

# **A Comparative Study of Alkali Activated Slag and Fly Ash-Based Geopolymer Concrete**

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**ABSTRACT:** The research focuses on the strength properties of alkali activated slag (AAS) and fly ash based Geopolymer concrete. Although there are numerous studies that have assessed the suitability of AAS and fly ash based Geopolymer as the binder in concrete, the main focus of these studies has been the strength properties of the concrete. The effect of sodium oxide dosage and activator modulus on the compressive strength of concrete specimens was explored and the results used to design suitable AAS and Geopolymer concrete mixes. Concrete testing has included measurements of workability, and compressive strength. It is concluded that AAS and fly ash based Geopolymer concretes can exhibit comparable strength to OPC and slag-blended OPC concretes.

**KEYWORDS:** Alkali activated slag, Geopolymer, Fly ash, Concrete, Ground granulated blast furnace slag (GGBS).

## **I. INTRODUCTION**

Portland cement is widely used as binder in the construction throughout the world. It is widely known that the production of Portland cement consumes considerable energy and at the same time contributes a large volume of CO<sub>2</sub> to the atmosphere. However, Portland cement is still the main binder in concrete construction prompting a search for more environmentally friendly materials. One possible alternative is the use of alkali-activated binder using industrial by-products containing silicate materials.<sup>1</sup> The most common industrial by-products used as binder materials are fly ash (FA) and ground granulated blast furnace slag (GGBS). GGBS has been widely used as a cement replacement material due to its latent hydraulic properties, while fly ash has been used as a pozzolanic material to enhance the physical, chemical and mechanical properties of cements and concretes.<sup>2</sup>

GGBS is a latent hydraulic material which can react directly with water, but requires an alkali activator. In concrete, this is the Ca(OH)<sub>2</sub> released from the hydration of Portland cement. While fly ash is a pozzolanic material which reacts with Ca(OH)<sub>2</sub> from Portland cement hydration forming calcium silicate hydrate (C-S-H) as the hydration product. Thus, when used with Portland cement, GGBS or fly ash will not start to react until some Portland cement hydration has taken place. This delay causes the blended cements to develop strength more slowly at early ages compared to the normal Portland cement.

Recent research has shown that it is possible to use 100% fly ash or slag as the binder in mortar by activating them with an alkali component, such as; caustic alkalis, silicate salts, and non silicate salts of weak acids.<sup>3,4</sup> There are two models of alkali activation. Activation by low to mild alkali of a material containing primarily silicate and calcium will produce calcium silicate hydrate gel (C-S-H), similar to that formed in Portland cements, but with a lower Ca/Si ratio.<sup>5</sup> The second mechanism involves the activation of material containing primarily silicate and aluminates using a highly alkaline solution. Hence the aim of the research is to evaluate the performance and suitability of fly ash based geopolymer and alkali activated slag (AAS) as an alternative to the use of ordinary Portland cement (OPC) in the production of concrete.

## **II. MATERIALS**

The Scanning Electron Microscope (SEM) image of GGBS used to produce blended and alkali activated slag (AAS) concrete is shown in figure 1. The properties of this slag were conformed to AS 3582.2-2001 (Standards Australia, 2001). The fly ash (FA) used to manufacture FA-based geopolymer was a low calcium fly ash (class F fly ash) from Gladstone power station conforming to AS 3582.1-1998 (Standards Australia, 1998). A SEM image of the FA is

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shown in figure 2. Ordinary Portland cement (OPC) used to produce control and a blended concrete was general purpose (GP) cement. Chemical analysis of these materials is given in Table 1.

Figure 1

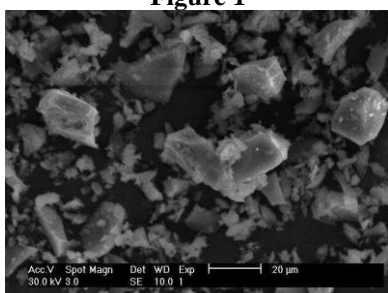


Figure 2

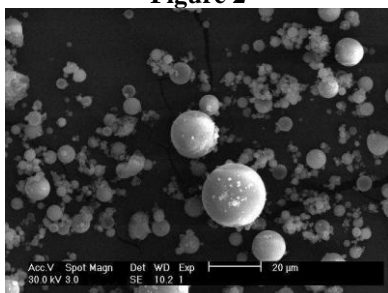


Table 1: Chemical composition of binder (Mass %)

