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A Comprehensive Study on Geopolymer Concrete Optimized by Taguchi Method Subjected to Elevated Temperature

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Abstract: Geopolymer Concrete (GPC), an innovation in the field of green concrete, is the best alternative to cement in the construction industry. It reduces the carbon footprint *vis-a-vis* conventional cement production, thus reducing the potential for global warming. Adding boric acid during GPC production improves workability. The scope of this work is to determine the best possible design mix, created with the backing of the Taguchi analysis. The results detail the optimum combination of ingredients required to meet both fresh and hardened properties of GPC at ambient and elevated temperatures.
Key words: Workability, Optimum Mix design, Fresh & hardened properties.

Introduction

Worldwide, the construction boom seems never-ending, for which, concrete is indispensable. Cement manufacture is one of the main culprits in global warming - to obtain one ton of cement, 4.7 million BTU of energy, corresponding to 400 pounds of coal, is used, generating a whole ton of carbon dioxide. A 'green' binder is the alternative, and endeavours have been effected using saw-dust, rice-husk ash, sugarcane ash, metakaolin, silica fumes *et al*, to control and reduce the detrimental effect of cement manufacture, without compromising either on quality of material or durability of the structure.

A potential, sustainable alternative for cement concrete is GPC (1). Several researchers have implemented the Taguchi analysis for cost-effective production of GPC. Shadi, Rahi et al. studied the effects of water and oven-curing at 90º C in GPC trials and concluded that oven-curing produces maximises compressive strength (2). Ankur Mehta et al. studied the water-absorption capabilities of GPC at various curing temperatures (3), analysing the results to determine the best combination of materials. Fly-ash-based GPC needs oven-curing, incorporation of GGBFS contributed to desired workability, setting time and compressive strength (4). Blending GGBS and fly-ash with sodium-based alkaline activators provides better workability and compressive strength (5). Substituting manufactured sand instead of river sand to GPC enhances the freezing and thawing effect and also improves residual compressive strength at elevated temperatures (6). M. Bastami et al. used analysis of variance to evaluate the mechanical and physical properties of conventional concrete. The data obtained from the studies depicts that ANOVA can be useful to understand the effect of each parameter for strength (7). Marble dust & glass fibres can substitute cement by upto 50% in cement concrete (Orguzhan Kelestemur et al.) the results are analysed with L16 orthogonal array (8). Muhammad et al. carried out L9 orthogonal array for assessing the behaviour of GGBS based GPC and results show that GGBS increases the setting time (9). Harun Tanyildizi et al. used L32 orthogonal array for evaluating the mechanical properties of GPC (10). The main parameters are polymerization type, percent of silica fume and heating temperature. The specimens are exposed to 600º C. The results determined that with increase in temperature polymerisation and strength decreases.

Several trials have been made by multiple authors on fly ash, GGBS, OPC, a combination of fly ash and GGBS, and marble dust using L9 orthogonal array system of Taguchi method. Since there is limited research in L18 orthogonal array, it is necessary to arrive at an optimal mix proportion of geopolymer concrete (GGBS+SCBA) using L18 orthogonal array, considering 7 variables with 3 levels of factors to identify the critical values of the control factors of the GPC. The Taguchi method was used to design an experiment to find out the effect of seven parameters on the cost and strength of concrete mixes.

1. Materials

The preliminary requisites on the selected materials tabulated below:

1.1 Preliminary test on aggregates

Physical property	**10mm aggregate**	**20mm aggregate**	**M Sand**
Sieve Analysis	IS:383-1970	IS:383-1970	Zone-IV
Bulk density	The density of loose sand = 1353.31 Kg/m^3 The density of compacted sand = 1534.16 Kg/m^3	The density of loose sand = 1264Kg/m^3 The density of compacted sand = 1479 Kg/m^3	The density of loose sand = 1317.53 Kg/m^3 The density of compacted sand = 1572.96 Kg/m^3
Water absorption	1.4%	1.6%	1.25%
Specific gravity	2.72	2.7	2.6

1.2 Preliminary test on source materials and alkaline materials

Table 1.2.1 : Physical properties of source materials

Physical property	**GGBS**	**SCBA**
Specific gravity	2.92	1.6
Fineness	3.1%	64%

Table 1.2.2 : Physical properties of alkaline materials

Molecular formula	NaOH	Na_2SiO_3
Molecular weight	40g	122.062g
Density	1470kg/m^3	1600kg/m^3

