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Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method

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Keywords

method, condition, design, geopolymer, concrete, ggbfs, ambient, taguchi, curing

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Design of Geopolymer Concrete with GGBFS at Ambient Curing Condition Using Taguchi Method

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Abstract

In this paper, the Taguchi method has been used to design optimum mix proportions for geopolymer concrete with ground granulated blast furnace slag (GGBFS) as aluminosilicate source at ambient curing condition. The influences of binder content, alkaline activator to binder content (Al/Bi) ratio, sodium silicate to sodium hydroxide (SS/SH) ratio, and sodium hydroxide (SH) concentration on the geopolymer concrete were investigated. A total of nine mix designs were evaluated. It was found that specimens with a binder content of 450 kg/m^3, Al/Bi ratio of 0.35, SS/SH ratio of 2.5, and SH concentration of 14 M produced the highest 7-day compressive strength (60.4 MPa). However, the setting time was found to be short. Hence, fly ash (FA), metakaolin (MK), and silica fume (SF) were used as partial replacement of GGBFS in different proportions to increase the setting time. It was found that the setting time improved for the partial replacement of GGBFS with FA, MK, and SF.

Keywords: Geopolymer, Taguchi method, Compressive strength, Setting time

Highlights

- Geopolymer concrete with GGBFS has been produced at ambient curing condition
- GGBFS improved early strength development of geopolymer concrete
- Compressive strength reduced for partial replacement of GGBFS with FA, MK, and SF
- Setting time increased for partial replacement of GGBFS with FA, MK, and SF
- Workability increased for partial replacement of GGBFS with FA, MK, and SF

1. Introduction

Climate change due to global warming is a critical environmental issue having considerable negative impacts on all living organisms in this world. Global warming is caused by greenhouse gas emissions including the emission of methane, nitrous oxide, and carbon dioxide into the atmosphere. It was reported that globally the production of cement contributed to about 5 to 7% of total carbon dioxide (CO_2) emission into the atmosphere [1].

In 2013, the production of cement in Australia contributed to the emission of 36 billion tonnes of CO_2 [2]. It is estimated that the production of one tonne of Ordinary Portland Cement (OPC) releases about one tonne of CO_2 into the atmosphere [3, 4]. The consumption of cement in the world for 2014 was 3.7 billion metric tonnes [5]. Considering an annual growth of 4%, the consumption of cement by 2020 will be 4.7 billion metric tonnes. Hence, the development of green concrete without OPC has become important. Research investigations on geopolymer concrete [6, 7] and alkali activated concrete [8-11] as an alternative for OPC concrete started a few decades ago and have recently gained popularity as construction materials. This paper deals only with geopolymer concrete.

Geopolymer concrete does not contain any OPC and hence it is considered as green concrete. Geopolymer concrete is proven to have good mechanical properties with reduced greenhouse gas emissions [5]. It not only reduces the carbon footprint compared to OPC but also uses a large amount of industrial waste material such as slag, fly ash, and silica fume [5].

There are two main components in geopolymer concrete: an alkaline activator and the source of aluminosilicate materials. The most common alkaline activator is a combination of sodium silicate and sodium hydroxide. However, potassium silicate and potassium hydroxide can also be used. The alkaline activator plays an important role in the polymerization process

[12]. The source materials of the binder used in geopolymer concrete depend on the source of the aluminosilicate. These aluminosilicate materials must be rich in aluminate (Al) and silicate (Si). These aluminosilicate materials can be a by-product material such as slag [13], fly ash [14-16], and silica fume [17]. In addition, the aluminosilicate can be obtained from natural sources including clay and metakaolin [18]. The choice of source material for the production of geopolymer concrete depends on several factors including cost, availability, and application [19].

Most of the previous studies use heat to cure geopolymer concrete; as such its use is limited to precast concrete members. Geopolymer concrete in ambient curing condition will have wider applications in situ construction as well as in precast construction. Ambient curing conditions will reduce the energy and cost associated with the heat curing process.

The setting time, workability, and compressive strength of geopolymer concrete and paste were investigated in the available literature. Rao and Rao [20] investigated the final setting time and compressive strength of geopolymer mortar. The main aluminosilicate source material (Class F) fly ash was partially replaced with a ground-granulated blast furnace slag, and the alkaline activator was a mixture of sodium silicate with sodium hydroxide solution. It was found that the final setting time was significantly reduced when the fly ash was replaced by GGBFS. In another study, Lee and Lee [21] investigated the setting time and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature. The test results showed that the setting times of the alkali-activated fly ash/slag paste decreased as the amount of slag and the concentration of the SH solution increased. Nath and Sarker [22] investigated the workability and compressive strength of fly ash-based geopolymer concrete. It was found that workability was significantly reduced and compressive strength of fly ash-based geopolymer concrete was increased when GGBFS was used as a small proportion of the binder.

A large number of studies were conducted on geopolymer concrete, but there is still no consensus on the influence of different parameters on the properties (e.g., compressive strength and workability) of geopolymer concrete. The main parameters which influence the properties of geopolymer concrete include aluminosilicate source, curing conditions, type of alkaline activator, combination and concentration of the activator, and the alkaline activator to binder ratio [23]. It might be difficult to investigate the influence of all the parameters in a single investigation. However, through a well-designed experimental program, the parameters which influence the proportion of geopolymer concrete can be adequately investigated [23]. The well-known Taguchi method [24] can be used for this purpose.

The Taguchi method is a fractional factorial design method which uses a special set of arrays called orthogonal arrays (OA) for the design of experiments to investigate a large number of variables with a small number of experiments. The design of experiments using OA is quite efficient compared to traditional experiment design methods [25]. The OA reduce the number of experiments and minimize uncontrollable parameters [25]. For instance, when using four parameters at three proportions, the traditional factorial design needs 3^4 or 81 test runs, while the Taguchi method requires only 9 test runs. The Taguchi method uses a signal-to-noise (S/N) ratio for optimization. The S/N ratio helps in data analysis and prediction of optimum result. In effect, OA provides a set of well-balanced experiments and S/N ratio serves as objective function for optimization. The main advantages of the Taguchi methods are the efficiency, cost effectiveness, robustness, and ease of interpretation of the output.

