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Development of Sustainable Slag-based Geopolymer Concrete Using Different Types of Chemical Admixtures

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Abstract

Geopolymer concrete (GPC) has achieved a wide popularity since innovating it as an alternative to conventional concrete because of its superior mechanical characteristics and durability, in addition to being a green concrete due to its low negative impact on the environment. However, GPC still suffers from the problem of its poor workability which suppresses its spread in construction applications. This study investigated the most effective parameters on the workability of GPC including GGBFS content, water to binder ratio, and dosage of different types of chemical admixtures, Naphthalene-Based Admixture (NPA) and Polycarboxylate-Based Admixture (PCA), using Taguchi approach and Analysis of Variance (ANOVA) analysis considering the compressive strength at the different concrete ages. It was observed that NPA, in the geopolymer concrete, improved the compressive strength compared to PCA. The NPA-based mixes achieved the highest 28-day compressive strength, 69 MPa, with about 27.8% more than the highest 28-day compressive strength achieved by the PCA-based mixes, 54 MPa. The obtained results revealed that the NPA has achieved the best improvement for both the workability, in terms of initial slump value and slump loss rate, and the compressive strength of GPC mixes compared to PCA.

Keywords Geopolymer concrete, Ground granulated blast furnace slag, Chemical admixture, Taguchi method, Compressive Strength, Slump

1 Introduction

The cement industry accounts for around 8% of total CO_2 emissions in the atmosphere worldwide (Olivier et al., 2013). Geopolymer concrete (GPC) is an environmentally friendly kind of concrete that utilizes less or no Portland cement. GPC is finding its way towards replacing conventional construction materials as green materials (Almutairi et al., 2021; Amer et al., 2021a, 2023; Amran et al., 2020; Farooq et al., 2021; Hassan et al., 2019; Ma et al., 2018). Geopolymer materials are on their approach to becoming green alternatives to conventional construction materials, but research is currently confined due to poor workability (Amer et al., 2020a, 2021b; Hammad et al., 2021; Heshmat et al., n.d.; Provis, 2018; Verma & Dev, n.d.; Verma et al., 2022; Zhang et al., 2021)

The chemical composition of GPC is slightly different from that of conventional concrete (Kumar et al., 2022; Verma & Dev, 2021; Verma & Dev, n.d.). Because of the very viscous silicate component in the combination, GPC has a poorer workability than conventional concrete. The workability of geopolymer concrete or mortar using Ground Granulated Blast Furnace Slag (GGBFS) as an additive decreased as the GGBFS content (Jindal, 2019; Verma & Dev, 2022). It was reported that adding GGBFS to GPC accelerates the geopolymerization

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reaction and the setting process. The initial and ultimate setting durations of GPC with GGBFS were dramatically shortened. The disparity between the start and final setting times, on the other hand, reduces as the GGBFS content rises.

The rapid setting might be attributed to the production of additional geopolymeric gel together with C–S–H (Fang et al., 2018). In contradiction to the previous statement, as the proportion of GGBFS increases, the setting time lowers, making it harder to handle the newly generated mixture, which may be managed by applying an appropriate retarder.

The inclusion of GGBFS increases the mechanical strength development of ambient cured GPC to an extent that is dependent on the GGBFS concentration (Jindal, 2019). For every 10% increase in GGBFS content, there is a considerable rise in 28-day compressive strength of 10 MPa (Nath & Sarker, 2014). The improvement in strength of geopolymer mortar specimens was much greater than that of GPC specimens. With the addition of 30% GGBFS, GPC reached compressive strength of 55 MPa and geopolymer mortar reached 63 MPa after 28 days (Nath & Sarker, 2014). The Si/Al ratio in the mixture also affects compressive strength; a higher Si/Al ratio enhances compressive strength. The inclusion of GGBFS raises the Si/Al ratio, which in turn raises the calcium alumino-silicate hydrate (C–A–S–H), resulting in a boost in compressive strength. The bonding strength and abrasion resistance of geopolymer composites including GGBFS are remarkable (Hu et al., 2008). Since bond strength is one of the most important elements affecting the lifetime of repair materials, geopolymer materials containing GGBFS may be an outstanding product for use as a repair material (Hu et al., 2008).

The workability of fly ash-based GPC was found to be reduced as the GGBFS content is increased. It was mostly owing to the rapid calcium reaction and the angular structure of the GGBFS. Workability was significantly reduced when the alkaline solution to binder ratio was reduced from 0.40 to 0.35 (Deb et al., 2014).

Recently, it was recorded that the Naphthalene-Based Admixtures (NPA) are more effective than the Polycarboxylate-Based Admixtures (PCA) as superplasticizers for GPC to improve workability (Nabil et al., 2020; Özen et al., 2020; Refaie et al., 2023). This can be attributed to PCA molecules being more sensitive to pore solutions with a high pH, higher number of ionic species and higher ionic strength. However, the adequacy of superplasticizers is strongly impacted by the chemistry of the aluminosilicate precursors and the activating solution (Lu et al., 2021). Hence, the differing types of raw material sources are one of the causes for the poor compatibility between geopolymers and commercial superplasticizer (Xie & Kayali, 2016) so conflict has been found and a research gap was focused. However, studies focused on investigating the effect of chemical admixtures on GPC are few and still limited. Therefore, prospective studies are needed to ensure its effect and make it clearer.

Although many studies have been performed on GPC, there is still no agreement on the effect of various factors on the characteristics of GPC, especially compressive strength and workability. The aluminosilicate source type, curing conditions, type of alkaline activator, composition and concentration of the activator, and the alkaline activator to binder ratio and type of superplasticizer are the important key factors in determining the properties of GPC (Li et al., 2019; Paruthi et al., 2022). A gap of research is assigned in determining the impact of all these variables in the traditional factorial design of experiments. However, applying a well-designed experimental program by employing an advanced approach such as Taguchi technique, which is a fractional factorial design method uses a special set of arrays called Orthogonal Arrays (OA), facilitates the investigation of a large number of parameters with a small number of experiments (Hadi et al., 2017; Nazari et al., 2012). The Taguchi method in designing tests is greater beneficial when weighed against standard methods. Orthogonal arrays are used for generating appropriate experiment designs, and it is possible to investigate at the correlation between the levels of the experimental factors and their levels. For enhancement of the process, the Taguchi technique analyzes the data using the signal-to-noise (SN) ratio (Dave & Bhogayata, 2020). For improvement purposes, the Taguchi approach has been widely used in the field of concrete technology to optimise the mix design. The impact of several mix design parameters on the fresh and hardened properties of GPC was investigated using the Taguchi technique (Ansari et al., 2023). At present, ANOVA (Analysis of Variance) is probably the most prevalent statistical technique for evaluating assumptions. When analyzing multiple samples concurrently, the analysis of variance is an effective approach.

