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# Effect of Chemical Composition of Different Source Materials on 28th Day Compressive Strength of Geopolymer Concrete Cured Under Ambient Conditions

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## Abstract

There have been increasing efforts in recent years to minimize the amount of cement used in concrete. Efforts at partial replacement have been successful and regulations are promulgated to standardize and use such successful formulations. There is now worldwide research aimed at complete replacement of cement by activating industrial materials that are rich in silica and alumina with alkaline solution. The present study aims at complete elimination of cement through the development of a geopolymer concrete containing fly ash and ground granulated blast furnace slag (GGBS), activated by sodium based alkaline activators. The effect of replacing up to 50% fly ash by GGBS is also studied. The strength parameters are measured for a mixture of sodium silicate and sodium hydroxide solution having concentrations from 2M to 12M. The samples are cured under ambient conditions. Compressive and split tensile strengths of cubes and cylinders for all mixtures were measured on the 28<sup>th</sup> day of casting. The overall data pertaining to compressive strength and chemical components along with curing temperature is compiled to achieve generalized predictable results. Comparative charts were developed in terms of temperature, quantity of NaOH and SiO<sub>2</sub>/CaO for compressive strength.

## 1 Introduction

Portland cement concrete is an artificial stone that is made by mixing Portland cement, water, sand and crushed stone aggregate. It has developed into an important building material in the world, partly due to the fact that it is manufactured from natural materials available in all parts of the globe, and also because it is a versatile material that offers architectural freedom. The large demand for

cement and other construction material has been spurred in recent years by explosive developments in infrastructure and this has resulted in problems related to climate change, sustainability, durability of structures and resource productivity (Mehta, P. K., 2003).

Extensive research is being carried out in the area of cement substitutes. Geopolymers are being considered as good replacements for cement (Mehta, P. K., 2003). The complex process of geopolymerization has been explained by Davidovits (Davidovits, J, 1999), Barbosa (Barbosa, V. F., MacKenzie, K. J., & Thaumaturgo, C., 2000), Duxon (Duxson, P.; Himenez, A. Fernandez; Provis, J. L.; Lukey, G. C.; Paloma, A.; Deventer, JSJ Van., 2007) and many others. This mechanism includes four parallel stages, viz. dissolution of solid aluminosilicate materials, oligomerization of Si and/or Si–Al in aqueous phase, polymerization of the oligomeric species, and bonding of undissolved solid particles in the polymer. Based on laboratory tests on fly ash based Geopolymer binder, Palomo, Grutzeck, and Blanco have shown that the curing temperature, curing time, and type of activator affected the compressive strength (Paloma, A., Grutzeck, M. W., & Blanco, M. T., 1999). Van Jaarsveld, van Deventer, and Lukey confirmed the importance of curing at elevated temperature for fly ash based geopolymeric material (Van Jaarsveld, J. G., Van Deventer, J. S., & Lukey, G. C., 2002). Hardjito, Wallah and Rangan showed that the use of solids/water ratios of 0.174, 0.197 and 0.220 resulted in 5-7% decrease of compressive strength for similar type of Geopolymer concrete. They also studied creep and shrinkage effects on fly ash based geopolymer concrete (Hardjito, D., Wallah, S. E., Sumajouw, D. J., & Rangan, B. V, 2004).

The present paper describes the effective use of fly ash, GGBS and their combination as a replacement to cement in concrete along with the mixture of sodium silicate and sodium hydroxide solutions as alkaline activators. The samples have been cured under ambient conditions as well as in oven. The results have been compiled and the chart with respect to chemical components have been developed that predicts 28 days compressive strength up to 25-30% of accuracy.

## 2 Experimental Program

The physical and chemical properties of the source materials are shown in table 1. Class F fly ash (dark grey coloured) was procured from the silos of local thermal power station. GGBS was obtained from a manufacturing company in Goa. It was a fine light brown coloured powder.

