Effect of the Main Parameters on the Properties of Geopolymer Concrete

Mahmoud Al-Azab, Mohamed Ragab, Mohamed Kohail, Mona Abdel-Wahab

Abstract— In recent years, geopolymers have received considerable attention because of their environmental benefits. Geopolymer concrete (GPC) utilizes solid industrial aluminosilicate-based waste materials, such as fly ash, rice husk ash, silica fume, or ground granulated blast furnace slag (GGBFS) to produce a low-cost and environmentally friendly material as an alternative to Portland cement. Heat cured GPCs have been studied extensively to establish their properties and it has been found that they are capable of achieving comparable and in some cases better properties than ordinary Portland cement concrete. However, very few attempts to assess the properties of ambient-cured GPC are reported in the literature. This research aims to investigate the fresh and hardened properties of ambient cured GGBFS-Fly ash based geopolymer concrete. Nine mixes (designed by Taguchi method) were carried out with variables GGBFS to fly ash ratio, binder content, sodium silicate (SS) to sodium hydroxide (SH) ratio, and activator molarity. Slump test was conducted to investigate the fresh properties while compressive strength test, splitting test, and flexure test were conducted to investigate the hardened properties. The experimental results revealed that using GGBFS as 100% of binder content could increase the mechanical properties at the expense of workability which can be improved using fly ash as ratio of binder content.

INDEX TERMS— Mechanical properties, Geopolymer concrete, Slag, Fly ash, Ambient curing, Taguchi method.

1. INTRODUCTION

Concrete is the key building material used for construction activities and development projects throughout the world. Portland cement (PC) is ordinarily used as the main binder to produce concrete; however, it is not an enviro-friendly material. The production of Portland cement depletes natural resources and results in the emission of a large amount of greenhouse gases. Recently, increasing demand for PC led to an increase in its production, where the global production of PC exceeds 3 billion tons [1]. Geopolymer concrete (GPC) composed of one or combined aluminosilicate sources and one or combined alkaline activators. The activator solutions produce an environment with a high pH value (e.g. hydroxides, silicates, carbonates or sulfates) [2]. The alkaline activators are necessary to be reacted with the alumino-silicate source to produce cementitious materials. Usually, alkaline salts are utilized as alkaline activators for Alkaline Activated Concrete (AAC). Among of all these activators, sodium hydroxide and sodium silicate are the most widely available chemicals [3], [4]. The fresh properties of GGBFS-Fly ash based geopolymer concrete were investigated by many researchers[5]–[7]. The hardened properties of GGBFS-Fly ash based geopolymer concrete were investigated widely more than fresh properties. Naidu et al. [8] experimented to study strength properties of GPC using low calcium fly ash replacing with slag in 5 different percentages. Sodium silicate (103 kg/m3) and sodium hydroxide of 8 molarity (41kg/m3) solutions were used as alkalis in all 5 different mixes. With maximum (28.57%) replacement of fly ash with slag, achieved a maximum compressive strength of 57 MPa, maximum tensile strength of 11.4 MPa, and maximum flexural strength of 7.06 MPa for 28 days. Madheswaran et al.[9] studied the influence of GGBFS on geopolymer concrete. The types of GPC mixes taken with different molarities of sodium hydroxide solution and GGBFS. The measured compressive strength of geopolymer mix is in the range from 24 MPa to 60 MPa and maximum of 60 MPa for 100% GGBFS and 7M sodium hydroxide solution at 28 days. Rajini et al. [10] studied the effect of class F fly ash and GGBFS on the mechanical properties of GPC at different replacement levels (FA0- GGBFS100, FA25- GGBFS75, FA50- GGBFS50; FA75- GGBFS25, FA100, GGBFS0). The outcome of experiments illustrates that compressive strength and split tensile strength of GPC are maximum of 60.23 MPa and 3.56 MPa for the FA0- GGBFS100 at 28 days irrespective of curing period. The compressive strength and split tensile strength of GPC decrease with increasing FA content in the mix in all cases of curing periods. Krishnaraja et al. [11] studied mix proportions with fly ash partially replaced in the range of 10% to 50% by GGBFS of total binder content and tests were carried on the density, compressive strength and split tensile strength of GPC. It was concluded that replacement of GGBFS in fly ash-based GPC up to 50% produced better compressive strength and tensile strength of 39.23MPa and 4.94 MPa respectively.