To promote the application of green geopolymer materials, the effects and mechanism of commercial superplasticizers and the optimum mix design on the mechanical properties of slag-based geopolymer concrete, were studied in this research (Verma et al., 2022). The main objective of this study is to investigate the most effective parameters on the workability of slag-based geopolymer concrete including GGBFS content, water to binder ratio, and type and dosage of chemical admixture using Taguchi approach and ANOVA (Analysis of Variance) considering the compressive strength at the different ages at the ambient curing conditions.

2 Experimental Program

2.1 Methodology

Design of experiments in this research work was conducted using Taguchi method which is a fractional factorial design method. This method uses a special set of arrays called Orthogonal Arrays (OA) for the design of experiments to investigate a large number of parameters with a small number of experiments. Design of experiments using OA is quite efficient compared to traditional experiment design methods. The OA reduces the number of experiments and minimizes uncontrollable parameters. The OA selection is related with the total degrees of freedom (DOF) of the operation, which is the summation of the single DOF for each of the investigated parameters. The single DOF of each parameter is equal to the product of subtracting one from the number of levels of this parameter. Hence, the OA's DOF should not be smaller than the obtained total DOF of the operation (Canbolat et al., 2019; Ferdous et al., 2017). For this study, three parameters with three levels each were selected, the single DOF of each parameter was equal to two, thus the total DOF of the operation was equal to 6. So, the Taguchi criteria based on L9 OA array were selected. The investigated parameters in this study were binder (GGBFS) content, water to binder (W/B) ratio, and admixture dosage. These parameters with their corresponding levels are presented in Table 1. By applying Taguchi criteria based on L9 array, nine mixes were obtained as presented in Table 2.

Taguchi method uses a Signal-to-Noise (S/N) ratio for optimization. The S/N ratio minimizes the effect of uncontrollable parameters (noise), while maximizing the effect of investigated parameters (signal) (Dagdevir & Ozceyhan, 2021; Eskandarinia et al., 2022). So, the S/N ratio helps in data analysis and prediction of optimum result. There are 3 Signal-to-Noise ratios of common interest for optimization: (a) smaller is better, selected when the target is to minimize the measured property [$S/N = -10\ Log_{10}$ (Mean of sum of squares of measured data)]; (b) larger is better, selected when the target is to maximize the measured property [$S/N = -10\ Log_{10}$ (Mean of sum squares of reciprocal of measured data)]; (c) nominal is better, selected when the target is to target the measured property [$S/N = 10\ Log_{10}$ (Square of mean/Variance)] (Hasçalik & Çaydaş, 2008). As this study aims to maximize the workability and compressive strength of mixes, the S/N ratio was selected as a larger is better. The Minitab program was employed to calculate the S/N ratios. Finally, the results were interpreted using the analysis of variance (ANOVA) to find the optimum level and the participation percentage of each parameter. The Qualitek-4 program was used to perform the ANOVA analysis (Ferdous et al., 2017; Taiwo et al., 2020). Fig. 1 shows a flowchart illustrating the aforementioned methodology.

Table 1 Parameters and levels used in Taguchi design

Parameters	Level 1	Level 2	Level 3
GGBFS content (kg/m^3)	350	450	550
W/B ratio	0.3	0.4	0.5
Admixture dosage* (%)	1	2	3

* Percentage from the GGBFS content

Table 2 Mixes matrix obtained from Taguchi design

Mix No.	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)
Mix1	350	0.3	1
Mix2	350	0.4	2
Mix3	350	0.5	3
Mix4	450	0.3	2
Mix5	450	0.4	3
Mix6	450	0.5	1
Mix7	550	0.3	3
Mix8	550	0.4	1
Mix9	550	0.5	2

2.2 Materials

In this research, GGBFS was utilized as the binder of studied GPC mixes. The chemical composition of GGBFS is shown in Table 3. The used coarse aggregate was natural crushed limestone of 10 mm nominal maximum size, and the used fine aggregate was natural sand of fineness modulus 2.77. The used aggregates were total saturated surface dry to ensure that the water will satisfy the mixture requirement. Sodium silicate solution and sodium hydroxide solution were mixed together to prepare the alkaline activator. The sodium hydroxide solution was prepared by dissolving sodium hydroxide flakes in potable water, while the sodium silicate solution was obtained from a local supplier. The chemical composition of Sodium Hydroxide (SH) flakes and Sodium Silicate (SS) solution are shown in Tables 4 and 5, respectively. Two different chemical admixtures were used in this study, naphthalene-based admixture (NPA) and polycarboxylate-based admixture (PCA). Tables 6 and 7 show the characteristics of used admixtures.

