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REVIEW

Factors Influencing Compressive Strength in Fly Ash-Based Geopolymer Concrete: A Comprehensive Review

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Abstract
The amount of cement used has increased phenomenally due to the development and massive expansion of the infrastructure sector. The manufacture of cement requires more incredible embodied energy and produces greenhouse gases. Geopolymer concrete (GPC) was developed to alleviate the environmental adverse effects caused by carbon dioxide emissions (CO_2) and the extensive use of fossil fuels in cement manufacturing. GPC concrete is more durable and has better mechanical properties than traditional concrete; for all types of concrete composites, including GPC, compressive strength (Cst) is the most essential engineering property. The result is impacted by a multitude of factors, encompassing the number of binder materials utilized, the proportion of alkaline activators to binder (AL/Bi), the quantity of additional water incorporated, the dosage of superplasticizers, the ratio of alkaline activators (AAR), the concentration molarity of hydroxide of sodium (SHy), the temperature of curing, and the duration of cure. This review article aims to illustrate how these various parameters affect the compressive strength of fly ash-based geopolymer concrete (FAGPC). To accomplish this, an extensive dataset was gathered and analyzed. The results indicate that the compressive strength of FAGPC is mainly influenced by the temperature for curing, the amount of sodium hydroxide, and the amount of alkaline in the binder.

Keywords Fly ash · Activators solutions · Superplasticizer dosage · NaOH · Na_2SO_3 · Curing

1 Introduction

Concrete is the second most often used material worldwide (Abdalla et al. 2022a, b; Amiri et al. 2021; Bezabih et al. 2023; Chu et al. 2021; Danish et al. 2022; Kanagaraj et al. 2022). Ordinary Portland cement (OPC) is the primary constituent of concrete (Abdalla et al. 2022a, b; Rashad 2014). OPC is responsible for around 5–7% of worldwide carbon dioxide (CO_2) emissions (Alahmari et al. 2023; Assi et al. 2016; Garg et al. 2023; Khalil et al. 2020; Kotop et al. 2021; Samuvel Raj et al. 2023; Shumuye et al. 2021; Sukontasukkul et al. 2018; Visintin et al. 2017; Zhao et al. 2021). Cement production requires significant raw materials and energy, which harms the environment. For a future building that is environmentally friendly, an alternative to OPC concrete is geopolymer concrete (GPC) (Gill et al. 2023a, b; Robayo-Salazar et al. 2018), which has a substantially lower environmental impact than Portland cement concrete (Gill et al. 2023a, b; Panesar 2019). In 1978, Davidovits initially presented Geopolymers as a novel family of inorganic polymer binders (Abdel-Gawwad and Abo-El-Enein 2019; Ekinci et al. 2019; Jindal et al. 2017; Kanagaraj et al. 2023; Moradikhou et al. 2023). The two primary components of geopolymers, inorganic aluminosilicate materials, are an alkaline activator solution and a raw material rich in SiO_2 and Al_2O_3 (Adak and Mandal 2019; Aslani and Asif 2019; Hardjito et al. 2015; Salas et al. 2018). GPC possesses exceptional chemical and mechanical properties to Portland cement-based concrete (PCC) for civil engineering applications. These properties include greater mechanical strength and rapid hardening (Karakoç et al. 2014; Karthik et al. 2017; Yaseri et al. 2017), higher resistance to fire or elevated temperatures (Cheng and Chiu 2003; Sakkas et al. 2014; Sarker et al. 2014), low permeability and resistance to salts, acids, and chloride penetration depth (Ganesan et al. 2015; Lee and van Deventer 2002), and lower creep effects (Zhang

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et al. 2013). Polymerization is the chemical reaction between an alkaline solution and a binder material containing aluminosilicate, as shown in Fig. 1 (Ahmed et al. 2021a, b).

The GPC polymerization process is influenced by several factors, like the amount of oxide in the source material, the concentration of SHy, the alkaline activator ratio (the ratio of SHy to SSi), the method of curing used, as well as the duration of time it is left to cure (Podolsky et al. 2021; Van Deventer et al. 2012). Materials rich in alumino-silicates are utilized as binders in geopolymer concrete like fly ash (FA) (Abdulrahman et al. 2022; Amin et al. 2022; Amran et al. 2021), ground granulated blast furnace slag (GGBFS) (Bouaissi et al. 2019; Nagajothi and Elavenil 2021; Shahmansouri et al. 2020), rice husk ash (RHA) (Beigh and Haq 2024; Nuaklong et al. 2020; Thumrongvut et al. 2022), metakaolin (MK) (Jindal et al. 2023; Moradikhou et al. 2020), silica fume (SF) (Mashri et al. 2023; Singh et al. 2023), red mud (RM) (Bellum et al. 2021; Liang and Ji 2021), and palm oil fuel ash (POFA) (Mahamat Ahmat et al. 2023; Mashri et al. 2023), or any blend among these ashes containing or without containing cement, and performance activity are primarily influenced by their fineness, glassy phase content, and chemical composition (Feng et al. 2019). FA is the most prevalent utilized source binder material as a cheap ingredient in geopolymer concrete, with general availability, more excellent ore, and tremendous potential for geopolymer preparation (Pavithra et al. 2016). FA is a finely chopped byproduct of the burning of pulverized coal. Before reaching the flue gages of chimneys, particles are filtered from the engine using electrostatic precipitators or some other technique (Ahmaruzzaman 2010; Gorai et al. 2003). FA is classified by oxide composition as class F or class C. FA mainly consists of SiO_2, Al_2O_3, Fe_2O_3, and CaO, with lesser amounts of various ores, as presented in Table 1. Class F fly ash has a total percent SiO_2, Al_2O_3, and Fe_2O_3 content of over 70% and a CaO content of < 10%, considered low calcium FA. In contrast, class C fly ash should have a total percent SiO_2, Al_2O_3, and Fe_2O_3 content of between 50 and 70% and a CaO content of more than 20%, considered high calcium FA (Antiohos and Tsimas 2007; Bankowski et al. 2004), is fewer compared to FA with high calcium content, fewer compared to FA with a high calcium content; FA with low calcium is acceptable in the formation of GPC because it is readily available, has an abundance of oxide compounds, and requires less water (Hardjito et al. 2004, 2015).

In conclusion, much research has been offered to review the effect of different factors on the physical, mechanical, durability, and microstructure characteristics of FAGPC. However, Cst is a crucial mechanical characteristic of concrete, serving as a reliable indicator of the overall quality of the concrete. Despite the vast research in this area, studies on factors influencing compressive strength in fly ash-based geopolymer concrete are very scanty. Therefore, a comprehensive and systematic review is needed to assess the impact of different percentages variables and curing circumstances on the Cst of FAGPC at differing ages for curing and temperatures. In this study, the effect of several parameters regarding the Cst of FAGPC was investigated, including binder content, AL/Bi, SHy molarity, SSi/SHy ratio, curing temperature and duration, superplasticizers, and extra water content.

