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INFLUENCE OF SUPERPLASTICIZERS ON THE PERFORMANCE OF GEOPOLYMER CONCRETE DEVELOPED BY A BINARY-WASTE BINDER

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ABSTRACT

Geopolymer Concrete (GPC) has emerged as a sustainable alternative to traditional cement-based concrete owing to its lower carbon footprint and utilization of industrial by-products. However, challenges related to its workability persist, limiting its widespread adoption in structural applications. This study investigates the effect of 4 different types of superplasticizers, three naphthalene-based and one polycarboxylate-based, on the workability and compressive strength of binary waste-based GPC, aiming to improve its fresh-state properties. The reference mix comprised a binder content of 450 kg/m³, consisting of 60% ground granulated blast furnace slag (GGBFS) and 40% waste glass powder (WGP), with a water-to-binder ratio (W/B) of 0.45, a solution modulus (Ms) of 1, and a sodium oxide (Na_2O) content of 9% by binder weight. The superplasticizers were used at a fixed dosage of 2% by weight of the binder. The workability was assessed through slump and slump loss tests. The findings revealed that the initial slump of the developed mixes was similar to the reference mix; however, slump loss results indicated that the admixtures used in this study were ineffective in extending the duration of workability retention of GPC mixes, suggesting poor compatibility with GPC compared to conventional cement-based concrete. Moreover, most of the tested admixtures significantly reduced the compressive strength of the GPC mixes compared to the reference mix; expect for the mix incorporating the naphthalene-based admixture Type G (low-range water reducer), which attained a 28-day CS of 42.9 MPa, closely matching that of the reference mix.

KEYWORDS: Slag, Glass Powder, Admixtures, Slump, Compressive Strength.

تأثير الملدنات الفائقة على أداء الخرسانة الجيوبوليمرية المطورة باستخدام مادة رابطة ثنائية من مخلفات الصناعة

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الملخص

نشأت الخرسانة الجيوبوليمرية كبديل مستدام للخرسانة التقليدية المعتمدة على الأسمنت، وذلك بفضل بصمتها الكربونية المنخفضة واستخدامها لمخلفات الصناعة كمواد بديلة للأسمنت. ولكن مع ذلك، لا تزال التحديات المتعلقة بقابلية التشغيل للخرسانة الجيوبوليمرية قائمة، مما يحد من انتشار استخدامها في التطبيقات الانشائية. ويهدف هذا البحث إلى دراسة تأثير أربعة أنواع مختلفة من الإضافات الملدنة الفائقة: ثلاثة أنواع من مشتقات النفثالين وواحدة من

مشتقات البولي كربوكسيليت؛ على قابلية التشغيل ومقاومة الضغط للخرسانة الجيوبوليمرية المطورة باستخدام مادة رابطة ثنائية من مخلفات الصناعة، وذلك بغرض تحسين خواص الخرسانة الجيوبوليمرية الطازجة. وتضمنت الخلطة المرجعية محتوى من المواد الرابطة يبلغ ٤٥٠ كجم/م٣، والذي يتكون من ٦٠٪ مسحوق خبث الأفران و٤٠٪ مسحوق الزجاج المعاد تدويره، مع نسبة ماء إلى المادة الرابطة قدرها ٠,٤٥ ومعامل المحلول قيمته ١ ومحتوى أكسيد الصوديوم بنسبة ٩٪ من وزن المادة الرابطة. وتم استخدام الإضافات الملدنة الفائقة بجرعة ثابتة تبلغ ٢٪ من وزن المادة الرابطة. ومن ثم، تم تقييم قابلية التشغيل للخرسانة الجيوبوليمرية عن طريق اختبار قياس الهبوط و اختبار قياس معدل الفقد في الهبوط. وأظهرت النتائج أن قيم الهبوط للخلطات المطورة كانت مشابهة لقيمة الهبوط للخلطة المرجعية، في حين أن نتائج اختبار قياس معدل الفقد في الهبوط أظهرت أن الملدنات الفائقة لم يكن لها تأثير ملحوظ في إطالة مدة احتفاظ الخلطة بقوام تشغيلي مناسب، مما يشير إلى عدم توافق هذه الإضافات مع الخرسانة الجيوبوليمرية مقارنةً بالخرسانة الأسمنتية. علاوة على ذلك، فإن معظم أنواع الإضافات المستخدمة في هذه الدراسة أدت إلى انخفاض ملحوظ في مقاومة الضغط للخرسانة الجيوبوليمرية مقارنةً بالخلطة المرجعية، باستثناء الخلطة التي كانت تحتوي على الإضافة المشتقة من النفثالين (مخفض الماء منخفض المدى)، والتي حققت مقاومة ضغط بعد ٢٨ يومًا بلغت ٤٢,٩ ميغاباسكال، وهي قريبة من مقاومة الخلطة المرجعية.

