Asian Journal of Civil Engineering (2024) 25:4893–4910
https://doi.org/10.1007/s42107-024-01087-9

RESEARCH

Effects of alkaline concentration on workability and strength properties of ambient cured green geopolymer concrete

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Received: 16 January 2024 / Accepted: 1 June 2024 / Published online: 2 July 2024

Abstract

Geopolymer concrete, made with by-products from industrial waste, is a promising construction material that reduces carbon dioxide emissions and eliminates the need for natural resources used in traditional Portland cement. Despite numerous studies conducted over the years to investigate different characteristics of geopolymer concrete, there remains a lack of understanding on how various factors affect its properties. In this investigation, we explore the setting time, workability and compressive strength of ambient-cured geopolymer concrete, using GGBS and class F fly ash as geopolymer binder. We consider the quantity of sodium hydroxide (SH), fly ash to GGBS ratio and binder content to alkaline solution ratio (AS/B) as influencing factors. Based on experiments with 45 mixes of geopolymer concrete, we found that increasing SH concentration and GGBS content, as well as reducing AS/B ratio, decreased workability by about 60% and shortened setting time by 63–71%. However, a reduction in AS/B ratio and increased replacement of GGBS led to improved compressive strength. Compared to mixes with various SH concentrations, a slight decrease in strength was observed at higher SH concentrations (10 M and 12 M). These findings will be useful to produce geopolymer concrete components with greater strength.

Keywords GGBS · Fly ash · Workability · Geopolymer concrete · Compressive strength · Initial and final setting time

Introduction

The global population growth and rising insistence for buildings has led to a surge in concrete production and consumption, with ordinary Portland cement being the conventional choice for construction. Conventionally, the Portland cement is utilized for the making of concrete to meet the infrastructure development. Because of this around 3 billion tons of cement is manufactured per year in global level. Cement manufacturing is the cause for around 8 percent emission of CO_2 (Aslani, 2015). This is also the primary source of environmental degradation and also for depletion of natural resources (Ravikumar et al., 2010). For these reasons, the researchers are focusing to utilize the supplementary cementitious materials and also trying to invent the green materials to promote sustainability in the construction field (Zhang et al., 2014). Geopolymer, coined by Prof. Davidovits in the 1970s (Avudaiappan et al., 2023a; Davidovits, 2005),

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is an inorganic binding material that does not necessarily require cement for the production of concrete. Instead, it relies on reactive alumina-silica rich source materials and an activating solution (Jayanthi et al., 2023; Topark-Ngarm et al., 2014). Unlike conventional cement concrete, which obtains strength through the C–S–H gel formation, geopolymer concrete achieves strength through the geopolymerization of leachable alumina and silica precursors. This process involves three stages: dissolution of oxide compounds from Al-Si rich materials in an alkaline environment, orientation of dissolved compounds proceed by gelation, and polycondensation of the amorphous gel to form stable 3-D alumino-silicate structures (Ma et al., 2018). Some of the examples for alumina and silica rich materials are Rice hush ash, silica fume, GGBS fly ash etc. Alkaline activators employed consist of a combination of sodium silicate solution or potash-based activating solution with sodium hydroxide (SH). (Mehta & Siddique, 2017). Geopolymer concrete based on fly ash requires heat curing to initiate the polymerization reaction. However, studies have shown that the temperature required (around 65 to 80 °C) to achieve comparable mechanical properties with conventional cement concrete is not practical for real-world applications (Mehta & Siddique, 2016; Prakash et al., 2023; Ryu et al., 2013; Shehab et al., 2016). To overthrow this issue, researchers has explored the addition of calcium materials, such as GGBS, calcined clay, and calcium chloride, to geopolymer systems. This not only reduces the energy and cost of heat curing but also widens its applications in the construction field (Gao et al., 2015; Kuranlı et al., 2022; Rafeet et al., 2019; Rekha, 2021; Sheeba et al., 2023a).

Previous research has mainly focused on examining the effects of GGBS geopolymer concrete based on fly ash (). Nath and Sarker (2014; Arunachalam & Henderson, 2023) studied the effects of slag replacement and liquid alkaline type on the hardened and fresh geopolymer, but they did not investigate the solution of alkaline concentration and ratio of alkaline solution (AS/B) to binder content. Lee and Lee (Lee & Lee, 2013) proposed an optimum slag of 15–20% of the total binding material by only considering the strength properties and setting of geopolymer concrete bases on fly ash-GGBS. Despite slag's substantial influence on geopolymer concrete's workability when mixed with fly ash, this attribute was disregarded while slag content was being determined. Sheebha et al. (2023b) investigated the setting time of geopolymer concrete and compressive strength based on fly ash-based by incorporating GGBS content from 0 to 50%, but workability properties were not given much attention.

In addition to the slag replacement level, other factors such as combination of alkaline solution and sodium hydroxide to ratio of binder are also crucial in finding the optimum mix of geopolymer concrete. Therefore, more investigation is necessary to explore the mechanical properties, workability and setting time of geopolymer concrete.

While utilization of fly ash-based mixes has shown promise in improving hardened and fresh concrete properties, there is still much to learn about many phenomenon which influence the performance of geopolymer systems. One major issue with geopolymer concrete is its slow strength development and setting. To get a deeper understanding on outcome of various parameters like setting time, workability, and compressive strength, this studies intent to comprehensively examine the ustilization of GGBS and fly ash in geopolymer concrete. Specifically, the study will investigate the impact of several factors such as AS/B ratio, sodium hydroxide concentration and GGBS replacement levels under ambient curing conditions. The source materials utilized for this study include GGBS and flyash, while the alkaline solution will be produced by combining sodium silicate with sodium hydroxide.

The research investigate utilization of GGBS and fly ash as source materials for geopolymer binder in concrete has significant implications for the construction industry. This innovative approach to concrete production eliminates the need for traditional cement, The outcome from the study highlight the influence parameters of geopolymer concrete, including compressive strength, setting time, and workability. The findings demonstrate that increasing GGBS content and reducing AS/B ratio can lead to improved compressive strength, making it a alternative to traditional concrete. However, this study also highlights the trade-offs between setting time, workability and strength when using geopolymer concrete. This study offers valuable insights into the determinants that impact the characteristics of geopolymer concrete. Such insights can facilitate the creation of construction materials that are more environmentally friendly, with decreased carbon emissions and enhanced longevity. The novelty of this study lies in its comprehensive exploration of the effects of various factors on the properties of geopolymer concrete, particularly focusing on the influence of GGBS content, sodium hydroxide concentration, and alkaline solution to binder ratio. While previous studies have investigated individual factors, our research systematically examines their combined effects, providing valuable insights into optimizing geopolymer concrete production. This holistic approach distinguishes our study from existing literature.

Materials and methods

Materials

The fly ash is procured from Tuticorin thermal plants, Tamil Nadu, India. The substance exhibits a dark grey hue and possesses a specific gravity of 2.20. The study employs GGBS as an additional binding material, which possesses a specific gravity of 2.80 and exhibits an off-white color. The study utilized fly ash and GGBS, as illustrated in Figs. 1 and 2. And Fig. 3 shows the particle size distribution of fly ash and GGBS and aggregates. The fly ash and GGBS chemical properties are presented in Table 1. The present study involved the addition of GGBS at different proportions, namely 0%, 25%, and 50%, to the overall binder content. Aggregates play a critical role as inert components in the construction of concrete. In this investigation, a blend of granite blue metals with dimensions of 20 mm and 12.5 mm is chosen as coarse aggregate, while fine aggregate is gathered locally and the fine M-sand conforms to zone II of IS 383:2002 (1970). Table 2 presents the physical characteristics of the coarse and fine aggregates that were utilized.