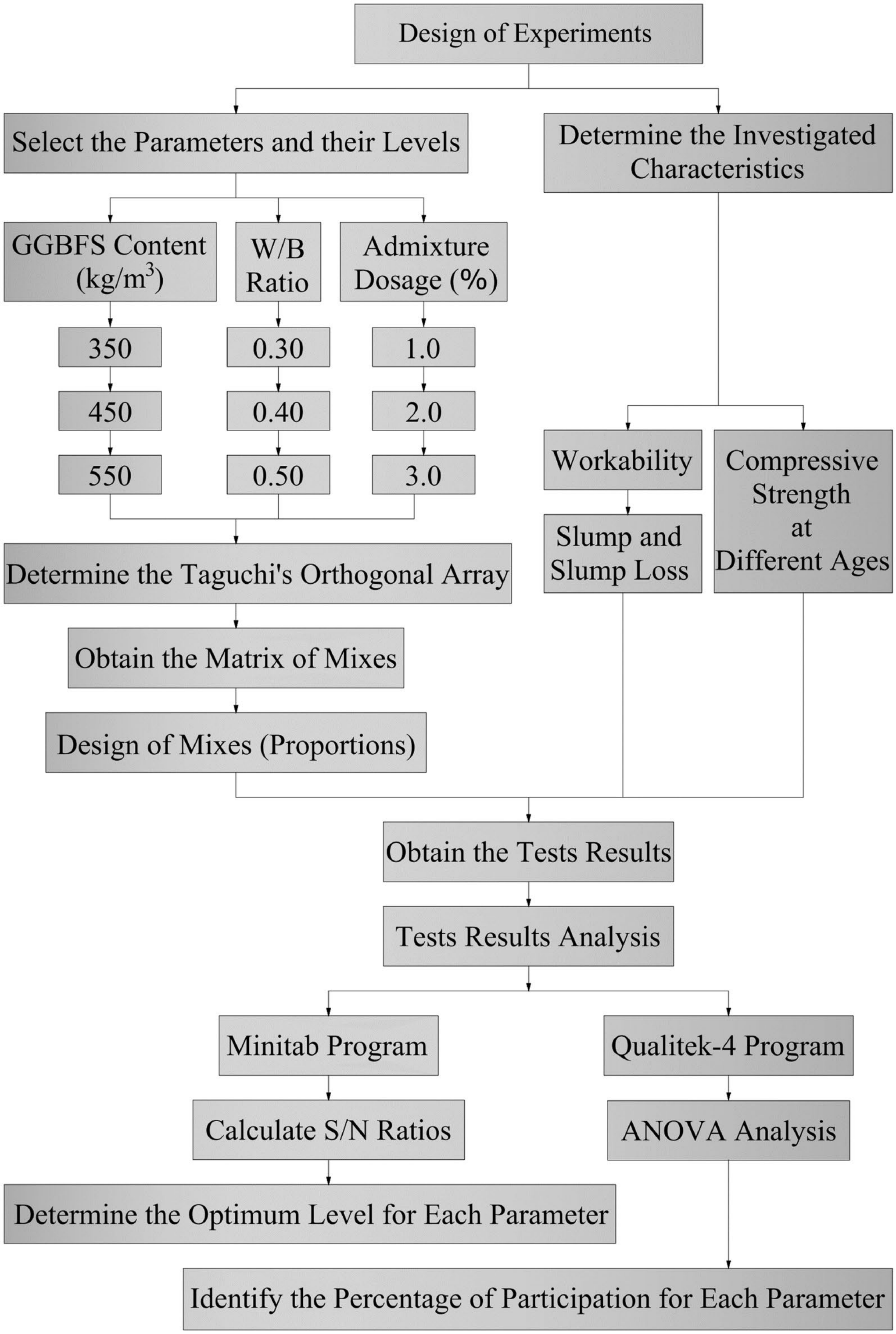

Fig. 1 Flowchart of the methodology considered in the study plan

Table 3 The chemical composition of used GGBFS

Component	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	Cl
Content (%)	39.8	1.20	11.2	34.4	7.6	0.45	0.013

Table 4 The chemical composition of used SH

Component	Na_2O	H_2O
Content (%)	60.25	39.75

Table 5 The chemical composition of used SS

Component	Na_2O	SiO_3	H_2O
Content (%)	11.98	31.0	57.0

Table 6 Characteristics of used NPA admixture

Base	Appearance/ color	Density (at 20 °C)	Chlorides
Naphthalene formaldehyde sulphonate	Brown liquid	1.20 kg/l	No

Table 7 Characteristics of used PCA admixture

Base	Appearance/ Color	pH value	Solid content	Density (at 20 °C)	Chlorides
Polycarboxylates	Clear liquid	4.0	40%	1.08 kg/l	No

2.3 Design of Mixes

GPC mixes were designed based on the matrix that obtained from Taguchi design, Table 2, and by applying the absolute volume method to determine the proportions of mixes. Nine mixes were designed for each type of admixture, with a total number of eighteen mixes, as presented in Tables 8 and 9.

2.4 Mixing Protocol

In this study, GPC was prepared by mixing dry materials, GGBFS and aggregates, in the drum mixer in dry condition for 2 min. Then, the pre-prepared alkali activator was added to the dry mixture in the drum and mixed for another 4 min until the homogeneity of the mixture was reached. The preparation process of the alkali activator was by mixing the SH flakes, SS solution and water for about one hour before adding it to the dry mixture until its average temperature was about 30 °C.

2.5 Specimens Preparation and Testing

The workability of performed mixes was expressed through both slump and slump loss tests. The slump test was carried out immediately after mixing the concrete according to ASTM C143 (2015). The slump loss often refers to the loss of concrete workability with time. The slump loss, for all mixes, was recorded every 5 min immediately after mixing.

The compressive strength of conducted mixes was determined using cubic specimens with dimensions of $100 \times 100 \times 100$ mm according to BS EN 12390-1 (2012). The specimens were cast into steel molds which were placed on a vibrator to provide a suitable compaction to eliminate any air bubbles inside the concrete specimens. After 24 h, the specimens were removed from the molds and cured in the ambient temperature of 25 ± 2 °C until testing. The compression tests were

Table 8 Mix proportions of NPA-based mixes (kg/m^3)

Mix No.	GGBFS	SS	SH	Water	F.A.[a]	C.A.[b]	NPA
Mix1-N	350	113	36	24	665	1330	3.5
Mix2-N	350	113	36	57	635	1269	7.0
Mix3-N	350	113	36	90	604	1208	10.5
Mix4-N	450	145	46	29	605	1209	9.0
Mix5-N	450	145	46	71	565	1130	13.5
Mix6-N	450	145	46	122	526	1051	4.5
Mix7-N	550	177	56	32	544	1088	16.5
Mix8-N	550	177	56	94	496	991	5.5
Mix9-N	550	177	56	146	447	895	11.0

[a] *F.A.* fine aggregate

[b] *C.A.* coarse aggregate

Table 9 Mix proportions of PCA-based mixes (kg/m^3)

Mix No.	GGBFS	SS	SH	Water	F.A.[a]	C.A.[b]	PCA
Mix1-P	350	113	36	24	665	1330	3.5
Mix2-P	350	113	36	57	635	1269	7.0
Mix3-P	350	113	36	90	604	1208	10.5
Mix4-P	450	145	46	29	605	1209	9.0
Mix5-P	450	145	46	71	565	1130	13.5
Mix6-P	450	145	46	122	526	1051	4.5
Mix7-P	550	177	56	32	544	1088	16.5
Mix8-P	550	177	56	94	496	991	5.5
Mix9-P	550	177	56	146	447	895	11.0