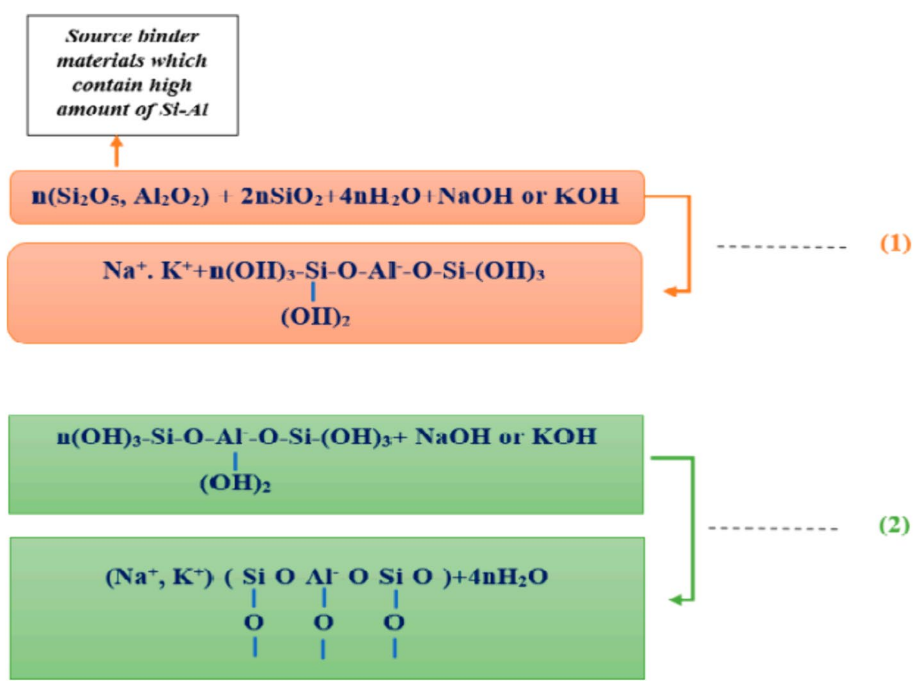


Fig. 1 Chemical reactions that occur during geopolymerization (Ahmed et al. 2021a, b)

Table 1 The chemical constitutes fly ash

References	SiO_2	AL_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	LOI
Sherwani et al. (2022a, b)	56.00	24.00	4.00	7.00	2.00	–	–	–	3.00
Nagajothi et al. (2022)	63.32	26.76	2.49	5.55	0.29	0.0004	0.0002	0.36	0.97
Dinh et al. (2023)	54.62	24.27	6.14	8.389	1.134	0.258	0.801	0.279	2.704
Gupta et al. (2021)	61.74	25.23	2.15	5.98	0.32	–	–	0.27	2.15
Parveen et al. (2018)	62.5	29.02	1.1	4.22	–	0.2	–	0.22	0.52
Wardhono et al. (2017)	57.9	31.1	1.29	5.07	0.97	0.09	1	0.05	0.8
Xie and Ozbakkaloglu (2015)	62.3	28.1	0.5	2.1	1	0.5	1	0.4	2.5
Chindaprasirt and Chalee (2014)	49	31	5	3	3	4	1	0	0
Alex et al. (2022)	52.57	2669	1.26	11.32	0.89	0.46	0.79	1.64	1.28
Sarker et al. (2013)	42.4	21.3	13.2	15.7	2.2	0.9	2	1	0.4
Çevik et al. (2018)	51.5	23.63	1.74	15.3	1.2	0.38	0.84	0.28	1.78
Shaikh and Vimonsatit (2014)	48	29	1.76	12.7	0.89	0.39	0.55	0.5	1.61
Talha Junaid et al. (2016)	50.7	28.8	2.38	8.8	1.39	0.84	2.4	0.3	3.79
Padakanti et al. (2022)	63.47	24.33	4.84	4.54	1.19	0.13	0.93	0.23	–
Tayeh et al. (2021)	55.57	28.78	2.46	3.95	1.18	0.72	1.33	0.37	0.97
Tran et al. (2019)	51.1	25.6	4.3	12.5	1.5	0.8	0.7	0.24	0.6
Abiodun et al. (2023)	55.865	22.657	6.501	6.118	5.194	–	–	0.358	1.75
Waqas et al. (2021)	54.55	31.93	4.65	3.12	1.42	0.25	0.7	0.3	0.95
Maglad et al. (2022)	53.4	27.6	2.6	4.2	3.4	0.3	0.7	–	–
Xiao et al. (2021)	50.8	28.1	3.7	6.2	1.2	1.2	0.6	0.8	
Yang et al. (2022)	44.8	39.2	5.2	3.6	0.6	–	–	1.5	3.4
Eisa et al. (2022)	57.9	31.11	1.29	5.07	0.97	0.09	1	0.05	0.8
Harirchi and Yang (2022)	51.1	16.2	13.7	6.1	4.2	2.85	2.64	–	–
Horan et al. (2022)	44.7	23.2	3.2	24.2	0.8	–	–	0.6	0.4
Ionescu et al. (2022)	46.9	23.8	10.7	10.1	2.7	0.6	1.7	0.5	2.1
Chuewangkam et al. (2022)	28.54	14.94	26.37	18.14	2.01	1.05	2.8	4.56	
Sherwani et al. (2022a, b)	55	23	4	7	2	1	2	–	3

2 Methodology

Various databases, including Google Scholar, Scopus, Web of Science, MDPI, Taylor & Francis, and ScienceDirect, were utilized to do thorough literature searches during the database establishment. The literature provides information on geopolymer concrete, which incorporates various source binder components, including FA, RHA, $GGBF_S$, SF, and MK. Nevertheless, the review focused on experiments that utilized FA as a binding material to produce geopolymer concrete composites. Figure 2 depicts the flow chart that provides a more detailed overview of collecting and evaluating data.

3 Results and Discussions

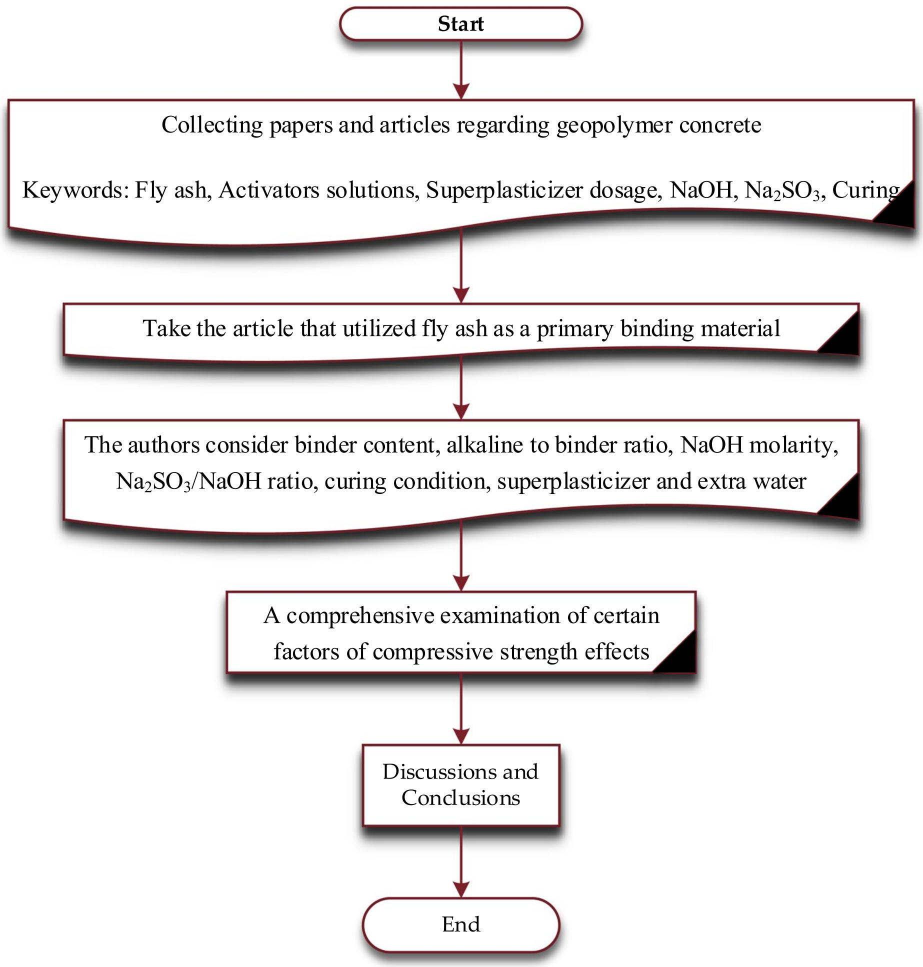
3.1 Factors Influencing the Compressive Strength of GPC

To manufacture large quantities of GPC with engineering properties that are reasonably consistent and predictable, one of the most important steps is to gain knowledge about the mechanical characteristics of the material. The following are important parameters that influence the performance of FAGPC, which include: (a) binder content; (b) activator solution-to-binder ratio; (c) concentration of SHy solution (molarity); (d) SSi to SHy solution ratio; (e) curing temperature; and (f) curing period.