The Taguchi method has been widely used in other engineering applications, but the application of the Taguchi method to geopolymer concrete is very limited [26-28]. Riahi et al.

[26] investigated the 2- and 7-day compressive strength of fly ash-based geopolymer concrete designed using the Taguchi method. They investigated the effects of SH concentration and curing condition on the compressive strength using the Taguchi method. Olivia et al. [27] designed nine geopolymer concrete mixes by considering the effects of aggregate content, sodium silicate to sodium hydroxide ratio, alkaline activator to fly ash ratio, and curing method. It was reported that the Taguchi method could be used to optimize the components of the geopolymer concrete mix. Khalaj et al. [28] found that split tensile strength of Portland cement-based geopolymers could be suitably designed using the Taguchi method.

The aim of this study is to propose an optimum mix proportion for geopolymer concrete by considering most influencing parameters resulting in high compressive strength and desirable workability at ambient curing condition by using the Taguchi method. The aim of the paper is achieved through extensive experimental investigations. The development of a mathematical model taking into account all the influential parameters is considered beyond the scope of the paper.

2. Experimental details

2.1 Materials

The materials used for geopolymer concrete in this study were ground granulated blast furnace slag (GGBFS), silica fume (SF), fly ash (FA), and metakaolin (MK). The GGBFS and SF were supplied by the Australian (Iron & Steel) Slag Association [29]. The FA classified as class F according to ASTM C618-08 [30], which was supplied by Eraring Power Station Australia [31]. The MK was supplied by Calix Australia [32]. The chemical compositions of GGBS, FA, and MK have been shown in Table 1.

Coarse aggregate with a maximum aggregate size of 10 mm and the river sand as the fine aggregate were used in this study. Sodium silicate solution blended with sodium hydroxide was used as an alkaline activator. Caustic soda (NaOH) was dissolved in potable water to produce sodium hydroxide solution with different concentrations. Sodium silicate solution (Na_2SiO_3) (Grade D) was supplied by PQ Australia [33]. The dry density of the sodium silicate solution was 1.53 g/cm^3. The sodium silicate solution (Na_2SiO_3) includes 14.7% sodium oxide, 29.4% silicate and 44.1% solids. High range water reducers (commercially available Glenium 8700) supplied by BASF Australia [34] were used to improve the workability of the geopolymer concrete.

2.2 Optimum mix design of geopolymer concrete

In this study, the Taguchi method [24] was used to explore the optimal mix design of geopolymer concrete in order to maximize the compressive strength at ambient curing condition. The Taguchi experimental design was performed by Qualitek-4 [35]. The main aim was to determine the optimal mix design to produce high strength geopolymer concrete considering the parameters that influence the compressive strength.

Four main parameters, including binder contents (400, 450, and 500 kg/m^3), Al/Bi ratio (0.35, 0.45, and 0.55), SS/SH (1.5, 2, and 2.5), and SH concentration (10, 12, and 14 M) were considered in the mix design (Table 2). A total of 9 trial mixes were prepared depending on L9 array obtained using the Taguchi method [24]. The component parameters are given for each trial mix (TM1-TM9) in Tables 3 and 4. The ratio of H_2O/Na_2O was kept constant at 12.5 in order to obtain geopolymer concrete with good workability [12]. The compressive strengths obtained from the trial mixes of geopolymer concrete were used in calculating the response index for each trial mix based on the signal-to- noise (S/N) ratio [36]. The response index for each parameter was determined by taking the average of the 7-day compressive strengths for the trial mixes which included the considered parameter. For example, parameter Al/Bi ratio of 0.35 was tested in three trials mixes: TM1, TM4, and TM7 (Table 3). The compressive strength of trial mixes TM1, TM4, and TM7 was 40.89, 56.05, and 52.23, respectively (Table 5). The response index for trial mixes TM1, TM4, and TM7 was equal to ((40.89+56.05+52.23)/3=49.72), which was greater than the response index for Al/Bi ratio of 0.45 and 0.55 (Fig. 3). Hence, the optimum Al/Bi ratio was 0.35. Finally, the results were evaluated by analyses of variable (ANOVA) to determine the optimum proportion, based on S/N ratio, of each parameter.

2.3 Specimens preparation and testing

Geopolymer concrete specimens were prepared by mixing the dry material (slag, coarse aggregate, and sand) in a pan mixer. Afterwards, alkaline activators (SS/SH) were added to the dry mix. Finally, water and superplasticizer were added. The procedure of the mixing geopolymer concrete implemented in this study was similar to that adopted in Rangan [3]. It should be noted that the mixing procedure may affect the compressive strength and workability of the geopolymer concrete. The dry materials were mixed for about 1 minute and then half of the amount of alkaline activator was added into the pan and mixed for about 2 minutes. The remaining amount of alkaline activator with water and superplasticizer were poured into the pan mixer and mixed for approximately 2 minutes until the mixture became well combined and homogeneous.

In this study, polyvinyl chloride (PVC) moulds of 200 mm length and 100 mm diameter (200 x 100 mm) were used for casting concrete to measure the compressive strength. The specimens were cast in three layers of geopolymer concrete and each layer was vibrated for

10 seconds. The specimens were left in the laboratory at an ambient condition for 24 hours. The specimens were then removed from the moulds and left in an ambient condition.

The compressive strength was measured according to Australian Standard (AS 1012.9-1999) [37] using W&T 1800 testing machine. The tests were carried out on three specimens for each mix on the 7th and the 28th day and average strengths are reported in Table 5.