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2. EXPERIMENTAL PROGRAM

2.1 Material Properties

2.1.1 Pozzolanic Material

Ground granulated blast furnace slag (GGBFS) and Type F fly ash (FA) with fineness modulus equals 4280 cm2/gm and 4555 cm2/gm respectively, were used as a total replacement of ordinary Portland cement in the concrete mixes. The chemical composition of these materials is shown in Table 1.

Table 1: Chemical Composition of Pozzolanic Materials.

Oxides	CaO	SiO_2	Al_2O_3	MnO	TiO_2	Fe_2O_3	MgO	Na_2O	K_2O	P_2O_5	LOI[a]
GGBFS	34.53	41.66	13.96	0.35	0.58	1.49	5.53	0.49	0.97	0.01	0.05
FA	0.57	62.09	28.08	0.04	2.27	4.54	0.49	0.06	1.05	0.44	<0.01

[a] LOI: Loss on ignition.

2.1.2 Activators

The used activators in this study were a combination of sodium silicate (SS) and sodium hydroxide (SH). Sodium silicate, known as “liquid glass” or “water glass”, is well-known due to wide commercial and industrial application. Sodium silicate products are produced as solids or thick liquids, depending on the desirable proposed use. The chemical composition of the sodium silicate solution used in this study is shown in Table 2.

Table 2: Chemical Composition of Sodium Silicate.

Constituent	Amount (%)
Na_2O	12.00
SiO_3	31.00
Water	57.00

Sodium hydroxide is a white solid, sold in the form of flakes, pellets, and granular, as well as in solution. It’s highly soluble in water; The chemical composition of the sodium hydroxide used in this study is shown in Table 3.

Table 3: Chemical Composition of Sodium Hydroxide.

Constituent	Amount (%)
Na_2O	60.25
Water	39.75

2.1.3 Aggregate

The physical properties of the used aggregate are shown in Table 4.

Table 4: Physical Properties of Aggregate.

Property	Specific gravity	Volumetric weight	% of fine materials	% of water absorption	Chloride ion content (% by weight)	Sulfate content (% by weight)
Fine aggregate	2.62	1.61	2.6	-	0.03	0.21
Coarse aggregate	2.677	1.531	0.7	2.2	0.015	0.18

2.2 Mix Proportions

Nine mixes of GPC with water to binder ratio equals 0.4 (designed by Taguchi method) were carried out with variables GGBFS to FA ratio, binder content, SS to SH ratio, and activator molarity with three levels for each variable chosen after reviewing many studies published in the literature. The mix proportions for 1m3 of concrete are shown in Table 5.

Table 5: Mix proportions of concrete (for $1m^3$).

Mix	GGBFS : FA	Binder (kg/m3)	SS:SH	SH (M)	GGBFS (kg/m3)	FA (kg/m3	Coarse agg.	Fine agg. (kg/m3)	SH (kg/m3	SS (kg/m3
1	100:0	350	2.0	8	350	0	1190	641	46.0	94.0
2	100:0	400	2.5	10	400	0	1120	604	45.7	114.3
3	100:0	450	3.0	12	450	0	1050	566	45.0	135.0
4	80:20	350	2.5	12	280	70	1190	641	40.0	100.0
5	80:20	400	3.0	8	320	80	1120	604	40.0	120.0
6	80:20	450	2.0	10	360	90	1050	566	60.0	120.0
7	60:40	350	3.0	10	210	140	1190	641	35.0	105.0
8	60:40	400	2.0	12	240	160	1120	604	53.3	106.7
9	60:40	450	2.5	8	270	180	1050	566	51.5	128.5

2.3 Testing Procedures

2.3.1 Slump Test

Workability of fresh GPC mixes was measured by slump test according to ASTM C143 [12]. The slump test was carried out immediately after mixing as shown in Figure 1.

Figure 1: The Performed Slump Test.

2.3.2 Compression Test

Three cubic specimens of dimensions 100 mm x 100 mm x 100 mm were prepared for each mix and cured at ambient temperature. The compression test was implemented at the age of 28 days according to ECCS 203 (Appendix 3) [13] using the 200 tons capacity testing machine as shown in *Figure 2*.

Figure 2: The Performed Compression Test

2.3.3 Flexure Test

Three prisms of dimensions 100 mm x 100 mm x 500 mm for each mix were cured at ambient temperature and tested to determine the flexural strength at age of 28 days. The test was conducted according to ECCS 203 (Appendix 3) [13]. The test specimen was supported on a pair of steel roller bearings near each end (300 mm span) while the load was applied to the specimen on its upper surface through a steel bearing roller as shown in *Figure 3*.

Figure 3: The Performed Flexure Test.

