STRENGTH PERFORMANCE OF GEOPOLYMER CONCRETE EXPOSED TO ELEVATED TEMPERATURE

Sanjay Kumar[1], S Jeeva Chithambaram[1], Manish Kumar[1], M M Prasad[1]

1. Dept. of Civil Engineering, NIT Jamshedpur, India

ABSTRACT. The paper studies the effect of elevated temperatures on the strength parameters of Geopolymer concrete with partial replacement of fly ash by Ground Granulated Blast Furnace Slag (GGBFS) with varying molarity of Sodium Hydroxide (NaOH) in the alkali activator mix. The experiments were conducted on Geopolymer concrete with partial replacement of fly ash by 10%, 20%, 30% and 40% GGBFS; Sodium Silicate (Na_2SiO_3) to Sodiu Hydroxide (NaOH) ratio taken as 2.5 and combinely considered as the alkaline activator solution; and four different NaOH concentrations viz. 8M, 10M, 12M and 14M respectively. The workability parameters were studied by slump test and the samples were cast and cured at ambient temperatures to study the compressive, split-tensile and flexural strength at 3, 7 and 28 days of maturity. Also, 28 days ambient cured geopolymer concrete specimens were exposed to elevated temperature ranging from 200°C to 1000°C at an interval of every 200°C for four hours each in muffle furnace. After exposed to elevated temperatures, their corresponding compressive strength, split tensile strength, flexural strength and their weight loss were studied. Experimental results indicate that the samples prepared with 12M NaOH and 30% GGBFS replacements gave the maximum strength in terms of ambient curing. The elevated temperatures had a direct relation of loss in weight with the increase in temperature. A similar trend was observed in the strength parameters as well with the elevated temperature but the rate of loss of strength decreased with the increase in temperatures.

Keywords: Geopolymer concrete, ambient temperature, elevated temperature, weight loss.

Dr Sanjay Kumar is an Associate Professor in Department of Civil Engineering, NIT Jamshedpur, INDIA. His research interests are Fibre-reinforced Concrete, Self-Compacting Concrete, Low Cost Building Materials and Geopolymer Concrete.

Mr S Jeeva Chithambaram is a Research Scholar in Department of Civil Engineering, NIT Jamshedpur, INDIA. His research interests are Self-Compacting Concrete, Geopolymer Concrete and Use of Supplemetary Cementitious Materials.

Mr Manish Kumar is a M. Tech Student in Department of Civil Engineering, NIT Jamshedpur, INDIA. His research interests are Concrete Technology, Self-Compacting Concrete and Geopolymer Concrete.

Prof M M Prasad is a Professor in Department of Civil Engineering, NIT Jamshedpur, INDIA. His research interests are Retrofitting of Buildings, Concrete exposed to Marine Environment, Micro-structural analysis and Geopolymer Concrete. Telephone: +91-9431372861; Email Id: mmprasad3@gmail.com

INTRODUCTION

Concrete is the most widely used construction material throughout the world. Portland cement is the primary cementitious ingredient. Cement production has increased over the years in developing countries [1]. Statistics shows that with nearly 381 million tons of cement production capacity, India was the second largest cement producer in the world [2] in the year 2013. The production of cement is not only energy intensive, but also responsible for emission of carbon dioxide (CO_2) in large quantity. It is estimated that, approximately 94.76x10^6 Joules of energy is required for the production of each ton of cement [3] and an equal quantity of CO_2 gas is released to the atmosphere [4, 5]. According to McCaffrey [6], the production of one ton of Portland cement generates and releases approximately one ton of carbon dioxide gas into the atmosphere. The quantity of CO_2 produced due to cement manufacturing contributes to about 5% of the total release of CO_2 to the atmosphere [7]. As a result, the need for alternative binders capable of achieving a sustainable and ecologically aware concrete proves to be essential to reduce the huge emission of CO_2 attributable to Portland cement.

