International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 07, July-2015

Development of High Strength Geopolymer Concrete using Low Molarity Naoh

Mr. Gautam L
M.Tech. Student
Department of Civil Engineering,
Reva Institute of Technology and Management,
Bengaluru 560064, India.

Dr. Prema Kumar W. P.
Senior Professor and P.G.Coordinator
Department of Civil Engineering,
Reva Institute of Technology and Management,
Bengaluru 560064, India.

Miss K.T. Sheethal
Assistant Professor
Department of Civil Engineering,
Reva Institute of Technology and Management,
Bengaluru 560064, India.

Dr. Prathap Kumar M. T.
Senior Professor and Research Coordinator
Department of Civil Engineering,
Reva Institute of Technology and Management,
Bengaluru 560064, India

***Abstract*— The development of geopolymer concrete (cementless concrete) offers great promise as an alternative construction material for the conventional Portland cement concrete. It uses industrial wastes as the ingredients in the binder thereby avoiding storage, disposal and environmental problems. The present work deals with a successful development of fly ash based and fly ash + GGBS based geopolymer concretes having 28 days compressive strength of 50 MPa and 70 MPa using NaOH solutions of low molarity at ambient curing. Twenty different mixes using NaOH solutions of molarity 3, 4, 5 and 6 were selected based on previous experience and judgment, cast and tested for compressive, splitting tensile and flexural strengths at different ages. Other parameters being the same, the water binder ratio is observed to have a significant effect on the compressive strength realized. The results obtained for geopolymer concretes are compared with those of corresponding conventional Portland cement concretes. The average compressive strength developed by geopolymer concrete (GPC) at 7 days is about 80% - 86% of the 28 days strength. The compressive strength developed by the corresponding conventional concrete at 7 days is about 60% of the 28 days strength. The average splitting tensile strength developed by GPC at 7 days is about 50% - 60% of the 28 days strength. The splitting tensile strength developed by corresponding conventional concrete at 7 days is about 37 % - 45% of the 28 days strength. The average flexural strength developed by GPC at 7 days is about 62% -74% of the 28 days strength. The flexural strength developed by corresponding conventional concrete is about 39 % - 44% of the 28 days strength. GPC in general attains higher early strength when compared to the corresponding ordinary Portland cement concrete. This is of great significance in practice as it reduces the time of deshuttering and increases the pace of construction with consequent cost savings.**

Keywords*— *Geopolymer Concrete; Portland Cement Concrete; Compressive Strength; Splitting Tensile Strength; Flexural Strength.

1. INTRODUCTION

In 1978, it was proposed [1] that binders could be produced by a polymeric reaction of alkaline liquids with the aluminum and silicon present in source materials of geological origins or byproduct materials such as rice husk ash and fly ash. These binders were named as geopolymers. Further, the pozzolonas [2] such as blast furnace slag might be activated by using alkaline liquids to form binder and thereby partially or completely replace ordinary Portland cement (OPC) in concrete. For the manufacture of geopolymer any material that contains mostly Silicon (Si) and Aluminium (Al) in amorphous form is a possible source material. Calcined kaolin or Metakaolin [1,3], low-calcium ASTM Class F FA [2,4], natural Al-Si minerals [5], combination of calcined mineral and non-calcined materials [6], combination of FA and metakaolin [4,7] and combination of GGBS and metakaolin [8] etc. have been used by researchers as source materials. The presence of calcium in high amount may interfere with the polymerization process and alter the microstructure and hence low-calcium (ASTM Class F) fly ash is preferred as a source material than high-calcium (ASTM Class C) fly ash [9]. Only FA and slag have proved to be suitable source materials for making geopolymers. The suitability of various types of FA as geopolymer source material has been investigated[10]. FA with higher amount of CaO produced higher compressive strength due to the formation of calcium-aluminate-hydrate and other calcium compounds especially in the early ages. The particle size, amorphous content, morphology and the origin of fly ash are the other characteristics that influenced the suitability of FA as a source material for geopolymers [11]. Combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate is the most common alkaline liquid used in geopolymerization [1, 2, 3, 5, 4, 6]. The mechanical properties of slag and fly ash based GPC were studied [12]. GGBS/fly ash based GPC with different molar concentrations such as 3M, 8M and 10M were produced. The target strength of around 40 MPa with low concentration of alkaline activator at 28 days, was achieved at normal ambient air curing condition. 100% fly ash with 10M NaOH under oven curing for 24 hours at 65deg C yielded 20 MPa strength at 28 days; 8M solution yielded 16 MPa. In respect of concrete with fly ash replacement of 10% with GGBS and liquid binder ratio reduced by 0.1, the mix set faster and began to harden within 24 hours. Under hot curing a 28 days compressive strength of 38 MPa was achieved. A 8 days compressive strength of 50 MPa was achieved at 50% fly ash replacement [12]. All the intricate details of production of geopolymer concrete especially those involving combination of GGBS and FA are not available in the existing literature. Existing literature mostly deals with the manufacture of geopolymer concrete using FA alone or GGBS alone. Development of geopolymer concrete using sodium hydroxide having a molarity of 8 and greater has been done. Development of geopolymer concrete using sodium hydroxide having lower molarity is scarce in the existing literature. The objective of the present study is to study the influence of low molarity alkaline solutions in producing high strength geopolymer concrete.