2.3.4 Splitting Tensile Strength Test

Three cylindrical specimens with dimensions 200 mm height and 100 mm diameter for each mix were cured at ambient temperature and tested to determine the splitting tensile strength at age of 28 days. The test was conducted according to ECCS 203 (Appendix 3) [13] . As shown in Figure 4, the test specimen was placed between the two jaws of a standard compressive testing machine having its axis horizontal and subjected to compressive line load through two loading bars positioned along the bottom and the top of plane of loading. Failure occurred due to splitting along the loaded diameter predominately under a state of biaxial compression/ tension stresses.

Figure 4: The Performed Splitting Tensile Strength Test.

3. Results and Discussions

3.1 Slump Test Results

Slump test was used to express the workability of all mixes. The slump value for the nine mixes designed using Taguchi method is presented in Figure 5. The highest slump value was 160 mm achieved by mix 9 (GGBFS:FA ratio is 60:40, binder content of 450 Kg/m3, SS:SH of 2.5 and SH (M) of 8). The lowest slump value was 50 mm achieved by mix 1 (GGBFS: FA ratio is 100:0, binder content of 350 Kg/m3, SS:SH of 2.0 and SH (M) of 8). To investigate the main effects of each factor on the slump value, Minitab program was used to calculate the Signal-to-Noise (S/N) ratio of each factor as shown in Figure 6.

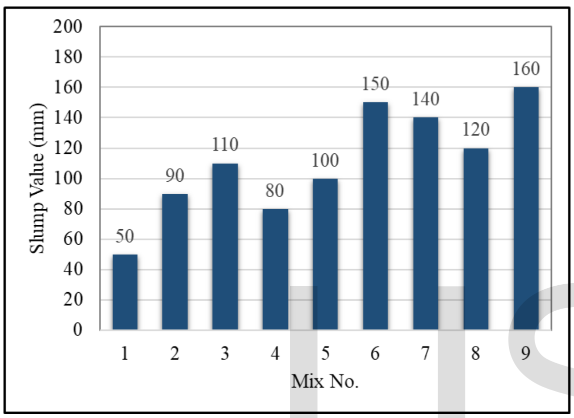

Figure 5: The Slump Value of GPC Mixes

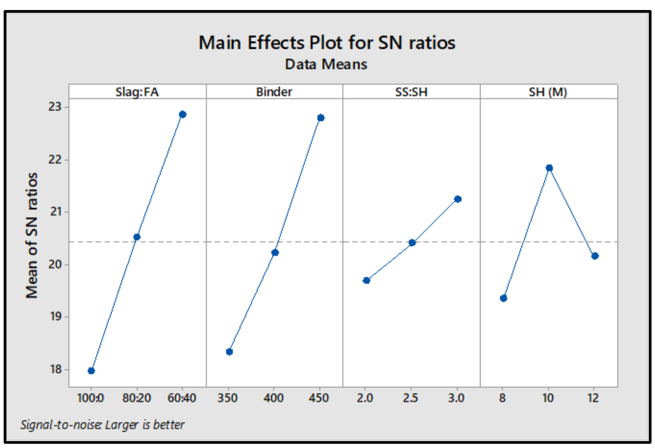

Figure 6: The Significance of Main Factors on the Slump Value of GPC Mixes (Minitab Program)

Figure 6 shows that the binder type (GGBFS: FA) as well as binder content are the most effective factors that affect the workability of GPC mixes where the optimum levels were 60:40 and 450Kg/m3 respectively. This indicates that the presence of GGBFS in the binder decreases the slump value and consequently the workability. This may be explained by the quick reactions of GGBFS with the alkaline solution, which in turn leads to quick setting and low slump value. Therefore, to produce more workable GPC mixes, the percentage of GGBFS in the binder should be decreased. Also increasing the binder content leads to increase the slump value.

3.2 Compressive Strength Results

The compressive strength results for the nine mixes designed using Taguchi method are presented in Figure *7*. The highest compressive strength after 28 days (fc28) was 48.7 MPa achieved by mix 8 (GGBFS: FA ratio is 60:40, binder content of 400 Kg/m3, SS:SH of 2.0 and SH (M) of 12) . The lowest fc28 was 28.7 MPa achieved by mix 7 (GGBFS: FA ratio is 60:40, binder content of 350 Kg/m3, SS:SH of 3.0 and SH (M) of 10). To investigate the main effects of each factor on the compressive strength value, Minitab program was used to calculate the Signal-to-Noise (S/N) ratio of each factor as shown in Figure *8*.