	Fly ash	GGBS
SiO <sub>2</sub>	53.57%	35.2%
Al <sub>2</sub> O <sub>3</sub>	32.97%	21.4%
Fe <sub>2</sub> O <sub>3</sub>	5.51%	1.8%
CaO	1.84%	31.2%
MgO	0.92%	8.4%
Na <sub>2</sub> O	0.37%	-
K <sub>2</sub> O	1.76%	-
TiO <sub>2</sub>	2.1%	-
SO <sub>3</sub>	0.46%	0.15%
P <sub>2</sub> O <sub>5</sub>	0.15%	-
Fineness (m <sup>2</sup> /kg)	325	400
Specific gravity	2.19	2.9

**Table 1:** Physical and Chemical properties of fly ash and GGBS

Coarse and fine aggregates were saturated-surface-dry as per Indian Standards. Coarse aggregates were obtained in crushed form; and were generally granite. River sand was used as fine aggregates. The alkaline solution was combination of sodium hydroxide (NaOH) solution and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) solution. NaOH solids were white coloured flakes having size (3-6 mm), 98% purity.  $\text{Na}_2\text{SiO}_3$  solution was in a thick gel form and was kept covered to avoid its drying and solidification. NaOH flakes and  $\text{Na}_2\text{SiO}_3$  solution were procured from local distributor. NaOH solution was prepared by dissolving the required amount of NaOH flakes in water to obtain a particular molarity. For the present study 2M, 4M, 6M, 8M, 10M and 12M solutions were considered. NaOH solids were added gradually to water and stirred for approximately 10 minutes until all flakes had dissolved. It was noticed that upon addition of NaOH solids to water, solution became hot as an exothermic reaction of dissolution carried out. Thus, as suggested in literature, NaOH solution was prepared one day prior casting (Hardjito, D., Wallah, S. E., Sumajouw, D. J., & Rangan, B. V, 2004) (Lloyd, N. A., & Rangan, B. V. , 2010). The mixture of NaOH solution and  $\text{Na}_2\text{SiO}_3$  was done just few minutes before its addition to source materials in concrete mixture. The ratio of alkaline liquids to source material is 0.55. Also ratio of  $\text{Na}_2\text{SiO}_3$  solution to NaOH solution is 2 and 1.5. Water needed to make solutions and wash aggregates was normal tap water available in the laboratory. Some amount of water was also added to source materials while mixing to increase the workability of the mix as super plasticizer was not used. The mixing, casting and curing of concrete was same as the conventional OPC concrete. The mixture proportion considered for these experimental tests is mentioned in table 2.

Materials	Quantity	Units
Source materials (fly ash/ GGBS/fly ash + GGBS)	425	$\text{kg/m}^3$
Coarse aggregates	1105	$\text{kg/m}^3$
Fine aggregates	505	$\text{kg/m}^3$
Alkaline liquid	233.75	$\text{kg/m}^3$

**Table 2:** Mixture proportion for Geopolymer concrete

Table 3 shows the chemical components of the source materials that contribute to the compressive strength of the developed geopolymer concrete. Following methodology was adopted while giving designations to mixture proportions for further reference.

**%F%SXM which is for: % of fly ash (F) +% of GGBS (S) + 'X' Molarity of NaOH solution**

For example; **70F30S12M** stands for 70% fly ash +30% GGBS with 12M concentration of NaOH.

Designation	$\text{Na}_2\text{O}$	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	CaO	NaOH flakes	$\text{H}_2\text{O}$
100F0S6M	24.48	273.49	140.12	7.82	18.70	166.33
100F0S8M	24.48	273.49	140.12	7.82	24.93	160.09
100F0S10M	24.48	273.49	140.12	7.82	31.16	153.86
100F0S12M	24.48	273.49	140.12	7.82	37.40	147.62
90F10S12M	24.32	265.68	135.21	20.30	37.40	147.63
80F20S12M	24.17	257.87	130.29	32.78	37.40	147.63
70F30S12M	24.02	250.07	125.37	45.25	37.40	147.63
60F40S12M	23.85	242.26	120.45	57.73	37.40	147.63
50F50S12M	23.69	234.45	115.54	70.21	37.40	147.63
0F100S2M	20.62	190.84	90.95	132.60	7.48	184.42
0F100S4M	20.62	190.84	90.95	132.60	14.96	176.94
0F100S6M	20.62	190.84	90.95	132.60	22.44	169.46
0F100S8M	20.62	190.84	90.95	132.60	29.92	161.98

**Table 3:** Chemical components of geopolymer concrete from different source materials

### 3 Results and discussions

The testing of samples was done on 3<sup>rd</sup>, 7<sup>th</sup>, 14<sup>th</sup>, 28<sup>th</sup>, 56<sup>th</sup> and 90<sup>th</sup> day. However, currently as all the values are related to 28 days strength of concrete, only those values are taken into consideration. The below mentioned table 4 shows the 28<sup>th</sup> day mean compressive strength and split tensile strength of the samples cast from different source materials and cured under ambient temperature.