The setting time of the geopolymer concrete was evaluated by partially replacing GGBFS with different proportions of FA, MK, and SF. The initial and final setting times reported in this study are the initial and final setting times of geopolymer paste without the coarse and fine aggregate. The initial setting time was measured from the start of the mixing to the time when the needle penetrates to a point 5 mm from the bottom of the base plate mould. The final setting time was measured from the start of the mixing to the time when the needle only makes an impression on the past surface.

The setting time of the geopolymer concrete was obtained by penetration resistance measurements according to ASTM C 191-08 [38]. Setting time tests were conducted under an ambient temperature of 25±2°C**.** The workability of fresh geopolymer concrete was measured by slump tests according to AS 1012.3.1[39]. The slump tests were conducted immediately after mixing at ambient conditions**.**

3. Results and discussion

3.1. Optimum components for geopolymer concrete with GGBFS

Compressive strength was used as the evaluation criterion for the 9 trial mixes (TM1-TM9) according to the Taguchi method, as shown in Fig. 1. The highest compressive strength was obtained by TM4 specimens with a binder content of 450 kg/m^3, Al/Bi ratio 0.35, SS/SH ratio of 2, and SH concentration of 14 M. The lowest compressive strength was obtained by TM9 specimens with a binder content of 500 kg/m^3, Al/Bi ratio 0.55, SS/SH ratio of 2, and SH concentration of 10 M. It is noted that SS/SH ratio for both mixes was 2.

The main differences between TM4 and TM9 is the binder content, Al/Bi ratio, and SH concentration. The effect of SH concentration on the compressive strength of the geopolymer concrete has not been completely agreed on by the researchers. Some of the studies showed that the high concentration of SH led to an increased compressive strength [40], but some other studies showed increase in the SH concentration led to lower compressive strength [41]. It can be seen in Fig. 2 that the compressive strength of the geopolymer concrete increased with increases in the SH concentration. It appears that there is a strong relationship between the aluminosilicate sources and SH concentration. The increase in the SH concentration dissolves the initial solid more and consequently increases geopolymerization reaction, which helps in achieving higher compressive strength [42]. It is considered that for geopolymer with GGBFS as the aluminosilicate source, SH concentration of 14 M might have the best effect on increasing the strength.

The compressive strength of the geopolymer concrete is also significantly influenced by Al/Bi ratio. In this study, specimens TM1, TM4, and TM7 achieved 7-day compressive strengths of 40.89, 56.05, and 52.23 MPa, respectively. These high compressive strengths showed that one of the main parameters affecting the geopolymer specimens is Al/Bi ratio. The increase in the Al/Bi ratio resulted in a decrease in compressive strength. The reason for this decrease in compressive strength can be attributed to the higher AL/Bi ratio of the mixture. Excess alkaline activator caused an increase in the amount of water in the mixture which hindered geopolymerization [43].

In particular, an increase in the Al/Bi ratio from 0.35 (TM4) to 0.55 (TM3) with the same SH concentration (14 M) resulted in a significant reduction in the 7-day compressive strength from 56.05 MPa (TM4) to 36.94 MPa (TM3) (Table 5). Based on the results obtained in this study it can be concluded that the influence of Al/Bi ratio on the compressive strength gain was significant. This is clearly demonstrated by the fact that for the same Al/Bi ratio, the compressive strength varied, depending primarily on the alkaline activator concentration as well as on the blend of binder.

One of the other parameters affecting the strength of geopolymer is binder content. Based on the test results obtained, it can be observed from Fig. 2 that with the increase in the binder content from 400 kg/m^3 to 450 kg/m^3, the compressive strength of the geopolymer concrete increased. However, the compressive strength decreased with the increase in the binder content beyond 450 kg/m^3.

Based on the above discussion, it is difficult to ascertain the optimum proportions for each considered parameter. Factorial analysis was conducted using Qualitek-4 [35] to investigate the effects of each parameter on the compressive strength of the geopolymer concrete. Factorial diagrams and the significance of the main parameters that affect the compressive strength have been shown in Figure 2 and Figure 3, respectively. The percentage of participation of each parameter and the optimum level of the considered parameters on the compressive strength is shown in Table 6.

Fig. 3 and Table 6 show that the Al/Bi ratio is the most significant parameter that influences the geopolymer concrete with a percentage of participation of 71.23% and Al/Bi of 0.35 as the optimum level. This indicates that the lower ratio of Al/Bi could produce higher compressive strength of geopolymer concrete (Fig. 2).

It can also be observed that the second influential parameter is the SH concentration with a percentage of participation of 11.66%. Table 6 shows that the SH concentration of 14 M is the optimum level. This indicates that a high concentration of SH produces high compressive strength of geopolymer concrete (Fig. 2).

The third influential parameter is the binder content with a percentage of participation of 10.09%. Table 6 shows that the binder content of 450 kg/m^3 is the optimum level, which indicates that binder content of 450 kg/m^3 produces high compressive strength of geopolymer concrete (Fig. 2). The SS/SH ratio has the lowest percentage of participation of 7.10%. Table 6 illustrates that SS/SH ratio of 2.5 is the optimum level. This indicates that a high ratio of SS/SH could produces high compressive strength of geopolymer concrete (Fig. 2).

Finally, TM10 mix was prepared and tested according to the optimum levels presented in Table 6, i.e., a binder content of 450 kg/m^3, Al/Bi ratio of 0.35, SS/SH of 2.5, and SH concentration of 14 M. The average of compressive strength of the TM10 was 60.4 MPa on the 7th day, which was greater than the compressive strengths obtained from the nine previous trial mixes (TM1-TM9). However, the setting time was found to be short. The initial and final setting times of the TM10 specimens were 25 minutes and 55 minutes, respectively. Such fast setting time behaviour may not be convenient for geopolymer concrete in conventional construction. Hence, FA, MK, and SF were used as partial replacements of GGBFS in different proportions to increase the setting time.

3.2 Effect of FA, MK, and SF on the setting time and workability of geopolymer concrete with GGBFS

Fig. 4 shows the setting time of the specimens by partially replacing GGBFS in TM10 with different proportion of FA, MK, and SF. Replacement of GGBFS with FA, MK, and SF ranged from 10% to 60%.

