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Strength and Durability Behaviour of Fly Ash Based Geopolymer Concrete in Structural Applications

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Abstract

The cement production which causes environmental pollution cannot be eliminated completely but its use can be reduced by utilizing other cementing materials. The production of Geopolymer with fly ash consume less energy and this technology has the ability to minimize the emissions by 80%. For the present work, a Geopolymer prepared from low-calcium fly ash is used in place of cement to produce M60 concrete. The experimental program consists of three main stages. In the first stage, mix design was done to prepare M60 concrete for both conventional and Geopolymer concretes. In the second stage, strength parameters of the concretes were assessed by testing cubes (for evaluating the compressive strength), prisms (for flexural strength) and cylinders (for split tensile strength) using those two concrete types. In the third stage, durability study was conducted on both conventional and fly ash based Geopolymer concretes. From this study it was observed that the Geopolymer concrete with fly ash showed higher compressive strength and lower tensile strength when compared with normal concrete of same grade. The durability properties of the Geopolymer concrete showed good resistance to acid, sulphate, sea water and corrosion.

Keywords: Geopolymer concrete, Materials, Mix design, Mechanical properties, Durability

Introduction

The environmental pollution due to construction activities needs to be treated as a serious issue and efforts need to be put towards reducing the utilization of pollution causing materials in construction(Dharek et al., 2018)Since the utilization of concrete and the pollution caused by cement production are increasing alarmingly, it is necessary to identify new alternate materials to cement which provides the required strength and durability to the concrete members (Dharek et al., 2020). Though it is difficult to completely eliminate the utilization of cement, many researchers put their efforts to reduce the quantity of cement in concrete and replacing it with new materials (Dharek et al., 2022). The various alternate materials used were fly ash, rice husk ash, slag, sludge, silica fume, Ground Granulated Blast Furnace Slag (GGBS), polymers (Sumalatha et al., 2020; Dharek et al., 2021).

In 1979, Professor Joseph Davidovits found that binders could be created by a polymeric reaction of pozzolanic materials and can be prepared from industrial by-products such as fly ash, blast furnace slag and rice husk ash and he named the new material as Geopolymer. Among various binders, Geopolymer has gained more importance in the past few years due to its adequate strength and durability characteristics when compared with normal concrete (Davidovits, 1991; Davidovits et al., 1999; Duxson et al., 2007; Provis and Van Deventer, 2009; Li et al., 2010; Komnitsas, 2011). The strength of Geopolymer concrete was studied by Jamkar et al., 2013, Vora and Dave, 2013, Shaikh and Vimonsatit, 2015, Reddy et al., 2016 and Dao et al., 2019. The durability studies on Geopolymer concrete were also conducted by many researchers (Law et al., 2015; Ganesan et al., 2015; Luhar et al., 2019; Cheema et al., 2009; Kabir et al., 2019).

Since fly ash based geopolymers are a potential substitute material for OPC especially in high temperature applications, their thermal mechanical properties are of interest. The properties of geopolymer concrete were studied by several researchers (Xie et al., 2019; Li et al., 2019; Jena and Panjgrahi, 2019; Amran et al., 2020; Noushini et al., 2020; Shahmansouri et al, 2020; Amran et al., 2021; Moghaddam et al., 2021; Shahmansouri et al., 2021). The present study focused on strength and durability studies on Geopolymer (low calcium fly ash based) concrete and the results were compared with those of normal concrete. Various trial mixes were done to obtain M60 grade Geopolymer concrete. Data for the design of mix proportions of M60 grade for both Geopolymer and normal concrete are included in this study. The salient factors that influence the strength properties of high strength hardened concrete have been identified. Also, the durability properties of both the concretes were achieved by various tests conducted on the specimens such as acid test, sulphate test, sea water test and corrosion test.