2. DEVELOPMENT OF GPC HAVING 28 DAYS COMPRESSIVE STRENGTH OF 50 AND 70 MPa

2.1 General

The present work deals with the development of (i) FA and GGBS based GPC and (ii) GGBS based GPC of high strengths using sodium hydroxide of low molarity and sodium silicate and ambient curing. The fine and coarse aggregates are the same as used in conventional concrete namely river sand and crushed stone. Standard and reliable procedures for mix design of geopolymer concretes are still in the development stage. Hence, a trial-and-error process, coupled with experience and judgment, was used to develop the aforesaid GPCs.

2.2 Materials Used

The physical properties and the chemical composition of fly ash and GGBS used in the present work are given in Tables 1 and 2 respectively.

TABLE 1: PHYSICAL PROPERTIES OF FLY ASH AND GGBS USED

Property	Fly ash	GGBS
Specific gravity	2.4	2.8
Fineness (m^2/kg)	425	395

TABLE 2: CHEMICAL COMPOSITION OF FLY ASH AND GGBS USED

Compound	Fly ash	GGBS
SiO_2	49.45	33.45
Al_2O_3	29.61	13.46
Fe_2O_3	10.72	0.31
CaO	3.47	41.7
MgO	1.3	5.99
Na_2O	0.31	0.16
K_2O	0.54	0.29
TiO_2	1.76	0.84
P_2O_5	0.53	-
Mn_2O_3	0.17	0.40
SO_3	0.27	2.74

In the present work, sodium hydroxide (NaOH) solution was prepared by dissolving pellets in water to obtain sodium hydroxide solution. In order to avoid evolution of excessive heat due to exothermic reaction during casting it was prepared one day prior to use. Sodium silicate solution is mixed with the sodium hydroxide solution at the time of casting. Generally Sodium Silicate, also known as liquid glass or water glass, is available in liquid (gel) form. A ratio of Na_2O to SiO_2 = 2 is used in the present investigation. The chemical composition and physical properties of sodium silicate are listed in Tables 3 and 4 respectively.

TABLE 3: CHEMICAL COMPOSITION OF SODIUM SILICATE (Na_2SiO_3)

Constituent	Percentage
Na_2O	15.90
SiO_2	31.40
H_2O	52.70

TABLE 4: PHYSICAL PROPERTIES OF SODIUM SILICATE (Na_2SiO_3)

Property	Value
Appearance	Liquid(Gel)
Color	Light yellow liquid (gel)
Boiling Point	102°C for 40% aqueous solution
Molecular Weight	122.06324g/mol
Specific Gravity	1.7

The physical properties and chemical composition of sodium hydroxide used in the present work are listed in Tables 5 and 6 respectively.