The initial setting time of the different mixes considered in this investigation varied from 25 to 75 minutes and the final setting time varied from 55 to 105 minutes. It was found that increase in the partial replacement of GGBFS with FA, MK, and SF resulted in increased initial and final setting times. When 60% of GGBFS were replaced with FA, the initial setting time increased from 25 minutes to 75 minutes and the final setting time increased from 55 minutes to 105 minutes. It was also observed that by replacing 60% of GGBFS with MK, the initial setting time increased from 25 minutes to 55 minutes and the final setting time increased from 55 minutes to 90 minutes. Finally, replacing 60% of GGBFS with SF, the initial setting time increased from 25 minutes to 70 minutes and the final setting time increased from 55 minutes to 100 minutes. From the test data, it can be seen that the GGBFS quickly reacts with alkaline activator compared to FA, MK, and SF. Thus, the setting time of geopolymer paste with GGBFS is shorter than the setting time with other pozzolanic materials. The reason for the short setting time can be attributed to the higher calcium content present in GGBFS (Table 1). The presence of high calcium content in GGBFS results in an increase in the reactivity of the geopolymer by forming an amorphously structured Ca-Al-Si gel. From the test data, it can be observed that the setting time has significantly increased when the GGBFS is partially replaced by FA, MK, and SF.

Fig. 5. shows the effect of partial replacement of GGBFS with different proportion of FA, MK, and SF on workability. The results were compared with the control geopolymer mixture TM10. It can be observed from Figure 5 that the slump of geopolymer concrete was influenced by the inclusion of FA, MK, and SF in the binder. The control geopolymer

mixture TM10, which contains 100% GGBFS, showed the lowest slump. The slump increased with the increase of FA, MK, and SF in the mixture. The effect was more significant at a higher ratio of FA, MK, and SF content. The trend was almost similar for all replacement ratios but more significant with 60% FA and SF. The reason for the increased slump of the mixtures is most likely due to the increased mobility of spherical shaped FA and SF in contrast to irregular shaped slag particles.

Thus, it can be concluded that to have a required value of setting time and workability a convenient combination of GGBFS and FA can be a promising option of geopolymer concrete.

3.3 Effect of FA, MK, and SF on the compressive strength of geopolymer concrete with GGBFS

The compressive strength of geopolymer concrete with different proportions of FA, MK, and SF as partial replacement of GGBFS is shown in Table 8 and Fig. 6. It was found that the compressive strength of geopolymer concrete decreased for partial replacement of GGBFS with FA, MK, and SF under ambient curing conditions. The geopolymer concrete with GGBFS has been shown to achieve a compressive strength of 60.4 MPa on the 7th day.

For a replacement of 60% GGBFS with FA, 41% decrease in the compressive strength of the geopolymer concrete was observed. In addition, by replacing 60% GGBFS with MK and SF, the decreases in compressive strength of geopolymer concrete were 58% and 52%, respectively. The reason for the decrease in compressive strength can be attributed to the decrease in the intensity of the calcium content when the amount of GGBFS was decreased in the mix. The decrease in calcium content in the mix results in a delay in the polymerization reaction and the formation of an amorphously structured Ca-Al-Si gel was hindered. Hence, slag based geopolymer modified with FA can be considered as a suitable binder for geopolymer concrete under ambient curing conditions for reasonably high compressive strength and adequate setting time.

4. Conclusion

Based on the experimental program presented in this study, following conclusions can be drawn:

1. The geopolymer concrete with a binder content of 450 kg/m^3, Al/Bi ratio of 0.35, SS/SH ratio of 2.5, and SH concentration of 14 M achieved the highest 7-day compressive strength (60.4 MPa) at ambient curing conditions.

2. The inclusion of FA, MK, and SF as partial replacement of GGBFS reduces the compressive strength of geopolymer concrete.

3. Replacement of the GGBFS with FA, MK, and SF increases the initial and final setting time of the geopolymer paste and increases the slump of the fresh concrete as well.

4. To increase the setting time of geopolymer concrete under ambient curing conditions, a combination of GGBFS with FA can be a possible solution, as the blend of GGBFS with FA achieved longer setting time compared with the blend of GGBFS with MK and SF.

5. The inclusion of FA in the GGBFS-based geopolymer mixture is found to be a suitable binder of geopolymer concrete for in situ construction, in addition to the precast construction, under ambient curing conditions, thus eliminating the necessity for heat curing.

Finally, the information presented in this study will be beneficial in the design of geopolymer concrete at ambient curing conditions in order to enhance the durability of geopolymer concrete and, in particular, to enhance its mechanical properties. In addition, the data presented in this paper will also be valuable in the selection and application of appropriate testing methods for the geopolymer concrete under ambient curing condition.

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Table 1

Chemical compositions (mass %) for GGBS [29], FA [31], SF [29], and MK [32].

Component	GGBS	FA	SF	MK
SiO_2	32.40	62.2	85.76	52.21
Al_2O_3	14.96	27.5	1.89	44.08
Fe_2O_3	0.83	3.92	0.56	-
CaO	40.70	2.27	0.92	1.69
MgO	5.99	1.05	0.81	-
K_2O	0.29	1.24	0.86	-
Na_2O	0.42	0.52	0.74	-
TiO_2	0.84	0.16	-	0.18
P_2O_5	0.38	0.30	-	-
Mn_2O_3	0.40	0.09	-	-
SO_3	2.74	-	0.3	-
LOI	NA	-	4.0	-

LOI: Loss of ignition

Table 2

Parameters and proportions used in the Taguchi experiment design.

Parameters	Proportion 1	Proportion 2	Proportion 3
Binder content (kg/m^3)	400	450	500
Al/Binder	0.35	0.45	0.55
SS/SH	1.5	2.0	2.5
SH (M)	10	12	14

Table 3

Parameters and values used in geopolymer concrete trial mixes.