Component	GGBS	PFA	OPC
SiO <sub>2</sub>	33.45	49.45	19.9
Al <sub>2</sub> O <sub>3</sub>	13.46	29.61	4.62
Fe <sub>2</sub> O <sub>3</sub>	0.31	10.72	3.97
CaO	41.74	3.47	64.27
MgO	5.99	1.3	1.73
K <sub>2</sub> O	0.29	0.54	0.57
Na <sub>2</sub> O	0.16	0.31	0.15
TiO <sub>2</sub>	0.84	1.76	0.23
P <sub>2</sub> O <sub>5</sub>	0.12	0.53	NA
Mn <sub>2</sub> O <sub>3</sub>	0.40	0.17	0.06
SO <sub>3</sub>	2.74	0.27	2.56
LOI	NA	1.45	NA

The alkaline activator used in this study was a sodium silicate based solution which means that the alkaline activator contained sodium silicate and sodium hydroxide. The properties of the Grade D sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) used are given in Table 2. The sodium hydroxide solution (NaOH) was prepared in a fume cabinet by dissolving sodium hydroxide pellets in deionised water at least 1 day prior to mixing. The coarse and fine aggregates used were prepared in accordance with AS 1141.5- 2000 and AS 1141.6.1-2000. The moisture condition of the aggregate was a saturated surface dry (SSD) condition. The coarse aggregates were obtained in crushed form, comprising basalt aggregate with specific gravity 2.99.

Table 2: Chemical and physical properties of liquid sodium silicate

Product Name	D <sup>TM</sup>	Product Name	D <sup>TM</sup>
WT. Ratio SiO <sub>2</sub> /Na <sub>2</sub> O	2.00	Density @ 68°F(20°C) LB/GAL	12.8
%Na <sub>2</sub> O	14.7	Density @ 68°F(20°C) G/Cm <sup>3</sup>	1.53
%SiO <sub>2</sub>	29.4	pH	12.8
Density @ 68°F(20°C) °BE'	50.5	Viscosity Centipoises	400
Characteristics	Clear to opalescent liquid		

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### III. EXPERIMENT

For alkali activated slag and fly ash based Geopolymer concrete, the variables considered in this study were: Dosage of Na<sub>2</sub>O (%Na<sub>2</sub>O) which is the ratio of Na<sub>2</sub>O content of alkaline activator to the mass of binder (GGBS for AAS or fly ash for FA based geopolymer). Activator modulus (M<sub>S</sub>); the mass ratio of SiO<sub>2</sub> to Na<sub>2</sub>O in alkaline activator. The mass of Na<sub>2</sub>O in the alkaline activator is the mass of Na<sub>2</sub>O in sodium silicate and the mass of Na<sub>2</sub>O equivalent in sodium hydroxide. For blended GGBS-OPC concrete, the variable considered was the ratio of GGBS to the total binder.

For the purpose of the durability study, the selection of the mixes to be used was based on the 28 day compressive strength; design strength of 50 ± 10 MPa was selected. This target strength was chosen to replicate standard strength for site concrete and to investigate if AAS and FA-based geopolymer concrete would perform satisfactorily in durability tests at normal strength. To achieve the target strength, 5% and 7.5% Na<sub>2</sub>O dosages were selected for AAS and FA-based geopolymer concrete respectively. Trial mixes were conducted by varying the quantity of water, for this purpose the water/solid (w/s) ratio was used. It was found that w/s ratio of 0.45 and 0.29 achieved the target strength for normal cured AAS and heat cured FA-based geopolymer concrete respectively. The quantity of water in the mix was the sum of water contained in the sodium silicate, sodium hydroxide and added water. The quantity of solid is the sum of GGBS or FA, the solid in the Na<sub>2</sub>SiO<sub>3</sub> solution, and the NaOH pellets.

Table 3 summarizes the details of variables for AAS and FA-based geopolymer concrete. Liquid sodium silicate and sodium hydroxide were blended in different proportions, providing an activator modulus (M<sub>S</sub>) in solution ranging from 0.75 to 1.25. The Na<sub>2</sub>O dosage (ratio of Na<sub>2</sub>O in alkaline activator to the mass of GGBS or FA), were 5% for AAS concrete and 7.5% for FA-based geopolymer concrete.

Table 3 Details of AAS and Geopolymer concrete mixes and variables					
AAS Concrete mixes	Variables		Geopolymer Concrete mixes	Variables	
	Na <sub>2</sub> O Dosage	M <sub>S</sub>		Na <sub>2</sub> O Dosage	M <sub>S</sub>
AAS5-0.75	5%	0.75	G7.5-0.75	7.5%	0.75
AAS5-1.00	5%	1.00	G7.5-1.00	7.5%	1.00
AAS5-1.25	5%	1.25	G7.5-1.25	7.5%	1.25

A water/binder ratio of 0.52 was used to prepare all blended GGBS-OPC and control concrete. Table 4 shows the mix proportion of the control and blended concrete mixes. The levels of GGBS replacement were 30% for S30, 50% for S50, and 70% for S70 of the total binder. The mix design for control (CTL) concrete was a normal concrete mix use in laboratory based on the British Method published by Department of the Environment (Teychenne, Franklin, & Erntroy, 1988). The AAS and FA-based concrete mix proportions were given in table 5.