Geopolymer is an inorganic alumino-silicate polymer synthesized from predominantly silicon (Si) and aluminum (Al) materials of geological origin, or byproduct materials, such as fly ash, rice husk ash, that are rich in silicon and aluminum[8]. The two major constituents of the Geopolymer binders are the source materials (Fly ash, Rice-husk ash, Silica fume, Slag, Red mud etc.) and the alkaline liquids (Sodium hydroxide with Sodium silicate, Potassium hydroxide with Potassium silicate)[9]. In India, one of the major sources of material for power generation is coal and it's by product- fly ash- is an environmental threat to the public, if not disposed-off properly. Only about 38% of fly ash generated in India is utilized and the remaining quantity is disposed in ash ponds or lagoons. So, the use of Geopolymer concrete with fly ash as alumino-silicate material helps to reduce the release of CO_2 emission (by eliminating the production of cement). In most situations, curing at high temperatures (oven curing) for manufacture of Geopolymer concrete may not be possible and so fly ash is partially replaced by GGBFS in percentages of 10%, 20%, 30% and 40% to enable ambient curing. Bernal et al.[10] assessed the mechanical and durability performance of concretes produced using ground granulated blast furnace slag (GGBFS) as sole binder and compared the corresponding performance with reference concretes produced using Portland cement (OPC).

The behavior of geopolymer paste and concrete exposed to elevated temperatures was studied by Kong and Sanjayan [11] and a decrease in the strength of geopolymer was observed due to differential thermal expansion between paste and aggregate. As reported by Haoyang Su et. al.[12], the mechanical properties of geopolymer concrete exposed to dynamic compression under elevated temperature had a remarkable weight loss within temperature ranges at about 200°C as well as from 600°C to 800°C. Also, for geopolymer concrete exposed to elevated temperature, the dynamic compressive strength increases up to 200 °C.

This study aims in development of geopolymer concrete with partial replacement of fly ash by 10%, 20%, 30% and 40% GGBFS; Sodium Silicate (Na_2SiO_3) to Sodium Hydroxide (NaOH) ratio taken as 2.5 and combinely considered as the alkaline activator solution; and four different NaOH concentrations viz. 8M, 10M, 12M and 14M respectively. The workability parameters were studied by slump test and the samples were cast and cured at ambient temperatures to study the compressive, split-tensile and flexural strength at 3, 7 and 28 days of maturity. An effort has been made to study the deferred strength and its corresponding weight loss on 28 days ambient cured geopolymer concrete specimens that were exposed to elevated temperature ranging from 200°C to 1000°C at an interval of every 200°C for four hours each in muffle furnace. After exposed to elevated temperatures, their corresponding compressive strength, split tensile strength, flexural strength and their weight loss were studied.

MATERIALS AND METHODS

Materials

Low calcium fly ash (Class F) confirming to IS 3812-2003 [13] obtained locally from Usha Martins Ltd., Jamshedpur having a specific gravity of 2.38 has been used as the base material. Ground granulated blast furnace slag has been procured from Tata Steel Plant, Jamshedpur that has the specific gravity 2.86. The chemical composition of the fly ash and GGBFS used in the present study is shown in Table 1.

Table 1 Chemical composition of Class F - fly ash

MATERIAL	CHEMICAL COMPOSITION (W/W)								
Fly ash	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_4	LOI
	65.60	26.53	5.49	0.31	0.76	0.36	0.23	0.31	0.41
GGBFS	30.97	17.41	1.13	36.97	8.81	0.69	0.46	-	1.72

Locally available sand from river Kharkai confirming to Zone II of IS 383–1987[14] with 4.75 mm maximum size and having specific gravity, fineness modulus and bulk density of 2.55, 2.73 and 1580 kg/m^3, respectively were used as fine aggregate. Locally available crushed stone with maximum size of 16mm confirming to IS 383-1987[14] having specific gravity, fineness modulus and bulk density of 2.78, 6.86 and 1630 kg/m^3 respectively has been used as coarse aggregate. A combination of commercially available sodium hydroxide (NaOH) in pellet form and sodium silicate solution (Na_2SiO_3) having a purity of 98% and 96% respectively was used. Tap water was used for mixing of sodium hydroxide (NaOH) solution.