Experiment series	Binder content (kg/m^3)	Al/Binder	SS/SH	SH (M)
TM1	400	0.35	1.5	10
TM2	400	0.45	2	12
TM3	400	0.55	2.5	14
TM4	450	0.35	2	14
TM5	450	0.45	2.5	10
TM6	450	0.55	1.5	12
TM7	500	0.35	2.5	12
TM8	500	0.45	1.5	14
TM9	500	0.55	2	10

Table 4

Mix proportions of trial mixes.

Mix	TM1	TM2	TM3	TM4	TM5	TM6	TM7	TM8	TM9
GGBS (kg/m^3)	400	400	400	450	450	450	500	500	500
Al/Bi	0.35	0.45	0.55	0.35	0.45	0.55	0.35	0.45	0.55
SS/SH	1.5	2	2.5	2	2.5	1.5	2.5	1.5	2
SS(kg/m^3)	84	120	157	105	145	149	125	135	183
SH (kg/m^3)	56	60	63	53	58	99	50	90	92
SH (M)	10	12	14	14	10	12	12	14	10
Superplasticizer (kg/m^3)	20	20	20	22.5	22.5	22.5	25	25	25
Water (kg/m^3)	48	48	48	54	54	54	60	60	60
Aggregate (kg/m^3)	1208	1182	1156	1161	1132	1102	1115	1082	1050
Sand (kg/m^3)	650	636	622	625	609	594	600	583	565
H_2O/Na_2O	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5

Table 5

Compressive strength of trial mixes of geopolymer concrete under ambient curing condition.

Trial mix	Compressive strength (MPa)	
	7 days	28 days
TM1	40.89	46.75
TM2	38.47	38.98
TM3	36.94	42.55
TM4	56.05	61.15
TM5	41.40	42.24
TM6	35.03	37.32
TM7	52.23	59.50
TM8	40.13	42.93
TM9	32.61	34.40

Table 6

Percentage of participation and Optimum levels of the considered parameters on the 7-day compressive strength.

Parameter	GGBFS Content	Al/Bi	SS/SH	SH
Percentage of participation (%)	10.09	71.23	7.01	11.66
Optimum Level	450 (kg/m^3)	0.35	2.5	14 (M)

Table 7

Changes in the compressive strength of geopolymer concrete for the partial replacement of GGBFS with FA, MK, and SF.

Replacing percentage (%)	7-day compressive strength (MPa)		
	FA	MK	SF
0	60.38	60.38	60.38
10	58.55	40.03	42.16
20	56.34	34.21	36.10
30	49.20	28.14	32.12
40	42.68	26.75	30.41
50	40.82	25.78	29.55
60	35.41	25.36	28.98

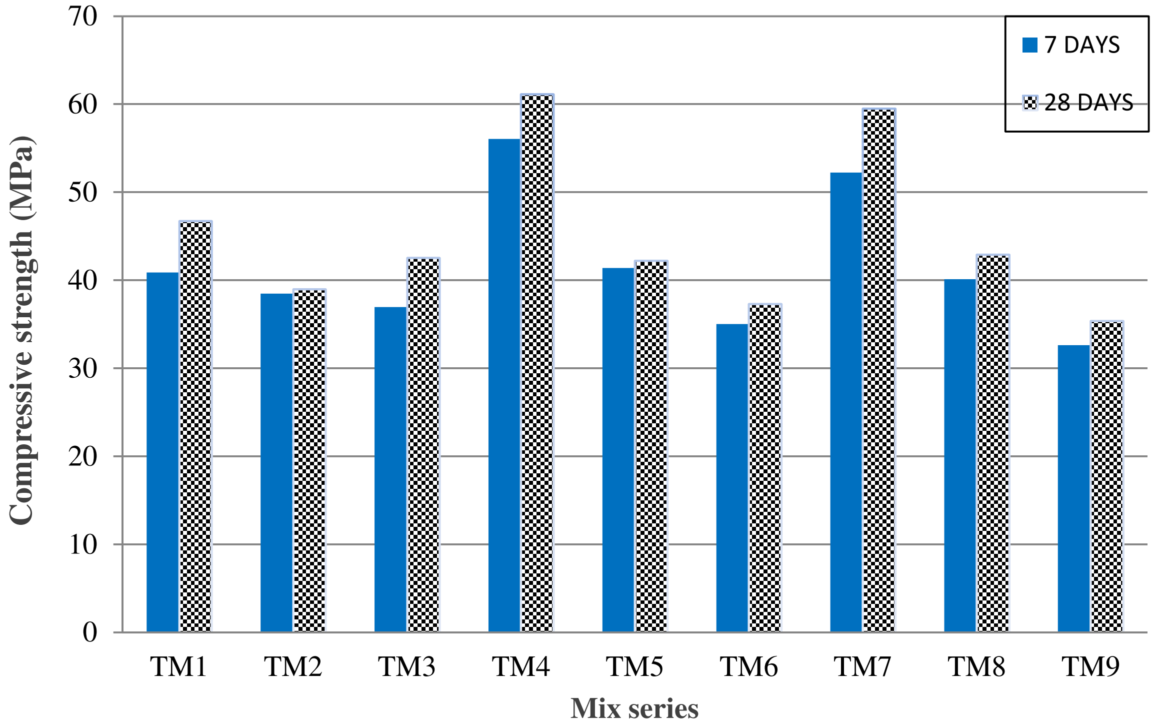
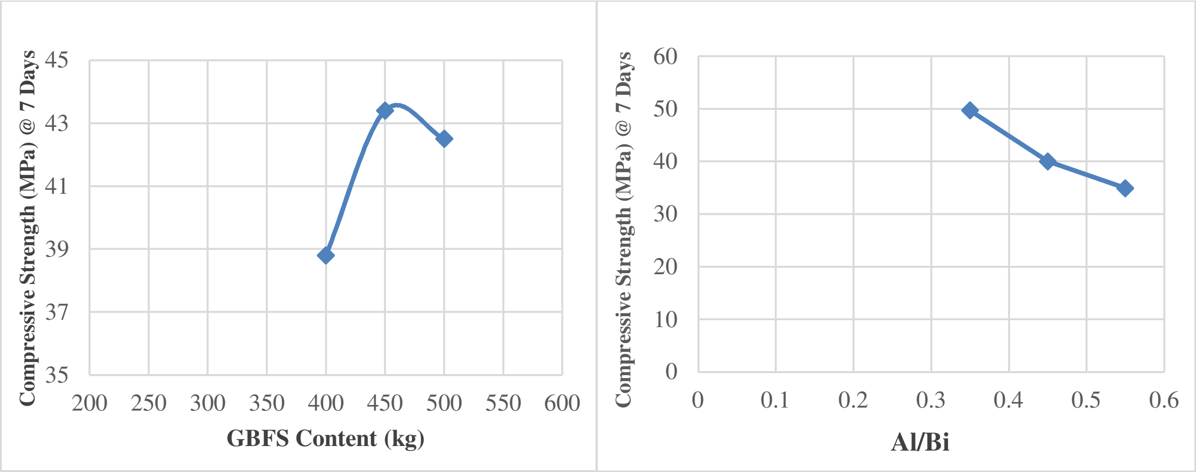
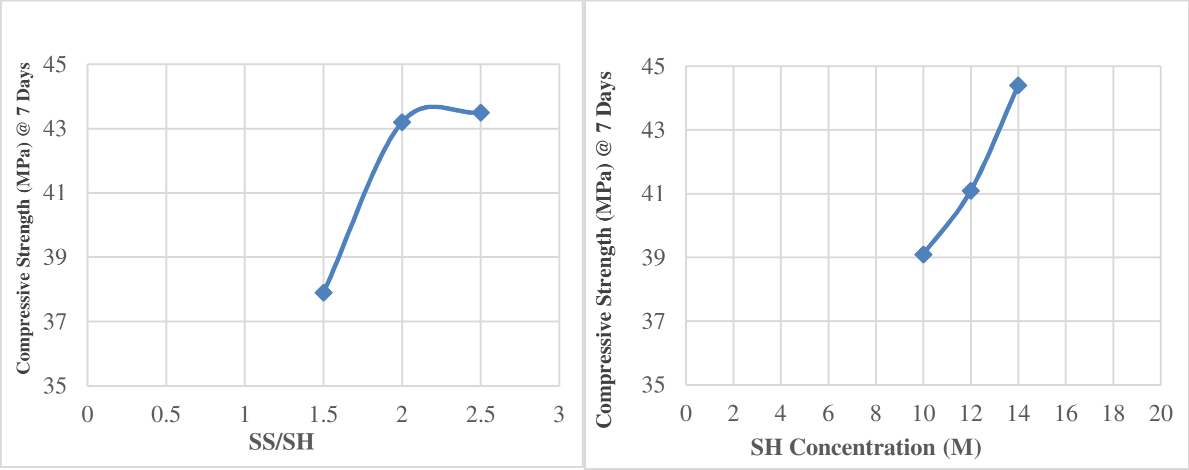


