Strength and Behaviour of Fly Ash-Based Geopolymer Concrete Beams

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1. Introduction

At Curtin University of Technology, research on the behaviour and engineering characteristics of geopolymer concrete based on fly ash has been ongoing since 2001. The evaluation of the geopolymer concrete's short- and long-term qualities is the focus of the study. Prior to now, the variables that affect geopolymer concrete's compressive strength were reported (Hardjito et al., 2004a, 2004b). Also, the long-term characteristics of geopolymer concrete, such as creep, shrinkage, and sulphate resistance, were studied (Wallah et al., 2003, 2004).

According to the findings of earlier study by the authors, geopolymer concrete has good resistance to sulphate attack, high strength, and very little drying shrinkage and fairly low creep (Hardjito et. al, 2004a, 2004b). According to other researches, geopolymers have great fire resistance and do not experience the alkali-aggregate reaction (Davidovits, 1999). (Cheng and Chiu, 2003).

The behaviour and strength of structural members made with geopolymer concrete need to be studied. Previous reports on reinforced geopolymer concrete columns' behaviour and strength (Sumajouw et al, 2004, 2005). The findings of a study on the flexural behaviour and strength of geopolymer concrete beams based on reinforced fly ash are presented in this publication. Longitudinal reinforcement ratio and concrete compressive strength were the main test programme variables. The load-deflection curves and the failure loads of the beams were measured as part of the test results. In the analytical work, the ultimate strength of beams was predicted using the design guidelines in the current Australian Standard, AS3600, for structures made of ordinary Portland Cement (OPC) concrete.

2. Geopolymers

Inorganic alumino-silicate polymers made mostly from silicon and aluminium components with geological origins or byproducts are known as geopolymers, according to Davidovids (1999). Materials containing silicon and aluminium are chemically integrated during the geosynthesis process. The foundation materials' silicon and aluminium atoms are induced to dissolve and produce the geopolymer binder using alkaline solutions.

Geopolymer pastes were used in early experiments on this material. These experiments have demonstrated the strength and durability of geopolymer binders (Davidovitds, 1987). In order to strengthen structural parts, Balaguru et al. (1997) employed geopolymers in place of organic polymers as adhesives. It was discovered that the substance is resilient to UV light and resistant to fire. Ground blast furnace slag was utilised by Davidovits and Sawyer (1985) to create geopolymer binders. In the creation of pre-cast concrete products, the binders served as additional cementing components.

3. Fly ash-based geopolymer concrete

Geopolymer concrete is produced without the presence of Portland cement as a binder. Instead, the base material such as fly ash that is rich in Silicon (Si) and Aluminium (Al) are activated by alkaline solution to produce the binder. In this study, low calcium fly ash is used as the base material. The Silicon and the Aluminium in the fly ash are activated by a combination of sodium hydroxide and sodium silicate solutions to form a binder that binds the aggregates and other un-reacted materials. The manufacture of geopolymer concrete is carried out using the usual concrete technology methods.

The previous research on fly ash-based geopolymer concrete conducted by authors studied the short-term and the long-term properties. Various salient parameters that influence the compressive strength of geopolymer concrete were investigated (Hardjito *et al*., 2004a, 2004b). It was found that the elastic constants, and the stress-strain relations of geopolymer concrete were similar to those of Portland cement concrete (Hardjito *et al*., 2004c). Also, the material possesses high compressive strength, undergoes very little drying shrinkage and moderately low creep, and shows excellent resistance to sulfate attack (Wallah *et al*., 2003, 2004).

4. Experimental Work

Materials and mix proportions

Three types of aggregates, i.e. 10 mm, 7mm, and fine sand were used. The fineness modulus of the combined aggregates was 4.5. Low calcium fly ash obtained from a local power station was used as the base material. The chemical composition of the fly ash as determined by X-Ray Fluorescence (XRF) test is given in Table 1. Commercial grade sodium hydroxide (NaOH) in pellet form (97% purity) dissolved in water, and sodium silicate solution (Na_2O=14.7%, SiO_2=29.4% and water=55.9% by mass) were mixed together and used as the alkaline activator. The concentration of the sodium hydroxide solution was 14 moles (M). In other words, there were 14 moles of NaOH per litre of solution, or 14x40 = 560 grams of NaOH pellets per litre of solution, where 40 is the molecular weight of NaOH.