الكلمات المفتاحية : خبث الأفران، مسحوق الزجاج، الإضافات، الهبوط، مقاومة الضغط.

1. INTRODUCTION

Geopolymer concrete (GPC) started gaining significant attention in recent years owing to its environmental advantages. Unlike conventional concrete that utilizes ordinary Portland cement as a binder, GPC utilizes industrial by-products and waste materials (such as ground granulated blast furnace slag (GGBFS) and fly ash) with the incorporation of an alkaline solution to form a binder similar to cement. This not only contributes to the reduction of the carbon emissions of cement production but also helps transforming waste materials into useful applications. Recent studies estimated that the use of GPC as an alternative to conventional Portland cement concrete would result in a reduction of approximately 80% of CO_2 emissions that are associated with the production of concrete [1]. In addition to its environmental benefits, GPC also exhibits good mechanical properties. In fact, several studies reported that slag-based GPC achieved high compressive strength (CS) values [2-4]. However, the poor workability of GPC remained one of the primary challenges hindering its use in structural applications [5,6]. Moreover, researchers investigated the effect of incorporating several waste materials into slag-based geopolymers, such as waste glass powder (WGP) [7-10] and silica fume [11]. However, many of the studies that investigated the workability of binary waste-based GPC have not yielded satisfactory results, preventing its effective use on construction sites. To further address this issue, researchers have begun incorporating various admixtures into the GPC mixes.

Several studies have investigated the influence of superplasticizing admixtures on the fresh-state properties of geopolymers, particularly focusing on slag-based binders. A study on slag-based GPC mixes incorporating naphthalene-based and polycarboxylate-based admixtures has been invistigated [5]. Their results indicated that naphthalene-based admixture consistently exhibited higher slump values, with a maximum slump of 200 mm, representing a 67% improvement over the 120 mm achieved by polycarboxylate-based admixture. Based on these findings, the authors concluded that the naphthalene-based admixture was more effective than the polycarboxylate-based admixture in enhancing the workability of slag-based GPC. Similarly, a sulphonated naphthalene formaldehyde and polycarboxylate ether admixtures has been compared [12]. They found that the naphthalene-based admixture outperformed the polycarboxylate-based admixture not only in terms of mini-slump values but also in extending the setting time. The effect of incorporating three superplasticizer types—naphthalene-based, melamine-based, and polycarboxylate-based—on the relative slump of one-part alkali-activated pastes containing 50% slag and 50% fly ash in the binder has been investigated [13]. Their results revealed a significant enhancement in slump compared to the control mix, with relative improvements of 225%, 249%, and 262% for naphthalene-based, melamine-based, and polycarboxylate-based admixtures, respectively, reporting that the polycarboxylate-based admixture achieved the highest enhancement in workability among the studied admixtures. It has been reported that similar improvements in workability [14]. They observed that the incorporation of 4% polycarboxylate-based superplasticizer to alkali-activated pastes composed of 50% slag and 50% fly ash resulted in a significant delay in both initial and final setting times by 50 and 70 minutes, respectively, indicating a notable effect on the setting behavior of the pastes. It has been found that the spread diameter increased to 175 mm and 173 mm with the addition of 2% polycarboxylate-based and naphthalene-based admixtures, respectively, compared to the 150 mm spread in the reference mix, suggesting a moderate improvement in the flow properties of the mixes [15].