[a] *F.A.* fine aggregate

[b] *C.A.* coarse aggregate

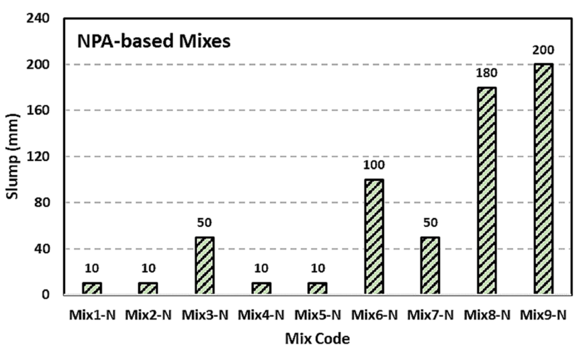

Fig. 2 Slump values of NPA-based mixes

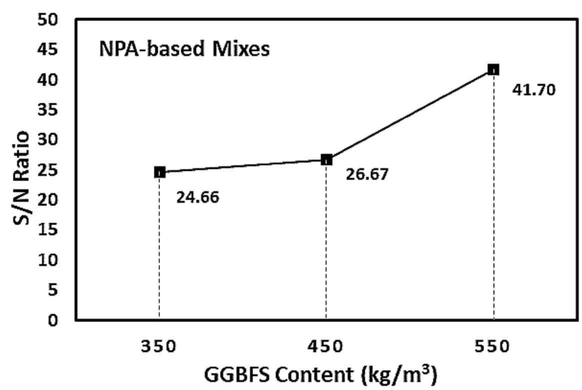

Fig. 3 S/N ratio of GGBFS content levels of NPA-based mixes for the slump value

performed, according to BS EN 12390-3 (2019), at the ages of 7 days and 28 days. For each age, three specimens for each mix were tested to calculate the mean value.

3 Tests Results and Discussion

3.1 Slump Test

3.1.1 NPA-based Mixes

The obtained slump values of all NPA-based mixes are presented in Fig. 2. It can be seen that Mix1-N, Mix2-N, Mix4-N and Mix5-N have achieved the lowest slump value (10 mm). The W/B ratios of these four mixes were the lowest W/B ratios (0.3 and 0.4), which means the strong effect of this ratio on the workability even in the presence of NPA with high dosage. Whereas, the highest slump value (200 mm) was achieved by Mix9-N, which has a slag content of 550 kg/m^3, W/B ratio of 0.5 and NPA dosage of 2. This may be attributed to that increasing the fine powder (slag) content in a mix improves the lubrication of the mix and reduces friction between its components, and thus improves its workability; in addition to it is well known that increasing the W/B ratio with adding chemical admixture improves the workability of mixes accordingly.

The Minitab program was employed to calculate the Signal-to-Noise (S/N) ratio, based on larger is better, for each studied parameter to demonstrate the effect of each on the slump value, as presented in Figs. 3, 4 and 5. Also, ANOVA analysis was performed using Qualitek-4 program to determine both the participation percentage and optimum level for the studied parameters, as shown in Table 10.

It can be noticed from Table 10 that the GGBFS content was the most significant parameter that affected the slump value of NPA-based mixes with a participation percentage of 57.09% and optimum level of 550 kg/m^3. This indicates that the increase of GGBFS content in the mix increases the slump value and hence the workability as presented in Fig. 3. This may be attributed to the lubrication that occurred by increasing the fine particles in the mix which leads to reduce friction between the mix components.

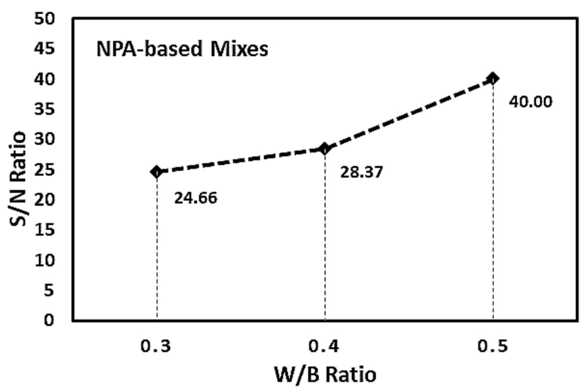

Fig. 4 S/N ratio of W/B ratio levels of NPA-based mixes for the slump value

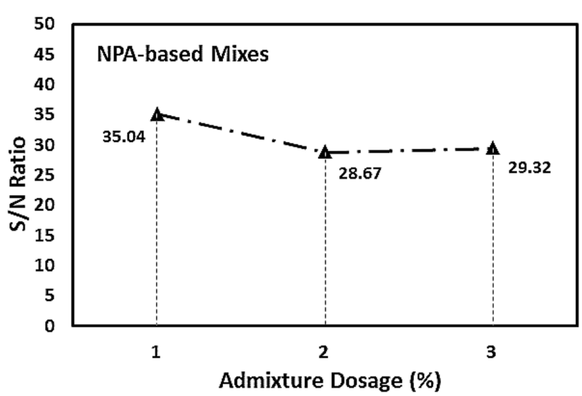

Fig. 5 S/N ratio of admixture dosage levels of NPA-based mixes for the slump value

Table 10 Percentage of participation and optimum Level of the studied parameters on the slump value for NPA-based mixes

Parameter	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)
Percentage of participation (%)	57.09	29.89	13.02
Optimum level	550	0.5	1.0

The most influential parameter after GGBFS content was the W/B ratio with a participation percentage of 29.89% and optimum level of 0.50 as shown in Table 10. This indicates that the higher W/B ratio improves the slump value and thus the workability of NPA-based mixes as presented in Fig. 4. Using a high W/B ratio in the mix increases the total water content and hence decreases the used activator concentration and consequently slow down the polymerization process which leads to prolong

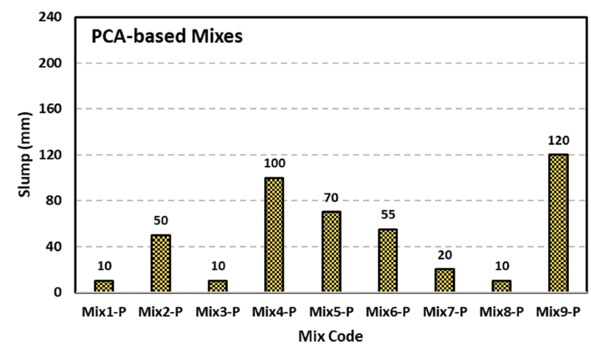

Fig. 6 Slump values of PCA-based mixes

the setting time and increase the slump value (Amer et al., 2021b).

The NPA dosage was the least effective parameter on the slump value of NPA-based mixes with a participation percentage of 13.02% as listed in Table 10. The optimum level of the NPA dosage was 1%, but without a big difference about the other levels as shown in Fig. 5. This indicates that this dosage range of this type of admixture is not govern on the workability significantly.