A commercially available naphthalane based superplasticiser was used to improve the workability of geopolymer concrete.

Table 1 -- Chemical composition of fly ash (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*)
48.0	29.0	12.7	1.78	0.39	0.55	1.67	0.89	1.69	0.5	-	1.61

*) *Loss on ignition*

The mixture proportion for the geopolymer concrete was taken from earlier studies (Hardjito *et al*., 2002). In the concrete mixtures, the combined aggregates occupied 77% by mass, the fly ash 17%, and the alkaline activator solution 6%. The percentage of the superplasticiser to the mass of fly ash was 1.5%. Table 2 shows the mixture proportion of geopolymer concrete used in the present study.

Table 2 -- Mixture proportion of geopolymer concrete

Material	Mass (kg/m^3)
Coarse and fine aggregates	1830
Fly ash	404
Sodium hydroxide solution (14M)	41
Sodium silicate solution	102
Superplasticizer	6

Test specimens

Two series comprising six beams were made. Two beams of the first series were reinforced with deformed steel bars (N-bars) of diameter of 12 and 24mm respectively. Four beams of the second series were reinforced with deformed steel bars (N-bars) of diameter of 12, 16, 20, and 24mm. The lateral reinforcement was deformed steel bars (N-bars) of diameter of 12mm.

The geopolymer concrete was designed to achieve compressive strengths ranging from 35 to 40 MPa. The results of test on samples of the longitudinal steel are given in Table 3. All the beams were designed to fail in a flexural mode. The details of the beams are given in Table 4 and are shown in Figure 1.

Table 3 -- Steel reinforcement properties

Diameter (mm)	Nominal area (mm^2)	Yield Strength (MPa)	Ultimate Strength (MPa)
12	110	545	680
16	200	560	690
20	310	560	635
24	450	555	660

Table 4-- Specimen details

Series	Beam	A_{st} (mm^2)	A_{sc} (mm^2)	d (mm)	Tensile Reinforcement ratio (%)	Slump of fresh concrete (mm)	Concrete compressive strength (MPa)
1	GBI-1	330	220	257	0.64	255	34
	GBI-4	1350	220	251	2.69	255	34
2	GBII-1	330	220	257	0.64	235	46
	GBII-2	600	220	255	1.18	254	42
	GBII-3	930	220	253	1.84	254	42
	GBII-4	1350	220	251	2.69	235	46