However, not all studies report similarly strong effects. The impact of using different dosages (1%, 2%, and 3% by binder weight) of sulphonated naphthalene formaldehyde and polycarboxylate ether on geopolymer pastes and mortars has been explored [6]. Their findings indicated only marginal improvements in setting times, with the naphthalene-based admixture performing slightly better. Similarly, it has been observed that at typical low dosages (1–2%), water-reducing admixtures had minimal influence on the flow diameter of geopolymer mortars [16]. However, they reported that a more noticeable increase in the flow of the mixtures was observed only at a higher dosage of 5%.

In terms of CS, several studies have shown varying effects of the incorporation of superplasticizer on the mechanical performance of slag-based geopolymers. It has been observed that both melamine-based and polycarboxylate-based admixtures led to a reduction in 28-day CS across all of the alkali-activated mortar mixes tested, particularly in systems containing 100% slag, where CS decreased by 12% and 14%, respectively [17]. Similarly, it has been stated that admixtures, regardless of type or dosage, did not improve CS of slag-based mortars and instead caused a reduction, with the most pronounced decline of 29.7% recorded in a mix containing 5% naphthalene-based admixture [16]. It has also been reported that minor reductions in unconfined compressive strength, with decreases of 6% and 4% at a 2% dosage of solid naphthalene sulfonate and polycarboxylate superplasticizer solution, respectively [15].

In contrast, it has been reported that a positive effect of polycarboxylic ether-based superplasticizer on CS [18]. Their study showed a steady increase in strength with higher dosages, reaching 40.2 MPa at 28 days with 3% dosage, representing approximately a 10.4% increase in CS compared to the mix without any admixture.

The inconsistencies in prior findings highlight the lack of clarity regarding the effectiveness of superplasticizers in slag-based geopolymer systems; while some studies report notable improvements in workability, others find their impact to be limited or insignificant. Additionally, most research has focused on the effect of superplasticizers on slag-based geopolymer pastes and mortars, with limited investigation into slag-based geopolymer concrete. Furthermore, the influence of superplasticizers on the workability of slag-based geopolymers has mostly been assessed through slump and setting times, yet their effect on the rate of slump loss over time, which is an important factor for evaluating the workability retention of GPC, remains underexplored.

This study, which is part of an ongoing research program, aims to investigate the effects of incorporating various types of superplasticizing admixtures into GPC with GGBFS and WGP as binders. The research focuses on evaluating the influence of these admixtures on the initial slump, the rate of slump loss over time, and the compressive strength of GPC, with the goal of developing a comprehensive understanding of their role in enhancing both the fresh and mechanical properties of the GPC, thereby promoting its practical use in structural applications.

2. EXPERIMENTAL PROGRAM

2.1. Materials

The main components of GPC utilized in this study are: GGBFS, WGP, coarse aggregate, fine aggregate, alkaline activators (sodium silicate and sodium hydroxide), water, and admixtures. GGBFS is a by-product of the steel manufacturing process, while WGP is a by-product obtained from glass manufacturing. X-ray fluorescence (XRF) analysis was performed on both GGBFS and WGP to determine their chemical composition. The results of the XRF analysis showed that GGBFS is mainly composed of SiO_2, CaO and Al_2O_3 which represent approximately 39.15%, 33.75%, and 14.07% of its mass, respectively. On the other hand, WGP is primarily composed of SiO_2 which represents 98.69% of its mass. Coarse aggregate in the form of crushed coarse aggregate (20 mm nominal maximum size) was used, while fine natural sand (fineness modulus = 2.55) was utilized as fine aggregate. The specific gravity of coarse aggregate was found to be 2.61, while the fine aggregate had a specific gravity of 2.63. Moreover, a mixture of sodium hydroxide solution and liquid sodium silicate served as the alkaline activator for the GPC mixes. The chemical composition of sodium hydroxide (SH) consisted of 60.25% Na_2O and 39.75% H_2O, whereas the sodium silicate (SS) was composed of 57% H_2O, 31% SiO_2 and 11.98% Na_2O. Moreover, 4 different types of superplasticizer admixtures were used to enhance the workability of the GPC mixes: naphthalene-based superplasticizer type F, naphthalene-based superplasticizer type G (low-range water reducer), polycarboxylate-based superplasticizer type G, and naphthalene-based superplasticizer type G (mid-range water reducer). **Fig. 1** illustrates samples of the admixtures used in this study. Moreover, the solid content of each admixture was determined by weighing a sample of each admixture to record its initial weight. The results of the solid content (% by mass) of each admixture are indicated in **Table 1**.