3.1.1 Binder Content

Besides its cost-effectiveness, availability, and enhanced capacity for geopolymer preparation, FA is frequently utilized to create geopolymer concrete as a source binder material (Feng et al. 2019; Pavithra et al. 2016). For instance, according to a report by Al-Azzawi et al. (2018) an experimental investigation was conducted to investigate the impact of varying fly ash amounts on FAGPC's bond and Cst. They discovered the geopolymer concrete's bond and Cst rose with the percentage of fly ash added. Cst improved most noticeably when the fly ash concentration was raised from 300 to 500 kg/m^3. According to Jindal et al. (2017), the specimens' Cst increased with an increase in the fly ash

Fig. 2 The methodology flowchart for the study



amount under ambient and heat-cured conditions. After 28 days, the Cst grew between 21 and 42 Mpa when the FA amount was raised within 350 and 400 kg/m^3. Similarly, Ramujee and PothaRaju (2017) provided evidence that when the mass of fly ash in geopolymer concrete was raised, this also increased the material's Cst. According to most studies, increasing fly ash increased the Cst of FAGPC. This suggests that fly ash with a more excellent glassy phase and finer particle size exhibits more reactivity, leading to a quicker polymerization rate and stronger concrete (Diaz et al. 2010; Komljenović et al. 2010; Kumar and Kumar 2011). In addition, the geopolymer concrete matrix's microstructure becomes denser and more compact as the fly ash volume grows in a given mixture. Furthermore, because of their smooth exterior and round form, fly ash particles facilitate motion within the aggregate particles (Rickard et al. 2011). Consequently, minimizing the fly ash quantity compromises the FAGPC's ability to consolidate and compact appropriately, diminishing bonding and compressive strength. However, when the fly ash amount went up, particles in the fine fraction grew in volume within the GPC matrix, filling gaps and voids created by an aggregate particle and thereby improving compressive strength (Ahmed et al. 2021a, b; Al-Azzawi et al. 2018).

3.1.2 Ratio of Alkaline to Binder (Al/Bi)

The "alkaline solution" in geopolymer concrete comprises SHy and SSi. The "binder content" comprises all the fly ash or other source binders (Ahmed et al. 2021a, b; Mohammed et al. 2021). The activators significantly influence the polymerization process. When the Si and Al are dissolved in the activator, polymerization forms the binding material rapidly (Shilar et al. 2022). The reactivity of FA was enhanced by utilizing an activator made from NaOH and Na_2SiO_3 (de Azevedo et al. 2021; Mendes et al. 2021). According to Aliabdo et al. (2016), the chemical admixture amount, additional water content, SHy/SSi ratio, and SHy molarity were held constant at 10.5 kg/m^3, 35 kg/m^3, 0.4, and 16, respectively. The Cst of FAGPC was raised by increasing the alkaline-to-binder ratio up to 0.4; subsequently, the outcome was the opposite, as shown in Fig. 3.

A study by Fang et al. (2018) looked at the impact of the ratio of AL/Bi on fly ash-slag-based geopolymer concrete

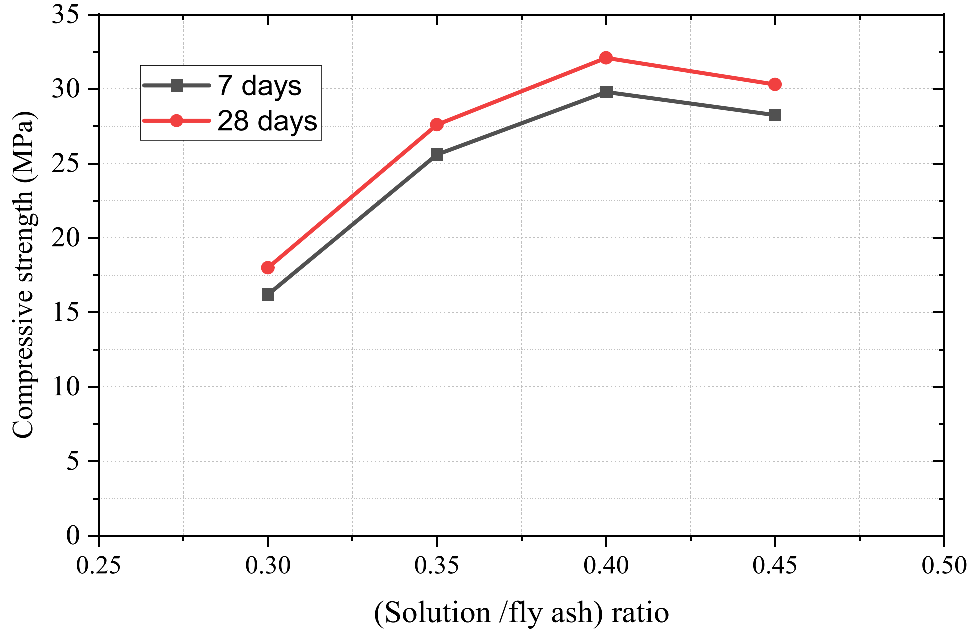


Fig. 3 The impact of SHy and SSi on fly ash on fly ash-based GPC's Cs (Aliabdo et al. 2016)

cured in an ambient environment. According to their findings, increasing the AL/Bi ratio has a remarkable impact on the Cst of geopolymer concrete containing composite fly ash and slag at lower ages. However, it has no such effect at later ages. This discovery argues that reducing the AL/Bi ratio will speed up the process of fly ash-slag geopolymer concrete being activated by alkaline. This acceleration occurs because a reduction in consistency is observed in the mixture of geopolymer concrete (Rafeet et al. 2017). Gels, specifically calcium aluminate silicate hydrate (C–A–S–H) and sodium aluminate silicate hydrate (N–A–S–H), rapidly form in a geopolymer concrete blend containing a low AL/Bi ratio. This procedure helps fly ash-slag geopolymer concrete gain its early-age strength (Lloyd et al. 2009). In another investigation by Ghafoor et al. (2021), it was observed that increasing the AL/Bi ratio from 0.4 to 0.5 reduced the Cst of GPC cured at ambient temperature by around 19.0% and 3.4% for NaOH molarities of 8M and 10M, respectively. Nevertheless, the Cst of GPC exhibited an approximate increase of 8.4%, 9.7%, and 14.9% for NaOH molarities of 12M, 14M, and 16M, respectively. Similarly, Nath and Sarker (2015) found an increase in the Cst of GPC with increasing NaOH molarity. This results from water consumption increasing as the molarity of NaOH increases. Water acts as a solvent for the movement of particles and various ions, significantly influencing the geopolymerization process (Hu et al. 2018). Furthermore, raising the Al/Bi ratio from 0.5 to 0.6 reduced Cst by approximately 6.1%, 8.8%, 13.8%, 22.2%, and 14.0% for NaOH molarities of 8M, 10M, 12M, 14M, and 16M, respectively. It was noticed that higher concentrations of NaOH led to the GPC mixes becoming sticky, resulting in a decrease in the workability of GPC. The water content was critical to the dissolution of ions throughout the polymerization process (Karakoç et al. 2014). In addition, Verma and Dev (2022) studied the impact of the ratio of AL/Bi on the Cst of GGBFS fly ash-based GPC. The range of the AL/Bi ratio was 0.40–0.70. The authors concluded that strength grows as the AL/Bi ratio increases, although it decreases randomly beyond 0.60 ratios. The GPC mix design optimized the Cst at 0.60 AL/Bi ratios, as shown in Fig. 4.

In conclusion, it was demonstrated that when the AL/Bi ratio was raised, the strength of low SHy concentrations cured in a room environment reduced, as shown in Fig. 5, which was taken from Ghafoor. This finding demonstrated that raising the alkaline liquid's molarity produced a more prominent solid component in relation to the amount of water, which considerably impacted the polymerization process and raised compressive strength (Hu et al. 2018).