Mixing, Casting and Curing

Alkaline activator solution releases large quantity of heat while mixing and hence the alkaline solution was prepared 24 hours prior to the mixing process with dry mix. Different molar concentrations, viz. 8M, 10M, 12M and 14M of NaOH with Na_2SiO_3 was chosen with the ratio of sodium silicate to sodium hydroxide, by mass, taken as 2.5. The alkaline liquid to binder ratio was taken as 0.45 to achieve high workability. Fly ash and fine aggregates were dry mixed for two minutes to achieve homogenity. Later, the calculated quantity of coarse aggregate was added and mixed for an additional 2 minutes. Poly-Carboxylic Ether (PCE) based superplasticizer was used at 2.5%, by mass, of fly ash to achieve workability. Finally, the mixeed alkaline liquid and superplasticizer solution was added gradually to the dry mix and mixed well for 4 to 5 minutes. No proper mix design is available for mix design of geopolymer concrete. Hence, trial and error method was used to obtain a good workable mix with proper compressive strength. The details of the mix proportions of geopolymer concrete has been summarized in Table 2.

Table 2 Mix Proportion of Geopolymer Concrete

MIX	FLY ASH (kg/m³)	GGBFS	COARSE AGGREGATE (kg/m³)	FINE AGGREG-ATE (kg/m³)	NAOH CONTENT (kg/m³)		NA_2SIO_3 SOLUTI-ON (KG/M³)
					Pellets	Water	
8M1	357	40	1277	547	13	38	128
8M2	318	79					
8M3	278	119					
8M4	238	159					
10M1	357	40	1277	547	16	35	128
10M2	318	79					
10M3	278	119					
10M4	238	159					
12M1	357	40	1277	547	18	33	128
12M2	318	79					
12M3	278	119					
12M4	238	159					
14M1	357	40	1277	547	21	30	128
14M2	318	79					
14M3	278	119					
14M4	238	159					

The mix designation M1 to M4 denotes the partial replacement of fly ash by GGBFS by 10% to 40% at every 10% interval whereas the numbers 8 to 14 before the letter 'M' denotes the NaOH molar concentrations.

After thorough mixing, the geopolymer concrete in fresh state was tested for workability as by slump test. Later, the mixed geopolymer concrete in fresh state was cast to produce cube specimens of size 100x100x100 mm, cylider specimens of size 100 mm dia. x 200 mm height and beam specimens of size 100x100x500 mm to study the compressive strength, split-tensile strength and flexural strength of geopolymer concrete, respectively. Table vibrator was used for compaction of cast specimens. All cast specimens in the mould were allowed to stay for a resting period of 24 hours. Later on, the specimens were removed from the mould and cured at room temperature (ambient) before being tested at 3, 7 and 28 days of maturity. Efforts have been made to study the weight loss and deferred strength parameters of geopolymer concrete after exposing the specimens to elevated temperatures for four hours ranging from 200°C to 1000°C at every 200°C interval.

RESULTS AND DISCUSSION

Workability Test Results

Workability of different geopolymer concrete mixes with respect to NaOH concentration is assessed by slump test and is given in Figure 1.

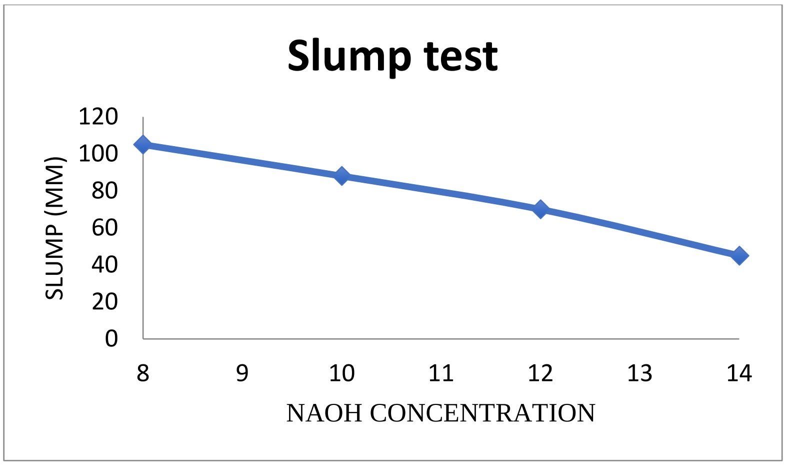

Figure 1 Slump of geopolymer concrete with varying NaOH concentration

From Fig. 1, it is seen that the slump values decreases from 105 mm for geopolymer concrete with 8M NaOH concentration to 45 mm for geopolymer concrete with 14M NaOH concentration. This may be due to the viscous nature of alkaline solution. In other words, with increase in the NaOH concentration, the alkaline solution solution becomes thick thus reducing the workability of geopolymer concrete.