3.1.2 PCA-based Mixes

The recorded slump values of all PCA-based mixes are shown in Fig. 6. It can be observed that Mix1-P, Mix3-P, Mix7-P and Mix8-P have achieved the lowest slump value (10–20 mm). Whereas, the highest slump value (120 mm) was achieved by Mix9-P, which has a slag content of 550 kg/m^3, W/B ratio of 0.5 and NPA dosage of 2, which was compatible with the optimum NPA-based mix (Mix9-N) but with a lower slump value. This indicates that the effect of NPA admixture on the workability is better than the PCA admixture, which agrees with the findings of Wu et al., (2021).

Also, the Minitab program was employed to calculate the Signal-to-Noise (S/N) ratio, based on larger is better, for each studied parameter to demonstrate the effect of each on the slump value of the PCA-based mixes, as presented in Figs. 7, 8 and 9. Table 11 shows the participation percentage and optimum level for the studied parameters which were obtained from the Analysis of Variance (ANOVA) analysis.

It can be observed from Table 11 that the PCA dosage was the most significant parameter that affected the slump value of PCA-based mixes with a participation percentage of 57.16% and optimum level of 2%.

The most influential parameter after PCA dosage was the GGBFS content with a participation percentage of 31.28% and optimum level of 450 kg/m^3 as shown in Table 11.

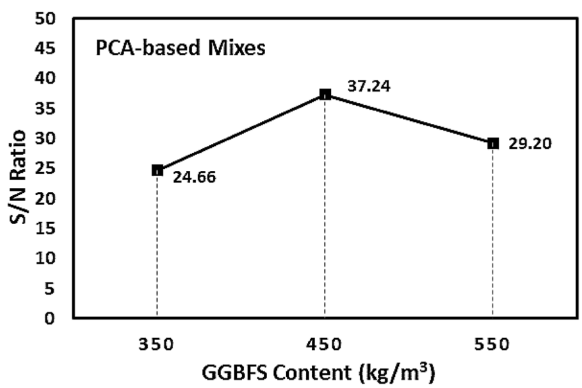

Fig. 7 S/N ratio of GGBFS content levels of PCA-based mixes for the slump value

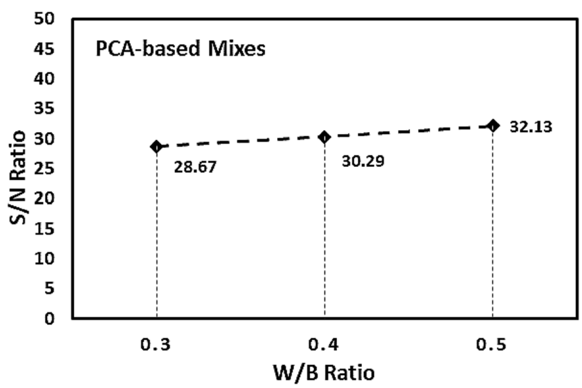

Fig. 8 S/N ratio of W/B ratio levels of PCA-based mixes for the slump value

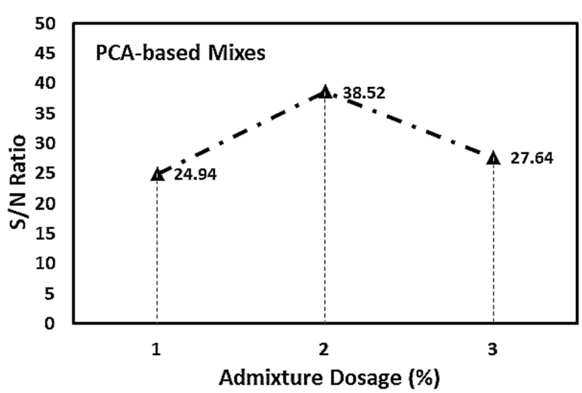

Fig. 9 S/N ratio of admixture dosage levels of PCA-based mixes for the slump value

The W/B ratio was the least effective parameter on the slump value of PCA-based mixes with a participation percentage of 11.56% as listed in Table 11. The optimum level of was 0.5 (maximum used ratio). This indicates that increasing the W/B ratio increases the slump value, as presented in Fig. 8, and thus improving the workability of PCA-based mixes. This is consistent with what has been proven for the NPA-based mixes, but with a lower influence.

Table 11 Percentage of participation and optimum Level of the studied parameters on the slump value for PCA-based mixes

Parameter	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)
Percentage of participation (%)	31.28	11.56	57.16
Optimum level	450	0.5	2.0

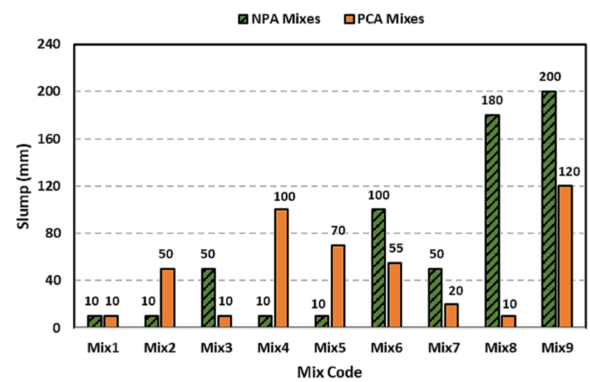

Fig. 10 Comparison between NPA and PCA mixes in the obtained slump values

Table 12 Comparison between NPA and PCA mixes in the obtained optimum levels for the slump value

Admixture Type	Optimum level			Maximum obtained slump value (mm)
	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)	
NPA	550	0.5	1.0	200
PCA	450	0.5	2.0	120

3.1.3 NPA vs PCA Mixes

A comparison was made between the NPA-based mixes and PCA-based mixes to distinguish between them through the results obtained from both experiments and analysis process as presented in Fig. 10 and Table 12. It can be observed that the NPA-based mixes achieved the best slump values for most of mixes, in addition to having the highest slump value of 200 mm, with about 67% more than the highest slump value achieved by the PCA-based mixes (120 mm). Moreover, the optimum level of the NPA dosage that obtained from ANOVA analysis was 1.0% which was the lowest level among the studied range, while the obtained optimum level of the PCA dosage was 2.0% as presented in Table 12. However, the NPA-based mixes achieved the best slump values, which indicates that the efficiency of NPA in improving the workability of GPC is higher than that of PCA. The molecular structures of superplasticizers may be destroyed in alkali activators, especially for polycarboxylate-based superplasticizers.

3.2 Slump Loss

The slump test was conducted on all investigated mixes every 5 min immediately after mixing to observe the slump loss rate. Figs. 11 and 12 present the recorded slump values with time for NPA-based mixes and PCA-based mixes, respectively. Through these figures, it can be observed that the NPA-based mixes achieved the best initial slump value of 200 mm and the lowest rate of slump loss (90 mm after 15 min and 55 mm after 20 min), while the best PCA-based mix achieved an initial slump value of 120 mm and a rate of slump loss (10 mm after 15 min and zero after 20 min). This confirms that the NPA is more effective that PCA in improving the workability of fresh-state GPC.