The activating solution utilized for this experimentation is sodium-base, having a fixed ratio of 2.5 for Na_2SiO_2/NaOH solution, as per previous research (Deb et al., 2014; Fang et al., 2018; Prakash et al., 2021). Sodium hydroxide solution was prepared using commercially available pellets with 98% purity, as shown in Fig. 4, and the solution molarity was varied from 4 to 12 M. The solution of alkaline was produced by combining the SH with SS solution, which is readily available in the market, as illustrated in Fig. 5.

Sodium hydroxide solution with various molarity were prepared by diluting with potable water conforming to IS 456: 2000 (2000). To increase workability, geopolymer concrete uses a super-plasticizer known as Poly Carboxylic Ether (PCE).The pH of superplasticizer ranges from 6 to 7 with a specific gravity of 1.08. Figure 6 illustrates the chemical combination used in this study (Table 3).

The numerous mixtures geopolymer concrete was evaluated by varying the binder to alkaline solution ratio (0.35, 0.40 and 0.45), GGBS incorporation (0%, 25% & 50%) and concentration of SH (4 M, 6 M, 8 M, 10 M & 12 M). To produce 1 m^3 of concrete geopolymer, SH to SS ratio is kept constant as 1:2.5 (Mehta & Siddique, 2016; Ryu et al., 2013; Shehab et al., 2016) and also 4% of total binder content was used for concreting as super plasticizer quantity. The mixture of fine aggregate of maximum 4.75 mm size, coarse aggregates of 12.5 mm and 20 mm with 35%, 26% and 39% of total aggregate content respectively, were taken as aggregates. By assuming the aggregate ratio of 0.70 in weight of concrete per one cubic meter, the coarse and fine aggregate of size 12.5 mm and 20 mm were calculated as 436 kg/m^3, 498 kg/m^3 and 747 k/m^3. The alkaline solution is partitioned into SH solution and SS solution in accordance with the prescribed ratio of 2.5. Furthermore, the amount of SH solution needed for the required molarity is controlled by the quantity of SH pellets dissolved in potable water as a function of molecular weight, whereas the amount of sodium

Fig. 2 GGBS

Fig. 1 Fly ash

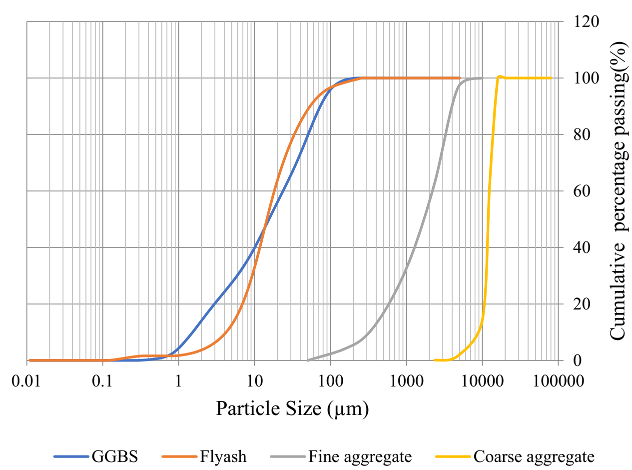

Fig. 3 Particle size distribution of GGBS, fly ash, fine and coarse aggregate

Table 1 Chemical properties of fly ash and GGBS

Source material	SiO_2	Al_2O_3	Fe_2O_3	$Ti\ O_2$	CaO	K_2O	P_2O_5	MgO	$S\ O_3$
Fly ash (%)	55.41	29.69	8.48	2.02	1.39	1.01	0.70	0.45	0.32
GGBS (%)	31.75	16.91	0.61	1.11	39.79	0.47	-	6.23	1.62

Table 2 Fine and coarse aggregate—physical properties

Material	Specific gravity	Fineness modulus	Water absorption (%)
M-Sand	2.72	2.50	0.5
Coarse aggregate of 20 mm size	2.80	7.37	0.2
Coarse aggregate of 12.5 mm size	2.96	6.97	0.4

Fig. 4 Sodium hydroxide in pellet form

Fig. 5 Sodium silicate solution

silicate solution was constant. Heat is released during the dissolution of SH in water. Therefore it should be blended 24 h prior to the mixing of concrete. The prepared alkaline solution is displayed in Fig. 7.

Fig. 6 ViscoCrete: PCE-based chemical admixture

The mixing process for geopolymer concrete was taken out in two steps. In the first step, known as the dry mix, the GGBS and fly ash source materials were blended with the coarse aggregates and fine for 2 min using a drum type mixer machine until homogeneity was achieved. The second step involved the wet mix, during which the super plasticizer and alkaline solution were gradually mixed for 2–3 min. The freshly mixed geopolymer concrete was subjected for workability test using a slump cone apparatus, as shown in Fig. 8. The concrete is immediately placed in cube molds of size 150 mm, as depicted in Fig. 9, and allowed to cure under ambient conditions, as shown in Fig. 10. After 24 h, the cubes are demolded and kept at the room conditions till the testing day. To ensure accuracy, three identical samples were casted for each mix proportion.

Methods

Workability

The concrete's workability is an important factor, and the measurement of slump is a common method for assessing it. In this study a slump cone test on geopolymer concrete including newly mixed GGBS and fly ash, following the guidelines given in IS 1199:2018. The test involved filling the concrete in slump cone at three layers and compacting by tamping rod through 25 blows at each layer. After compaction, excess concrete was removed, and the mould was gently lifted vertically that the concrete subside. The value of the slump was measured by determining the height from the mould to the slipping level of concrete. Testing of slump cone test is illustrated in Fig. 11.

Table 3 Mix proportion of Geopolymer Mixtures in (kg/m^3)

SH molarity	Fly ash	GGBS	Fine Agg	CA- 12.5	CA—20	SH Pellets (kg)	SH solution (Lit)	SS solution	SP (4% Binder)	AS/B
4 M	500	0	435	498	747	8	50	125	20	0.35
	375	125	435	498	747	8	50	125	20	0.35
	250	250	435	498	747	8	50	125	20	0.35
6 M	500	0	435	498	747	12	50	125	20	0.35
	375	125	435	498	747	12	50	125	20	0.35
	250	250	435	498	747	12	50	125	20	0.35
8 M	500	0	435	498	747	16	50	125	20	0.35
	375	125	435	498	747	16	50	125	20	0.35
	250	250	435	498	747	16	50	125	20	0.35
10 M	500	0	435	498	747	20	50	125	20	0.35
	375	125	435	498	747	20	50	125	20	0.35
	250	250	435	498	747	20	50	125	20	0.35
12 M	500	0	435	498	747	24	50	125	20	0.35
	375	125	435	498	747	24	50	125	20	0.35
	250	250	435	498	747	24	50	125	20	0.35
4 M	480	0	435	498	747	9	55	137	19	0.40
	360	120	435	498	747	9	55	137	19	0.40
	240	240	435	498	747	9	55	137	19	0.40
6 M	480	0	435	498	747	13	55	137	19	0.40
	360	120	435	498	747	13	55	137	19	0.40
	240	240	435	498	747	13	55	137	19	0.40
8 M	480	0	435	498	747	18	55	137	19	0.40
	360	120	435	498	747	18	55	137	19	0.40
	240	240	435	498	747	18	55	137	19	0.40
10 M	480	0	435	498	747	22	55	137	19	0.40
	360	120	435	498	747	22	55	137	19	0.40
	240	240	435	498	747	22	55	137	19	0.40
12 M	480	0	435	498	747	26	55	137	19	0.40
	360	120	435	498	747	26	55	137	19	0.40
	240	240	435	498	747	26	55	137	19	0.40
4 M	460	0	435	498	747	10	59	148	18	0.45
	345	115	435	498	747	10	59	148	18	0.45
	230	230	435	498	747	10	59	148	18	0.45
6 M	460	0	435	498	747	14	59	148	18	0.45
	345	115	435	498	747	14	59	148	18	0.45
	230	230	435	498	747	14	59	148	18	0.45
8 M	460	0	435	498	747	19	59	148	18	0.45
	345	115	435	498	747	19	59	148	18	0.45
	230	230	435	498	747	19	59	148	18	0.45
10 M	460	0	435	498	747	24	59	148	18	0.45
	345	115	435	498	747	24	59	148	18	0.45
	230	230	435	498	747	24	59	148	18	0.45
12 M	460	0	435	498	747	28	59	148	18	0.45
	345	115	435	498	747	28	59	148	18	0.45
	230	230	435	498	747	28	59	148	18	0.45