Hardened Properties of Geopolymer Concrete

Compressive strength

The compressive strength test for the casted cubes of size 100mmx100mmx100mm has been performed by following the requirements of IS: 516-1959. Three numbers of specimens have been tested at 3, 7 and 28 days of maturity & their corresponding results are given in Table3.

Table 3 Compressive strength of geopolymer concrete

NAOH CONCENTRATION	% REPLACEMENT OF GGBFS	COMPRESSIVE STRENGTH (N/mm^2)		
		3 Day	7 Day	28 Day
8	10	18.00	24.00	29.67
	20	18.67	24.58	29.00
	30	19.00	27.30	31.25
	40	19.42	25.75	30.08
10	10	20.58	25.67	32.08
	20	20.25	25.58	31.00
	30	25.90	26.25	35.08
	40	21.17	25.83	30.75
12	10	26.33	30.92	33.67
	20	25.17	31.08	35.08
	30	27.33	32.00	35.93
	40	27.50	29.75	33.97
14	10	21.33	30.00	31.50
	20	22.25	29.75	33.42
	30	22.58	30.08	33.83
	40	21.92	29.83	32.92

From Table 3, it can be seen that the 28 day maximum compressive strength of 35.93 (N/mm^2) was found for geopolymer concrete with 30% partial replacement of fly ash by GGBFS having 12M NaOH concentration. The compressive strength of geopolymer concrete is seen to increase with addition of GGBFS as partial replacement of fly ash upto 30%. Further addition of GGBFS, i.e., 40% partial replacement of fly ash by GGBFS resulted in a decreased compressive strength irrespective of the NaOH concentration. On the other hand, the compressive strength increased with increase in NaOH concentration upto 12M, beyond which a slight reduction in compressive strength was found. This may be attributed to the excessive hydroxide ions that hinders the geopolymerization process.

Split-Tensile Strength

Split-tensile strength test has been performed on cylinder specimens having a diameter of 100mm and 200mm height. The test has been performed after 3, 7 and 28 days of maturity and the results are presented in Table 4.

Table 4 Split-tensile strength of geopolymer concrete

NAOH CONCENTRATION	% REPLACEMENT OF GGBFS	SPLIT-TENSILE STRENGTH (N/mm^2)		
		3 Day	7 Day	28 Day
8	10	1.44	1.92	2.37
	20	1.49	1.97	2.32
	30	1.52	2.18	2.50
	40	1.55	2.06	2.41
10	10	1.65	2.05	2.57
	20	1.62	2.05	2.48
	30	2.07	2.10	2.81
	40	1.69	2.07	2.46
12	10	2.11	2.47	2.69
	20	2.01	2.49	2.81
	30	2.19	2.56	2.87
	40	2.20	2.38	2.72
14	10	1.71	2.40	2.52
	20	1.78	2.38	2.67
	30	1.81	2.41	2.71
	40	1.75	2.39	2.63

From Table 4, it can be seen that the 28 day maximum split-tensile strength of 2.87 (N/mm^2) was found for geopolymer concrete with 30% partial replacement of fly ash by GGBFS having 12M NaOH concentration. It can be seen that, addition of GGBFS as partial replacement of fly ash upto 30% has the maximum split-tensile strength irrespective of the NaOH concentration and age of maturity. Further addition of GGBFS, i.e., 40% partial replacement of fly ash by GGBFS resulted in a decreased split-tensile strength irrespective of the NaOH concentration. On the other hand, the split-tensile strength increased with increase in NaOH concentration upto 12M, beyond which a slight reduction in compressive strength was found. It can be seen that the split-tensile strength follows a similar trend with regard to split-tensile strength of geopolymer concrete.

Flexural strength

Beam specimens having size 100x100x500mm has been tested for flexural strength of geopolymer concrete after 3, 7 and 28 days of maturity and the results have been presented in Table 5.