Materials and Methods

Preparation of Normal concrete (NC)

The materials used for the preparation of NC (M60) are Ordinary Portland cement (53 grade), Silica fume (42 kg/m^3), 12.5 mm down sized coarse aggregates and 4.75 mm down sized fine aggregates. To increase the workability of concrete, Conplast Sp 430 super plasticizer as per mix designs was mixed. The materials were uniformly mixed in the concrete mixer by adding water and super plasticizer.

Preparation of Geopolymer concrete (GPC)

The GPC was prepared with Aggregates (coarse and fine), Low-calcium fly ash (ASTM Class F), GGBS, Alkaline Liquids (Sodium silicate and Sodium hydroxide) and Superplasticizer. The dry mixing was done with concrete mixer for about 3 minutes and then the alkaline solutions and water were mixed. To get a uniform mixture, the mixer was operated for another 4 minutes. Total 12 trial mixes were prepared and the details are given in Table 1.

Table 1. Mix details of GPC

Mix no.	Al: Binders	Coarse aggregates kg/m^3	Fine sand kg/m^3	Fly ash kg/m^3	GGBS kg/m^3	NaOH Solution kg/m^3	Molarity	Na_2SiO_3 Solution kg/m^3	Extra Water (%)	SP %	Curing Time hrs
1	0.30	1295	555	382	42	36	8	90	3	3	24
2& 5	0.35	1295	555	366	40	41	8	103	3	3	24
3	0.40	1295	555	355	39	44	8	112	3	3	24
4	0.45	1295	555	342	38	48	8	122	3	3	24
6	0.35	1295	555	366	40	41	12	103	3	3	24
7	0.35	1295	555	366	40	41	14	103	3	3	24
8	0.35	1295	555	366	40	41	14	103	3.3& 6.3	3	24
9	0.35	1295	555	366	40	41	14	103	3.3& 6.3	3	48

10	0.35	1295	555	366	40	41	14	103	3.3& 6.3	3	72
11	0.30	1295	555	424	-	36	8	90	3	3	24
12	0.35	1295	555	406	-	41	8	103	3	3	24

Specimen Preparation

(a) For Strength studies

Cubical specimens of size 100 mm (for compressive strength), cylindrical specimens of size 100 x 200 mm (for split tensile strength) and prism shaped specimens of size 75 x 75 x 450 mm (for flexural strength) each of 6 in number were prepared with GPC and same of normal concrete.

(b) For Durability studies

Six cubical moulds of size 100 mm each for acid test, sulphate attack test and sea water resistance test, six cylindrical moulds of size 100x200 mm for corrosion test were used to prepare specimen of geopolymer concrete and same of normal concrete.

Methodology

The first stage came to an end by having the mix proportions of M60 grade for both conventional and fly ash based Geopolymer concretes (Table 2).

Table 2. Comparison of materials used for NC and GPC

Concrete	GPC	NC
Materials	M60 kg/m^3	M60 kg/m^3
Cement (kg/m^3)	-	370
Fly ash (kg/m^3)	363	-
GGBS (kg/m^3)	46	-
Silica fume (kg/m^3)	-	45
Coarse aggregates (kg/m^3)	1290	1050
Fine sand (kg/m^3)	553	718
NaOH Solution (8M) (kg/m^3)	43	-
Na_2SiO_3 Solution (kg/m^3)	105	-
Water (l/m^3)	16.24	150
Superplasticizer (%)	3	2.5

In the second stage, cubes of required size were prepared to evaluate the strength properties of both GPC and NC. The third stage was carried out by casting 100 mm cube specimens and keeping them under observation for six weeks for carrying out acid resistance test, sea water resistance test, sulphate resistance test and 100 mm X 200 mm cylinders for corrosion resistance test of both the concretes. The durability properties under various conditions were then noted with respect to time.

Results and Discussion

Variations in strength properties with binder content, molarity, water content, GGBS content and curing time

Table 3 represents the strength variation with respect to ratio of alkaline liquid to binders where it can be observed that the cube strength corresponding to one day is higher with this ratio. The cube strength also increases with increase in molarity (Table 4). The effect of water content and curing time on strength and the effect of GGBS on strength are shown in Tables 5 and 6 respectively.