Fig. 7 Sodium-based alkaline solution

Fig. 8 Fresh geopolymer concrete

Fig. 9 Casted specimens

Setting time

The geopolymer concrete time of setting is decisive from Vicat apparatus as per IS 4031 (Part 5)-1988(1988) standard, for measuring both the final and initial times of setting. The test is carried out utilizing a 1 mm square Vicat needle at frequent intervals. The initial setting time refers to the duration that transpires from the moment water is introduced to the binding agent until the point at which the needle of the Vicat apparatus infiltrates the paste of geopolymer at

Fig. 10 Cubes under ambient curing

Fig. 11 Slump cone test on geopolymer concrete

5–7 mm depth from the base of the mould. To measure this, the 1 mm square Vicat needle was replaced with a needle that has a cutting-edge circular attachment. Once the geopolymer paste hardens, the needle is lowered into it, and as it penetrates, an imprint is left behind even while the attachment remains unimpressed. The Vicat apparatus used for finding the final and initial time of setting in geopolymer concrete, shown in Figs. 12 and 13.

Compressive strength

The geopolymer concrete compressive strength is assessed using the parameters specified by IS: 516–1959 (2004). The study employed a Compression Testing Machine (CTM), depicted in Fig. 14, to evaluate compressive strength on geopolymer concrete produced by GGBS and fly ash after 7 and 28 days of curing. The specimens were positioned within the CTM by ensuring that the longitudinal axis of the sample was in alignment with the center thrust of the compression plates. The specimen underwent a gradual and continuous application of load until its failure, without any sudden impact. The concrete specimen's compressive strength

Fig. 12 Initial setting time test

Fig. 13 Final setting time test

was ascertained through the division of the peak load by the cross-sectional area that was undermined. Each test result were determined via collecting the mean of three samples.

Results and discussions

Workability

The geopolymer concrete's workability is generally lesser compared to conventional cement concrete due to presence of silicate's, which makes geopolymer concrete sticky. However, despite having a low slump value, geopolymer concrete

Fig. 14 Compression test on geopolymer concrete cube

can still be effectively compacted on a vibrating table. Based on the compaction condition, the workability of geopolymer concrete is classified as low, medium, or high, depending on the slump value (Prakash et al., 2023). Slump measurement of 90 mm or higher is taken as high workable concrete, while 50–89 mm and less than 50 mm are categorized as medium and low workable concrete. Previous studies have demonstrated addition of GGBS in the binder content enhances the workability of concrete geopolymer (Gao et al., 2015; Mehta & Siddique, 2016; Shehab et al., 2016). This could be due to GGBS angular dimensional shape and rapid reaction of calcium compared to the fly ash spherical shape. Figure 15 illustrates the slump values of geopolymer concrete. The results indicate that the workability of geopolymer concrete based on fly ash-based is higher than that of fly ash-GGBS based geopolymer concrete mixes. The influence of the molar concentration of sodium hydroxide on the rheological properties of geopolymer concrete produced from fly ash is significant. As the SH molarity increases from 4 to 12 M, the slump value of geopolymer concrete based on FA with AS/B ratios of 0.35, 0.40, and 0.45 decreased from 110, 125, and 136 mm to 52, 58, and 61 mm, respectively.

The impact of GGBS addition on workability by geopolymer concrete based fly ash-was studied and is depicted in Fig. 16. From the results it is evident that the inclusion of GGBS results in reduction of workability. At lower concentrations of SH (4 M and 6 M), the addition of 25% and 50% GGBS led to a slump reduction of 4–9% and 9–15%, respectively. When the SH molarity was raised from 8 M, 10 M, and 12 M, the maximum slump reductions for GGBS replacement of 50% were 20%, 52.31%, and 59.62%, respectively, when comparing to the corresponding geopolymer concrete made of fly ash. The reduction in slump is more significant for a 50% GGBS replacement than for a 25% replacement at all AS/B ratios (0.35, 0.40, and 0.45). The minimum value of slump 21 is observed at geopolymer

