out using the usual concrete technology methods.

The stress-strain relations and Young's modulus of fly ash-based geopolymer concrete for various compressive strengths have been reported elsewhere. These test data have shown that these properties of geopolymer concrete are similar to that of OPC concrete [15].

The previous studies have shown that the compressive strength is influenced by several factors such as curing time, curing temperature, water content in the mixture, and sodium silicate-to-sodium hydroxide liquid ratio by mass. It was also found that curing at 60°C for 24 h was sufficient to achieve the required compressive strength [16].

The previous studies on geopolymer concrete mainly investigated the short-term and long-term properties. Heat-cured fly ash-based geopolymer concrete possesses high compressive strength, undergoes very little drying shrinkage and moderately low creep, shows excellent resistance to sulfate attack, and resists acid attack [16–20].

Experimental Programme

Materials and mixture proportions

In this research, low-calcium ASTM Class F dry fly ash obtained from Collie Power Station, Western Australia was used as the base material. The chemical composition of the fly ash as determined by X-ray Fluorescence (XRF) analysis is given in Table 1.

The alkaline solutions used in this study were sodium hydroxide in flake form (NaOH with 98 % purity) dissolved in water and sodium silicate solution (Na_2O=14.7%, SiO_2=29.4%, and water=55.9%). Both the solutions were mixed together and the alkaline liquid was prepared at least one day prior to use.

Three types of locally available aggregates comprising 10 mm and 7 mm coarse aggregates, and fine sand were used. The fineness modulus of combined aggregates was 4.50.

The longitudinal reinforcement was 12 mm deformed bars (N500 grade), while the lateral reinforcement was 6 mm diameter wires. Six columns contained four 12 mm (N 12) deformed bars, and the other six were reinforced with eight 12 mm deformed bars (N 12) as longitudinal reinforcement. These arrangements gave reinforcement ratios of 1.47% and 2.95% respectively. The test specimens were manufactured and heat-cured using the technology to make geopolymer concrete reported in earlier work [16–20]. In this study, the test specimens were steam-cured at 60° C for 24 h.

The column cross-section was a 175 mm square. The height of the columns was 1500 mm. Due to the use of end assemblages at both ends of test columns, the effective length of the columns measured between the centers of the load knife-edges was 1684 mm.

The mixture proportions (Table 2) were developed from previous studies conducted by the authors. The mixtures were designed to achieve an average compressive strength of 40 MPa (Series-1) and 60 MPa (Series-2). A commercially available naphthalane based Superplasticizer was used in order to improve the workability of the fresh concrete. Because the capacity of the laboratory pan mixer was only 70 l, several batches of concrete were made for each mixture. The slump of fresh concrete and the compressive strength of hardened concrete were measured for each batch of concrete. These results indicated that the properties of both fresh and hardened concrete from various batches were consistent. The slump of fresh concrete varied between 220 and 240 mm. The average compressive strengths of concrete, as measured by crushing 100 × 200 mm cylinders, for the test columns are given in Table 3.

Instrumentation and test procedure

All columns were tested in a Universal test machine with a capacity of 2500 kN. Two specially built end assemblages were used at the ends of the columns (Figure 1a). This arrangement simulated an ideal hinge support condition, and has been successfully used in previous column tests [21–23]. An automatic data acquisition unit was used to collect the data during the test. Six calibrated Linear Variable Differential Transformers (LVDTs) were used. Five LVDTs measured the lateral deflections, and were placed at selected locations along the height of test columns. One LVDT was placed on the perpendicular face to check the out of plane movement of columns during testing.

Table 2 Mixture proportions

Material	Mass (kg/m^3)	
	Series-1	Series-2
10 mm aggregates	555	550
7 mm aggregates	647	640
Fine sand	647	640
Fly ash	408	404
Sodium hydroxide solution	41 (16M)	41 (14M)
Sodium silicate solution	103	102
Superplasticizer	6	6
Extra added water	26 (GCI)	16.5 (GCII)

Table 1 Composition of fly ash as determined by XRF (mass %)

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	H_2O	LOI*
47.8	24.4	17.4	2.42	0.31	0.55	1.328	1.19	2.0	0.29	-	1.1

* Loss on ignition

Table 3 Summary of experimental results

Column No.	Concrete Strength* (MPa) [f'_c]	Load Eccentricity** (mm) [e]	Longitudinal Reinforcement		Test Results	
			Bars	Ratio (%) [ρ]	Failure Load (kN)	Mid-height deflection at failure load
GCI-1	42	15	4N12	1.47	940	5.44
GCI-2	42	35	4N12	1.47	674	8.02
GCI-3	42	50	4N12	1.47	555	10.31
GCI-4	43	15	8N12	2.95	1237	6.24
GCI-5	43	35	8N12	2.95	852	9.08
GCI-6	42	50	8N12	2.95	666	9.40
GCII-1	66	15	4N12	1.47	1455	4.94
GCII-2	66	35	4N12	1.47	1030	7.59
GCII-3	66	50	4N12	1.47	827	10.70
GCII-4	59	15	8N12	2.95	1559	5.59
GCII-5	59	35	8N12	2.95	1057	7.97
GCII-6	59	50	8N12	2.95	810	9.18