Table 3. Strength variation with respect to ratio of alkaline liquid to binders

Mix No.	Alkaline liquid: Binders	Cube strength 1 day
1	0.30	60.2
2	0.35	64.2
3	0.40	79.2
4	0.45	80.2

Table 4. Effect of molarity on cube strength

Mix No.	Molarity	1 day Cube strength
5	8	64.2
6	12	67.8
7	14	78

Table 5. Effect of water content and curing time on strength

Mix No.	Time hrs	1day Cube strength for 3.3% water	1day Cube strength for 6.3% water
8	24	84	78
9	48	92.5	77.5
10	72	95	80.5

Table 6. Effect of GGBS on strength

Mix no.	Alkaline liquid: Binders	1day Cube strength with GGBS	1day Cube strength without GGBS
8	0.30	60.2	44
9	0.35	64.2	48.2

Strength Characteristics of Concretes (GPC and NC)

Compressive Strength of Concretes

The compressive strengths of both GPC and NC for M60 grade concrete are presented in the table 7. It can be observed that the strength values of GPC are higher than those of NC.

Table 7. Compressive strength results of GPC and NC

Days	NC-M60 MPa	GPC-M60 MPa
7	26	72
14	59	81
28	85	88

Split tensile strength of Concretes

The split tensile strength values corresponding to M60 grade concretes of GPC and NC are given in Tables 8 and 9. The average split tensile strength of GPC and NC respectively are 3.54 MPa and 4.47 MPa. From these results it can be observed that the GPC shows slightly lower values of tensile strength when compared with NC.

Table 8. Split tensile strength values of GPC

Tensile Load Applied (N)	Split Tensile Strength (MPa)
120000	3.79
120000	3.79
80000	2.52
120000	3.80
120000	3.80
110000	3.52

Table 9. Split tensile strength values of NC

Tensile Load Applied (N)	Split Tensile Strength (MPa)
150000	4.72
140000	4.41
130000	4.11
140000	4.42
150000	4.72
140000	4.43

Flexural Strength of Concretes

The flexural strength values of GPC and NC for M60 grade concrete are presented in Tables 10 and 11. The average flexural strength of GPC and NC respectively are 6.454 MPa and 6.757 MPa which shows that there is a slight decrease in flexural strength of GPC when compared with NC.

Table 10. Flexural strength of NC

Mix no	DG reading	divisions	P (Kgf)	P (N)	f = Pl/bD2	$0.7\sqrt{fck}$
1	20	100	615.01	6033.21	6.435	6.454
2	21	105	645.76	6334.87	6.757	6.454
3	22	110	676.51	6636.53	7.078	6.454
4	21	105	645.76	6334.87	6.757	6.454
5	20	100	615.01	6033.21	6.435	6.454
6	22	110	676.51	6636.53	7.078	6.454

Table 11. Flexural strength of GPC

Mix no	DG reading	divisions	P (Kgf)	P (N)	f = Pl/bD2	$0.7\sqrt{fck}$
1	20	100	615.01	6033.21	6.435	6.566
2	23	115	707.26	6938.19	7.401	6.566
3	22	110	676.51	6636.53	7.078	6.566
4	18	90	553.51	5429.89	5.791	6.566
5	24	120	738.01	7239.85	7.722	6.566
6	19	95	584.26	5731.55	6.113	6.566

Comparison of Durability Properties Between M60 GPC and NC

Acid resistance test (2N HCl -10% by Weight)

The acid test results of GPC and NC respectively are shown in tables 12 and 13. The Figure 1 shows the profiles showing the variations in weight loss with respect to each material. The changes in compressive strength during acid test are shown in Figure 2 where it can be observed that the variations in strength were very minimal.