Table 5 Flexural strength of geopolymer concrete

NAOH CONCENTRATION	% REPLACEMENT OF GGBFS	FLEXURAL STRENGTH (N/mm^2)		
		3 Day	7 Day	28 Day
8	10	2.97	3.43	3.81
	20	3.02	3.47	3.77
	30	3.05	3.66	3.91
	40	3.08	3.55	3.84
10	10	3.18	3.55	3.96
	20	3.15	3.54	3.90
	30	3.56	3.59	4.15
	40	3.22	3.56	3.88
12	10	3.59	3.89	4.06
	20	3.51	3.90	4.15
	30	3.66	3.96	4.20
	40	3.67	3.82	4.08
14	10	3.23	3.83	3.93
	20	3.30	3.82	4.05
	30	3.33	3.84	4.07
	40	3.28	3.82	4.02

From Table 5, it can be seen that flexural strength of geopolymer concrete follows a similar trend with regard to the compressive and split-tensile strength. It is seen that the 28 day maximum flexural strength of 4.20 (N/mm^2) was found for geopolymer concrete with 30% partial replacement of fly ash by GGBFS having 12M NaOH concentration. It can be seen that, addition of GGBFS as partial replacement of fly ash upto 30% has the maximum split-tensile strength irrespective of the NaOH concentration and age of maturity. Further addition of GGBFS, i.e., 40% partial replacement of fly ash by GGBFS resulted in a decreased flexural strength irrespective of the NaOH concentration. On the other hand, the flexural strength increased with increase in NaOH concentration upto 12M, beyond which a slight reduction in flexural strength was found.

Properties of Geopolymer Concrete Exposed to Elevated Temperatures

The 28 days matured specimens were subjected to elevated temperatures from 200°C to 1000°C with an interval of every 200°C and their corresponding weight loss and deferred strength were studied. Fig. 2 to Fig. 7 shows the behavior of Geopolymer concrete with 30% GGBFS as partial replacement of fly ash exposed to elevated temperatures with varying NaOH concentrations.

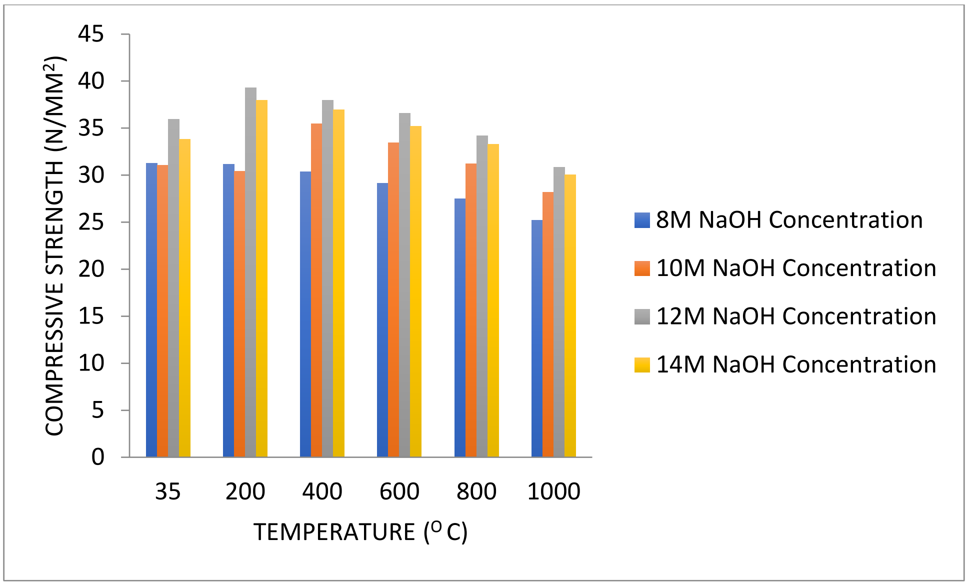

Figure 2 Compressive strength of geopolymer concrete exposed to elevated temperature