3.1.3 Sodium Hydroxide Molarity

One of the crucial parameters influencing FAGPC performance is the concentration of sodium hydroxide. As a result, several studies have been undertaken to highlight the impacts of this issue. According to Aliabdo et al. (2016), the Cst of the FAGPC mixture exhibited an initial increase as the molarity of sodium hydroxide rose, reaching its peak at 16 M, after which it subsequently declined, as shown in Fig. 6. Furthermore, they noticed that the optimal NaOH concentration for 48 h of curing at 50 °C was 16 M. Also, Chindaprasirt et al. (2011) achieved similar outcomes by employing different concentrations of SHy, varying between 8 and 20M. They observed a maximum Cst of 32.2 MPa at

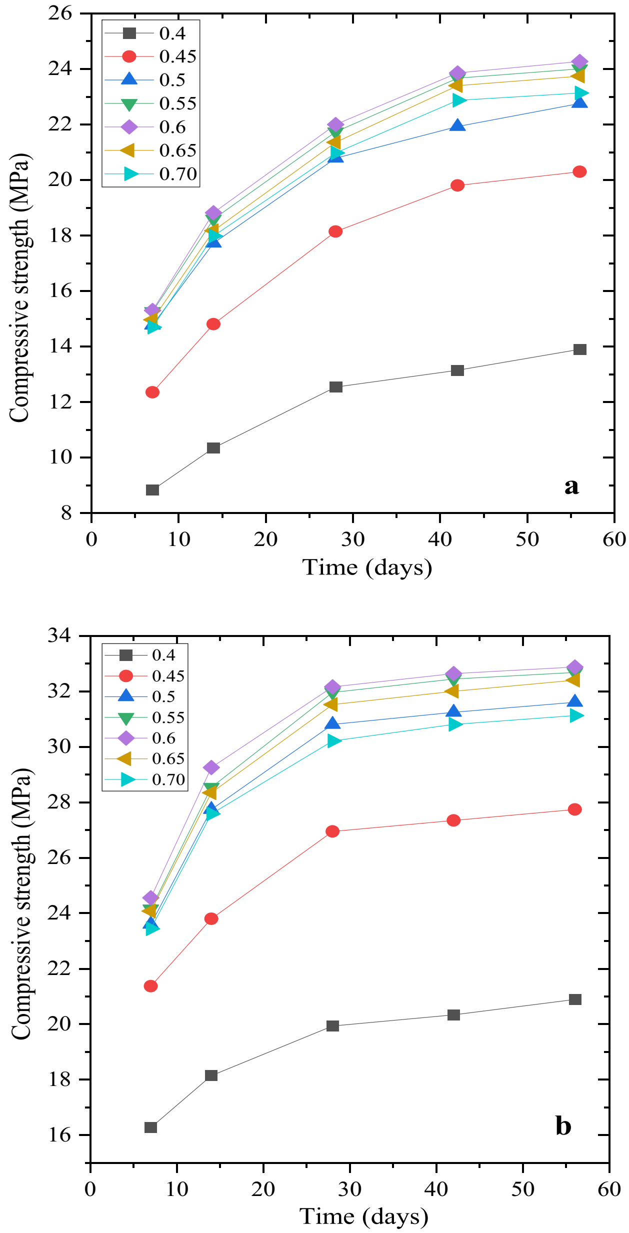


Fig. 4 Cast of **a** ambient-cured GPC and **b** oven-cured GPC (Verma and Dev 2022)

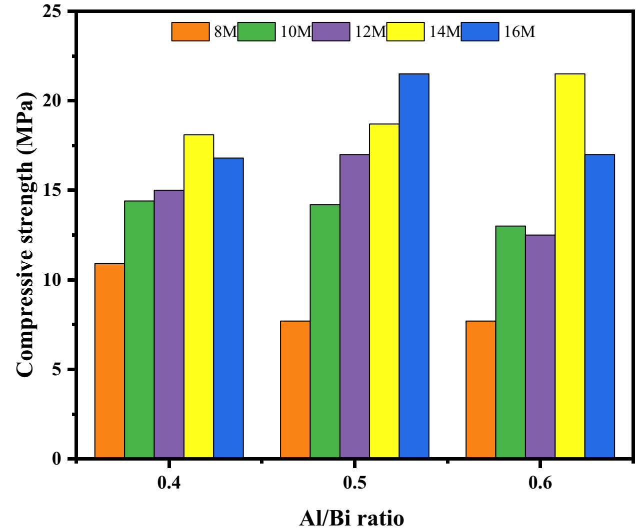


Fig. 5 Impact of sodium hydroxide molarity and AL/b ratios on FA-GPC's compressive strength at 1.5 SS/SH (Ghafoor et al. 2021)

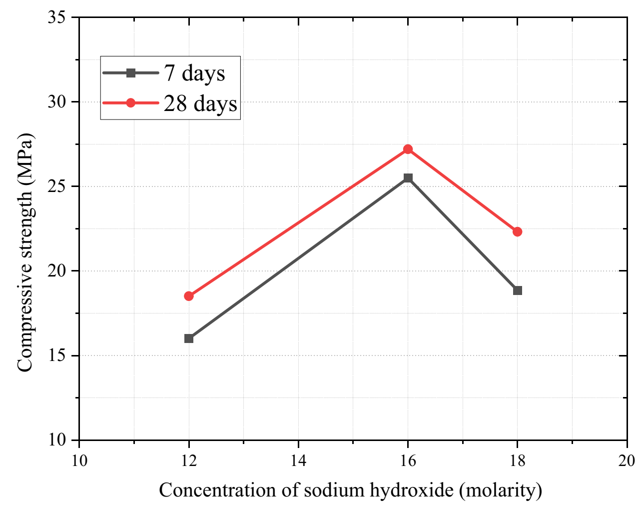


Fig. 6 The effects of varying molar concentrations of SHy on the Cst of FAGPC after 7 and 28 days (Aliabdo et al. 2016)

a concentration of 16 M after ambient curing for 28 days. Chithambaram et al. (2018) carried out an experiment investigation to show how varying molarities of SHy affect the mechanical properties of FAGPC. The researchers conducted experiments using four distinct molarities and four varying temperatures for curing. They observed that raising the molarity led to an enhancement in compressive strength, reaching its peak at 12 M. However, further increases in molarity resulted in a fall in Cst. Consistent findings have been documented in other attempts, regardless of the utilization of different concentrations (Topark-Ngarm et al. 2015). The consequence of SHy molarity on fly ash metakaolin-based self-compacting geopolymer concrete was investigated by Arun et al. (2019). They observe that when the molarity rises, the strength rises as well. This is because an elevation in the concentration of SHy facilitates better alumina and silica leaching, which improves geopolymerization and raises strength. Verma and Dev (2020) examined the influence of SHy on the mechanical properties of fly ash-slag-based geopolymer concrete. According to their research, the Cst of the mix design rises as the molarity of SHy increases. However, after reaching a specific threshold, the Cst diminishes in the oven-cured specimens. The oven-cured 14 M mix achieves a maximum Cst of 34.2 N/mm^2 after 56 days, whereas the ambient-cured 16 M mix reaches a Cst of 25 N/mm^2 after the same duration as shown in Fig. 7. Ghafoor et al. (2021) examined the impact of activators on the Cst of FAGPC throughout the process of curing at normal temperature. Their findings indicate that the Cst of FAGPC initially rose as the molarity of SHy increased up to 14 M, but subsequently declined. Alghannam et al. (2021) examined the effect of SHy molarity on geopolymer concrete Cst, and