Table 12. Acid test values of GPC

GPC	Test	Initial	Final	Load	Cube Strength	% Weight loss/increase
Days		(gms)	(gms)	(tonnes)	MPa	
7	W1	2360	2386	82	82	-1.10169
14	W2	2406	2430	80	80	-0.99751
21	W3	2470	2486	70	70	-0.64777
28	W4	2452	2474	72	72	-0.89723
35	W5	2454	2478	68	68	-0.978
42	W6	2414	2440	67	67	-1.07705

Table 13. Acid test values of NC

NC	Test	Initial	Final	Load	Cube Strength	% Weight loss/increase
Days		(gms)	(gms)	(tonnes)	MPa	
7	W1	2458	2442	82	82	0.650936
14	W2	2436	2422	80	80	0.574713

21	W3	2432	2418	64	64	0.575658
28	W4	2432	2416	70	70	0.657895
35	W5	2426	2414	72	72	0.494641
42	W6	2416	2409	66	66	0.289735

Figure 1. Percentage weight loss with number of days of Acid resistance test

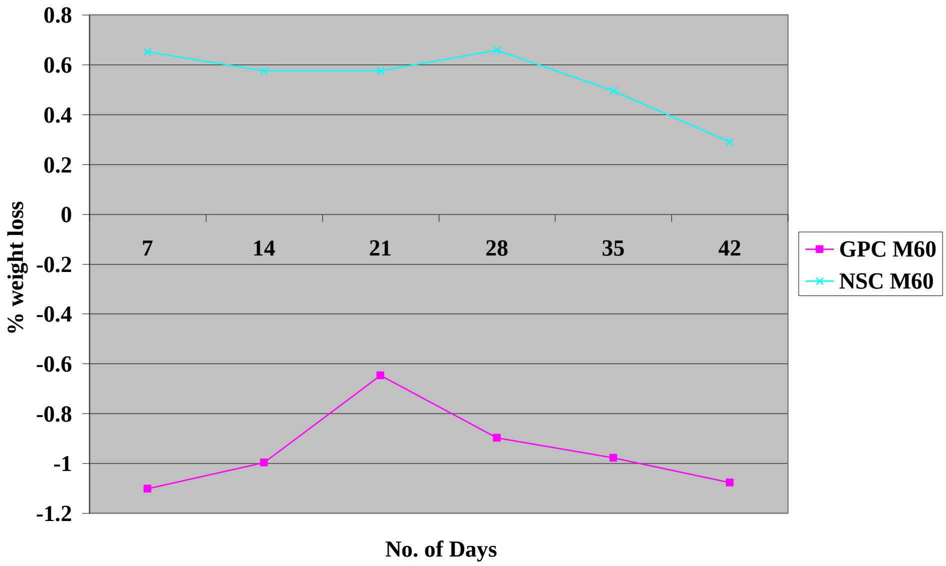
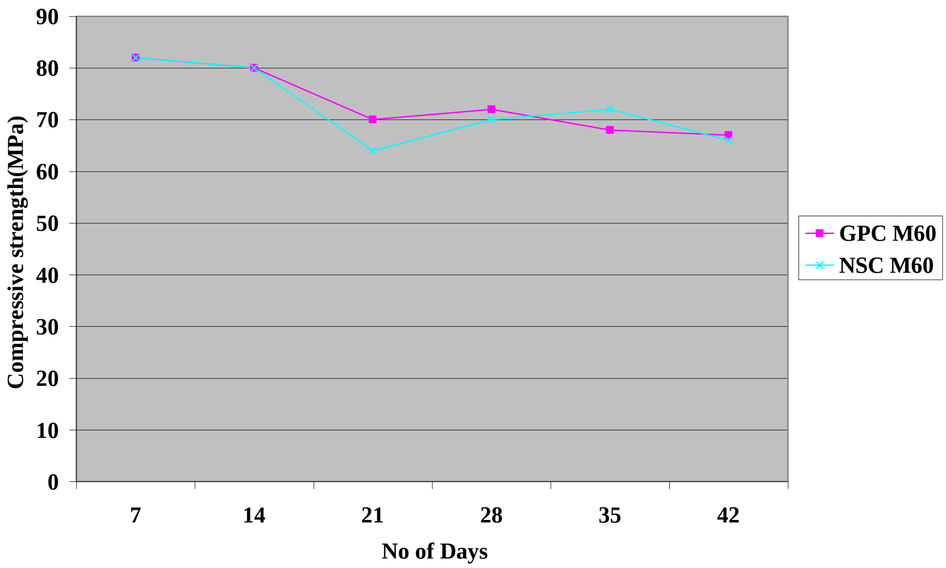