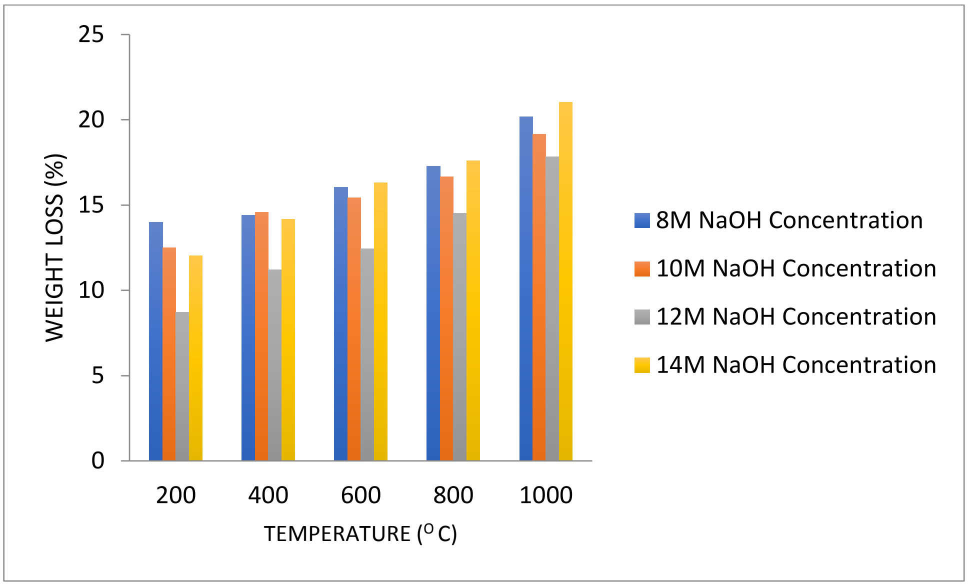

Figure 3 Weight loss of geopolymer concrete cube specimens exposed to elevated temperature

From Fig. 2, it is seen that geopolymer concrete exposed to elevated temperture showed a decrease in the compressive strength. It can be seen that the compressive strength of geopolymer concrete having 12M NaOH concentration increased from 36 N/mm^2 for ambient curied geopolymer concrete to 39N/mm^2 for geopolymer concerte exposed to 200 °C. When the temperature increases further, a decreases in the compressive strength of geopolymer concrete can be seen. This increase in compressive strength when exposed to 200 °C may be attributed to the polymerization reation that takes place in the aluminosilicates due to the presence of heat. Similarly, from Fig. 3, the weight loss of geopolymer concrete is seen to increase with increase in temperature. The maximum weight loss of 21% is seen for geopolymer concrete cube specimens exposed to 1000 °C.

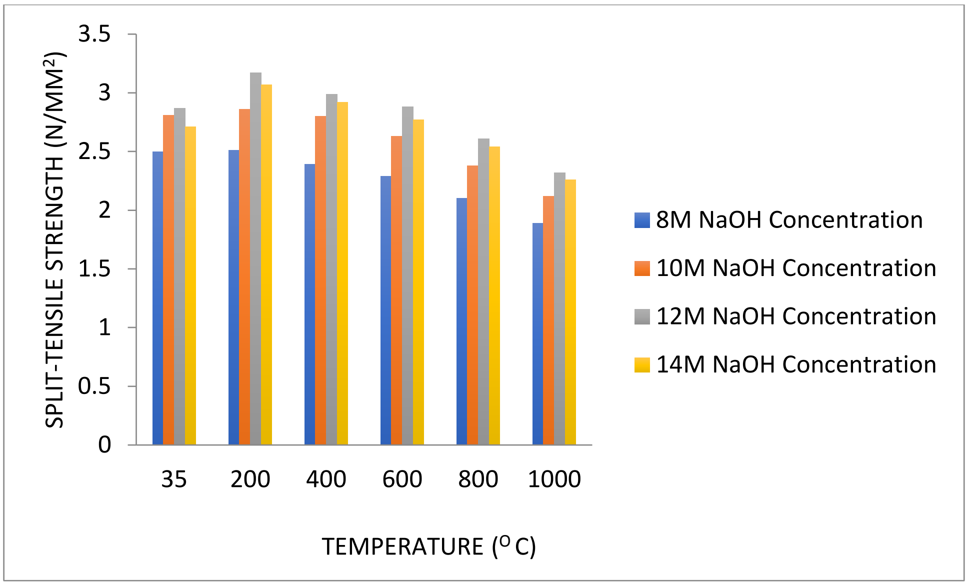

Figure 4 Split-tensilee strength of geopolymer concrete exposed to elevated temperature