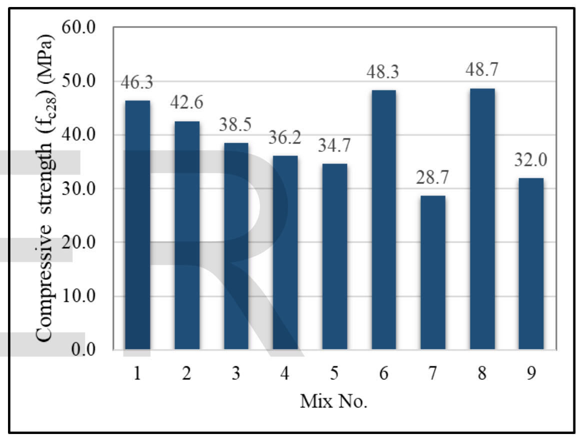

Figure 7: Compressive Strength of GPC Mixes

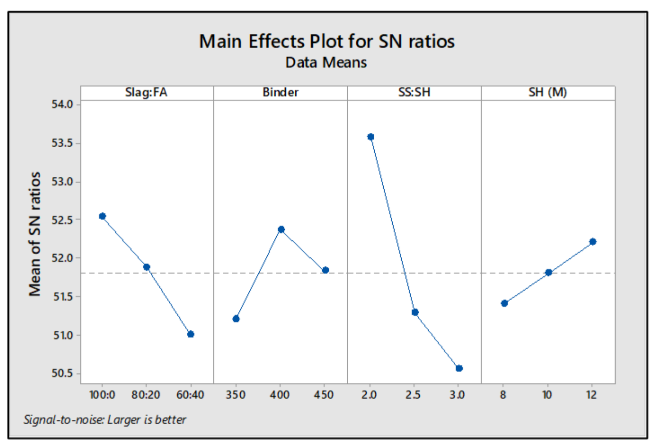

Figure 8: The Significance of Main Factors on the f_{c28} of GPC Mixes (Minitab Program)

Figure *8* shows that the ratio between activators (SS:SH) is the most significant factor that affects f_{c28} of GPC mixes. The level of 2.0 is the optimum level. It can be observed that increase SH content has great effect in enhancing the compressive strength due to increasing the concentration of the alkaline solution in the GPC mix which in turn increases the hydration products and hence the compressive strength. Noting that increase the GGBFS:FA ratio increases the compressive strength, and this may be explained by the quick reactions of GGBFS with the alkaline solution.

3.3 Flexural Strength Results

The flexural strength results for the nine mixes designed using Taguchi method are presented in Figure 9. The highest flexural strength after 28 days (fb28) was 4.0 MPa achieved by mix 1 (GGBFS: FA ratio is 100:0, binder content of 350 Kg/m3, SS:SH of 2.0 and SH (M) of 8). The lowest fb28 was 1.3 MPa achieved by mix 7 (GGBFS: FA ratio is 60:40, binder content of 350 Kg/m3, SS:SH of 3.0 and SH (M) of 10). To investigate the main effects of each factor on the flexural strength value, Minitab program was used to calculate the Signal-to-Noise (S/N) ratio of each factor as shown in Figure 10.

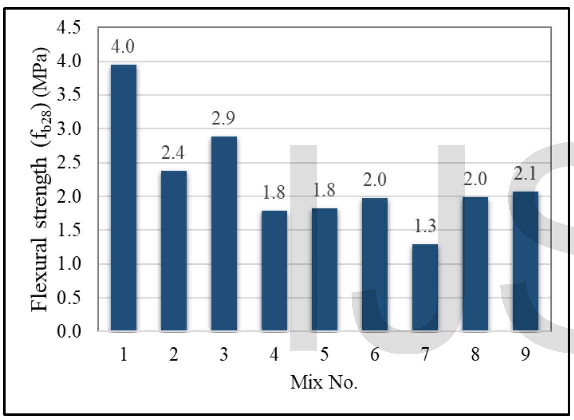

Figure 9: Flexural Strength of GPC Mixes

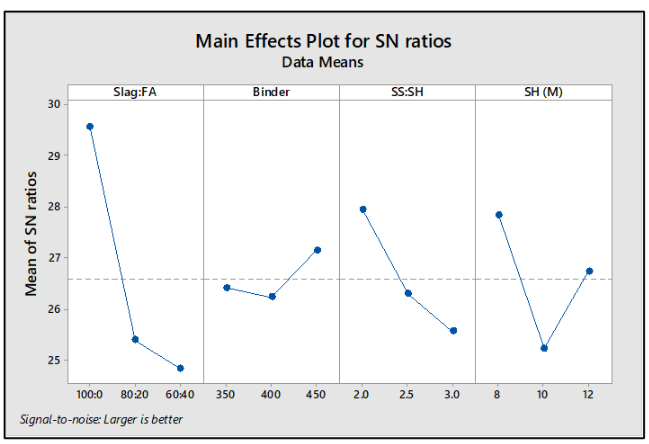

Figure 10: The Significance of Main Factors on the f_{b28} of GPC Mixes (Minitab Program)