Designation	Compressive strength (N/mm <sup>2</sup> )	Split tensile strength (N/mm <sup>2</sup> )	Split tensile strength in terms of corresponding compressive strength
100F0S6M	29.62	2.43	8.2%
100F0S8M	31.7	2.7	8.5%
100F0S10M	32.86	2.84	8.6%
100F0S12M	33.7	3.15	9.3%
90F10S12M	35.33	2.35	6.7%
80F20S12M	46.67	2.89	6.2%
70F30S12M	52.31	3.27	6.3%
60F40S12M	52.8	2.98	5.6%
50F50S12M	46.67	3.16	6.8%
0F100S2M	43.33	1.85	4.3%
0F100S4M	54.33	1.86	3.4%
0F100S6M	59.53	2.17	3.6%
0F100S8M	61.65	2.64	4.3%

**Table 4:** Strength properties of geopolymer concrete from different source materials

Summarizing all the above values and determining the overall range of compressive strength, following table 5 shows the corresponding chemical components that are responsible for developing the strength for geopolymer concrete with different source materials and varying concentration of alkaline solution.

Source Materials	Fly ash	Fly ash + GGBS	GGBS	Range
Compressive strength (N/mm <sup>2</sup> )	29-34	35-52	52-65	29-65
Split tensile %	8-9%	6-7%	3-4%	3-9%
H <sub>2</sub> O/Na <sub>2</sub> O	6-6.8	6.05-6.25	7.85- 9	6 to 9
SiO <sub>2</sub> /Na <sub>2</sub> O	11.17	9.9-10.9	9.25- 11	9.25-11.25
Al <sub>2</sub> O <sub>3</sub> /Na <sub>2</sub> O	5.72	4.88-5.56	4.4-5.4	4.4-5.7
Al <sub>2</sub> O <sub>3</sub> /CaO	17.92	1.65-6.66	0.685	0.685-17.92
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	1.95	1.97-2.03	2-2.1	1.95-2.1
SiO <sub>2</sub> /CaO	34.97	3.34-13.09	1.35-1.45	1.35-35
% Na <sub>2</sub> O	3.61	3.49-3.58	2.65-3	2.65-3.65
%SiO <sub>2</sub>	40.29	34.54-39.14	28-29	28-40.5
%CaO	1.15	2.99-10.34	19-21	1.15-21
%H <sub>2</sub> O	21.75-24.5	21.75	21-27	21-27
% of NaOH flakes	2.75-5.5	5.51	1-5	1-5.5
%Al <sub>2</sub> O <sub>3</sub>	20.64	17.02-19.92	13.4-14.3	13.5-20.6

**Table 5:** Overall Strength values along with the corresponding chemical constituents

Following are important points observed from above mentioned table 5. Overall compressive strength from 29 N/mm<sup>2</sup> to 62 N/mm<sup>2</sup> can be achieved, with source materials having different chemical properties, when cured under ambient temperatures. The range of split tensile coefficient is 3% to 9% with respect to 28 days compressive strength with different source materials. The main factors that affect strength are percentages of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, H<sub>2</sub>O, Na<sub>2</sub>O and concentration of NaOH flakes in the binder. Other parameters are almost with the difference of 1-2% in all types of binders. Rearranging the table 5 by averaging the materials having difference of about 1-2% only in matrix, table 6 gives us a better idea of the role of ratios in the development of strength along with the combination of the rearranged standard chemical components.