Figure 2. Variation in Compressive strength with number of days of Acid resistance test



Sulphate resistance test ($MgSO_4$ - 5% by Weight)

The sulphate resistance test results of GPC and NC respectively are shown in tables 14 and 15. The profiles showing the variations in weight loss with respect to each material are shown in Figure 3. The variations in compressive strength are shown in Figure 4.

Table 14. Sulphate resistance test values of GPC

GPC	**Test**	**Initial**	**Final**	**Load**	**Cube Strength**	**% Weight loss/increase**
Days		(gms)	(gms)	(tonnes)	MPa	
7	W1	2496	2504	88	88	-0.32051
14	W2	2484	2490	86	86	-0.24155
21	W3	2456	2464	80	80	-0.32573
28	W4	2476	2479	85	85	-0.12116
35	W5	2454	2461	79	79	-0.28525
42	W6	2510	2518	86	86	-0.31873

Table 15. Sulphate resistance test values of NC

NC	**Test**	**Initial**	**Final**	**Load**	**Cube Strength**	**% Weight loss/increase**
Days		(gms)	(gms)	(tonnes)	MPa	
7	W1	2448	2446	86	86	0.081699
14	W2	2450	2446	83	83	0.163265
21	W3	2488	2484	79	79	0.160772
28	W4	2410	2408	70	70	0.082988
35	W5	2488	2478	72	72	0.401929
42	W6	2443	2430	64	64	0.532133

Figure 3. Percentage weight loss with time for Sulphate resistance test

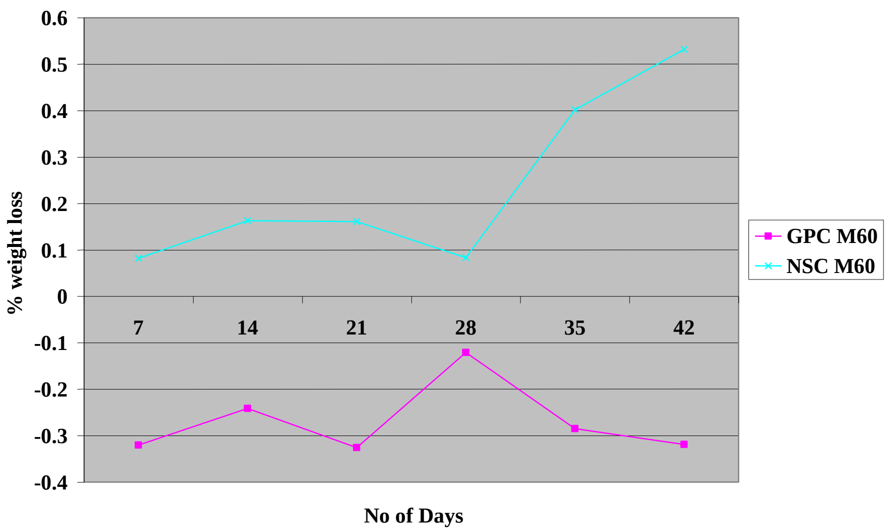
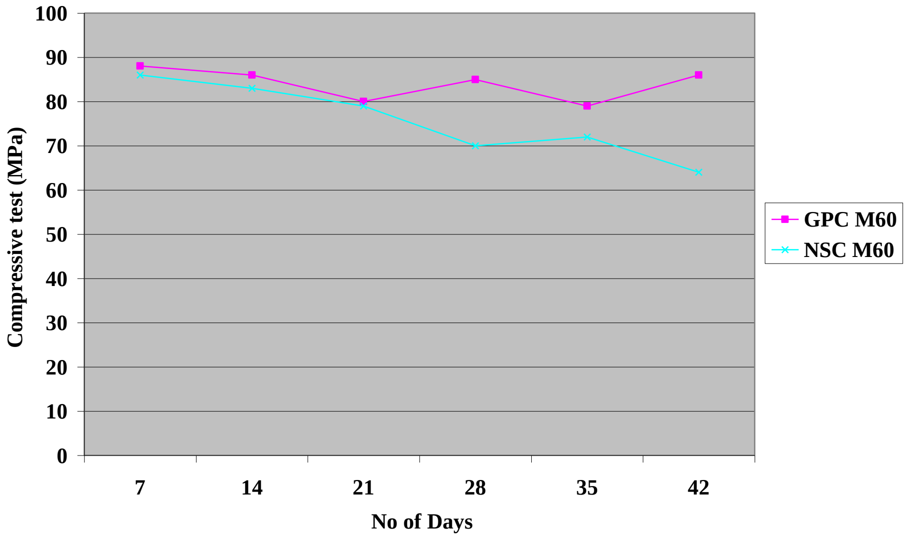