TABLE 5: PHYSICAL PROPERTIES OF SODIUM HYDROXIDE (NAOH)

Property	Value
Appearance / Color	Pellets /white
Boiling Point	102°C for 40% aqueous solution
Molecular Weight	39.997 g/mol
Specific Gravity	1.5

TABLE 6: CHEMICAL COMPOSITION OF SODIUM HYDROXIDE (NAOH)

Constituent	Percentage
Carbonate (Na_2CO_3)	2.00
Chloride (Cl)	0.01
Sulphate (SO_2)	0.05
Lead (Pb)	0.001
Iron (Fe)	0.001
Potassium (K)	0.10
Zinc(Zn)	0.02

Aggregates from local sources were used. The size of the coarse aggregates ranged from 6mm to 20mm. Prior to use in the concrete, both the coarse and fine aggregates are kept in saturated–surface dry condition (SSD). As per IS 2386 (part1, part 2, part 3) – 1963 tests were carried out on coarse and fine aggregates. It is observed that the fine aggregate used in the present work conforms to zone II. Tables 7, 8 and 9 give the results of sieve analysis of fine aggregate (river sand), 20 mm and down size coarse aggregates and 12 mm and down size coarse aggregates respectively. Tables 10, 11 and 12 give the properties of fine aggregate (river sand), 20 mm and down size coarse aggregates and 12 mm and down size coarse aggregates respectively.

TABLE 7: SIEVE ANALYSIS OF FINE AGGREGATE (RIVER SAND)

IS Sieve Size (mm)	Weight retained (kg)	% Weight retained	Cumulative % weight retained	Cumulative % weight passing
4.75	0.0265	2.65	2.65	97.35
2.36	0.0305	3.05	5.70	94.30
1.18	0.121	12.1	17.80	82.20
0.6	0.238	23.8	41.60	58.40
0.3	0.367	36.7	78.35	21.65
0.15	0.153	15.3	93.65	6.35
Pan	0.0165	1.65	-	-
Fineness Modulus			2.39	

TABLE 8: SIEVE ANALYSIS OF COARSE AGGREGATE (20MM AND DOWN)

IS Sieve Size (mm)	Weight retained (Kg)	Cumulative Weight retained (Kg)	Cumulative % weight retained	Cumulative % weight passing
80	0	0	0	100
40	0	0	0	100
20	1.940	1.940	38.8	61.2
10	2.956	4.896	97.92	2.08
4.75	0.062	4.958	99.16	0.84
2.36	0.042	5	100	0
1.18	0	5	100	0
0.6	0	5	100	0
0.3	0	5	100	0
0.15	0	5	100	0
Fineness Modulus			7.35	

TABLE 9: SIEVE ANALYSIS OF COARSE AGGREGATE (12MM AND DOWN)

IS Sieve Size (mm)	Weight retained (Kg)	Cumulative Weight retained (Kg)	Cumulative % weight retained	Cumulative % weight passing
10	0.809	0.809	16.18	83.82
4.75	3.304	4.113	82.26	17.74
2.36	0.124	4.237	84.74	15.26
1.18	0.170	4.407	88.14	11.86
0.6	0.104	4.511	90.22	9.78
0.3	0.039	4.550	91.0	9.00
0.15	0.278	4.828	96.56	3.44
Fineness Modulus			6.49	

TABLE 10: PHYSICAL PROPERTIES OF FINE AGGREGATE

Property	Value
Specific Gravity	2.673
Bulk density	1.65gm/cc
Fineness Modulus	2.39

TABLE 11: PHYSICAL PROPERTIES OF COARSE AGGREGATE (20 MM & DOWN)

Property	Value
Specific Gravity	2.60
Bulk density	1.58g/cc
Fineness Modulus	7.35

TABLE 12: PHYSICAL PROPERTIES OF COARSE AGGREGATE (12 MM & DOWN)

Property	**Value**
Specific Gravity	2. 78
Bulk density	1.57g/cc
Fineness Modulus	6.49

2.3 Trial Mixes

No standard mix design procedures are available for GPCs unlike conventional cement concrete since GPCs are a new class of construction materials. Therefore, by trial and error, the proportioning of GPC was done considering strength and workability characteristics in view. An attempt has been made here to develop high strength GPC mixes of strengths 50MPa and 70 MPa with a molarity as low as 3M, 4M, 5M and 6M in ambient curing. The ratio of NaOH to Na_2SiO_3 was kept at 0.5. In this study 20 different geopolymer concrete trial mixes were considered. In the first five mixes, the concentration of NaOH was 3 molars; in the second five mixes, the concentration of NaOH was 4 molars; in the third five mixes, concentration of NaOH was 5 molars and in the last five mixes, concentration of NaOH was 6 molars. No extra water was added. The GPC with slag alone as source material and GPC with a combination of slag and flyash were considered. The details of the trial mixes are shown in Table 13.