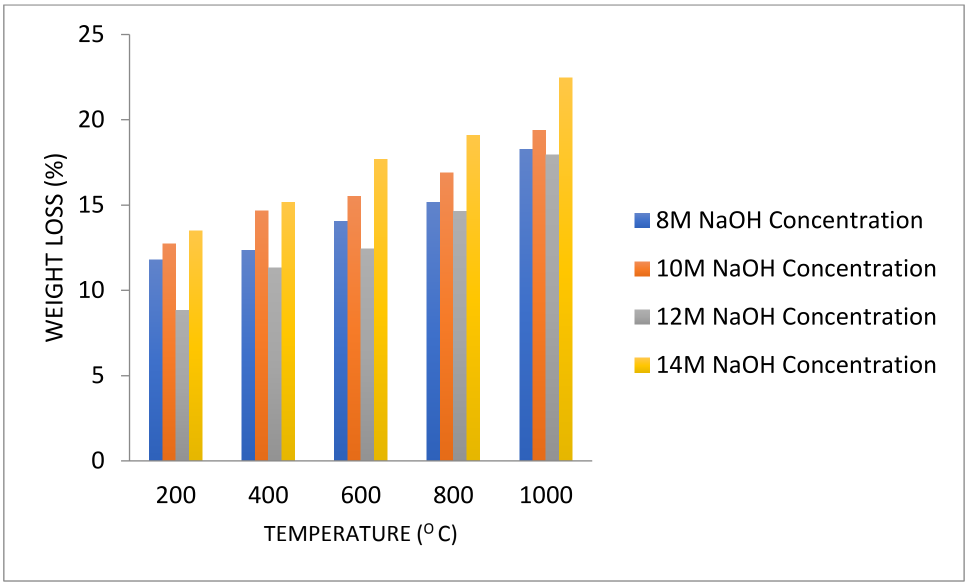

Figure 5 Weight loss of geopolymer concrete cylinder specimens exposed to elevated temperature

From Fig. 4, it can be seen that the split-tensile strength of geopolymer concrete follows the same trend of the compressive strength. The maximum split-tensile strength of 3.17N/mm^2 was seen for geopolymer concrete having 12M NaOH concentration when exposed to 200 °C and the corresponding weight loss was found to be 12.7%. From Fig. 5, it can be seen that the maximum weight loss of 22.45% was seen for geopolymer concrete cylinder specimens exposed to 1000 °C.

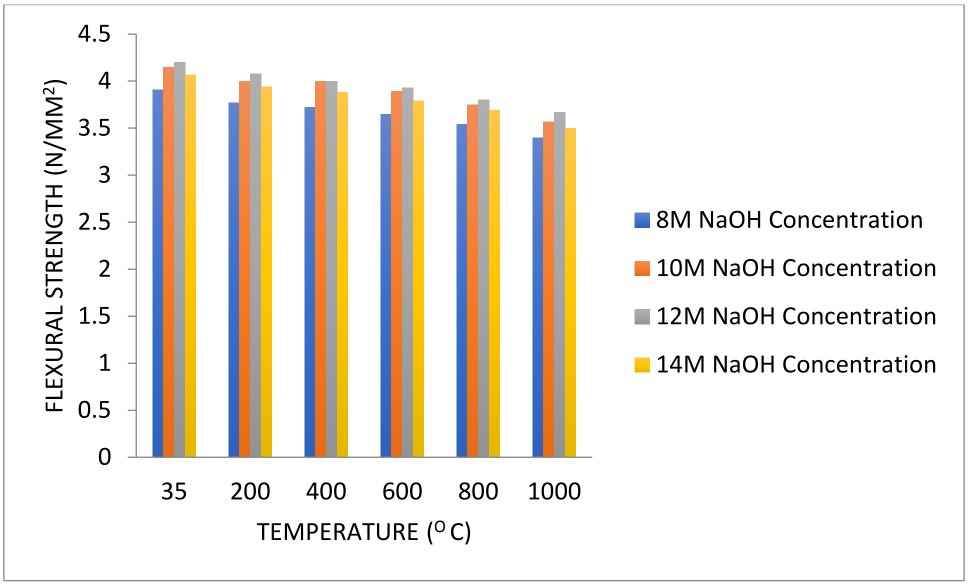

Figure 6 Flexural strength of geopolymer concrete exposed to elevated temperature