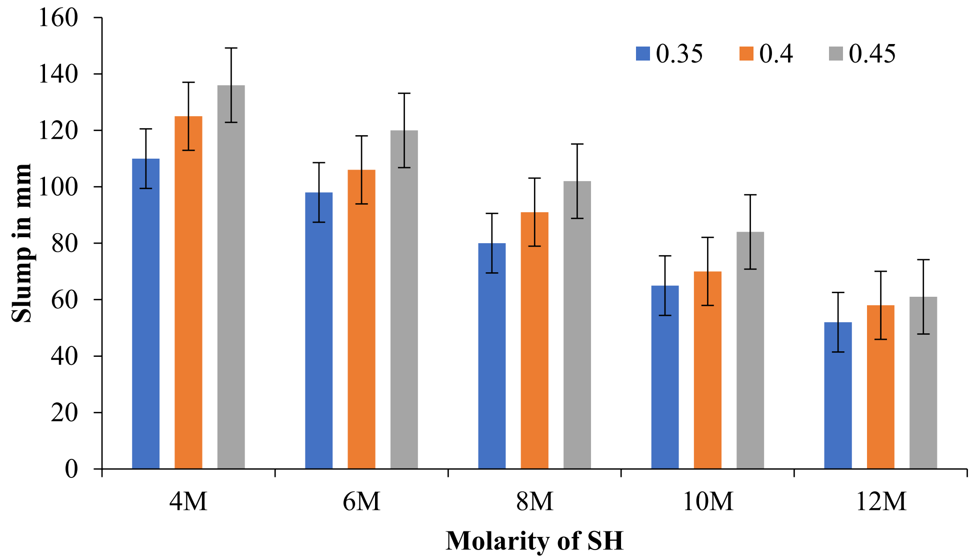

Fig. 15 Slump values of geopolymer concrete based on fly ash

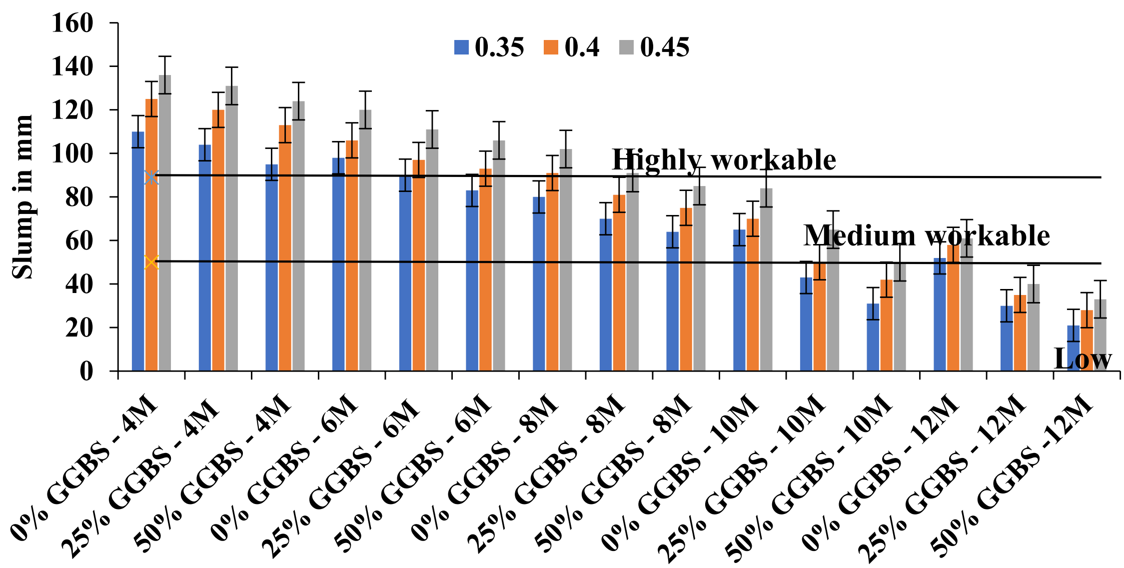

Fig. 16 slump values of different mixes of geopolymer concrete

mix of 12 M with AS/B ratio of 0.35 and GGBS replacement of 50%. The impact of GGBS is more pronounced when molarity levels increased (10 M and 12 M) and an AS/B ratio of 0.35, as reported in previous studies (Fang et al., 2018).

Effects of SH concentration

When the slump values are compared with the different molarities of SH solution, the workability reduces when the molarity rises, is shown in Fig. 15. The study found that the 12 M combinations exhibited a reduction of 69–78 percent when compared to geopolymer concrete consisting of GGBS and flyash with molarity 4 M, irrespective of the AS/B ratio. However, the percentage reduction in slump is rather substantial when the GGBS quantity raised from 25 to 50%. It discovers that the influence of sodium hydroxide molarity was significantly more obvious in mixes with a higher level of GGBS replacement. When the 4 M geopolymer concrete based on GGBS and fly ash mixtures are compared to the 8 M concrete samples, only a 30–33 percent reduction in slump was detected. For AS/B ratios of 0.35 and 0.40, the slump value of 10 M and 12 M concrete mixtures made with GGBS was less than 50 mm. Increasing the SH molarity causes the alkaline solution to become more viscous, which is the primary cause of this phenomenon. (Rafeet et al., 2019).

Effects of AS/B ratio

The effects of AS/B ratio could be noticed well in the concrete mix when varying the percentage of GGBS and concentration of SH and the slump deviation for three different AS/B ratio of 0.35, 0.40 and 0.45 was presented in Figs. 17, 18 and 19, respectively. As demonstrated in the Figs. 16, 17 and 18, the geopolymer concrete with AS/B ratio of 0.35 showcased relatively lower slump values when compared to the other concrete mixtures with 0.40 and 0.45 AS/B ratio. The slump values for the AS/B ratio of 0.45 are in between 136 and 33 mm, whereas the value of slump for the other ratios of 0.40 and 0.35 are in the ranges of 125–28 mm and 120–21 mm, respectively. When AS/B ratio was substituted from 0.45 to 0.40 and 0.45 to 0.35, the highest slump reduction of 23.08 percent and 38 percent was recorded. The results demonstrate the significance of the alkaline activator content in the key parameter for geopolymer concrete workability, which aligns with the outcomes of previous studies. (Gao et al., 2015; Shehab et al., 2016).

Setting time

The setting time is a important property of concrete that refers to the time taken for concrete to become rigid. It could be divided into final and initial time of setting depending on the degree of rigidity. The standard Vicat apparatus is used to determine the setting time of geopolymer paste under laboratory conditions. According to Indian standard recommendations, the final and initial setting time of OPC concrete should be not less than 30 min and not more than 600 min. In this study, all geopolymer concrete mixes had an initial setting time of more than 30 min. However, all fly

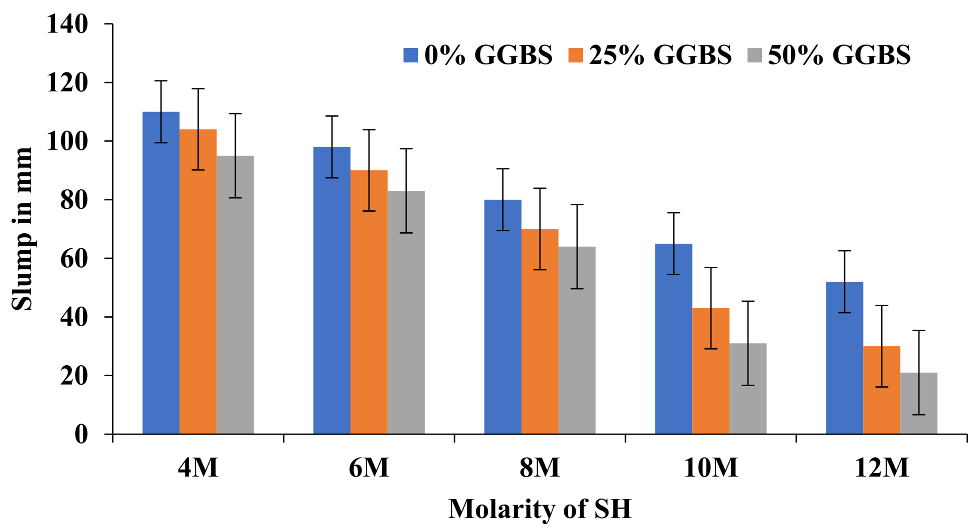

Fig. 17 Slump values of geopolymer concrete with AS/B ratio of 0.35

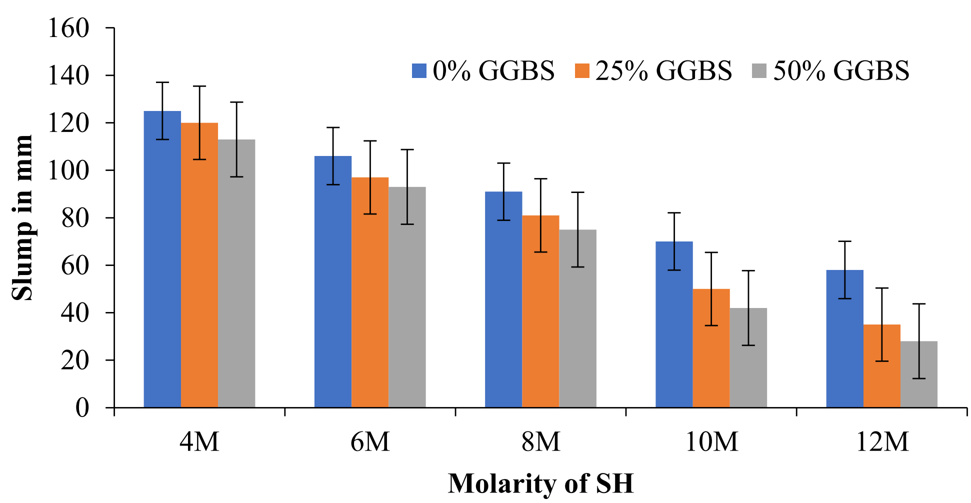

Fig. 18 Slump values of geopolymer concrete with AS/B ratio of 0.40

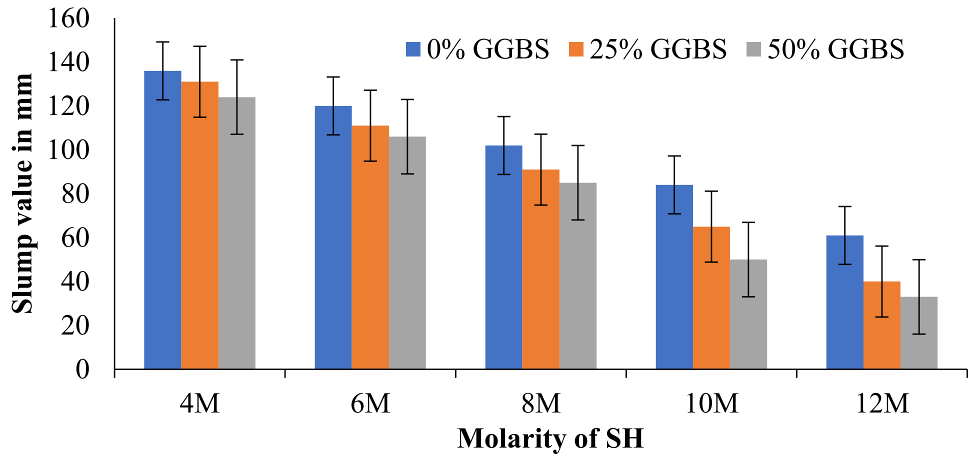

Fig. 19 Slump values of geopolymer concrete with AS/B ratio of 0.45

ash and GGBS based geopolymer concrete mixes, except the fly ash-based geopolymer concrete, achieved final setting within 10 h.