Mix No	Molarity of NaOH	FA (kg/m^3)	GGBS (kg/m^3)	Fine Agg (kg/m^3)	Coarse Agg (kg/m^3)	AAS (kg/m^3)	W/B ratio
1	3	0	300	897	900	225	0.62
2	3	0	350	852	900	225	0.53
3	3	50	300	838	900	225	0.53
4	3	50	350	793	900	225	0.46
5	3	0	350	852	900	225	0.47
6	4	0	300	897	900	244.2	0.64
7	4	0	350	852	900	244.2	0.55
8	4	50	300	838	900	244.2	0.55
9	4	50	350	793	900	244.2	0.48
10	4	0	350	852	900	244.2	0.47
11	5	50	300	805	900	264	0.57
12	5	50	350	760	900	264	0.5
13	5	50	250	849	900	264	0.67
14	5	50	300	760	900	264	0.57
15	5	50	300	805	900	264	0.57
16	6	50	300	805	900	285	0.51
17	6	50	350	760	900	285	0.52
18	6	50	250	849	900	285	0.69
19	6	50	300	805	900	285	0.59
20	6	50	300	760	900	285	0.59

2.4 Mixing, Compaction, Casting and Curing

For preparing the NaOH solution, appropriate amount of NaOH pellets were dissolved in one litre of water for the desired concentration of NaOH (3M, 4M, 5M and 6M) one day in advance. Alkaline activator with the combination of NaOH and Na_2SiO_3 was prepared just before mixing with the binder. The fly ash along with the GGBS and aggregates were first mixed dry in the laboratory together for about three minutes in the mixer. Later, for another 5 minutes the prepared alkaline solution is thoroughly mixed with the dry mix to make the fresh GPC. In the present study the alkaline liquid ratio (Na_2SiO_3 / NaOH) used was 0.5 for all the mixes. The alkaline activator and the binder were mixed together in the mixer until a homogeneous paste was obtained. For each mix the mixing was done within 5 minutes. After one day the specimens were demoulded. The demoulded specimens were kept at ambient room temperature and cured. Nine GPC cubes of 15 cm size were cast for each trial mix. No segregation or bleeding was observed. All the mixes were viscous in nature and this may be due to NaOH solution.

2.5 Compressive Strength of Trial Mixes

Compressive strength test was conducted using a 1000 kN capacity compression testing machine on hardened geopolymer concrete specimens at 3, 7 and 28 days. Cubes of size 150 mm x 150 mm x 150 mm were used. The compressive strength results are given in Table 14

The following are observed from the strength results obtained

Table 14: Compressive strength of trial mixes of GPC

Mix No.	Compressive Strength (MPa)			p_3 / p_{28}	p_7 / p_{28}
	3 Day (p_3)	7 Day (p_7)	28 Day (p_{28})		
1	25.38	38.68	47.17	0.53	0.82
2	21.11	29.55	31.33	0.67	0.94
3	23.7	41.78	53.65	0.44	0.77
4	24.88	30.63	50.77	0.49	0.60
5	28.02	37.33	46.78	0.59	0.79
6	37.45	42.80	49.47	0.76	0.87
7	40.63	47.14	51.30	0.79	0.92
8	35.43	49.51	56.34	0.63	0.88
9	39.49	54.00	60.19	0.66	0.90
10	51.54	54.99	67.04	0.76	0.81
11	40.87	46.2	53.82	0.76	0.86
12	47.43	53.08	60.58	0.78	0.88
13	32.87	40.89	46.65	0.70	0.88
14	42.00	45.41	55.27	0.76	0.82
15	56.45	56.90	71.07	0.79	0.80
16	40.72	50.5	63.37	0.64	0.79
17	51.84	57.18	67.95	0.76	0.84
18	32.91	34.25	37.91	0.86	0.90
19	54.44	66.27	71.85	0.76	0.93
20	53.20	62.40	69.30	0.76	0.90

The following are observed from the strength results obtained:

(a) 3 Molar GGBS Geopolymer Concrete

The mix nos. corresponding to 3 Molar GGBS Geopolymer Concrete are 1, 2 and 5. The 28 days strength achieved in Mixes 1 and 5 are slightly short of 50 MPa. To achieve the required 28 days strength of 50 MPa, the W/B ratio in Mix 5 may be further reduced.