Fig. 1. The 7- and 28-day compressive strength of the geopolymer concrete specimens.



a) Binder content

b) Al/Bi



c) SS/SH

d) SH Concentration (M)

Fig. 2. Factorial diagrams of the main parameters that affect the 7-day compressive strength of geopolymer mix under ambient curing condition.

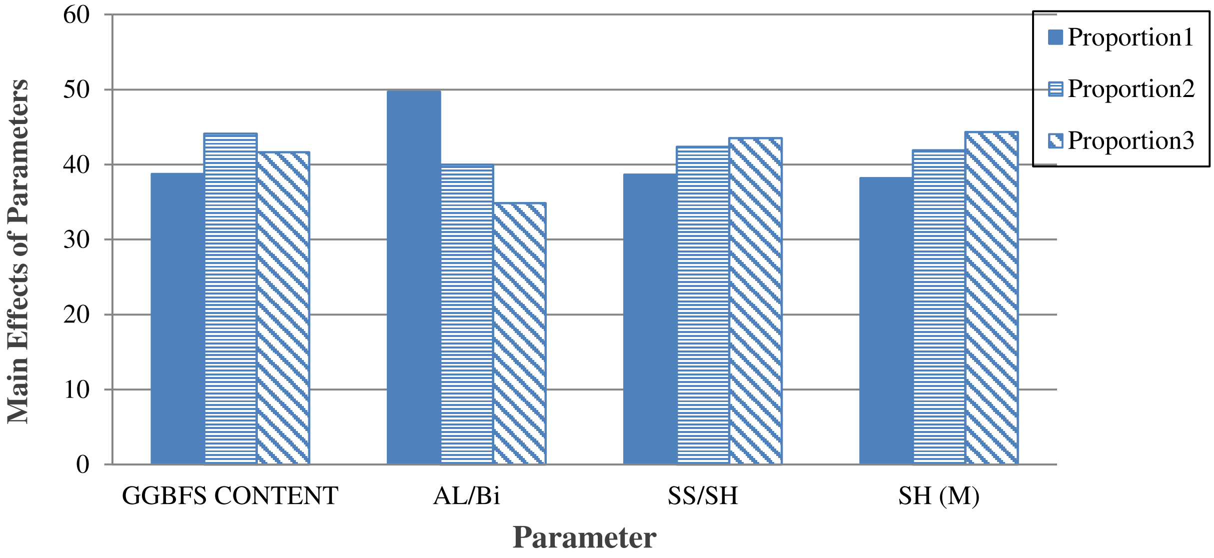


Fig. 3. The significant of the main parameters that affect the 7-day compressive strength of mixes.