Table 1.2.3 : Chemical composition of GGBS

Test Conducted	***Results***	***Requirements As Per Is:16714-2018***
Manganese oxide (MnO)(%)	0.07	Maximum 5.5
Magnesium oxide (MgO)(%)	7.07	Maximum 17.0
Sulfide sulphur (S)(%)	0.47	Maximum 2.0
Sulphate (SO_3)	0.18	Maximum 3.0
Insoluble residue (Max) (%)	0.78	Maximum 3.0
Chloride content	0.021	Maximum 0.1
Loss on ignition	0.08	Maximum 3.0
$\frac{CaO + MgO + \frac{1}{3}Al_2O_3}{SiO_2 + \frac{2}{3}Al_2O_3}$	1.28	Minimum 1.0
$\frac{CaO + MgO + Al_2O_3}{SiO_2}$	2.00	Minimum 1.0
Glass content (%)	88.7	Minimum 85.0

Table 1.2.4; Chemical composition of bagasse ash

Sl.no.	*Test*	*Unit*	*Results*
	Silicon as SiO_2	%	76.062
	Iron as Fe_2O_3	%	5.609
	Aluminum as Al_2O_3	%	4.948
	Calcium as CaO	%	1.860
	Magnesium as MgO	%	1.487
	Sodium as Na_2O	%	0.552
	Potassium as K_2O	%	1.776
	Fixed carbon	%	0.71

2. Specimen Preparation & Testing

GPC specimens were prepared by dry-mixing materials such as binder contents, 20mm &10mm down size aggregates and crusher sand as fine aggregates. Liquid chemicals (alkali activators) along with boric acid were added. The Rangan method of operating procedure was followed and trial mixes were blended for a duration of 2 min. After achieving homogeneity, liquid concrete workability of each trial mix was recorded. Finally, a metal mould of size 150mm was used to cast concrete. Specimens were subjected to ambient curing at lab temperature.

Table 2.1 : Mix design for $1m^3$ of concrete

Mix-proportion per cubic meter	
GGBS	280kg
SCBA	120kg
Sodium hydroxide- solids	18.28
Distilled water	38.86
Sodium silicate	142.86
Fine aggregate –M sand	680
Coarse aggregate	1100
20 mm downsize aggregates	550
10 mm downsize aggregates	550
Water	50
Boric acid	1%

Figure 2.1.1: Batching of the materials as per mix design

Figure 2.1.2: Dry mix in the pan mixer (left) and the wet mix (right)

Figure 2.1.3 : Compaction by tamping rod

Figure 2.1.4 : Cast specimens

3. Optimization of trial mix by Taguchi method

In this study Taguchi method of analysis has been used to determine the optimum mix proportion for M30 grade geopolymer concrete. Five parameters are considered as a factor codes which includes Binder content (GGBS+SCBA) % (70%+30%, 80%+20%), Alkali activator to binder ratio (0.4, 0.5 & 0.6), Molarity (4, 8 &12M), ratio of sodium silicate to hydroxide (1:2.5, 1:2 & 1:1.5) and boric acid (1, 2 & 3%). Experimental layout considers eight response factors. L-18 orthogonal array has been utilized for trial mix design (MD).

The compressive strength obtained from all the 18 mixes were used in calculating response index for each of trial mix. The response index was determined by taking the average strength at 3 days, 7 days & 28 days, at ambient & elevated temperatures, with final results evaluated by ANOVA.

Materials	**Level 1**	**Level 2**	**Level3**
GGBS + SCBA	(70% + 30%)	(80% + 20%)	-
NaoH + $NasiO_3$ ratio	1:2.5	1:2	1:1.5
Molarity	4M	8M	12M
Admixture	1%	2%	3%
AAC/BC	0.5	0.4	0.6
Curing days	3 days	7 days	28 days

Table 3.1 : Table of control factors with factor levels

Code	**Parameter/control factors**	**Unit**
A	Alkaline liquid	Kg/m^3
B	Binder content	Kg/m^3
c	Coarse aggregate	Kg/m^3
d	Manufacture sand	Kg/m^3
e	water	Kg/m^3

The orthogonal array of Taguchi method selected for the experiment is (2^1x 3^6).

The value of these three levels is calculated by varying the positive and negative values for the obtained mix design. This experiment's orthogonal array is L18 = (2 ^{1}x 3^2) as it is mixed level.