(b) 4 Molar GGBS Geopolymer Concrete

The mix nos. corresponding to 4 Molar GGBS Geopolymer Concrete are 6, 7 and 10. The required 28 days compressive strength of 50 MPa has been achieved in all the mixes.

(c) 3 Molar (GGBS+FA) Geopolymer Concrete

The mix nos. corresponding to 3 Molar (GGBS+FA) Geopolymer Concrete are 3 and 4. The required strength of 50 MPa is almost achieved in Mixes 3 and 4.

(d) 4 Molar (GGBS+FA) Geopolymer Concrete

The mix nos. corresponding to 4Molar (GGBS+FA) Geopolymer Concrete are 8 and 9. The required 28 days compressive strength of 50 MPa has been achieved in all the mixes.

(e) 5 Molar (GGBS+FA) Geopolymer Concrete

The mix nos. corresponding to 5 Molar (GGBS+FA) Geopolymer Concrete are 11, 12, 13, 14 and 15. The required 28 days compressive strength of 50 MPa has been achieved in mixes 11, 12 and 14. The required 28 days compressive strength of 70 MPa has been achieved in mix 15.

(f) 6 Molar (GGBS+FA) Geopolymer Concrete

The mix nos. corresponding to 6 Molar (GGBS+FA) Geopolymer Concrete are 16, 17, 18, 19 and 20. The required 28 days compressive strength of 50 MPa has been achieved in mixes 16 and 17. The required 28 days compressive strength of 70 MPa has been achieved in mixes 19 and 20.

In further work, Mixes 3 and 8 are considered under one category and Mixes 15 and 19 under the second category. It is to be noted that for geopolymer concrete considered in this work no conventional curing was done. However, during the first few days after casting, it is advisable to keep the exposed surface of the concrete moist to prevent surface cracks that may be caused due to shrinkage.

2.6 Mix Proportions of M50 and M70 Grade Conventional Concrete

Mix design calculations were made for conventional concretes of grades M50 and M70 in accordance with IS 10262: 2009. Ultra Tech Cement conforming to 53 grade with specific gravity of 3.15 was used. Chemical admixture used was superplasticizer Glenium with a specific gravity of 1.25. Coarse and fine aggregates that were used for the development of GPC were used for the development of conventional concrete also. The details of the trial mixes are given in Table 15. Table 15 also gives the 28days compressive strength. The required 28 days compressive strength of 50 MPa was achieved in one trial.

Three trials were used for achieving 70 MPa strength.

TABLE 15: TRIAL MIX DETAILS FOR CONVENTIONAL CONCRETE

Grade	Trial No.	Cement (kg/m^3)	Water (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	Chemical admixture (kg/m^3)	W/C ratio	28 days Compressive strength (N/mm^2)
M70	1	350.22	178.86	708	1225.40	3.5	0.45	60.00
	2	394	157.60	789.11	1097.257	7.88	0.4	70.80
	3	375.23	157.60	808.46	1098.70	5.678	0.42	70.22
M50	1	315.20	157.60	856.73	1098.558	6.304	0.50	52.00

2.7 Compressive, Splitting Tensile and Flexural Strengths of GPC and Conventional Concrete (CC) at 7 and 28 days

Table 16: 7 and 28 days of strengths of GPC and CC

Strength (N/mm^2)		GPC		Conventional concrete M50	GPC		Conventional concrete M 70
		Mix 3	Mix 8		Mix 15	Mix 19	
Comp. strength	7 Days	41.78 (77.87%)	54.99 (82.03%)	31.10 (59.80%)	56.90 (80.06%)	66.27 (92.23%)	39.25 (55.43%)
	28 Days	53.65	67.04	52.00	71.07	71.85	70.80
Splitting tensile strength	7 Days	2.78 (51.48%)	2.85 (49.56%)	1.94 (37.30%)	3.45 (58.27%)	3.76 (61.63%)	2.4 (44.03%)
	28 Days	5.4	5.75	5.20	5.92	6.10	5.45
Flexural strength	7 Days	3.8 (73.78%)	3.9 (74.42%)	1.95 (39.39%)	3.3 (61.11%)	3.76 (63.70%)	2.31 (44.42%)
	28 Days	5.15	5.24	4.95	5.40	5.90	5.20

Table 16 shows comparative variation of compressive, splitting tensile and flexural strengths of GPC and Conventional Concrete(CC) for the trial mixes 3, 8 15 and 19 of GPC and M50 and M70 grades of CC at 7 days and 28 days.