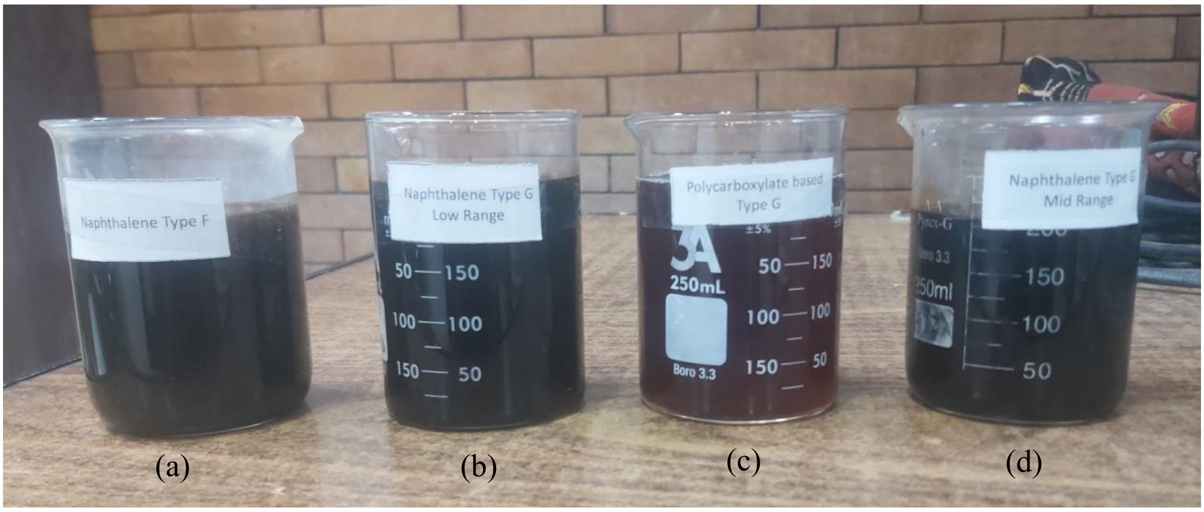

Fig. 1: Admixtures used in the production of GPC mixes
(a) Naphthalene-based superplasticizer type F, (b) Naphthalene-based superplasticizer type G (low-range water reducer), (c) Polycarboxylate-based superplasticizer type G, (d) Naphthalene-based superplasticizer type G (mid-range water reducer)

Table 1: Solid content of utilized admixtures

Admixture Type	Solid content (% by mass)
Naphthalene-based superplasticizer Type F	41.3
Naphthalene-based superplasticizer Type G (low-range water reducer)	32
Polycarboxylate-based superplasticizer Type G	42.7
Naphthalene-based superplasticizer Type G (mid-range water reducer)	35

2.2. Mixes Design and Proportions

This study aims to investigate the effect of utilizing different types of superplasticizing admixtures on the workability and CS of GPC. The reference mix (Mix-0) used in this study had the following mixing parameters: a binder content of 450 kg/m^3, consisting of 60% GGBFS and 40% WGP, with a W/B of 0.45, a solution modulus (Ms) of 1, and a sodium oxide (Na_2O) content of 9%. The reference mix was selected based on prior experimental work which aimed to optimize the ratio of GGBFS to WGP in the GPC binder. This mix was the one that demonstrated optimal performance, combining both good workability and satisfactory CS. However, the workability results were still limited compared to ordinary Portland cement concrete. Hence, 4 new mixes were developed in this study by using 4 different types of admixtures while maintaining the same design parameters as Mix-0. All admixtures were added at a fixed dosage of 2% by weight of binder, derived from the average recommendations of the admixtures data sheets. The water content of the admixture was subtracted from the free water present in the mix to maintain a constant water-to-binder ratio (W/B) across all mixes. The design parameters of the mixes are presented in **Table 2**. Moreover, **Table 3** indicates the proportions of the mixes used in this study.