Table : 3.2 : Mix Proportion with various parameters

Mix design	**Binder content (GGBS+SCBA)%**	**AAC/BC**	**Molarity**	**Ratio of NaOH + Na_2SiO_3**	**Boric acid**
MD 1	(70+30)	0.5	4	1:2.5	1%
MD 2	(70+30)	0.5	8	1:2.5	1%
MD 3	(70+30)	0.5	12	1:2.5	1%
MD 4	(70+30)	0.4	4	1:2	2%
MD 5	(70+30)	0.4	8	1:2	3%
MD 6	(70+30)	0.4	12	1:1.5	2%
MD 7	(70+30)	0.6	4	1:2	3%
MD 8	(70+30)	0.6	8	1:1.5	2%
MD 9	(70+30)	0.6	12	1:1.5	3%
MD 10	(80+20)	0.5	4	1:1.5	3%
MD 11	(80+20)	0.5	8	1:2.5	1%
MD 12	(80+20)	0.5	12	1:2	2%
MD 13	(80+20)	0.4	4	1:2	3%
MD 14	(80+20)	0.4	8	1:1.5	1%
MD 15	(80+20)	0.4	12	1:2.5	2%
MD 16	(80+20)	0.6	4	1:1.5	2%
MD 17	(80+20)	0.6	8	1:2.5	3%
MD 18	(80+20)	0.6	12	1:2	1%

4. Results and Discussion

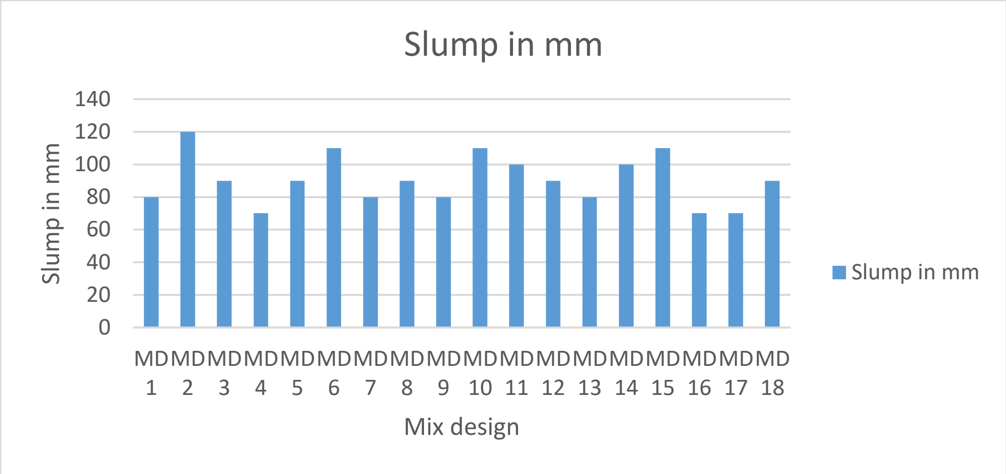
The compressive strength of GPC at ambient and elevated temperatures followed by workability readings have been considered for assessing the response index evaluation criteria, as per the Taguchi method as shown in Table 1.

4.1 Slump test

Various attempts were made varying the percentages of boric acid from 1 to 3% in the trial mix. It was observed that as the percentage of boric acid increases the workability decreases. The optimum percentage of boric acid is 1% only. The slump results of the attempted trial mixes appear in the following table with graphical representation.

Table 4.1.1. : Slump values

Mix Design	**3 days Compressive strength(N/mm^2)**	**7 days Compressive strength(N/mm^2)**	**28 days compressive strength(N/mm^2)**
MD1	19.4	35.7	40.79
MD2	24.7	42	55
MD3	25.02	43.30	57.76
MD4	28.74	50.30	50.60
MD5	35.7	62.49	66.40
MD6	19.6	35.3	39.5
MD7	16.7	30.2	34.6
MD8	25.3	36.3	40.84
MD9	30.2	35.7	41.19
MD10	31	52.70	53.30
MD11	39.4	67.17	67.97
MD12	31.1	49.89	58.50
MD13	29.4	59.50	56.49
MD14	43.3	73.77	74.09
MD15	43.96	74.74	77.11
MD16	24.29	41.3	47.23
MD17	25.1	43.18	45.75
MD18	26.3	44.9	45.08