3.3 Compressive Strength

3.3.1 NPA-based Mixes

The compression test was conducted on all NPA-based mixes and the compressive strength was determined at ages of 7 days and 28 days as presented in Fig. 13. It can be noticed that Mix8-N has achieved the highest 28-day compressive strength, 69 MPa. Whereas, the Mix2-N has recorded the lowest 28-day compressive strength, 57 MPa. The GGBFS content, W/B ratio and admixture dosage of Mix8-N and Mix2-N are 550 kg/m^3, 0.4 and 1, and 350 kg/m^3, 0.4 and 2, respectively, as listed in Table 2. The two mixes have the same W/B ratio but different in GGBFS content and admixture dosage, which indicates the significant effect of these two parameters on the

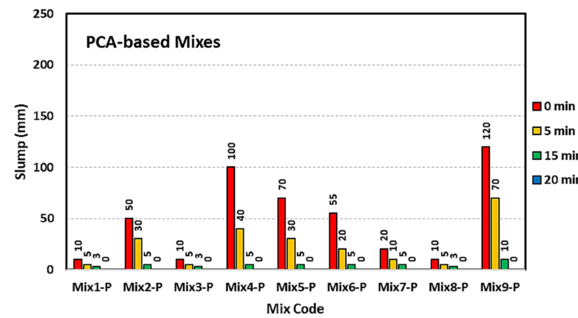

Fig. 12 Slump value with time for PCA-based mixes

compressive strength. It can be explained that increasing the GGBFS content increases the compressive strength to the fact that the GGBFS is the source of the aluminosilicates that interact with the activator and thus increasing it leads to an increase in the polymerization and hydration products (Bernal et al., 2011). Moreover, increasing the admixture dosage leads to an increase in the liquid content in the mixture, which may lead to an increase in the voids content and thus reduce the compressive strength, in addition to that increasing the dose of admixture may negatively affect the effectiveness of the used activator.

The Signal-to-Noise (S/N) ratio, based on larger is better, was calculated, using the Minitab program, for each studied parameter to demonstrate the effect of each on the 28-day compressive strength of the NPA-based mixes, as presented in Figs. 14, 15 and 16. Table 13 shows the participation percentage and optimum level for the studied parameters which were obtained from the ANOVA analysis.

It can be seen from Table 13 that the GGBFS content was the most significant parameter that affected the 28-day compressive strength of NPA-based mixes with a participation percentage of 42.53% and optimum level of 550 kg/m^3. This confirms that the increase of GGBFS content, aluminosilicate source, in the mix increases

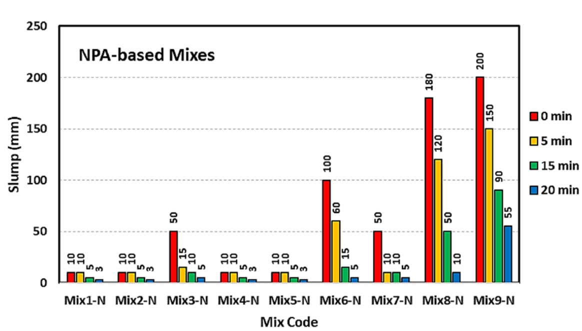

Fig. 11 Slump value with time for NPA-based mixes

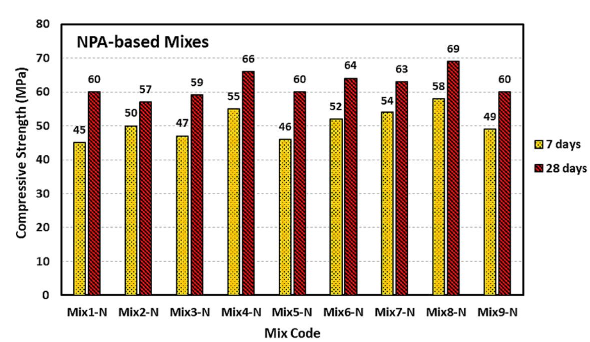

Fig. 13 Compressive strength results of NPA-based mixes

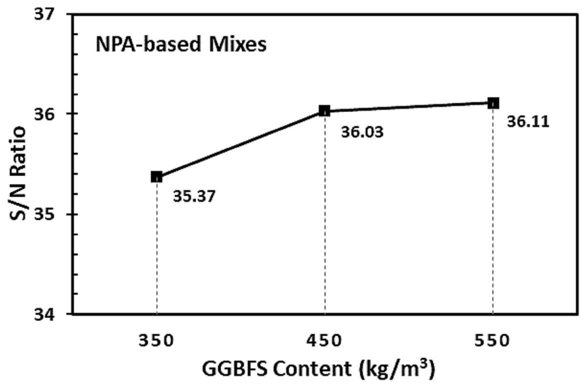

Fig. 14 S/N ratio of GGBFS content levels of NPA-based mixes for 28-day compressive strength

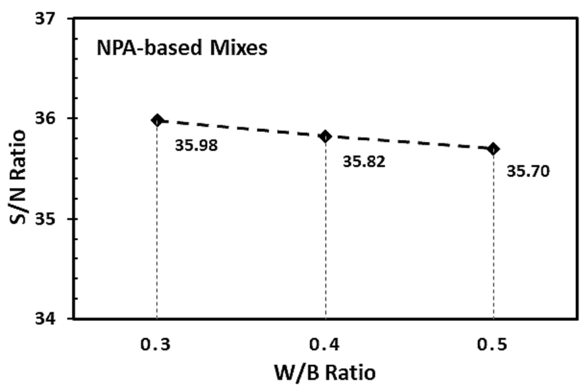

Fig. 15 S/N ratio of W/B ratio levels of NPA-based mixes for 28-day compressive strength

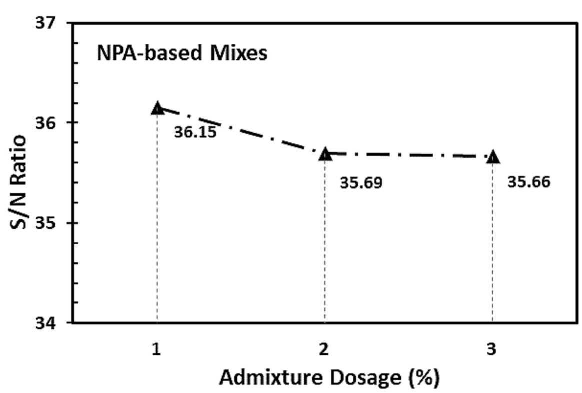

Fig. 16 S/N ratio of admixture dosage levels of NPA-based mixes for 28-day compressive strength

the compressive strength as presented in Fig. 14 (Bernal et al., 2011).