Table 2: Design Parameters of Mixes

Mix ID	Superplasticizer Type	Binder content (Kg/m^3)	GGBFS: WGP (%)	Na_2O* (%)	Ms**	W/B	C.A:F.A*** (by weight)	S.P. Dosage**** (%)
Mix-0	---	450	60:40	9	1	0.45	2:1	---
Mix-$_{N.F.}$	Naphthalene-based superplasticizer type F	450	60:40	9	1	0.45	2:1	2
Mix-$_{N.G.L.}$	Naphthalene-based superplasticizer Type G (low range water reducer)	450	60:40	9	1	0.45	2:1	2
Mix-$_{P.G.}$	Polycarboxylate-based superplasticizer Type G	450	60:40	9	1	0.45	2:1	2
Mix-$_{N.G.M.}$	Naphthalene-based superplasticizer Type G (mid-range water reducer)	450	60:40	9	1	0.45	2:1	2

* Percentage from Binder Content.
** Solution modulus (SiO_2/Na_2O)
*** C.A:F.A means the coarse aggregate to fine aggregate ratio by weight
**** Superplasticizing admixture percentage by weight of binder

Table 3: Proportions of Mixes (kg/m^3)

Mix ID	GGBFS	WGP	SS	SH	Water	F.A.*	C.A.**	S.P.***
Mix-0	270	180	131	41	112	539	1078	0
Mix-$_{N.F.}$	270	180	131	41	106	535	1078	9
Mix-$_{N.G.L.}$	270	180	131	41	106	536	1078	9
Mix-$_{P.G.}$	270	180	131	41	106	535	1078	9
Mix-$_{N.G.M.}$	270	180	131	41	106	536	1078	9

* F.A. : Fine Aggregates.
** C.A.: Coarse Aggregates.
*** S.P.: Superplasticizing admixture.

2.3. Mixing Protocol

The alkaline solution was prepared by dissolving the sodium hydroxide in the mixing water, and the solution was set aside to cool down. Then, the sodium silicate was added to the solution, which was left to cool down once more. The dry mix, consisting of GGBFS, WGP, coarse and fine aggregates, was mixed in the concrete mixer. After that, the admixture was added to the alkaline solution, and the resulting mixture was then added to the dry mix. Finally, the GPC mix was mixed thoroughly in the mixer until a homogenous consistency was achieved.

2.4. Specimens Preparation and Testing

In this study, slump and slump loss measurements were carried out in order to evaluate the workability of the developed GPC mixes. The slump and slump loss tests were carried out according to ASTM C143 [19]. The value of the initial slump was recorded immediately after mixing. Moreover, for slump loss, the slump value was measured at intervals of approximately 5 minutes until the mix became unworkable. On the other hand, the CS test was performed according to BS EN 12390-3 [20]. Cubes with dimensions 100x100x100 mm were prepared in accordance with BS EN 12390-1 [21], were cast into molds and allowed to set for 24 hours; then the cubes were demolded and left in the laboratory for ambient curing until the age of testing. The GPC mixes were tested after 1, 3, 7, and 28 days to assess their CS.

3. RESULTS AND DISCUSSION

3.1. Workability

3.1.1. Slump

The slump test results for the developed mixes using admixtures, in comparison with the reference mix (Mix-0), are presented in **Fig. 2**. As clearly indicated in the figure, all GPC mixes exhibited similar behavior, with slump values ranging from 225 mm to 250 mm. The mix incorporating the polycarboxylate-based superplasticizer Type G (Mix-P.G.) recorded the lowest slump value of 225 mm, while Mix-N.G.M., incorporating the naphthalene-based superplasticizer Type G (mid-range water reducer), exhibited the highest initial slump value of 250 mm. This indicates that the effect of the utilized admixtures on the initial slump of the GPC was negligible.

These findings are consistent with those obtained before by [16], who emphasized that commercial superplasticizers exert minimal influence on the fresh-state properties of geopolymer mixtures. Likewise, it has been reported that the improved flowability achieved through superplasticizer incorporation was notably less significant in geopolymers than in traditional cement-based materials [15].

The limited performance of superplasticizers can be attributed to their instability under the highly alkaline conditions present in the geopolymers [16,22,23]. Another possible explanation is that adsorption of the superplasticizing admixtures onto the precursor particles in SS solution was considerably reduced compared to that in water [15].