Graph 4.1.2: Variations of slump values

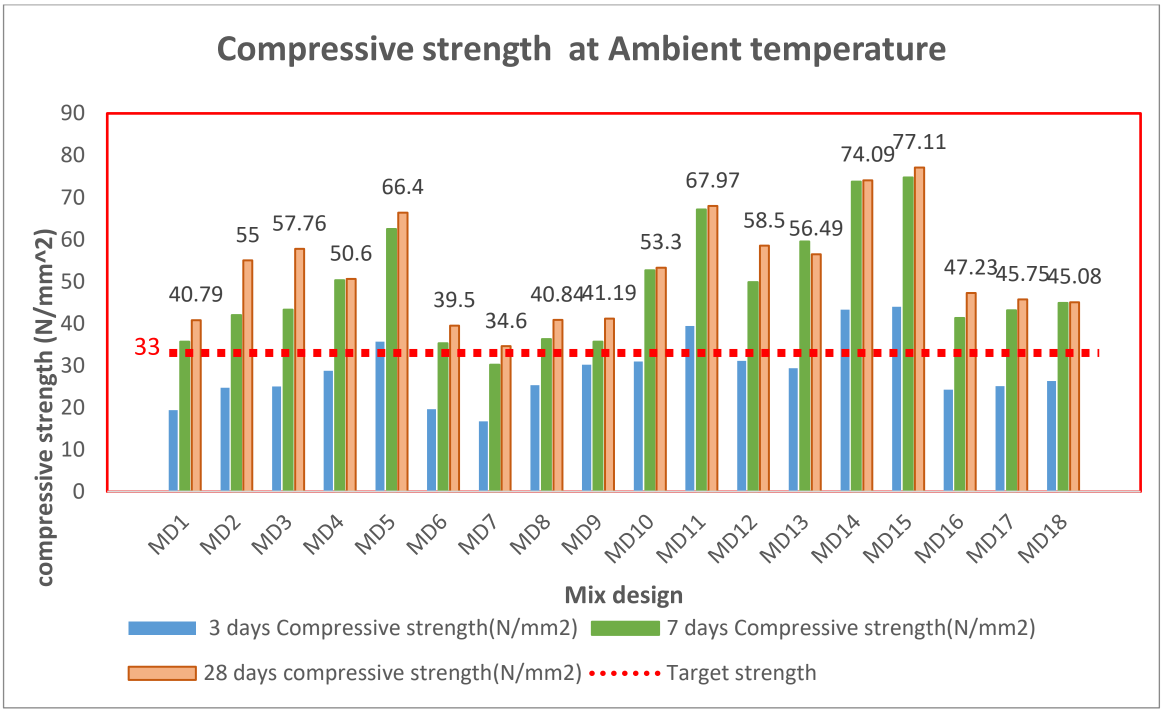
5. Test On Properties Of Hardened Concrete Compressive Strength At Ambient And At Elevated Temperatures

5.1 Compressive Strength of GPC at Ambient Temperature

Using the Taguchi method L18 of orthogonal array, 18 mix-design GPC cubes were cast. Compressive strength of all designs, measured after 3, 7 and 28 days of curing, are displayed in the graph below:

Table 5.2 : Results of compressive strength of GPC at ambient temperature

Mix design	Slump in mm	Mix design	Slump in mm
MD1	80	MD10	110
MD2	120	MD11	100
MD3	90	MD12	90
MD4	70	MD13	80
MD5	90	MD14	100
MD6	110	MD15	110
MD7	80	MD16	70
MD8	90	MD17	70
MD9	80	MD18	90



Graph 5.3 : Variations of compressive strength at ambient temperature

As per mix design the compressive strength is 33 N/mm2 (target strength) for grade M30 after 28 days. The graph depicts the test result strength of all 18 mix designs using the Taguchi approach. Taguchi analysis indicated that the optimum parameters for compressive strength of concrete at ambient temperature were obtained. MD7= 34.6 N/mm2, MD 6= 39.5 N/mm2, MD 1=40.79 N/mm2, and MD 8 =40.84 N/mm2 were close to the target strength. Mix designs 7, 2, 1 and 8 are sufficient for the manufacturing of geopolymer concrete. Mix design 7 of 4M with compressive strength of 34.6 N/mm^2 (which is close to the target strength), proves the variables of the MD7 are best combination for the optimal geopolymer concrete.

The strength levels of the other design mixes being higher than necessary, are presently superfluous.