Effects of fly ash to GGBS ratio

In this experimental investigation, Figs. 20 and 21 illustrate the variation in initial and final setting times for different slag percentages of geopolymer pastes, AS/B ratios, and SH concentrations. The results show that final and initial setting time dramatically decreased for incorporation of GGBFS to the mixtures. Geopolymer made solely of fly ash exhibited an extremely long initial and final setting time of 245–480 min, which is consistent with previous research (Hadi et al., 2019; Leonard Wijaya & Jaya Ekaputri, 2017; Mallikarjuna Rao & Gunneswara Rao, 2015). The initial setting times for mixtures containing 25% GGBS and lower SH concentrations, such as 4 M and 6 M, ranged from 145 to 300 min. However, when the amount of GGBS increased to 50%, the corresponding values decreased to 110–235 min. The use of higher molarities of SH, such as 8 M, 10 M, and 12 M, reduced the initial setting time by 60–80% compared to geopolymer paste without GGBS. Additionally, the incorporation of GGBS into the geopolymer pastes decrease the range of final setting time from 1420–1100 min to 385–90 min, 1600–1420 min to 455–100 min, and 1680–1450 min to 480–108 min for AS/B ratio from 0.35, 0.40, and 0.45. In comparison to the fly ash-based geopolymer paste, the final

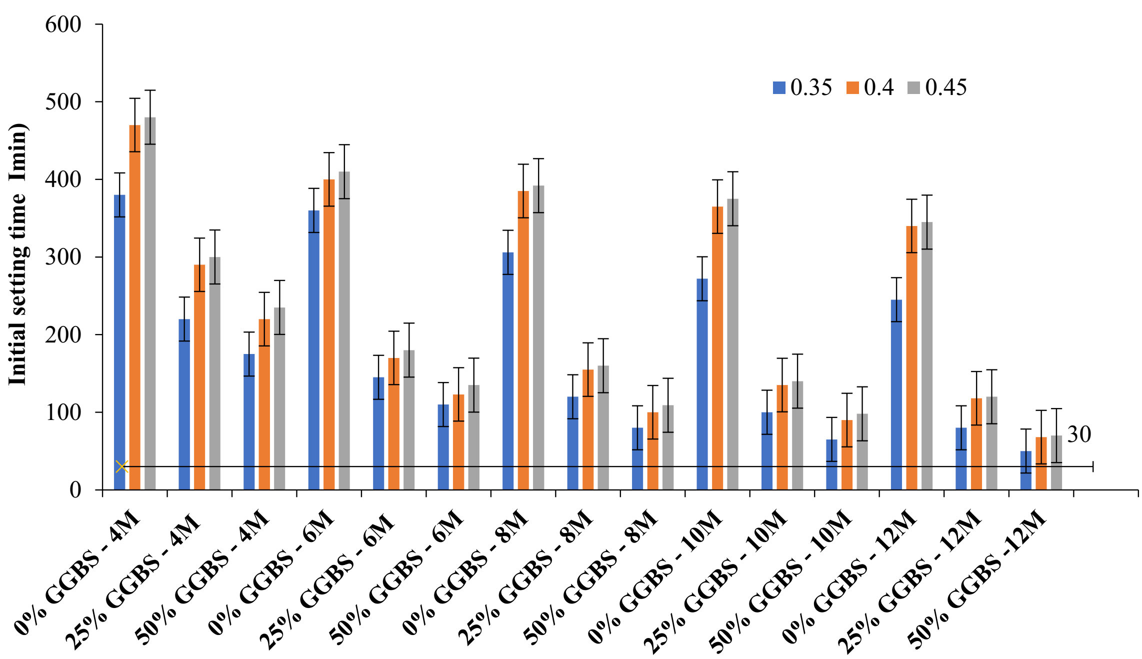

Fig. 20 Initial setting time of geopolymer concrete mixes

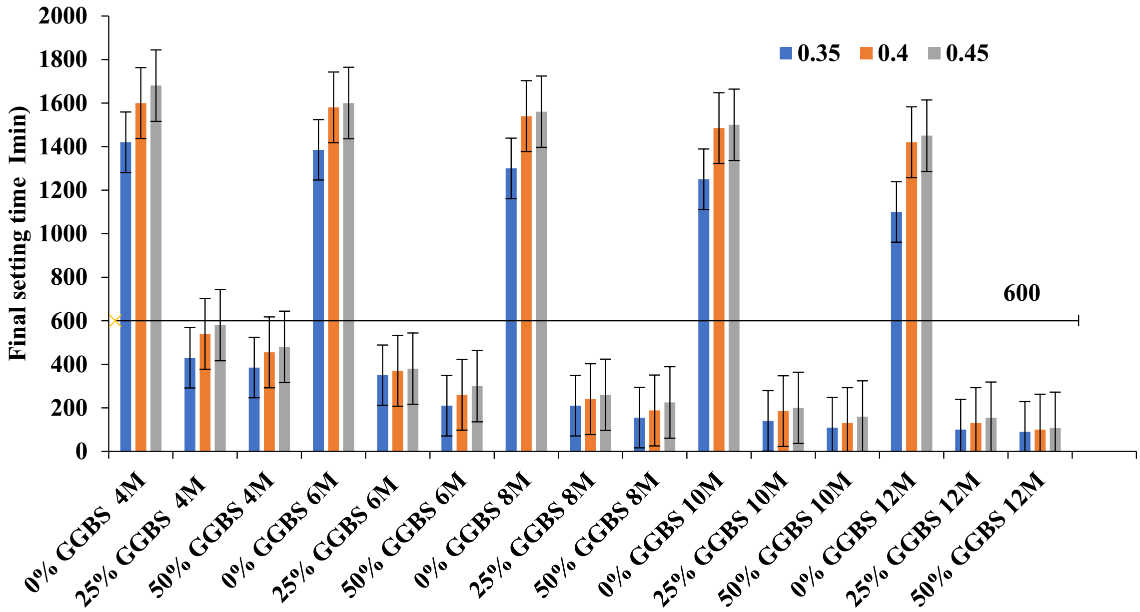

Fig. 21 Final setting time of geopolymer concrete mixes

setting time experienced a reduction ranging from 65 to 93%.

The integration of more GGBS in the mixture leads to a considerable setting time reduction. In OPC, the production of C–S–H gel C–S–H gel by the interaction between cement and water is directly linked to its setting process. Similarly, for geopolymer paste, the evolution of N–A–S–H gel is crucial. As GGBS contains a large proportion of CaO, geopolymer paste mixes made with GGBFS may generate both N–A–S–H gel and C–S–H early on (Lee & Deventer, 2002; Xie et al., 2019). Consequently, geopolymer paste mixes with higher GGBFS content require less time for both initial and final setting.