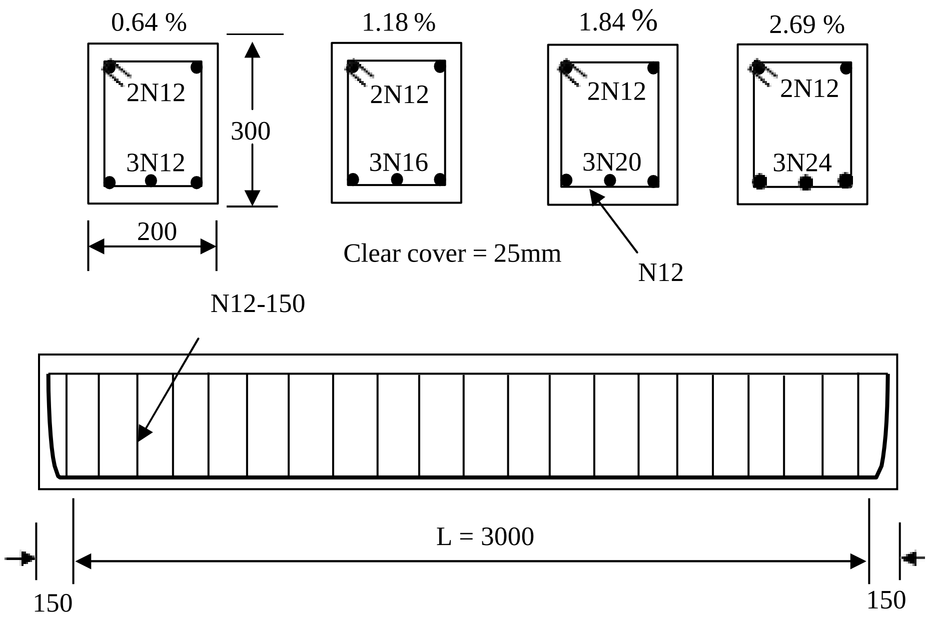

Figure 1 – Geometry and details of Geopolymer concrete beams

Manufacture of specimens

The coarse aggregates and the sand, in saturated surface dry condition, were first mixed dry in a horizontal pan mixer with the fly ash for about three minutes. Towards the end of this mixing, the alkaline activator solution was added to the solid particles and the mixing continued for another four minutes. Immediately after mixing the fresh concrete was cast into the molds. All beams were cast horizontally in wooden molds in two layers. Each layer was compacted using a stick internal compacter. With each mixture, a number of 100mm diameter by 200mm high cylinders were also cast. Due to the limited capacity of the laboratory mixer, six mixes were needed to cast two beams at a time.

After casting, all the specimens were kept at room temperature for three days before curing in the steam-curing chamber. The beams were cured at a temperature of 60^{o}C for 24 hours. After curing, all the specimens were removed from the curing chamber, demoulded, and left at room temperature until the day of testing.

5. Test of beams

All beams were tested in a Universal test machine with a capacity of 2500 kN. The beams were simply supported over a span of 3000mm, and subjected to two concentrated loads placed symmetrically on the span. The distance between the loads was 1000mm. The specimens were tested under monotonically increasing load until failure. The movement of the platens of the test machine was maintained approximately constant at 0.5mm/sec.

An automatic data acquisition unit was used to collect the data during the test. Linear Variable Data Transformers (LVDTs) were placed at selected locations of the beam. All loads and the deflection data were electronically recorded. The rate of data capture varied from 10 to 50 samples per second. In order to ensure enough data for tracing the load-deflection curve near the peak load, higher rate was used when the test beam was approaching the expected peak load.

6. Test results

In all cases, the flexural cracks formed in the pure bending moment zone. As the load increased, existing cracks propagated and new cracks developed in the shear spans. For some beams diagonal cracks also developed in the shear spans. Figure 2 shows some of the beams after failure; others were similar.