Table 4: Mix proportion of control and blended concrete (Kg/m <sup>3</sup> )						
Mix	Binder (kg)		Aggregate (kg)			Water (kg)
	OPC	GGBS	Sand	7-mm	10-mm	
CTL	428	-	784	346	693	222
S30	296	127	784	346	693	220
S50	210	210	784	346	693	219
S70	125	293	784	346	693	217

Prior to mixing and casting, the materials were batched into sealed buckets at least one day in advance. Moisture contents were taken of the fine and coarse aggregate, the day before each cast, and the batched

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masses for the aggregate and water were adjusted to obtain an overall saturated surface dry (SSD) condition for the aggregate. The liquids (sodium silicate, NaOH, and additional water) were blended prior to mixing.

Mix	Binder (kg)		Aggregate (kg)			Activator (kg)		Added water (kg)
			sand	7-mm	10-mm	Na <sub>2</sub> SiO <sub>3</sub> (liquid)	NaOH (10M)	
AAS5-0.75	GGBS	419	784	346	693	53	56	137
AAS5-1.00		415	784	346	693	71	46	136
AAS5-1.25		412	784	346	693	87	33	135
G7.5-0.75	FA	476	784	346	693	90	95	40
G7.5-1.00		467	784	346	693	119	75	38
G7.5-1.25		461	784	346	693	147	56	36

The mixing procedure for control and blended concrete was carried out in accordance with AS 1012.2-1994. The mixing was performed using a 120-litre mixer; the mix was then poured into 150 mm x 150 mm x 150 mm cube moulds and vibrated for 1 minute. The blended GGBS-OPC, control, and AAS concrete specimens were demoulded after 24 hours followed by water curing at 20°C for 6 days and then left at an environmental control room (50%RH, 20°C) prior to testing. From the earlier studies, the most suitable curing methods for FA-based geopolymer is heat curing, therefore after leaving for 24 hours at room temperature, the specimens were wrapped with plastic at the top to prevent the evaporation, and left in the oven for 24 hours at 80°C and then allowed to cool in the mould at room temperature before they were demoulded. The specimens were then left at the environmental control room (50%RH, 20°C) until testing.

## IV. RESULTS AND DISCUSSIONS

The strengths of the blended GGBS-OPC, AAS and FA-based geopolymer concrete are shown in Table 6. The comparison of the compressive strength of AAS and FA-based Geopolymer concrete with 100% OPC concrete and blended OPC- GGBS concrete at 7 days is shown in Figure 3. It should be noted that heat curing was applied to the FA-based geopolymer concrete to achieve structural integrity. Heat curing in general will result in increased early strengths. As such a comparison of the 14 and 28 days strengths will give a better assessment of the comparable strengths, than the 7 days data. The compressive strengths at 14 and 28 days were given in Figure 4 and Figure 5 respectively.

Mix	Slump in mm	Compressive Strength (MPA)		
		7 days	14 days	28 days
CTL	80	38.0	51.8	57.0
S30	75	31.7	46.5	49.5
S50	65	27.8	46.9	53.2
S70	55	24.7	35.6	42.9
AAS5-0.75	150	25.0	32.9	36.6
AAS5-1	95	35.4	44.3	45.3
AAS5-1.25	70	37.0	43.5	43.5
G7.5-0.75	collapse	39.1	44.4	46.1
G7.5-1	collapse	51.3	53.3	53.6
G7.5-1.25	collapse	52.5	56.9	57.3