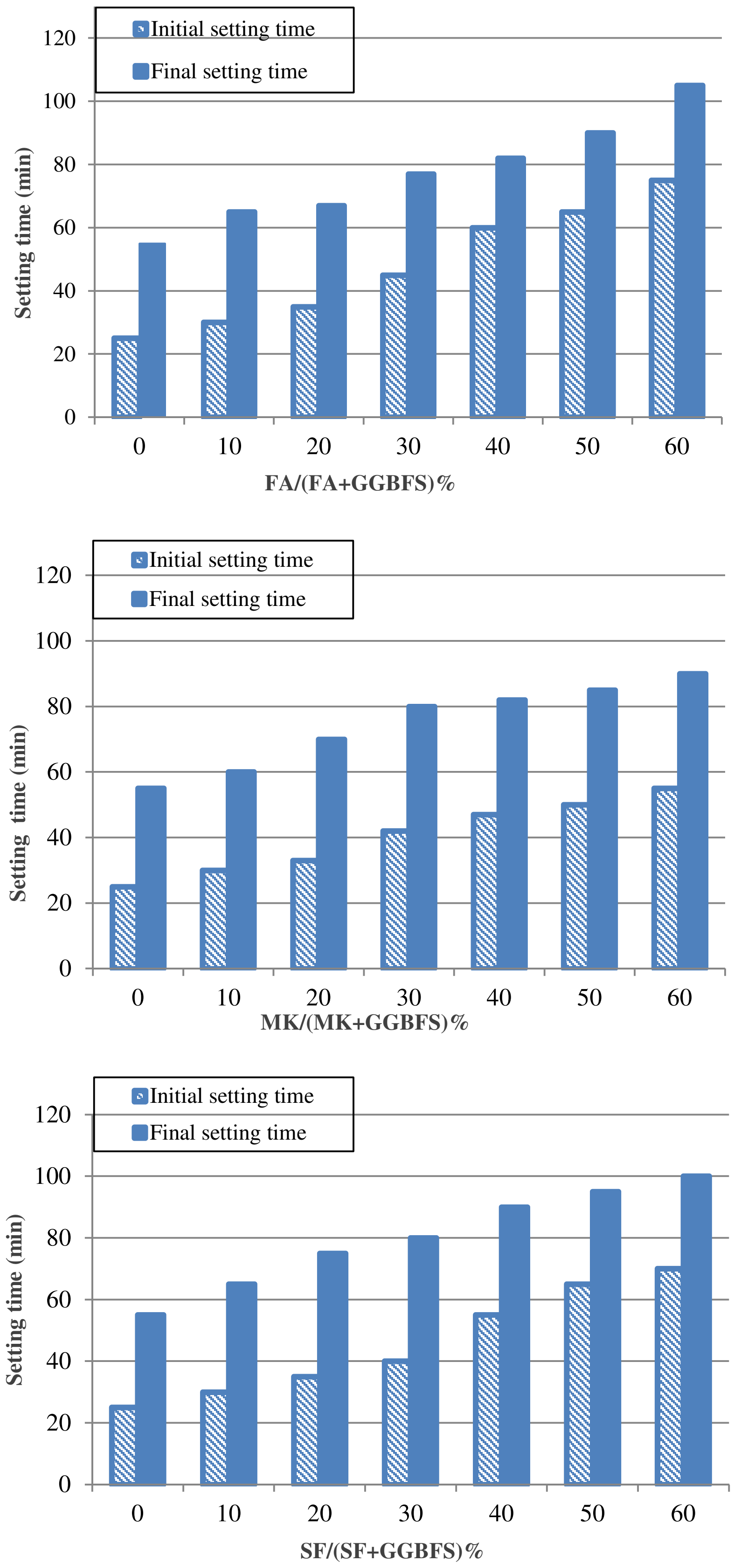
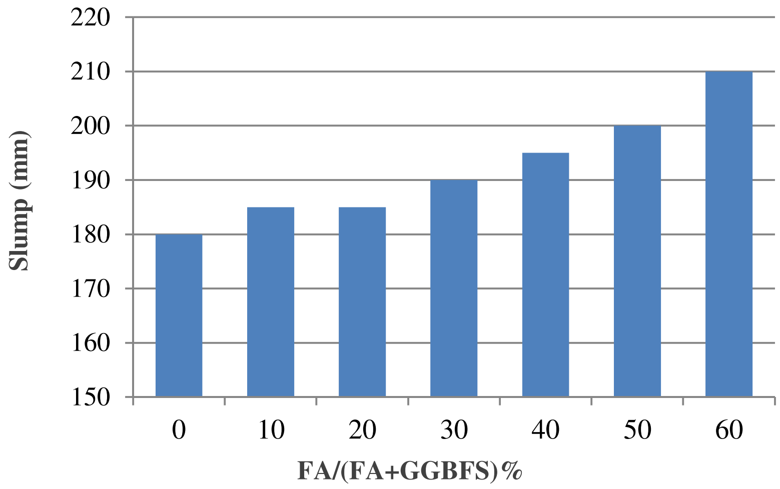
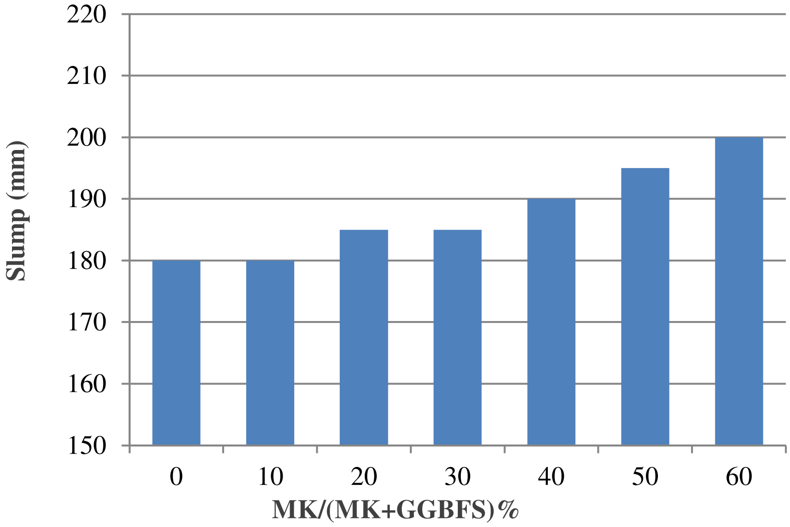


Fig. 4. The effect of partial replacement of GGBFS with FA, MK, and SF on the setting time.