	Source Materials			Range
	29-34	35-52	52-65	
Compressive strength (N/mm <sup>2</sup> )	29-34	35-52	52-65	29-65
Split tensile coefficient	8-9%	6-7%	3-4%	3-9%
H <sub>2</sub> O/Na <sub>2</sub> O	7.5	7.5	7.5	6 to 9
SiO <sub>2</sub> /Na <sub>2</sub> O	10.25	10.25	10.25	9.25-11.25
Al <sub>2</sub> O <sub>3</sub> /Na <sub>2</sub> O	5.05	5.05	5.05	4.4-5.7
Al <sub>2</sub> O <sub>3</sub> /CaO	17.92	1.65-6.66	0.685	0.685-17.92
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	1.98	1.98	1.98	1.95-2.1
SiO <sub>2</sub> /CaO	34.97	3.34-13.09	1.35-1.45	1.35-35
% Na <sub>2</sub> O	3.15	3.15	3.15	2.65-3.65
%SiO <sub>2</sub>	40.29	34.54-39.14	28-29	28-40.5
%CaO	1.15	2.99-10.34	19-21	1.15-21
%H <sub>2</sub> O	24	24	24	21-27
% of NaOH flakes	2.75-5.5	5.51	1-5	1-5.5
%Al <sub>2</sub> O <sub>3</sub>	20.64	17.02-19.92	13.4-14.3	13.5-20.6

**Table 6:** Overall Strength values along with the corresponding chemical constituents after rearranging the values

From the above summary table 6, it shows that the strength development is dependent on the chemical composition of source material, especially SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>/CaO ratio. Concrete cast from any source material has relatively higher strength when the ratio SiO<sub>2</sub>/CaO is within 1.5-2 and when SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> is almost 2. This type of source material gains strength partially due to hydration in the presence of calcium and silica and partially due to geopolymerization of silica and alumina in the presence of sodium based alkaline activator. The pattern of strength gain, which is a combination of hydration and polymerization is a complicated process and research continues to be performed to understand it (Esther, O., Elie, K., Uphie, C. M., & Cristina, L., 2011) (Palomo, A., Krivenko, P.; Garcia-Lodeiro, I.; Kavalerova, E.; Maltseva, O.; Fernandez-Jimenez, A., 2014).

Source material shows lower strength development at ambient temperatures if the ratio of SiO<sub>2</sub>/CaO is within 15-35. This type of behaviour is observed even though the ratio of SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> is about 2. This material requires additional heat to gain strength at a faster rate and for higher values. The rate of formation of S-A-O bond is lower at ambient curing than when cured in an oven. The polymerization continues at a low rate and hence gradual but continuous increase in strength is observed at the later stage as well. This type of material can gain strength by the mechanism of pure polymerization (Esther, O., Elie, K., Uphie, C. M., & Cristina, L., 2011) (Palomo, A., Krivenko, P.; Garcia-Lodeiro, I.; Kavalerova, E.; Maltseva, O.; Fernandez-Jimenez, A., 2014).

For the source material having SiO<sub>2</sub>/CaO value 3-13, the rate of strength gain at ambient temperature is low, but faster than material having ratio greater than 15. This type of material gives additional strength on heat curing but to a smaller extent. Here also, the combination polymerization

and hydration is a possibility mechanism for strength gain. The degree of nature of process purely depends on  $\text{SiO}_2/\text{CaO}$  ratio. If the ratio goes beyond 10, the strength gain mechanism could be due to polymerization. If  $\text{SiO}_2/\text{CaO}$  ratio is below 10, the strength gain may be due to the hydration process (Esther, O., Elie, K., Uphie, C. M., & Cristina, L., 2011) (Palomo, A.; Krivenko, P.; Garcia-Lodeiro, I.; Kavalerova, E.; Maltseva, O.; Fernandez-Jimenez, A., 2014).

If the average content of binder material is analyzed from table 6, it is observed that about 32% of the binder content is a mixture of  $\text{H}_2\text{O}$  (24%), NaOH flakes (5%) and  $\text{Na}_2\text{O}$  (3%). The rest is in the form of  $\text{SiO}_2$ , CaO and  $\text{Al}_2\text{O}_3$ . Further, as  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio is almost 2, the ultimate governing factor for determination of strength will be the ratio of  $\text{SiO}_2/\text{CaO}$ . Depending on this ratio, the material will develop strength through the process suggested above. The following graph (figure 1) gives the overall view of compressive strength with variables such as  $\text{SiO}_2/\text{CaO}$  and % of NaOH flakes in the binder considering the effect of temperature. Same graph is plotted considering the increasing values of  $\text{SiO}_2/\text{CaO}$  ratio. Refer figure 2.