* The compressive strength was measured by crushing test cylinders on the day of column tests

** Load eccentricity obtained by adjusting the adaptor plate of the end assemblages before the test

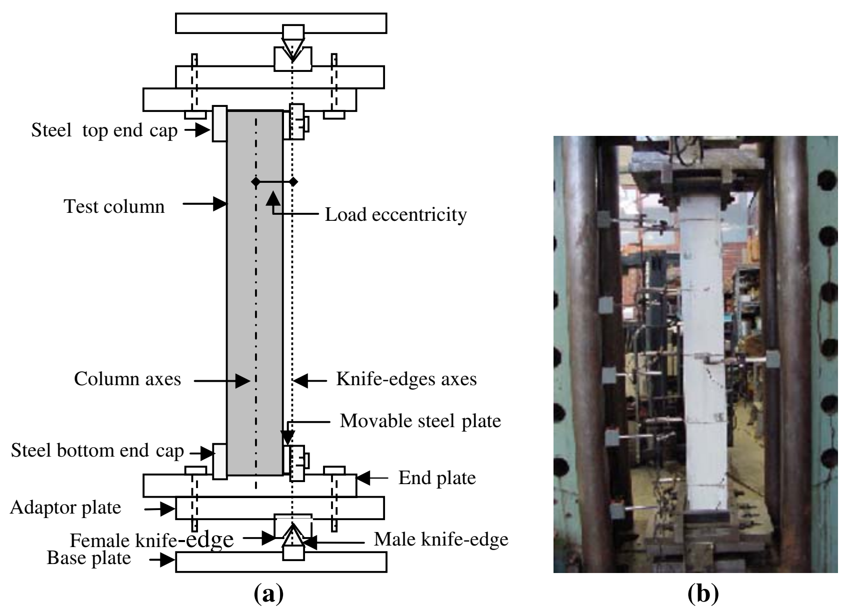

Fig. 1 **(a)** End assemblage arrangement; **(b)** Column before the test

To eliminate loading non-uniformity due to uneven top or bottom surface, preparation of the column ends was done by smoothly grinding the surfaces of each end before testing. Before placing the column in the machine, the end assemblages were adjusted to the desired load eccentricity. The line through the axes of the knife-edges represented the load eccentricity. The base plates were first attached to the top and bottom platens of the test machine. The adaptor plate, with female knife-edge, was attached to base plate and fitted to male knife-edge. The specimen was then placed into the bottom end cap, and the test machine platens were moved upward until the top of the column was into the top end cap. To secure the column axes parallel to the axes of the knife-edges, a 20 kN preload was applied to the specimen.

The specimens were tested under monotonically increasing axial compression with specified load eccentricity. The tests were conducted by maintaining the movement of the test machine platens at a rate of 0.3 mm/sec. All loads and deflection data were electronically recorded using a data logging system. Figure 1 shows the column configuration before the tests.

Results and Discussion

The compressive strength of concrete was measured by crushing the test cylinders on the day of column

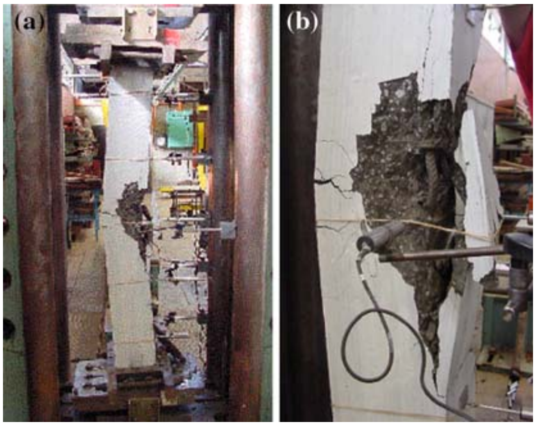

Fig. 2 **(a)** Column after the test; **(b)** Typical failure mode (GCII-4)

tests. The salient experimental results are given in Table 3. As expected, cracks initiated at column mid-height on the tension face. As the load increased, the existing cracks propagated and new cracks initiated along the tension face and spread out towards the ends of columns. The width of cracks varied depending on location. The cracks at the mid-height widely opened near failure. The location of the failure zone varied from mid-height section to an extreme of 250 mm below or above mid-height. The failure was due to crushing of concrete in the compressed face near the mid-height of columns (Fig. 2). The failures were generally brittle. A sudden and explosive failure with a short post-peak behavior was characterized by columns with smaller load eccentricity, higher concrete strength, and higher longitudinal reinforcement ratio.

The load versus mid-height deflection graphs of test columns are presented in Fig. 3. In general, the deflections decreased with an increase in the concrete compressive strength and an increase in the percentage of longitudinal reinforcement ratio. As expected, deflections increased with the increase in load eccentricity.