Effects of SH concentration

In Fig. 22a–c, the initial setting time variations for GGBS incorporation of 0%, 25%, and 50% are presented. Figs. 22 and 23 depict the results on improving the molarity of SH on the final and initial setting times. The study shows that fly ash-based geopolymer's final and initial setting times decreased from 380–480 min to 245–345 min and 1420–1680 min to 90–108 min, respectively. With a 25% replacement of GGBS and 4 M concentration of SH, the initial time of setting come down from 380–480 min to 220–300 min, and the final time of setting decreased from 1420–1680 min to 430–580 min. When slag concentration rises from 25 to 50%, the setting times decreased to 175–235 min and 385–480 min, respectively for the initial and final. While increasing the molarity of SH from 4 to 6 M, 8 M, 10 M, and 12 M, the initial setting time decreased by nearly 34–63% and 37–71% for the GGBS replacement of 25% and 50%, respectively. The final time setting of geopolymer paste containing 25% and 50% GGBS decreased by 18–76% and 38–80%, respectively. As the SH concentration rises, more hydroxide ions are present, which may speed up the breakdown of source materials, shortening the geopolymer mixtures setting time. (Somna et al., 2011).

Effects of AS/B ratio

The study examined the influence of various AS/B ratios (0.35, 0.40, and 0.45) on the final and initial geopolymer paste setting times. Results showed that the AS/B ratio is reduced from 0.45 to 0.40, the initial and final time of setting dropped by 8.8 and 16.44%, respectively. Reducing ratio of AS/B from 0.45 to 0.35 lowered initial time of setting from 480–70 min to 380–50 min and final of time setting from 1680–108 min to 1420–90 min. The reduced solution content caused by the lower AS/B ratio leding to a lesser setting time. Previous research has shown that a lowering the AS/B ratio reduces the consistency of geopolymer concrete, which causes the raw materials to react more quickly (Rafeet et al., 2017).

Compressive strength

The concrete's compressive strength is a crucial parameter which helps to ensure its quality and durability. As per the standards specified in IS: 456-2000(Kuranlı et al., 2022), the minimum concrete grade required for constructing reinforced concrete structures is M20. Additionally, concrete used for

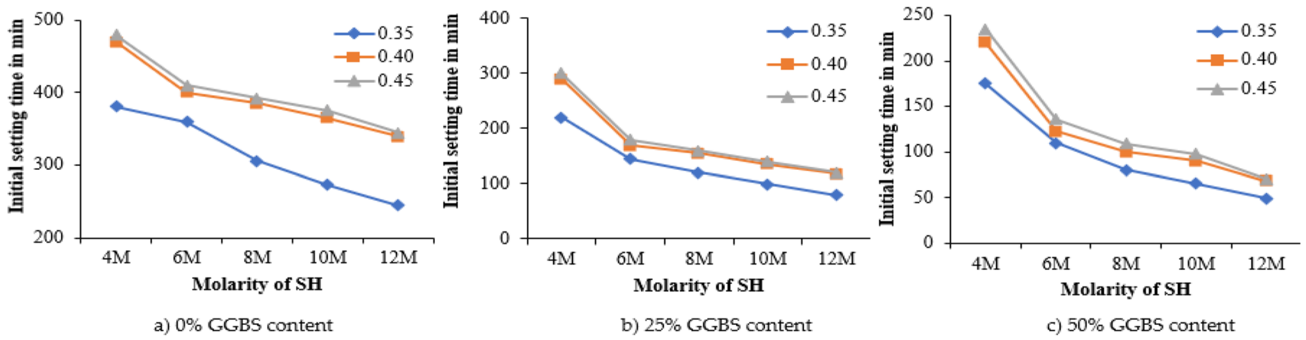

Fig. 22 Initial and Final setting time of geopolymer concrete different proportions of GGBS content

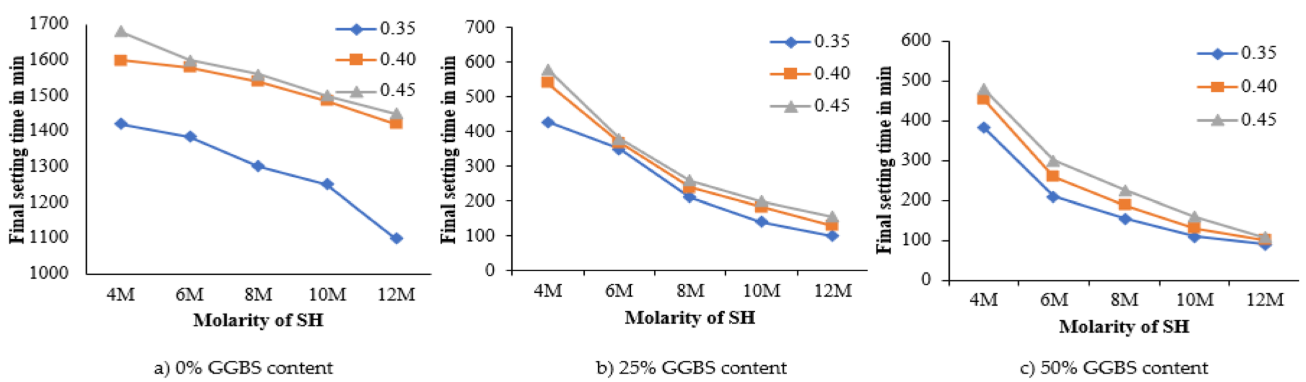

Fig. 23 Initial and Final setting time of geopolymer concrete different proportions of GGBS content

engineering applications, as stated in ACI 318-05(Rekha, 2021), must possess a 28-day compressive strength of at least 28 MPa. To evaluate the geopolymer concrete strength made with GGBS and fly ash, various factors such as molarities of SH, AS/B ratio, and slag replacement were considered.

Effects of fly ash to GGBS ratio

The geopolymer concrete's mechanical strength by varying levels of GGBS replacement was evaluated at the 28-day and 7 days curing stages, as shown in Figs. 24 and 25. The compressive strengths at 28-day for geopolymer concrete based on fly ash with AS/B ratios of 0.35, 0.40, and 0.45 were in the ranges of 13.35–24.95 MPa, 12.64–23.66 MPa, and 10.68–22.75 MPa, respectively. However, the compressive strength of geopolymer concrete with fly ash alone is relatively low while comparing to fly ash-GGBS based geopolymer concrete. The reason for this is because the reactivity of fly ash is only induced at temperatures of 60–85 °C, and the temperature in the curing room is not sufficient to activate fly ash particles with the alkaline solution (Avudaiappan et al., 2023b; Sheeba et al., 2023c). The inclusion of GGBS accelerates the dissolution of fly ash, thereby enhancing the condensation of amorphous gel even under ambient curing (Puligilla & Mondal, 2013). GGBS enhanced 7-day compressive strength by 16–91% as the replacement amount increasing from 0 to 25%. Moreover, the inclusion of 50% GGBS increased the strength from 12.90 and 14.46 MPa to a maximum of 43.58 and 45.76 MPa, respectively. The incorporation of GGBS in concrete can enhance the C–A–S–H gel development, that minimizes the pores and improves the GGBS- fly ash based geopolymer concrete's microstructure. (Provis et al., 2015; Wan et al., 2017).