From Table 16, it is observed that

- The average compressive strength developed by GPC (Mixes 3 and 8) at 7 days is about 80% of the 28 days strength. The compressive strength developed by conventional concrete of grade M50 is about 60% of the 28 days strength. It is clear that the compressive strength of GPC developed at 7 days is higher than that of conventional concrete.
- The average compressive strength developed by GPC (Mixes 15 and 19) at 7 days is about 86% of the 28 days strength. The compressive strength developed by conventional concrete of grade M70 is about 55 % of the 28 days strength. It is clear that the compressive strength GPC developed at 7 days is higher than that of conventional concrete.
- The average splitting tensile strength developed by GPC (Mixes 3 and 8) at 7 days is about 50% of the 28 days strength. The splitting tensile strength developed by conventional concrete of grade M50 is about 37 % of the 28 days strength. It is clear that the splitting tensile strength of GPC developed at 7 days is higher than that of conventional concrete.
- The average splitting tensile strength developed by GPC (Mixes 15 and 19) at 7 days is approximately 60% of the 28 days strength on an average. The splitting tensile strength developed by conventional concrete of grade M70 is about 45 % of the 28 days strength. It is clear that the splitting tensile strength of GPC developed at 7 days is higher than conventional concrete.
- The average flexural strength developed by GPC (Mixes 3 and 8) at 7 days is about 74% of the 28 days strength. The flexural strength developed by conventional concrete of grade M50 is about 39 % of the 28 days strength. It is clear that the flexural strength of GPC developed at 7 days is higher than conventional concrete.
- The average flexural strength developed by GPC (Mixes 15 and 19) at 7 days is about 62% of the 28 days strength on an average. The flexural strength developed by conventional concrete of grade M70 is

about 44 % of the 28 days strength. It is clear that the flexural strength of GPC developed at 7 days is higher than conventional concrete.

3. CONCLUSIONS

Based on the present work, the following conclusions are made.

- The present work demonstrates that geopolymer concretes having 28 days compressive strengths of 50 MPa and 70 MPa can be successfully developed with FA+GGBS as the main binder and using sodium silicate and sodium hydroxide having molarity as low as 3M, 4M, 5M and 6M at ambient curing. Other parameters being the same, the W/B ratio is observed to have a significant effect on the strength realized.
- The average compressive strength developed by GPC at 7 days is about 80% - 86% of the 28 days strength. The compressive strength developed by the corresponding conventional concrete at 7 days is about 60% of the 28 days strength. The compressive strength of GPC developed at 7 days is higher than that of corresponding conventional concrete.
- The average splitting tensile strength developed by GPC at 7 days is about 50% - 60% of the 28 days strength. The splitting tensile strength developed by corresponding conventional concrete at 7 days is about 37 % - 45% of the 28 days strength. The splitting tensile strength of GPC developed at 7 days is higher than that of the corresponding conventional concrete.
- The average flexural strength developed by GPC at 7 days is about 62% -74% of the 28 days strength. The flexural strength developed by corresponding conventional concrete is about 39 % - 44% of the 28 days strength. The flexural strength of GPC developed at 7 days is higher than that of the corresponding conventional concrete.

- GPC attains higher early strength when compared with ordinary Portland cement concrete with the use of low molarity alkaline solutions. This is of great significance in practice as it affects the time of deshuttering and pace of construction.

ACKNOWLEDGMENT

The authors gratefully acknowledge the encouragement and support provided by the Management, Principal and Head of the Department of Civil Engineering **Dr. Y. Ramalinga Reddy**, Reva Institute of Technology and Management, Bengaluru 560064.

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