As shown in Figure *10* the most effective factor affecting f_{b28} is the ratio between GGBFS:FA with optimum level 100:0 which in turn increases the hydration rate explained by the quick reactions of GGBFS with the alkaline solution. It is noticed that increasing SS content leads to increase workability and getting minimum voids that increase the tensile strength.

3.4 Splitting Tensile Strength Results

The splitting tensile strength results for the nine mixes designed using Taguchi method are presented in Figure 11. The highest splitting tensile strength after 28 days (ft28) was 5.2 MPa achieved by mix 1(GGBFS: FA ratio is 100:0, binder content of 350 Kg/m3, SS:SH of 2.0 and SH (M) of 8). The lowest ft28 was 2.0 MPa achieved by mix 7 (GGBFS: FA ratio is 60:40, binder content of 350 Kg/m3, SS:SH of 3.0 and SH (M) of 10). To investigate the main effects of each factor on the splitting tensile strength value, Minitab program was used to calculate the Signal-to-Noise (S/N) ratio of each factor as shown in Figure 12.

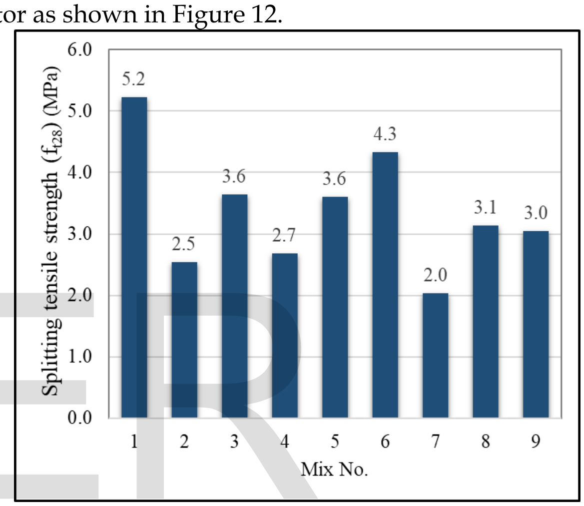

Figure 11: Splitting Tensile Strength of GPC Mixes

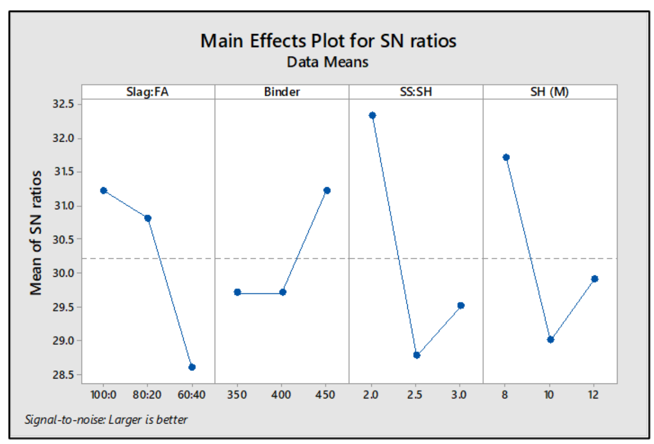

Figure 12: The Significance of Main Factors on t the f_{t28} of GPC Mixes (Minitab Program)

As shown in Figure *12* the factors that affect f_{t28} are like that affect f_{b28} due to similar reasons most notably is the ratio between SS:SH with the optimum level of 2.0.

4. Conclusions

Based on the results of this experimental study, the following can be concluded:

- Increasing the amount of GGBFS at the expense of Fly ash in the binder decreases the slump value and consequently the workability of GPC. Also increasing the binder content leads to increase the slump value.
- Increase the sodium hydroxide content has significant effect in enhancing the compressive strength of GPC noting that increasing the GGBFS: Fly ash ratio increases the compressive strength as well.
- Using GGBFS as 100% of binder content could increase compressive strength, flexural strength and splitting tensile strength at the expense of workability which can be improved using fly ash as ratio of binder content.

5. References

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