Furthermore, it has been noted that the observed increase in flowability with the addition of superplasticizers in GPC mixes was primarily due to the water contained in the superplasticizer, rather than the superplasticizer itself [16]. This aspect, according to [16], has often been overlooked in previous studies. However, in this study, the water content of the admixtures was accounted for by subtracting it from the free water, ensuring a constant water-to-binder ratio (W/B) across all implemented mixes. This approach hence explains why the addition of superplasticizers did not show any significant effect.

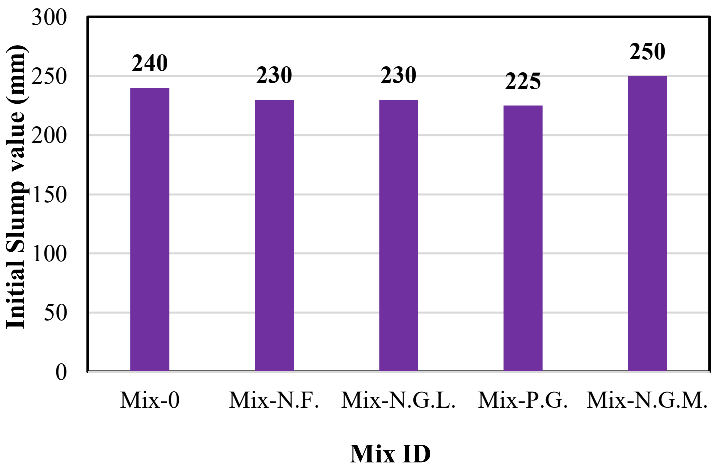

Fig.2: Initial Slump of GPC mixes

3.1.2. Slump Loss

The slump loss behavior of the developed mixes, in comparison with the reference mix (Mix-0), was the primary focus of this study. This study aimed to investigate whether the incorporation of a specific admixture could further extend the time during which the mix maintained its workability.

The mixes were considered unworkable when they reached a slump value of 50 mm. The results of slump loss with time of the developed GPC mixes are presented in **Fig. 3**.

Despite having initial slump values close to Mix-0, the developed mixes incorporating admixtures showed a faster rate of slump loss, as illustrated in **Fig. 3**. In fact, the rate of slump loss of Mix-N.F., incorporating naphthalene-based superplasticizer Type F, was much higher than Mix-0, as it reached a slump value of 50 mm after 39 minutes only, compared to Mix-0 that recorded a duration of 52 minutes. Moreover, Mix-N.G.L., Mix-P.G. and Mix-N.G.M. became unworkable after 47 minutes, 50 minutes and 46 minutes, respectively, which are relatively close to but still lower than Mix-0. The poor performance of commercial admixtures in improving the slump loss with time in GPC may be attributed to the instability of superplasticizers in highly alkaline conditions [16], highlighting their lack of compatibility with GPC when compared to conventional cement-based concrete.