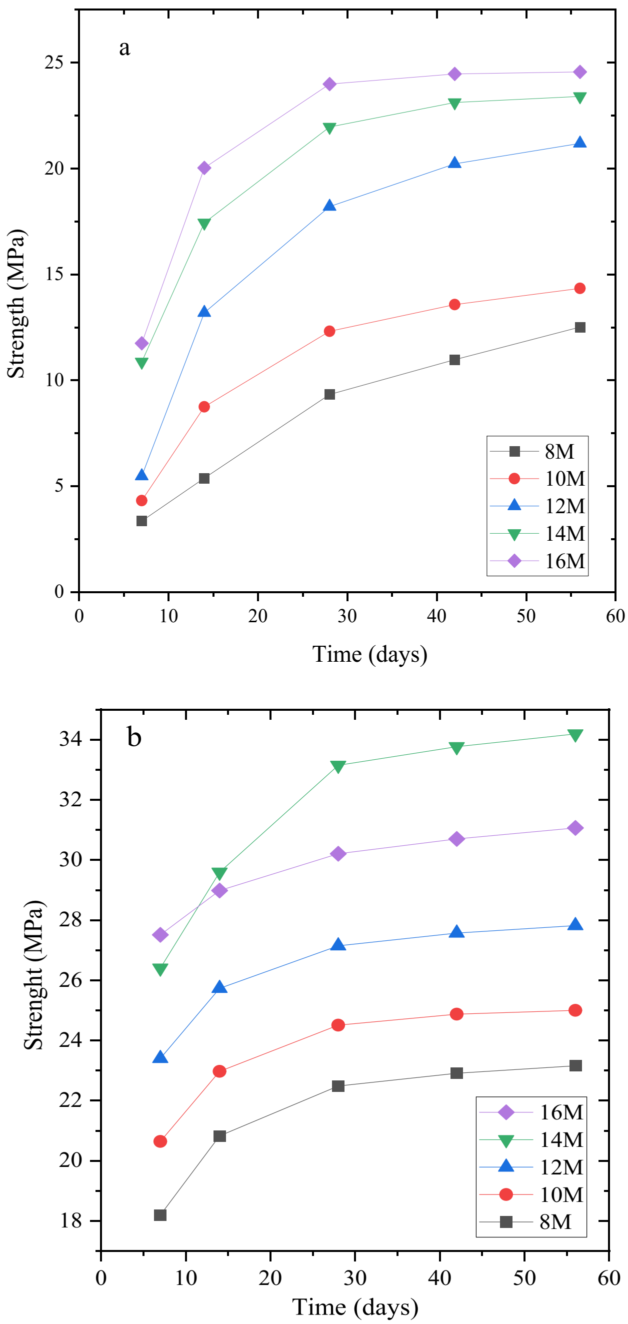


Fig. 7 Strength of **a** ambient-cured GPC and **b** oven-cured GPC (Verma and Dev 2020)

Initially, two molarity values of 14 M and 20 M were chosen. The findings indicated that the Cst decreased as the molarity was elevated from 14 to 20 M. This relationship between molarity and Cst is consistent with previous findings (Aliabdo et al. 2016; Kantarcı et al. 2019). However, the inverse trend has also been noted (Hardjito et al. 2004; Parveen et al. 2018; Wang et al. 2005). Pratap et al. (2023) examined the effect of SHy molarity on the Cst of geopolymer concrete prepared with fly ash and phosphogypsum. The findings indicated that the strength characteristics raised with increasing molar concentration, peaked at 12 M, and then fell as the concentration of SHy increased further as shown in Fig. 8. The observed variation in Cst clearly demonstrates the influence of SHy molarity on geopolymer concrete. The reason behind this is SHy creates the alkaline climate that geopolymer gels need to bind together (Alam et al. 2019; Pavithra et al. 2016; Reddy et al. 2018). Raising the concentration of SHy can speed up the breakdown of aluminosilicates, encouraging the quick creation of geopolymer gels and the attainment of superior compressive, flexural, or split tensile strength (Liang and Ji 2021; Muthukrishnan et al. 2021; Verma and Dev 2020; Zakira et al. 2023). However, after the SHy molarity reached 12, all Cst dropped. The reduction in strength can be ascribed to the delay of geopolymerization induced by an overabundance of soluble silicates, specifically when the molar concentration surpasses 12 (Verma and Dev 2020), resulting in the extraction of the Al^{3+} and $Si4^{+}$ ions by leaching (Bheem et al. 2023). This may have potentially compromised the synthesis of C–A–S–H and N–A–S–H gel structures, consequently resulting in a fall in the material's Cst (Ranjbar et al. 2020).

Typically, the Cst of FAGPC composites is enhanced as the molarity of SHy grows. This effect is due to the fullest breakdown of aluminum and particles of silicon throughout the polymerization procedure (Nath and Sarker 2017). An increase in SHy molarity leads to a more significant dissolution of Al and Si particles, consequently resulting in an enhancement of the Cst of geopolymer concrete mixtures (Görhan and Kürklü, 2014).

3.1.4 Sodium Silicate to Sodium Hydroxide Ratio (SSi/SHy)

SSi and SHy work together as binders in GPC mix designs. Changes in the ratio of SSi to SHy directly affect the behavior of the GPC mix design. Several research investigating the impact of the alkaline solution ratio on the engineering characteristics of GPC mixes have been documented in the literature.

In research by Aliabdo et al. (2016) the impact of FAGPC was assessed under three distinct SHy/SSi ratios: 0.3, 0.4, and 0.5. Based on this research, an increase in the SSi/SHy ratio resulted in a corresponding increase in Cst, as depicted in Fig. 9. Despite the use of various SSi/SHy ratios,

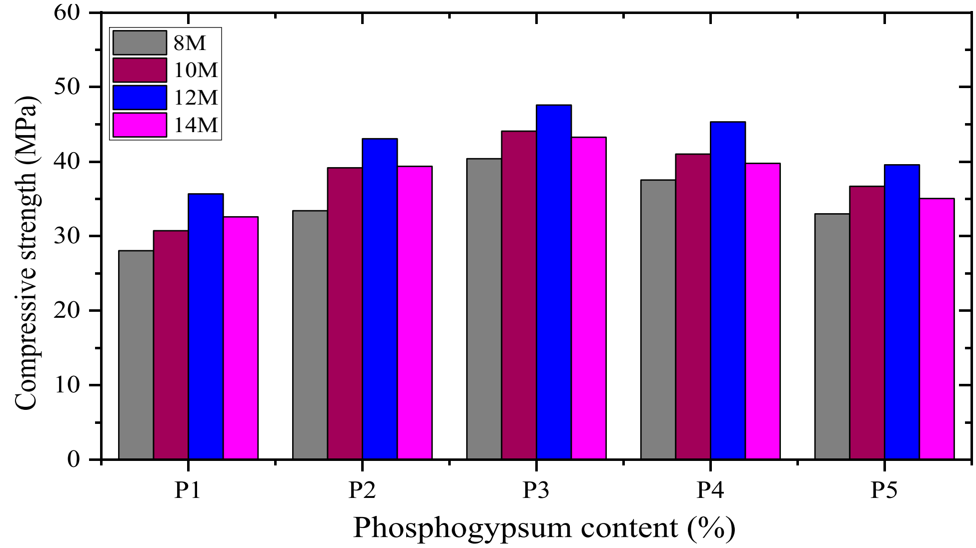


Fig. 8 Variation in compressive strength concerning PG concentration and NaOH molarity (Pratap et al. 2023)