5.4 Compressive strength (N/mm^2) of GPC at elevated temperature

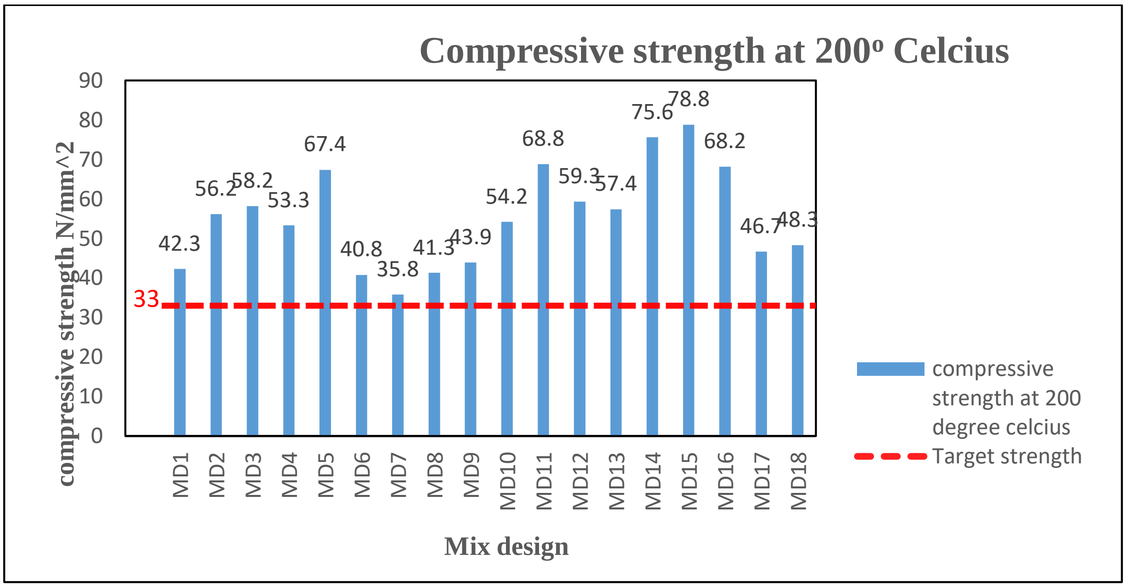
Changes in mechanical properties of concrete subjected to elevated temperatures depend on the type of materials and the effect of environmental conditions, like moisture content and initial strength of the concrete, before exposure to high temperature [15].

The residual Compressive strength of geopolymer concrete at elevated temperature diminishes as the temperature rises. Specimens are tested at elevated temperatures of 200^0 C, 400^0 C, 600^0 C and 800^0 C. The test results are tabulated below:

Compressive strength of GPC at 200⁰ C

Table 5.3.1 : Results of compressive strength of GPC at 200⁰ C

Compressive strength (N/mm^2) at 200⁰ C			
Mix design	**Compressive strength(N/mm^2)**	**Mix design**	**Compressive strength(N/mm^2)**
MD1	42.3	**MD10**	54.2
MD2	56.2	**MD11**	68.8
MD3	58.2	**MD12**	59.3
MD4	53.3	**MD13**	57.4
MD5	67.4	**MD14**	75.6
MD6	40.8	**MD15**	78.8
MD7	35.8	**MD16**	68.2
MD8	41.3	**MD17**	46.7
MD9	43.9	**MD18**	48.3



Graph 5.3.2 : Variations of compressive strength at 200⁰ C

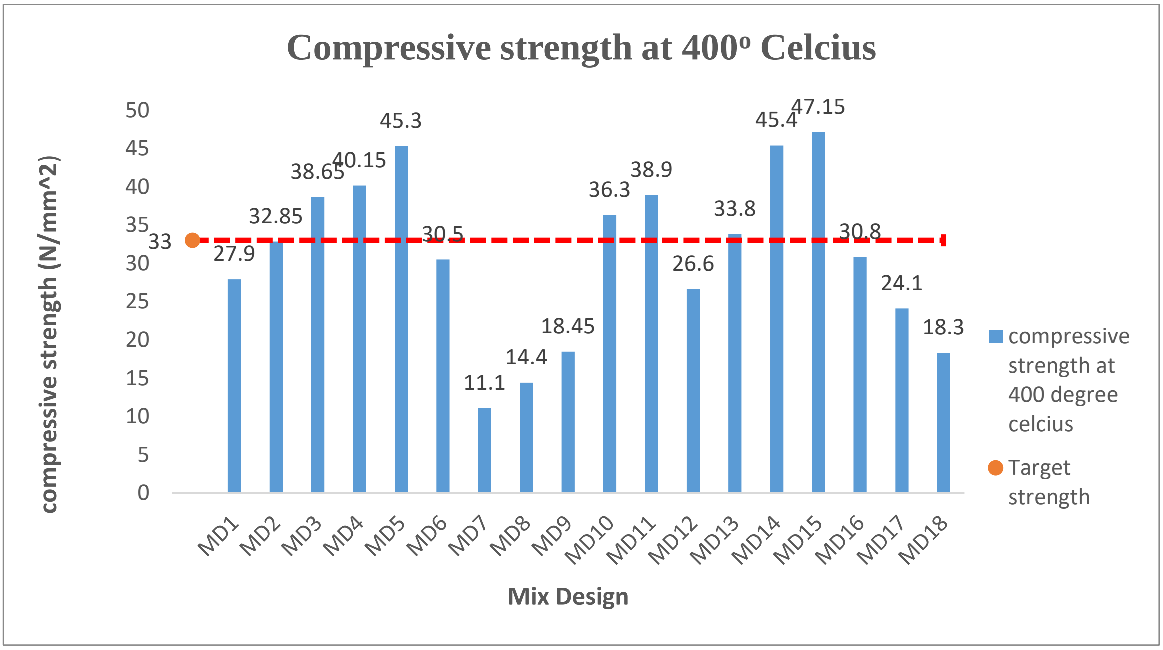
As per mix design the compressive strength is 33 N/mm2 (target strength) for grade M30 after 28 days. The graph depicts the test results strength of all 18 mix designs using the Taguchi approach.