The NPA dosage was the most influential parameter after the GGBFS content with a participation percentage

Table 13 Percentage of participation and optimum Level of the studied parameters on the 28-day compressive strength for NPA-based mixes

Parameter	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)
Percentage of participation (%)	42.53	20.63	36.85
Optimum level	550	0.3	1.0

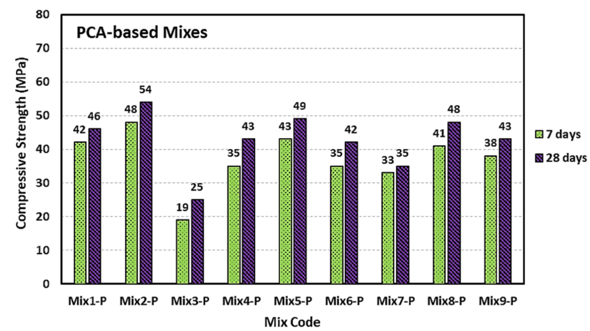

Fig. 17 Compressive strength results of PCA-based mixes

of 36.85% and optimum level of 1% as shown in Table 13. This indicates that the use of admixture should be in an optimal dosage because increasing the dose may lead to an increase in the liquid content in the mixture and thus increase the voids and may lead to a dilution of the activator concentration, which leads to a decrease in the compressive strength as presented in Fig. 16.

The least effective parameter on the 28-day compressive strength of NPA-based mixes was the W/B ratio with a participation percentage of 20.63% as listed in Table 13. The optimum level of W/B ratio was 0.3 which was the lowest studied level which confirms that the higher W/B ratio decreases the compressive strength as is well known for concrete manufacturing in general, Fig. 15. Using a high W/B ratio in the mixture increases the total water content, and hence increases the voids content and decreases the used activator concentration, and consequently decreases the hydration and polymerization products which leads to decrease the compressive strength.

3.3.2 PCA-based Mixes

The reported 28-compressive strength of all PCA-based mixes at ages of 7 days and 28 days is as presented in Fig. 17. It can be seen that Mix2-P has achieved the highest 28-day compressive strength, 54 MPa. Whereas, the Mix3-P has recorded the lowest 28-day compressive strength, 25 MPa. The GGBFS content, W/B ratio and

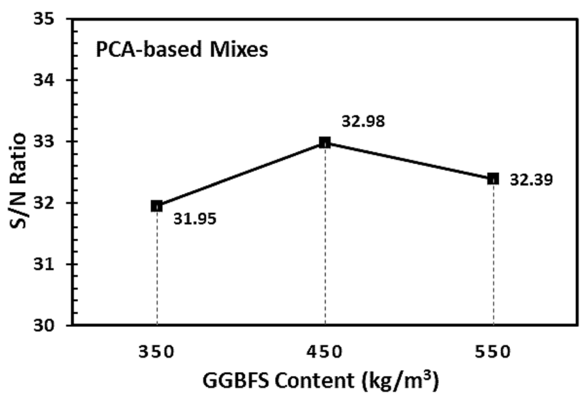

Fig. 18 S/N ratio of GGBFS content levels of PCA-based mixes for 28-day compressive strength

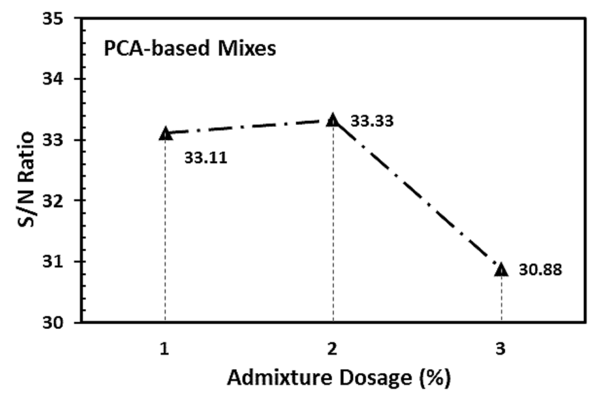

Fig. 20 S/N ratio of admixture dosage levels of PCA-based mixes for 28-day compressive strength

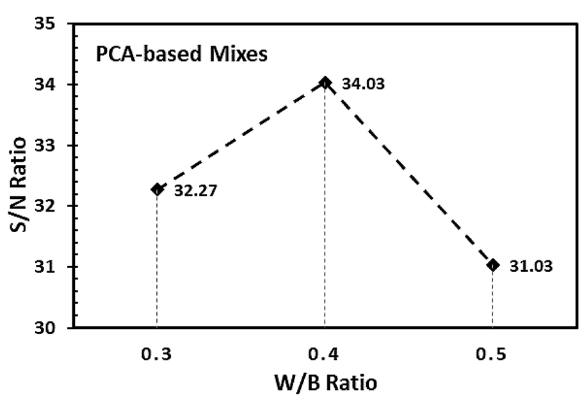

Fig. 19 S/N ratio of W/B ratio levels of PCA-based mixes for 28-day compressive strength

Table 14 Percentage of participation and optimum Level of the studied parameters on the 28-day compressive strength for PCA-based mixes

Parameter	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)
Percentage of participation (%)	15.47	50.90	33.63
Optimum level	450	0.4	2.0

admixture dosage of Mix2-P and Mix3-P are 350 kg/m^3, 0.4 and 2, and 350 kg/m^3, 0.5 and 3, respectively, as listed in Table 2. The two mixes have the same GGBFS content but different in W/B ratio and admixture dosage, which indicates the significant effect of these two parameters on the compressive strength of the PCA-based mixes. It seems that PCA is not effective significantly at the higher GGBFS content. Also, increasing the W/B ratio and PCA dosage decrease the compressive strength as proven before for the NPA-based mixes.

The calculated S/N ratios of each studied parameter are presented in Figs. 18, 19 and 20. Also, the obtained participation percentage and optimum level for each parameter are shown in Table 14.