A slender column is a compression member in which the load-carrying capacity of the cross-section is reduced by the lateral deflection caused by the slenderness of the column. The test columns are slender columns. The load capacity of slender columns may be calculated using a stability analysis. The details of such analysis are described elsewhere [24, 27].

The load capacity of the test columns was calculated using a simplified stability analysis proposed earlier by Rangan [24], as well as by the design provisions contained in the Australian Standard AS3600 [25] and the American Concrete Institute Building Code ACI 318–02 [26]. The simplified stability analysis has been proven to be accurate in the case of OPC concrete slender columns under equal load eccentricities [22], and for the high strength OPC concrete slender columns under unequal load eccentricities [23].

The load capacity of columns is influenced by load-eccentricity, concrete compressive strength, and longitudinal reinforcement ratio. As expected, as the load eccentricity decreased, the load capacity of columns increased. The load capacity also increased when the compressive strength of concrete and the longitudinal reinforcement ratio increased (Table 4). A summary of comparison between the experimental values and calculated values is given in Table 4. Excellent correlation between the values is seen.

Conclusions

The paper presented the experimental and analytical results on the behaviour and the strength of reinforced

Fig. 3 Load versus mid-height deflection curves of columns

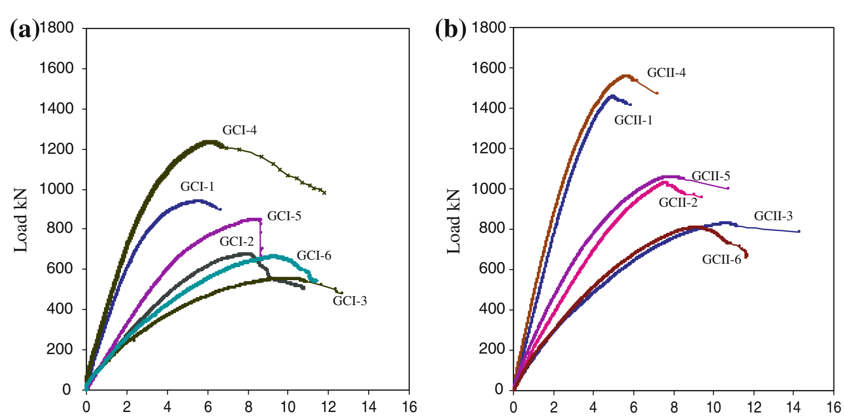

Table 4 Comparison between experimental and predicted failure loads

Column No.	f'_c	e	ρ	Test Failure Load (kN)	Predicted Failure Load (kN)			Failure Load Ratio		
					Rangan[24]	AS3600[25]	ACI 318–02[26]	Test/Rangan	Test/AS3600	Test/ACI318–02
GCI-1	42	15	1.47	940	988	962	926	0.95	0.98	1.01
GCI-2	42	35	1.47	674	752	719	678	0.90	0.94	0.99
GCI-3	42	50	1.47	555	588	573	541	0.94	0.97	1.03
GCI-4	43	15	2.95	1237	1149	1120	1050	1.08	1.10	1.18
GCI-5	43	35	2.95	852	866	832	758	0.98	1.02	1.12
GCI-6	42	50	2.95	666	673	665	604	0.99	1.00	1.10
GCII-1	66	15	1.47	1455	1336	1352	1272	1.09	1.08	1.14
GCII-2	66	35	1.47	1030	1025	1010	917	1.00	1.02	1.12
GCII-3	66	50	1.47	827	773	760	738	1.07	1.09	1.12
GCII-4	59	15	2.95	1559	1395	1372	1267	1.11	1.14	1.23
GCII-5	59	35	2.95	1057	1064	1021	911	0.99	1.04	1.16
GCII-6	59	50	2.95	810	815	800	723	0.99	1.01	1.12
							Average	1.01	1.03	1.11
						Standard Deviation		0.066	0.059	0.077

fly ash-based geopolymer concrete columns. Low-calcium (ASTM Class F) fly ash was used as the source material to make geopolymer concrete. The silicon and the aluminium in the fly ash reacted with a combination of sodium hydroxide solution and sodium silicate solution to form the paste that bound the loose aggregates and other un-reacted materials to produce geopolymer concrete.

Twelve reinforced columns were made and tested. As expected, the column load capacity increased as the load eccentricity decreased. The column capacity also increased with an increase in the longitudinal reinforcement ratio and an increase in the concrete compressive strength.

The load capacity of test columns correlated well with the value calculated using a simplified stability analysis. The load capacity of test columns also agreed well with the value calculated using the design provisions contained in the Australian Standard AS3600 and American Concrete Institute Building Code ACI 318–02.

The results presented in the paper demonstrate that heat-cured low-calcium fly ash-based geopolymer concrete has excellent potential for applications in the precast industry. The products currently produced by this industry can be manufactured using geopolymer concrete. The design provisions contained in the current standards and codes can be used in the case of geopolymer concrete products.

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