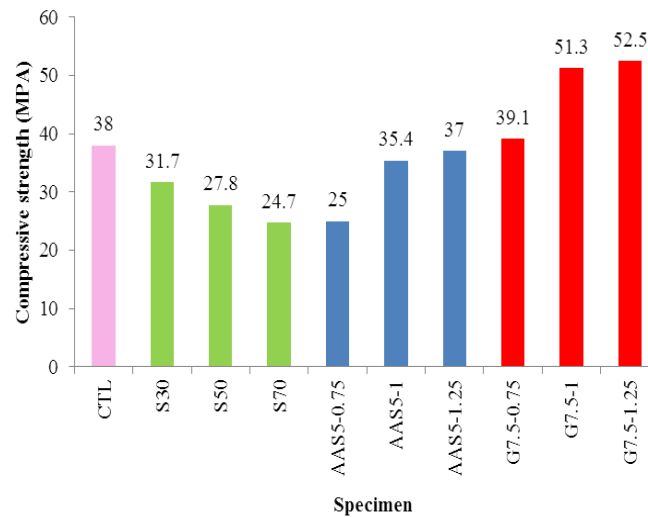


Figure 3: Compressive strength at 7 days

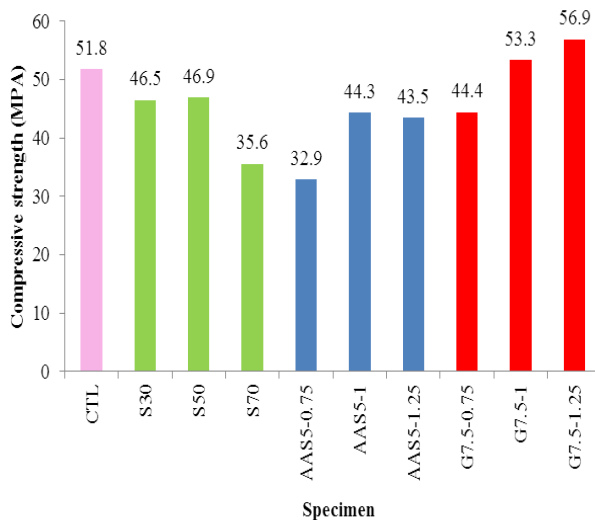


Figure 4: Compressive strength at 14 days

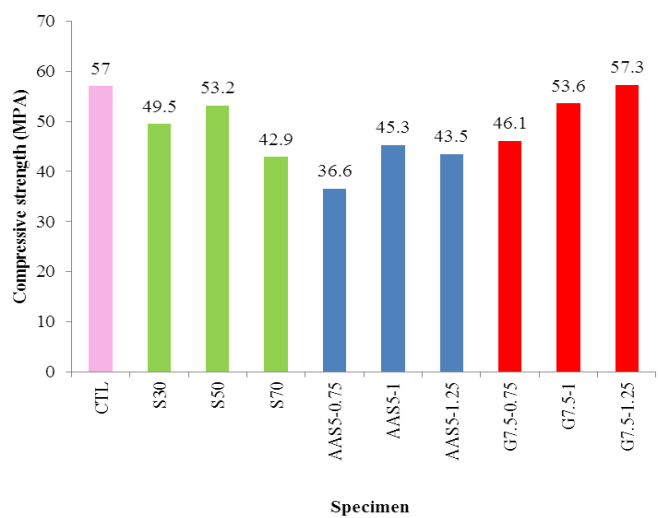


Figure 5: Compressive strength at 28 days

## V. CONCLUSIONS

The main conclusion which can be drawn from the investigation of the strength properties of AAS and FA-based geopolymer concrete is  $\text{Na}_2\text{O}$  dosage had a significant influence on the strength of both AAS and fly ash based Geopolymer concrete. For AAS binder the  $\text{Na}_2\text{O}$  is needed to maintain the alkalinity of the mixes, the condition needed to assist the dissolution of the slag and the adsorption of ions in solution on the surface of the slag. For FA-based geopolymer binder, the alkali has two roles. Firstly, to partially balance the charge of aluminates groups in the tectosilicate, and secondly to increase the solubility of the alumina silicate. The activator modulus also influenced the strength of both the AAS and FA-based Geopolymer binder, although it was not as significant as the  $\text{Na}_2\text{O}$  dosage especially for FA-based geopolymer binder. Increasing the modulus means increasing

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the quantity of anions of sodium silicate. Investigation into the microstructure of concrete showed that the number of pores of the matrix of both AAS and FA-based geopolymer concrete reduced as the activator modulus increased. However micro cracks were found in all AAS specimens and seemed to reduce as the modulus increased. At  $M_S=1.25$ , wider micro cracks formed at the interface between C-S-H and unreacted silica. The major hydration product found in all samples of the AAS matrix was amorphous to poorly crystalline C-S-H with Ca/Si ratios of 0.94 – 1.24. The matrix of FA-based geopolymer binder was a composite of geopolymer matrix and unreacted silica. This matrix mainly comprised Si-Al-O (siloxo) with the ratio of Si/Al  $\approx$  1.22 to 2.42.

Both  $Na_2O$  dosage and activator modulus can be used as variables in designing the mix for AAS and FA-based geopolymer concrete. The  $Na_2O$  dosage of 5% and activator modulus,  $M_S=1$  at water to binder ratio (W/b) = 0.45 was found to be the optimum for AAS concrete, whereas for FA-based geopolymer concrete it was  $M_S=1.25$  at W/b=0.29. The  $Na_2O$  dosage of 7.5% for FA-based geopolymer concrete gave a comparable performance with OPC concrete, however, a higher  $Na_2O$  dosage i.e. 15% can be used if higher strength is required.

Based on the strength study it is concluded that AAS and FA-based geopolymer binder could have a comparable strength with that of OPC and blended GGBS-OPC concrete depending on the  $Na_2O$  dosage and alkali modulus.

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