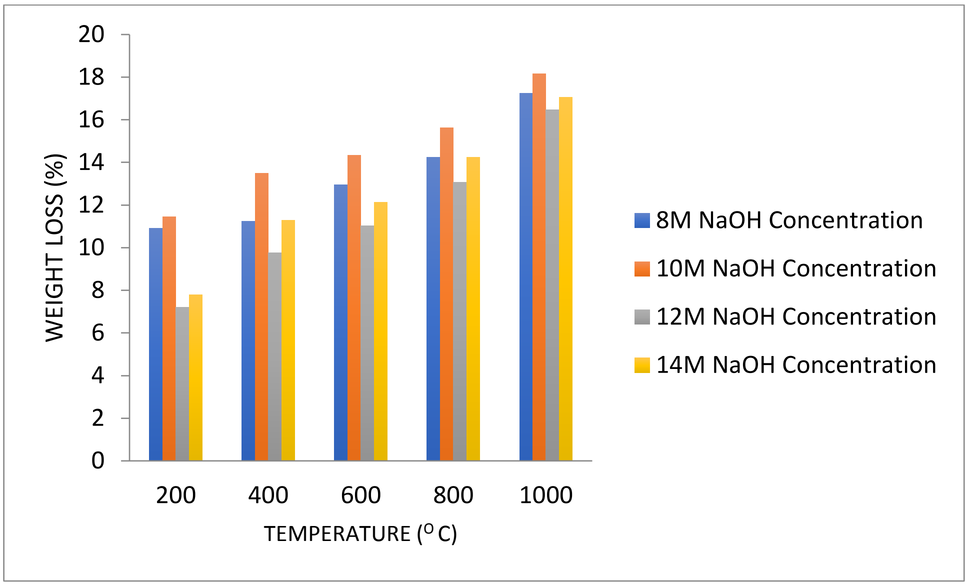

Figure 7 Weight loss of geopolymer concrete beam specimens exposed to elevated temperature

From Fig. 6, a gradual decrease in the flexural strength of geopolymer concrete can be seen when exposed to elevated temperatures. The maximum weight loss of 18% was seen for geopolymer beam specimens having 10M NaOH concentration when exposed to 1000 °C. From Fig. 7, it can be seen that there is a marginal decrease in the weight loss of geopolymer beam specimens having 12M NaOH concentration as compared to that of geopolymer beam specimens having 10M NaOH concentration.

CONCLUSION

Based on experimental results and rational discussion, the following conclusions were arrived:

- The workability in terms of slump of Geopolymer concrete decreases with increase in NaOH concentration.
- The 3, 7 and 28 day compressive, split-tensile and flexural strength of Geopolymer concrete have been found to be increased with addition of GGBFS up to 30% irrespective of NaOH concentration. Further addition of GGBFS resulted in a marginal decrease in compressive, split-tensile and flexural strength of Geopolymer concrete.
- The 3, 7 and 28 day compressive, split-tensile and flexural strength of Geopolymer concrete increases with increase in NaOH concentration from 8M to 12M, beyond which the strength decreases marginally.
- The 28 day maximum compressive, split-tensile and flexural strength of Geopolymer concrete has been found to be 35.93 N/mm^2, 2.87 N/mm^2 and 4.20 N/mm^2 for Geopolymer concrete having 12M NaOH concentration with 30% partial replacement of fly ash by GGBFS.
- Geopolymer concrete exposed to elevated temperatures showed a increase in the compressive and split-tensile strength with constant raise in temperature to 200 °C beyond which the strength decreases gradually.
- Flexural strength of Geopolymer concrete decreases gradually with increase in temperature when exposed to elevated temperatures.
- The percentage weight loss of Geopolymer concrete exposed to elevated temperature with increase in temperature from 200 °C to 1000 °C.

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