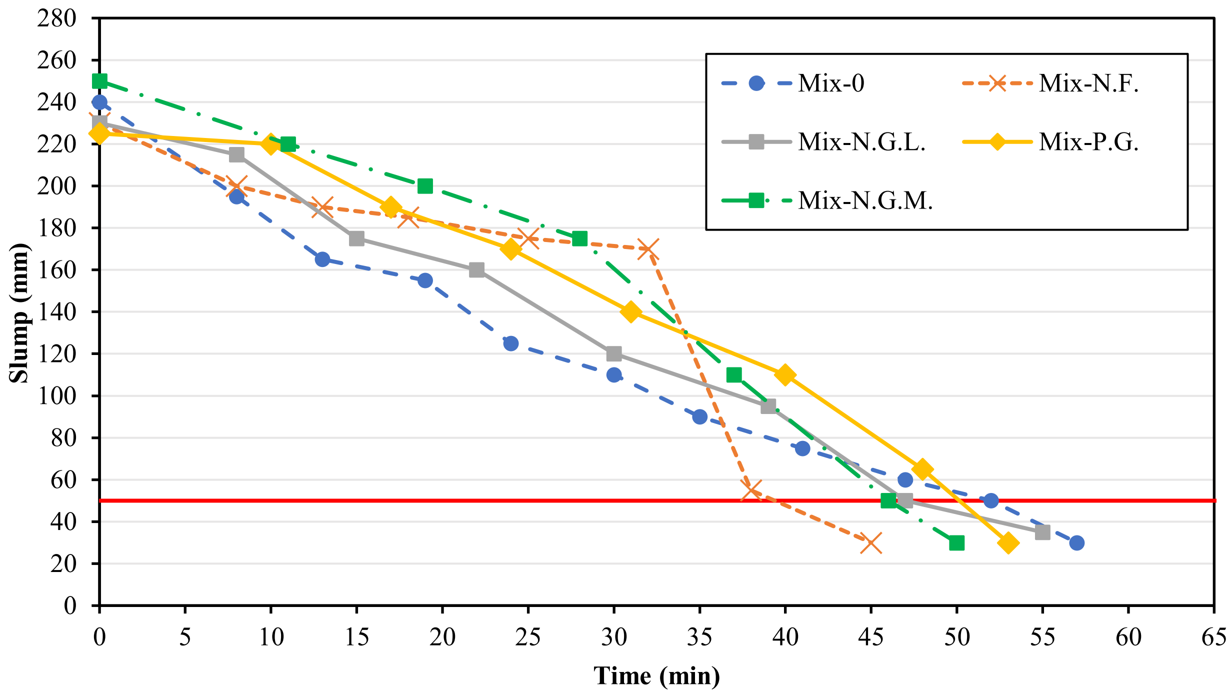

Fig. 3: Slump loss with time of the GPC mixes

3.2. Compressive Strength

The recorded CS results of the GPC mixes at 1, 3, 7, and 28 days are presented in **Fig. 4**. As depicted in the figure, Mix-N.G.L achieved a 28-day CS of 42.9 MPa, which was nearly identical to that of the reference mix (Mix-0). However, Mix-N.G.M. and Mix-N.F. attained a 28-day CS of 36.3 MPa and 35.75 MPa, respectively, demonstrating a reduction of 16.5% and 17.5%, respectively, compared to Mix-0. Moreover, Mix-P.G., incorporating polycarboxylate-based superplasticizer Type G, recorded the lowest 28-day CS with a value of 29.63 MPa, exhibiting a reduction of 32% compared to Mix-0. It is clear from the results that the used superplasticizers did not exert a positive influence on the CS of the slag-based GPC.

A similar pattern was also observed by [16], who reported that slag mortar mixes incorporating naphthalene-based and polycarboxylate-based superplasticizers exhibited lower CS results compared to the reference mix. However, it is evident from **Fig. 4** that the effect of the reduction in CS was more pronounced in the mix containing polycarboxylate-based admixture, which complies with findings of [5] who conducted a comparison between the effect of incorporation of naphthalene-based and polycarboxylate-based admixtures on the CS of slag-based GPC and reported that the naphthalene-based admixture demonstrated better effectiveness and compatibility with the slag-based GPC, resulting in a 27.8% higher compressive strength compared to the polycarboxylate-based admixture. This also comes in agreement with the results obtained before

[17], which stated that the addition of polycarboxylate-based admixture in alkali-activated slag pastes reduced the 28-day CS by 14% compared to the reference mix.

A possible explanation for the reduction in the CS of the GPC mixes is that the incorporation of superplasticizers alters surface activity and can entrap air bubbles, thereby reducing the geopolymer's compactness and mechanical strength [17,15].