Effects of SH concentration

The geopolymer concrete strength development for various concentrations of SH was investigated and presented in Figs. 23 and 24. The results indicates compressive strength at 28-day of fly ash and fly ash-GGBS-based geopolymer concrete rises with increase in concentration of SH. However, rise in molarity after 8 M slightly reduces the geopolymer concrete's compressive strength for 10 M and 12 M specimens. The presence of leachable aluminosilicates is a critical factor in the strength development of concrete geopolymer. Higher SH concentrations may impede polymerization, decreasing geopolymer concrete

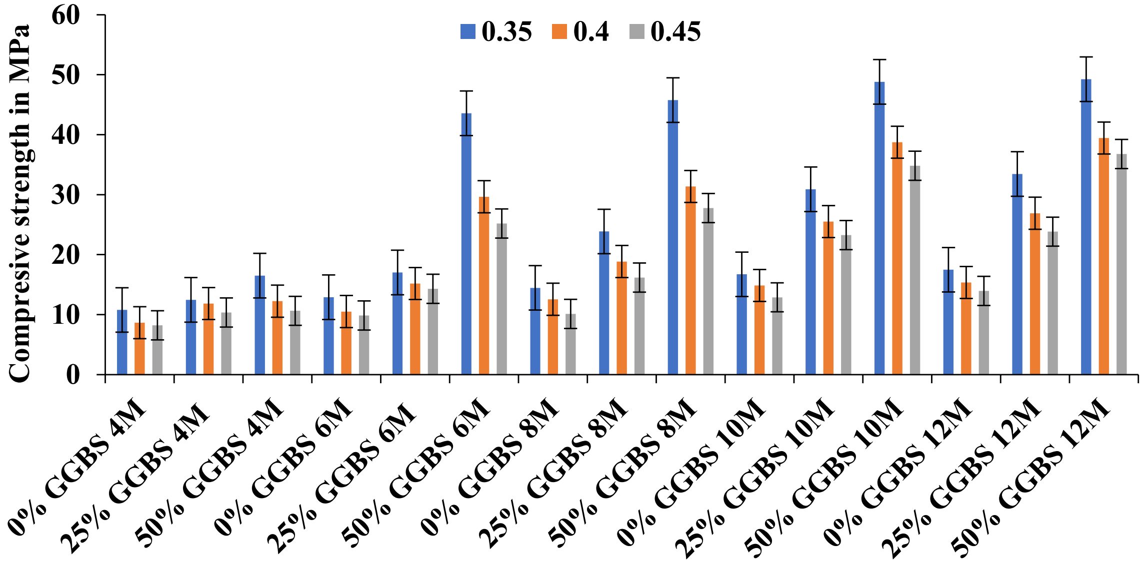

Fig. 24 7-day compressive strength of geopolymer concrete mixes

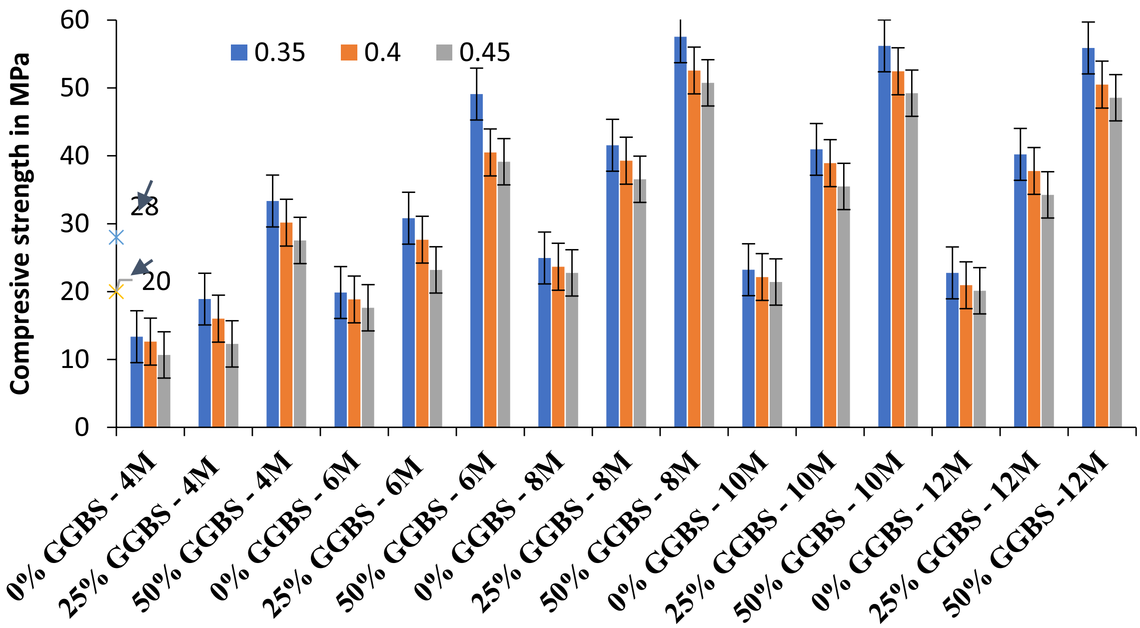

Fig. 25 28-day compressive strength variation of different geopolymer concrete mixes

strength (Ryu et al., 2013; Sheeba et al., 2023a). Between 8 to 12 M, SH concentration reduced strength by 7%. It is observed that 60–80% of the strength was reached within 7 days of curing. The strength of 4 M geopolymer mixtures was relatively low, ranging from 8.22–10.78 MPa, 10.34–12.46 MPa, and 10.63–16.49 MPa for GGBS replacements of 0%, 25%, and 50%, respectively. This was attributed to the lower concentration of SH, which was not sufficient to activate the source materials (Ryu et al., 2013).. The highest strength of 57.53, 52.56, and 50.75 MPa was achieved in GGBS- fly ash (1:1) based concrete geopolymer with SH molarity of 8 M for the AS/B ratio of 0.35, 0.40, and 0.45,, which was 73%, 74%, and 84% higher than the corresponding samples with 4 M concentration of SH.

Effects of AS/B ratio

The impact of AS/B proportion of geopolymer concrete on compressive strength at 7 and 28 day are given in Figs. 26, 27 and 28, respectively. It was represented that the decrease in AS/B ratio rises the compressive strength. At higher level of GGBS, the difference between compressive strength with different AS/B ratio was higher at 7 day of curing, while it was comparatively low when cured up to 28-day which was consisted by the previous research (Mehta & Siddique, 2016) reported that the quantity of alkaline solution may strongly affect strength at early age, whereas the 28-day strength was not much affected. Normally, the activation of source materials would accelerated due to the lesser consistency of mixtures with low AS/B ration (Bellum et al., 2022). The range of compressive strength at 28-day were 13.35–57.53 MPa for geopolymer concrete with AS/B ratio of 0.35, while it was decreased to 12.64–52.56 MPa and 10.68–50.75 MPa when AS/B ratio increased to 0.40 and 0.45. Because of quick formation of reaction products in mixes with low AS/B ratio, greater compressive strength was attained during the early stage of 7 days. The strength attainment rate was becomes slow after 7 days of curing because most of the source materials were reacted in the early age of curing itself (Xie et al., 2019).

Conclusion

The experimental tests are carried out on forty-five mixes of Geopolymer concrete to analyze the impact of GGBS to fly ash ratio, alkaline solution to binder content, and concentration of SH on the hardened and fresh concrete properties of Geopolymer concrete. The following inferences are made in regard to the data obtained.

The study found that the effectiveness of geopolymer concrete made from fly ash and GGBS was negatively impacted by elevated levels of SH and increased replacement levels of GGBS, as well as a reduction in the AS/B ratio.

Higher molarity of SH resulted in more pronounced effects of GGBS replacement level on geopolymer concrete's workability, with samples at 50% replacement and higher SH concentration possessing more slump loss.

The findings of the study indicate that a rise in the SH molarity, a reduction in the AS/B ratio, and an augmentation in the GGBS proportion led to a noteworthy decline in the geopolymer paste's initial and final setting times, which is formulated using fly ash and GGBS.

Higher concentration of 12 M concrete mixes showed a reduction of 60–71% and 73–78% in initial and final setting times, respectively, comparing to 4 M geopolymer concrete mixes. The optimum performance blend is AS/B ratio of 0.35 with 50% GGBS-8 M.