The specimens of geopolymer concrete were subjected to elevated temperature of 200⁰ C for 2 hours. It was observed that MD 7 = 35.8 N/mm^2, followed by MD 6 = 40.8 N/mm^2, providing the best combination of variables for proximity to targeted strength. All other mix designs displayed higher increases in strength when subjected to elevated temperature of 200⁰ C.

Compressive strength of GPC at 400^0 C

Table 5.3.2 : Results of compressive strength of GPC at 400^0 C

Compressive strength at (N/mm^2) 400^0 C			
Mix design	**Compressive strength(N/mm^2)**	**Mix design**	**Compressive strength(N/mm^2)**
MD1	27.9	**MD10**	36.3
MD2	32.85	**MD11**	38.9
MD3	38.65	**MD12**	26.6
MD4	40.15	**MD13**	33.8
MD5	45.3	**MD14**	45.4
MD6	30.5	**MD15**	47.15
MD7	11.1	**MD16**	30.8
MD8	14.4	**MD17**	24.1
MD9	18.45	**MD18**	18.3



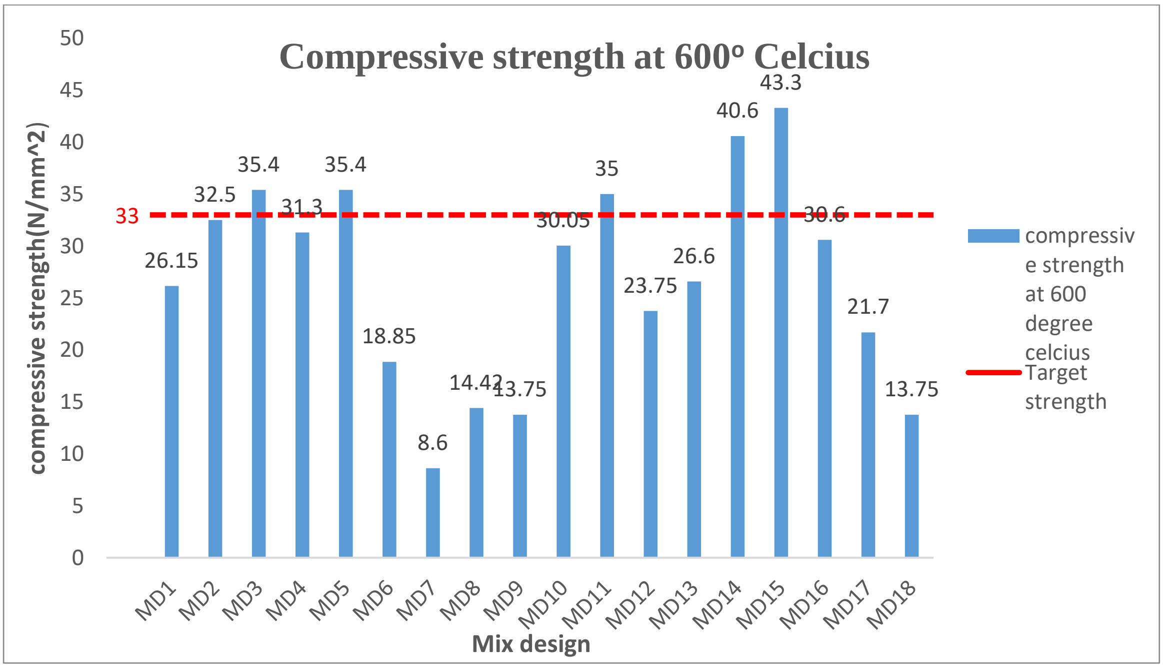
Graph 5.3.3 : Variations of compressive strength at 400^0 C

After subjecting the specimens of GPC to elevated temperature of 400º C for 2 hours, the test results displayed that MD 2 = 32.8 N/mm^2, MD 3=38.65 N/mm^2, MD 13 =33.8 N/mm^2, MD 10 = 36.3 N/mm^2 and MD 11= 38.9 were the best combination of variables for proximity to targeted strength, since these mix designs were capable of withstanding 400^0 C.