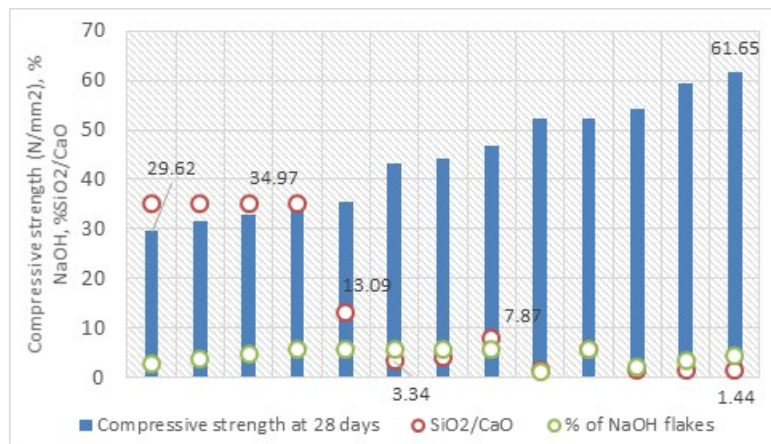


Figure 1: Effect of % of NaOH flakes and  $\text{SiO}_2/\text{CaO}$  on compressive strength of Geopolymer concrete cured at ambient temperature (plotted against increasing values of compressive strength)

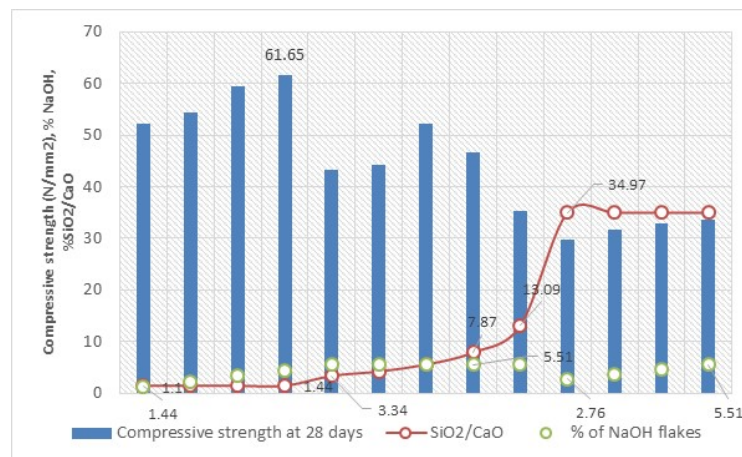


Figure 2: Effect of % of NaOH flakes and  $\text{SiO}_2/\text{CaO}$  on compressive strength of Geopolymer concrete cured at ambient temperature (plotted against increasing values of  $\text{SiO}_2/\text{CaO}$ )

These graphs can be divided into 3 zones, depending  $\text{SiO}_2/\text{CaO}$  values. They can be useful in customizing the proportions of source materials with respect to desired compressive strength. For example, if concrete having compressive strength of  $50 \text{ N/mm}^2$  is needed, then there are various possibilities which can be predicted from the graph. If the matrix has  $\text{SiO}_2/\text{CaO}$  ratio as 1.44, then addition of 1% of NaOH flakes and curing at ambient temperature will give the desired strength. If the matrix has  $\text{SiO}_2/\text{CaO}$  ratio as 5-7%, then addition of 5% of NaOH flakes and curing at ambient temperature will give the desired strength. Likewise, many more results can be predicted from the above chart. Additions and alterations in the mixture proportion and manipulation of the curing temperature can help achieve desired strength of the concrete or predict the strength of concrete. The prediction of compressive strength or customizing the concrete mixture proportion can be done through this data. Note: these results may vary depending on fineness of source material, purity of alkaline activators and temperature of curing.

The benefits of strength, durability and costs make geopolymers worthwhile replacements to cement and it is in the best interest of the construction industry to be aware of and start using this material. Immediate adoption is impeded by absence of codal regulations and specifications, and it is perhaps an uphill task to replace a material that has been extensively used for more than 150 years. Although the application of geopolymer in practical construction has already begun in some parts of world, it will take time to understand the material and its technology and make it accepted worldwide (Paloma, A., Grutzeck, M. W., & Blanco, M. T., 1999).

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