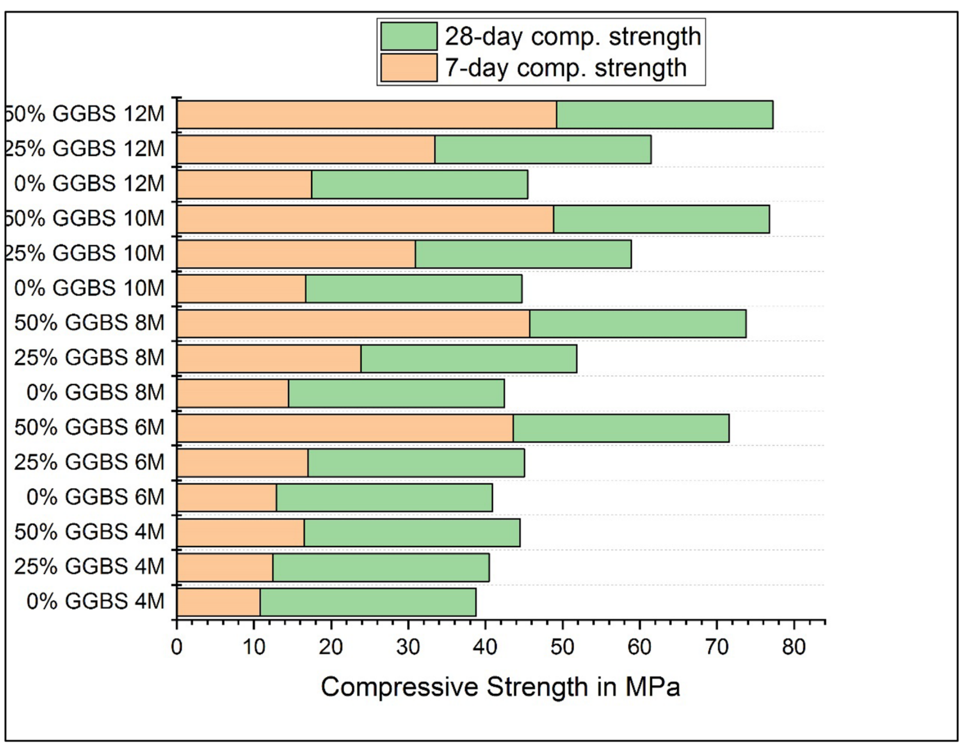

Fig. 26 7- and 28-day compressive strength results of geopolymer concrete—AS/B ratio of 0.35

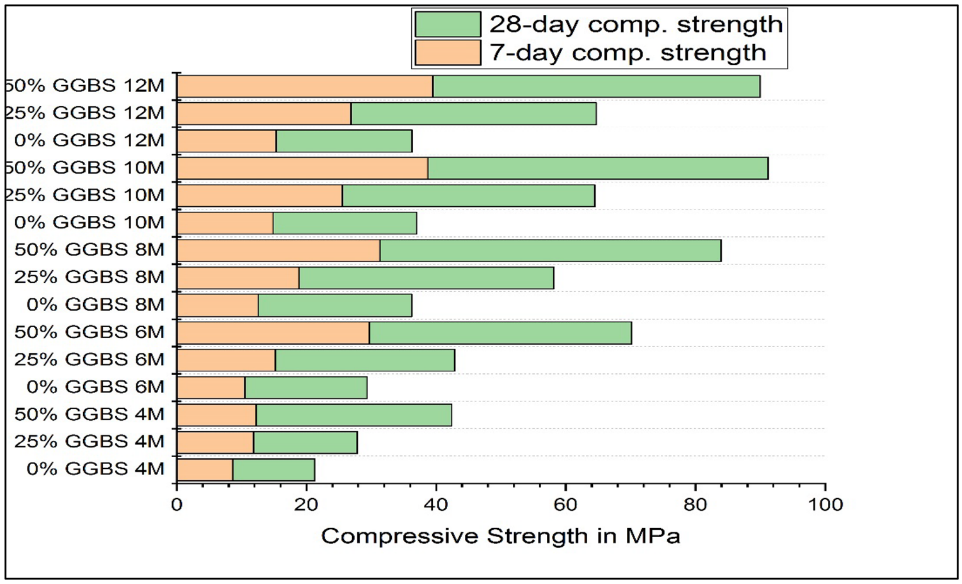

Fig. 27 7 and 28 day compressive strength results of geopolymer concrete—AS/B ratio of 0.4

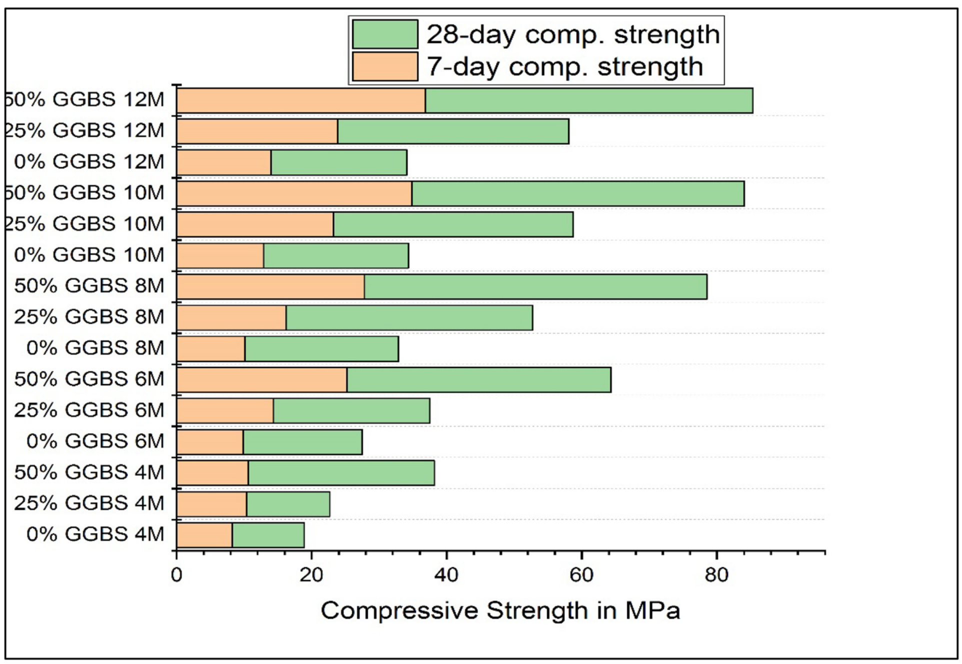

Fig. 28 7 and 28 day compressive strength results of geopolymer concrete—AS/B ratio of 0.45

Compressive strength of fly ash and GGBS based concrete geopolymer increased with increasing GGBS content and decreasing AS/B ratio.

The increase in concentration of SH enhanced the compressive strength of geopolymer concrete up to the 8 M concrete mixes, with a minimum depletion in compressive strength observed in concrete mixes with higher SH concentration (10 M & 12 M).

Regardless of molarity and AS/B ratio, the maximum compressive strength is obtained with increasing replacement level of GGBS content.

Acknowledgements The authors gratefully acknowledge the Government College of Engineering, Tirunelveli and Alagappa Chettiar Government College of Engineering and Technology for performing the experimental works. Dirección de Investigación de la Universidad Católica de la Santísima Concepción, Concepción, Chile. Centro Nacional de Excelencia para la Industria de la Madera (ANID BASAL FB210015 CENAMAD), Pontificia Universidad Católica de Chile, Vicuña Mackenna 7860, Santiago, Chile

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Funding The authors have not disclosed any funding.

Data availability Available on request.

Declarations

Conflict of interest There is no conflict of interest among the authors.

Informed consent statement Not applicable.

Institutional review board statement Not applicable.

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