Compressive strength of GPC at 600^0 C

Table 5.3.4 : Results of compressive strength of GPC at 600^0 C

Compressive strength at (N/mm^2) 600^0 C			
Mix design	**Compressive strength(N/mm^2)**	**Mix design**	**Compressive strength(N/mm^2)**
MD1	26.15	**MD10**	30.05
MD2	32.5	**MD11**	35
MD3	35.4	**MD12**	23.75
MD4	31.3	**MD13**	26.6
MD5	35.4	**MD14**	40.6
MD6	18.85	**MD15**	43.3
MD7	8.6	**MD16**	30.6
MD8	14.42	**MD17**	21.7
MD9	13.75	**MD18**	13.75



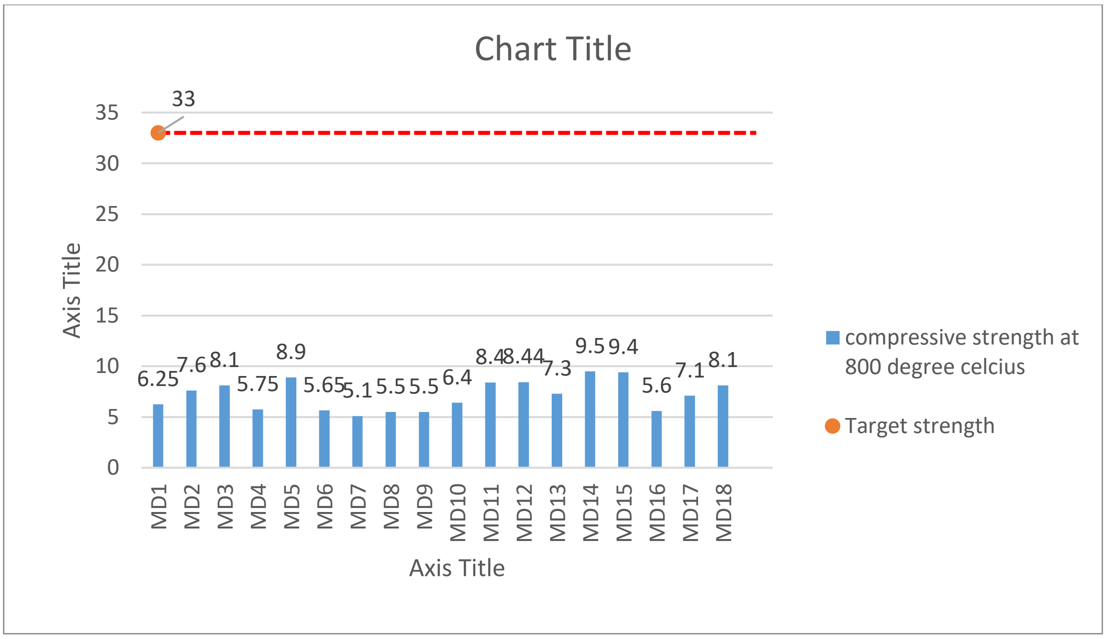
Graph 5.3.5 :Variations of compressive strength at 600^0 C

Subjecting the GPC specimens to 600º C for 2 hours resulted in readings of MD 3 = 35.4 N/mm^2 and MD 5 = 35.4 N/mm^2 having best combination of variables for proximity to targeted strength. These two mix designs (MD 3, MD5) were restrained to 600^0 C since they had the capacity to withstand that elevated temperature. Mix designs 3 and 5 are sufficient for the manufacturing of geopolymer concrete.

Compressive strength of GPC at 800^0 C

Table 5.3.6 : Results of compressive strength of GPC at 800^0 C

Compressive strength at (N/mm^2) 800^0 C			
Mix design	**Compressive strength(N/mm^2)**	**Mix design**	**Compressive strength(N/mm^2)**
MD1	6.25	**MD10**	6.4
MD2	7.6	**MD11**	8.4
MD3	8.1	**MD12**	8.44
MD4	5.75	**MD13**	7.3
MD5	8.9	**MD14**	9.5
MD6	5.65	**MD15**	9.4
MD7	5.1	**MD16**	5.6
MD8	5.5	**MD17**	7.1
MD9	5.5	**MD18**	8.1



Graph 5.3.7 : Variations of compressive strength at 800^0 C

None of the 18 mix designs could withstand an elevated temperature of 800^o C, proving that they are inadequate for use of GPC.