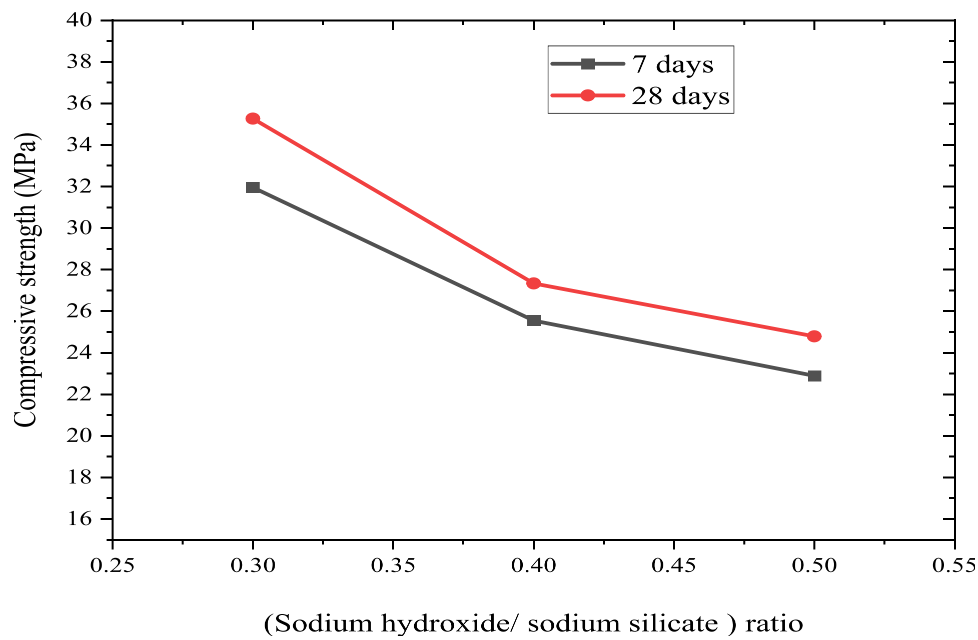


Fig. 9 The impact of varying SHy to SSi ratios on the Cst of FAGPC at different stages of curing (Aliabdo et al. 2016)

similar outcomes have been found in other studies (Das and Shrivastava 2020; Nath and Sarker 2017; Topark-Ngarm et al. 2015). Also, Hadi et al. (2017) employed the Taguchi approach to develop Optimal blend ratios for geopolymer concrete; The highest Cst was observed for a specific ratio of SSi/SHy equal to 2.5. Research conducted by other researchers came to the same conclusion (Abdullah et al. 2011; Aliabdo et al. 2016; Aziz et al. 2020; Joseph and Mathew 2012). (Vora and Dave 2013), Conversely, it was demonstrated that a ratio of 2 led to a greater Cst. According to Al-Azzawi et al. (2018) the Cst of FAGPC increased as the ratio of SSi/SHy rose in all geopolymer concrete compositions, even when fly ash levels ranged from 300 to 500 kg/m^3. Based on the findings of Verma and Dev (2020) the Cst increases as the ratio in the mix design increases, but beyond a certain point, it drops in both curing condition samples. The greatest Cst is at SSi/SHy of 2.5, as shown in Fig. 10.

The examination of the impact of the alkaline solution ratio indicates that changes in this ratio affect both the initial properties and the long-term properties of GPC (Pradhan et al. 2022). As alkaline activators, SHy and SSi are often utilized. The SSi to SHy ratio is set at 2.5 in order to attain the appropriate fresh and hardened properties (Bakri et al. 2012; MEMON et al. 2013; Nuruddin et al. 2011). Furthermore, according to numerous researchers, compressive strength reduced above SSi/SHy of 2.5. The findings confirmed the hypothesis that the microstructure of geopolymer concrete undergoes modifications with increasing amounts

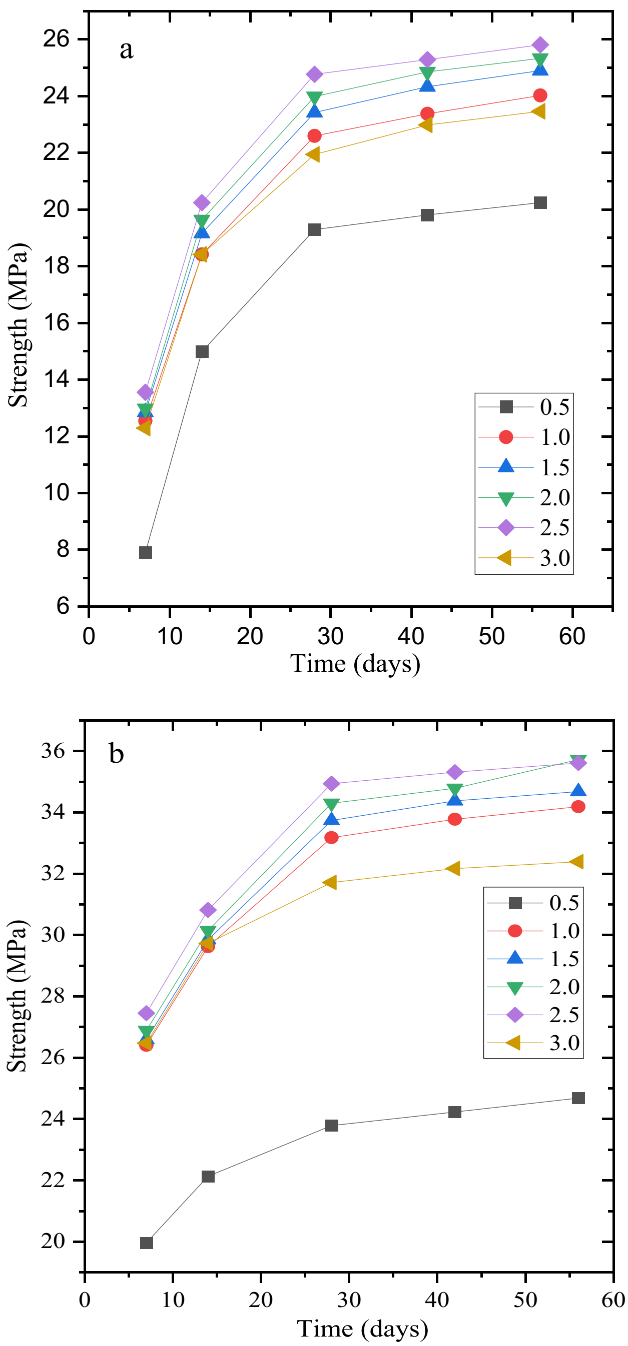


Fig. 10 Compressive strength of **a** ambient cured GPC and **b** oven-cured GPC (Verma and Dev 2020)

of SSi. However, the decrease in Cst was attributed to an insufficient quantity of SHy in the mixture, which hindered the completion of the procedure for dissolution during geopolymer developing (Sagoe-Crentsil and Weng 2007; Weng and Sagoe-Crentsil 2007), or due to an excessive concentration of OH– ions in the GPC blend (Feng et al. 2019).

Contrary to prior findings, a smaller number of Studies pointed out the Cst of FAGPC decreased as the ratio of SSi to SHy rose. Ghafoor et al. (2021) did a study to evaluate how activators impact the mechanical characteristics of FAGPC during curing under room environmental conditions. Their research demonstrates that an increase in the SSi/SHy ratio from 1.5 to 2 decreased Cst. When the ratio of SSi to SHy was raised from 2 to 2.5, comparable patterns were seen (Ghafoor et al. 2021). The observed outcome can be attributed to the inverse relationship between the SSi/SHy ratio and the quantity of SHy solution and hydroxide ions (OH-). This decrease in concentration leads to a reduction in the development of N–A–S–H gels, which are responsible for the primary 3D network that directly influences the microstructure of geopolymer concrete. Consequently, the Cst diminishes (Phoo-ngernkham et al. 2015; Ridtirud et al. 2011). As a result, it is recommended that the SSi to SHy ratio be within the scope of 1.5–2.5 in order to gain FAGPC with superior compressive strength.

3.1.5 Curing Temperature and Age

The temperature for curing substantially affects the geopolymerization reaction, which is responsible for the increase in strength. Typically, there are three curing methods for GPC: ambient curing, oven curing, and steam curing.