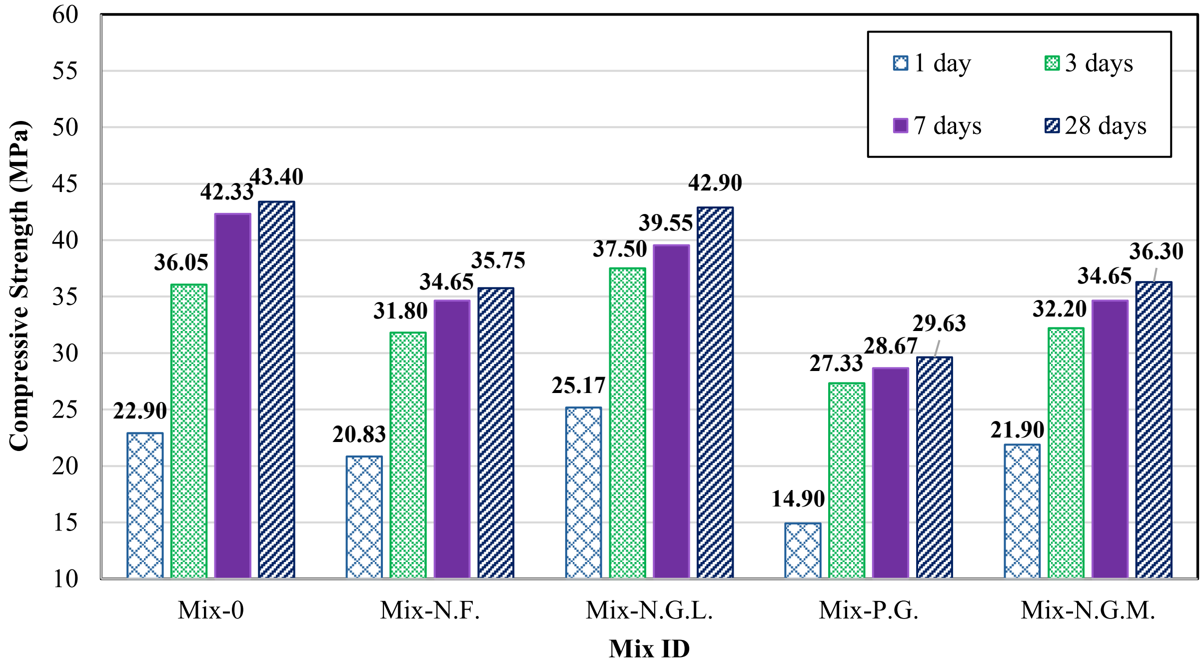

Fig.4: 1,3,7,28 days Compressive Strength (CS) of GPC mixes

CONCLUSIONS

This study focused on assessing the effect of utilizing 4 different types of admixtures on the initial slump, the slump loss and the CS of binary waste-based GPC. Based on the findings, the following conclusions can be derived:

- The utilized admixtures had a negligible effect on the initial slump of the GPC, given that all tested GPC mixes, including the reference mix, exhibited similar behavior, with slump values ranging from 225 mm to 250 mm.
- The mix incorporating the polycarboxylate-based superplasticizer (Type G) became unworkable after 50 minutes, demonstrating no significant loss in the total duration of workability retention compared to the reference mix. However, this mix recorded the lowest 28-day CS with a value of 29.63 MPa, reflecting a significant reduction of 32% compared to the reference mix.
- The incorporation of the naphthalene-based superplasticizer (Type F) had an adverse effect on both workability retention and CS of the GPC. In fact, it led to faster stiffening of the GPC, as this mix became unworkable after just 39 minutes, while the reference mix remained workable for 52 minutes. Additionally, it recorded a 28-day CS of 35.75 MPa, reflecting a 17.5% reduction relative to the reference mix.
- The mix containing the naphthalene-based superplasticizer Type G (low-range water reducer) became unworkable after 47 minutes, which was relatively close to but still lower than the reference mix. However, this mix attained a 28-day CS of 42.9 MPa, which was nearly identical to that of the reference mix, yielding the best performance among the tested admixtures.

- The slump loss results indicate that the admixtures used in the developed mixes did not extend the workability duration as intended. Instead, they led to a faster slump loss compared to the reference mix. This indicates a lack of compatibility between the used admixtures and GPC when compared to conventional cement-based concrete, which is possibly caused by the instability of these admixtures in the highly alkaline environment of GPC.

FUTURE RECOMMENDATIONS

Based on the previous findings of this study, the following recommendations are proposed for future research:

- The use of naphthalene-based superplasticizer Type G (low-range water reducer) at a higher dosage could be investigated, as it did not significantly affect the CS of the GPC, and its slump loss results were comparable to the reference mix.
- Further investigation into other types of admixtures is recommended, as they may exhibit better compatibility with GPC.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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