Figure 4. Variation in Compressive strength with time for Sulphate resistance test



Sea water resistance test (NaCl - 5% by Weight)

The sea water resistance test results of GPC and NC respectively are shown in tables 16 and 17. The profiles showing the variations in weight loss with respect to each material are shown in Figure 5. The variations in compressive strength are shown in Figure 6.

Table 16. Sea water resistance test values on GPC

GPC	**Test**	**Initial**	**Final**	**Load**	**Cube Strength**	**% Weight loss/increase**
Days		(gms)	(gms)	(tonnes)	MPa	
7	W1	2478	2486	86	86	-0.32284
14	W2	2452	2458	79	79	-0.2447
21	W3	2456	2461	77	77	-0.20358
28	W4	2460	2467	79	79	-0.28455
35	W5	2468	2474	78	78	-0.24311
42	W6	2408	2416	87	87	-0.33223

Table 17. Sea water resistance test values on NC

NC	**Test**	**Initial**	**Final**	**Load**	**Cube Strength**	**% Weight loss/increase**
Days		(gms)	(gms)	(tonnes)	MPa	
7	W1	2466	2460	84	84	0.243309
14	W2	2364	2354	78	78	0.423012
21	W3	2426	2415	75	75	0.453421
28	W4	2364	2353	71	71	0.465313
35	W5	2404	2394	79	79	0.415973
42	W6	2464	2457	83	83	0.284091