Hardjito et al. (2004) carried out research to look at the impact of varying temperatures needed for curing in the oven on the Cst of FAGPC. Their findings demonstrated that as the oven curing temperature rose, the Cst increased, as shown in Fig. 11. Nevertheless, the increase in Cst was not substantial over the 60°C curing temperature. Another study was conducted by Adak et al. (2017) for evaluating how different curing conditions affect FAGPC's mechanical characteristics. According to Fig. 12, the Cst of the specimens treated under elevated curing circumstances was greater than that of specimens cured under ambient curing settings at the ages of 3, 7, and 28 days. Chithambaram et al. (2018) observed that the compressive strength of FAGPC raised initially as the temperatures in the oven rose up to 90^{O} C, but then declined. Hassan et al. (2019) assessed the impact of different curing situations on mechanical characteristics of FAGPC. The researchers reported that the Cst of FAGPC after 7 and 28 days varied from 10.50 to 31.11 MPa when subjected to heat curing at 75 °C. However, when subjected to ambient curing, the Cst decreased to a range of 4.5–10 MPa. Moreover, it was discovered that the Cst of FAGPC exhibited a 67% increase in comparison to ambient curing conditions for a duration of 28 days when subjected to a temperature of 75 °C. Based on Sajan et al. (2021) the Cst of the geopolymer exhibits an upward trend as the curing temperature rises from 20 to 60 °C. They discovered that the strength development of geopolymer cured at 60 °C is much more than at lower temperatures. Verma and Dev (2022) reported that the strength of the GPC mix design decreases

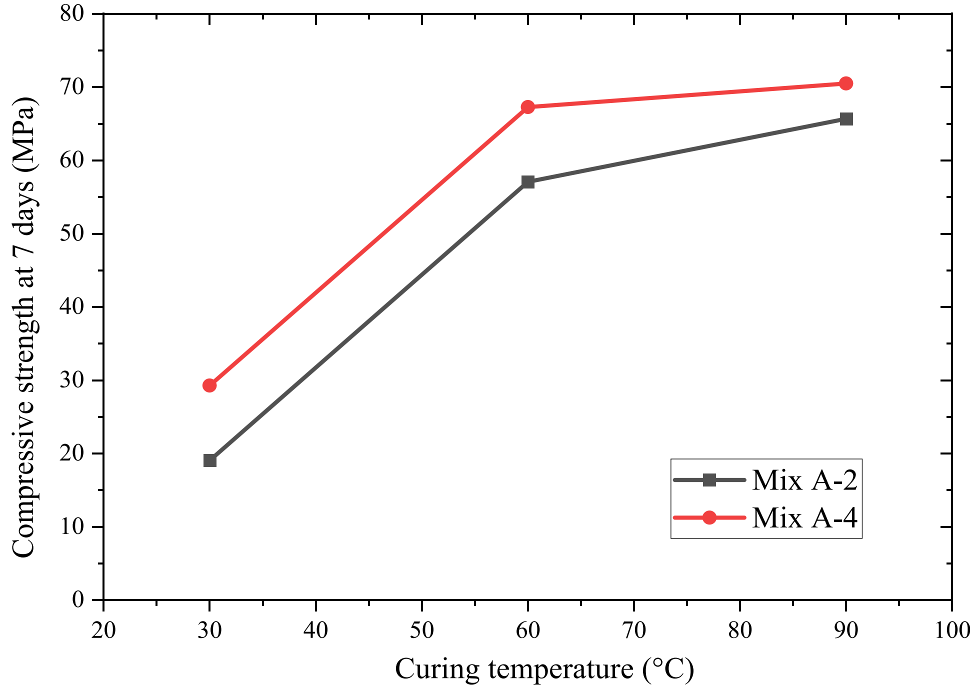
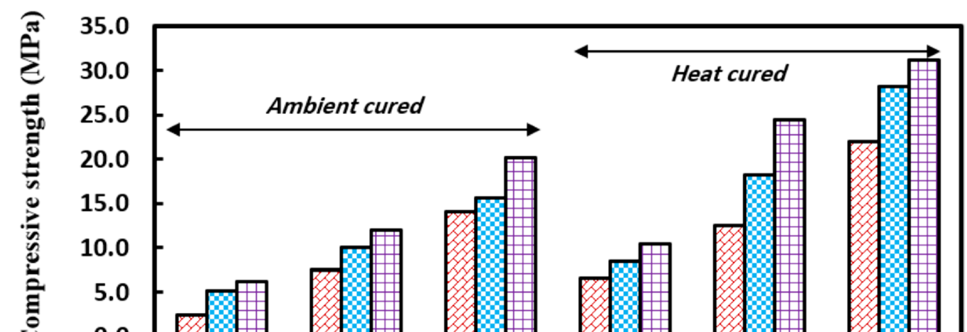


Fig. 11 Effect of different oven curing temperatures on the compressive strength (Hardjito et al. 2004)



	3 Days	7 Days	28 Days	3 Days	7 Days	28 Days
M1A0FA	2.5	7.6	14.0	6.57	12.49	22
M1A5FA	5.2	10.0	15.6	8.43	18.2	28.23
M1A10FA	6.2	12.0	20.2	10.36	24.44	31.2

Fig. 12 Impact of various curing conditions on the compressive strength of FA-GPC (Adak et al. 2017)

above the curing temperature of 100^{O} C, but it increases with further curing temperature increases.

Most of the research used elevated curing temperature to cure GPC as opposed to other types of curing conditions, and it was discovered that the most often used curing temperature varied from 60 to 80. The Cst of specimens subjected to oven treatment is higher than that of specimens cured under ambient conditions. The increase in temperature of the geopolymer concrete specimens leads to an acceleration of the geopolymerization process, resulting in an enhancement of the compressive strength. (Albitar et al. 2015).

On the other hand, Increasing the heat curing period to 90 h (Hardjito et al. 2004; Vora and Dave 2013), and 110 h increased Cst (Patankar et al. 2014). Kumar et al. (2017) used a closed steam chamber and a hot air oven to cure geopolymer concrete. Regardless of the curing method used, around 80–90% of the Cst achieved after 28 days was reached within 7 days. This was achieved by initially curing the samples at a temperature of 60 °C for 24 h, followed by maintaining them at room temperature until testing. Additional experiment conducted by Nguyen et al. (2020) revealed that within 7 days, over 93% of the 28-day Cst can be achieved. In addition to that some researchers investigated the effect of microwave curing on the strength of geopolymer. Microwave heating uses internal energy dissipation to excite molecular dipoles in electro-magnetic regions, resulting in faster and more consistent heat transfer (Kim et al. 2015). In a study conducted by Graytee et al. (2018), it was shown that geopolymer pastes treated in a microwave oven had significantly higher compressive strength compared to the control group that underwent traditional oven curing at 90 and 120 °C for the identical duration. Because microwave radiation promoted a higher hydration degree of precursors in geopolymer, Kastiukas et al. (2020) said that it took less time to make precast geopolymer concrete with the desired strengths using microwave radiation than oven curing. Under enhanced temperature curing, the ideal strengths can be achieved by precisely adjusting the temperatures, powers, and curing time to eradicate micro-cracking from the samples.