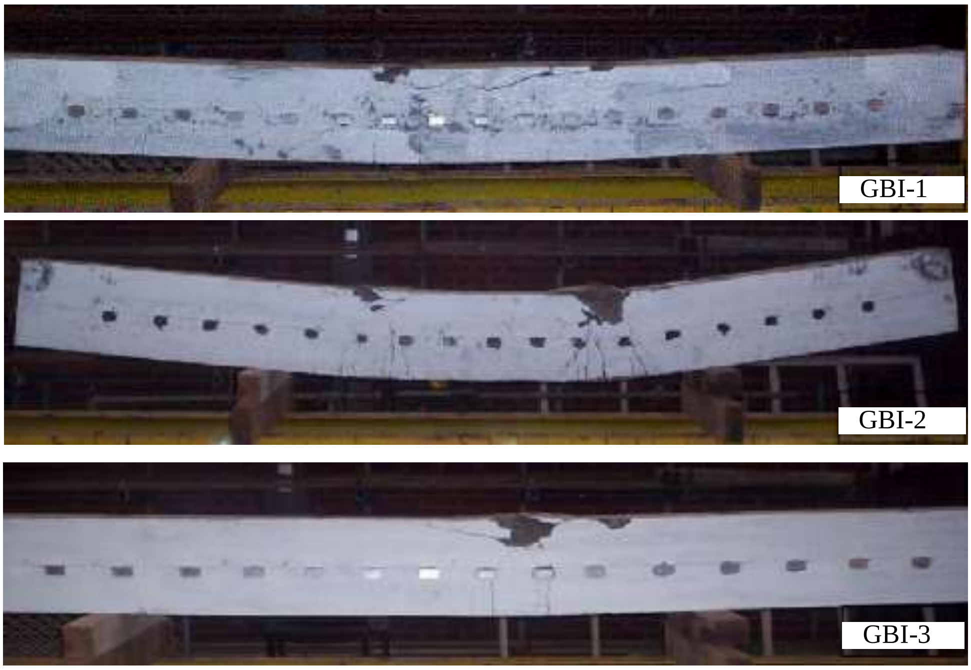

Figure 2 – Beams after test

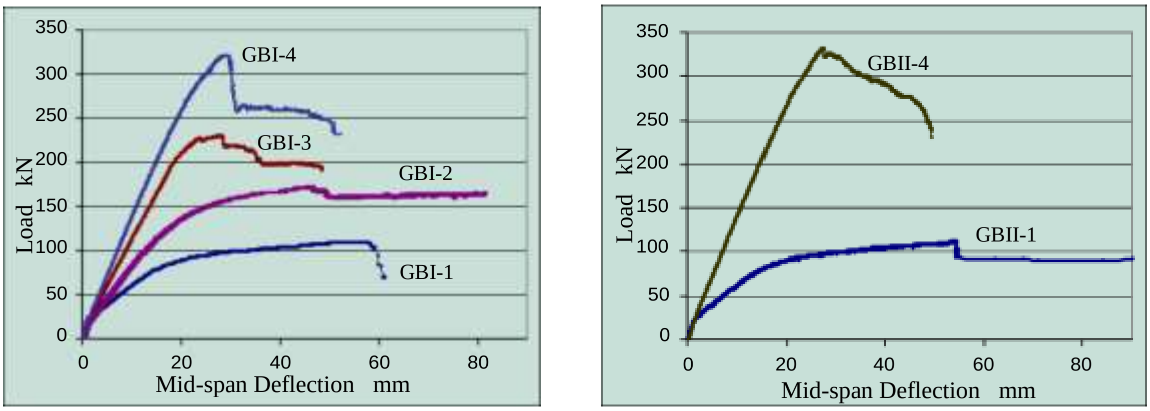

Figure 3 – Load versus Mid-span deflection curves of Beams

All the beams failed in a flexural mode. The cracks at the mid-span widely opened near failure. The location of the failure zone varied between the loads. As expected, the failure was due to crushing of the concrete in the compression zone. The failure was generally ductile. The load versus mid-span deflection curves are shown in Figure 3.

The flexural capacity of the beams is influenced by the concrete compressive strength and the longitudinal tensile reinforcement ratio. As expected, as the longitudinal tensile reinforcement ratio increased the flexural capacity of the beams increased. The flexural capacity also increased when the compressive strength of concrete increased (Table 5).

The flexural strength of the beams were calculated using the design provisions contained in the Australian Standard for concrete structures, AS 3600, as illustrated elsewhere (Warner *et al.*, 1998). The calculated ultimate bending moments are also given in Table 5. It can be seen that the calculated values agree well with the test results. In the case of beams GBI-1 and GBII-1 with a tensile steel ratio of 0.64%, the calculated values are conservative due to the neglect of the effect of strain hardening of tensile steel bars on the ultimate bending moment.

Table 5 -- Summary of results

Beam	Tensile Reinforce-ment ratio (%)	Concrete compressive strength (MPa)	Failure Load (kN)	Mid-span Deflection at Failure Load (mm)	Ultimate Moment (kNm)		Ratio Test/Cal-culated
					Test	Calculated	
GBI-1	0.64	34	112.6	56.63	56.30	45.71	1.24
GBI-2	1.18	42	175.3	46.01	87.65	80.56	1.09
GBI-3	1.84	42	233.7	27.87	116.85	119.81	0.98
GBI-4	2.69	34	326.00	29.22	163.00	155.31	1.05
GBII-1	0.64	46	116.7	54.27	58.35	42.40	1.28
GBII-4	2.69	46	337.4	27.47	168.70	162.31	1.04

7. Conclusions

The paper presented the results of the behaviour and the strength of reinforced fly ash-based geopolymer concrete beams. Based on these results, the following conclusion are drawn:

1. The behaviour and the strength of reinforced geopolymer concrete beams are not different to that of Ordinary Portland Cement (OPC) concrete beams.
2. As expected, when the longitudinal tensile reinforcement ratio increased the flexural capacity of the beams increased. The flexural capacity also increased when the compressive strength of concrete increased.
3. The flexural strength of reinforced geopolymer concrete beams can be calculated using the design provisions contained in the Australian Standard for concrete structure, AS 3600.

8. References

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