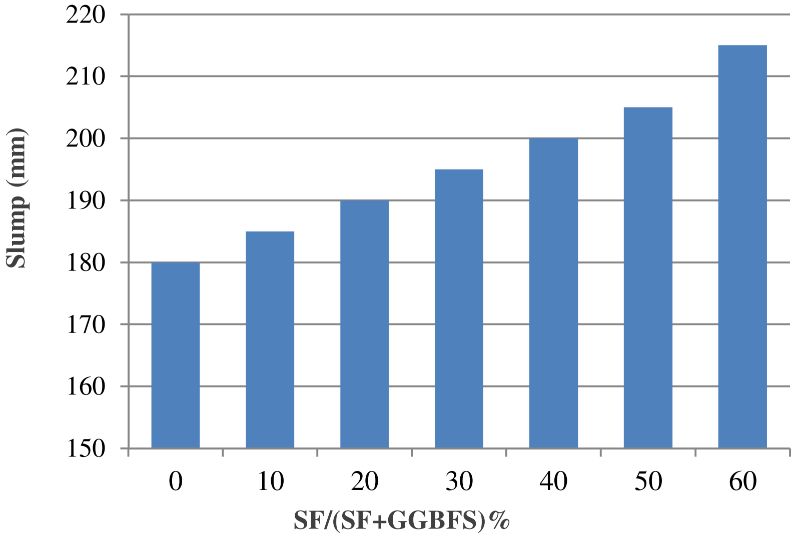


Fig. 5. The effect of partial replacement of GGBFS with FA, MK, and SF on the workability.

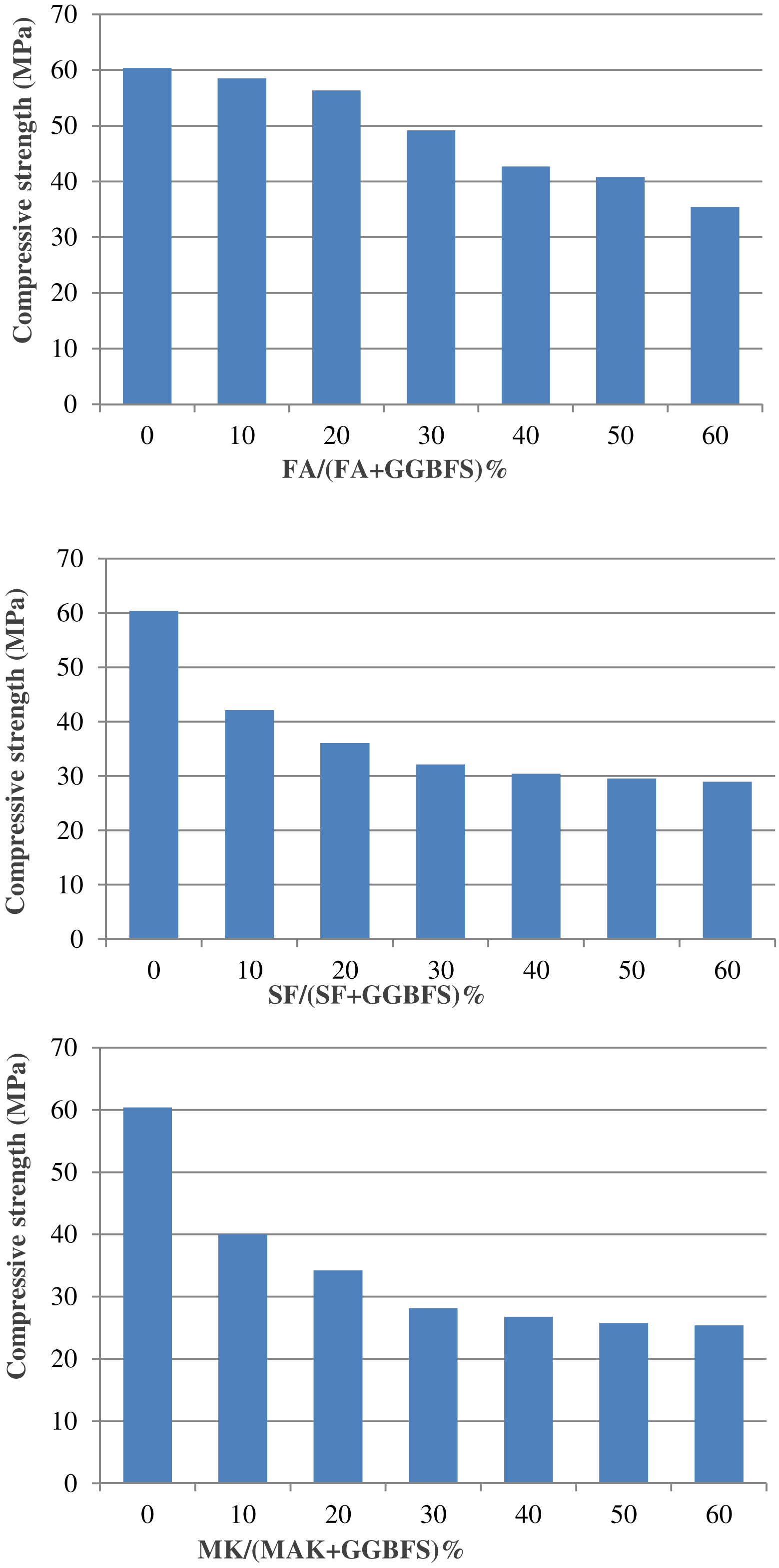


Fig. 6. The effect of partial replacement of GGBFS with FA, MK, and SF on the 7-day compressive strength.