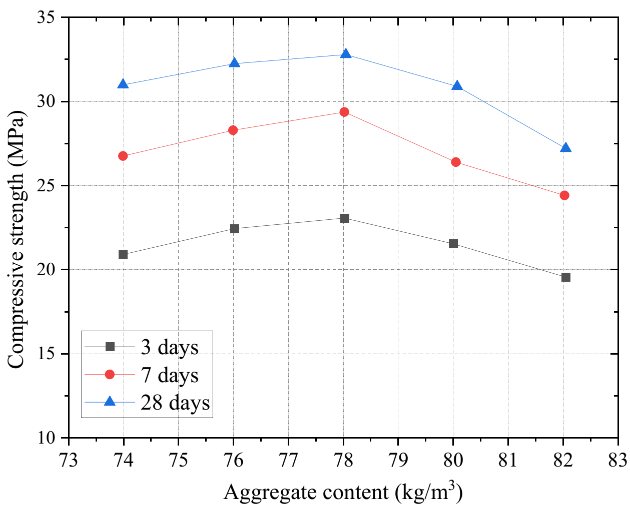
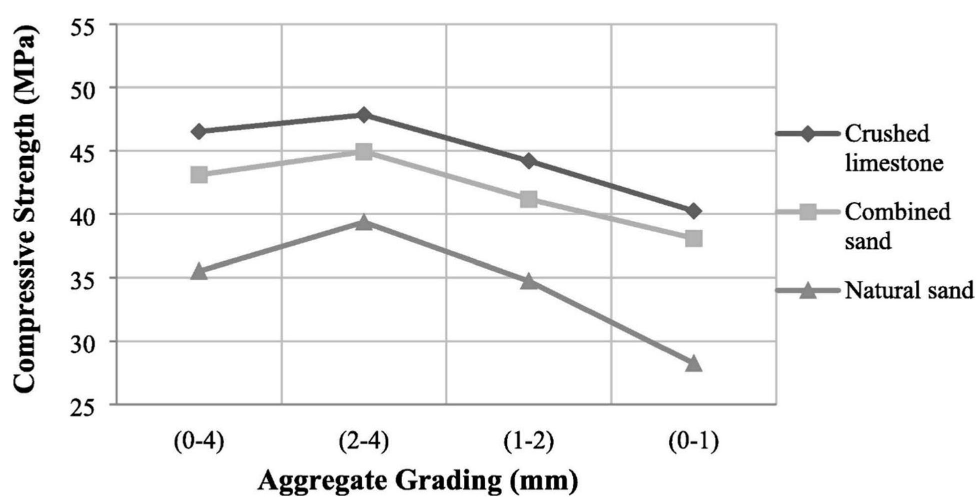


Fig. 13 Effect of aggregate content on the Cst of FAGPC (Chithambaram et al. 2018)

3.1.6 Aggregate Content

Geopolymer concrete compositions use the same aggregates as ordinary concrete, including both fine and coarse particles. Chithambaram et al. (2018) examined the effect of total aggregate content on the Cst of FAGPC at different molarities and curing temperatures. They utilized five different volume fractions of total aggregate contents, ranging from 74 to 82%. As illustrated in Fig. 13, it was found that the Cst of FAGPC grew as the total aggregate content increased up to 78% and then decreased because of insufficient binding material to keep the aggregates together. Mermerdaş et al. (2017) used three different kinds of aggregates: crushed sand, river sand, and a combination of crushed and river sand. The geopolymer mortar mixtures' Cst varied from 28.2 to 47.8 MPa on 1 day, when the specimens were cured for 24 h at 90 °C. Furthermore, it was shown that the geopolymer mixture containing crushed sand had a higher Cst in comparison to other aggregates. This was ascribed to the angular form and rough surface texture of the crushed sand, which raise the surface-to-volume ratio and enhance the binding properties between the aggregates and paste matrixes. Furthermore, they stated that, in comparison to the other classes, the crushed sand with a coarser grade (2–4 mm) had the highest Cst, as seen in Fig. 14. The Cst of geopolymer concrete based on fly ash and GGBFS was studied by Nuaklong et al. (2016), with different grades and quantities of fine aggregate. By using recycled concrete aggregates, they claimed to be able to create FAGPC with a Cst of 30–38 MPa after 7 days. However, this value is marginally lower than the Cst of 38–41 MPa after 7 days achieved by FAGPC made with crushed limestone aggregate.

Fig. 14 Cst of GPC with different aggregate grading (Mermerdaş et al. 2017)



3.1.7 Extra Water and Superplasticizer Dosage

Two important aspects strongly influence the hardened properties and workability of FAGPC: the superplasticizer and water content. Due to its higher viscosity compared to water, the alkaline solution used in geopolymer concrete, consisting of SHy and SSi, creates a mixture that is more adhesive and cohesive than ordinary concrete (Deb et al. 2014). To further improve the workability of the geopolymer concrete mixture, additional water and superplasticizer are used.

Hardjito et al. (2004) performed a test experiment to evaluate the impact of dose of superplasticizer on the compressive strength of FAGPC. They employed a range of water reduction admixtures. The results they obtained reveal that adding superplasticizer to the geopolymer concrete mixture enhances workability of the FAGPC in one sense and has no effect on Cst up to approximately 2% fly ash by mass on the other. When the dosage of the superplasticizer was increased after 2%, the compressive strength decreased. Incorporating additional water into the geopolymer concrete mixture under different curing temperatures resulted in a considerable decrease in Cst. Similarly, a research investigation has been conducted by Aliabdo et al. (2016) to investigate the impact of higher water and superplasticizer concentrations on the Cst of FAGPC. They came to the conclusion that Cst dropped with increasing amounts of water added to the geopolymer concrete mixture. This reduction in Cst was below 10% but not exceeding 30 kg/m^{3}of further water, however, the percentage rose to 24% when an additional 35 kg/m^3 of water was utilized. Furthermore, evidence demonstrated that the Cst of FAGPC exhibited a slight decrease with an increase in the dosage of the superplasticizer. Another experiment was done by Albitar et al. (2015) to assess the effect of superplasticizer and water to binder ratio on the Cst of FAGPC. With an increase in the dose of superplasticizer and the water to binder ratio, there was a significant decrease in Cst. Gupta et al. (2021) assessed the impact of superplasticizers on compressive strength. With increasing amounts of superplasticizer (1%, 2%, and 3%), two types of samples are created. They found that a 3% superplasticizer dosage provides the greatest increase in mechanical properties.

In general, the Cst of the geopolymer concrete composite is reduced as the amount of water and superplasticizer in the mixture is increased. This is because the increased quantity of these components leads to a decrease in contact with the source of the activating solution and the material that reacts. Additionally, increased excess water content in geopolymer concrete reduces its compressive strength. This is because water evaporates from the material during high temperature curing inside ovens, creating empty spaces and hollows inside the structure. Moreover, the introduction of excess water can impact the alkalinity of the GPC matrix, resulting in a deceleration of the polymerization process.

4 Conclusions and Recommendations

4.1 Conclusions

Geopolymer concrete is seen to be highly appropriate when considering sustainable development. Many of the requirements are met by this unique concrete, including high strength, the use of secondary materials, a low carbon trace, minimal levels of greenhouse gas emissions, strong resistance to frost, and so on. This study included a revised data analysis of the compressive strength of geopolymer concrete. The following conclusions can be drawn.

1- The ratio of alkaline solution to binder (Al/Bi) significantly affects the compressive strength of FAGPC. Some scholars assume that as the Al/Bi grew, the Cst improved. Simultaneously, numerous researchers observed a decline in compressive strength with increased Al/Bi ratio.
2- Raising the molarity of SHy can enhance the compressive strength of FAGPC composites. Maintaining the molarity of SHy within the range of 10 –16 M was recommended to achieve the desired Cst behavior in FAGPC blends.
3- The compressive strength value for FAGPC increases as the ratio of SSi to SHy increases, but only until about 2.5 before it starts to go down again.
4- The Cst of the geopolymer concrete is diminished by raising the water content or introducing additional water to the FAGPC.
5- Including superplasticizer increases the Cst of FAGPC composites, reaching a peak at approximately 2.5% fly ash amount.
6- The heat-curing protocol is the most effective curing procedure for achieving early and high compressive strength in FAGPC.
7- For successful polymerization and sufficient Cst in FAGPC, it is recommended to utilize oven curing temperatures ranging from 50 to 80 °C and a curing time of 24 h.

4.2 Recommendations

Existing literature comprehensively analyses the compressive strength of geopolymer concrete produced from fly ash. However, the amount of research conducted that concentrates on the composite's other mechanical properties is still somewhat restricted. To enable this composite to meet the standards of the construction sector, it is necessary to thoroughly assess specific mechanical parameters, such as modulus of elasticity, splitting tensile strength, and flexural strength. To better understand GPC mechanical behavior, the microstructure/nanostructure and chemistry of geopolymers must be thoroughly explored.

Author Contributions The article was written with the collaboration of Both contributors. All authors agreed on the article's final version. Both authors contributed to the writing and editing of the articles and the concept design and study proposal. The scientific information was gathered, and the text was written with help from Both authors.

Declarations

Conflict of interest The authors acknowledge no conflicting interests regarding this research.

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