It can be observed from Table 14 that the W/B ratio was the most significant parameter that affected the 28-day compressive strength of PCA-based mixes with a participation percentage of 50.90% and optimum level of 0.40 kg/m^3. The PCA dosage was the most influential parameter after the W/B ratio with a participation percentage of 33.63% and optimum level of 2%. The least effective parameter was the GGBFS content with a participation percentage of 15.47% and optimum level of 450 kg/m^3. From these observations, it can be drawn that the PCA is more effective in lower GGBFS content and in higher W/B ratio and PCA dosage compared to the NPA.

3.3.3 NPA vs PCA Mixes

The compressive strength results that obtained for both NPA-based mixes and PCA-based mixes were compared to distinguish between them as presented in Fig. 21 and Table 15. It can be observed that the NPA-based mixes achieved the highest 28-day compressive strength of 69 MPa, with about 27.8% more than the highest 28-day compressive strength achieved by the PCA-based mixes (54 MPa) with coefficient of variance (1–5%). It can also be noted that NPA-based mixes achieved the highest values of both early-age and late-age compressive strengths. Moreover, the strength gain of NPA-based mixes from 7 to 28 days is higher than that of PCA-based mixes, which confirms that the NPA is more effective and compatible with both fresh-state and hardened-state of geopolymer concrete. This complies with past research that reported that polycarboxylate did not improve the fluidity of alkali-activated slag, only naphthalene-based had a slight effect

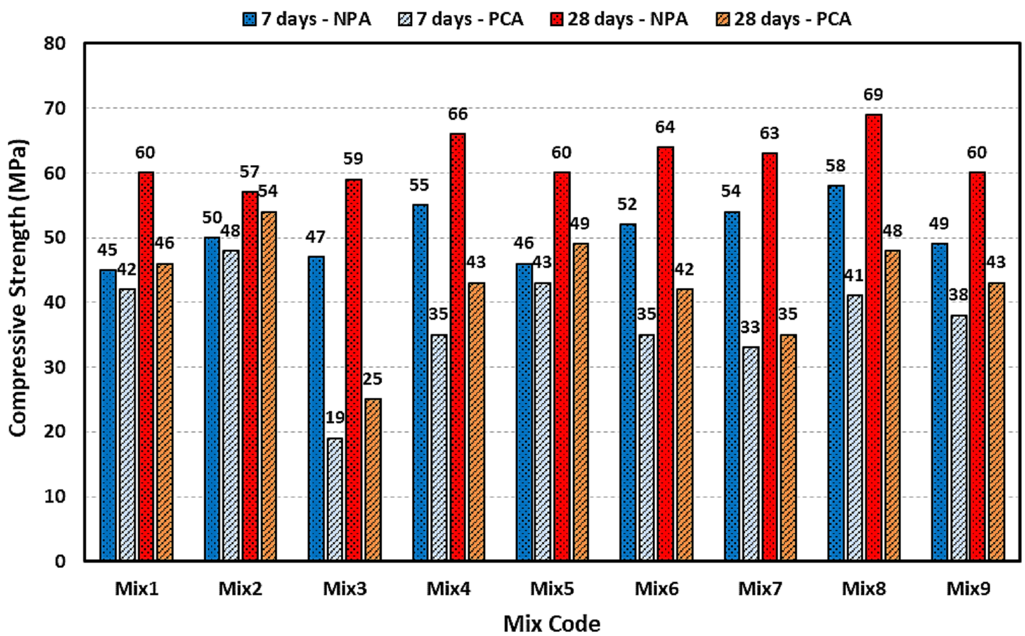

Fig. 21 Comparison between NPA and PCA mixes in the obtained compressive strength results

Table 15 Comparison between NPA and PCA mixes in the obtained optimum levels for the 28-day compressive strength

Admixture type	Optimum level			Maximum obtained 28-day compressive strength (mm)
	GGBFS content (kg/m^3)	W/B ratio	Admixture dosage (%)	
NPA	550	0.3	1.0	69
PCA	450	0.4	2.0	54

because of their formulation that does not transform in alkaline NaOH solution (Xiong & Guo, 2022). This agreed with the study that concluded that the polycarboxylate-based superplasticizers were the most adequate kind when utilizing fly ash-based geopolymer activated by NaOH and Na_2SiO_3 activators. However, when utilizing NaOH solution activated slag, the naphthalene-based superplasticizers were the most adequate kind (Xiong & Guo, 2022). It was concluded that, the factors that influence the compatibility of water reducers and geopolymers were the characteristics of the precursor particles and the water reducer admixtures and alkaline activator solutions (Xiong & Guo, 2022).

Regarding the mechanism of naphthalene-based water reducer in slag-based geopolymer, naphthalene-based water reducer is adsorbed on slag powder particles, then the particles are dissipated by electrostatic repulsion. However, regarding the mechanism of PCA, the lateral chains still remain bound.

Table 15 shows that the NPA has a better effect in the case of high GGBFS content, 550 kg/m^3, and low W/B ratio, 0.3, even if a low dose is used, 1%, compared to PCA which needs a large dosage with lower GGBFS content and higher W/B ratio.

4 Conclusions

This paper investigated the most effective parameters on the workability of GPC including GGBFS content, water to binder ratio, and dosage of different types of chemical admixtures, Naphthalene-Based Admixture (NPA) and Polycarboxylate-Based Admixture (PCA), using Taguchi approach and Analysis of Variance (ANOVA) analysis. This study will enhance the engineering properties of geopolymer concrete for use in the concrete industry and thus be a good and successful alternative to cement-based concrete. Based on the results from this study, the following conclusions were obtained:

- The efficiency of naphthalene-based admixtures (NPA) on improving the workability, in terms of initial slump value and slump loss rate, of the geopolymer concrete mixes was better than that of polycarboxylate-based admixtures (PCA). The NPA-based mixes achieved the best initial slump value of 200 mm and the lowest rate of slump loss (90 mm after 15 min and 55 mm after 20 min), while the best PCA-based mix achieved an initial slump value of

120 mm and a rate of slump loss (10 mm after 15 min and zero after 20 min).

- Using NPA, in the geopolymer concrete, improved the compressive strength compared to PCA. The NPA-based mixes achieved the highest 28-day compressive strength of 69 MPa, with about 27.8% more than the highest 28-day compressive strength achieved by the PCA-based mixes (54 MPa).
- Among the studied parameters, the GGBFS content was the most significant parameter that affected both workability and compressive strength of NPA-based mixes, while the admixture dosage and W/B ratio were the most significant parameters that affected the workability and compressive strength of PCA-based mixes, respectively.

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Author contributions
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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
No competing interests exist in the submission of this manuscript, and manuscript is approved by all authors for publication. The author declares that the work described was original research that has not been published previously, and not under consideration for publication elsewhere.

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