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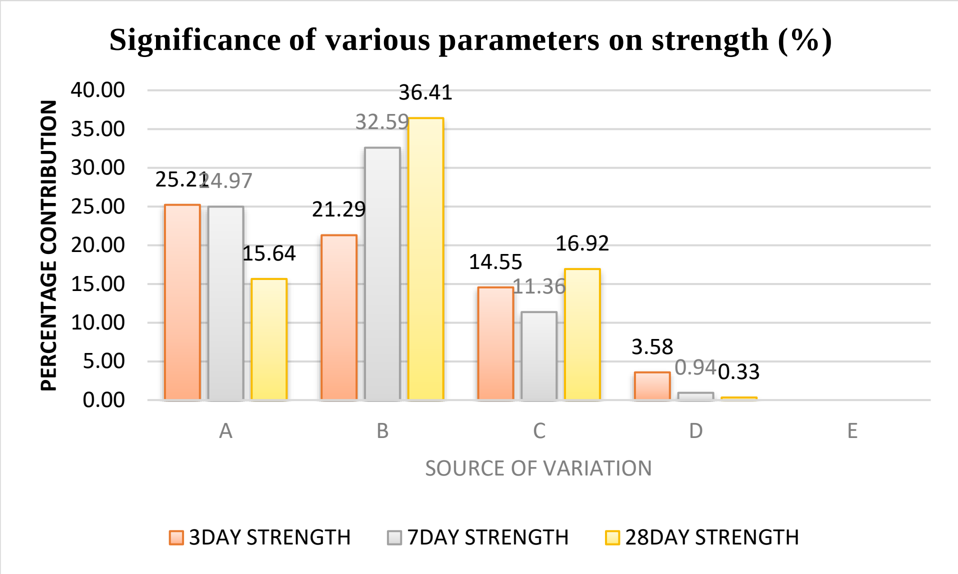

5.3.8 Overall Summary of Individual Parameters

Effect of Parameter A

The effect of binder additive on strength measured after 3, 7 & 28 days is 25.21%, 24.97% and 15.64% respectively. The contribution of GGBS & SCBA in terms of strength is 27.82%, 4.32%, 4.32% and 20.39% at sustained elevated temperatures of 200, 400, 600 and 800° C respectively.

Effect of Parameter B

The ratio of effect of alkali activator to binder content on 3 days, 7 days & 28 days strength is 21.29%, 32.59% and 36.41% respectively. The contribution of parameter B in terms of strength will be 23.34%, 65.76%, 45.83% and 23.10% at sustained elevated temperatures of 200, 400, 600 and 800° C respectively.

Effect of Parameter C

The effect of Molar concentration of solution on 3 days, 7 days & 28 days strength is 14.55%, 11.36% and 16.92% respectively. The contribution of parameter C in terms of strength is 4.67%, 2.31%, 4.81% and 27.68% at sustained elevated temperatures of 200, 400, 600 and 800° C respectively.

Effect of Parameter D

The effect of ratio of sodium hydroxide to sodium silicate solution on 3 days, 7days & 28 days strength will be 3.58%, 0.94% and 0.33% respectively. The contribution of parameter Din terms of strength will be 0.91%, 0.81%, 2.25% and 3.86% at sustained elevated temperatures of 200, 400, 600 and 800° C respectively, indicating that parameter D in mix design calculation is less significant.

Effect of Parameter E

The effect of boric acid in mix design is not significant for either strength or workability but it does not mean that it has no role to play in trial mixes. The workability results for all the trial mixes are in the range of 100 to150 mm.

6. Conclusion

GGBS and baggase-ash-based GPC was optimized using the dynamic Taguchi approach**.** The output results of slump, compaction factor and compresssive strength of the geopolymer concrete obtained under optimized conditions are displayed by graphical representation. It was comfirmed that the geopolymer manufactured under optimum conditions exhibits good compressive strength at ambient temperature. The compressive strength reduces when it is exposed to elevated temperatures. Geopolymer concrete shows good workability with long term strength.

From experimental observation, the following conclusions are derived:

- GPC has been achived by the mixes designed by Taguchi method.

- Among the 7 control factors, AAC/BC, the ratio of NaOH+$NaSiO_3$ and molarity of NaOH have significant effects on the strength of GPC.
- Boric acid has no noteworthy impact on the strength of GPC.
- Taguchi analysis indicated that the optimum measurements for compressive strength of concrete at ambient temperature were obtained from MD 7 = 34.6 N/mm2, MD 6 = 39.5 N/mm2, MD 1 = 40.79 N/mm2, and MD 8 = 40.84 N/mm2, proximate to target strength.
- This investigation proves that MD 6 and MD7 display adequte strength for GPC at 200^0 C.
- The present investigation also displays that MD 2, MD3, MD 13, MD 10 and MD11 have adequte strength for use of geopolymer concrete at 400^0 C.
- MD3 and MD 5 has demonstrate adequate strength for GPC at 600^0 C.
- None of these 18 mix designs could sustain temperature of 800^0 C.
- As the percentage of the GGBS increases the strength increases.
- It has observed as the molarity increases the compressive strength also increases.
- No spalling, cracks or other physical changes are found till 600^0 C.
- From the ANOVA table it is clear that contribution of parameters A, B & C are significant in terms of strength and workability, whereas contribution of parameter E is negligible.

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