Figure 5. Percentage weight loss with time for Sea water resistance test

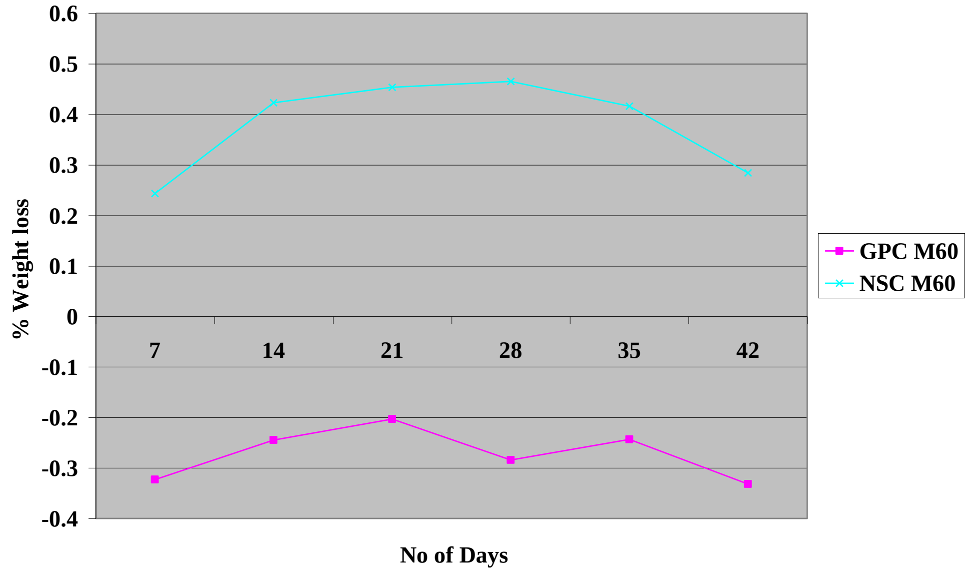
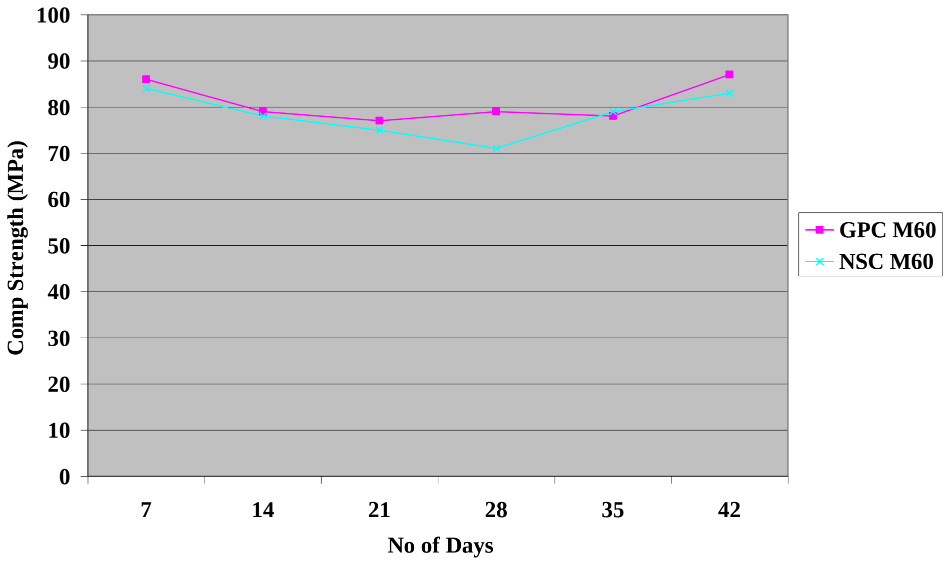


Figure 6. Variation in Compressive strength with time for Sea water resistance test



Corrosion test results

The sea water resistance test results of GPC and NC respectively are shown in tables 18 and 19. The values of mass loss for GPC are slightly lower than those of NC.

Table 18 Corrosion test values of NC

% Mass Loss	Time (mins)	Peak Current (Amp)
1.8	48	3.8
2.6	62	3.7
4.5	95	3.6
7.9	118	3.5

8.8	145	3.2
9.8	172	3.1

Table 19 Corrosion test values of GPC

% Mass Loss	Time (mins)	Peak Current (Amp)
1.6	48	4.0
1.8	62	4.1
2.6	95	4.0
3.7	118	3.9
6.6	145	4.1
8.5	172	4.2

Conclusions

The geopolymer concrete which gained importance due to its environmental benefits has been studied to evaluate its characteristics with respect to strength and durability. The geopolymer concrete was prepared with low-calcium fly ash and trial mixes corresponding to M60 grade were tested. The test results of GPC and NC showed that there is a considerable increase in compressive strength of GPC (around 30%) when compared with NC. There was a slight reduction in tensile and flexural strengths of GPC but the differences are minimal. The durability properties of both the concretes were achieved by various tests conducted on the specimens such as acid test, sulphate test, sea water test and corrosion test. There was an increase in weight loss and decrease in compressive strength during the durability tests in both geopolymer and normal concretes but the reduction in strength for GPC is very minimal. This shows the potential of GPC for acid resistance, sulphate resistance and resistance to sea water. From the corrosion resistance test, it was observed that the geopolymer has better resistance property than the conventional concrete. From this research work, it can be concluded that, GPC (fly ash-based) has exceptional characteristics and is suitable for structural applications.

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